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Exploring the Formation Mechanism of Radical Technological Innovation:
An MLP Approach

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ABSTRACT

This paper identifies three stages in the radical technological innovation process, namely formation process in niches, breaking out of niches and entering regimes, and new regime formation. It then adopts multi-level perspective (MLP) to explore the formation process, operating mechanism, breakthrough path, and impact factors of radical technological innovation. A three-phase model, which includes formation of radical innovation, breakout of radical innovation, and new regimes construction, is proposed to analyze radical technological innovation. The model is adopted in a case study to analyze the leapfrogging development of technologies in China's mobile communication industry. This paper enriches technological innovation theory and provides supports for policy making and guidance for industries/enterprises practices regarding technological innovation in emerging economies.

KEYWORDS

Innovation, MLP, Multi-Level Perspective, Radical Technological Innovation

1. INTRODUCTION

Technological innovation is a main power to promote economic growth (Chen & Lei 2020; Chen & Xie 2018; Hämäläinen & Inkinen 2019; Kumar and Chanda 2018; Lei et al 2019, 2020; Lu 2016; Sui and Liu 2020; Tan et al 2010; Wang et al 2007; Wipulanusat et al 2020; Xu et al 2008, 2011, 2013, 2014, 2016, 2018, 2020; Xu and Viriyasitavat 2014, 2019; Yang et al 2018; Zhang et al 2018). Particularly, radical technological innovation generates substantial competitive advantages for enterprises (Li 2018, 2020). Schumpeter (1942) first introduced the concept of innovation into the field of economic growth. Later, Utterback and Abernathy (1975) categorized innovation into incremental innovation and radical innovation based on technologies' novelty. Given that technology discontinuity (Tushman & Anderson, 1986) and disruptive technologies (Christensen, 2013) generate leapfrog value for customers, scholars proposed the concepts of breakthrough technology innovation, disruptive innovation, and radical innovation. They have investigated breakthrough technology innovation, disruptive innovation, and radical innovation intensively from diverse perspectives.

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However, existing innovation literature focuses on either enterprises' internal innovation practices or their innovation in business model. Manufacturing process is considered as the only origination of innovation. According to tech-sociology theory, factors, such as institution, user, and social network, affect technology development (Bleda & Río, 2013; Llerena & Matt, 2006). A comprehensive analysis of innovation process and its impact factors is missing. A hierarchical structure of impact factors for radical innovation is not available.

Accordingly, this paper adopts Multi-level Perspective (MLP) to analyze the formation motivation of radical innovation. It presents the temporal structure and hierarchical structure of factors that affect radical innovation and explores the formation mechanism of radical innovation. In specific, this paper identifies three stages in the radical technological innovation process. It then applies MLP to explore the formation process, operating mechanism, breakthrough path, and impact factors of radical technological innovation. A three-phase model, which includes formation of radical innovation, breakout of radical innovation, and new regimes construction, is proposed to analyze radical technological innovation. At the end, the model is applied in a case study to analyze the leapfrogging development of technologies in China's mobile communication industry. This paper makes theoretical and practical contributions by enriching technological innovation theory and providing supports for policy making and guidance for implementing technological innovation.

2. LITERATURE REVIEW

2.1. Breakthrough Technological Innovation, Disruptive Innovation, and Radical Innovation

Breakthrough technological innovation refer to the new technologies that depart from existing technological trajectory (Li 2012, 2013a, b; Luo & Zhang 2015; Wu & Wang 2014). Wu and Wang (2014) proposed four paths of breakthrough technological innovation in strategic emerging industries, including the paths of high-end penetration of peripheral modules, key breakthroughs in key modules, architectural rules reconstruction, and module-architecture coupling upgrading. Luo and Zhang (2015) proposed five phases in breakthrough technological innovation, including fuzzy front-end creative generation, research and development, pilot production, commercialization and formation of new technology standards. Jiang, Li, Yin, and Qu (2017) pointed out that breakthrough technological innovation consists of two phases: product development and market development. Shao, Zhan, and Wu (2017) analyzed the process of breakthrough technological innovation from two perspectives, namely creative idea and implementation of new product development.

Disruptive innovation usually enters low-end market or new market first and then gradually invades mainstream market (Li & Zang, 2015; Shi, Yu, & Xiang, 2016; Xue, 2016; Vecchiato,2017; Zang & Li, 2016). It originates from new technologies and the changes of business models or potential processes (Christensen, 2006). Adner (2002) explored the formation mechanism of disruptive innovation from the perspective of users' needs and pointed out that the changes of requirement structure are important preconditions for disruptive innovation. Li and Zang (2015) pointed out that latecomers, who aim to gain competitive advantages vis disruptive innovation, need to recognize opportunities, reconstruct value network, and destruct mainstream market. Shi, Yu, and Xiang (2016) found that the process of disruptive innovation has less technical proprietary and more technological opportunities. Su, Liu, Wang, Chen, & Jiang (2016) revealed the evolution trajectory of disruptive technologies and proposed the concept of patent impact factor to realize the early recognition of disruptive technology. Xue (2016) proposed the market knowledge-knowledge integration ability - disruptive innovation framework for disruptive innovation required by market. Zang and Li (2016) explored how latecomers choose the best time to enter a market through disruptive innovation by considering market, technology, industry, and policy. Dou, Dai, Li, and Tian (2018) analyzed the disruptive innovation path of Defense Advanced

Research Projects Agency and presented a 5-phase analytical model, which consists of technology choice, project organization, project implementation, technology transformation and project exit.

Dosi (1982) defined radical innovation as an extraordinary breakthrough introduced by new technological paradigm. Freeman (1992) noted that radical innovation is a discontinuous process. The characteristics of radical innovation are determined by technology, enterprise competence, and market. Radical innovation generates new technologies, which disrupt the development trajectory of existing technologies, secure the path-dependence of technology development, and exhibit technology discontinuousness. Implementing radical innovation might destroy enterprises' existing knowledge accumulation or technological capability, such as the capabilities accumulated in the areas of R&D, manufacturing, and marketing. Therefore, enterprises need to control the resources invested on existing technologies. This causes the increase of sunk costs. Existing technologies satisfies users' needs in the main market, whereas new technologies could provide wholly different performance attributes, which meet users' needs in an emerging market, or create new value network and change users' behavior. The focus on radical innovation has gradually shifted from technological novelty and technological discontinuity to commercialization phase of new technologies.

Existing studies have revealed that radical innovation can be initiated by new entrants. For instance, Henkel, Rønde, and Wagner (2015) pointed out that radical innovation is easier generated by new entrants than by incumbents, because more entrants in an industry tend to generate more qualified radical innovations, and the new entrants will realize the commercialization of innovation through technology transfer or authorization. Slayton and Spinardi (2016) indicated that extra large amount of process innovation is required in the process of radical innovation's expansion from niche to regime. Beck, Lopes-Bento, and Schenker-Wicki (2016) noted that public R&D funding has significant positive effect on radical innovation but not on incremental innovation. Van Lancker, Mondelaers, Wauters, and Van Huylenbroeck (2016) analyzed the three phases in a radical innovation and explored the system functions of each phase via the lens of an organizational innovation system. Table 1 lists the existing research on disruptive innovation, breakthrough technological innovation, and radical innovation.

Studies on innovation process disperse in the aspects of market-entry process, product formation process, technological invention, and its commercialization. Although scholars defined breakthrough technological innovation, disruptive innovation, and radical innovation from different perspectives, these concepts seem to refer to the same object. Among the studies on disruptive technologies, some focus on market (Luo & Zhang 2015; Wu & Wang,2014), whereas others highlight new technologies (Jiang et al., 2017; Shao et al., 2017). Su, et al. (2016) and Dou, et al. (2018) argued that because disruptive technologies focus on new technologies created by major technological paradigm changes, they emphasize novelty in innovations. They concluded that the concepts of disruptive innovation and radical innovation are exchangeable.

2.2 Multi-Level Perspective

Multi-level Perspective (MLP) refers to an analysis on a socio-technological system consisting of niches, regimes, and landscapes (Geels, 2002, 2004; Geels & Schot, 2007; Smith, Voß, & Grin, 2010). It focuses on the dimensions of society and recognition in innovation process and extends the evolutionary economics into socio-technological transition (Geels, 2006; Raven & Geels, 2010). MLP emphasizes the effects of niches process, existing socio-technological regimes, and landscapes on the development of new technologies.

As fertile soil, niches provide protective space for radical innovation (Geels, 2002, 2004; Geels & Kemp, 2007; Geels &Schot, 2007; Lopolito, Morone, & Taylor, 2013; Markard & Truffer, 2008; Smith et al., 2010). Examples of niches include research institutes or R & D labs in enterprises. Markard and Truffer (2008) categorized niches into technology niche and market niche. Technology niche is a complicated adaptive system. The advantages of new technologies are not significant in technology niche. Therefore, new technologies need supports from niche actors and institutions. Market niche is

Table 1. Existing research on disruptive innovation, breakthrough technological innovation, and radical innovation

Scholars	Topic	Connotation	Innovation process	Industry/ enterprise types	Situation factor
Xue(2016)[6]	Disruptive innovation	Not necessarily be motivated by new technologies, more market-motivated	Market knowledge, knowledge integration ability, disruption innovation	Technological small and micro enterprises	Market knowledge
Shi et al.(2016)[7]	Disruptive innovation	Entering into market from new technological trajectory through introducing new attributes or attribute set			Technological regime
Li and Zang(2015)	Disruptive innovation	Technology simple and convenient, low product price and simple function, positioned in low-end market and new market	Opportunity recognition, value network reconstruction, mainstream market destruction	Innovative science and technology enterprises(Media Tek)	Construction of competitive advantage
Zang and Li(2016)	Disruptive innovation	Not related to complicated technologies reform, launch easy-use and low price product, invasion into mainstream market through product performance improvement	Low-end market entry, new market entry, mixed market entry	Innovative science and technology enterprises(MI company)	
Vecchiato(2017)	Disruptive innovation	Bring about attributes that are different from mainstream	Disruptive technologies firstly satisfy the needs of social relations, new market merges, new entrants recognize new market, new entrants develop product that could meet both the needs of mainstream market and emerging market	Mobile communication and image industry	Managerial recognition
Su et al.(2016)	Disruptive innovation	Develop along a new technological path, and make the whole technological system and its product component/ performance/cost to achieve radical breakthrough	Early technology recognition, several technical breakthrough	Smart mobilephone	
Dou et al.(2018)	Disruptive innovation	Transformative substitution of traditional technologies in an unexpected way	Technology choice, project organization, project implementation, technology transformation, project exit	Defense Advanced Research Projects Agency	SNM
Wu and Wang(2014)	Breakthrough technological innovation	Leading to completely change of the whole industry, and ultimately become to be new industry innovation	High-end penetration of peripheral modules path, key breakthroughs in key modules path, architectural rule reconstruction path, module-architecture coupling upgrade path	Strategic emerging industries	Modularization
Luo and Zang(2015)	Breakthrough technological innovation	Leapfrog of technology development, novelty of product implication, commercialization of innovation result	Fuzzy front-end creative generation, R&D, pilot production, commercialization, new technological standards formation	New technology-based small enterprises	Knowledge management
Jiang et al.(2017)	Breakthrough technological innovation	Measure innovation from two aspects of technology breakthrough and market destruction, emphasizing huge leap of technology performance and destruction of market structure	Product development(idea formation phase and product formation phase), market development(the phase of niche market occupation and mainstream market occupation)		Innovation network

continued on next page

Table 1. Continued

Scholars	Topic	Connotation	Innovation process	Industry/ enterprise types	Situation factor
Shao et al.(2017)	Breakthrough technological innovation	Measuring innovation from the degree of technology alteration and market destruction, emphasizing huge leap of technology performance	Creative idea phase and implementation phase of new product development		
Henkel et al.(2015)	Radical innovation	Creating a breakthrough	Generating radical innovation by start-up enterprise, acquiring innovation and commercializing by incumbents	Electronic design automation industry	
Slayton and Spinardi(2016)	Radical innovation	Discontinuous, needs to develop new knowledge and new product	Radical innovation in the niche, expansion from niche to regime(need extra radical innovation)	Boeing 787	MLP
Beck et al.(2016)	Radical innovation	New resolution that is different from previous one			R&D funding
Van Lancker et al.(2016)	Radical innovation		Idea creation, invention, commercialization		Organizational system innovation

natural abnormal phenomena of existing regimes. In market niche, the unique selection criterion is completed. The formation of market niche is one of the key factors for the success of technological changes (Rennings, Markewitz, & Vögele, 2013).

Regimes refer to a series of not wholly coherent rules used by various social groups (Geels, 2002). Regimes are embedded in social groups and can be understood as a deep structure of socio-technological system. In accordance with a taxonomy of micro- meso-macro, niches belong to the micro level and regimes refer to a coherent, highly related, and stable structure that lie in meso level. Regimes are featured by certain product and technology, knowledge stock, user practices, anticipation, normalization, and institutions (Markard & Truffer, 2008). Regime analysis focuses on the pressure generated by technological changes for enterprises, such as standards, profitable capabilities, skills, and knowledge. Regime analysis also considers the pressure comes from institutional structure, including the changes of broader political economic environments or socio-cultural attitudes and trends (Geels, 2004). Regimes represent the selection environment of technological development in one domain or an industry. They provide guarantee for the stableness of existing technology development and the occurrence of technological trajectory. The resource-dependent relationship required by regimes' operation binds regime members. Thus, one element's change will lead to other elements' changes (Geels, 2002). Existing regime possesses lock-in effect (Geels, 2011), implying the rules set, such as shared beliefs, life styles and user practices, institutional arrangements, and skills, build the barrier that inhibits the diffuse of radical innovation(Markard & Truffer, 2008). Any attempt to avoid existing regime members and cultivate alternative regime could face the strong resistance from the stakeholders in the existing regime.

Regimes provide a relatively stable structure. But this does not mean that regimes are unchangeable. Regime reform is incremental and path-dependent (Geels, 2002; Smith et al., 2010). Regimes will be in a stable status when there is no influence brought by external factors. However, this is a relative stability, which is a dynamic stability (Geels & kemp, 2007; Geels & Schot, 2007; Raven & Verbong, 2007). Dynamic stability implies the occurrence of incremental innovation, such as the continuous improvements of production process, and the accumulation of small adjustments leads to stable trajectory. Regime dynamics may come from the tensions caused by the influences of internal and external factors. It further creates opportunities for niches to acquire focus and influence (Smith et al., 2010).

Landscape is an external structure or context (Geels, 2002), in which actors interact, including environment and population changes, new social movements, political consciousness alteration, broad economic adjustments, emerging scientific paradigms, and cultural development (Smith et al., 2010). The behavioral structure generated by landscape is more rigid than that of regimes. Therefore, landscape is not affected directly by actors or changed (Geels, 2004). As a result, changes of landscape usually occur incrementally (Geels & Schot, 2007). Research on landscape mainly focuses on its effect on regimes and niches. Changes of landscape generate a continuous spur, which is called selection pressure (Smith, Stirling, & Berkhout, 2005). The spur forces existing technologies to accommodate the pressure. Geels (2011) noted that the origin of the pressure is usually related to the socio-technological continuous development, such as climate changes and peak oil theory. Lopolito et al. (2013) grouped the pressure into three categories, namely economic pressure, social pressure, and technological pressure. Occurring at the enterprise level, economic pressure can alter enterprise's profitable capabilities, such as pricing, competition, and contracts. Social pressure originates from institutional structure and tradition. It is generated by changes of broad political economic environment and alteration of socio-cultural attitudes and trends, such as alteration of population structure, emergence of consumption culture, and global new liberalism model. Technological pressure originates from the changes of technical designs elaborated by engineers and researchers. The pressure of landscape is the sources of regime reform, which arouses regime responses and creates opportunities for niches (Lopolito et al., 2013).

There is an embedded relation among niche, regime, and landscape (Geels, 2002; Smith et al., 2010). In specific, niches are embedded in regimes, which are embedded in a landscape. Accordingly, landscape provides a macro-level structural context. Niche and regime lay in a broad landscape consisting of social and material factors. In the structure, each level represents a factor configuration, and a higher level is more stable (Geels, 2011). Regimes exert structural strength on radical innovation originated in niches (Smith et al., 2010), which inhibit the diffusion of radical innovation. It is difficult for radical innovation to diffuse out of niches when regimes are strong and stable. Meanwhile, the configuration will loosen when regimes face problems. At that time, radical innovation escapes from niches and combines into socio-technological configuration (Geels, 2002). The structure of niches is like that of regimes. However, there are great differences in stability and rules constraints between niches and regimes. The community of regimes is large and stable, whereas that of niches is small and unstable. The rules of regimes are stable and clear, whereas the rules of niches are unstable and in the forming process (Geels & kemp, 2007). Consequently, rules exert more influence on regimes than on niches. Landscape represents external environment consisting of processes and factors, which affect niches and regimes (Markard & Truffer, 2008). The effects are usually bidirectional. Development of landscape stabilizes existing regime (Geels & kemp, 2007), and therefore, hinders the development of niches. For instance, factors in landscape, such as the growth of family wealth and car ownership and increased population mobility, stabilize the car-based transportation system. On the other hand, changes in landscape generate pressure on regimes and create opportunities for niche technologies. For instance, climate changes and energy shortages exert pressure on transportation sector and promote new energy technologies. In turn, some regimes have a great influence on the development of landscape, such as the catalytic effect of aerospace and communication regimes on socio-economic globalization. As the elements in the action mechanism, niches and regimes affect activities through social structure, whereas landscape affects niches and regimes through actors' perception and explanation (Geels & Schot, 2007; Smith et al.,2005). Pressures generated by landscape usually do not make regime actors alter immediately. The alter of regimes involves conflicts, debates, power struggle, and explanation process (Smith et al., 2005).

MLP focuses on the dynamics and interaction among niche, regime, and landscape and examines how the interaction promote the transformation from one niche technology to one regime technology.

Thus, MLP provides an analytical perspective for technological innovation process. It has been applied in transition research. For example, Geels and Schot (2007) pointed out that transition originates from the interaction among niche, regime, and landscape. Niche innovation triggers internal motivation. Landscape changes exert pressure on regimes. And regimes' instability provides opportunity window for niche innovation. Moreover, MLP proposes three problems that policy portfolio needs to resolve, namely the instability of existing regime, promotion of niche innovation, and the process of transforming niche innovation into main regime (Smith et al., 2010).

3. RADICAL INNOVATION'S FORMATION MECHANISM

3.1 Motivation of Radical Innovation

The motivation of niche innovation originates from pressure in regimes. Pressure in regimes changes in the following five situations. (1) Landscape changes exert pressures on regimes, and result in reconfiguration of regimes' internal structure. For instance, the pressures originated from climate changes on energy and transportation sectors result in searching new technology and altering public policies. Moreover, values and ideology also generate pressure on regimes. (2) Internal technological problems lead to actors' exploration and investment on new technological directions. Some technological problems, such as existing technologies' bottlenecks and increased returns, weaken the trusts on existing technologies and alter the anticipation about new technologies. (3) Pressures generated by negative externalities, such as environmental influence, health threats, and focus shift to safety. Regime actors usually ignore these negative externalities. However, newcomers focus on these negative externalities and utilize these opportunities for implementing innovation. (4) Regime generates pressure and creates opportunities for niches when existing technologies cannot meet users' preferences. Users' needs change when users focus on negative externalities, consumption culture changes, prices changes, or users contacts new technologies and find new functions. (5) Strategies and competition between enterprises disclose regimes and provide opportunities for radical innovation. Technological innovation is the way to acquire competitive advantages. Enterprises invest in radical innovation when they consider a niche possess strategic potential in the long run.

3.2 The Formation Mechanism of Radical Innovation

Radical technological innovation involves not only the creation of new knowledge and new technologies, but also the process of commercialization (Llerena & Matt, 2006; Schumpeter, 1947). Scholars pointed out that new technologies perform poorly in the initial stage and need to accommodate existing socio-technological regimes. However, existing regimes encourage the incremental innovation of existing technologies and resists radical innovation that could result in change of regimes. Therefore, radical innovation needs to experience a difficult process before entering market. Scholars proposed several frameworks to analyze how a radical innovation can successfully enter regimes, such as strategic niche management (Kemp, Schot, & Hoogma, 1998) and transition management (Rotmans, Kemp, & Van Asselt, 2001). Particularly, Geels and Schot (2007) pointed out that transition originates from the interaction among niche, regime, and landscape. Niche innovation triggers internal motivation. Landscape changes exert pressure on regimes. And regimes' instability provides opportunity window for niche innovation.

To explore the formation process, operating mechanism, and breakthrough path of radical technological innovation, we present a three-phase model for radical technological innovation based on MLP as shown in Figure 1. We identify three stages in the radical technological innovation process, namely formation process in niche, breaking out of niche and entering regime, and new regime formation.

Niches are a source of transition idea and capability (Smith et al., 2010). Technological knowledge and capabilities accumulated in niches provide basis for technology experimentation. Depending

Figure 1. The three-phase model for radical technological innovation

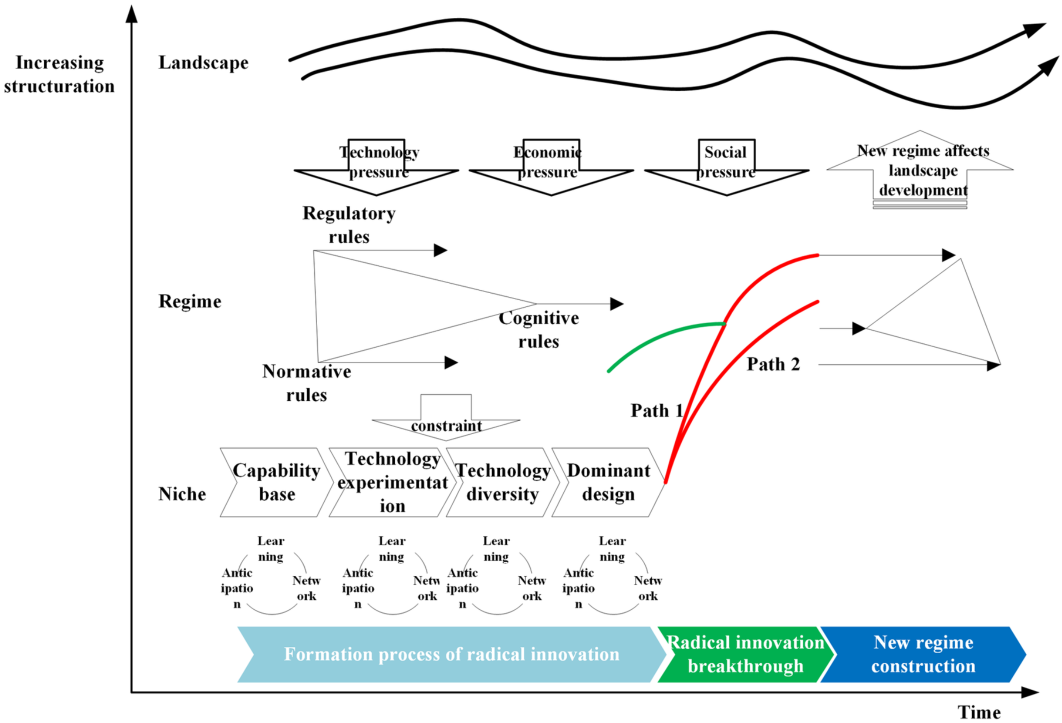
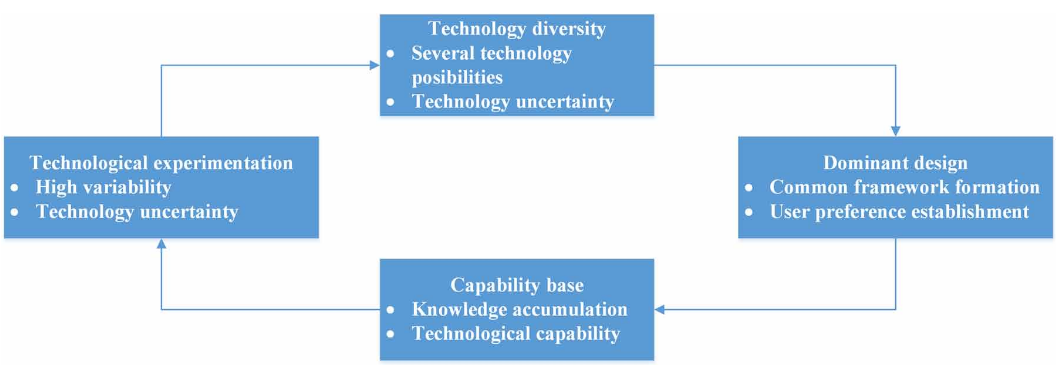


Figure 2. The formation process of radical technological innovation



on these technological knowledge and capabilities, the small actor network (usually newcomers) dedicates on radical innovation (Geels & Schot, 2007). Niche actors acquire the best design through experimentation and exploit user needs (Geels & Kemp, 2007). In this stage, technological experimentation has high uncertainty and variability because it is a trial and error procedure. It allows attempt in all directions and results in technology diversity. However, co-existence of various technologies will not last long. Radical innovation proceeds to stability gradually and forms a dominate design (Geels, 2002). Figure 2 illustrates the formation process of radical innovation.

3.3 The Operating Mechanism of Radical Innovation

Radical innovation activities in niches need some operating mechanisms. Anticipation, learning, and network are the three most important mechanisms and they are the basis for niche success. Moreover, some external factors, such as government, generate impact (Geels, 2011; Geels & Schot, 2007; Lopolito et al., 2013; Suurs, Hekkert, & Smits, 2009).

Anticipation of a radical innovation is the basis for actors to implement technological experimentation (Van der Laak, Raven, & Verbong, 2007). The anticipations of actors may differ initially. They negatively affect how objectives are ascertained and their priority (Smith et al, 2005). The initial obstacles can be overcome through formulating a shared vision among potential actors (Lopolito et al., 2013). In this stage, new technologies represent a hope for success because they lack clear functions or market and represent an interesting direction for development. Smith et al. (2005) pointed out that the important roles played by innovation vision, including describing a possible space, tools for ascertaining problems, a stable framework to set goals and monitor processes, and constructing actor network. The uncertainty of radical innovation is high because new technologies usually perform poorly and with high costs. The benefits generated by adopting new technologies are not clear. Although there are many supporters for new technologies, few choose the new technologies in practice. Radical innovation generates breakthroughs only when risks significantly decrease or anticipative profits significantly increase (Lopolito et al., 2013; Rennings et al., 2013).

Articulation of technology anticipation is vital for constructing socio-technological problems. To a large extent, encouraging actors attempt to resolve these problems. Anticipation is dynamic, affected by not only external environments but also the experimental results in niches. Anticipation will become more solid and stable when experimental results confirm initial visions, and plenty of actors will share the vision (Lopolito et al., 2013).

Learning mechanism is pivotal for improving technologies (Raven, 2005). Niches provide location for learning process (Geels, 2002, 2004). Scholars focus on different learning process. For instance, Geels (2002, 2004) categorized learning process into learning by doing, learning by using, and learning by interacting. Lopolito et al. (2013) noted that learning by doing and learning by interacting are the two main learning processes in niche. Amara, Landry, Becheikh, and Ouimet (2008) identified five learning processes in innovation novelty, including learning by searching, learning by training, learning by using, learning by doing, and learning by interacting.

Learning mechanism is embedded in each process. It promotes the dynamic evolution of niches. New knowledge needs to be learned constantly. Furthermore, how to transform new knowledge into new technologies needs to be learned in the process of technological experimentation. In the trial and error testing stage, new technologies are created through constant learning and accumulation. Learning mechanism promotes the process of dominant design formation through learning technological performance, user preference, and technological directions. Learning mechanism also promotes the accumulation of technological competence and knowledge through acquiring and absorbing internal and external resources.

Network provides resources for niche innovation activities. A single enterprise usually does not possess sufficient resources needed by technological experimentation. It relies on other actors in a niche to acquire important resources (Smith et al., 2005). The acquisition and transformation of resources need the support from a stable social network, including manufacturers, users, policy makers, and other social groups. The radical innovation's protective space role is supported by the social network constructed in niches. Relying on the knowledge spillover of the emerging social network, other actors' accumulated resources can be utilized to realize resources sharing in the network and to promote radical innovation. Moreover, the utilization of information technologies, such as internet+, big data, and IoT, promotes network formation and the efficiency of information transmission and processing, and further highlights network externalities.

Network scale and strength change in different stages of niche development. In the initial experimentation phase, the emerging network scale and strength are small and fragile due to the small number of enterprises involved in the innovation process and the limited resources invested. As more actors are involved, especially the enrollment of powerful sectors that generate the strategic resources needed by experimental activities, the network expands gradually and the actors' position in the network ascertains. Thus, their contributions to experimentation become clearer (Lopolito et al., 2013).

The involvement of government facilitates niche innovation to acquire broad social identification. Government can increase the success probabilities of new technologies and shorten development cycle through establishing rational policies. Lopolito et al. (2013) proposed two policy approaches, namely promoter and subsidizing, to promote niche innovation. Promoter aims to raise enterprises' anticipation to innovation values and future benefits. It promotes the generalization and application of new technologies. For example, government can create a beneficial environment for niche technologies through information dissemination. The information dissemination-based polity tools help to maintain a large number of niche technology supporters, and promote the emergence of a dense network, through which knowledge can be exchanged effectively, resources can be shared quickly, and ultimately, manufacturing costs can be decreased. In the initial experimentation phase, niche innovation encounters many unfavorable conditions and the process is hard. This weakens the anticipation to new technologies, decreases network resources, and delays niche innovation. Consequently, policy makers need to provide a favorable environment to promote the emergence of a stable niche. As the number of promoters increases, the scale and emergence speed of niches and the scale of supporter network increase. The other policy approach refers to government's subsidies to manufacturers that would like to weaken market selection mechanism and encourage the application of new technologies via innovation. Lopolito et al. (2013) noted that niches develop quickly when subsidy reaches up to 5%. Each policy approach has its advantage. Promoter role performs well in stability, while subsidy role performs better in the aspect of efficiency.

3.4 The Breakthrough Path of Radical Innovation

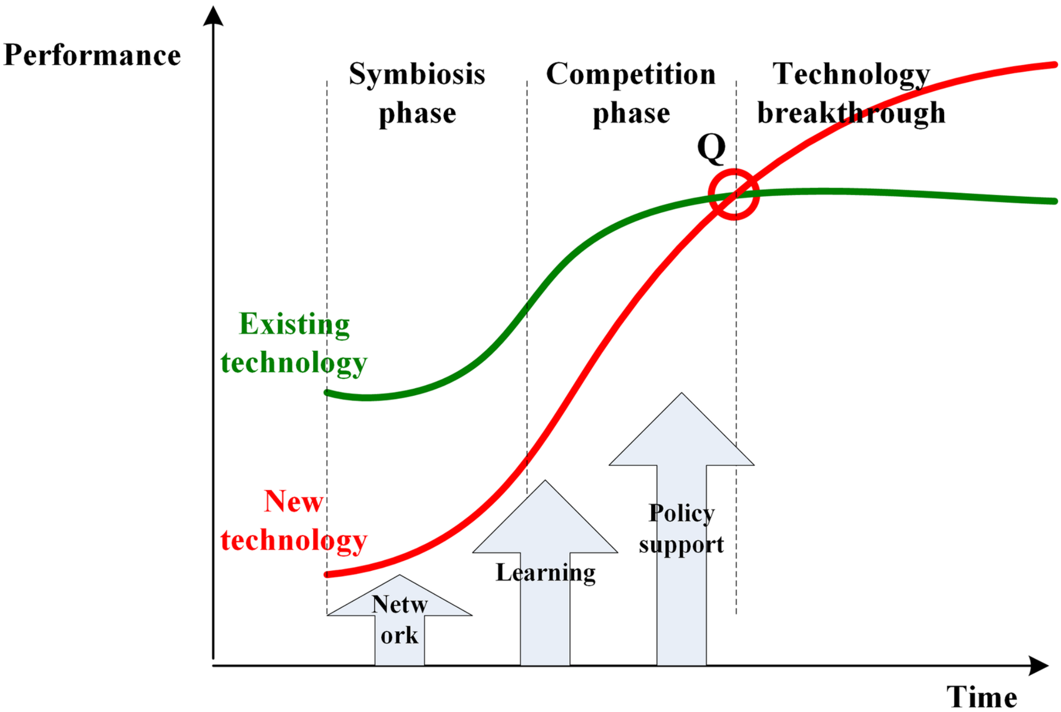
Changes in landscape occur when existing technology development encounters bottlenecks or when existing technology does not meet users' preference. They put stress on existing regimes and open the opportunity window for the interruption of non-regime members (Smith et al., 2005). Radical innovation breaks through niches when the constant processes of landscape and regimes create the opportunity window (Geels, 2002). However, not all niches utilize the opportunity window to make breakthrough. Some niches miss the opportunities when niche innovation is not sufficiently developed (Geels & Schot, 2007).

The relationship between radical innovation of niches and existing regime technologies can be competition or symbiosis (Geels & Schot, 2007). Competition implies that niche innovation will replace existing regime technologies, whereas symbiosis implies that niche innovation will not replace regime technologies through niche innovation. Instead, niche innovation enhances the problem-solving capabilities of existing regimes and improves performance of existing technologies. Based on the two kinds of relationships, this paper proposes two paths to acquire breakthrough of niche radical innovation, namely symbiosis-competition-breakthrough path and niche market entry-competition-market disruption path.

Symbiosis-competition-breakthrough path describes the three phases existing in the process of radical innovation breakthrough as illustrated by Figure 3. In the symbiosis phase, radical innovation does not compete with regime technology immediately due to its insufficient development in its initial stage and its disadvantage. Instead, radical innovation combines regime technologies, forming a common union as an add-on of regime technology or mixture to resolve the bottleneck encountered by regime technologies.

Regime technologies and product performance can be improved through the symbiosis combination of new and existing technologies. Radical innovation acquires constant improvement in the symbiosis relationship with regime technologies and then can be easier to be accepted by

Figure 3. Symbiosis-competition-breakthrough path



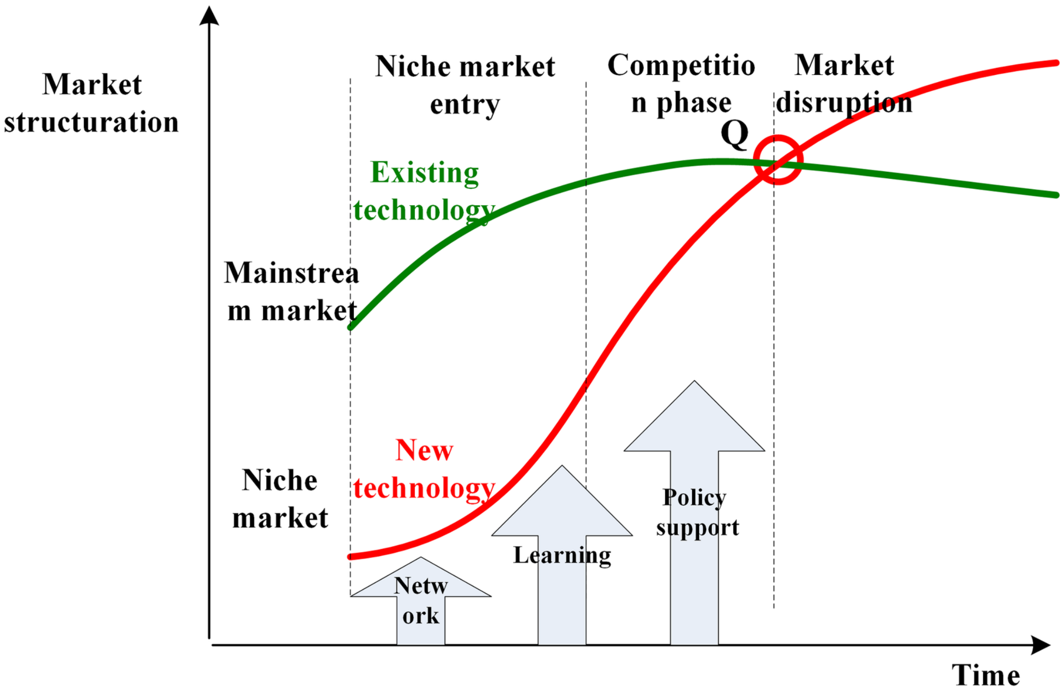
market. Next, the new technologies enter the stage of competition. The development speed of new technologies will be faster than regime technologies. The new technologies will gradually dominate in the competition with regime technologies and be adopted in practice. When reaching point Q in Figure 3, radical innovation will exceed regime technologies. They will break through niches and become dominant technologies in regime.

Niche market entry-competition-market path is illustrated in Figure 4. Because of the insufficient development and poor performance in the initial development stage, radical innovation is usually less competitive in the mainstream market where the regime technologies dominate. However, the performance attributes of radical innovation can meet lead users' or low-end market users' needs. Consequently, radical innovation develops by utilizing its performance advantage in new market or low-end market. It breaks through niches through co-growing with new markets or low-end markets). The competences and experiences accumulated in niche market enable radical innovation to acquire rapid development. The fast-improving performance and gradually decreasing costs change users' needs in the mainstream market. Market shares of radical innovation will increase gradually. At point Q in Figure 4, the market shares of radical innovation will exceed that of regime technologies. The product performance attributes of radical innovation lead user's needs in the mainstream market. Consequently, radical innovation destructs the market successfully.

3.5 The Impact Factors on Radical Innovation Breakthrough

Components and complements technologies significantly affect radical innovation breakthrough. The replacement of existing technologies by new ones is not only the competition between the two types of technologies, but also the competition between the existing technology ecosystem and the new one.

Figure 4. Niche market entry-competition-market disruption path



Components and complements technologies challenge the emergence of new technology ecosystem and create extending opportunities for existing technology ecosystem (Adner & Kapoor, 2010, 2016). The performance that radical innovation achieves may be hindered by technology bottleneck in the ecosystem, while the performance of existing technologies gets enhanced through the improvement of component and complement technologies. This will delay the breakthrough of radical innovation. For instance, the development of electric vehicle needs not only the vital breakthrough of powertrain and cell technologies (component), but also sufficient charging piles (complement).

Network and learning guarantee the breakthrough of radical innovation. The technology utilized in a stable social institutional framework is assumed to be the dominant technology. The dominant technology evolves along a fixed direction that is independent of external influences. It then forms a predictable technological trajectory. The connections of heterogeneous elements promote the stability of socio-technological figuration. To shake existing regime and lay the foundation for transformation, radical innovation must overcome the relatively stable structure of existing regime. Moreover, the new technology usually mismatches with established social institutional framework. Consequently, the breakthrough of the new technology experiences a hard time (Geels, 2002). Organizational learning and network relationship play a vital role in the replacement process (Sun & Zhao, 2017). The breakthrough of radical innovation is a process of niche accumulation, in which, niche innovation breaks through and dominates when the social network in the niche becomes bigger and rules become more stable (Geels & Schot, 2007). However, instead of leapfrogging from niches to regimes immediately, radical innovation's utilization in market niche is an incremental process (Geels, 2002), accompanying with constant learning. Rules and the stability of social network result from constant learning (Geels, 2004).

The breakthrough of radical innovation needs to coordinate cognitive rules, behavior rules, and technological rules (Bleda & Del Río, 2013). The new technology needs to develop cognitive and behavior rules to enter regimes.

Government can provide policy support for the breakthrough of radical innovation. For the industries with predictable technological trajectory, government can co-develop or provide market protection. For the industries with changeable technological trajectory, government can deal with changeability problem through investigating technological development trend and sharing relative information (Lee & Lim, 2001). Radical innovation needs creativity to break through and replace regime technology. Consequently, radical innovation breakthrough needs an industrial or national innovation system, which coordinates enterprises, government, and academia.

3.6 Regime Structure Change and New Regime Construction

Regime structure needs to be reconfigured for accommodating new technologies after radical innovation's breakthrough. The adjustment of regime structure, including social expectation, institutions, network, and user practices, embodies regulatory rules, normative rules, and cognitive rules. Rules and regulations are needed to assure normal usages of new technologies and promote its development. In addition, government subsidy benefits existing technology's stability. The establishment of technology standards plays an important role in leading development direction of new technologies and stabilizing existing technological trajectory. Moreover, intellectual rights, patents, and contracts should be focused on in the process of technology usage. In terms of normative rules, because user activities and lifestyle may change, regime actors need to adjust their cognition of mutual roles and the expectation of adaptive behaviors. Meanwhile, social network will be reconfigured to accommodate technology alteration. Regarding cognitive rules, designers and engineers, who act as users for new technologies, need to acknowledge the performance and operating methods of new technologies first. Then they need to combine new technologies with manufacturing process and produce new products. At the end, they need to shift their focus from existing technologies to new technologies and master the development trends of new technologies.

A new regime forms when the adjustment of regime structure is completed and when the new social network is stable. The effective operation and development of regime needs to coordinate several actors. Government become important regime member by providing some important resources, such as legality. On the other hand, government can acquire benefits through some ways, such as taxes. Focal firm and research institutes are vital for the operation of regimes. Research institutes provide new knowledge and new technologies, whereas focal firm provides productivity to transform new technologies into new products. There is no decisive power in regime transformation, in which the effective policy leverage cannot solely rely on government to issue orders. The high reform inertia of some actors will hinder the reform. Consequently, regime transformation needs the coordination of several actors.

4. A CASE STUDY

In the traditional 1G and 2G development stage of mobile communication technology, China adopted the strategy of technology introduction and imitation learning by implementing technology catching under foreign mature standard framework (Zhan & Li, 2011). In the evolution from 2G to 3G, China made a huge investment on developing its own standards. Initiating standard cultivation from 2003, Chinese firms promoted the technologies to flow across the industry through cooperative R&D and focused on accumulating experiences. The Ministry of Industry and Information Technology granted TD-SCDMA license to China Mobile in January 2009. This marked the commercialization of China's own 3G standards. The cultivation of 3G laid a solid foundation for the development of 4G. In the TD-LTE development stage, the Ministry of Information Industry supported to establish 4G promotion working group for initiating the development of Chinese own 4G standards. China submitted TD-LTE standard to International Telecommunications Union in 2009. TD-LTE started to serve Shanghai World Expo in 2010. Thereafter, China's technical standards in mobile communication industry started to affect the evolution direction of global 4G standard (Zhang & Yu, 2016). In the current 5G development stage, Chinese enterprises, represented by Huawei and China Mobile, have implemented advanced technologies R&D to lead the future technical standards in mobile communication industry. The technology development of Chinese mobile communication industry, experiencing from imitation learning in 1G and 2G technical standard development stage to its own innovation in 3G and 4G development stage and to technology catching up in 5G development stage, illustrated the cultivation of radical innovation and innovative development process.

4.1 The Formation Process of Radical Innovation

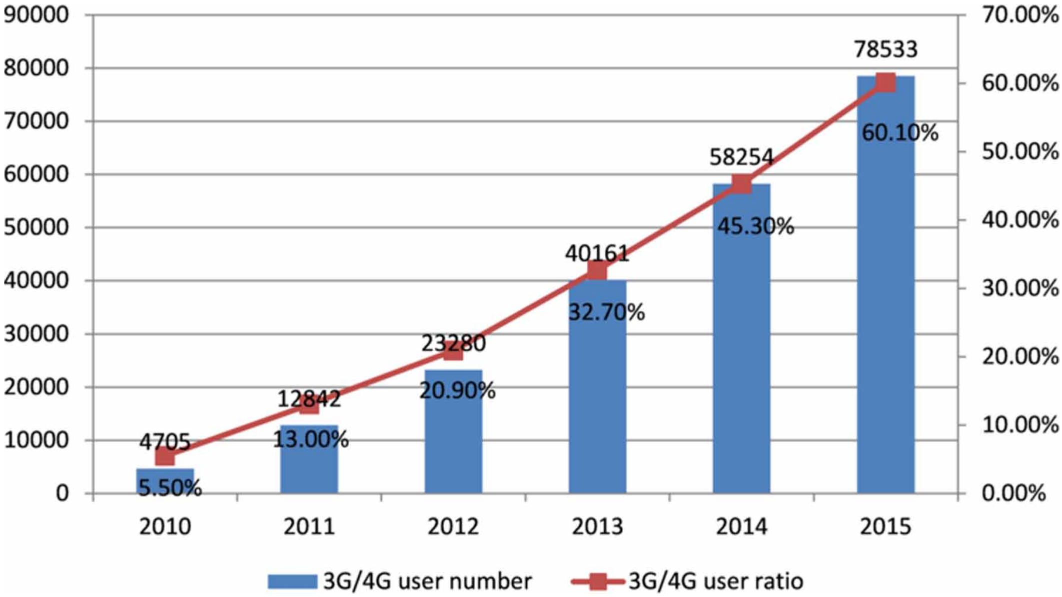
In the 1G and 2G development stage of mobile communication, China's technological competences was weak, and a mature industry chain was not available. Consequently, China had to adopt foreign technology standards. Chinese enterprises learned, absorbed, and transformed advanced technologies through cooperating with foreign enterprises. This technology learning process enabled Chinese enterprises to accumulate some technological competences. In 3G development stage, China invested more in R&D, established network with 3G technical standard participants to implement technology cooperative R&D, and accumulated R&D experiences. The development of cooperative network is vital for knowledge and technology flow across industry unions and promotes the formation of China's own 3G standards. Based on the accumulated technological competences and experiences, China actively implemented R&D of frontier technologies. Hence, China-dominated TD standards affect the development direction of global mobile communication industry standard in 4G stage.

Government's policy support played an important role in the establishment of China's own mobile communication standards. Public R&D funding significantly and positively affected radical innovation (Beck et al., 2016). Chinese government provided funding to support the basic research, technology experimentation, frontier technology development, and new technology's industrialization of its own standards through research projects, such as TD-SCDMA R&D and industrialization project and wireless broadband special project. The goal is to promote creation of new knowledge and advancement of technological competences. Moreover, Chinese government played a vital role in promoting knowledge flow and technology cooperation. For instance, the TD Industry Union, established in 2002, was supported by the Ministry of Science and Technology and the Ministry of Information Industry, aiming to cultivate TD industry. Chinese government announced to support China's own 3G mobile communication standards in 2005. Due to the weak technological competences in cell phones and chips, China Mobile worked with chip and cell phone manufacturers to implement cooperative R&D. In the TD-LTE development phase, the Ministry of Information Industry supported to establish 4G promotion working group. On the other hand, the policy support from Chinese government raised Chinese enterprises' anticipation on the development of mobile communication technologies, promoting more Chinese enterprises to invest on new technology development.

4.2 The Breakthrough of Radical Innovation

Due to the insufficient performance and high utilization costs in the initial stage when 3G/4G entered the market, many users still chose to use 2G cell phones. At that time, the existing technology and the new technology coexisted. This implied that the emergence of new mobile communication technology did not propel existing technology to exit the market immediately. With the incremental improvement and decrease of utilization costs, the market shares of 3G/4G technologies increased quickly and the new technology soon dominated the market (Aceto et al 2020; Li et al 2013, 2018; Lu 2020; Lu and Ning 2020; Lu & Zheng 2020; Xu 2016; Xu and Duan 2019; Xu, He Li 2014). In January 2009, the Ministry of Industry and Information Technology granted 3G license to China Telecom, China Mobile, and China Unicom, the main cell phone network carriers in China. This implied that 3G technological standard formally entered China. By the end of May 2014, the number of 3G users reached up to

Figure 5. The numbers of 3G/4G users in China from 2010 to 2015



0.3 billion in China[1]. In December 2013, China Mobile acquired 4G license and initiated to provide 4G services to users in some cities. With the rapid popularization of 4G network service and cell phones, the age of mobile Internet started in China. The new technology guided the transformation of users' needs. According to *the 2015 Statistical Bulletin of Communication Operations* published by the Ministry of Industry and Information Technology, the permeability of mobile broadband users (3G/4G) in 2015 reached up to 60.1% in China. The number of new 4G users increased 0.29 billion and reached 0.39 billion[2], as illustrated in Figure 5. By the end of March 2017, the number of mobile broadband users (3G and 4G) was nearly 1 billion, 74.1% of the total number of cell phone users. With users' incremental transformation from 2G/3G to 4G, 4G users increased rapidly and reached 0.84 billion, 62.1% of the total number of cell phone users[3]. By the end of March 2018, the number of 4G users reached 1 billion, 72.2% of the total number of cell phone users[4]. This implied that 4G technology dominated the market.

The rapid development of 3G and 4G technologies was driven by the following factors. Firstly, learning capability is the foundation of radical innovation to break through. Chinese enterprises accumulated technological competence in 1G and 2G stages through technology introduction, absorption, and re-innovation. Strong learning capability enables them to transform foreign advanced technologies into their own technological competence and to innovate independently in 3G/4G stage. Chinese enterprises learned constantly in cooperation innovation and ultimately realized the knowledge creation with their own intellectual rights and the development of technological standards. Secondly, network provided the resources needed for the breakthrough of radical innovation. Chinese enterprises, represented by China Mobile and Huawei, established an industry union that consisted of service network, hardware devices, and terminals, to realize knowledge flow through network. The union promoted technological standard development and industrialization of 3G/4G. The three main cell phone network carriers in China actively deployed the construction of 4G base stations to expand 4G service network. By the end of 2015, the number of 4G base stations was around 2 million. These base stations enabling 4G network to cover 95% of China[5]. The popularization of 4G smart mobile phone promoted the rapid development of 4G. Thirdly, policy support effectively promoted the breakthrough of radical innovation. The report of the Nineteenth National Congress proposed to construct network nation, digital China, and intellectual society. These goals need the support of 4G. Consequently, 4G received policy support in recent years. For instance, Chinese government actively promoted speed up and cost reduction. Thus, cell phone network carriers launched several 4G preferential packages, which attracted users to switch to 4G technology.

(Resource: Public data)

4.3 The Construction of New Regime

The adoption of 4G technology promoted the reconfiguration of regime structure. The changes of regulatory rules mainly embodied in technology standards. China Mobile adopted TD-LTD, which is the 4G network standard developed by Chinese enterprises. In terms of normative rules, the existing value chain reconfigured and constructed new value network surrounding 4G technology. A comprehensive industry chain formed and consisted of chips, devices, and cell phones. Moreover, with the rapid popularization of 4G network service and cell phones, China entered the age of mobile Internet, when people's lifestyle and behaviors are deeply influenced by mobile Internet. With the services provided by 4G, people communicate and do shopping anytime and anywhere by hold a 4G cell phone in their hands. The new technology also changed the cognitions of designers and engineers, who explore newer technology for mobile Internet. China-dominated TD-LTE standard was supported by main mobile communication manufacturers across the world and realized commercialization globally. Thus, Chinese enterprises actively implemented pre-technology layout to dominate development of future technologies.

5. CONCLUSION

This paper identifies three stages in the radical technological innovation process, namely formation process in niches, breaking out of niches and entering regimes, and new regime formation. It then adopts MLP to explore the formation process, operating mechanism, breakthrough path, and impact factors of radical technological innovation. A three-phase model, which includes formation of radical innovation, breakout of radical innovation, and new regimes construction, is proposed to analyze radical technological innovation. At the end, the model is adopted in a case study to analyze the leapfrogging development of technologies in China's mobile communication industry. This paper makes theoretical contributions as below.

This study considers each level in the operating process of MLP. It conducts a comprehensive analysis, in which social network theory and value chain theory are embedded. The model that this study proposes clearly identifies the three phases in radical technological innovation, namely formation process, breakthrough of radical innovation, and the construction of new regime. In the formation phase, radical innovation follows the process of capability basis-technological experimentation-technological diversity-dominant design. In this process, anticipation, learning, and network are three important mechanisms. Government plays an important role as well. In the breakthrough phase, radical innovation follows two paths: symbiosis-competition-breakthrough path and niche market entry-competition-market disruption path. When the new technology develops insufficiently, symbiosis-competition-breakthrough path is adopted. When the new technology develops sufficiently, niche market entry-competition-market disruption path is adopted. The new technology enter niche market first, and then dominates the mainstream market gradually. In the phase of new regime construction, regime structure needs to be reconfigured for accommodating the new technology after radical innovation's breaking through and entering regimes. Regulatory rules, normative rules, and cognitive rules should be adjusted.

This paper also provides practical implications. In the case study, the proposed three-phase model is adopted to analyze the development of technologies in China's mobile communication industry. The case study indicates that enterprises in emerging economies should focus on new technology cultivation and new technology industrialization. To become a leader of industrial technologies, enterprises should establish industry union, develop their own standards, and explore cutting edge technologies. In addition, they should analyze the effects of learning capabilities, social network, and public policy on innovation process.

This paper has limitations. First, as suggested by Slayton and Spinardi (2016), some radical innovations not only occur in niches, but also happen in the process of innovation diffusing from niches to regimes. Consequently, future research should examine the details of innovations generated in niches and in the diffusion process. In this way, the factors that affect innovation process can be clearly identified. Second, empirical studies based on large sample data is needed to verify the model proposed in this study.

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ENDNOTES

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