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THE LONG MARCH TO CATCH UP:
A HISTORY-FRIENDLY MODEL
OF CHINA'S MOBILE COMMUNICATIONS INDUSTRY

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ABSTRACT

This paper develops a history-friendly model of the process of catch-up by Chinese firms in the mobile communications industry. It aims to explain how the sectoral environment in terms of segmented markets and generational technological change facilitated the catch-up of domestic firms with respect to foreign multinationals. Segmented markets provided a nurturing environment in peripheral markets for the survival of domestic firms starting with low level capabilities in their infant stage. Generational technological change opened windows of opportunities for domestic firms to catch-up with foreign multinationals in new product segments. Segmented markets and generational technological change allowed domestic firms to leverage their initial advantages in peripheral markets to catch-up in core markets. Counterfactual simulations highlight that the process of catch-up was facilitated by relatedness across technological generations. This paper contributes to the literature on catch-up and industry evolution by illustrating the role of technological change and market regimes in the process of catching-up.

Key words:
catch-up, industry evolution, mobile communications, market regime, technological change

JEL Codes:
O30, O10, L10

Highlights

A simulation model is developed to explain the process of catch-up by latecomer firms

The explanation resides in a certain combination of market and technological regimes

Segmented markets provide latecomers with a nurturing ground in their infant age

Technological changes open windows of opportunities in new product segments

Latecomers cannot catch up if technological changes are fully competence-destroying

1. INTRODUCTION

A striking aspect of the dynamics of the global economy is the catch-up by firms of emerging economies in high-technology industries. While in the past catch-up was concentrated mostly in traditional industries in which low labor cost was a major driver of economic success, more recently this phenomenon has also spread to many high-technology industries in which innovation plays a major role. Firms from economies such as Korea, Taiwan, China and India have increased their innovativeness, penetrated both the American and European markets with advanced products, and increased their global market share in industries such as semiconductors, pharmaceuticals and telecommunications.

In these industries, the catch-up of latecomer firms has been associated with R&D, capability accumulation and an institutional context conducive to learning and innovation. A continuous effort in R&D and the development of various types of capabilities (from absorptive to technological and market capabilities) have been identified as key elements for catching-up (Katz, 1984; Bell and Pavitt, 1993; Lall, 1992). Other factors, such as institutions that favor the development of advanced skills and knowledge, and public policies that may help domestic firms to accumulate capabilities, are also key in the catch-up process (Freeman, 1987; Nelson, 2008; Lundvall, 2016).

The literature on catch-up has also pointed to the extreme variety across industries in the specific combination of factors that lead to catch-up. Differences across industries range from the role and type of technological change, the diversity in demand conditions, and the type and extent of public policy in a specific sector (Mowery and Nelson, 1999; Malerba and Nelson, 2011; Lee, 2013; Lee and Malerba, 2017).

One common observation from all this research is that catch-up is a long process that passes through multiple phases of upgrading. Some studies focus on the move by latecomer firms from original equipment manufacturing (OEM), to own design manufacturing (ODM),

to original brand manufacturing (OBM) (Amsden, 1989; Hobday, 1995; Sturgeon and Gereffi, 2009). Other studies propose a stage-based theory of the catch-up process during which latecomer firms go from duplicative imitation, to creative imitation, to innovation (Kim, 1997; Lee and Lim, 2001).

In most cases, this long process of catching-up in high technology industries takes place in contexts in which latecomer firms start with low level capabilities and move to compete with multinational companies which are market leaders and which have higher level capabilities. This process is made more difficult when latecomers are forced to cope with technologies that are in continuous change and that require advanced skills to be mastered.

Our research question is therefore the following: how did latecomer firms that had initially low level capabilities and that competed against advanced multinational corporations in their domestic market manage to survive, grow and catch-up in a high-technology industry? Often studies have pointed to the role of public policy that has protected and supported domestic firms in their quest for growth and catch-up (Freeman, 1987; Dodgson et al., 2008; Malerba and Nelson, 2012; Lee and Malerba, 2017). But in other cases public policy has not played a pivotal role. In such cases, what are the factors that have been conducive to catch up?

An interesting case to examine is that of the catch-up of Chinese firms in the telecommunication industry in both domestic and global markets. According to the "Telecommunications Equipment Vendor Leadership Scorecard" published by Infonetics Research[1] in 2013, Chinese firms Huawei and ZTE, were ranked No.1 and No.6 among the six largest global vendors of telecom-equipment[2]. In the segment of mobile handsets, Chinese firms increased their market share from a negligible one to 71% in the domestic market and

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[1] A research and consulting firm that specializes in the telecom market.

[2] The rest of the six top telecom-equipment vendors include Ericsson (No.2), Cisco (No.3), Nokia Siemens Networks (No.4), and Alcatel-Lucent (No.5).

to 25% in the global market within three decades[3].

Historically, the telecom-equipment industry has been dominated by a small number of multinational enterprises (MNEs) from advanced economies. The industry has been characterized by complex technologies, high R&D expenditures and major investments. Thus this industry represents a challenging environment for latecomers that want to enter the industry with their own final products. In this context, what explains the ability of Chinese firms to catch-up rapidly?

Most of the scholarship on the Chinese telecommunication industry on this topic is qualitative and focuses on the reach of industrial leadership (Fan, 2006; Mu and Lee, 2005; Lee et al., 2017; Yu et al., 2017). The long, evolutionary process of catching-up by domestic firms from an initial level of low capabilities and from a situation in which domestic firms faced tough competition by multinational corporations still remains to be studied in depth both in qualitative way and in more formal modelling. In this paper, we concentrate on the role that the sectoral environment has played in this process.

We propose that the combination of both a specific market regime and a specific technological regime that have characterized the mobile communications industry greatly affected the process of catching-up by Chinese firms. To be more specific, we propose that (a) segmented markets allowed domestic firms with low level capabilities to survive and grow during their infant stage by providing them with a sheltered market (the large peripheral market) in which Chinese firms had a comparative advantage over multinational corporations; (b) generational technological change in telecommunications opened windows of opportunities for domestic firms to catch-up with foreign MNEs in new product segments

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[3] Here, market shares are calculated by retail volume in 2014 based on data from the Passport database (last access on 9th November 2016). The domestic (global) market shares of major Chinese mobile phone producers are as following: Xiaomi 14.0% (3.9%); Lenovo 10.9% (5.3%), Huawei 10.0% (3.7%), Yulong 9.8% (2.6%), Vivo 6.7% (1.8%), ZTE 5.2% (2.4%), Oppo 4.7% (1.4%), Tianyu 4.3% (1.1%), Gionee 3.2% (1.1%), TCL 1.5% (1.2%), Meizu 0.9% (0.2%).

in the more advanced core market. This combination of demand regimes (segmented markets) and technological regimes (generational technological change) facilitated the catching-up of Chinese domestic firms with respect to foreign MNEs.

We address this research question by using a combination of empirical industry analysis and simulation modelling, following the methodology of history-friendly models (Malerba et al., 2016). History-friendly models are simulation models aimed at replicating the most salient facts of a specific industry and at studying the role of specific factors on the historical development, by running history-divergent simulations.

In the history-friendly setting, our model qualitatively replicates the catching-up process by Chinese firms that historically occurred in the domestic core market over multiple technological generations (from 2G to 4G). Our exploration of history-divergent settings generates three main results. First, it shows that the mere existence of a peripheral market is not enough to guarantee the success of the catching-up process, but its size is a fundamental dimension to take into account. Second, it shows that also generational technical change is not sufficient to guarantee a successful catch-up process: domestic firms need time and opportunities to accumulate resources and experience, and this is possible if there is a peripheral market in which the competition of MNEs is weaker.

Third, our model shows that latecomer firms are able to exploit windows of opportunities opened by new technological generations in order to catch-up with established leading companies only if there is a certain degree of relatedness across generations. This result seems in contrast with the conventional wisdom on technological changes that indicates that established firms are challenged by new entrants which introduce competence-destroying discontinuities (Tushman and Anderson, 1986), architectural innovations (Henderson and Clark, 1990) and disruptive innovations (Christensen, 1997). However, latecomer firms in the context of developing countries cannot be equated to late entrants and startups in the context

of developed countries (Mathews, 2002). The latter may enter an industry with a high level of technological capabilities developed in related industries (Klepper, 2002), or inherited from best-performing parents (Klepper, 2016), or transferred by star scientists from top-ranked universities (Zucker et al., 1998). They have also access to the knowledge base and resources of their home country (e.g. advanced human capital market, financial markets, IPR regime, local advanced university research) that allow them to develop and exploit competence-destroying technologies. Latecomer firms, instead, operate in the context of developing countries. Therefore they are constrained by the development stage of their home country: they enter an industry with a low level of technological capabilities, then upgrade through a long-term process of capability-building. This represents a long march towards the technological frontier.

The contributions of this paper are the following. First, the paper contributes to the literature on the impact of technical change on incumbents and latecomer firms by pointing out that latecomer firms are not similar to late startup entrants in developed countries. They cannot catch-up with foreign MNEs if technological change is competence-destroying, because such technological change will disrupt the capability-building process of latecomer firms. Second, the paper adds to the literature on industry evolution by showing that the competition between latecomer firms entering with low capabilities (domestic firms) and incumbents with advanced capabilities (foreign multinationals) may be greatly shaped by the sectoral environment in terms of demand and technological regimes. Third, this paper contributes to the literature on catch-up by adopting a modeling approach to analyze the long-term process of catching up by latecomer firms. Fourth, our findings suggest that firms with a strategic intent of catch-up should actively consider the role that segmented markets and the type of technological change may play in high technology industries.

The paper is organized in the following way: Section 2 presents the history to be

explained and the catching up of Chinese firms in this industry with respect to foreign multinationals, while Section 3 proposes some basic mechanisms that can explain this catch-up. Section 4 presents the history friendly model of catch up in the telecommunication industry. Then in Section 5 the results of the history friendly simulation and of some history-divergent simulations are presented. A general discussion concludes the paper.

2. THE HISTORY TO BE EXPLAINED: THE G-STORY OF MOBILE COMMUNICATIONS INDUSTRY

Mobile communication technologies are one of the most widely adopted applied-technologies in the world. Since Martin Cooper, a Motorola engineer, made the first public call through a mobile handset in 1973 (Fuentelsaz et al., 2008), the number of mobile connections has reached 7.6 billion (GSMA Intelligence, 2016), surpassing the number of the global population. Although consumers may be familiar with end-user equipment such as mobile handsets, the whole picture of the mobile communications is much broader. To enable end-to-end communications, a system which consists of the end-user equipment, the wireless access network, and the core network is needed. Due to the high complexity of the technological environment, and to the importance of interoperability, technological standards are collectively agreed by international consortia. We do not model the process through which standards are set by international bodies, but this feature has an important implication for the purposes of this paper. In fact, cooperative standards are a key driver of generational technical change.

Since its inception, the mobile communications industry has witnessed four generations of technologies[4] (Qualcomm, 2014). Each new generation of mobile communications

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[4] More details about the history of this technology can be found in Fuentelsaz et al.(2008) and Hamil and Lasen (2005).

significantly improved the previous state-of-the-art by adopting different technologies. As Figure 1 illustrates, different generations of mobile communication systems differ from each other, not only in terms of the end-user equipment, but also in terms of the wireless network and the core network. These differences will be further discussed below.

INSERT FIGURE 1 ABOUT HERE

2.1 First generation (1G) mobile communications technologies

1G mobile communication systems provide users with analog voice services. The wireless access of 1G systems is based on the Frequency Division Multiple Access (FDMA) technology, which is a technology that separates different users by using different radio frequencies. Data services are not available in the 1G era.

China had a brief history of 1G communications in early 1990s, during which the country imported the Total Access Communication System (TACS) from foreign MNEs such as Ericsson. However, all TACS networks were shut down in 1997, before domestic firms could enter the industry (Jin and Von Zedtwitz, 2008).

2.2 Second generation (2G) mobile communications technologies

Unlike the 1G mobile communication systems that rely on the analog technology, the 2G mobile communications are based on the digital technology. Although the main functionality of 2G systems is still to handle voice communications, 2G systems also provide users with limited data services such as Short Message Service (SMS). In the 2G era, there are mainly two wireless standards, the Europe-developed GSM and the US-developed CdmaOne. GSM systems adopt a wireless technology called Time Division Multiple Access (TDMA), which separates different users by using a different time slot for each user. In contrast, CdmaOne

systems utilize a wireless technology called Code Division Multiple Access (CDMA), which separates different users by using a different code for each user.

The first GSM network in China started its operations in September 1993 in Jiaxing, a medium city of the advanced, coastal province of Zhejiang (Lu et al., 2007; Wu, 2008). In 1994, GSM was selected as a national standard in China (Hillebrand, 2013), and by the end of 1995, China's major cities in the Pearl River Delta Region (e.g., Shenzhen, Guangzhou) and the Yangtze River Delta Region (e.g., Suzhou, Wuxi, Changzhou) were covered by GSM networks (Wu, 2008). All these networks were built upon imported equipment from foreign MNEs.

However, in the 2G era also Chinese domestic firms entered the mobile communications industry. Huawei started its R&D activities in the GSM technology in 1995 (Wen, 2017). Two years later, it was able to develop China's first "domestically built" GSM system in the lab (Hong et al., 2012; Zhang, 2011), that was deployed in 1998 in a remote region of China, Inner Mongolia (Zhang, 2011). By 1999, the biggest Chinese firms (Huawei, ZTE, Datang) had all entered the GSM market (Hong et al., 2012). Still, they had to face an aggressive reaction strategy from foreign MNEs, that engaged in a war price (Wen, 2017), exploited their first mover advantage due to lock-in network effects (Hong et al., 2012), and later regained control of their joint ventures (Shanghai Bell, BISC) to slow down the transfer of capabilities to local companies (Harwit, 2008).

So, in the early 2000s, four major foreign MNEs (Motorola, Nokia, Ericsson, and Siemens) still had around 90% of China's GSM system market (Mi and Yin, 2005; Yu, 2011) [5]. Domestic firms (e.g., Huawei and ZTE) were forced to adopt again the strategy of "using the countryside to encircle the cities" that they had already used in the 1990s in the market of telephone switches. Huawei developed GSM network solutions for rural areas needs (large-

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[5] Market shares reported in this subsection and in the following ones are reported in terms of units.

scale coverage, flexibility in onsite installation), that were deployed in peripheral regions such as Guizhou, Sichuan, and Hunan (Wen, 2017). ZTE became a major supplier of equipment for the Xiaolingtong [6] system deployed by China Telecom and China Netcom (Harwit, 2008), and was also able to enter the CDMA market when the standard was introduced in China under pressure from the US.

Still, in the fixed-line era, demand from rural areas had been sustained by the policy of bringing telephone access in all villages, officially stated in the 9th Five-Year Plan (Wen, 2017). Just focusing on the rural areas in China could not be sufficient to fuel the catching-up in the new mobile technology: learning from their failures in the fixed-line communications equipment market, foreign MNEs made more efforts to pre-empt the high-end mobile communications equipment market (Zhang, 2011). Therefore, domestic firms were somehow forced to look for new opportunities abroad, adopting the same strategy of going first to the "countryside" (i.e. emerging countries)[7].

Huawei had already started its operations abroad in the fixed-line business: in 1995 it established its first overseas subsidiary in Hong Kong (Liu, 2010), and in 1996 it entered Russia. After that, it entered the Latin American market in 1997, the African market in 1998, and other Asian markets in 2000 (Wu et al., 2017), extending its overseas activities also to the GSM business. ZTE followed a similar strategy, since this was aligned to the institutional "going-out" policy set out under the leadership of Jiang Zemin from the mid 1990s, and formally stated in the Tenth Five-Year Plan in the early 2000s (Hong et al., 2012). In a few years, Chinese firms became the leading telecom equipment supplier for "Global South"

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[6] The Xiaolingtong technology offers mobile services by connecting end users to existing fixed-line networks through micro-cell radio. This technology is based on the Personal Handy Phone System (PHS), a Japanese technology developed in 1995 (Yuan et al., 2006).

[7] In 2006, Ren Zhengfei, founder of Huawei, described this process as follows: "We were thrown into the most intensive competition, and we had to seek chances for survival in a narrow space. When we started to explore the international market, all the fertile lands had been occupied by Western companies. We could only see hope in remote areas, countries or regions in turbulence, and places with harsh natural conditions. These locations were our last hope because Western companies were hesitant to make bigger investment there" (Tian and Wu, 2015, p. 36).

countries. Still in 2007, however, the combined market share of Huawei and ZTE reached only 13% of China's GSM market, whereas the market share of Ericsson was about 42% (Hong et al., 2012).

2.3   Third generation (3G) mobile communications technologies

Compared with 2G systems, 3G systems provide users with a much higher speed. Although the specific data rates of 3G systems depend on the specific wireless standards, the data rates are often higher than 2 Mbps (Fan et al., 2002), with some versions (e.g., WCDMA/HSPA+) reaching the data rates as high as 63 Mbps (Qualcomm, 2014).

In the 3G era there are mainly three international wireless standards: WCDMA (developed in the Europe), CDMA2000 (developed in the US), and TD-SCDMA (developed in China). The main difference between TD-SCDMA and the other two standards resides in the duplexing mode, which differentiates how systems transmit the uplink data (data from end-user equipment to the base station) and the downlink data (data from the base station to end-user equipment). TD-SCDMA adopts the Time Division Duplex (TDD) mode, which uses a single frequency bandwidth to handle both uplink data and downlink data. Instead, both WCDMA and CDMA2000 adopt the Frequency Division Duplex (FDD) mode, which needs a pair of frequency bandwidths to handle uplink data and downlink data separately. Interestingly, all of the three international 3G standards were commercialized in China.

Some Chinese domestic firms actively upgraded their technological capabilities in the 3G era. For example, one domestic firm, Datang, developed the country's own 3G standard, TD-SCDMA, which was accepted by the International Telecommunications Union (ITU) as one of the international 3G standards (Gao, 2014). Other Chinese firms like Huawei and ZTE, successfully developed products that followed the other two 3G standards (WCDMA and CDMA2000).

The Chinese government released the 3G licenses in January 2009, which marked the beginning of China's 3G era, but Chinese firms were already active in international markets well before that moment. In this era, Chinese domestic firms (Huawei and ZTE) successfully caught up with foreign MNEs in terms of 3G system equipment. For example, Huawei signed its first 3G WCDMA network contract with a European telecom operator (Telfort B.V.) in December 2004, after winning four WCDMA deals in developing countries (China Daily, 2005). And in 2009, the combined market share of Huawei and ZTE in the domestic 3G system equipment market reached 53%, a share higher than the combined market share of MNEs (Hong et al., 2012). However, they were still lagging behind foreign MNEs in the mobile handset market: in 2009, the market share of Huawei and ZTE in the domestic mobile handset market was about 5.4% and 4.7% respectively, much lower than the market share of foreign MNEs (e.g., Nokia and Samsung had 36.0 % and 19.4% of the domestic market respectively, in the same period, as reported by Euromonitor International, 2016).

2.4 Fourth generation (4G) mobile communications technologies

Although 3G communication systems offered users much better data services compared with 2G systems, the speed of 3G systems is still not fast enough to support data-demanding applications, such as high-quality video streaming, online gaming, three-dimensional (3D) visuals, and so on (Rathore et al., 2012). 4G systems are designed to provide users with "high-speed" and "low-cost" mobile Internet, with the data rates as high as 300 Mbps (Qualcomm, 2014). 4G systems are optimized for data communications by combining different technologies, such as Orthogonal Frequency Division Multiple Access (OFDMA), Multiple Input Multiple Output (MIMO), and an all-IP based design. These technologies do not only provide users with much higher speed of the mobile Internet, but also provide users with better quality of services (e.g., lower latency). In the 4G era, different wireless standards

converged to a unified standard, LTE, which can operate in both the FDD mode and the TDD mode.[8]

In December 2013, the Chinese government released the 4G licenses, which marked the beginning of China's 4G era. The transition from 3G to 4G once again offered domestic firms an opportunity to catch-up with foreign multinationals in the new product segment. For example, Huawei, together with Ericsson, developed the world's first LTE networks for TeliaSonera in 2009[9]. Although LTE does not meet the ITU specification for 4G, the technology had often been considered as "4G" by telecom operators. In 2010, "LTE-Advanced" was officially accepted by ITU as a 4G technology (Chen et al., 2014). In this era, Chinese firms further increased its market shares in the mobile handset market. For example, in 2014, the retail volume of Huawei and ZTE's mobile phones accounted for 10.0% and 5.2% of the domestic market respectively. In contrast, Nokia had exited the market, and the leading foreign MNE, Samsung, just captured about 13.8% of the Chinese mobile handset market in the same period (Euromonitor International, 2016).

A comparison of different generations of mobile communications is shown in Table 1.

INSERT TABLE 1 ABOUT HERE

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3. THEORIZING ON THE CATCHING-UP DYNAMICS

Prior literature on catch-up defines it as a process by which latecomers narrow their gap with the leaders (Abramovitz, 1986). The gap can be measured either in terms of

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[8] Although there is another potential 4G technology, Wi-Max, evolved from a different development path (IEEE standards).

[9] Source: https://www.telegeography.com/products/commsupdate/articles/2009/12/14/teliasonera-launches-worlds-first-commercial-lte-networks-in-sweden-and-norway/

technological performance or in terms of market performance. However, technological catch-up and market catch-up are strongly related. Market catch-up facilitates technological catch-up by providing firms with crucial resources for technological upgrading, whereas technological catch-up facilitates market catch-up by allowing firms to introduce better products (Lee and Lim, 2001). Ultimately, a firm should move up the value-chain through the process of catching-up, migrating from low-value-added activities to high-value-added activities (Gereffi et al., 2001; Mudambi, 2008). To capture the two interrelated dimensions of catching-up, in this paper we define Chinese domestic firms' catching-up as the increase of their market share in the core market, a market that offers higher profits but also demands better quality[10] products and that can be exemplified by the Chinese urban market. Our definition of catching-up differs from the one used by Landini et al. (2017), that examine the change in industrial leadership. Rather than focusing on the change in industrial leadership, our focus is instead on latecomers' long march toward the leadership position. We are interested in understanding the long process by which firms have upgraded their capabilities and moved up in the value chain.

3.1 Market regimes and horizontal upgrading

At the beginning of the 2G era, domestic firms had relatively weaker technological capabilities compared with foreign MNEs, but they also had some comparative advantages (e.g., cheapness of their products) in the peripheral market. Such peripheral market (e.g., rural market in China and "Global South" international markets) allowed domestic firms to survive their infant age, and provided domestic firms with crucial resources for upgrading their technological capabilities.

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[10] Here, "quality" is used as a general term to refer to a combination of design, performance, technology, functionality, and so on.

3.1.1 Segmented markets. Segmented markets refer to a market regime where customers of different groups have different preferences in terms of the main attributes of the products (Allon and Federgruen, 2009). Segmented markets would facilitate domestic firms' catching-up with respect to foreign MNEs. On the one hand, segmented markets would reduce the first mover advantages of incumbents, because they would make difficult for incumbents to pre-empt the markets (Capone et al., 2013). On the other hand, segmented markets would allow domestic firms to survive their infant stage by leveraging on their comparative advantages (e.g., cheapness) in the peripheral market (List, 1983). This market therefore can be seen as a niche or submarket that provides opportunities for new firms (Christensen, 1997; Klepper and Sleeper, 2005), but also for less advanced technologies to persist and eventually grow (Adner and Snow, 2010). This means that the peripheral market provided domestic firms with a "nurturing ground" to accumulate critical resources for upgrading their technological capabilities. With increasing technological capabilities, domestic firms then can gradually catch-up with foreign multinationals in the core urban market.

3.1.2 Horizontal upgrading. In the history of China's mobile communications industry, some domestic firms actively exploited their comparative advantage in the peripheral market, to successfully upgrade into the core market. Domestic firms had a comparative advantage over foreign MNEs in the peripheral market for a few reasons. First, foreign MNEs somehow ignored the peripheral markets, possibly due to the fact that the core market *per se* was large enough. Thus, foreign MNEs did not have enough incentives to serve peripheral markets that offered relatively low profit margins (Mu and Lee, 2005). Second, due to cultural and linguistic barriers, foreign MNEs faced the "liability of foreignness" (Zaheer, 1995): this actually gave domestic firms a comparative advantage in Chinese rural markets. Third, peripheral markets in the "Global South" often presented technical problems analogous to those encountered by Chinese firms in the domestic rural markets. Consequently, a large

peripheral market allowed domestic firms, which did not have superior technologies at that time, to survive their infant age by exploiting ordinary technologies, and to accumulate resources and capabilities that could be later used to upgrade in the more competitive core market.

So, the historical and theoretical considerations just presented illustrate how market segmentation facilitated Chinese firms catching-up: domestic firms exploited the opportunities to catch-up with foreign MNEs because of the existence of a large peripheral market and the possibility of horizontal upgrading to the core market.

3.2   Technological regimes and vertical upgrading

In the beginning of the 2G era, domestic firms had relatively weak technological capabilities in 2G products. However, generational technological changes provided domestic firms with windows of opportunities to catch-up with foreign MNEs in new product segments.

3.2.1 Generational technological changes. "Generational technological changes" (Lawless and Anderson, 1996) refers to big technological advances within a technological paradigm. In this sense, generational technological changes are neither "disruptive" (Christensen and Bower, 1996) nor "incremental" (Tushman and Anderson, 1986). With generational technological changes, technology will change across different generations. However, there is still a certain degree of relatedness between an old generation and a new generation of a technology. Different generations of technologies often coexist in the market, but new generations determine the emergence of new niches due to the new features that they can offer (Lawless and Anderson, 1996).

Generational technological changes facilitate domestic firms' catching-up with respect to foreign MNEs for two reasons. First, generational technological changes open windows of

opportunities for latecomers, because to some extent, every firm is a newcomer in front of a new generation of technologies (Perez and Soete, 1988). Second, generational technological changes are not so disruptive, so that the knowledge learned by latecomers in a previous generation of technologies still serves as a base for latecomers' capability-building in a new generation of technologies.

The mobile communications industry is an industry characterized by generational technological changes. Each new generation of mobile communications adopts different technologies, enables new services, and therefore, creates technological opportunities for the development of new products, that can be appealing for new groups of customers.

For example, because 3G communication systems significantly increased the data transmission capability of the previous generation, the arrival of the 3G era introduced a group of products that offered computers with mobile Internet access, and it also created opportunities for a new generation of mobile phones characterized by different "size", "form", "function", and other attributes (Bangerter et al., 2014). Moreover, generational technological changes also brought new technological and market opportunities on the network equipment and the wireless access networks sides.

Because each generation of communication technologies is associated with a set of new products that work together to create a mobile communication system, we consider these new products as belonging to a generation-specific product segment (e.g., 2G products, 3G products, 4G products). The history-friendly model developed in this paper aims to show how generational technological changes facilitated domestic firms' catching-up by opening windows of opportunities in these generation-specific product segments.

3.2.2 Vertical upgrading. Generational technological changes open new product segments (e.g., 3G products, 4G products) that are associated with the new generations of technologies. Such new product segments would facilitate domestic firms' catching-up with

respect to foreign MNEs, because both domestic firms and foreign MNEs are newcomers in these new product segments. More importantly, foreign MNEs that have developed strong technological capabilities in a previous generation of technologies might be less prompt to enter the new product segment because of the "lock-in" effect (Christensen and Bower, 1996; Tripsas and Gavetti, 2000): a firm's strong capabilities in a previous generation of products may become a liability for upgrading into a new generation of products (Leonard-Barton, 1992). Instead, domestic firms with a sufficient level of technological capabilities in a previous generation are more likely to catch the opportunities brought by generational technological changes: the increase in technological capabilities due to the experience in the peripheral market in the previous generation enables domestic firms to compete with foreign MNEs in the core market in the next generation.

In the past decades, the telecom-equipment industry has witnessed multiple rounds of generational technological changes from 2G to 4G. Each generational technological change opened a window of opportunities for latecomers to catch-up with foreign MNEs. Some Chinese firms seized the windows of opportunities associated with such generational technological changes: these firms successfully reduced their technological gap with foreign MNEs in the new generation of technologies. For example, Huawei claimed that it held approximately 15% of all essential patents related to the LTE/EPC standard (a so-called 4G standard[11]), a much higher ratio compared with the 2% ratio related to the 2G GSM standard and the 6% ratio related to the 3G UMTS standard (Huawei, 2015). Since essential patents are patents that are needed to produce products conforming to a specific standard (Bekkers et al., 2011), Huawei's increasing share of essential patents in each new generation of the technology suggests a narrowing technological gap between Huawei and foreign MNEs.

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[11] Strictly speaking, LTE does not really meet the ITU requirements for 4G. But it has often been advertised as a 4G technology by telecom operators.

So, the theoretical and historical considerations just presented illustrate how generational technological changes facilitated Chinese firms catching-up: once they reached a certain level of technological capabilities, domestic firms exploited the opportunities to catch-up with foreign MNEs provided by the emergence of new products segments created by the generational technical changes.

3.3   Complementarity of market and technology forces in driving catch-up

A combination of a certain kind of market regime and technological regime is necessary for promoting latecomers' catching-up. Without a large peripheral market to provide domestic firms with a "nurturing ground", domestic firms cannot survive their infant age. And without generational technological changes, domestic firms may find it difficult to reduce their (market share) gap with foreign MNEs in the core market.

The complementarity between market and technological regimes is also due to the fact that firms never compete in terms of "technology" alone. Latecomer's catching-up is related to the offering of a good composition of acceptable technology and competitive price to the right market (Luo and Child, 2015). In fact, in their early history Chinese latecomer firms never became more technologically advanced than foreign MNEs. However, when Christopher Galvin visited Huawei's headquarter in Shenzhen, the chairman of Motorola *"was impressed by Huawei's products, saying that they were 'good and cheap.' "* (Tian and Wu, 2015, p. 202). In contrast, at that time Motorola was then suffering from the failure of its technology-led Iridium Satellite project.

4. THE MODEL

The "catch-up" process is an evolutionary process strongly influenced by historical factors. This study follows a "history-friendly" approach, to capture the evolutionary process

of catching up and to illustrate the mechanisms proposed by the verbal "appreciative theory" based on the history of the industry (Malerba et al., 2016). "History-friendly" models are simulation models based on the historical reconstruction of the key factors explaining the evolution of an industry (Malerba et al., 2016), which has been applied to many industries, including computers (Malerba et al., 1999), DRAM chips (Kim and Lee, 2003), pharmaceuticals (Malerba and Orsenigo, 2002), semiconductors (Malerba et al., 2008), synthetic dyes (Brenner and Murmann, 2016), and mobile phones and memory chips (Landini et al., 2017).

The model presented here focuses on the process of catching-up by Chinese firms in the mobile communications industry[12]. The model is directly inspired by the seminal work on history friendly models (Malerba et al., 1999), and following related works (Malerba and Orsenigo, 2002; Malerba et al., 2008; Malerba et al., 2016). In fact, the model presented in this paper is actually built by reusing and – when necessary – adapting to the specific context lower-level modules from the cited history-friendly literature. Appendix A classifies these modules in four broad categories (Market space, Technology space, Industry dynamics, Firm behavior): for each of them it presents a brief description, references, and differences due to the specific context of catching-up in the mobile communications industry.

The calibration process follows the history-friendly approach: it relies – in a highly qualitative way – on the empirical evidence of the mobile communications industry. As a starting point for the calibration process we employ the parameter values used in the past literature referred above, if a close connection between the parameters exists; otherwise, they are based on simplifying assumptions, reflecting our ignorance about their 'true' value. The final value of each parameter is identified within the calibration exercise with the aim of

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[12] The simulation code is written using the Java programming language. The code is available from the corresponding author upon request.

being close to the observed pattern of catching-up. The list of parameters and variables, the symbols that are used, and the values or range of values that they take in the history friendly setting are reported in Appendix B.

The model is also strictly related to the work by Landini et al., (2017), who modeled the changes in industrial leadership associated to catch up cycles. The two models share many characteristics, but they differ in a key aspect: here we explicitly model the latecomer firms "long march" towards a leadership position, whereas Landini et al. (2017) focused on leadership changes across countries[13].

4.1   Model overview

The model overview in Figure 2 captures the stylized facts of China's mobile communications industry. In the model, there are two groups of firms: domestic firms and foreign MNEs. At the beginning of the 2G era, domestic firms tend to have relatively low technological capabilities compared to foreign MNEs. Although the products of domestic firms tend to have a lower quality than the products of foreign MNEs, they are also cheaper than the products of foreign MNEs. On the demand side, there are two distinct and independent markets: the rural market and the urban market[14]. The customers in the rural market value cheapness more than quality, whereas the customers in the urban market value quality more than cheapness. The arrival of a new generation of mobile technologies creates a new product segment for each of the two markets, but it does not make obsolete existing product segments (Long and Laestadius, 2016). Firms can develop their technological

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[13] Further, more detailed differences are the following ones. Landini et al. (2017) focus on catching-up at the country level, consider a single attribute of the products ("quality"), and model generational technological change as a shift in the technological frontier. In this paper, we focus on catching-up at the firm-level, consider two attributes of the products ("quality" and "cheapness"), and model generational technological change as the emergence of new product segments.

[14] For simplicity, in the model we refer to a single country economy and therefore we use the terms "rural" and "urban" to refer to the peripheral and core markets, respectively. With respect to the historical occurrences, our definition of "rural areas" includes not only the rural areas of China, but also other emerging markets in Asia, Africa, and Latin America, as well as the low-end niches in advanced economies.

capabilities by investing in R&D. Domestic firms' catching-up is defined as the increase of their market share in the urban market.

INSERT FIGURE 2 ABOUT HERE

4.2 Market environment and firm sales activities

Firms compete in segmented markets (urban and rural) based on the perceived merit of design (*M*) of their products in each market and in each generation. The perceived merit of design is the value that customers in a market assign to a product based on the quality and the cheapness of that product. Generally speaking, customers in the rural market care more about the cheapness of the product, whereas customers in the urban market care more about the quality of the product. As long as the quality and the cheapness meet some minimum requirements, the merit of design is determined by a Cobb-Douglas function as specified in Equation 1. However, if either the quality or the cheapness is lower than the minimum value required by a market, the merit of design of a product will be zero for that market. Specifically, the merit of design of a product produced by firm *f* at time *t* for generation *g* as perceived by customers in market *k* is given by:

$$M_{f,g,k,t} = \alpha \cdot \left(Q_{f,g,t} - \lambda_{g,k}^Q\right)^{\gamma_k^Q} \cdot \left(C_{f,g,t} - \lambda_{g,k}^C\right)^{\gamma_k^C} \tag{1}$$

where $Q_{f,g,t}$ and $C_{f,g,t}$ represent the quality and the cheapness of the product of firm *f* in generation *g* at time *t*, respectively; $\lambda_{g,k}^Q$ and $\lambda_{g,k}^C$ are minimum thresholds for quality and cheapness, respectively, that the product must reach to get a strictly positive merit of design; γ_k^Q and γ_k^C represent the relative weight of quality and cheapness, respectively in determining the merit of design, and α is a scale parameter. The merit of design is a key determinant of

the market performance of each firm, because it determines its market share. The share of a

product produced by firm f at time t for generation g in market k is the relative merit of the

design of the product as compared to all competing products in that market, that is:

$$S_{f,g,k,t} = \frac{M_{f,g,k,t}}{\sum_f M_{f,g,k,t}} \tag{2}$$

The cheapness variable in Equation 1 expresses the idea that consumers – keeping

constant other characteristics of a product – always prefer a lower price, and they might

actually prefer not to buy at all if the price is too high. Formally, cheapness is represented by

the inverse of the price, adjusted by a segment-specific scale parameter (v_g), that is:

$$C_{f,g,t} = \frac{v_g}{p_{f,g,t}} \tag{3}$$

Firms serving customers in the submarkets emerging with generation g, will set the price

according to the following mark-up rule:

$$p_{f,g,t} = c_{f,g,t} \cdot \left(1 + m_{f,g,t}\right) \tag{4}$$

where c represents the production cost and m is the markup ratio. The production cost is

the sum of a segment-specific baseline production cost that differs across different

generations of products and a firm-specific component that increases with the quality of a

firm's products:

$$c_{f,g,t} = c_g + \varphi \cdot Q_{f,g,t} \tag{5}$$

Generally speaking, a new generation of products tends to have a higher baseline

production cost than an old generation of products (e.g., 3G products cost more than 2G

products); moreover, high quality products are more costly to produce than low quality

products[15].

The second element determining the price is the mark-up ratio[16]. Firms decide the value

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[15] This means that production costs can change over time only to address changes in quality. For simplicity, we do not consider here cost changes due to learning by doing or process innovations.

[16] The debate on the use of pricing routines is still open (Bloch and Metcalfe, 2018), but there is a wide consensus on the fact that the choice of markup is influenced by considerations about both costs and

of the mark-up based on their past market shares in the industry, given a certain level of price elasticity. However, in the model there are two markets (rural and urban) characterized by different price elasticities, and although firms can sell their products on both markets, they cannot operate price discrimination and must charge only one price. Therefore, firms will compute the target mark-up in both markets, and will set the price using a mark-up ratio which is a weighted average between these two values. The weight assigned to each market-specific mark-up is equal to the share of the firms profits that are generated from sales in that market. Formally, the mark-up used by firm f at time t for its product in generation g is expressed as:

$$m_{f,g,t} = w_{f,g,t-1} \cdot \frac{s^R_{f,g,t-1}}{\eta^R - s^R_{f,g,t-1}} + \left(1 - w_{f,g,t-1}\right) \cdot \frac{s^U_{f,g,t-1}}{\eta^U - s^U_{f,g,t-1}} \tag{6}$$

where $s^R_{f,g,t-1}$ ($s^U_{f,g,t-1}$) is the market share of firm f at time t -1 for its product in generation g in the rural (urban) market, η^R (η^U) is the price elasticity of demand in the rural (urban) market, and $w_{f,g,t-1}$ is the share of profits generated by the rural market[17]. Since cheapness is more relevant in the rural market than in the urban market, we assume that the price elasticity is higher in the rural market and that firms always confront the elastic part of the demand curve (i.e. $\eta^R > \eta^U > 1$).

The profits earned by a firm in each market are computed as follows:

$$\pi_{f,g,k,t} = \left(p_{f,g,t} - c_{f,g,t}\right) \cdot \chi_{f,g,k,t} \tag{7}$$

where $\chi_{f,g,k,t}$ is the number of consumers in market k buying at time t from firm f for products in generation g, which is obtained as the product between the total number of

competition (Hall and Hitch, 1949; Kalecki, 1971).

[17] A markup ratio based on past market shares and price elasticity has been used in past evolutionary models (Winter, 1984; Kim and Lee, 2003; Malerba et al., 2016; Landini et al., 2017). It represents the markup that a profit-maximizing firm would choose in an asymmetric Cournot equilibrium. The use of lagged values for the market shares implies that firms do not have reliable information about the changes in the future market shares due to the innovation process by all firms. Moreover, it also simplifies the problem of interdependence between price and market share.

consumers in a specific market (e.g., rural market for 3G products) and the market share of the firm in that specific market. We assume that the total number of consumers increases over time for exogenous reasons not explicitly modeled here, according to a logistic growth path:

$$\chi_{g,k,t} = \frac{\Phi_{g,k} \cdot \chi^0_{g,k} \cdot e^{h \cdot t}}{\Phi_{g,k} + \chi^0_{g,k} \cdot (e^{h \cdot t} - 1)} \tag{8}$$

where $\Phi_{g,k} > 0$ is the carrying capacity of market k for products of generation g, $\chi^0_{g,k}$ is the initial number of customers in market k for products of generation g, and h is the rate of growth of the market (we assume it is equal for all markets and generations). For simplicity, we assume that the carrying capacity of market k is the same for different generations of products, which is given by Φ_k.

The total profits earned by a firm in each period is given by the sum of its profits in each market and generation, that is:

$$\pi_{f,t} = \sum_{g,k} \pi_{f,g,k,t} \tag{9}$$

4.3   Technological environment and firm innovation activities

The second element of a product that is evaluated by consumers in Equation 1 is quality ($Q_{f,g,t}$). The quality of a product is given by:

$$Q_{f,g,t} = \delta_g \cdot r_{f,g,t} \tag{10}$$

where $r_{f,g,t}$ represents a firm's technological capability in generation g and δ_g is a generation-specific parameter that translates technological capabilities into quality. To increase the quality of their products and meet the consumers requirements, firms need to develop technological capabilities in the specific generation by investing their R&D resources in that technological generation and the associated product segment.

The relationship between firm R&D investments in a generation and the technological capabilities developed by the firm in that generation is stochastic in nature.

The amount of resources invested in research activities by firm f in a specific technological generation g and period t ($B_{f,g,t}$) and the unit cost of R&D activities (c^{RD}), which is constant across time, firms and generations, determine the number of innovative trials of new technological capabilities. This number is equal to $floor(B_{f,g,t}/c^{RD})$. The firm will retain the highest level of capabilities among the extracted values, provided that this is higher than the current level of capabilities. All the values of the new capabilities are extracted from a normal probability distribution[18] whose mean ($r^*_{f,g,t}$) depends on the current level of capabilities in the specific technological generation and the level of capabilities in the previous generation, that is:

$$r^*_{f,g,t} = \theta \cdot r_{f,g-1,t} + (1 - \theta) \cdot r_{f,g,t} \tag{11}$$

where θ represents relatedness between technological generations, that is the extent to which capability development in the current technological generation depends on the capabilities developed in the previous generation[19].

The two types of firms (domestic firms and foreign MNEs) in the industry differ in their initial level of technological capabilities ($r^0_{f,g}$)[20]. At the beginning of the 2G era, foreign MNEs have relatively greater technological capabilities compared to domestic firms.

Both types of firms face two strategic choices. The first choice is about what proportion of the total profits they should invest in R&D. We assume that firms allocate a fixed proportion ρ_f of their profits to R&D expenditures. In this paper, we focus on the role of market and technological regimes on domestic firms' catching-up, instead of firm strategies *per se*. Therefore, we do not differentiate firms by their propensity to invest in R&D and we

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[18] To avoid infinite growth, there is an upper bound to the level of capabilities.

[19] Since our simulation starts from the 2G era, the rule of weighted average does not apply to capability development in the 2G product segment.

[20] The initial level of capabilities of domestic firms is drawn from a uniform distribution in the range [0.01, 0.25], whereas the initial level of capabilities of MNEs is drawn from a uniform distribution in the range [0.5, 0.75].

assume that all firms invest all of their profits in R&D (that is, $\rho_f = \rho = 1$).

The second strategic choice relates to the arrival of a new generation of mobile technologies which opens a window of opportunities for firms to enter a new product segment (e.g., 3G products or 4G products). Therefore, this choice concerns how firms allocate their limited R&D resources across different product segments related to different technological generations, once they have emerged. The probability of a firm entering into a new product segment is a function of its technological capabilities in the current generation of products. Firms with "too low" capabilities in the current generation of products may not be able to enter a new generation of products, because of insufficient absorptive capacity (Cohen and Levinthal, 1990). On the contrary firms with "too high" capabilities in the current generation of products may be reluctant to enter a new generation of products, because of the "lock-in" effect due to past investments in R&D (Christensen and Bower, 1996)[21].

Therefore, the probability of upgrading into the new technology g $(v_{f,g,t})$ is given by:

$$v_{f,g,t} = \tau \cdot r_{f,g-1,t} \cdot \left(1 - r_{f,g-1,t}\right) \tag{12}$$

where τ is a scale parameter to bound at 1 the maximum probability, which is obtained at intermediate levels of capabilities in the previous generation.

Once a firm enters a new product segment, it has to allocate the R&D budget to increase its technological capabilities in that segment. The exact amount of R&D budget allocated to a new product segment depends on a firm's total R&D budget and its risk aversion (σ_f) toward the latest generation of products. The risk aversion parameter is firm-specific and time-invariant, and is drawn at entry from a uniform probability distribution between 0 and 1. So, the R&D budget allocated to latest generation product segment $\hat{g}$ is formally expressed as:

$$B_{f,\hat{g},t} = \left(1 - \sigma_f\right) \cdot B_{f,t} \tag{13}$$

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[21] For simplicity, we refer here only to R&D investments. Analogous lock-in effects could also originate from other forms of investments (e.g. specialized machinery, marketing).

Therefore some firms allocate a small proportion of their total R&D budget to the latest generation of products, whereas other firms allocate a large proportion. Once the R&D budget for the latest generation of products has been allocated, the rest of the R&D budget is split among previous generation(s) of products by further iterations of the same rule presented above.

4.4   Industry dynamics

At the beginning of the simulation, a given number of domestic firms and foreign MNEs is active in the market. To reflect the historical occurrences of the industry, we allow for entry by small, domestic firms whenever an incumbent domestic firm exits: historically, as a new cohort of domestic firms (e.g., Oppo, Gionee, and Meizu) entered into the industry, some of the early domestic firms (e.g., Ningbo Bird and Amoi) exited the industry. Replacement of MNEs is not explicitly modeled, as the focus of the paper is on the catch-up process by domestic firms rather than on the competitive dynamics between multinational, leader firms.

A firm will exit the industry if the evaluation score on its profits $(E_{f,t})$ is lower than the threshold ε. The evaluation score takes into account both current performance and past performance, so that a firm is allowed to recover from a temporary poor performance, and is given by:

$$E_{f,t} = \omega \cdot \pi_{f,t} + (1 - \omega) \cdot E_{f,t-1} \tag{14}$$

where the parameter ω represents the weight of a firm's current profits in determining a firm's status of survival.

5. SIMULATION RUNS

In this section, we present average results from 1000 simulation runs[22]. First, we run the history-friendly simulation with the aim to replicate some stylized facts of the history. Then, we run history-divergent simulations with the aim to see how the history might change if the sectoral environment was different.

5.1   History-friendly simulation

The simulation starts from the 2G era (period 1 to period 80), and continues throughout the 3G era (period 81 to period 130), and the 4G era (period 131 to period 180). These 180 periods correspond to the 18 years of history of China's mobile communications industry (e.g., 1998-2016), so that each simulation period presents approximately one month in the history. We take 1998 as a starting point of our analysis, since in this year the first domestically built GSM network was launched by a Chinese firm (Huawei), specifically in Inner Mongolia, a rural region of China (Zhang, 2011). At the beginning of the 2G era, there are 10 domestic firms and 8 foreign MNEs. The difference between domestic firms and MNEs is that at the beginning domestic firms have relatively low technological capabilities, whereas foreign MNEs have relatively high technological capabilities.

Figure 3a shows the evolution of the market share of the initial 10 domestic firms' in the urban market. The x-axis refers to time, and the y-axis to market shares. The three curves represent three different product segments. In the 2G product segment domestic firms have a relatively small market share (between 8 % and 19 % overall). However, as generational technological changes open new product segments, domestic firms tend to increase their

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[22] In the case of market shares, the 5th percentile and 95th percentile simulation values are also reported as dashed lines.

market shares in new product segments. For example, the market share of domestic firms in the 3G product segment grows rapidly, and it eventually exceeds the market share of domestic firms in the 2G product segment. Similarly, the initial growth rate of domestic firms' market share in the 4G product segment is even greater than the initial growth rate of domestic firms' market share in the 3G product segment. The market share of domestic firms in the 4G market becomes eventually greater than their 3G market share. Since catching-up of domestic firms is defined as the increase of domestic firms' market share in the urban market, the upward slope of these market share curves captures the speed of domestic firms' catching-up.

INSERT FIGURE 3 ABOUT HERE

Figure 3b shows the average number of the (initial) domestic firms alive in the industry since the beginning of the simulation in 1000 runs. The number of (initial) domestic firms alive reflects the competitive pressure for domestic firms in the industry. The interesting finding from Figure 3b is that there is a quick decline in the number of firms in the early periods: some domestic firms cannot survive their infant ages. For example, over the past decades, there have been a few Chinese domestic firms that have been successful in terms of catching-up (e.g., Huawei, ZTE and to a less extent, also Datang). However, other domestic firms (e.g., Ningbo Bird, Amoi) eventually exited (or almost exited) the industry.

5.1.1 Sensitivity analysis. Before proceeding with history-divergent simulations, we check the robustness of the above results by the means of sensitivity analysis. The sensitivity analysis follows the method described by Landini et al. (2017), which allows us to explore the robustness of results to variations of parameters within a certain range. We checked the robustness of our results with different ranges of variation, starting from [-10%, +10%] until

[-40%, +40%] of the original parameter value in the history-friendly setting. The results from the sensitivity analysis are encouraging. Although the shape of the market share curves changes slightly as the range of variation increases, the stylized fact always remains the same: domestic firms tend to gradually catch-up with foreign MNEs in the urban market over multiple generations of technological changes. Further details about the sensitivity analysis are provided in Appendix C.

5.2   History-divergent simulations

5.2.1 Small rural market. The history friendly model allows us to conduct some counterfactual experiments regarding how the history might have changed if some of the historical conditions would have been different. If domestic Chinese firms really benefited from a relatively large rural market in their catching-up process, we may expect to see that Chinese firms would be less likely to catch-up with foreign MNEs if the size of the rural market is small.

Figure 4a and Figure 4b show the results from 1000 runs of such history-divergent simulation. In this history-divergent simulation, we kept everything else the same, except that we reduced the size of the rural market. As expected, results from Figure 4a and Figure 4b show that without a large rural market to provide domestic firms with an initial nurturing ground, most of the domestic firms do not survive their infant age. Almost all of the initial 10 domestic firms exited the market in the 2G era, soon after the beginning of the simulation. In this case, there is a high rate of exit and entry of domestic firms, but the new entrants have relatively low technological capabilities, and therefore they cannot enter the urban market.

INSERT FIGURE 4 ABOUT HERE

5.2.2 Weak technological relatedness. To explore the role of generational technological

changes in the catching-up process, we also conduct a history-divergent simulation in which we assume that there is weak technological relatedness between a new generation of technologies and an old generation of technologies. In this case, we kept everything else the same as in the history-friendly setting, but we decreased the θ (the relatedness parameter) to one twentieth of its original value in the history-friendly setting. This represents a technological regime under which the technological changes are "competence-destroying" (Tushman and Anderson, 1986), because the capability development for the new generation of technologies is almost unrelated to firm capabilities in the old generation of technologies. The results are shown in Figure 5a and Figure 5b. In such a technological regime, domestic firms can only obtain a small market share in the urban market, because this type of technological change disrupts latecomers' capability-building process. In fact, domestic firms are able to enter the urban market only after the MNEs are already well established in it, because they need more time and resources to meet the minimum quality requirements of the consumers of the new generation products.

This result seems surprising at the first glance, because the prior literature on competence-destroying technological changes (Anderson and Tushman, 1990; Tushman and Anderson, 1986) suggests that technological changes of this type favor new entrants instead of incumbents. However, this stream of literature was originally developed in the context of developed economies, in which "new entrants" are often technologically advanced firms that enter an industry with "competence-destroying innovations". In contrast, "latecomer firms" in the context of emerging economies are different from "new entrants" in the context of advanced economies, because "latecomer firms" are often resource-poor firms that lack advanced technologies (Mathews, 2002). Therefore it is unlikely for such "latecomer firms" to enter an industry in the presence of "competence-destroying innovations". Instead, the catching-up process is a capability-building process through which latecomers gradually

move from being imitators to being innovators (Kim, 1997). When technological change is competence-destroying, it does not only make obsolete the existing capabilities of incumbents: it also disrupts the capability-building process of latecomer firms. In fact, even if both types of firms have to develop new capabilities from scratch, established MNEs develop capabilities faster than domestic firms, because they have more resources (e.g., higher R&D expenditures) to face such type of technological change.

These considerations are reinforced by looking at the extreme case of no relatedness across different generations of technologies. As Figure 6 shows, when the technological change is completely competence-destroying, domestic firms are not able to upgrade into the 3G and 4G product segments within the time frame of our simulations. This confirms the idea that the process of capabilities accumulation of latecomer firms – their "long march" – can slow down so much to be virtually interrupted if new technological generations are unrelated to past technologies.

INSERT FIGURE 5 ABOUT HERE

INSERT FIGURE 6 ABOUT HERE

5.2.3 Strong technological relatedness. We further explore how the history could have been different when the capability-building for a new generation of products is strongly related to a firm's capability in an old generation of products. In this case, we kept everything else the same as in the history-friendly setting, but we increased θ (the relatedness parameter) to twenty times of its original value in the history-friendly setting. This represents a technological regime under which the technological changes are "competence-enhancing"

(Tushman and Anderson, 1986), because the development of capabilities in a new generation of products largely depends on firm capabilities in an old generation of products. The results are shown in Figure 7a and Figure 7b. Like in the history-friendly case, domestic firms upgrade into new product segments (3G or 4G), and catch-up with foreign MNEs in terms of market shares in the urban market. However, further increases in technological relatedness do not provide any further advantage to domestic firms with respect to MNEs.

This result is consistent with the explanations provided in the previous case (Case 2). Although the traditional view on the "competence-enhancing" technological changes suggests that such technological changes would favor incumbents instead of new entrants (Tushman and Anderson, 1986), the technological regime under such a setting also represents an environment that ensures the continuity of the capability-building process by latecomer firms. Under such a technological regime, latecomer firms achieve a satisfactory performance by making a good composition of acceptable quality and competitive price (Luo and Child, 2015). A certain amount of technological relatedness (or competence-enhancing technical change) is necessary to get this acceptable quality. Once this level of quality is reached, however, a stronger competence-enhancing process does not provide increasing advantages to domestic firms, because their strength lies more in the price/cheapness dimension.

INSERT FIGURE 7 ABOUT HERE

5.2.5 Complementarity of market and technological conditions. In the above sections, we have discussed the roles of market regimes and technological regimes separately. To better understand how the market and the technological regimes work together to facilitate latecomers' catching-up, we further compare the evolution of domestic firms' urban market share under different combinations of market and technological conditions. To be more specific, we compare the following four combinations: (1) small rural market, weak technological relatedness (Figure 8a), (2) small rural market, strong technological relatedness (Figure 8b); (3) large rural market, weak technological relatedness (Figure 8c); (4) large rural market, strong technological relatedness (Figure 8d).

The results from such comparisons show that, when the rural market is small, domestic firms cannot catch-up, regardless of the degree of technological relatedness. This means that without a large rural market to provide domestic firms with an initial "nurturing ground", domestic firms cannot survive their "infant age", not mentioning catch-up with MNEs.

However, when there is a large rural market, the extent to which domestic firms can catch-up depends on the degree of technological relatedness between the new generation of technologies and the previous generation of technologies. If there is weak technological relatedness, domestic firms tend to exhibit a moderate level of catch-up in terms of their market shares in the urban market. Instead, if there is a strong technological relatedness, domestic firms tend to exhibit a greater level of catching-up in terms of their market share in the urban market. This means that a certain degree of relatedness between a new generation and an old generation of technologies is necessary for domestic firms' catching-up, because such relatedness ensures the continuity of latecomers' capability-building process. However, generational technical change by itself is not a sufficient condition to obtain a successful catch-up process, because domestic firms need some time and opportunities to accumulate

resources and experience, which is guaranteed by the existence of a large rural market in which the competition of MNEs is much weaker.

INSERT FIGURE 8 ABOUT HERE

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6. DISCUSSION AND CONCLUSION

This paper develops a history-friendly model of China's mobile communications industry to examine the role of the sectoral environment in terms of market regimes and technological regimes in the process of domestic firms' catching-up. The environment that Chinese domestic firms faced in the mobile communications industry was characterized by segmented markets and generational technological changes. The two characteristics together facilitated domestic firms' catching-up with respect to foreign MNEs.

Segmented markets allow domestic firms to survive their infant age by leveraging on their comparative advantages (e.g., cheapness) in the peripheral market, whereas generational technological changes open windows of opportunities in new product segments. As domestic firms proceed along the catching-up process, they tend to enhance their technological capabilities (and also their product quality), although they may lose some of their initial advantages in terms of cheapness. Because customers in the peripheral market (low-end market) care more about the cheapness of the products, whereas customers in the core market (high-end market) care more about the quality of the products, domestic firms that successfully upgrade their technological capabilities migrate from the low-end market to the high-end market. In the model, we operationalize the "peripheral market" as the "rural market" and the "core market" as the "urban market", also to echo the military strategy of Mao Zedong "using the countryside to encircle and finally capture the cities" that inspired

Huawei (The Economist, 2011). However, this expression should be considered as a metaphor, that refers to the process through which latecomer firms expand from the "price-sensitive" low-end market to the "quality-sensitive" high-end market. Historically, this process was not confined to the Chinese domestic market, but characterized also the internationalization strategies of Chinese firms. In fact, when Chinese telecom equipment firms started to internationalize, they tended to start from other emerging markets in which they had competitive advantage (or at least less disadvantage) against established MNEs. For example, both Huawei and ZTE actively targeted other emerging markets such as countries in Asia, Latin America, and Africa. This strategy has been consistently adopted even when Huawei started to expand into the more advanced Western European and North American markets: in these markets, Huawei has been actively targeting small and medium-size telecom operators. Because these small and medium-size operators are more resource constrained compared with the top tier operators, they often have a different evaluation on the quality and the price of telecom products.

Generational technological changes provided domestic firms with windows of opportunities for catching-up with foreign MNEs in new product segments. The history-divergent simulations show that if the generational technological changes are too radical, domestic firms actually cannot catch-up, differently from what the common understanding in the literature on technological discontinuities would suggest (Tushman and Anderson, 1986; Henderson and Clark, 1990; Christensen, 1997). This contrast is only apparent, as latecomer firms in the context of developing countries are different from new entrants in the context of developed economies. The knowledge and resources available to new entrants in developed countries – including advanced human capital, financial markets, a strong IPR regime, and innovation culture – are in general largely unavailable to latecomer firms in developing countries. New entrants from developed countries typically enter an industry with a high level

of technological capabilities, which can be adapted from a related industry (Klepper, 2002), inherited from a parent firm (Klepper and Sleeper, 2005), and accessed through interaction with other firms in a cluster (Breschi and Lissoni, 2001) or with other local actors, including top-ranked universities (Zucker et al., 1998). Latecomer firms from developing countries instead enter an industry with a low level of technological capabilities, because they are constrained by the development stage (Mathews, 2002) and the industrial structure (Hidalgo et al., 2007) of their home country. For example, Huawei was founded in 1987, less than ten years since the start of the Chinese Economic Reforms (Tian and Wu, 2015). At that time, it would have been impossible for a Chinese firm to enter an industry with a high level of technological capabilities. So, these capabilities have been built through a long-term process of accumulation by building linkages with advanced firms and leveraging resources from such linkages (Mathews, 2002), as well as by independent learning through imitation and far-from-the-frontier innovation (Xiao et al., 2013). Actually, "innovation" has rarely been mentioned in Huawei's internal documents (Tian and Wu, 2015), and its top executives, including the founder Ren Zhengfei, often emphasized the dangers for the company of a too radical change or innovation (Zhang, 2011)[23].

The process of capabilities accumulation to catch-up has another important implication for our argument. Competence-destroying and disruptive innovations have a negative impact on incumbent firms, because these firms are constrained by their current capabilities (Leonard-Barton, 1992), investments (Christensen and Bower, 1996), complementary assets (Tripsas, 1997), and cognitive frameworks (Tripsas and Gavetti, 2000), that have been shaped by their past history. However, when latecomer firms face technological changes they also bear the marks of their difficult, long march to get there. In this process, they develop

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[23] Tian and Wu (2015) report many statements from which caution towards radical change emerges clearly. Ren Zhengfei said: "Any arbitrary innovation would be wasting our past investment" (p. 169) and another top executive said: "Any radical change or innovation is undesirable" (p. 169).

routines, capabilities and cognitive frames, and make specific investments, that are tailored to the current technology, and could constrain their capacity to adapt to a radical change. In a sense, latecomer firms are very similar to incumbent MNEs, but they are just endowed with less capabilities.

These considerations are embedded in the assumption of our model that the only systematic difference between domestic firms and foreign MNEs is in their level of initial capabilities. In Appendix D we explore the possibility that MNEs are endowed with worse adoption routines compared to domestic firms, due to less flexible cognitive representations (Tripsas and Gavetti, 2000). Our results with weak or no technological relatedness, i.e. with competence-destroying technological change, are not affected by this change: even if MNEs are at disadvantage in adopting the new technology, domestic firms face the much bigger challenge of building from scratch new capabilities in the poor-resources context of a developing country, and are not able to enter the core market until they develop a good-enough product that meets the minimum quality requirements.

6.1   Contribution

Our model demonstrates that a certain-level of technological relatedness across generations is necessary for latecomers' catching up, because it ensures the continuity of the capability-building process within latecomer firms. Therefore, it provides a better understanding of the dynamic catching-up process through which latecomers climb up the ladder of the value chain.

More specifically, the contributions of this paper are four. First, this paper contributes to the literature on technological change by showing that competence-destroying technological changes might have a detrimental effect on latecomer's catching up, because such technological change would disrupt the capability-building process of latecomer firms. In

fact, the mechanism behind the "catch up" of latecomer firms in the context of developing countries is different from the mechanism behind the success of new entrants in the context of developed countries. This can have important implication for policy makers and industry practitioners in developing countries when dealing with competence-destroying technical change.

Second, this paper contributes to the literature on industry evolution by showing that the evolution of an industry and the dynamics of market structure in terms of competition between domestic firms and foreign multinationals is shaped by the sectoral context. Here the sectoral context is addressed in terms of two key dimensions of a sectoral system: the market regime and the technological regimes (Malerba, 2002; Malerba and Adams, 2014). Moreover, although prior studies on industry evolution have examined the life cycle of products (Abernathy and Utterback, 1978; Suarez and Utterback, 1995) and the competition of firms within an industry (e.g., Klepper, 2002), much of such theorization is based on single-product industries. This paper sheds light on the competition between domestic firms and foreign multinationals when the main products change through generational technological changes.

Third, this paper contributes to the literature on catch-up. Although early research on the topic of catch-up was mainly focused on the country-level (Abramovitz, 1986), there has been an increasing need for a better understanding of the micro-foundations of the catching-up process (Katz, 1984; Bell and Pavitt, 1993; Fagerberg et al., 2006). Prior studies that attempted to address firm-level catching-up have suggested that certain types of industrial environment might promote successful catching-up. For example, Perez and Soete (1988) and Lee and Malerba (2017) conceptually argued that technological change might open the "windows of opportunities" for latecomers. This paper contributes to this stream of literature by modeling the micro dynamics of the catching-up process. The history-friendly modeling approach is an appropriate tool to study the catching-up process, because it allows to examine

rigorously some stylized facts of the history, and because it develops detailed reasoning regarding possible alternative dynamics.

Fourth, although this paper is focused on how certain sectoral environments in terms of market and technological regimes facilitate domestic firms' catching-up, it also has implications for the catch-up strategies of firms (Awate et al., 2012; Kumaraswamy et al., 2012). Since peripheral markets play a vital role in domestic firms' catching-up, emerging market firms should actively target those markets, not only domestically but also internationally. In addition, emerging market firms with a strategic intent of catching-up should actively search opportunities in new product segments created by generational technological changes.

6.2　　Limitations and future research

One limitation of this study is that it does not explicitly model different firm strategies. In this paper the heterogeneity of firms is treated as a result of random variations. We made this choice because the main purpose of this paper was to demonstrate the role of the market and technological regimes on domestic firms' catching-up. However, we acknowledge that not all firms can equally benefit from such sectoral environments. Our current research explores the role of firm strategies in the catching-up process of emerging-market firms taking into account the sectoral environment.

In addition, this paper does not address the role of institutions (e.g., governments, public research institutions) in the catching-up process of domestic firms. There is increasing evidence about the role that institutions play in the process of industry evolution (Boschma and Capone, 2015) and more specifically in the catching-up (Landini and Malerba, 2017). Governments might facilitate domestic firms' catching-up by using different policy tools (e.g., procurement policies or standards policies), whereas public research institutions might facilitate domestic firms' catching-up by reducing technological uncertainty. This may be an

additional relevant feature of a sectoral context, which has been emphasized by the literature on sectoral systems (Mowery and Nelson, 1999; Malerba, 2002). Future research can further investigate how different institutions played a role in the catching-up process of domestic firms under the sectoral environments that we consider in this paper.

Finally, this paper is developed based on the observation from a single industry which has some specific characteristics. For example, in the mobile communications industry, technological standards do not come from market competition, but they are collectively agreed upon by multiple stakeholders. However, as new major technological changes, labelled by some observes as the Fourth Industrial Revolution has been blurring sectoral boundaries (Schwab, 2017), the interdependence among different stakeholders will further increase. We expect to see more and more contexts (e.g., autonomous driving) in which technological standards will be collectively agreed upon by different stakeholders, and in which generational technological change will be particularly relevant. We believe that our results can be applied to other contexts that share these characteristics with the mobile communications industry.

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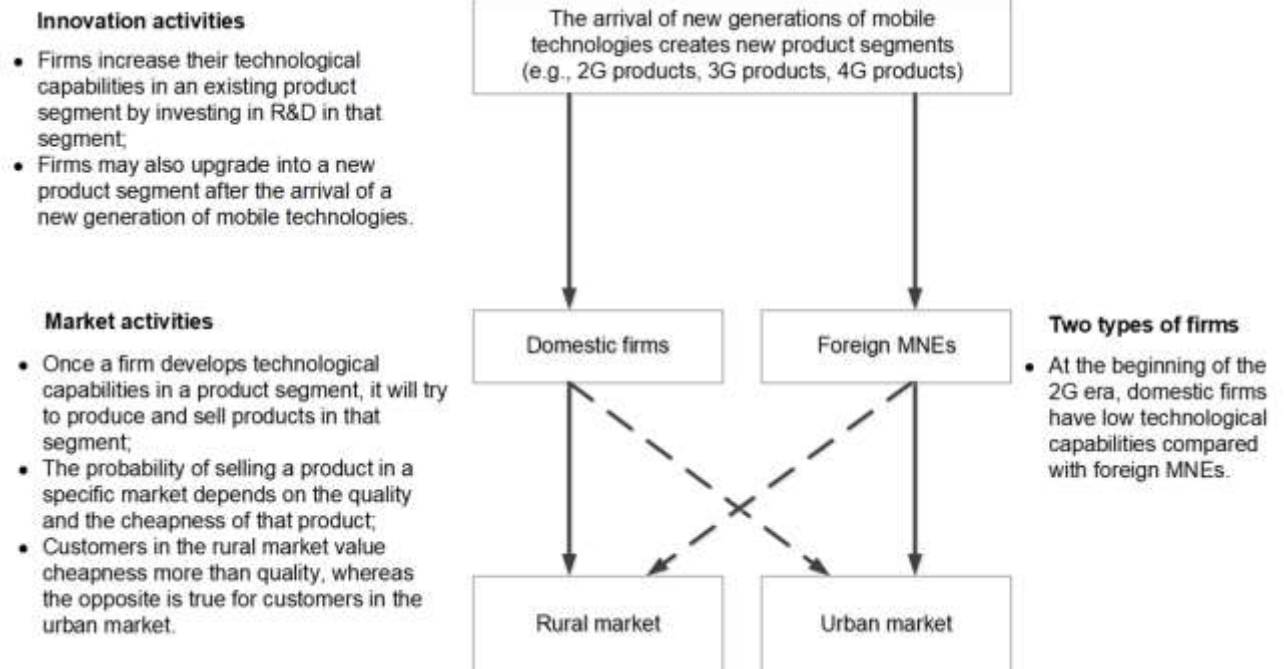
FIGURES

Figure 1. Different generations of mobile communication systems.
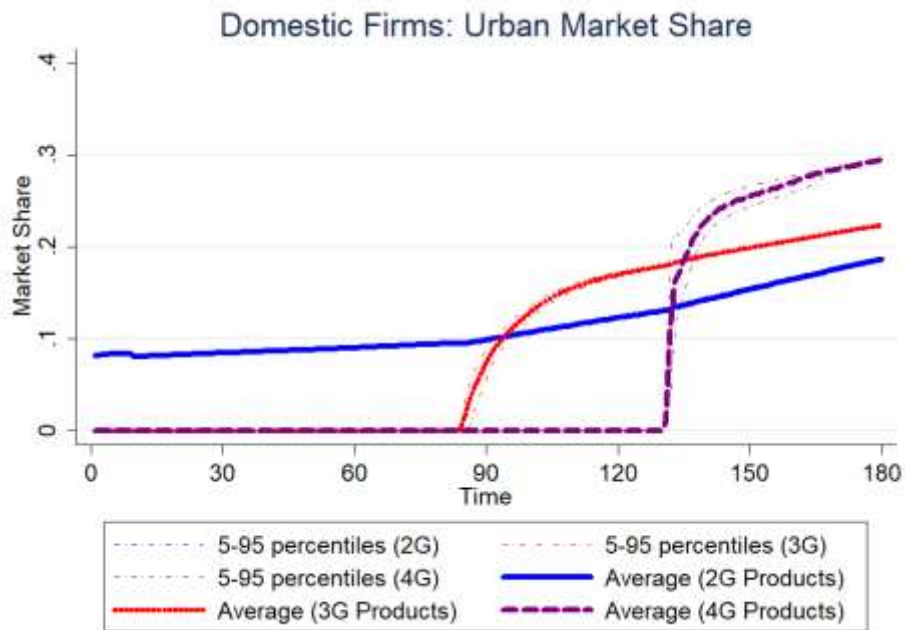[SIZE: 1 column]
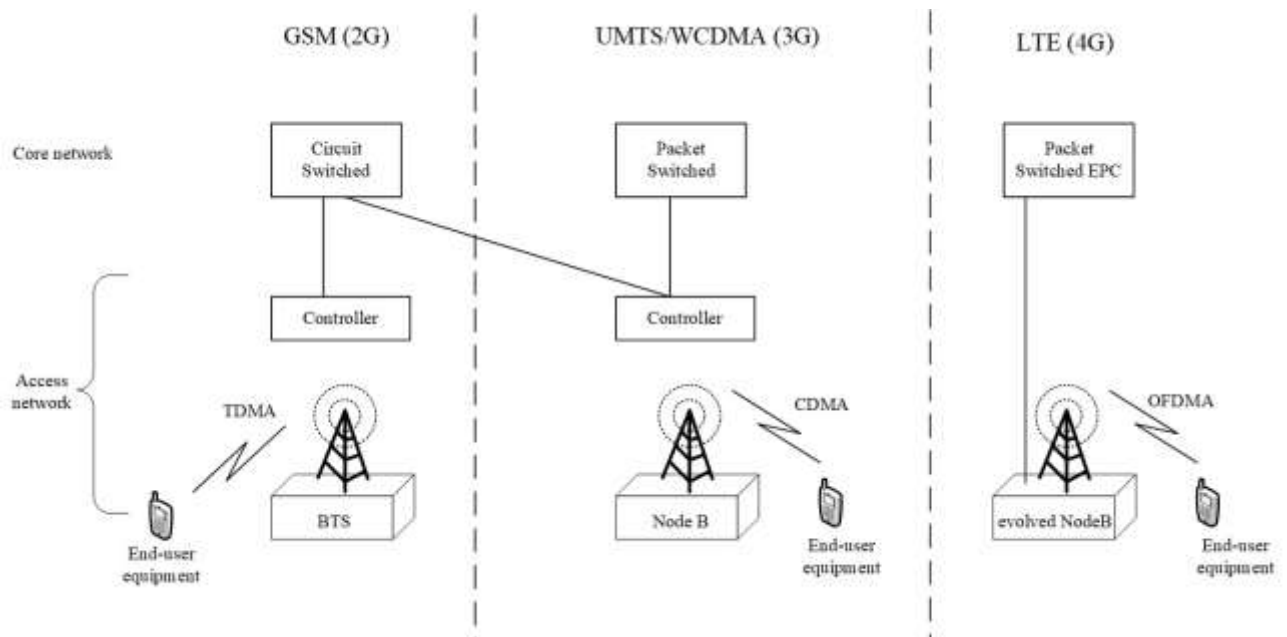
Note: modified from Nohrborg (2016)'s figure published on the 3GPP official site. GPRS, an extension of GSM (the so-called 2.5 G), is dropped from this study.

Figure 2. Model overview.
[SIZE: 2 columns]

Innovation activities

- Firms increase their technological capabilities in an existing product segment by investing in R&D in that segment;
- Firms may also upgrade into a new product segment after the arrival of a new generation of mobile technologies.

Market activities

- Once a firm develops technological capabilities in a product segment, it will try to produce and sell products in that segment;
- The probability of selling a product in a specific market depends on the quality and the cheapness of that product;
- Customers in the rural market value cheapness more than quality, whereas the opposite is true for customers in the urban market.

The arrival of new generations of mobile technologies creates new product segments (e.g., 2G products, 3G products, 4G products)

Domestic firms

Foreign MNEs

Rural market

Urban market

Two types of firms

- At the beginning of the 2G era, domestic firms have low technological capabilities compared with foreign MNEs.

Figure 3. History-friendly simulation.
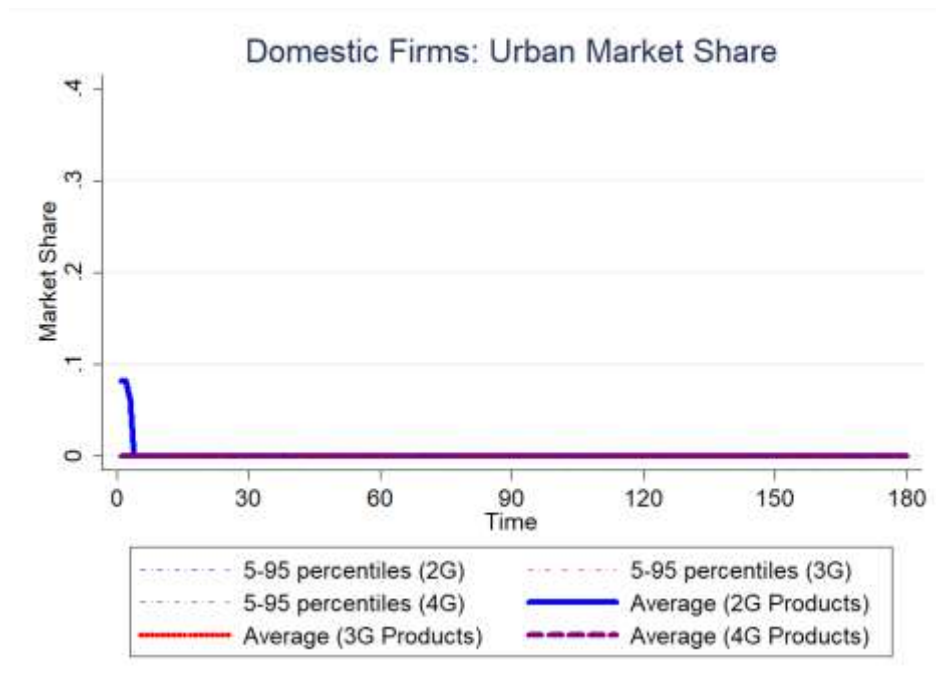[SIZE: 1 column for 3.a, 1 column for 3.b]
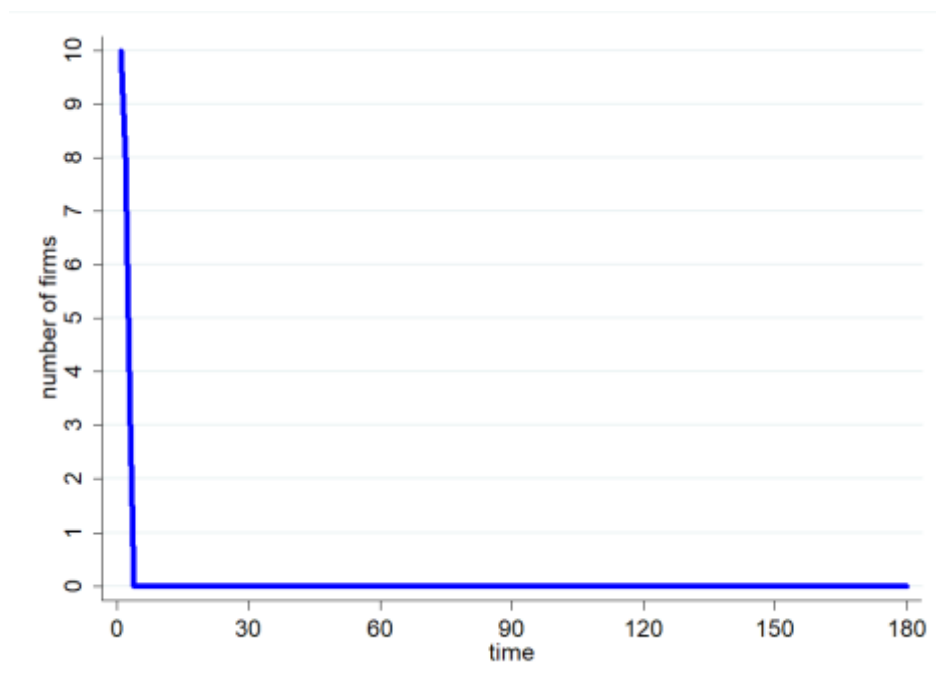

a. Domestic firms' market share in the urban market.
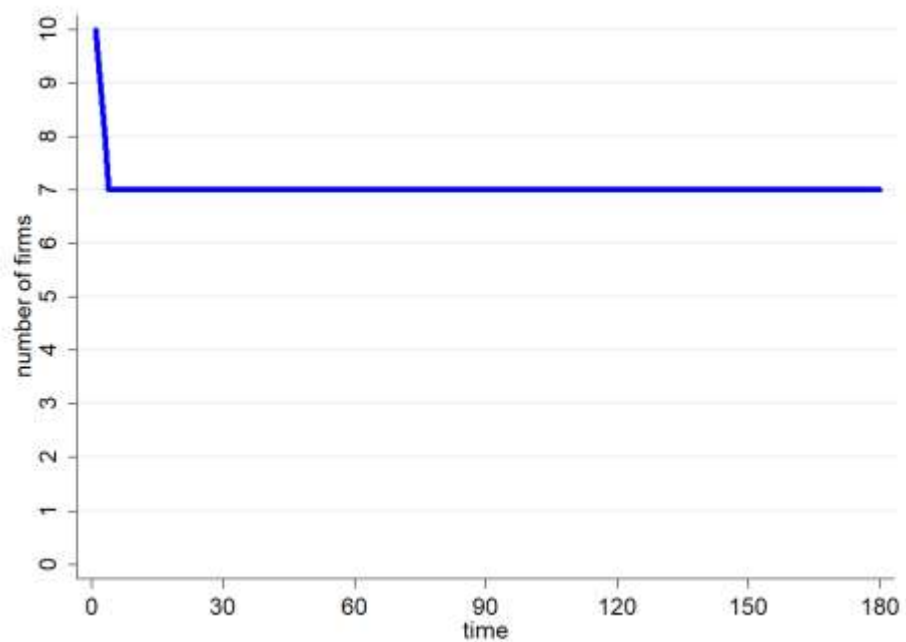
b. Average number of (initial) domestic firms alive.

Figure 4. Small rural market ($\Phi_R = 10000$).
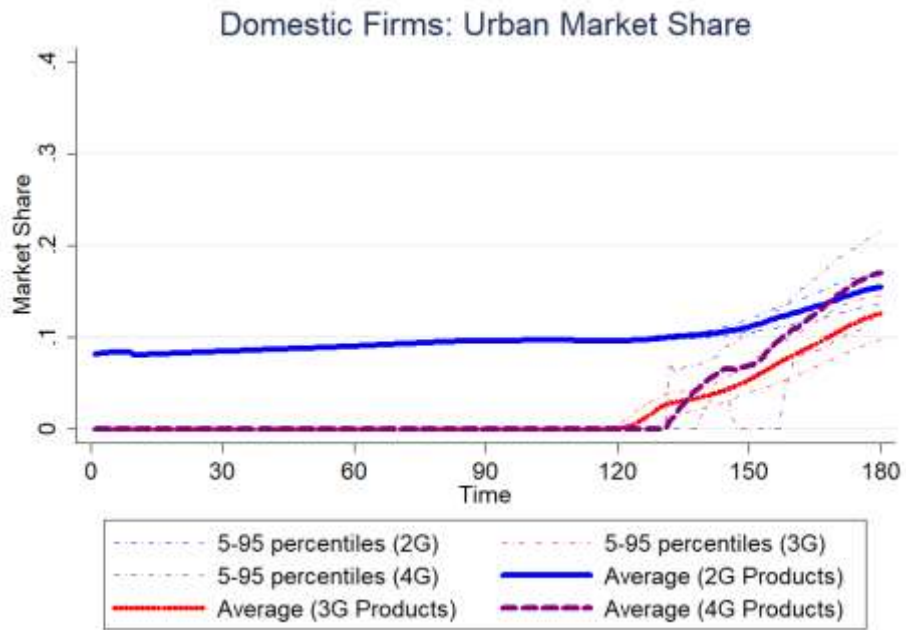[SIZE: 1 column for 4.a, 1 column for 4.b]
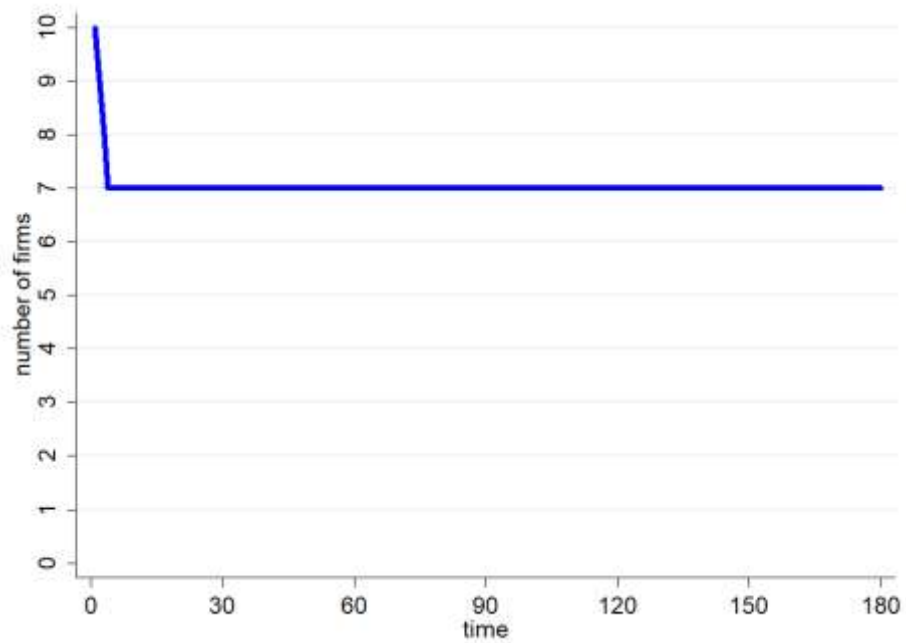

a. Domestic firms' market share in the urban market.

b. Average number of (initial) domestic firms alive.

Figure 5. Weak technological relatedness ($\theta = 0.0005$).
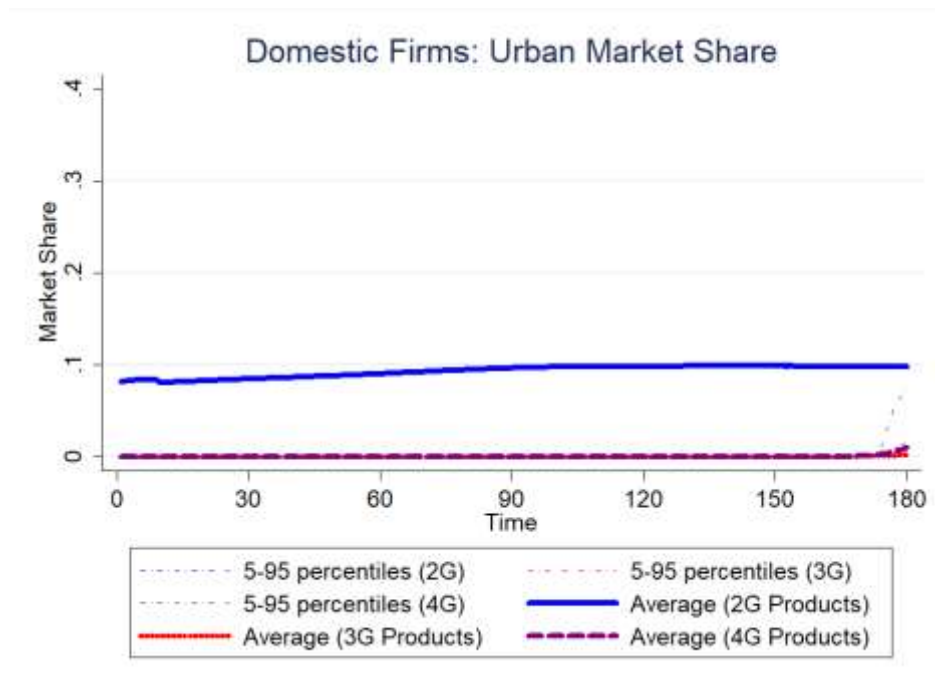[SIZE: 1 column for 5.a, 1 column for 5.b]
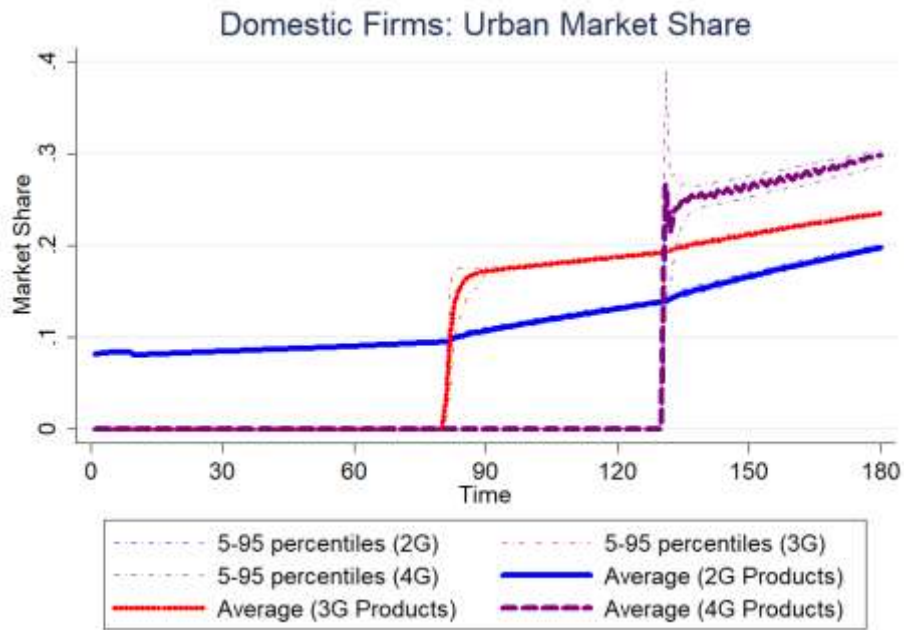

a. Domestic firms' market share in the urban market.

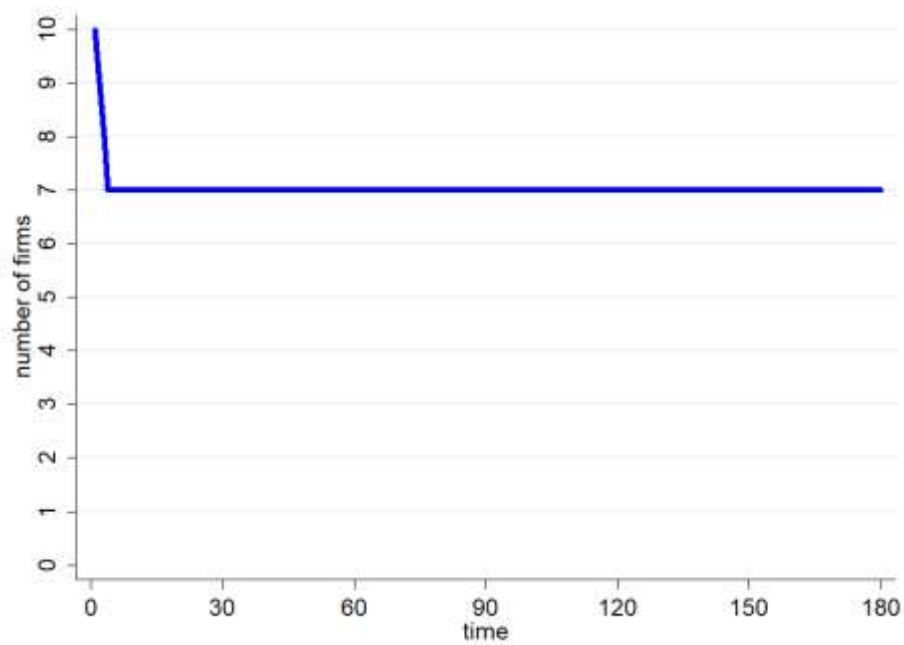b. Average number of (initial) domestic firms alive.

Figure 6. No technological relatedness ($\theta = 0$). Domestic firms' market share in the urban market.
[SIZE: 1 column]

Figure 7. Strong technological relatedness ($\theta = 0.2$).
[SIZE: 1 column for 7.a, 1 column for 7.b]

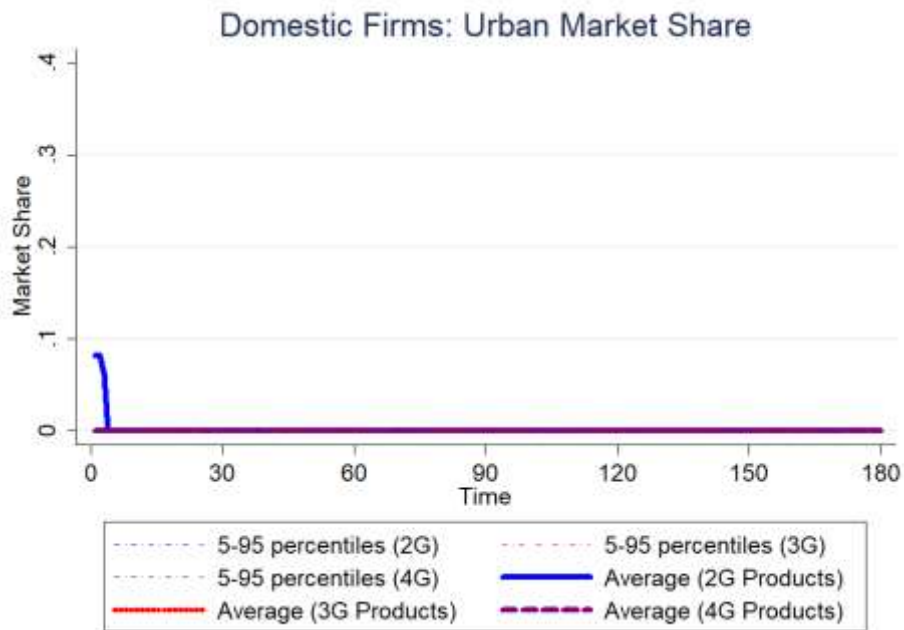a. Domestic firms' market share in the urban market.

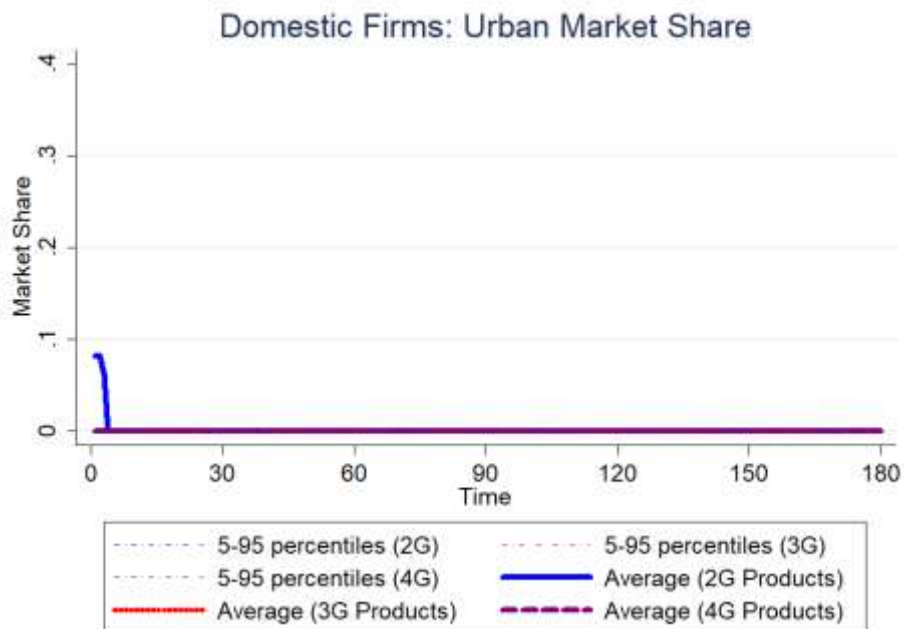b. Average number of (initial) domestic firms alive.

Figure 8. Complementarity of market and technology forces.
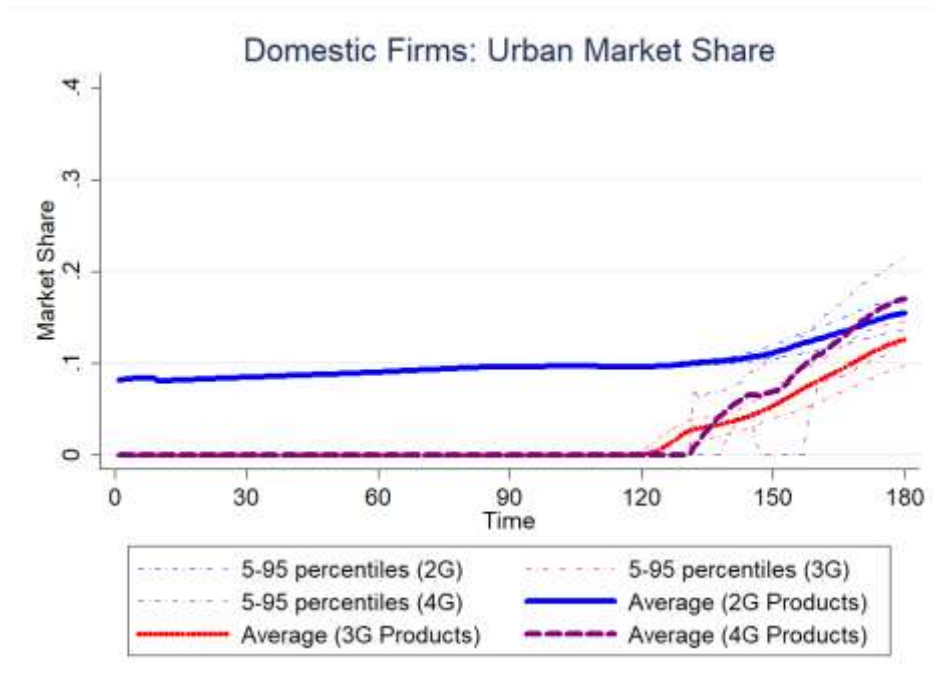[SIZE: 1 column for 8.a, 1 column for 8.b, 1 column for 8.c, 1 column for 8.d]
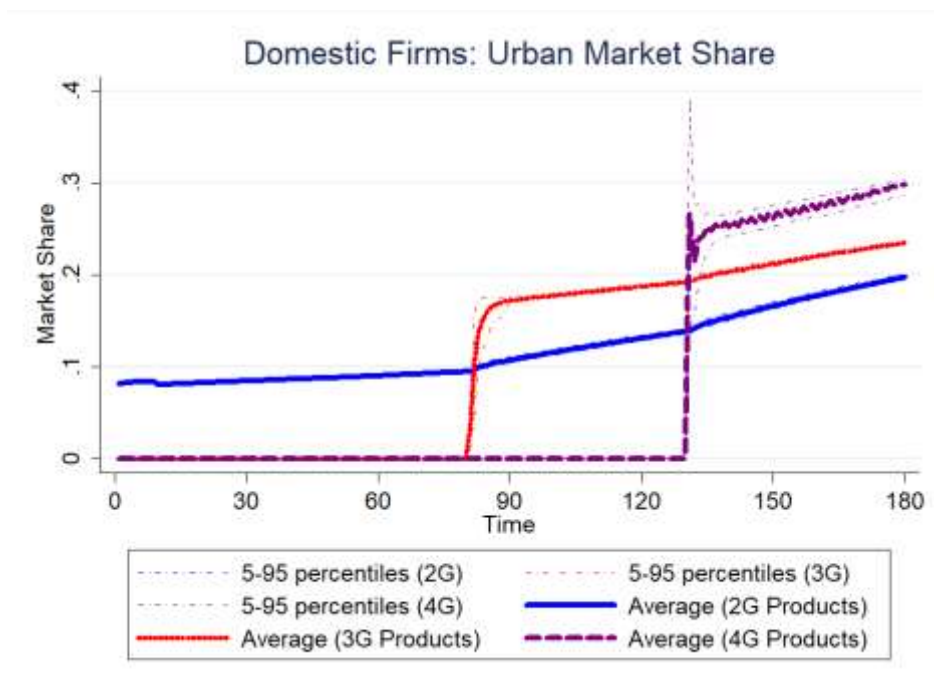

a. $\Phi_R = 10000;\ \theta = 0.0005$

b. $\Phi_R = 10000;\ \theta = 0.2$

c. $\Phi_R = 30000; \theta = 0.0005$

d. $\Phi_R = 30000; \theta = 0.2$

TABLES

Table 1. Comparison of different generations of mobile communications technologies

Generation		1G	2G	3G	4G
End-user equipment		Analog mobile cell phones	Feature phones	Smart phones, mobile broadband modem, tablets, etc.	Smart phones, mobile broadband modem, tablets, etc.
Wireless Access		FDMA	TDMA, CDMA	CDMA	OFDMA, MIMO
Core network		Circuit-based	Circuit-based	Circuit-based & Packet-based	Packet-based (fully IP-based)
Standards		AMPS, TACS, NMT	GSM, CdmaOne	WCDMA, CDMA2000, TD-SCDMA	LTE (including TDD and FDD modes)
Major Services	**Voice**	(analog) Voice	Voice	Voice	Voice over IP
	Data	No data service	Limited Internet	Internet	High speed Internet

Note. Modified from Table 1 of Adachi (2001) with additional information from Qualcomm (2014) and Telesystem Innovations (2010).

APPENDIX A: COMPARISON TO PREVIOUS HISTORY-FRIENDLY MODELS

The model presented in this paper directly builds on previous history friendly models about the computer, semiconductor, and pharmaceutical industries (Malerba et al., 1999, 2008, 2016; Malerba and Orsenigo, 2002) by reusing and adapting to the specific context of the Chinese mobile communications industry lower-level modules from these models. Table A.1 groups the key elements of the model into four broad categories: Market Environment, Technology Environment, Industry Dynamics, and Firm Behavioral Rules. For each element, it presents a brief description, references, and differences due to the specific context of catching-up in the mobile communications industry. References to specific papers are provided when an element is derived from that model. We refer instead to a more recent book on history friendly models (Malerba et al., 2016) when an element is common to all three models reported above.

Elements grouped under the Market Environment category refer to the characteritics of the model that describe the demand dimension. In the model, we assume that there are two distinct markets as in Malerba et al. (1999, 2008), but to be closer to our historical case we assume that the two markets are not independent: therefore the same product in principle can be sold on both markets. Consumer preferences about quality and price are modelled following Malerba et al. (1999, 2008) with a Cobb-Douglas function with minumum requirements, which is quite common also in other modelling approaches (e.g. Adner and Levinthal, 2001). Market share computation follows from the relative merit of design of each product, as determined by consumer preferences and product characteristics (Malerba et al., 2016). The biggest difference with the previous literature in the market dimension is about demand growth. Malerba et al. (1999, 2008) did not model explicitly this aspect, that still played an important role in the development of the mobile communications sector. On this point, we follow Landini et al. (2017) model featuring mobile phones, that characterizes demand time evolution using the logistic growth path.

The Technology Environment category includes all aspects about technological change and innovation. Following Malerba et al. (1999), innovation is characterized as a continous process of improvement of product quality, driven by the accumulation of capabilities. For simplicity, in this model we assume that other factors, such as experience or distance from the technological frontier, are all summarized under the capabilities label. The development of capabilites occurs cumulatively within each firm (Malerba et al., 2008). The past literature emphasized the role of public knowledge as a non-cumulative factor. Due to

the relevance of generational technical change, the non-cumulative element in our model is associated to the arrival of new generations of technologies, and the specific capabilities they require. The arrival of new generation is associated to the emergence of new market opportunities and occurs at time periods exogenously set to be coherent with the history of the industry (Malerba et al., 1999, 2008). To pursue their innovation activities, firms sustain R&D costs: for simplicity, as in past works (Malerba et al., 2016) the unit cost of R&D is constant for all firms and in all periods.

Industry Dynamics refer to the elements defining the entry and exit of firms. There are two types of firms (domestic and MNEs). Firm type is set exogenously (Malerba et al., 1999, 2008), but firms differ for their initial endowment of capabilities and not for the adopted technology. Entry occurs at the beginning of the simulation (Malerba et al., 2016), but to resemble historical occurences we allow for replacement of domestic firms. Exit depends on past performance (Malerba et al., 1999, 2008), using profits rather than market share as performance measure.

Finally, the Firm Behavior category includes the decision rules of the firms in different domains. First, firms set the price of their products using a markup rule (Malerba and Orsenigo, 2002; Landini et al., 2017), taking into account competition in both markets. Second, firms allocate to R&D investment a fixed prooprtion of their profits (Malerba et al., 2016), specifying the amount for each technological generation. Third, firms decision to adopt a new technology depends on technological capabillities (Malerba et al., 1999), associated to the current technology rather than to the incoming one.

Table A.1. Model building blocks: similarities and differences with previous history friendly models

Domain	Specific Element	Description	Source	Differences
Market Environment	Number of markets	There are two distinct markets characterized by different consumers preferences	Malerba et al., 1999; 2008	A product can be sold on both markets
	Consumers preferences	Consumers evaluate quality and price (Cobb-Douglas with minimum requirements). Preferences are homogenous within each market.	Malerba et al., 1999; 2008	
	Market share	Market shares are computed as relative merit of design	Malerba et al., 2016	
	Market growth	Logistic growth	Landini et al., 2017	
Technology Environment	Role of technological capabilities	Capabilities accumulation drives product quality	Malerba et al., 1999	Other factors (experience, technological frontier) are not included.
	Development of technological capabilities	Capabilities development is partly cumulative	Malerba et al., 2008	The non-cumulative element is the new generation capabilities, not the public knowledge
	R&D cost	Unit R&D cost is constant across firms and time.	Malerba et al., 2016	
	Generational technical change	Exogenous arrival of new technologies, associated to new markets	Malerba et al., 1999; 2008	
Industry Dynamics	Firm type	Exogenous number of firms for each type: domestic and MNEs	Malerba et al., 1999; 2008	Firm types differ for the initial endowment of capabilities, not for adopted technology
	Entry	Exogenous waves of entry	Malerba et al., 2016	Replacement of domestic firms
	Exit	Exit rule based on performance in past periods	Malerba et al., 2008	Performance metric is profit, not market share
Firm Behavior	Pricing	Markup pricing	Malerba & Orsenigo, 2002 Landini et al., 2017	The markup takes into account competition in both markets
	R&D investment	Fixed proportion of profits	Malerba et al., 2016	Profits are allocated to multiple technology generations
	Adoption of new technology	Related to technological capabilities	Malerba et al., 1999	Adoption affected by the existing technology, not by the new technology

APPENDIX B: INDEX OF PARAMETERS AND VARIABLES

Symbol	Description	Value / Range
$B_{f,\hat{g},t}$	R&D budget allocated to latest generation $\hat{g}$ by firm f at time t	$\mathbb{R}_+$
$B_{f,t}$	Total R&D budget of a firm f at time t	$\mathbb{R}_+$
$C_{f,g,t}$	Cheapness of the product by firm f at time t in generation g	$\mathbb{R}_+$
$c_{f,g,t}$	Firm-specific production cost at time t in generation g	$\mathbb{R}_+$
c_g	Generation-specific baseline production cost	$c_{2G} = 10$
		$c_{3G} = 15$
		$c_{4G} = 20$
c^{RD}	R&D unit cost	100
$E_{f,t}$	Evaluation score for exit decision	$\mathbb{R}_+$
F	Number of firms	$F^{DOM} = 10$
		$F^{MNE} = 8$
f	Index for firms	$\mathbb{N}$
g	Index for generation-specific product segment	$\{2G, 3G, 4G\}$
h	Market growth rate	0.001
k	Index for market	R: rural
		U: urban
$M_{f,g,k,t}$	Merit of design perceived by customers in market k of product by firm f at time t in generation g	$\mathbb{R}_+$
$m_{f,g,t}$	Mark-up ratio of firm f at time t in generation g	$[0, \frac{1}{\eta_k - 1}]$
$Q_{f,g,t}$	Quality of firm f product at time t in product segment g	$[0, \delta_g]$
$p_{f,g,t}$	Price of firm f product at time t in product segment g	$\mathbb{R}_+$
$r_{f,g,t}$	Technological capability of firm f at time t in product segment g	$[0,1]$
$s_{f,g,k,t}$	Market share of firm f at time t in product segment g and market k	$[0,1]$
T	End of simulation	180
t	Index for time	$\mathbb{N}$
$w_{f,g,t}$	Weight of rural market to set mark-up	$[0,1]$
α	Scale parameter in Equation 1	1000

Symbol	Description	Value
γ_k^C	Weight assigned to cheapness by customers in market k	$\gamma_R^C = 0.8$ $\gamma_U^C = 0.2$
γ_k^Q	Weight assigned to quality by customers in market k	$\gamma_R^Q = 0.2$ $\gamma_U^Q = 0.8$
δ_g	Processing coefficient of technological capabilities into product quality in generation g	$\delta_{2G} = 100$ $\delta_{3G} = 500$ $\delta_{4G} = 1000$
ε	Threshold for exit decision	300
η_k	Price elasticity of demand in market k	$\eta_U = 1.25$ $\eta_R = 1.5$
θ	Technological relatedness parameter	0.01
$\lambda_{g,k}^C$	Minimum required cheapness in product segment g and market k	$\lambda_{2G,R}^C = 40 \quad \lambda_{2G,U}^C = 20$ $\lambda_{3G,R}^C = 20 \quad \lambda_{3G,U}^C = 10$ $\lambda_{4G,R}^C = 10 \quad \lambda_{4G,U}^C = 5$
$\lambda_{g,k}^Q$	Minimum required quality in product segment g and market k	$\lambda_{2G,R}^Q = 3 \quad \lambda_{2G,U}^Q = 9$ $\lambda_{3G,R}^Q = 5 \quad \lambda_{3G,U}^Q = 15$ $\lambda_{4G,R}^Q = 10 \quad \lambda_{4G,U}^Q = 30$
ν_g	Scale parameter in Equation 3	$\nu_{2G} = 1500$ $\nu_{3G} = 1000$ $\nu_{4G} = 500$
$\pi_{f,t}$	Profit of a firm f at time t	$\mathbb{R}_+$
ρ	Proportion of profits allocated to R&D budget	1
σ_f	Risk aversion of firm f towards the latest technology generation	$[0, 1]$
τ	Scale parameter in Equation 12	4
$\upsilon_{f,g,t}$	Probability of upgrading into the new technology g	$[0, 1]$
Φ_k	Carrying capacity for each generation-specific product segment of market k	$\Phi_U = 20000$ $\Phi_R = 30000$
φ	Processing coefficient of quality into production cost	0.08
χ_k^0	Initial number of customers in each generation-specific product segment of market k	$\chi_R^0 = \Phi_R/2$ $\chi_U^0 = \Phi_U/2$
ω	Weight of current profits in exit decision	0.75

APPENDIX C: SENSITIVITY ANALYSIS

In this section, we conduct sensitivity analyses to test the robustness of the results by following Landini et al. (2017). The sensitivity analyses mainly involve two steps.

Step One: Identify relevant parameters. In this step, we identify parameters that will be further explored in the sensitivity analyses. We excluded two types of parameters from the sensitivity analyses: "structural parameters" that define the structure of the model (e.g., time periods, or threshold values) and "focal parameters" that are explored in counterfactual simulations (e.g., market size, technological relatedness). After excluding these parameters, we obtain a list of parameters whose variation will be explored in the sensitivity analyses. We call these parameters "general parameters" (Landini et al., 2017).

Table C.1. List of general parameters for sensitivity analyses

| Symbol	Description	Value
F^{DOM}	Initial number of domestic firm	10
F^{MNE}	Initial number of MNEs	8
$\gamma_R^Q (\gamma_R^C)$	Weight assigned to quality (cheapness) by customers in rural market	0.2 (0.8)
$\gamma_U^Q (\gamma_U^C)$	Weight assigned to quality (cheapness) by customers in urban market	0.8 (0.2)
δ_{2G}	Processing coefficient of technological capabilities into product quality in 2G	100
δ_{3G}	Processing coefficient of technological capabilities into product quality in 3G	500
δ_{4G}	Processing coefficient of technological capabilities into product quality in 4G	1000
ν_{2G}	Scale parameter in Equation 3 in 2G	1500
ν_{3G}	Scale parameter in Equation 3 in 3G	1000
ν_{4G}	Scale parameter in Equation 3 in 4G	500
c_{2G}	Baseline production cost in 2G	10
c_{3G}	Baseline production cost in 3G	15
c_{4G}	Baseline production cost in 4G	20
ε	Threshold for exit decision	300
c^{RD}	R&D unit cost	100
η_R	Price elasticity of demand in rural market	1.5
η_U	Price elasticity of demand in urban market	1.25
h	Market growth rate	0.001

Some of the above parameters should be grouped together in the sensitivity analyses to preserve the relationships among their values. First, δ_g represents a group of parameters: the relationships among δ_{2G}, δ_{3G}, and δ_{4G} need to be preserved, so that a new generation of products has better quality than old generations of products. Second, ν_g represents a group of parameters: the relationships among ν_{2G}, ν_{3G}, and ν_{4G} need to be preserved, so that a new generation of products is more expensive than old generations of products. Third, c_g represents a group of parameters: the relationships among c_{2G}, c_{3G}, and c_{4G} need to be preserved, so that the baseline production cost will be higher for a new generation of products. Fourth, γ_U^Q and γ_R^Q are grouped together to ensure that urban customers care more about quality than rural customers do; moreover, γ_U^C and γ_R^C are determined to ensure that the sum of the exponents is equal to 1. Finally, η^U and η^R are grouped together to ensure that rural customers are more price sensitive compared to urban customers.

In order to test the robustness of results to changes in these relationships, and preserving at the same time their economic meaning, we introduce some ratio parameters that are subject to the sensitivity analysis. For example, in the history-friendly setting, the ratio between ν_{3G} and ν_{2G} is 0.67 (1000/1500). In the sensitivity analyses, we allow this ratio to vary within certain ranges, just as what we did for any other general parameters. After considering all the general parameters (and ratios), we identified 18 variables whose variation will be explored below.

Step Two: Sampling and simulation. In this step, we run simulations with different sets of parameter values drawn through a procedure described by Landini et al. (2017): First, we specify the range of variation for each parameter. Second, we divide the range of variation into 18 equally probable intervals. Third, we randomly extract 18 sets of parameter values from these intervals, ensuring that "each interval is sampled once and only once" (Landini et al., 2017). Each set of parameter values represents a distinct configuration of the model that is equivalent to the "history-friendly" model. We run 1000 simulations for each of these 18 configurations. Lastly, we calculate the average value of outcome variables from these 18000 simulations (18×1000) and check if the results are similar to the ones that we have obtained from the "history-friendly" simulation.

The results from the sensitivity analyses reported in Figure C.1 are encouraging. Although the shape of market share curves changes slightly as we increase the range of variation, all the figures present the same stylized fact, that is domestic firms demonstrate their "long march to catch-up" with foreign MNEs in the urban market over time.
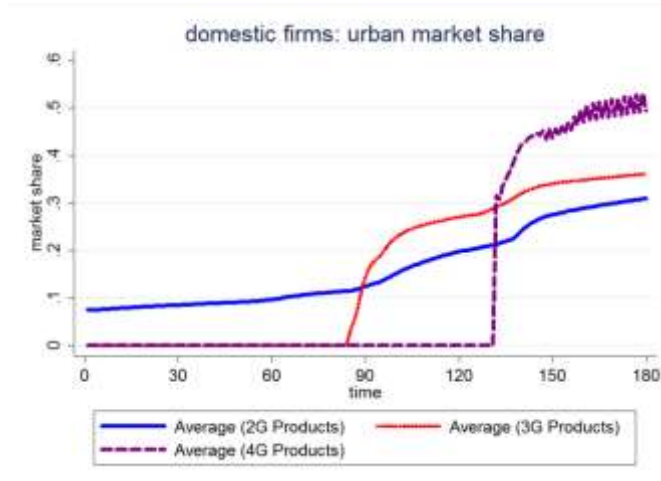
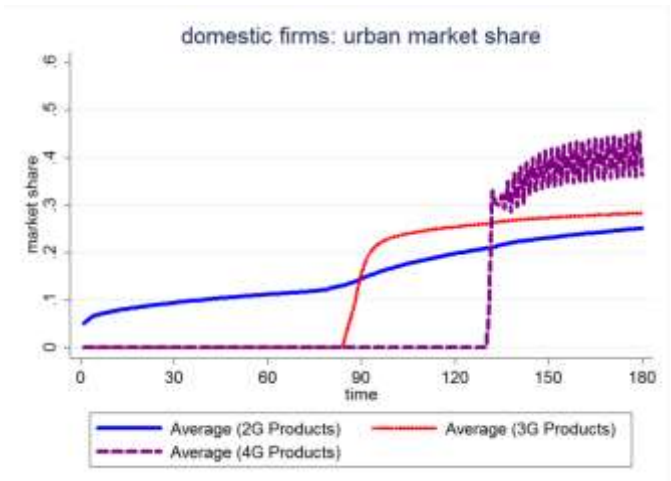**Figure C.1.** Results from the sensitivity analyses
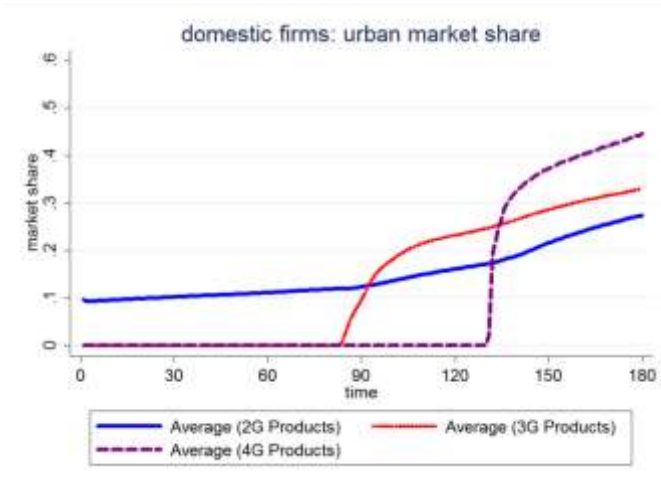
(A) Range of variation: -10% to +10%
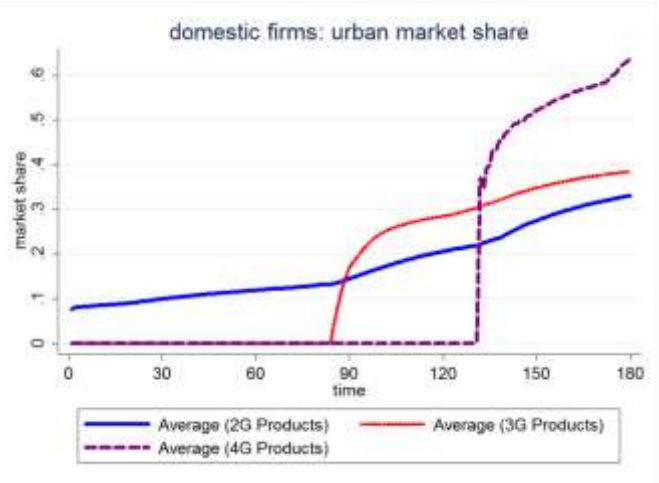
(B) Range of variation: -20% to +20%

(C) Range of variation: -30% to +30%

(D) Range of variation: -40% to +40%

Note: We tested different ranges of variation for all parameters with respect to their original values in the history-friendly setting, starting from [-10%, +10%] until [-40%, +40%]. The only exception is for the demand elasticity parameters. Following Landini et al. (2017), we restricted the variation of elasticity parameters within a small range [-10%, +10%] to avoid abnormal markup ratios in the mark-up equation.

## APPENDIX D: RIGID COGNITIVE FRAMEWORKS IN MNES

Often, radical technical change damages incumbent firms, because these firms are constrained not only by their current capabilities, but also by their cognitive frameworks (Tripsas and Gavetti, 2000), that have been shaped by their past history. Also latecomer firms have a long history, during which they develop capabilities and cognitive frames, that could constrain their capacity to adapt to a radical change. So, latecomer firms are very similar to incumbent MNEs, but they are endowed with less capabilities.

These considerations are embedded in the assumption of our model, that the only systematic difference between domestic firms and foreign MNEs is in their level of initial capabilities. In this section, we conduct further counterfactual simulations that allow us to introduce in our model some elementary form of heterogeneity in adoption routines between domestic firms and MNEs, due to different cognitive frameworks.

To do this, we consider Equation 12, which describes the adoption routine for all firms in our model. Adoption of a new technology depends on the level of capabilities in the current technological generation, and is also affected by a scale parameter τ, which determines the maximum value of the adoption probability in each period. This parameter can be interpreted as a firm-specific determinant of adoption, that depends on the cognitive frameworks of the firm. Lower values of the parameter imply a cognitive framework less open to changes, and therefore a lower probability to adopt a new technology.

Our analysis is conducted in the cases of weak or no technological relatedness, i.e. with competence-destroying technological change. Here, we assume that the τ parameter is equal to 4 (as in the baseline case) for domestic firms, and instead is much lower (1) for MNEs. Results are reported in Tables D.1 and D.2: they show that even if MNEs are at disadvantage in adopting the new technology, domestic firms face the much bigger challenge of building from scratch new capabilities in the poor-resources context of a developing country, and are not able to enter the core market until they develop a good-enough product that meets the minimum quality requirements. In general, this happens much later than the period in which MNEs adopt the new technology.

Figure D.1. Weak technological relatedness ($\theta = 0.0005$)
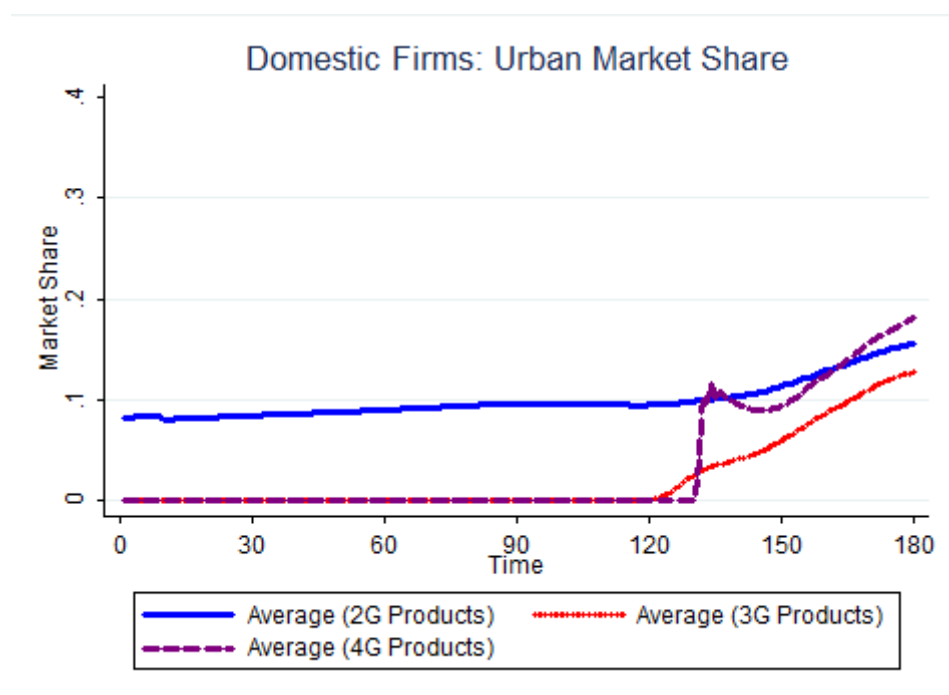
Figure D.2. No technological relatedness ($\theta = 0$)
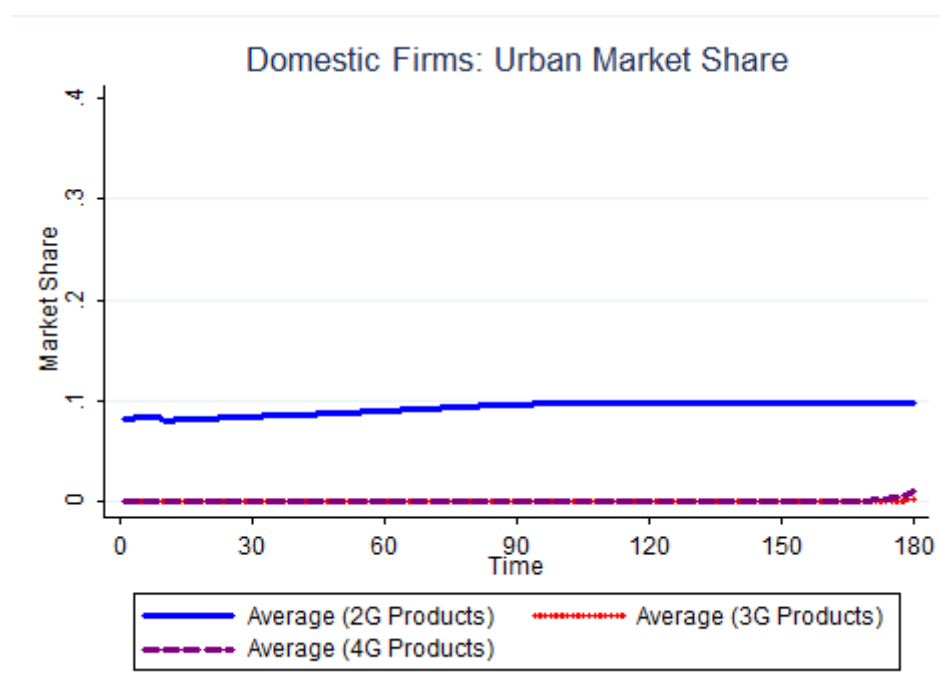
APPENDIX E: LIST OF ABBREVIATIONS

1G	First generation (mobile communications)
2G	Second generation (mobile communications)
3G	Third generation (mobile communications)
4G	Fourth generation (mobile communications)
AMPS	Advanced Mobile Phone System
CDMA	Code Division Multiple Access
EPC	Evolved Packet Core
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HSPA+	Evolved High-Speed Packet Access
LTE	Long Term Evolution
Mbps	Megabits per Second
MIMO	Multiple Input Multiple Output
NMT	Nordic Mobile Telephony
OFDMA	Orthogonal Frequency Division Multiple Access
SMS	Short Message Service
TACS	Total Access Communication System
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TD-SCDMA	Time Division - Synchronous Code Division Multiple Access
UMTS	Universal Mobile Telecommunications System
WCDMA	Wideband Code Division Multiple Access