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AN ANALYSIS OF SPECTRUM ALLOCATION FOR THE MOBILE PHONE SERVICES

A minor dissertation submitted to the UNIVERSITY OF CAPE TOWN in partial fulfilment of the requirements for the degree of Master of Commerce in Economics Science.

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Abstract

This paper investigates the relationship between the spectrum allocation policy and the mobile broadband cost in 135 countries between 2012 and 2019, with a particular focus on developing countries. We construct a panel data collected from various sources such as World Development Indicator (WDI), International Telecommunication Union (ITU) - ICT Price Baskets (IPB), Global Mobile Frequencies Database of Spectrum Monitoring Technology Advisors databases and other additional sources to conduct our empirical analysis.

We estimate a system of equations - demand and supply for mobile broadband services with the following findings. First, demand for mobile Internet is negatively impacted by the price of 1GB of mobile broadband, as suggested by economic theory. Second, GDP per capita has a positive impact on the mobile broadband penetration.

In the pricing equation, 79% of overall variation in mobile broadband price is explained by the list of exogenous variables included in our model specification. We find that the mobile broadband price is decreasing with population density which is an indication of economies of scale. Moreover, the price of mobile broadband increases with Herfindahl-Hirschman Index. Also, prices decrease when the market structure changes from monopoly to competition. The price of mobile broadband decreases for a greater volume of radio spectrum available to all the operators within country. Moreover, auction mechanism of spectrum allocation reduces the mobile broadband price.

Our results imply that the regulatory authority and policy makers need to promote access of radio spectrum for mobile services. Moreover, a spectrum assignment mechanism based on auctions contributes to the economic efficiency by reducing marginal cost and prices of mobile broadband services.

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List of abbreviations

APG	Average Price per one Gigabyte
EU	European Union
FCC	The Federal Communications Commission
GB	Gigabyte
GDP	Gross Domestic Product
GDPpc	Gross Domestic Product per capita
GSA	the Global mobile Suppliers Association
GSMA	Global System for Mobile Communications Association
HHI	Herfindahl-Hirschman Index
ICASA	Independent Communications Authority of South Africa
ITU	International Telecommunication Union
LMIC	Low- and Middle-Income Countries
OECD	Organization for Economic Co-operation and Development
PPP	Purchasing power parity
Q	Demand for mobile internet
UK	United Kingdom
UMTS	The Universal Mobile Telecommunications System
US	United States of America
WDI	World Development Indicators

I. Introduction

Since the commercial launch in 1990s, mobile telecommunication has been a success story globally and greatly contributed to economic growth. Historically, households access Internet services using fixed line connections. Ten years ago, mobile phone usage was limited to calling and texting, but advances in mobile telecommunications technology and deployment of 4G and more recently 5G networks, resulted an increased usage of mobile broadband. Now mobile phones dominate fixed-line networks for internet access in both developed and developing economies.

The arrival of smartphones greatly contributed to development of digital economy and increased demand for mobile data, which led to spectrum scarcity in many countries. Radio spectrum is a limited and valuable resource managed by state agencies. The electromagnetic spectrum is an essential input for mobile services to transmit voice, data, or video. Specific amount of radio frequency is deployed from 3 kHz to 300 GHz to provide mobile wireless services and this can be segmented as bands of frequencies to use or re-use infinitely (ITU, 2008). Recent development of 4G or 5G technologies increased pressure on spectrum management. In particular, spectrum should be allocated in a way to deliver a maximum gain for the society through efficient usage (ITU, 2018). Moreover, the process of spectrum allocation needs to adhere to the international standard to avoid radio-frequency interference (Cave, 2002). Therefore, regulatory authorities need to release a certain portion of the spectrum for mobile services like 4G or 5G technology and other services. Demand for access of radio spectrum for mobile has been growing rapidly as the demand for mobile data continues to grow. It increased by eightfold between 2015 and 2020. In 2020, the average smartphone generates about 4.4 GB of traffic data in a month[1].

Thus, expanding of mobile broadband services requires additional spectrum to be allocated. Adding a portion of spectrum to the existing spectrum band is necessary for a successful implementation of 5G technology. For instance, the Federal Communications Commission (FCC) of US intends to make available 500 MHz spectrum band for mobile broadband by 2020 (Earle & Sosa, 2013). At the same time, the selling spectrum became an important source of revenues for the governments worldwide[2]. But the negative consequence of the revenue maximization from the sale of spectrum, is that this undermines the promotion of digital economy. More specifically, high

[1] https://www.sciencedirect.com/topics/computer-science/mobile-data-traffic
[2] https://www.gsma.com/spectrum/wp-content/uploads/2018/12/spectrum_pricing_positioning_2017.pdf

price of spectrum for mobile networks services can delay investment decisions, slow the speeds of data transfer, reduce network capacity or depress incentive for retail price competition (GSMA, 2017).

From economic perspective, the primary objective of charging fees on spectrum allocation should be to encourage the efficient use of awarded spectrum through investment and high network quality. Efficiency ensures that mobile broadband services are affordable to the consumers and in return stimulate the digital economy. In this way, mobile service providers can deliver the highest benefits to the society. In most cases, spectrum band is awarded or sold by auction, beauty context or direct award through administrative process. Recently, license awarding via auction became most prevalent and this method tends to be most efficient. However, raising revenues from auction also results higher cost of mobile services.

The prices paid for spectrum are potentially impacted by several factors such as network infrastructure availability, general state of the economy, market conditions or policy implications (Foster, 2016). The price of spectrum should result in efficient use of spectrum, high connectivity quality and accessibility of mobile services. But at the same time, affordability of mobile services needs to be considered by policy makers. Specifically, mobile internet usage should be affordable given that 91 percent of internet users worldwide relied on mobile data services to access internet by October 2020[3].

The report on the cost of 1GB of mobile data in 228 countries in 2020 highlights that there are large price differences in mobile data across countries[4]. Recent academic papers and policy tried to establish a link between cost of mobile voice services and spectrum allocation policy. Among other factors, the amount of spectrum available to the mobile operators and specific spectrum allocation policies are at the discretion of policy makers and may impact the cost of mobile services.

This paper explores economic principles of spectrum usage in the context of provision of mobile broadband services. Our goal is to analyse the relation that could exist between the prices of mobile data and the spectrum allocation policies. We analyse how the retail price of mobile data price

[3] https://www.statista.com/statistics/617136/digital-population-worldwide/
[4] https://www.cable.co.uk/mobiles/worldwide-data-pricing/

respond to different spectrum allocation policies, where we control for other relevant variables such as total minutes of communication, cost of capital, alternative connection access and GDP per capita.

For this purpose, we combined data from different sources including World Development Indicator (WDI), International Telecommunication Union (ITU)-ICT Price Baskets (IPB), Global Mobile Frequencies Database of Spectrum Monitoring Technology Advisors databases and other additional sources, which we use to estimate demand and supply equations for mobile data.

We estimated the demand function of mobile data using a fixed-effect model, in which about 68% of overall variation of demand is explained by the set of variables in the model. The demand for mobile data is negatively impacted by the price of 1GB, as suggested by economic theory. Second, GDP per capita has a positive impact on the mobile broadband penetration. On the supply side, 79% of overall variation of mobile broadband price is explained by the set exogenous variables in the model. The mobile broadband price substantially decreases with the population density which is an indication of economies of scale. Moreover, the price of mobile broadband decreases with a decrease in market concentration. The spectrum amounts available to the mobile operators and the auction and radio spectrum sharing rules are determined by the regulators. Our results suggest that the price of mobile broadband decreases as radio spectrum amounts available to all the operators in each country increases. Moreover, changing from non-auction mechanism of spectrum assignment to auction mechanism results in a decrease in the average price per 1GB of mobile broadband by 42.7%.

Our study is organized as follows. First, we discuss relevant literature on spectrum regulation followed by a discussion of spectrum allocation policy. Next, we introduce econometric model and present the data. Finally, we present the estimation results and conclude our analysis.

II. Literature review

There is a growing body of empirical literature on competition in mobile telecommunications markets and spectrum allocation policies, which we review in this section.

1. Impact of market structure on prices equilibrium

We expect that the more competitive is the market of mobile services the lower should be the retail prices, which aligns with the paper on spectrum allocation policies by Thomas and Muñoz (2009). They used panel data from wireless telephone markets in 28 countries to study the relationship between retail prices of mobile voice services and spectrum band. They find that more concentrated markets are associated with lower equilibrium prices.[5] In a related paper, Aker and Mbiti (2010) study mobile phone coverage in Sub-Saharan Africa using data on demographic indicators, geographic characteristics, financial access, etc. They find that market with limited competition is associated with higher mobile voice prices. Similarly, Seim & Viard (2008) used data on tariff plans of wireless services to study the effect of market structure on cellular technology adoption and pricing over the period 1996-1998. Their result shows that new entrants in the mobile telecommunication market are associated with lower price. More recently, Grzybowski, Nicolle, & Zulehner (2018) investigated the impact of competition on prices of mobile services in France using the launch of low-cost brands and entry of Free Mobile measured for competition. They find that competition in mobile phone industry contributes to nearly 56.1% of the total price decline. In an older paper, Grzybowski (2008) study on the impact of regulation on the retail prices in fixed-line telephony across the European Union indicates that 82% of price decrease in fixed-line was due to the liberalization of the telecom industry. Moreover, Hawthorne & Grzybowski (2019) use six waves survey of data a 134,000 sample in South Africa to study the welfare effect of entry and regulation in the telecom industry by means of discrete-choice model. They conclude that new entry in the market impacts the price equilibrium and consumer welfare even if benefits of competition are not equally distributed.

Our study also contributes to the existing literature on how market structure impacts mobile broadband prices. Mutinda (2016) used panel data to investigate the impact of market structure on mobile prices in fifteen emerging markets over the period 2006 - 2015. He used HHI as a proxy for market concentration, where higher concentration implies lower prices of mobile services. Likewise, Calzada & Martínez-Santos (2016) study the cost of mobile broadband over 2011-2014 using data from mobile operators in 37 countries. They found that higher market concentration results in lower mobile broadband prices. There is also a number of older studies which

[5] Market concentration is measured by Herfindahl-Hirschman Index (HHI) which determines the market competitiveness.

investigated the impact of market structure (including inter- and intra-platform competition) on the fixed broadband (Dauvin & Grzybowski, 2014; Sangwon, Mircea & Seonmi, 2011; Aron & Burnstein, 2003; Gruber & Koutroumpis, 2013).

In the estimation of reduced-form model using the mobile broadband prices data from 37 countries over the period of 2011-2014, Calzada and Martínez-Santos (2016) conclude that market concentration measured by Mobile Virtual Network Operators (MVNOs) is responsible for 2% of price decrease. The deployment of mobile broadband is mainly driven by the population density, standardization policy and fixed broadband pricing according to the study of Sangwon, Mircea & Seonmi (2011) on the OECD countries between 2000 and 2008. Their results confirmed that mobile and fixed broadband services are complement in OECD.

2. Spectrum property right

There is a large number of papers and reports published about spectrum property rights. The Nobel Prize winner Ronald Coase was one of first economist who criticized the Federal Communications Commission's method of allocating spectrum in his article published in 1959. He has clearly and succinctly suggested that spectrum should be allocated using market methods rather than through administrative and bureaucratic approach of assignment. He argued that market-based allocation of resources leads to efficient outcomes. It would essentially contribute to decentralize information on spectrum which privilege demand and supply interaction. In this way, prices can be determined by market dynamics which is meaning that sellers and buyers interact in the market. As a result, spectrum radio would have their highest value of use.

Similarly, Berresford & Leighton (2004) suggest that an implementation of better regulation on spectrum can spawn improvement for consumers outcome. As for Ronald Coase, these authors also advocate for marketization of spectrum allocation which requires a flexible allocation mechanism. And price mechanism setting should be coupled with property rights to provide an efficient allocation. Additionally, Faulhaber (2003) highlights two regimes of property rights. For them, economist favored market-based of spectrum allocation to promote efficiency outcome while engineers preferred a commons-based property to promote new technologies. They showed that both models of regimes could co-exist to meet needs for the near-term future not only in terms of efficiency of spectrum allocation but also the new technologies development.

For Vany (1998), market-based policy of allocation of spectrum will be implemented through auction approach of assignment. He further suggested a "commoditization" of spectrum and thus it will lead to open access to diverse users. However, Robinson (1998) claimed that the public interest of radio spectrum is an obstacle to implement spectrum property rights. He basically argued that property rights will eliminate most responsibilities of public interest obligation that imposed by licenses. With spectrum property rights, consumers can make choices on an open market. He concluded that recognition of spectrum property right will achieve full market efficiency. Furthermore, any inefficiency use of spectrum will be penalized by the market dynamics and there is no need for an administrative monitoring (Prasad & Sridhar, 2015; Robinson, 1998).

3. Literature on spectrum auctions

The approaches of radio spectrum assignment such as auction and related fees alter the efficiency of mobile services including broadband services. Hazlett (2008) studied broadly the auction spectrum allocation process in the early stages in the United States in his paper of Optimal Abolition of FCC Spectrum Allocation. The fundamental argument of assigning wireless license via auctions is the contribution to the improvement of assignment process, reducing political discretion and placing spectrum rights in the hands of the best users of spectrum. Hazlett (2008) highlights two broad advantages of using auction method to assign spectrum: firstly, less red tape by setting up private right ownership and secondly, an efficiency of spectrum utilization. In this regard, Cramton (2001) reports that the UK government policy of implementing 3G through auction was highly successful. The objective of achieving a less monopolistic and more efficient outcome is undoubtedly achieved in the most competitive way. At the same time, the government did raise considerable revenue from the auction assignment.

However, a practical auction design is not also without risk in the market structure. Considering an ascending auction case, Klemperer (2002) in his article "What Really Matters in Auction Design" mentioned that this auction mechanism can lead to market collusion. The bidders can make agreement among them at early stage of auction when the price is still low. They collude to not push the price and decide who should win the prize. In this way, ascending auction can facilitate collusion. Additionally, Klemperer (2002) raises the risk of entry deterrence and predation.

However, Bulow and Klemperer (1996) highlight that an attraction of more bidders can lead to an efficiency of auction usage and profitability for auctioneers. But there is assumption with ascending auction mechanism that firms with high value will be potentially winners and this creates disincentive environment for new entrants. In this perspective, an ascending auction will be potentially more vulnerable method than other type of auction. Sealed-bid auction appear to be better for profitability because they attract more competitors (bidders), and predation and collusion are avoidable. But efficiency under sealed-bid auctions is questionable compared to ascending auction mechanism.

When auction spectrum is implemented to allocate wave frequency to mobile phone services, it involves cost that needed to be considered in the evaluation of spectrum management policies. Bauer (2003) discuss the relation between spectrum fees[6] and business decisions of mobile service providers. This seems to be interesting since many countries are relying on auctions to determine spectrum fees, yet some countries chose to determine this fee administratively mainly for 2G assignment or previous generations. The license fee is not without impact on price of mobile services. Consequently, Bauer (2003) suggests that license fee will not only increase prices for residential but also plays an important role in financial health of service providers as well as investment decisions. Firms have incentive to collude to cover high spectrum fees paid through high prices of services.

Furthermore, Thomas & Muñoz (2009) and Williamson & Wood (2016) show that additional spectrum availability is associated with decreasing cost of mobile services. Similarly, GSMA (2015) report indicates that more spectrum band is needed for the mobile operators to carry more data traffic. This report also forecasted that additional spectrum band of 600-800 MHz needs to be available to the mobile broadband by end of 2020. With respect to this literature, our paper contributes on the change of mobile broadband cost resulting from the availability of additional spectrum band for mobile phone services.

III. Mobile telecom industry

1. Mobile broadband

Demand for mobile data has grown tremendously over the years particularly in the developing and emerging economies. According to GSMA report (September 2020), nearly 3.8 billion individuals

[6] License fees consist of an administrative and a frequency use component.

were using mobile internet by the end of 2019. Three quarters of them are living in Low- and Middle-Income Countries (LMICs). Another credible source namely Cellular Telecommunications and Internet Association's (CTIA) indicates that wireless data traffic was estimated to be 37.06 trillion megabytes in the US as of 2019[7]. It continues to grow especially in the rural area where there is a lack of network infrastructure. Hence, mobile internet connection constitutes a great pillar of development for connectivity gap in many developing countries.

In addition, mobile internet is the only available option for many poor people where broadband fixed line requires greater infrastructure network setting and technologies investments. Consequently, mobile broadband did not only make many people to change the way to communicate but also contributes to access portable devices such as tablets, smartphone and personal computers and affects substantially how to run business. Figure 1 shows a rapid growth of cellular mobile subscription in the Low- and Middle-Income Countries and the evolution of mobile broadband subscriptions from 2010 to 2019. This figure particularly shows mobile phone usage rose at an unprecedented scale from the year 2010, which is remarkable trend for mobile phone accessibility in the LMICs. In 2019 for instance, around 6.6 billion cellular mobile subscribers are estimated in LMICs while about 8 billion worldwide, and the number of subscribers is expected to record a rapid growth over coming years. The same trend is observed in the mobile broadband subscriptions. The growing of the mobile broadband subscriptions is tremendous from 2010 as shown in figure 1.

In this perspective, many researchers, policy makers and regulators are concerned with the affordability of mobile gigabyte for internet connection for poor people and its related cost. According to the cable.co.uk reports, the cost of 1 GB of mobile data appears to be a concern in many developing countries over 2019-2020. In these reports, it is highlighted that four of the six countries where mobile data is most expensive are in Sub-Saharan Africa with Zimbabwe as the most expensive country in 2019. Same trend is observed in 2020. Accordingly, mobile internet remains unaffordable across Africa for millions of people[8]. However, Asian countries have made better progress in terms of internet access as three of the five countries with cheapest mobile data

[7] Cellular Telecommunications Industry Association: https://www.ctia.org/positions/spectrum/

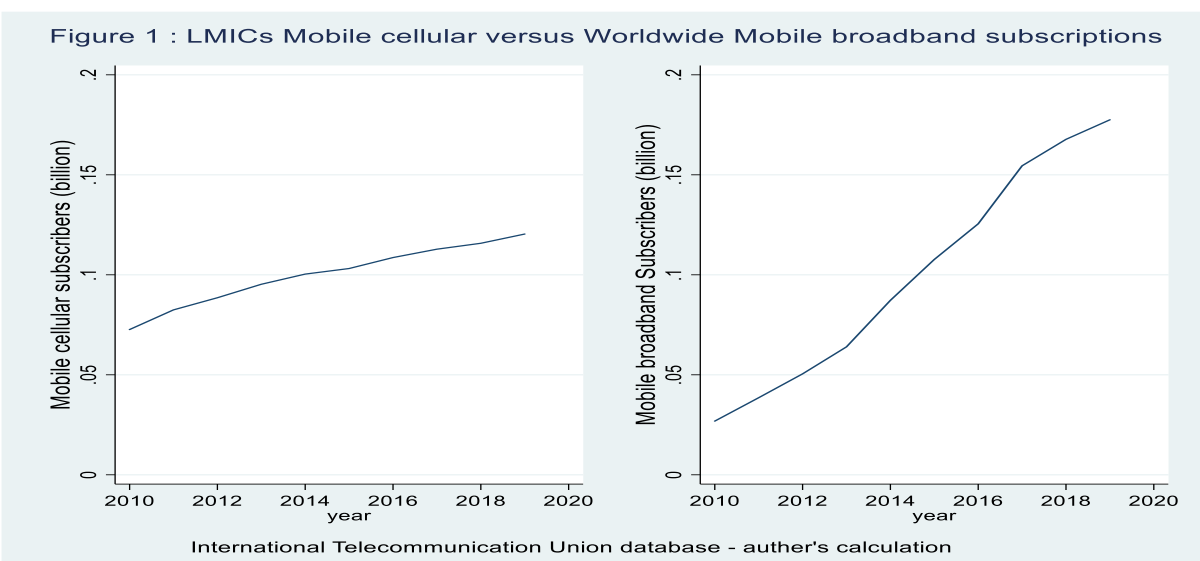
[8] https://a4ai.org/mobile-data-prices-fall-across-low-and-middle-income-countries/

are in the Asian continent. Particularly, India appears to be a place where it is cheapest to buy mobile data worldwide.

Policy makers must make sure that mobile phone firms provide the best mobile broadband services and available to a great number of their consumers. This can be achieved by allowing competition in the marketplace for the less developed countries. For instance, nearly 80% of the mobile services' consumers have choice among at least five operators over variety service including voice and data services in the US which sounds to be a competitive market (Earle & Sosa, 2013).

Mobile internet accessibility and affordability have a particularly important impact in the rural area for LMICs. This enhances the connectivity level for millions of people. A large investment in up-to-date infrastructures and technologies will contribute to reduce the cost of the mobile internet[9]. In addition, competition in the marketplace along with a sound regulation policy will not only lower the cost of mobile broadband but also deliver better connection quality and accelerate accessibility. Spectrum allocation policies for mobile phone industry need to be considered seriously the rapid development of mobile broadband services. This will ultimately contribute diversifying the availability of mobile services, growing the mobile service offered, and reducing the cost of mobile services. In the following sections, we analyse the spectrum policy allocation benchmark.

Figure 1: LMICs Mobile Cellular versus Worldwide Mobile broadband subscriptions



[9] https://data.worldbank.org/indicator/IT.CEL.SETS?end=2019&start=1980&view=map

2. Radio spectrum management

a. Spectrum Policy allocation

For mobile telecoms to provide wireless services, they need to obtain the right amount and type of spectrum bands for their services. Spectrum band for mobile phone is initially designed for voice services (Prasad & Sridhar, 2015) but with the increase of demand for different type (s) of wireless services, it has been expanded to be used for multi-wireless services. Compared to certain applications (such as garage door openers, car looks or Wi-Fi), mobile phones require much power and bandwidth which is creating spectrum band scarcity (Cramton, 2013).

Radio spectrum for mobile services ranges between 3 kHz and 300 GHz for usage of various wireless technologies[10]. This means, cellular operators that need to deliver a specific technology with variety of services requires a specific band. For instance, 3G technology that is provided by operator Vodafone in India operates at 2100 or 900 MHz band while 4G technology provided by the same operator operates at 2100, 1800, 900 or TDD 2300 MHz band[11]. Therefore, for these bands to be implemented, one needs to release the right amount of spectrum band. The 20 MHz of spectrum in the 1800 MHz band released by India government in 2004 for mobile service (Prasad & Sridhar, 2015) is an example.

An implication of national government policy is involved through spectrum regulations to release the radio spectrum for mobile services. Mostly, national government mandates the ministry of communication or independent regulation agency to play the role of a regulator along with international institution in the process of spectrum allocation policy. Each country or region has its own body of regulatory for governing spectrum usage. For instance, the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) are the two main federal regulatory authorities to regulate spectrum in the Unites Stated. The Office of Communication (Ofcom) is the body mandated for the management of radio spectrum in the United Kingdom (UK), etc. Country regulatory agency needs to coordinate with international institutions to harmonize the allocation of radio spectrum. It is done by the assistance of United Nations specialized agency namely The International Telecommunication

[10] https://www.ee.co.za/article/look-spectrum-management-policies-efficient-use-radio-spectrum.html
[11] https://www.kimovil.com/en/frequency-checker/IN

Union (ITU) via its Radio Regulation and The World Radiocommunication Conference which is held every three to four years.

In addition, regulatory agencies need to collaborate with other departments in the conventional spectrum process in several countries. Country like India, spectrum allocation is coordinated by several government bodies in charge of communication and telecommunications. Telecom Regulatory Authority of India (TRAI) is more of national advisory body than regulatory while other government entities intervene in the spectrum regulation itself. To be more precise, the Wireless Planning and Coordination (WPC) in India has the responsibility of radio spectrum policy, planning, licensing, administration, monitoring, and enforcement. So, every single country has its own organization and coordination of spectrum allocation.

Nevertheless, country regulatory authority has the broad mandate to ensure an efficient and effective management of radio spectrum including licensing and assignment process. Spectrum allocation process has technical and commercial considerations, and the regulators have responsibility of an efficient management so that providers can access to the needed frequency band for their services. And ultimately citizens gain a greater benefit from provided services. Therefore, regulators need to adopt an appropriate policy approach to allocate appropriately spectrum band in efficient, transparent, harmonized, and equitable way to operators. Key regulatory decisions are the method of spectrum license assignment, number of licenses to be allocated and rules (Hazlett, 2004). And spectrum users have permission to operate only according to the terms of the allocated license.

From economic point of view, regulators target to increase public welfare, societal benefits, and reflects public interest (Berlemann & Mangold, 2009). Consequently, they need to adopt fair approaches in their allocation taking into consideration technical, economic, and commercial aspects of radio spectrum that we mention in the previous paragraph. Regarding the technical aspect, regulators must not only make sure an efficient use of spectrum through commercially viable amounts so that operators will best make use of it but also, they need to harmonize with international frequency bands to minimizing the cost of networks and facilitating the international roaming. To ensure a commercial viability of spectrum allocation, regulators are also responsible for balancing competition and achieving economies of scale.

In this perspective, Berlemann & Mangold (2009) identify exclusive license usage, licensed spectrum for shared usage and open spectrum as basic approaches to allocate radio spectrum. Each of these approaches presents a policy approach in the process of allocation. The Universal Mobile Telecom System (UMTS)[12] in Europe is an example of exclusive license usage where users have exclusive and transferable flexible use of right for an allocated specific spectrum band. This policy approach is called exclusive model. The second approach, licensed spectrum for shared usage where specific spectrum is restricted to a specific technology. The Digital Enhanced Cordless Telecommunications (DECT)[13] is an example of licensed spectrum for shared usage model. And the last approach, open spectrum, is a model that allows all users to access any range of spectrum under the rules of technical standard and regulations required for sharing spectrum.

Many countries follow the ITU recommendations on radio spectrum methods to manage their spectrum. Two core methods of spectrum assignment are identified namely non-market-based and market-based approaches of assignment (ITU, 2018, 2016). Once policy regulators decided the spectrum allocation for use of service(s), then they proceed to the assignment of spectrum to an individual(s) user upon request of the license. Accordingly, regulators must solve the mutual exclusivity when a demand for a specific frequency band is not geographically limited to an area. However, if mutually exclusive spectrum requests could exist, then frequency band can assign through spectrum assignment methods.

Regulators seek to achieve economics goal through spectrum management. We can demonstrate two main economic goals related to spectrum resources. Firstly, like any resource, spectrum as a limited and valuable resource, should be allocated with a view to maximize the net benefit to society. We are referring here as economically efficient distribution of the resource. This can be achieved by pursuing both optimum spectrum occupancy and effective frequency utilization. The second economic goal that is relevant to radio spectrum management is “rent” – a mobile telecom company that has a spectrum license sells mobile broadband services to their clients (individuals or companies) and, in return, people use these services to provide other services (gig economy,

[12] UMTS is a 3G technology for networks derived from the GSM standard. It is designed to provide multi-mobile services with multi-operators supporting a wide range of global mobile-communication standards.
[13] DECT is a digital wireless technology for telephony that is used both for home and business.

online education, online shopping, etc.). The rent can be quantified by price mechanism of spectrum management.

As we mentioned earlier, to achieve these economic objectives, regulators have firstly two non-market-based approach of spectrum assignment which are comparative hearing processes[14] and lotteries. In practice, in the comparative hearing process of assignment distinguished from other by the fact that applicants are evaluated based on published national criteria[15]. The spectrum management authority has responsibility to determine who is going to be awarded the spectrum license for the best of use. Typically, regulators compare all the proposals based on the pre-set criteria to decide which applicant is to be awarded the license. However, it has been demonstrated that this method is not without weakness – it acquires disadvantages as it is time-consuming[16] and resource-intensive (Cramton, 2002). The process could lead to lack of transparency (McMillan, 1995). In addition, comparative hearing selection may be contested by unsuccessful applicants as decision of assignment is often based on the minor difference. Hence, with comparative hearing method, the ability of regulatory authorities to successfully identify the best suited to provide a service is literally limited (Cramton, 2002) and the method has an advantage of flexibility of the license right.

After years of comparative hearings usage to assign spectrum, many countries decided to switch to lotteries' method to avoid drawback of comparative hearings and unacceptable delays in cellular license assignment (Cramton, 2002). In the lotteries' method, random selection is done among all spectrum applicants in the process of assignment. As a result, lotteries may reduce red tape and encourage more applicants to participate compared to the comparative hearing. Lotteries had also succeeded to assign spectrum quickly (McMillan, 1995). As in the comparative hearings process, lotteries' method may not also contribute to assign the spectrum to those who value it most highly and do not guarantee to generate revenue for government unless regulators ensure to gain substantial application fees from lottery and entry fees are adjusted. Lottery's method can also attract speculators and frivolous applicants with no technical competence or experience in the

[14] In many cases, comparative hearing is referring to as a beauty contest. In the process, the applicant with most attractive proposal will be awarded the radio spectrum after reviewing all the proposals by the regulators.
[15] Criteria of the selection include population to be served, quality of service, and speed of service implementation.
[16] For instance, FCC took an average of two years to award thirty cellular licenses at the time that beauty contest method is used to assign spectrum.

telephone mobile industry and have no intention to operate in the industry in which wireless business operators need to negotiate and buy spectrum form the winners (Milgrom P. 2004, McMillan 1995). This creates additional cost to procure radio spectrum and it is difficult to put the spectrum in the hand of firms that can use it. However, a spectrum lottery winner has a possibility to transfer their spectrum right to a third-party for further usage which capture a resource rent (ITU, 2018).

Along with comparative hearings and lotteries' methods, we have market-based approach of assignment which is recent development for many countries in the telecom industry. And lotteries' method of spectrum assignment was abandoned to switch to market-based mechanism of allocation. Following that, the usage of the radio spectrum resources efficiency depends heavily on how the spectrum is managed, many countries have changed conservative way of spectrum management to market-based strategies for spectrum allocation and assignment to promote the development of new wireless technologies. In this perspective, policy makers, telecom industry officials, and academic experts have paid much attention to market-force prevalence in spectrum resource management. Therefore, many countries have adopted the strategies of free market mechanism to determine how spectrum resources are allocated, assigned, and used. The key predominant strategy is auction. The latter presents some advantages and promotes more effective and efficient use of radio spectrum. In the next section, we will be discussing the auction mechanism as well as the flexibility and transferability of spectrum.

b. Spectrum auctions

Auction is one of the oldest form of markets to sell goods and services. Nowadays, a wide range and value of objects are sold at auctions (Krishna, 2009). Automobile wholesale, livestock and commodity, durable goods (e.g., used machinery), perishable goods (e.g., fish), precious goods (e.g., large amount of diamonds), financial assets (e.g., US T-bill), bankrupt firms, construction contracts, and limited natural resources in the form of public property (e.g., land, oil right, timber right,) are sold by means of auctions in several countries around the world (Krishna 2009, Klemperer 1999 & Milgrom 1987). In recent times, selling the electromagnetic spectrum for communication at auctions becomes enormously popular method of spectrum allocation (Krishna 2009). In 1990s, spectrum auction became a popular approach to assign license of radio frequencies among developed markets since New Zealand became the first country to authorize the auction mechanism for radio spectrum allocation as part of its Radio Communications Act of 1989[17]. Following that, United Kingdom used spectrum auction in 1990 (McMillan, 1994). Since then, several countries including United States, Colombia, Australia, Argentina, India, and many other developing countries have gradually shifted from administrative processes of assignment (lotteries or beauty contest) to auctions to assign commercial spectrum license including mobile spectrum band right.

Auctions are market-based mechanism of spectrum assignment. It is worth noting that, in general, an auction is designed to be used as an assignment mechanism when we only have circumstance that demand for spectrum exceeds the supply (ITU, 2018). While depending on a country circumstance, several factors influence the auction method instead of non-market-base approaches of spectrum assignment. These factors are country's level of economic development, level of communication infrastructure development, investment climate, greater demand for spectrum, less restriction on foreign ownership and trade, among others. Additionally, implementation of auction mechanism needs a solid underpinning legislation. This means that political authorities need to authorize spectrum band for which services must be auctioned, the nature of spectrum right including geographic coverage, the availability of bandwidth, etc. And the conditionality of usage such as services restrictions, license conditions, so on.

By way of illustration, FCC in the United States is one first regulatory authority to use largely auctions method to assign radio spectrum. Up today, FCC conducted about 80 spectrum auctions and raised revenue over $60 billion for the U.S. Treasury[18]. Another example, the early auctions on 3G raising nearly $100 billion in Europe (Cramton, 2002). Hence, auctions' method has become most preferred to assign radio frequency in the United States, in Europe and in many other countries. Auctioning of spectrum has shown a greater success of assigning the radio spectrum to those value it the best in many countries (Cramton, 2002). Spectrum auction is purposely used for

[17] The Radiocommunications Act is the primary legislation in New Zealand. It sets out how to manage the radio spectrum including registration of Radio Frequencies, management rights and licensing system, certification process for approved persons, guidance on compliance and enforcement, and disputes process. Additionally, Radiocommunications Regulations 2001 Also plays a key role in the spectrum regulation in New Zealand.

[18]https://en.wikipedia.org/wiki/Spectrum_auction#:~:text=Since%20July%201994%2C%20the%20FCC,of%20which%20has%20been%20collected)

a greater market participation and competition. A large body of literature identifies auction approach for greater efficiency of market and revenue raising for government. For McMillan (1995), auction is the best mechanism of spectrum allocation to avoid monopolistic nature of mobile industry. In addition, auction is quicker and more econonmical than non-markets-based method of allocation. Spectrum auction is fair and promotes transparency more than any other methods of allocation in the sense that applicants can easily track and verify their application if they lost (McMillan 1995, Cramton 2002).

In an auction mechanism, spectrum licenses are awarded by a bidding process among the many competing spectrum applicants (ITU, 2018). When the radio spectrum is assigned at auctions, firms with highest value for the spectrum usage are likely to make the highest bid, hence they tend to win the bid (Cramton 2002). As a result, spectrum winner can value the spectrum at highest level in the marketplace. Auctions can take various forms and different characteristics depending on the country-specific spectrum allocation policy. Mainly, four standard forms of spectrum auction have been developed around the world and discussed in the academic literature[19]. These are ascending-bid ("English") auction[20], descending-bid ("Dutch") auction[21], first-price sealed-bid auction[22] and second-price sealed-bid auction[23] (Milgrom & Weber 1982, Milgrom P. R. 1985, Milgrom P. R. 1987, Klemperer 1999, Wall, C. 1997, Krishna 2009).

With times, many variants of auction have been developed from these existing frameworks. For instance, Japanese variant auction[24] is drived from the English style auction. FCC auctions are also ascending-bid but with multiple or simultanous bidding where bidders have possibility to bid on multiple licenses at the time and the winner wins all the license that he bids at highest price

[19] Auction theory including its modelling is discussed in detail by Milgrom & Weber (1982).
[20] In English auction, auctioneer opens the auction by announcing the reserve price or lowest price in smaller increment and the price is raised if there are at least two bidders interested to bid. The bidders are continuously called up to make their intention to bid, the process ends when there is a single bidder. The later wins the auction and pay the price the second-last bidder proposed.
[21] In contrast to English auction, the Dutch auction process, auctioneer starts by highest price of the bid and continuously lower the price until remains only one bidder. The winner pays the last given price.
[22] first-price sealed-bid auction works straightforward than the previous forms of auction, bidders are called out to submit bids in sealed envelope in their possible highest price. The bidder submitted the highest bid wins the bid and pays the amount that he bid.
[23] In the second price sealed-bid auction, bids are also submitted in sealed envelope as in the first-price sealed-bid but the winner pays the second-highest bid.
[24]In the Japanese auction, the lowest price is displayed in an electronic screen. The price is continuously raised, and a bidder who wishes to be active at the current price depresses a button. He releases if he wants to be withdrawn from the auction (Milgrom & Weber, 1982).

(Connolly, Zaman, Roark & Trivedi, 2018). FCC development also other forms of auction namely set-aside for entrepreneurs[25], and "closed auction" for small business or designated entities.

Certain economists distinguish the auction by its design. We can think of open bidding auction versus single sealed-bid auction (Cramton, 2002). From an economics perspective, an open bidding design reveals easily information and the valuations of the spectrum to the bidders thus winner's curse is reduced as bidders can condition their bids on the available information. While sealed-bid design can help to avoid collusion and yield higher revenue (Milgrom P. R., 1987). Auctions can be also classified as simultaneous open bidding versus sequential auctions (Cramton, 2002). The sequential auction process limit information availabile to bidders. And the bidders have to guess the price when they set the bid. In a simultanous bid auction[26], multiple licenses are sold at the same time. Information on prices of the licenses is available to the bidders in ahead of time.

Moreover, auction is used as a flexible policy instrument to address a variety of policy goals to achieve social and market competition objectives. Government can decide to redress the past wrong of spectrum allocation where some lobbying or collusive bidding was observed. In this respect, government can take into consideration of these in the auction design by giving a price preference to unrepresentative-owned firms or by permitting only designed firms to bid the auction (McMillan, 1995). For instance, the United States used spectrum auction in the form of set-aside license to allow minority-owned firms, women-owned, rural telephone companies and small business to get license and operate in the more geographic extension.

In this respect, FCC assigned 120 MHz for Personal Communication Service (PCS) based on discriminatory participation rule (Earle & Sosa, 2013). The objective was to meet some standard competitive market and achieve social goal by incentivizing the small business and "entrepreneurs" to enter the wireless market. Incentive criterias of participation are such that bidding credit and installment payment financing for small or very small business with limited revenue to acquire the spectrum right though auctions.

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[25] Entrepreneurs refer those who have entities that "*earned less than $125 million in gross revenues during each of the two years prior to the auction and ...[have]... assets of less than $500 million when filing ...[their]... application to participate*."

[26] Simultaneous ascending auction has been developed and standardized in the United States by FCC and many other countries such as Canada, the Netherlands, UK, Mexico, and Australia have used also this design.

Many other public policies can be addressed through the auctions mechanism. If for instance, government aims to promote technology innovation – it can reward highly innovative firms by incentivizing them to get license at reduced price. Government can also fight against monopolization of the mobile phone industry or promote local companies using auction by developing discriminatory participation rules that limit amount of spectrum to a single firm that is more representative in certain area which makes it easier for new firms to enter the telecommunication industry under auction.

Following these arguments, when some Europeans countries were conducted The Universal Mobile Telecommunications System (UMTS) auction, the public policy objective was to change the structure of domestic market by increasing the number of wireless network providers through spectrum auction mechanism. They used two main discrimination participation rules namely set asides[27] and license acquisition limits for certain operators. In this perspective, UK auctioned two block paired of spectrum band, one larger (2x15 MHz paired) and another smaller band (2x10MHz) nationwide for 3G. In this assignment process, the UK government implemented a policy that encourage additional entries in the market through restriction of license to new entrants. In addition to that, it was not allowed to bidder to win more than one bid and 3G license was non-tradable in the secondary market at the time of auction. A similar policy was implemented in Germany when the government was assigning 120 MHz of paired spectrum for 3G technoloy. With this mechanism, German's 3G resulted in two new entrants in the mobile telephone industry.

As we said earlier, the primary objectives of national governments on the spectrum policy allocation and using of spectrum auction are efficienct usage of spectrum and revenue maximization for the government. These can be achieved by variety of spectrum policy forms. Auction surely put the license in the hand of winner with the highest private value but winner does not always maximize highest social value and experiences have demonstrated auction method favors the incumbents than new entries (Cramton, 2002). In this way, social welfare cannot always be improved through auctions. Consequently, regulatory autoritories needs to pay much attention to the outcome of spectrum auction and impose safegards for potential failure of auction.

[27] Set asides refers to the restriction of spectrum applicant based on discriminatory criteria.

c. Transferability and flexibility of spectrum

While auction method is most suited and preferred for spectrum assignment in contrast to other mechanism of allocation, many economists recommend spectrum band to be shared and give the spectrum user a flexibility to transfer their spectrum right so that the initial associated economic efficiency of spectrum resource distribution can be maintained. Radio spectrum sharing result of several aspect such as technical, administrative, or commercial. And spectrum can be shared in several dimensions: time, geography, or space dimension (Foster, 2008).

If spectrum users have an unlimited technical flexibility of their spectrum right in the choice of consumers services and can freely transfer the spectrum bands to other services, markets or entities that are not initially assigned for. They can adjust their inputs in line with cost and demand of the provided services (ITU, 2018). This ensures an economics efficiency use of spectrum bands by the operators. The associated economic value is more relevant when mobile services providers have a possibility and flexibility to allocate their radio spectrum to other service. Spectrum sharing is a best way to optimize wireless communications channels[28]. The US department of commerce states that spectrum sharing as "*allowing multiple categories of spectrum users to safely share the same frequency bands contributes significantly to efficient use of spectrum*".

Sharing spectrum can improve use of underutilized amount of spectrum Huang & Chen (2009). Firms transfer the portion of radio spectrum that are not used or not efficiently used to other best users under strict adherence of terms of assigned license. Law must prevent any misusing or abusing of spectrum. A solid policy of spectrum sharing is required in both technical and technological frameworks in order to implement an efficient and best use of spectrum.

From GSMA manual guidelines for mobile telephone spectrum, solid framework and size of spectrum are main drive of spectrum sharing success. First and foremost, enough amount of spectrum must be available to the operators in the area where demand for mobile service is substantially growing. Secondly, right spectrum sharing frame should be followed. In this regard, some key challenges need to be addressed adequately such as usage of rights and limitations, access terms, guarantee of access, etc. for a best implementation of sharing.

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[28] https://www.nist.gov/topics/advanced-communications/spectrum-sharing#:~:text=What%20is%20Spectrum%20Sharing%3F,demand%20is%20crowding%20the%20airwaves.

Mobile phone spectrum sharing can be a best way to explore in order to meet the growing demand mobile phone service (GSM, 2021). In additional to management of exclusive spectrum license, regulators need to set a public policy of spectrum sharing that can help operators to operate with the system of sharing. A policy that allows to prevent potential technical and practical issues resulting from sharing spectrum such as radio-frequency interference. A commercial incentive must prevail through voluntary base of sharing so that the spectrum users deliver best mobile services. In this way, both incumbent users and new users make best profit of spectrum sharing.

It is worth to note that while spectrum sharing holds potential, exclusive mobile spectrum license remains central of success in the faster mobile broadband services. Exclusives of spectrum license are critical component for a successful history of mobile broadband services in the mobile network. However, Policy makers see more and more spectrum sharing policy as a potential substitution of additional spectrum availability for 4G or 5G mobile services (GSM, 2021). Spectrum managers need to develop appropriate approaches of spectrum sharing implementation.

IV. Econometrics model

1. Theoretical specification

A simple model based on the papers of Hazlett & Muñoz (2009) and Kim (2011) is presented as follows: We assume that there are N firms in the market and they homogenously supply mobile phone services with q_i output level where firm is identified by i. We assume that there is no initial incumbent. And $\sum_i q_i = Q$ is an aggregate level of output, its associated price is given by the inverse demand function $P(Q)$.

Firm i's cost functions is given by the following equation:

$$C_i(q_i) = c(K_i, S_i)q_i \quad (1)$$

Thomas W. Hazlett (2009) states on p.427 "*cost function implies constant marginal cost given a particular level of capital (K_i) and the amount of spectrum (S_i) allocated to the license awarded firm i. When quantity decisions are made, capital and spectrum are fixed, and the prices paid for* *these resources are sunk*." Assuming symmetric investment, we set $K_i = K$ for all firms, the marginal cost is a decreasing function in capital[29] and spectrum[30].

The Cournot competition model allows to set the market share by $s_i = {q_i}/{Q}$ and price elasticity of demand by $\varepsilon(Q)$. When we consider S the total amount of spectrum (MHz) assigned to wireless service (such as mobile broadband service) to a given license, then $S_i = \phi_i S$ where $0 < \phi_i \leq 1$. Consequently, the pricing equation can be defined in the following way:

$$P(Q) = \left[1 + \frac{HHI}{\varepsilon(Q)}\right]^{-1} \sum_{i=1}^{N} s_i \, c(K, \phi_i S) \qquad (2)$$

When spectrum allotments are equal across competitive licenses, we should have the following pricing equation:

$$P(Q) = \left[1 + \frac{HHI}{\varepsilon(Q)}\right]^{-1} c\left(K, \frac{S}{N}\right) \qquad (3)$$

This pricing Equation 3 is a function of the elasticity of demand $\varepsilon(Q)$, the investment level K, the amount of allocated spectrum S, and the Herfindahl-Hirschman Index (HHI)[31]. Cost function, $c(.)$. And it is treated as an implicit function of capital, K, and total amount of spectrum allowed to firm.

The elasticity demand function can be presented as follows:

$$Q = \lambda Y^{\delta} F^{\rho} P^{\varepsilon}. \qquad (4)$$

We convert the demand function for wireless telephony service of Hazlett & Muñoz (2009) to demand for megabyte mobile internet which is a function of income Y, price of mobile data bundle p, and the alternative price of internet connection F[32]. If mobile and fixed internet are not substitute services, ρ can be ambiguous.

[29] Capital K represents cost of engineering and technique skills needed to supply a wireless service.
[30] Spectrum S is the amount of radio frequency measured in MHz.
[31] HHI is defined as measure of mobile phone market concentration.
[32] This presents fixed-line internet service.

2. Empirical estimation

Several empirical studies have investigated the relationship between retail price of mobile voice service and spectrum allocation and have been applied in different places around the world. Their linkage has been clearly established. For Hazlett & Muñoz (2009), expansion of equation 3 and 4 by log-log version, we will be able to implement system of price and demand equations empirically taking account all the variables. By log-log transformation, we have the following equations:

Empirical pricing equation

$$\begin{aligned}\mathbf{ln}(\boldsymbol{APG_{it}}) = \; & \boldsymbol{\alpha_0} + \boldsymbol{\alpha_1}\,\mathbf{ln}(\boldsymbol{Q_{it}}) + \boldsymbol{\alpha_2}[\mathbf{ln}(\boldsymbol{Q_{it}})]^2 + \boldsymbol{\alpha_3}\,\mathbf{ln}(\boldsymbol{HHI_{it}}) + \boldsymbol{\alpha_4}[\mathbf{ln}(\boldsymbol{HHI_{it}})]^2 \\ & + \boldsymbol{\alpha_5}\,\mathbf{ln}(\boldsymbol{Spectrum_i}) + \boldsymbol{\alpha_6}[\mathbf{ln}(\boldsymbol{Spectrum_i})]^2 + \boldsymbol{\alpha_7}\,\mathbf{ln}(\boldsymbol{Density_{it}}) \\ & + \boldsymbol{\alpha_8}[\mathbf{ln}(\boldsymbol{Density_{it}})]^2 + \boldsymbol{\alpha_9}[\mathbf{ln}(\boldsymbol{Spectrum_i}) * \mathbf{ln}(\boldsymbol{Density_{it}})] \\ & + \boldsymbol{\alpha_{10}Auction3G_i} + \boldsymbol{\alpha_{11}Competitionlevel_{it}} \\ & + \boldsymbol{\alpha_{12}CompetitionAuthority_i} + \boldsymbol{\alpha_{13}SpectrumSharing_i} + \boldsymbol{\eta_{it}} \ldots (5)\end{aligned}$$

Empirical demand equation

$$\begin{aligned}\mathbf{ln}(\boldsymbol{Q_{it}}) = \; & \boldsymbol{\beta_0} + \boldsymbol{\beta_1}\,\mathbf{ln}(\boldsymbol{APG_{it}}) + \boldsymbol{\beta_2}[\mathbf{ln}(\boldsymbol{APG_{it}})]^2 + \boldsymbol{\beta_3}\,\mathbf{ln}(\boldsymbol{GDP_{it}}) + \boldsymbol{\beta_4}[\mathbf{ln}(\boldsymbol{GDP_{it}})]^2 \\ & + \boldsymbol{\beta_5}\,\mathbf{ln}(\boldsymbol{Alterprice_{it}}) + \boldsymbol{\beta_6}[\mathbf{ln}(\boldsymbol{Alterprice_{it}})]^2 + \boldsymbol{\varepsilon_{it}} \ldots\ldots\ldots\ldots\ldots\ldots..(6)\end{aligned}$$

Then i and t (2012 ….2019) denote the country and year respectively, and ln stands for natural logarithm. $\boldsymbol{\alpha_0}$ and $\boldsymbol{\beta_0}$ are respectively intercepts of price and demand equations.

The mobile internet demand, $\boldsymbol{ln}(\boldsymbol{Q_{it}})$, included in the empirical equation 5 is derived from elasticity of demand $\varepsilon(Q)$ function in equation 3. ln ($\boldsymbol{HHI_{it}}$) variable in equation 5 is clearly identified back to equation 3 in the theoretical specification. Quadratic terms are included in equation 5 to capture the potential non-linearity effects.

$\boldsymbol{ln}(\boldsymbol{spectrum_{it}})$ and $\mathbf{ln}(\boldsymbol{Density_{it}})$ variables are matching back to the cost function in equation 3. In addition, interaction effect between spectrum amount and population density, $[\mathbf{ln}(\boldsymbol{Spectrum_i}) * \mathbf{ln}(\boldsymbol{Density_{it}})]$, is also included to capture implicitly the empirical approximation of cost function. $\boldsymbol{Auction3G_i}$, $\boldsymbol{Competitionlevel_{it}}$ and $\boldsymbol{Competition\ Authority_i}$ are additional variables that instantly impact the Average of Prices per 1 Gigabyte of mobile data, $\mathbf{ln}(\boldsymbol{APG_{it}})$.

The elasticity demand function**, Q**, in equation 4 is empirically reported in equation 6 where $\mathbf{ln}(\boldsymbol{APG_{it}})$, $\mathbf{ln}(\boldsymbol{GDP_{it}})$ and $\mathbf{ln}(\boldsymbol{Alterprice_{it}})$ variables are defined as price of mobile data bundle p, income Y, and the alternative price of internet connection F, respectively. Description of all variables is reported in table 1.

3. Strategy of estimation

The strategy of empirical estimation is to estimate Equations 5 and 6 which represent a system of two simultaneous equations. The procedure of estimation is a one-way fixed effect of panel data model to control the country-specific effect such as institutional difference, political instability, level of democracy, etc. We use the standard fixed-effect model to estimate the demand Equation 6 where only variables that change with time are included, and the output is reported in Table 4. However, we need to be careful when we are estimating the pricing Equation 5 as it includes many time-invariant or rarely changing variables like auction, sharing spectrum or categorical competition level variables.

We follow the basic approach of efficient Estimation of Time-Invariant and Rarely Changing Variables in Panel Analyses so called "Fixed Effects Vector Decomposition" developed by Plümper and Troeger (2007).

This approach allows to estimate our time-invariant and rarely changing variables by means of a fixed-effect model. We estimate the price equation in three stages. Our estimation approach is also similar to the one implemented by (Green, 2011; Hazlett & Muñoz, 2009a, 2009b). In this approach, we distinguish three steps of estimation.

Step 1: *Standard fixed-effect model estimation*. We use the standard fixed-effect model to estimate the price equation by including only time-variant variables in the regression as the time-invariant variable are naturally dropped from the regression. This step is used to obtain the estimated unit-effect $\hat{u}_i$, which includes all the time-invariant variables, the constant terms, and the mean effect of time-variant variables. It is defined in the following way:

$$\hat{u}_i = \bar{Y} - \sum_{k=1}^{k} \mathrm{B}_k^{FE} \bar{X}_{ki} - \bar{e}_i \quad \text{(7)}$$

Where B_k^{FE} is obtained from Fixed-Effect estimation and $\bar{X}_{ki}$ is the average set of time-variant variables. The regression of this step is reported in the table C 1 (see appendix C) where $\hat{u}_i$ value is calculated in each specification.

Step 2: *Pseudo-fixed effects, and time-invariant and rarely changing variables*. We estimate Equation 8 by regressing the estimated fixed-effect obtained from step 1 on all the time-invariant and rarely changing variables by means of Fixed-Effect to obtain the average residuals. Auction, spectrum sharing, and spectrum amount are referred to as time-invariant variables while competition level variables refer to rarely changing variable.

$$\hat{u}_i^{Markup} = \theta_0 + \phi_1 \ln(Spectrum_i) + \varphi_2[\ln(Spectrum_i)]^2 + \theta_3 Auction4G_i + \theta_4 Competitionlevel_{it} + \theta_5 SpectrumSharing_i + \omega_i \ldots\ldots \quad (8)$$

Where ω_i represents the pseudo-fixed effects of the pricing equation. Table C 2 (see appendix C) reports the output for this step.

Step 3: *Fitting pooled OLS model.* We run the full model by means of pooled OLS model. We estimate the Equation 9 where both time-variant and time-invariant variables are included as well as the average residuals from step 2. This is last stage of Fixed Effects Vector Decomposition procedure. The coefficient of the average residuals should be equal to one or very close to one (Rault & Sova, 2007). And this coefficient of residual improves the efficiency of the estimation and the Fixed Effect Vector Decomposition produces less biased estimator (Plümper, T. & Troeger, 2007; Rault & Sova, 2007).

$$Y_{it} = \alpha + \beta_k \sum_{k=1}^{k} X_{kit} + \delta_k \sum_{j=1}^{j} Z_{ji} + \rho Residuals_i + \epsilon_{it} \ldots\ldots \quad (9)$$

Where X_{kit} and Z_{ji} are set of time-variant and time-invariant variables, respectively. X_{kit} variables are included in the step 1 regression and Z_{ji} are those in the step 2 estimation. The estimation of this equation is displayed on table 5. Specification 2 is our most preferred and we will be using the adjusted Average Price per 1 GB (APG) estimation for the analysis in this paper.

Alternative estimation: Two alternative strategies of estimation can be explored. These are simple pooled OLS regression for pricing equation and the three-stage estimation for systems of simultaneous equations. But none of these estimations can help to get rid of country-specific fixed effects that can influence the demand and price of mobile broadband. This gives a plausible reason to use Fixed Effects Vector Decomposition procedure to interpret our results.

Specification selection: we run different specifications in the model to allow statistically significant level. We start with the general specification where all the variables are included and we progressively drop insignificant variables, while at the same time controlling for the multicollinearity issue throughout the estimation. We run estimation of both adjusted and non-adjusted average price per megabytes[33] and fixed-line broadband price on every specification. The different regression show that our results are consistent.

V. Data and variables

The data constitutes a panel data over 2012-2019 periods for 135 countries and the description of our variables is presented in the following table.

Table 1: description of variables

VARIABLES	DATA SOURCE	DESCRIPTIONS
$\boldsymbol{ln}(\boldsymbol{APG_{it}})$	ITU – ICT Price Baskets (IPB)	Average of Prices per 1 Gigabyte of mobile data (APG) in i country for t year. The data is in a monthly allowance based. Mobile-broadband cost for 1 GB of each country over 2012-2017 while the cost of period of 2018-2019 is 1.5 GB.
$\boldsymbol{ln}(\boldsymbol{APGa_{it}})$	IPB	APGa is adjusted to 1 GB for all the years.
$\mathbf{ln}(\boldsymbol{Alterprice_{it}})$	IPB	Alternative price of connection other than mobile broadband. Average of price per gigabyte of fixed-broadband data for each country at t year. Fixed-broadband basket price is in a monthly data usage of 1 GB for the period of 2012-2017. The price of monthly usage over the period of 2018-2019 refer to 5 GB.
$\mathbf{ln}(\boldsymbol{Alterpricea_{it}})$	IPB	Average of price per gigabyte of fixed broadband is adjusted to 1 GB for all the years.
$\boldsymbol{ln}(\boldsymbol{Q_{it}})$	International Telecommunication Union (ITU)	Data refer to the active mobile broadband subscriptions which is proxied for mobile internet demand. There are subscriptions of only data for mobile broadband that refers to mobile broadband services. Subscriptions are based on Prepaid and pay-per-use data only via datacards, USB modem/dongle and tablets. Subscriber should access internet at least in the last three months.
$\boldsymbol{ln}(\boldsymbol{spectrum_{it}})$	Spectrummonitoring.com	Spectrum amount represents an aggregate bandwidth available for mobile phone service by all operators in the telecom market for i country. It is measured by megahertz (MHz). Our main source is the Global Mobile Frequencies Database of

[33] See table 1 for definitions adjusted prices

	World Bank database	Spectrum Monitoring Technology Advisors. And the rest is available from World Bank database.
$\boldsymbol{ln(density_{it})}$	World Development Indicators (WDI) database	Population density refers to individuals per square kilometer of land area for i country at t year. Furthermore, population density refers to a midyear population size divided by the land area in square kilometers. WDI provides data for the period of 2012-2019.
$\boldsymbol{ln(GDP_{it})}$	WDI database	GDP per capita is Gross Domestic Product divided by midyear population in current international dollars $ converted by PPP conversion factor.
$\boldsymbol{Auction3G_i}$ $\boldsymbol{Auction4G_i}$	ITU ICT-EYE (data portal)	Auction mechanism of radio spectrum assignment is for 3G or 4G technology. The main different mechanisms that are identified by ITU in our sample are first-come first-served, beauty contest, in-band migration, and auction. A country can mix few or all the mechanisms to assign radio spectrum for 3G or 4G technology. We constructed a variable as a dummy variable, equals 1 if wireless license for mobile service is awarded via auction or combined with auction in the last spectrum assignment, 0 if country never used auction to assign spectrum in any stage of assignment. We only include auction for 3G in the regression to avoid multicollinearity.
Spectrum Sharing	ITU ICT-EYE (data portal)	Spectrum sharing is a dummy variable. It equals 1 if the country allows sharing radio spectrum, 0 otherwise.
Competition level	ITU ICT-EYE (data portal)	ITU provides information on competition level of mobile cellular of each country. Hence competition level is defined as categorical variable, equals 1 if mobile cellular market is a monopoly, 2 if partially competitive (duopoly for instance) and 3 if fully competitive.
Competition Authority	ITU ICT-EYE (data portal)	Competition Authority is a dummy variable. It is equal to 1 if a competition authority exists in the country, 0 if it does not exist. This variable is not included in the regression.
ln $\boldsymbol{(HHI_{it})}$	World Cellular Information Service (WCIS)	Herfindahl-Hirschman Index in the market mobile market ranges between 0 and 10 000. HHI is a numeric competition variable, and it is constructed based on the mobile cellular subscription. WCIS provides quarterly subscriptions for the period of 2012-2017 by operator and by country. We

	extrapolated data for 2018 and 2019 as they are missing in our sample.
ε_{it}	This error terms captures unobserved variables that influence the demand function.
η_{it}	This is error terms for pricing equation.

VI. Empirical results

1. Descriptive statistics

Table 2 Summary statistics: mean.

year	APG (US$)	APG (PPP)	Alterprice (US$)	Alterprice US$ (PPP)	GDPpc US$ (PPP)	Density	Spectrum (MHz)	Average Spectrum (MHz)	HHI (1-10000)
2012	22.6	27.2	41.7	91.6	21924.3	388.9	448.6	128.1	4305.8
2013	18.4	27.2	31.3	53.1	22691.7	393.1	448.6	128.1	4266.6
2014	16.8	25.2	30.1	41.8	23059.6	399.0	448.6	128.1	4271.2
2015	14.7	24.1	26.1	40.0	22622.6	404.4	448.6	128.1	4201.3
2016	14.3	22.7	29.5	41.6	23284.8	409.7	448.6	128.1	4202.1
2017	12.9	20.2	26.7	37.4	24603.0	413.2	448.6	128.1	4165.5
2018	13.2	19.9	28.2	41.4	25628.9	410.3	448.6	128.1	4128.9
2019	12.8	19.4	25.3	39.2	26760.1	415.7	448.6	128.1	4092.3
Total	15.5	23.1	29.6	47.8	23803.9	404.3	448.6	128.1	4217.9

Table 3 dummy variables

	Auction-3G		Auction-4G		Competition Authority existing		Spectrum sharing	
	Freq.	**Percent**	**Freq.**	**Percent**	**Freq.**	**Percent**	**Freq.**	**Percent**
No	60	56.07	45	42.06	34	26.77	29	25.00
Yes	47	43.93	62	57.94	93	73.23	87	75.00
Total	107	100.00	107	100.00	127	100.00	116	100.00

Figure 2: Evolution of Mobile Market Concentration

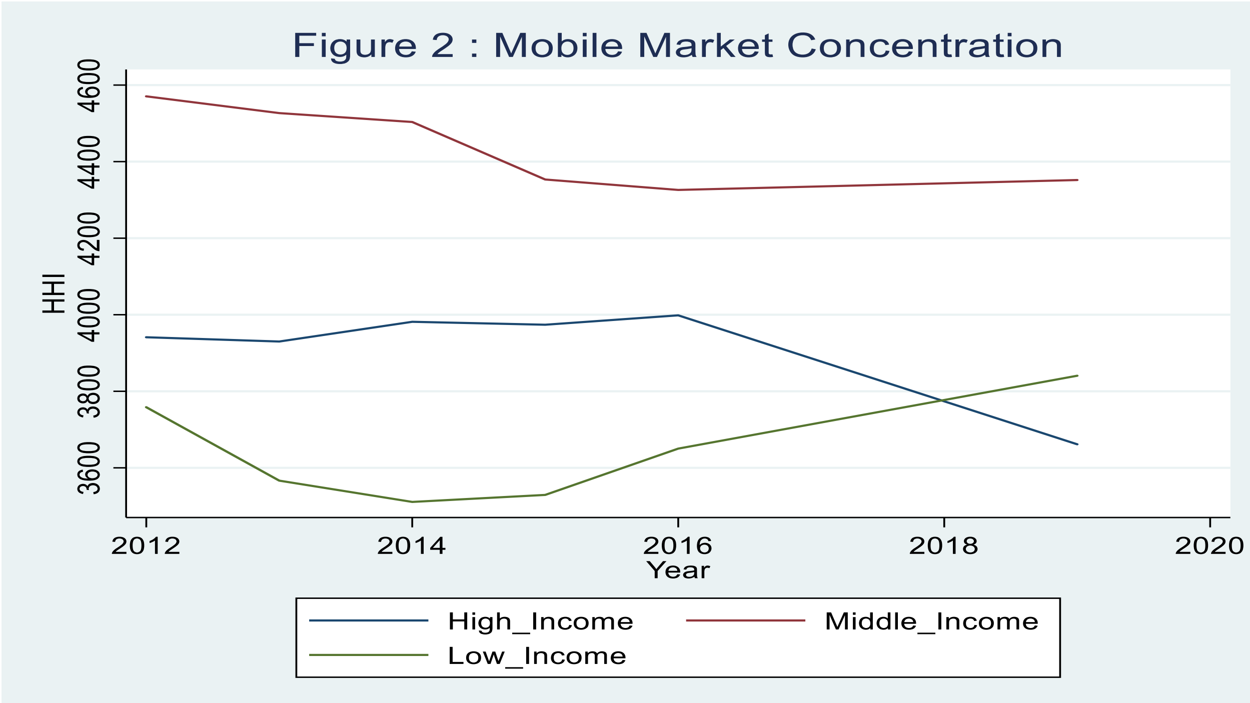


Figure 3: Competition level in the mobile market

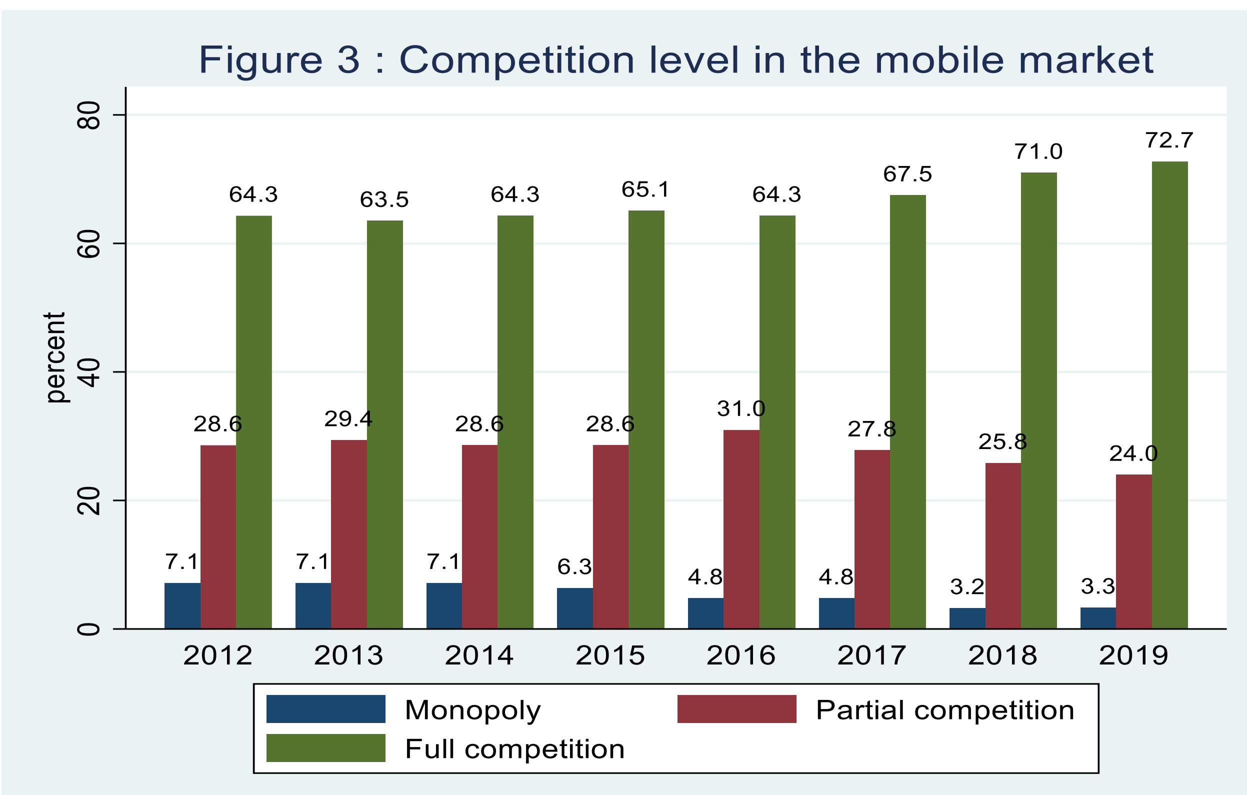


Table 2 shows the average value of the main variables that we are dealing with in model over the period 2012 – 2019. Column 3 presents the monthly Average Price per 1 GB in US international Dollars converted by PPP. And it declines over time with an average value of $23.1 for 1 GB of mobile data. The highest price is indicated in 2012 ($27.2) while the lowest price is indicated in 2019 ($19.4). The monthly cost of fixed broadband ($PPP) is reported in column 5 where the highest price for 1 GB is indicated in 2012 with average of $47.8 for all the years. The average GDP per capita in our sample is $23803.9. And the highest value of GDP per capita $26760.1 in 2019 (see column 6). This is increasing substantially over the period 2012-2019 which is expected. The population density in terms of people per square kilometer of land area has been increasing from 389 to 416 persons per square kilometre in our sample (see column 7) but the average remains 404 persons.

The summary of the radio spectrum in megahertz shows an average of 448.6 MHz available for all mobile services within country (see column 8). Each telecom firm could access approximately 128.1 MHz for mobile service in our sample. The Herfindahl-Hirschman Index (HHI) which is a measure of market concentration in mobile industry, and it decreases when there are large number of operators in the market. It is constructed from active cellular mobile, and it shows decreased over the period of 2012-2017 with an average of 4218. The HH index is also classifies countries by income groups and presented graphically in figure 2. This figure shows that the HH index keeps decreasing in middle-income countries[34] over the period of 2012-2019. This is an indication that middle-income economies attempted to liberalize the mobile market. We observe decreasing of HHI index between 2012 and 2014 and increasing over 2015-2019 periods in the low-income economies[35]. This is an expected trend as the number of firms to grow over time to make a transition to competitive market. In the high-income economies, the evolution of HH index is quite stable over the long period of time. It only declines from 2016. We need to note that we extrapolated values of HHI in 2018 and 2019 for all countries as we have missing data.

Many countries in our sample choose an auction mechanism for radio spectrum assignment. Table 3 reports that 57.94 percent of the countries adopted an auction as a mechanism of assignment to

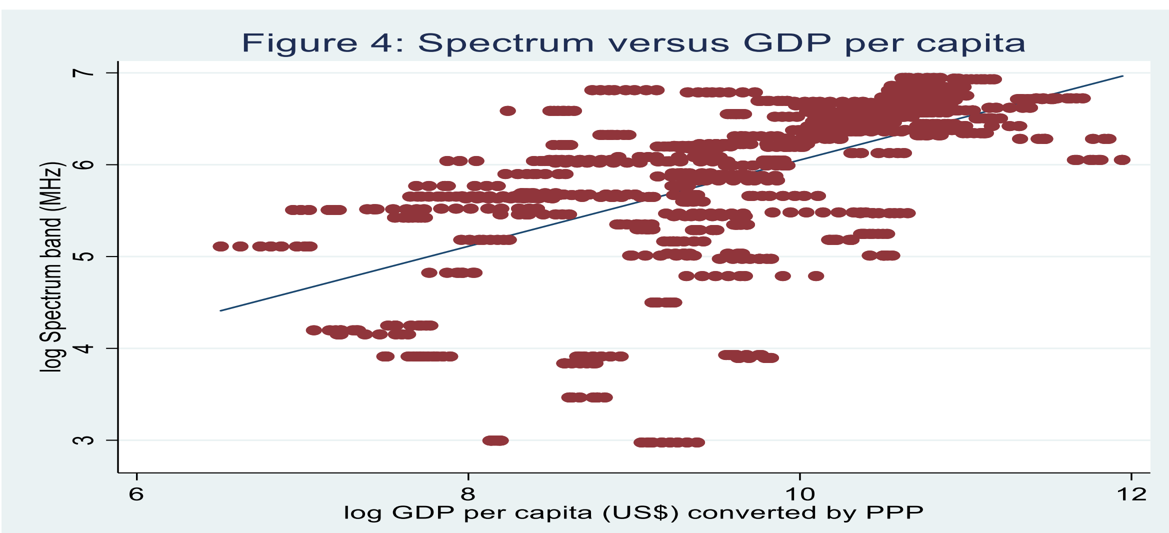
[34] World Bank classifies middle-income economies into lower- and upper-middle-income economies by GNI per capita in 2019. GNI per capita between $1,036 & $4,045 are lower-middle-income economies while those with GNI per capita $4,046 & $12,535 are upper middle-income economies.

[35] Low-income economies are those countries with GNI per capita of $1,035 OR less in 2019.

assign 4 G technology while 43.93 percent of them used auction for 3 G technology. The rest of the countries adopt first come first served, beauty contest, in-band migration, or other method. Some countries allow spectrum band sharing to achieve greater flexibility of spectrum usage and promote spectrum right. These countries represent about 75% in our sample (see column 9, table 4).

Figure 3 shows the level of competition. It appears that the full competition of the mobile market is most common trend in our sample – more than 60% are in the state of full competition[36]. The percentage of full of competition increases between 2012 and 2019. Level of full competition is 64.3% in 2012 while it is 72.7% in 2019. This is expected as number of telecom firms continue to increase over time in many countries. Trend of partial competition[37] and monopoly[38] markets are expected to decrease over time as the full competition increases. Some countries are in transition for competitive market refers to a partial competition. The Figure indicate that the portion of partial competition follows a decreasing trend from 2016 to 2019. A small number of countries still adopt monopoly mobile market, but it also decreases from 2014 to 2019. Some countries mandate competition authority in their jurisdiction to regulate the mobile market. About 73 percent of countries put in place of competition authority (see column 7, table 3).

Figure 4 : Spectrum versus GDP per capita



[36] ITU defines as full competition when any telecom company can get spectrum licence with no limit on number of licensees to provide mobile service.

[37] Partial competition is defined by ITU as a limitation of licensees in the market such as duopoly.

[38] UTI refers to a monopoly when mobile services are only provided by only one operator.

Figure 5: Spectrum versus Average Price per 1 GB of Mobile broadband

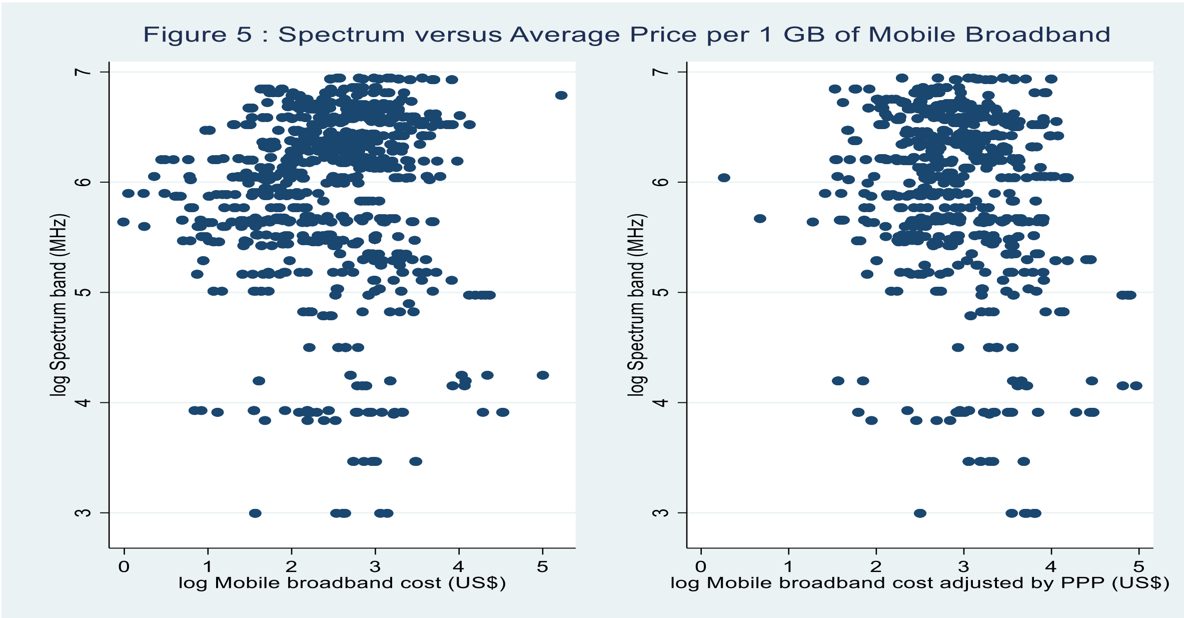


Figure 4 shows a positive relation between the radio spectrum and GDP per capita in our sample. A high radio spectrum allocation is related to high GDP per capita for many countries. This indicates that countries with higher GDP per capita makes effort to allocate more spectrum to telephone mobile services. In figure 5, we observe a high radio spectrum amount is associated with low mobile broadband cost. This can be seen as an additional spectrum amount available for mobile service makes decreasing the mobile broadband cost.

2. Estimation results

Table 4 fixed effect: demand equation

	Specification 1		**Specification 2**		**Specification 3**	
VARIABLES	**Log_Q**	**Log_Q**	**Log_Q**	**Log_Q**	**Log_Q**	**Log_Q**
Log_APG	-0.619***		-0.608***		-0.582***	
	(0.155)		(0.156)		(0.142)	
Log_APGsqr	0.110***		0.106***		0.0937***	
	(0.0298)		(0.0293)		(0.0260)	
Log_GDPpc	14.43***	14.66***	14.89***	14.51***	14.06***	13.81***
	(2.809)	(2.870)	(2.785)	(2.825)	(2.070)	(2.055)
Log_GDPpcsqr	-0.693***	-0.705***	-0.717***	-0.700***	-0.676***	-0.665***
	(0.136)	(0.140)	(0.135)	(0.137)	(0.101)	(0.0999)
Log_alterprice	0.531		-0.0815			
	(0.347)		(0.0830)			
Log_alterpricesqr	-0.109					
	(0.0694)					

Log_APGa		-0.557***		-0.481***		-0.477***
		(0.136)		(0.124)		(0.114)
Log_APGasqr		0.100***		0.0842***		0.0766***
		(0.0263)		(0.0229)		(0.0204)
Log_alterpricea		0.0751		-0.0784		
		(0.0840)		(0.0834)		
Log_alterpriceasqr		-0.0337*				
		(0.0188)				
Year						
2013	0.314***	0.312***	0.311***	0.312***	0.298***	0.300***
	(0.0607)	(0.0616)	(0.0621)	(0.0617)	(0.0599)	(0.0597)
2014	0.535***	0.531***	0.526***	0.531***	0.532***	0.537***
	(0.0776)	(0.0799)	(0.0788)	(0.0797)	(0.0758)	(0.0766)
2015	0.729***	0.728***	0.722***	0.735***	0.725***	0.738***
	(0.0853)	(0.0883)	(0.0864)	(0.0876)	(0.0815)	(0.0827)
2016	0.885***	0.881***	0.871***	0.889***	0.878***	0.894***
	(0.0929)	(0.0972)	(0.0950)	(0.0969)	(0.0906)	(0.0925)
2017	0.980***	0.976***	0.963***	0.986***	0.970***	0.990***
	(0.0994)	(0.105)	(0.103)	(0.105)	(0.0998)	(0.102)
2018	1.019***	0.845***	1.003***	0.846***	0.995***	0.951***
	(0.106)	(0.171)	(0.109)	(0.171)	(0.106)	(0.111)
2019	1.067***	0.892***	1.050***	0.896***	1.048***	1.006***
	(0.113)	(0.175)	(0.117)	(0.174)	(0.113)	(0.119)
Constant	-59.07***	-59.55***	-60.39***	-58.53***	-56.38***	-55.17***
	(14.50)	(14.93)	(14.50)	(14.71)	(10.79)	(10.72)
Observations	871	871	871	871	905	905
R-squared	0.676	0.674	0.672	0.671	0.676	0.676
Number of countries	123	123	123	123	125	125

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4 displays the estimation results of demand Equation 6 that we specified in section IV. This table reports the estimation of adjusted and non-adjusted values for Average Price per 1 GB of mobile broadband and fixed line broadband prices in each specification. Coefficients of all the variables are broadly in agreement in sign and in magnitude across different specifications. However, we are going to focus on the adjusted values (see column 7) to interpret our result. As the coefficient for price of fixed-lined broadband (alterprice) is statistically insignificant in specifications 1 and 2, we dropped it in the specification 3.

The overall result of our estimation of the demand equation is in line with theoretical expectations. The coefficient of Average Price per 1 GB (APG) is statistically significant and its sign is as expected. A 1 percent increase in the APG is associated with 0.477 percent decrease in the average demand for mobile internet (proxied by mobile broadband subscription) but at a decreasing rate, holding all the other variables constant. This is in line with underlying theory of the law of demand that price and demand of a normal good or service are inversely related to each other. The coefficient for GDP per capita is statistically significant at 1% level. A 1% increase in the GDP per capita leads to a 13.81% increase, on average, in the demand for mobile internet, ceteris paribus. This coefficient of GDP per capita is substantial and quite close to one on the finding of Hazlett & Muñoz (2009). This means that the role of GDP per capita in the mobile broadband penetration is important in our sample. Lastly, coefficients for dummies year are all positive and significant at 1% level and coefficient of year 2019 is greater than coefficient of any other year.

Table 5: Fitted pooled OLS regression: pricing equation.

	Specification 1		**Specification 2**		**Specification 3**	
VARIABLES	**Log_APG**	**Log_APGa**	**Log_APG**	**Log_APGa**	**Log_APG**	**Log_APGa**
Log_Q	0.980***	1.124***	0.928***	1.063***	0.910***	1.042***
	(0.0885)	(0.0925)	(0.0888)	(0.0919)	(0.0882)	(0.0915)
Log_Qsqr	-0.0408***	-0.0468***	-0.0392***	-0.0450***	-0.0386***	-0.0443***
	(0.00299)	(0.00314)	(0.00307)	(0.00313)	(0.00305)	(0.00311)
Log_HHI	-1.002**	-1.362***	0.148***	0.223***	0.150***	0.226***
	(0.399)	(0.409)	(0.0418)	(0.0484)	(0.0419)	(0.0483)
Log_HHIsqr	0.0835***	0.112***				
	(0.0255)	(0.0262)				
Log_density	-14.19***	-15.24***	-14.07***	-15.15***	-13.29***	-14.24***
	(0.372)	(0.414)	(0.410)	(0.410)	(0.390)	(0.385)
Log_densitysqr	0.150***	0.176***	0.160***	0.187***	0.000600	0.00178
	(0.00499)	(0.00567)	(0.00527)	(0.00589)	(0.00299)	(0.00374)
Log_spectrum	-4.313***	-3.546***	-4.246***	-3.477***	-4.946***	-4.292***
	(0.184)	(0.182)	(0.180)	(0.182)	(0.188)	(0.189)
Log_spectrumsqr	-0.308***	-0.283***	-0.305***	-0.281***	-0.275***	-0.246***
	(0.0194)	(0.0195)	(0.0211)	(0.0194)	(0.0206)	(0.0189)
Auction3G						
Yes	-0.328***	-0.513***	-0.366***	-0.557***	-0.181***	-0.342***
	(0.0291)	(0.0314)	(0.0294)	(0.0317)	(0.0284)	(0.0298)
Competition level						
Partial competition	-1.743***	-2.949***	-1.877***	-3.118***	-1.962***	-3.218***
	(0.0925)	(0.112)	(0.0643)	(0.110)	(0.0660)	(0.112)
Full competition	-1.294***	-2.399***	-1.438***	-2.578***	-1.495***	-2.645***
	(0.0849)	(0.0993)	(0.0530)	(0.0968)	(0.0542)	(0.0977)
Spectrum sharing						
Yes	0.944***	1.760***	0.908***	1.721***	0.871***	1.678***
	(0.0343)	(0.0488)	(0.0320)	(0.0480)	(0.0317)	(0.0471)

Log_interaction	1.918***	1.741***	1.888***	1.714***	1.998***	1.843***
	(0.0516)	(0.0491)	(0.0562)	(0.0481)	(0.0592)	(0.0513)
residuals	0.981***	0.935***	0.979***	0.935***	0.979***	0.936***
	(0.0257)	(0.0254)	(0.0275)	(0.0253)	(0.0276)	(0.0253)
Years						
2013	0.00150	0.0257	-0.000294	0.0234	-0.00180	0.0217
	(0.0545)	(0.0559)	(0.0645)	(0.0560)	(0.0646)	(0.0559)
2014	-0.0540	-0.00674	-0.0527	-0.00473	-0.0537	-0.00581
	(0.0539)	(0.0554)	(0.0619)	(0.0555)	(0.0620)	(0.0554)
2015	-0.194***	-0.116**	-0.196***	-0.117**	-0.197***	-0.119**
	(0.0538)	(0.0555)	(0.0627)	(0.0555)	(0.0628)	(0.0555)
2016	-0.214***	-0.108*	-0.216***	-0.109*	-0.218***	-0.111**
	(0.0542)	(0.0561)	(0.0632)	(0.0562)	(0.0634)	(0.0561)
2017	-0.166***	-0.0309	-0.170**	-0.0334	-0.172**	-0.0364
	(0.0547)	(0.0568)	(0.0671)	(0.0569)	(0.0671)	(0.0568)
2018	-0.0712	-0.313***	-0.0759	-0.316***	-0.0786	-0.319***
	(0.0562)	(0.0587)	(0.0680)	(0.0587)	(0.0680)	(0.0586)
2019	-0.0316	-0.251***	-0.0304	-0.245***	-0.0326	-0.247***
	(0.0575)	(0.0603)	(0.0709)	(0.0600)	(0.0707)	(0.0599)
Constant	46.25***	50.09***	42.57***	44.97***	42.81***	45.26***
	(1.873)	(1.976)	(1.272)	(1.370)	(1.284)	(1.373)
Observations	750	750	750	750	750	750
R-squared	0.774	0.788	0.773	0.787	0.774	0.788

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The results of pricing Equation 5 of section IV are reported in Table 5. The sign of the coefficients of different explanatory variables are broadly expected. Their magnitudes remain almost same across the specifications with adjusted and non-adjusted value for the dependent variable. Adjusted estimation of specification 2 (see Column 5) will be focusing to interpret our results. The 79% of overall variation of mobile broadband price is explained by the list of exogenous variables included in our model specification. The coefficient of the demand variable (log_Q) suffers from endogeneity problem, then we must be careful in its interpretation. However, its sign agrees with the finding of Hazlett & Muñoz (2009). The mobile broadband price is substantially decreasing with the population density which is an indication of economies of scale. It suggests that a 1% increase in the population density leads to a 15% decrease in the Average Price per 1 GB of mobile broadband approximately, ceteris paribus.

Regarding the variables that are related to the market structure namely the Herfindahl-Hirschman Index (numerical proxy for market concentration) and categorical variable competition level appear to be highly significant across the different specifications. Their signs are as expected. The sign of HHI coefficient become positive when we drop HHI square from the regression (see specifications 2 and 3). The price of mobile broadband increase with HHI and decrease with the level of competition in a country which is expected. Thus a 1% unit increase in the HH index will lead, on average, to a 0.22% increase in the price of mobile broadband, ceteris paribus. And changing from 100% monopoly (the omitted category) to 100% partial competition market drops approximately the mobile broadband price by 95.56% while changing from 100% monopoly to 100% full competition market decrease, on average, the price of mobile broadband by 92.41%, ceteris paribus.

Results from these variables related to the market competition level are in accordance with many existing empirical literatures on both voice mobile data and mobile broadband. Particularly, findings from Thomas & Muñoz (2009), Aker & Mbiti (2010), Seim & Viard (2008), Grzybowski (2008), Mutinda (2016) and Grzybowski, Nicolle & Zulehner (2018) and confirm the market concentration is associated with price of voice mobile data declining. Calzada & Martínez-Santos (2016) confirm that new entrants in the mobile industry contributes to price decreasing in mobile broadband.

The amount of spectrum available to the mobile service, the auction and radio spectrum sharing are the variables related to the policy and regulation of mobile market. They are all statistically significant. Given mobile broadband price is related to radio spectrum in an inverted U-shaped fashion, it therefore decreases at a decreasing rate with radio spectrum amount. The coefficient shows that a 1% unit of spectrum amount increase leads, on average, to 3.48% decrease in the average price per 1 GB of mobile broadband, ceteris paribus. In the related existing empirical literature, studies of Thomas & Muñoz (2009) and Williamson & Wood (2016) confirm our finding and they demonstrated that additional spectrum reduced cost of mobile services.

The 3G auction dummy variable is negatively related to the mobile broadband price while spectrum sharing has a positive impact on it. It indicates that changing from 100% non-auction mechanism of spectrum assignment of 3G technology to 100% auction mechanism leads to a drop of average price per 1GB of mobile broadband by 42.71%, ceteris paribus. The sign of coefficients for spectrum sharing is expected to impact negatively the mobile broadband price. But it indicates that allowing spectrum users to share their spectrum license will impact positively the price of mobile broadband.

The sign of the coefficient of interaction between spectrum and density is expected as it is a proxy for cost variable in the model. We expect that cost of mobile service such as capital and engineering costs is positively related to the mobile broadband price. Thus, 1% increase in the cost of mobile broadband services will lead to, on average, 1.7% increase in the Average Price per 1 GB of mobile data of mobile broadband, ceteris paribus. The year dummies appear to be significant for the years 2015, 2016, 2018 and 2019. They all have negative influence on Average Price per 1 GB of mobile broadband.

VII. Conclusions

This paper investigates the relationship between the spectrum allocation policy and the mobile broadband cost in 135 countries during the period 2012-2019. We constructed a panel data collected from various sources such as World Development Indicator (WDI), International Telecommunication Union (ITU)-ICT Price Baskets (IPB), Global Mobile Frequencies Database of Spectrum Monitoring Technology Advisors databases and other additional sources to conduct our empirical analysis.

Findings

Our results are broadly in agreement with underlying theories of economics. First, we estimated a demand function for mobile internet using fixed-effect model, where it is found that 68% of the overall variation in mobile internet demand is explained by the set of variables in the model. We find a lower demand for mobile broadband is associated with a higher price per 1GB. Also, there is a significant and positive impact of GDP per capita on mobile broadband penetration.

On the supply side, 79% of the overall variation of mobile broadband price is explained by the list of exogenous variables included in our model specification. The mobile broadband price substantially decreases with the population density, which is an indication of economies of scale. The price of mobile broadband decreases when mobile market is more concentrated. The variables related to the policy and regulation of the mobile market show expected results. The results suggest that the price of mobile broadband decreases for a greater volume of radio spectrum available to all the operators in each country. A change from non-auction mechanism of spectrum assignment to auction mechanism leads to a drop in the Average Price per 1GB of mobile broadband by 42.71%.

Policies implication

Our results imply that the regulatory authorities and policy makers need to promote access of radio spectrum for mobile services. Firstly, it requires an institutional reform to make additional spectrum available for mobile services for developing countries. This allows operators to have the required bandwidth for their services. Secondly, regulatory authorities must promote a spectrum assignment mechanism based on auctions that contributes to the efficiency usage of telephone mobile service by reducing marginal cost and prices of mobile broadband services. Thirdly, liberalization of spectrum license is a policy that allows operators to maximize the spectrum value as they enjoy flexibility usage of bandwidth. Liberalization also promotes property right of spectrum band.

Developing countries also need to develop a framework that enable appropriate policies action to promote a vast radio spectrum availability to meet the growing demand for mobile phone services in the context of developing countries. A development of inclusive policy of mobile broadband must be seen as economics growth driven in which broadband technologies and infrastructures are key areas to explore. In this regard, developing countries can seek to develop policies action base on either supply or demand side.

From supply-side policies perspective, Victor Mulas (2012) elaborated a quite comprehensive policy recommendations that are in line our findings. We believe that these policies can enable telecoms companies to respond to the growing demand for mobile broadband services in the developing countries context. First and foremost, regulatory authorities and policy makers need to implement a policy that can deploy wide networks of cost-effective mobile broadband. High availability of sufficient spectrum in quality and quantity is key for the success of cost-effective mobile broadband. Networks equipment and technologies that are designed to specific spectrum bands for mobile broadband development.

Alongside with the availability of spectrum bands policy, regulatory authorities need to set right policy in order to remove technological restriction on spectrum. A spectrum technology neutrality allows intensively operators make choice of the most efficient technology to deploy on mobile broadband development. Market-based of spectrum allocation (e.g., auction mechanism) contributes highly to implement this policy of spectrum technology neutrality. Additionally, promotion infrastructure and spectrum sharing policies are not to be neglected. Implementing of these policies do not only encourage new entrants in the mobile phone market but incentivize incumbent operations to develop common networks and to share costs which in return result lower investments cost.

All these aspects of policies actions on supply-side can stimulate low-cost of mobile broadband in which results economies of scale.

Policies makers and regulators may focus on demand-side policies to boost mobile broadband services. Policy on accessibility and affordability of broadband-enabled devices can reach greater audience of consumers. Increasing of availability of such affordable devices (tablets, smartphones, or computers) by providing low- or ultra-low-cost devices increases instantly mobile broadband penetration in developing countries. Promoting low cost of broadband-enabled devices significantly reduces the cost of mobile services including broadband. Government can promote low cost of these devices by subsidization of development of cheap handsets. Other demand-side policies can be explored in developing countries noted by Victor Mulas (2012) are: promotion of mobile applications as driver of broadband demand policy and decreasing of mobile broadband cost.

Future area of research to explore

Our paper contributes to the existing literature of the impact of spectrum allocation policy on the change of mobile internet price as it provides more evidence based on a larger sample. System of demand and supply equations allowed us to explore the research question that we aimed to answer. However, our research is not without limitation that needs to be investigated further.

Therefore, our analysis of supply equation has certain limitations which future similar research can address. For instance, the demand variable in Equation 5 is endogenous, which means its estimated coefficient would be biased. The sign of the demand variable coefficient in the pricing equation is expected to be negative as it is a case of the coefficient of mobile broadband cost in the demand equation. Future studies can address the endogeneity problem using a valid instrumental. Furthermore, future research can pursue the investigation of the mobile broadband cost with respect to its impact on the property right of spectrum.

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Appendix A: concepts definition

Management of spectrum for commercial users, specifically for mobile market is a domain of technique and it requires an implication of various actors/stakeholders. We therefore need to display some definition of technical concepts that readers need to be familiar with. These definitions are rather provided to understand policy aspect of spectrum management.

- **Spectrum allocation "***refers to the process of deciding what type(s) of service (s) can use a particular spectrum band for an allowed specific technology and business model and the regulatory authority determines how many competing operators will be licensed. While* **spectrum assignment** or **license assignment** *refers to the process used to decide who gets access to spectrum band and selection is done through conventional methods of assignment (comparative hearings, lotteries, or auctions).*" (ITU 2018; Hazlett 2004; GSMA 2017). Alongside with assignment of spectrum to type of service, spectrum band can be assigned by market or to firms (Hazlett T. & Roberto E. Muñoz, 2009).
- **Radio spectrum** or **radio frequency** is defined as *"means radiated electromagnetic energy measured in Hertz, below 300 GHz. Radio can be divided into a number of designated blocks, called bands, which are allocated to various categories of users for specific purposes* (ITU 2018, GSMA 2017)."
- GSMA defines **Spectrum band** or simply **band** as **"***a discrete block of spectrum that may be allocated for use by certain services (e.g., mobile services) and assigned by a national regulator to a specific user (e.g., a mobile operator)".*
- **Property right of spectrum** can refer to just as a **spectrum right** and ITU defines as "*use a specified frequency or range of frequencies in a particular location or throughout a nation or region for a particular time period within the ITU Radio Regulations*."
- ***Sharing spectrum*** is referring to "*an agreement between two or more telecoms firms to offer network access through their radio spectrum assets to each other's customers*." (GSMA, 2017)
- GSMA (2017) defines **Auction** as "*A method used by a regulator to assign a licence to a mobile operator allowing them to use a specific frequency band in a certain area, at certain times, for a specific period. There are numerous auction methods such as ascending clock auction, combinatorial clock auction, Dutch auction, English auction, sealed bid auction, and simultaneous (ascending) multi-round auction)"*

Appendix B: list of countries

Afghanistan
Albania
Algeria
Andorra
Argentina
Armenia
Aruba
Australia
Austria
Azerbaijan
Bahamas
Bahrain
Bangladesh
Belarus
Belgium
Bhutan
Bolivia (Plurinational State of)
Bosnia and Herzegovina
Botswana
Brazil
British Virgin Islands
Bulgaria
Burkina Faso
Cabo Verde
Cambodia
Cameroon
Chile
China
Colombia
Costa Rica
Cote D'Ivoire
Croatia
Cuba
Cyprus
Czech Republic
Democratic Republic of the Congo
Denmark
Dominican Republic
Ecuador
Egypt
Estonia
Eswatini
Finland
France
Georgia
Germany
Ghana
Greece
Guatemala
Guinea
Guinea-Bissau
Honduras
Hong Kong, China
Hungary
Iceland
India
Indonesia
Iran (Islamic Republic of)
Iraq
Ireland
Israel
Italy
Japan
Jordan
Kenya
Kiribati
Korea (Rep. of)
Kosovo
Kuwait
Kyrgyzstan
Lao People's Democratic Republic
Latvia
Lebanon
Lesotho
Liberia
Libya
Liechtenstein
Lithuania
Luxembourg
Macao, China
Malaysia
Malta
Mexico
Moldova
Mongolia
Montenegro
Morocco
Mozambique
Myanmar
Namibia
Nepal (Republic of)
Netherlands
New Zealand
Nicaragua
Nigeria
Norfolk Island
Norway
Pakistan
Palau
Panama
Papua New Guinea
Peru
Philippines
Poland
Portugal
Qatar
Romania
Russian Federation
Samoa
Saudi Arabia
Serbia
Singapore
Slovakia
Slovenia
Solomon Islands
South Africa
Spain
Sri Lanka
Sudan
Sweden
Switzerland
Taiwan, Province of China
Tanzania
Thailand

The	Turkey	Uruguay
Tonga	Ukraine	Viet Nam
Trinidad and Tobago	United Arab Emirates	Zambia
Tunisia	United Kingdom	

Appendix C: auxiliary tables

Table C 1 fixed effect: pricing equation

	Specification 1		**Specification 2**		**Specification**	
VARIABLES	**Log_APG**	**Log_APGa**	**Log_APG**	**Log_APGa**	**Log_APG**	**Log_APGa**
Log_Q	0.988***	1.199***	0.945***	1.150***	0.925***	1.125***
	(0.186)	(0.196)	(0.185)	(0.195)	(0.185)	(0.195)
Log_Qsqr	-0.0415***	-0.0503***	-0.0402***	-0.0488***	-0.0395***	-0.0481***
	(0.00617)	(0.00650)	(0.00616)	(0.00649)	(0.00614)	(0.00647)
Log_HHI	-0.796*	-0.835*	0.144**	0.230***	0.146**	0.233***
	(0.420)	(0.443)	(0.0598)	(0.0630)	(0.0597)	(0.0630)
Log_HHIsqr	0.0719**	0.0814**				
	(0.0318)	(0.0335)				
Log_density	-14.42***	-16.26***	-14.33***	-16.16***	-13.52***	-15.17***
	(2.888)	(3.042)	(2.896)	(3.051)	(2.823)	(2.976)
Log_densitysqr	0.152	0.187	0.163	0.198		
	(0.129)	(0.136)	(0.129)	(0.136)		
Log_interac	1.949***	1.859***	1.923***	1.829***	2.034***	1.964***
	(0.483)	(0.509)	(0.484)	(0.510)	(0.476)	(0.502)
Constant	7.701**	15.98***	5.278	13.24***	2.383	9.709***
	(3.632)	(3.826)	(3.479)	(3.666)	(2.613)	(2.754)
Observations	925	925	925	925	925	925
R-squared	0.298	0.423	0.293	0.419	0.292	0.418
Number of countries	128	128	128	128	128	128

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table C 2: Pseudo fixed-effect: time-invariant and rarely changing variables

	Specification 1		Specification 2		Specification 3	
VARIABLES	**u11**	**u21**	**u12**	**u22**	**u13**	**u23**
Log_spectrum	-4.344***	-3.686*	-4.286***	-3.621*	-5.000***	-4.490**
	(1.035)	(2.115)	(1.025)	(2.098)	(0.950)	(2.023)
Log_spectrumsqr	-0.317***	-0.312	-0.313***	-0.308	-0.283***	-0.270
Auction3G	(0.0947)	(0.194)	(0.0938)	(0.192)	(0.0870)	(0.185)
Yes	-0.328*	-0.538	-0.371**	-0.586*	-0.181	-0.355
	(0.172)	(0.351)	(0.170)	(0.348)	(0.158)	(0.336)
Competition level						
Partial competition	-1.704***	-3.101***	-1.830***	-3.244***	-1.918***	-3.351***
	(0.470)	(0.960)	(0.465)	(0.952)	(0.431)	(0.918)
Full competition	-1.226***	-2.479***	-1.361***	-2.631***	-1.420***	-2.703***
	(0.453)	(0.925)	(0.448)	(0.918)	(0.416)	(0.885)
Spectrum sharing						
Yes	0.958***	1.854***	0.920***	1.811***	0.881***	1.764***
	(0.194)	(0.395)	(0.192)	(0.392)	(0.178)	(0.378)
Constant	38.14***	34.51***	37.84***	34.18***	40.97***	38.00***
	(2.869)	(5.861)	(2.841)	(5.814)	(2.634)	(5.607)
Observations	750	750	750	750	750	750
R-squared	0.875	0.588	0.875	0.586	0.899	0.629

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

u11, u12 and **u13** are estimated unit-effects from estimation of non-adjusted APG from specification 1, 2 and 3 respectively in table C 1.
u21, u22 and **u23** are estimated unit-effects from estimation of adjusted APG from specification 1, 2 and 3 respectively in table C 1.