Charles University in Prague

Faculty of Social Sciences
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MASTER THESIS

Spectrum Auctions in Telecommunications

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Declaration of Authorship

The author hereby declares that he compiled this thesis independently using only the listed resources and literature, and the thesis has not been used to obtain a different or the same degree.

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Prague, May 16, 2014

Signature

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Abstract

Telecommunication sector is one of the most developing in last 20 years. The speed of the progress in inventing new technologies has to be balanced by proper radio spectrum management since radio spectrum is a scarce resource. The methods of assignment used in past such as beauty contests or lotteries are no longer those that rule the sector. To keep pace with new technologies, spectrum auctions were presented as a new method that ensures the best results for state. Since the companies are competing for the licenses, final price is getting higher and thereby higher revenues go to the state treasury. In this thesis the behavior of final price in the spectrum auctions was examined. In the end of the work, recommendations to NRAs were presented to conclude the results of the empirical examination.

JEL Classification	D44, L43, L51, L96, N40
Keywords	Telecommunications, spectrum, auctions

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Abstrakt

Telekomunikační sektor je jedním z nejvíce se rozvíjejících odvětví za posledních 20 let. Jelikož je radiové spektrum vzácným zdrojem, rychlost pokroku ve vynalézání nových technologií musí být vyváženo jeho vhodnou správnou. Metody přidělování spektra používané v minulosti, jako např. „beauty contests" nebo loterie, již nejsou těmi hlavními v tomto sektoru. Pro udržení kroku s novými technologiemi byly aukce spektra představeny jako nová metoda, která zajistí nejlepší možné výsledky. Vzhledem k tomu, že firmy v aukci soutěží o licence, zvyšuje se tím finální cena a tedy i výše příjmu do státní pokladny. Tato diplomová práce se zabývá zkoumáním chování výsledné ceny v aukcích spektra. Ke konci práce jsou představena doporučení jako sumarizace výsledků empirického zkoumání.

Klasifikace	D44, L43, L51, L96, N40
Klíčová slova	Telekomunikace, spektrum, aukce

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Acronyms

MVNO	Mobile Virtual Network Operator
CTO	Czech Telecommunication Office
ITU	International Telecommunication Union
FCC	Federal Communications Commission
NRA	National Regulatory Authority
PCS	Personal Communications Service
GSM	Global system for mobile communications
M2M	Machine-to-machine
ICT	Information and Communication Technologies
EC	European Union
EU	European Commission
FCFS	First-come-first-served

Master Thesis Proposal

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Proposed Topic:

Spectrum auctions in telecommunications

Topic Characteristics:

One of the most actual topics in Czech Republic is a revolution in telecommunications. Although the feeling from this process is positive, it also brings a lot of changes in functioning of competition policy in telecommunications. In the fall, Czech telecommunication office stepped up to big changes. These changes concerned mainly two segments of the telecommunication services. Entry of virtual operators (MVNOs) and spectrum auctions. Although these two things have different impact on telecommunications, they are interconnected. The frequencies that are an objective of the auctions are then used by the three main operators for reselling operations to the virtual operators.

We can assume that the impact of the auction on the costs of the main operators is evident and it should be included when analyzing the anticompetitive behavior of the companies that offer telecommunication services. This thesis is examining the contribution of spectrum auctions to the ongoing changes in telecommunications. I will uphold my research by the data collected by different telecommunication authorities such as CTO (Czech Telecommunication Office), ITU (International Telecommunication Union) or FCC (Federal Communications Commission). Also the basis for my study will be the literature survey of prior research works.

Hypotheses:

1. High closing price in auctions negatively influences the cost basis of the winning bidders.
2. Internal and external characteristics of the bidders influence the closing price.
3. Spectrum auctions are the only way how the telecommunication authority can regulate the market.

Methodology:

For better orientation in the topic, the analysis of the preceding literature will be the first step of my work. By this method I will examine several research studies and compare their outcomes. Also case studies will be supporting material for the thesis. This will be the basis for my own analysis where I will test the hypotheses stated above.

Secondly I will focus on evaluating the case of Czech telecommunications. For this purpose, the method that seems to be suitable is called Difference-in-Differences. By this approach I will be able to observe the course of values of variables and predict the change that would occur after the presence of auctions. If necessary, instrumental variables will be implemented also.

Outline:

1. Introduction
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    c. Case studies
4. Other methods of regulating telecommunication services
    a. Lotteries
    b. Comparative hearings
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    a. Comparative analysis
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6. Conclusions

Core Bibliography:

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Internet resources:

www.czso.cz

www.itu.int

www.fcc.gov

Author **Supervisor**

1 Introduction

In recent time, telecommunication services have become one of the most dynamic industries. Not only the experts are continuously inventing new technologies, but also the regulation of telecommunication services changed trying to correspond to a potential of possible entrants. These are the two factors that influence the shape of telecommunication services in last 20 years.

Telecommunication sector is large industry which comprises areas such as fixed telephony, mobile telephony, internet communication and data generally, radio and television. Specific topic is wireless telecommunication that uses radio frequencies to transmit signal without wires. The frequency spectrum is scarce resource and thus has to be managed by regulatory authority. In this thesis, the specifications of wireless services are stressed, as the main topic of the thesis is mobile services in telephony. Still the introduction to the topic of telecommunication sector as a whole will be done.

Thanks to the fact that the radio spectrum is no longer used to issue an analogue television signal, these frequencies appeared free to be used for another services. As the telecommunication technologies involved, it was natural for the governments to tend to assign the radio spectrum to telecommunication services. The only problem was how to do it. As the time passed, the practice moved from simple methods such as beauty contest to more sophisticated methods used now, called spectrum auctions. Even though former methods used in telecommunication sector will be discussed to compare the outcome with spectrum auctions, auctions will be thoroughly described in a separate chapter, where the theory of auctions will be added to contribute to this topic.

The author of the thesis examines the development of a spectrum allocation with an emphasis on spectrum auctions and their results. The important part of this thesis is also an empirical study of a closing price of auction and what modifies it. It is believed by the author that the environment in which the auction takes place and the detailed conditions NRA set have major impact on the result of the auction – final price. For governments this is an important study since the result of the auction will end in State Treasury. Empirical study of the final price and its behavior will be the main contribution of the thesis.

In the first part of the thesis, existing literature will be analyzed and used to summarize what the telecommunication services are about and what is the history. Complex problem of radio spectrum as a scarce resource will be discussed to stress the importance of appropriate method of spectrum assignment. In third chapter, the author will explain to the reader particular methods of allocation of radio spectrum. However the formerly used methods will not be described in such detail as the spectrum auctions. Fourth chapter will deeply explore the theory of auctions and the implementation on spectrum auctions including practical view of conducting spectrum auctions. In fifth chapter the empirical model will be constructed to examine what are the determinants of a closing price in auctions. Also a study of a closing price on financial situation of auction players will be examined. The author will uphold its research by data collected by different telecommunication authorities such as CTO (Czech Telecommunication Office), ITU (International Telecommunication Union) or FCC (Federal Communications Commission). Also the basis for the study will be the literature survey of prior research works. The most useful will be an article, Synergies in Wireless Telephony: the Broadband PCS Auctions (Cramton, Ausubel, McAfee, & McMillan, 1997), in which the authors also analyze an American spectrum auctions and their closing prices. Main task of the empirical analysis was to test following hypotheses:

1. Number of bidders has positive influence on the final price as higher number of bidders means more competition on the market.

2. When new entrant is present, the final price is getting higher as the incumbents do not want new one to enter the market.

3. When the bids are revealed in the auction, the final price is not as high as when the bids are sealed because the winner is not an object to “winner’s curse“.

In the end of the fifth chapter of the thesis outcome of the study will be compared to the base article. Afterwards there will be the conclusion to summarize results of the study.

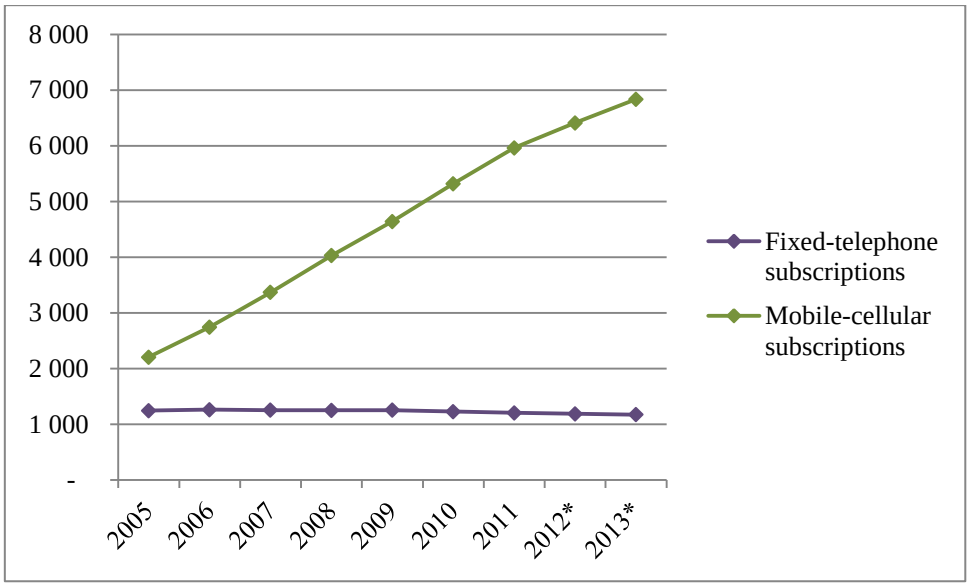
2 Telecommunication sector history

When speaking about industries, telecommunications is one of the youngest and the fastest developing. Also its market is really fast growing (Gruber, 2005). State authorities around the world are trying to support the scientists to develop more and more improved technologies to make the world smaller and to bring different places around the world closer. The other industries can profit from it, lower costs and thus improve their technology.

It is important also to note specifications of telecommunication industry. First of all, telecommunication technologies are used everywhere. Not only they are a part of the other industries used by companies and state authorities, but they have spread into the everyday life of individuals. Another important feature of telecommunication industry is a use of the radio spectrum. Since radio magnetic frequencies are limited, radio spectrum is managed as a scarce resource, which applies theory of public goods on it. In this chapter, the specifications of telecommunication industry will be discussed.

These days, the most common technology used by individuals is a mobile service supplied by telecommunication operators. This thesis will stick with this type of services and any information from now on will be related to it, if not stated otherwise. The reason for this is the massive change in the shape of services used by consumers. In figure 1, we can observe the trend in using mobile and fixed services. We can definitely see that mobile services are expanding with an increase in a growth rate while fixed services have a declining trend in a growth.

Figure 1: Fixed telephone and mobile-cellular subscriptions



Source: ITU

2.1 Technology development

As it was said above, telecommunication industry is a young industry with never ending technological development. These days, most technological progress was done in the field of mobile telecommunications such as connecting user through radio waves replaced connecting through wires. After Rudolf Hertz came with the idea of using radio magnetic spectrum in 1888, it took a century to introduce analogue technology cellular systems to public as a useful technology for commercial purposes. But still, analogue systems were not able to serve mass of users. This was enabled in 1990s when digital technology came (Gruber, 2005).

As Gruber (2005) explains in his book: *"The introduction of digital technology led to a breakthrough in performance, capacity and quality of mobile telecommunications. Digital technology, such as the European standard, GSM, made better use of the radio spectrum than analogue technology did and could therefore accommodate more subscribers. Lower unit costs could be achieved by spreading fixed costs over more subscribers."*

As the time passed, digital technologies started to rule the world and all around the globe scientists started to invent new technologies of telecommunications. With analogue technologies, problem of compatibility arose. With digital ones, there was an improvement on this issue. We can compare 1G (7 analogue systems applied) and

2G (4 digital systems applied) and see the difference in numbers. This move to convergence was also enabled by common action of American and European authorities for telecommunications (see section 2.2).With 2G, European countries stated a standard – GSM. But still, the technology was mainly constructed for transmition of voice. With the development of information technologies and internet, there was a need to develop new technology for transmition of data, which was called 3G and started to be adopted in Europe in 2003 (Gruber, 2005).

As the world needed to get faster and faster with large size data, the development of fourth generation (4G) started. The purpose of introducing new technology is to satisfy the needs of transmitting large volumes of data. Also there is a trend to converge the technologies, so there can be introduce a technology that can "provide seamless and high-reliable and quality broadband mobile communication service and ubiquitous service through wired and wireless convergence networks without the space problem and terrestrial limitation, by means of ubiquitous connectivity" (Hwang, Consulta, & Yoon, 2007). From the technical point of view, 4G promises downlink data rates over 100 Mbps, low latency, low costs of implementation and efficient use of radio spectrum (Krenik, 2008). All these features enable new user applications (including M2M applications) and using high definition features. Features of particular generations are presented in table 1 to summarize the development. It is right now when the world is waiting to implement 4G and benefit from its features.

Table 1: Mobile communication history

Property	**1G**	**2G**	**3G**	**4G**
Starting Time	1985	1992	2002	2010
Driven Technique	- Analogue signal processing	- Digital signal processing	- Intelligent signal processing	- Intelligent software - Auto configuration
Representative Standard	AMPS, TACS, NMT	GSM, TDMA	IMT-2000 (UMTS, WCDMA, CDMA2000)	OFDM, UWB
Service Type	- Voice - Mono-service - Person-to-person	- Voice, SMS - Mono-media - Person-to-person	- Voice, Data - Some multimedia - Person-to-machine	- Multimedia - Machine-to-machine

Source: Sun, Sauvola, & Howie (2001)

2.2 Role of NRAs

An indispensable part of telecommunication industry is a regulation. As discussed above, telecommunications are specific by the scarcity of radio spectrum. This influences the number of firms that are providing mobile services and keep it lower. In Gruber (2005) we can read about the history of the regulation of telecommunications. The author mentions the past, when telecommunication networks were considered as natural monopolies. The sector was inspected by regulatory authorities in two ways - ex-ante and ex-post. First mechanism gives the industry rules how to work and is applied specifically on the particular industry. Second mechanism is an application of competition law which examines if there is any exploitation of market power. In Europe, there was a history of state-owned monopolies in contrast to America, where telecommunication services were provided by privately held monopolies. The industry waited till 1980s, when first regulatory reforms have set the direction to competitive environment in telecommunications. Basic principle that was used from now on as an inspiration was a separation of the regulatory from the operational function (Gruber, 2005).

Since the specifications of telecommunication sector, we can easily come up with possible market failures in this industry. Firstly, as there is a great need for technological base, there are high entrance costs. A new entrant has to count with spending large amount of money on establishing the network infrastructure. This makes it easier for the incumbent who already has the infrastructure settled. Secondly, a new entrant has a big disadvantage of no customer basement as the costs for operation of network are decreasing with the number of customers. The facts mentioned above led NRAs to change their approach to telecommunication services and to abandon monopolistic structure. However, due to the scarcity of spectrum, there is still limited number of firms that can provide telecommunication services (Gruber, 2005).

In his article, de Streel (2008) observes a system of instruments used by European NRA. We can see his overview in table 2. There are two main branches of instruments - competition law and regulation. Competition law is a general set of rules applied on every industry. Main objective of competition law is consumer welfare, which makes it stuck with analyzing competitiveness of the environment. Competition law can be applied ex-ante as well as ex-post. Regulation, on the other hand, is applied only ex-ante, trying to prevent unwanted situation to happen, such as an abuse of significant market power (SMP).

Table 2: Competition law and sector regulation

	Competition Law – Ex post	Competition Law – Ex ante	Sector Regulation/ SMP regime
Objective	Maintain competition Increase competition → Market structure is broadly satisfactory		Increase competition Mimic competition → Market structure is not satisfactory
Burden of proof to intervene	1. Market definition 2. Dominant position 3. Anti-competitive conduct: agreement or abuse of dominance (high)	1a. Notified concentration 1b. Market definition 2. Significant impediment to effective Competition (low) (Conduct presumed)	1a. Market selection (very high) 1b. Market definition 2. SMP=dominant position (Conduct presumed)
Remedies	Mainly behavioural Fines Private damages	Mainly structural	Mainly behavioural

Source: de Streel (2008)

As it was concluded in the article of de Streel (2008), that due to the specifications of telecommunication industry, there is a good reason for intervention which is more severe than in other industries. This is caused by the scarcity of spectrum, which requires some authority to manage frequency use and monitoring of technology standards (Gruber, 2005). The aspect of radio spectrum as a scarcity resource will be discussed later.

Due to a management of radio spectrum by regulatory authorities, they can thus regulate the number of firms in the sector and thus the market structure. As this is decided on the national level, we can observe different approaches to this issue. In past, when analogue technologies were ruling the world, the telecommunication sector was represented by national monopolies. Later on, digital technology took the role of leading technology and authorities started to change their approach and to increase number of firms (OECD (2003) taken over from Gruber (2005)).

As it was mentioned above, another specification of telecommunication industry is height of costs when entering the market. Firms have to count with enormous costs of establishing the infrastructure in comparison to other sectors. Also another problem is the presence of a customer base. Bigger the base is more these fixed costs are dissolved in it. This increases barriers to entry in the industry and thus, when the regulatory authority wants to increase number of competing subjects, there is a need for regulation. As discussed by Kiessling & Blondeel (1998), this can lead to different approaches to incumbent and entering firms, called “regulatory

asymmetry". In comparison, there is another approach, regulatory symmetry, which is seen by the authors of the article as leading to economic efficiency. However, according to the specifics of the telecommunication industry, we can expect that such high barriers to entry in a form of fixed costs for establishing the infrastructure can be a good reason for asymmetric regulatory approach.

Over the time of telecommunication technology developments, there were different approaches and timing of movements in the regulatory framework present. In the past, main initiators of changes were ITU, agency of the United Nations founded in 1865 under the name International Telegraph Union and FCC as an authority monitoring American market of telecommunications, established in 1934. In last 30 years, it also has been European Union that is guarding the developments in telecommunications. Those three are the main institutions concerning telecommunication industry.

ITU as a United Nations agency covers national NRAs, institutions and also companies that are willing to participate in allocating global radio spectrum and setting technological standards. Through these processes, the agency is influencing the shape of ICTs around the world to "ensure networks and technologies seamlessly interconnect, and strives to improve access to ICTs to underserved communities worldwide" ("ITU," 2013).

Purpose of FCC is to regulate interstate and international communications including 50 American states and its territories. The regulation includes radio, television, wire, satellite and cable. As other regulatory authority, Commission's purpose is to promote competition, ensure competitive environment, manage radio frequencies and set regulatory framework ("FCC," 2013).

The youngest from the three institutions is European Commission. Since EU tries to supply the superior regulatory framework for member states, to ensure harmonization among countries, as it is in the USA, it is logical that one of the sectors, where EU is involved the most, is telecommunication industry. In the beginning, the main responsibility of EC as the EU primary regulatory authority, was to enable the transition from monopoly structures to oligopolistic structures where competition can take place (Kiessling & Blondeel, 1998). The reason for such intervention was a worry that monopolistic structures would harm implementation of the common market principle. Initiative that led to the new concept of telecommunication industry regulation in Europe, was the Green Paper issued in 1987, setting the basement for common telecommunications market. In this publication, EC introduced a plan for promotion of competitive environment and

deeper harmonization. Based on the Green Paper, EC introduced an action program to implement common telecommunication policy. Main ideas in the program were related to following issues. Pursuing the EU objectives, telecommunication action program underlined the priority of enhancement of competition in telecommunication market. By introducing competition, EU telecommunication market will be more competitive in context of world market. With this, also a tendency towards separating regulatory and operational activities is connected. Not only in the past there were monopolies, but also a lot of them were held by state. By separating regulatory and operational segments, telecommunication sector would not be linked to state activities and thus providing more competitive environment. Technology standard is more technical issue. As it was discussed before, within each generation of technological standard, there were different technologies used. During the development of the technologies, there was a trend established to standardize technology that would be used all around the world so global roaming would be possible.

In last decade, European Commission issued another important initiative that is reflecting the state of nowadays telecommunication market. The framework directive (FWD) is a quite new directive issued in 2002. As it is stated by EC: “This Directive requires the adoption of national measures in terms of access to electronic communications with a view to respecting the fundamental rights and freedoms of natural persons” (“EUROPA,” 2010). When comparing European Union telecommunication regulatory framework with ITU and FCC, we can see that EU started to reform telecommunication regulation later. While first publication – Green Paper – was issued in EU in 1987, in the USA, market for long-distance services was liberalized already in 1980. But in contrast to US regulatory framework, EU does not distinguish between local and long-distance services and thus measures of European Commission are applicable to state and supranational level (Kiessling & Blondeel, 1998).

2.3 Radio spectrum – allocation of the scarce resource

Transmition of voice, data or any kind of information without wires is enabled by radio magnetic waves. Particular parts of electromagnetic spectrum are denoted as frequency or radio channel and measured in units of MHz. Technology of information transmition through radio spectrum is used among others for mobile

telecommunication services. Problem with radio spectrum is that it has limited capacity. As it was discussed earlier, first methods of transition of information were analogue technologies. As these technologies were able to serve for a small number of users with limited capacity, they were abandoned and now digital technologies rule the world. The advantage of these technologies is that they permit to transmit bigger size of the information and the limit is pushed even further and further with every new type of digital technology. Also the advantage is that with digital technologies, radio spectrum can serves to much more users and it can thus enhance technological progress in other industries. Both these advantages mean together more efficient usage of radio spectrum.

As mobile telecommunications services are used all around the world and technologies have to be compatible, there is a need for spectrum management on local and international level. On the international level, supranational entities conduct intermodal allocation of spectrum so particular frequency blocks would be assigned to the same type of services and international communication would be enabled. Differently, intramodal allocation of spectrum is conducted by NRAs to influence a competitiveness of environment by assigning spectrum to certain number of firms. Unlike intermodal allocation which is operated regularly, intramodal allocation of spectrum has changed as the approach to the telecommunication regulation has moved from monopolistic perception to more competitive concept. This caused the assignment mechanisms of spectrum allocation used in the past, administrative ones (such as lotteries and beauty contests), to be left behind so new approach, market based one, took its place, particularly auctions (Gruber, 2005).

Deciding about assignment of spectrum is an important role of NRAs. By activities in spectrum assignment, NRAs are able to influence the market shape in the sector. Also assigning is connected to a technology, which should be used in the particular frequency. NRAs can decide to apply on it a technology that is commonly used, or to apply a technology, which could compete with others. When the technology is decided, there is a question of how to assign spectrum. In the beginning of mobile telecommunications, methods were more primitive and based a lot more on administrative process than on market. As the approach to telecommunication services evolved, method of spectrum assigning changed from administrative methods to market based ones, believing market power will do the best. This action took place in 1979 as the World Administrative Radio Conference assembled. On this conference, the main point was a review of assignment methods of that time and proposition of new design of telecommunications. Among the propositions, there were thoughts such as setting spectrum rights freely transferable so administrative

process will no longer be needed or using auction mechanism to allocate spectrum through market. Also an idea of license fees was presented on the conference. These concepts came from a group around Ronald Coase and his theory of property rights, supported by neoclassical theory of competitive markets (Melody, 1980). We can see that the image of competitive telecommunication sector was firstly presented before 35 years. Unfortunately, it took another 20 years to apply this concept in practice. As it can be read in the article of Melody (1980), a year after the conference, it was seen that it is improbable to use market based approach on telecommunications. According to the author of the article: "*The spectrum will continue to be allocated and assigned by means of an administrative process. This is required by the characteristics of the resource. The market cannot be an efficient substitute for the administrative process in achieving either allocation efficiency or the broader objectives of the process. As the spectrum becomes more valuable over time, the costs to society of inefficiency in the process will increase, but the broader political and social criteria are likely to assume new importance."*

As mentioned above, European Union is one of the institutions that try to conduct international regulation of radio spectrum. Particularly, it is European Commission and its Digital agenda. Main goal for Commission is to harmonize state frameworks so the structure of European telecommunication sector would be consistent with single market strategy. To achieve this state, in 1997 European Commission issued Licensing Directive (European Commission, 1997). To determine common telecommunication policy in Europe, the Directive sets a universal framework of licensing. From that time on, spectrum licenses should have been assigned according to a general rule set by this Directive. By pursuing this approach, NRAs have to apply general authorizations set by supranational body, which ensures licensing framework will be the same (similar) in all Member States. As in other EU market segments, there is usually a comment about specifics of the particular countries. This raises a question of how deep EC can go when setting the directive. Due to different history of particular Member States, the level of development of telecommunication sector varies through Europe. This makes country specific individual licenses more justified. To specify the issue, Member States are in various levels in transition from monopolistic structure of telecommunications to more competitive approach. When country is ready to open the market for competition, the position of incumbents is already weakened so it is equalized with a position of new entrant. But if monopolistic market structure is not yet destroyed, position of new entrant is worse than the position of incumbent. Then, there is need for NRAs to have an instrument to weaken the incumbent and favor the new entrant. Country can achieve this through its own specific license framework. However, we should not forget about European

subsidiary principle, which ensures Member States that their own specifications and rights will not be harmed.

3 Methods of spectrum assignment

Once frequency of spectrum is allocated to specific services (telecommunication sector, in our case), there is a task for NRA to choose a method of allocation. In past, as telecommunication services were based on national monopoly, there was no need to deal with assigning frequencies to more participants. State simply ruled the telecommunication sector including public services by itself. At the time national monopolies were privatized, there were still just one or two firms holding spectrum rights. In this situation, basic administrative methods of spectrum assigning were enough. But as the time went, with an attempt to introduce more competition to the telecommunication market, the transparency and competitive environment started to be priority aspects of telecommunications. At this point, it was the right time to come with more sophisticated method such as an auction. In this chapter, different groups of spectrum assignment methods will be discussed. Also the aspects of various types will be compared among each other. In context of historical changes, the chapter will start with the first-come-first served method, continue with lotteries and beauty contest and finish with auctions and discretionary measures as the designs that are now most common and are the main topic of this thesis. However, auctions will be more thoroughly discussed in next chapter.

3.1 First-come-first-served method

As there has been no history of telecommunication services in competitive environment and the sector was based on national monopoly, the administrative process kept going at least in a form of spectrum assignment mechanism, namely through first-come-first-served (FCFS) and lottery methods. Former one is based simply on fact that firm that come with need of frequencies earlier has an advantage of getting it. The advantage of this method is that it requires not so much administrative effort and discretionary interventions and the process of assigning is fast and straightforward. However, assigning radio spectrum to anybody who is first can result (and often did) in allocative inefficiency and unwanted strategic company decisions such as preemption of frequencies just in case somebody would want it (Gruber, 2005). Since allocative efficiency is not a target for NRA, the system functions sufficiently.

3.2 Lotteries

Another possible method of spectrum assignment, which is close to FCFS method, is use of lotteries. They were specifically used in United States for smaller digital markets as not so complicated method which also does not involve big administrative burden (Buigues & Rey, 2004). However, lotteries have the same disadvantage in allocative inefficiency as FCFS method. Although as it is noted in Gruber (2005): "*Allocative efficiency may be restored by allowing for resale of the license, but at the cost of violating the principle of equity."* This mechanism seems to give a sense to usage of lotteries for spectrum auctions. But as it is written in Genty (1999), lotteries do not enable NRA to assign the licenses among the candidates that would use them the most efficiently. To prevent unwanted results such as mentioned, another measure is possible to be implemented to prevent unwanted results in lotteries – firms can be authorized to participate in lottery by fulfilling basic criteria that can exclude unsatisfactory subjects. Of course, this additional measurement means a form of discretionary intervention and thus increases a probability of regulatory misuse. Another aspect of adding this measure is that lotteries than become a mix of themselves and beauty contests, with all the disadvantages of both methods. Also as the history of lotteries, not only in telecommunications, showed, it is not still competitive method to assign a spectrum, especially in countries were level of corruption is high. There we can expect that output of lotteries will be influenced by interest groups and somehow deformed.

3.3 Beauty contests

In last decades a method the most used across different countries is beauty contest. It is also called criteria contest to be closer to the meaning. This method is a package of more and less similar approaches that all can be summarized by saying that in beauty contests companies willing to have a radio spectrum assigned are compared and rated according to some criteria. The winner is the company that is the most corresponding to the perfect model of winning company. Again the assignment of radio spectrum is an administrative process as it was with previous methods. This means that no aspect of competition is playing any role in beauty contests, unless it is stated in the criteria for winner. The criteria set by NRA are announced before the beauty contest would take a place and are valued by relative weights. The winner is announced from companies that applied for spectrum, according to the fulfillment of beauty contest criteria. As it is said in Gruber (2005), as a result this method can be similar to an auction, if the primary criterion is an amount of money prepared to be paid. The most significant pitfalls when speaking about beauty contests is selection of

wrong candidate as a result of setting inappropriate criteria. Also there is no information about the length of the process which is a variable that every NRA can take responsibly and shorten the time as possible or the administration of the process can override the positive effect of a beauty contest.

As it is mentioned in Gruber (2005), there is one more problem that seems to tackle antitrust policy of NRA. It is asymmetric information that can be observed due to the fact that information collected by NRA for the purpose of beauty contest is provided by the companies that applied for spectrum. Thus NRA cannot be sure the information is credible.

3.4 Auctions

The main method of spectrum assigning that rules the world nowadays is spectrum auction. This is the most sophisticated method when comparing with the previous ones and also the most complex when speaking about conducting the spectrum assignment. This method represents the competitive component of NRA when conducting telecommunication sector. Since the companies are combatting against each other in the auction to get the radio spectrum, NRA makes sure there will be significant contribution to country's budget. Another advantage of this method is that companies are trying to get the radio spectrum by simply bidding more and more money in the auction, which leads to the end where only the most valuable bidder becomes a winner. Thus this is the one that will be able to use the spectrum in the most efficient way since he is the most interested in spectrum and is able to provide the biggest money base. This money base is ensuring the winner will be able to manage the development of assigned radio spectrum. Of course the spectrum auctions will be discussed more deeply in next chapter since the thesis is focused on them.

3.5 Discretionary decisions

On the contrary of spectrum auctions there are discretionary decisions. They are seen as an opposite situation than spectrum auctions simply because spectrum auctions represent order and rules that are stable and expected to be followed all the time. On the other hand we have discretionary decisions that are a tool of NRA to behave how it wants. In some countries we can observe that spectrum auctions are used for telecommunications and discretionary decisions are supplementary method to conduct radio spectrum for other types of means of wireless communication, for example television, radio, Wi-Fi etc. In any case, discretionary methods basically

mean that *"authority has large discretionary powers to grant spectrum to which it wants"* (Buigues & Rey, 2004). Due to this fact there are two disadvantages of this method that have to be pointed out. Firstly we cannot forget to mention the interest groups again. Every time there is some political power that has to be examined, there is an influence of interest groups. These groups can cause the discretionary decision is not actually done for public interest but for somebody's interest and thus the result is deviated from the optimal one. Secondly as the decisions are discretionary and not included in an overall concept of decisions, NRA or governmental authority can change the direction of decisions right away. Without analyzing mutual impact of new and old decisions, regulatory authority cannot be sure that the system and economy will not become fragile. Without any solid concept, the economy can be moving from nowhere to nowhere. But it is also important to note that even though there are some strong disadvantages, there are still properly used in cases of smaller sectors of communications such as those already mentioned, where the situation does not require so large emphasis on competitive environment and economic stability.

4 Theory of auctions in telecommunications

As the time goes in telecommunication sector, administrative methods are slowly left for new method of spectrum auctions which better fits nowadays economies. NRAs realize this method brings them more money and present the competitive approach how to handle telecommunications. As it was already said, the main line of spectrum mechanism is that this method of spectrum assignment is efficient because it is bought by a company that values it the most (Gruber, 2005). Spectrum auctions have widely spread across the world and thus were also modified to fit the country's specifics. These types of auctions, also called designs, influence the output of the auction. This is also a part of the econometric analysis done in next chapter. The main differences concern whether the bidding is held opened or sealed, if the bids are submitted in ascending or descending order, whether there is the winner's price paid in the auction or the second one. One important thing is whether the spectrum is auctioned sequentially or simultaneously, one by one or in packages. Of course it is natural that these characteristics of auctions are mixed together and used differently in particular cases. Sometimes a combinatorial auction is the case. It means that there are more parts in the auction and the parts are conducted with different rules.

By theorists the advantage of spectrum auctions is seen in fact that by an auction spectrum licenses are assigned at one time to more buyers, while the price is set by market mechanisms thanks to the fact that most of the time the participants of the auction know the market price of spectrum better than the regulator. The auction allows the regulator not to set the price as a first to let the participants to compete from the beginning (Genty, 1999). Basically the auctions are seen by the economists to be a right way how to manage the spectrum. There are five main reasons why this method of assigning radio frequencies is recommended by the theorists (McMillan, 1995):

- auctions reveal the firms' estimates of license values
- auctions are transparent and fair
- auctions attribute licenses to firms quickly and economically

- auctions are incentives to develop new technologies
- auctions generate revenue for the regulator

4.1 Revenue equivalence theorem

Every NRA, when preparing the assignment of radio spectrum, has to decide firstly about the method of assignment. If auction is agreed, then there are a lot of other questions that have to be answered before the auction is announced. All these aspects then play a role when finalizing the price in the auction, as it will be showed in next chapter.

To help NRAs to decide which auction design to use, there is a little guideline that was recorded by Vickrey (1961). It is called revenue equivalence theorem and basically speaks about the assumptions that makes the revenues of different auction designs equal and also efficient in a sense of awarding spectrum to the most valuable bidder. The four assumptions that ensure this state are as follows (Vickrey (1961) taken over from Gruber (2005)):

1. Independent private value – Each bidder knows the value of auctioned object by him, but is not sure about the price of it by his rival. Also each bidder is concerned about the other bidders till they can affect him.
2. Symmetry: All participants in the auction see the value of bids as a random variable from known distribution function.
3. Normalization: The award to a bidder who did not win is zero.
4. Risk neutrality: There is no additional award to a bidder if he wins; the award is measured in currency.

Although revenue equivalence theorem can guide NRA with some guiding principles, it cannot rely on them as much. We cannot be sure that these assumptions are in any case realistic. First of all, we can expect that the bidders will influence each other during the auction so much that there will be seen a pattern in bidding. Strong impact of bidder's bidding to another can be expected in auctions where the bids are revealed. Here the correlation of behavior of particular bidders will be strongly correlated. On the other hand, if NRA conducts auction with sealed bidding, the correlation will be much lower but then we may observe a phenomenon called 'winner's curse'. This is a case when bidder overestimates the value of the auctioned

item and overpays it. This causes bias in the estimate of the item's value which also violates the revenue equivalence theorem (Gruber, 2005). So, due to the fact that theory in practice has a lot of pitfalls, there are still a lot of things that the regulatory authority has to take into account and these parameters will be included in the econometric analysis to study what characteristics of country and auction have an impact on the result.

4.2 Auction design types

"Designing spectrum auctions is as much art as it is science."

(Cramton, 2002)

As the different designs of the auctions were already tackled, in this subchapter they will be discussed more thoroughly. This is a topic that is closely connected to the empirical analysis in next chapter since the auction design is something that heavily influences the final price in the auction. As it is written in Klemperer (2004), spectrum auctions cannot be applied by a method "one size fits all" and regulator has to take into account the economic conditions as widely as possible. Basically in practice the auctions are not distinguished according to particular characteristics. They are sorted according to the types. The characteristics mentioned above are thus included in the types in groups. The characteristics that are examined are as follows:

- **Revealed x sealed bidding:** NRA can decide if the information concerning bidding should be opened or closed. If revealed, bidders know from the beginning what are particular bids. Both methods have their pros and cons. Fundamental advantage of using revealed bidding is in information available to the participants of the auction. The value of the spectrum is revealed to all bidders which prevent the winner's curse to take a place. Bidders cannot thus condition their bidding decisions on the overall information about the market, not only base their decision on their internal information and may be nonrealistic assumptions. But on the other hand, more information means that bidders can use this information to collude and thus to achieve better outcome for them (Milgrom, 1987). Through their bidding strategy that is revealed during the auction they can send signals to other participants and the output can be

collusion. When the spectrum is auctioned using sealed bidding, participants cannot communicate with each other and the result is no collusion (Cramton, 2002). In the dataset of 108 observations all over the world, we have both revealed and sealed bid auctioned licenses present, both cases with similar frequency.

- **Ascending x descending bidding:** As there is a possibility for NRA to set ascending bid as a primary used method, sometimes there is descending bidding present. This means that anyone that stops bidding is the winner. Practically there is no auction with descending bidding in the dataset used in next chapter. This shows that descending auction is not so popular and we do not have to discuss this topic so deeply.

- **Winner's price paid x second one paid:** The winner's curse was already discussed. Because of this phenomenon the method of second price was created so the winner would not be burdened by overpaying the desired radio spectrum. When collecting the data from 18 countries, none of the licenses were auctioned with winner paying second price. The classical design of auctions is thus hugely prevailing and we cannot compare the differences statistically.

- **Sequential x simultaneous bidding:** The bids can be placed in one round at the same time or it can be sequential game. The economists are in favor of simultaneous bidding. Their argument is that sequential bidding limits the information available to the bidders and their ability to react to the bids of competitors is restricted. In contrast when bidding simultaneously, bidders get the same information about the value of spectrum in the same time which allows them to come up with multiple strategies how to react (Cramton, 2002). In reality, when finding data for empirical model, there was no case of sequential bidding within the dataset with 108 observations.

- **Bidding one by one x in packages:** Quite often the companies that need radio spectrum need more than one bandwidth offered to be able to provide services demanded by customers. But there are cases that this is unwanted, for example when the auction has to be prepared to weaken the main players and strengthen the weaker ones. Then NRA has a possibility to choose whether the bidders can bid for only one or more licenses and have packages. When bidders are allowed to bid on more than one package the incumbents have a tool to make the entrance of new competitor difficult. It is probable that the incumbent will get more licenses and the entrant will not be able to compete. According to the empirical study, NRAs around the world use package bidding most of the time, just 15 %

of the licenses in the collected data were licensed as single licenses without possibility of combining them.

- **Multiple x single round auctions:** If NRA wants bidders to compete for the licenses it can set that the auction will consist of more rounds. But also, as it will be seen in the data, there are auctions that consist just from one round. Specifically 22 licenses were auctioned by one round, what represents 20 % of the dataset. The number of rounds varies from 1 to 993 with median 18.

As it is mentioned above, particular characteristics are combined into types of auctions that are then used around the world. There are six types of auctions that are used not only for radio spectrum assignment but also in other areas of economic life. Suitability of these types and comparison of results of different types are the two main topics of publications about spectrum auctions.

- **English auction:** Is the most common type of the auction that is widely used for spectrum auction. The basic characteristic is that it is simultaneous ascending auction. The auction simply ends when there is just one bidder left who is willing to bid. FCC, national regulatory authority in United States, is using this design for spectrum auctions for a long time and usually the licenses are renewed after they expire if they are not reassigned again (Cramton, 2002).

- **Dutch auction:** Contrary to English auction, during Dutch auction the bidding run in descending order and the information about bidding is not revealed to participants. According to experiences gained by collecting the data, when none of the licenses were assigned in Dutch auction, we could say that regulators stick with the classic auction design, English auction, which is more traditional.

- **Anglo-Dutch auction:** This is a hybrid type of auction composed from English and Dutch auction. By this design NRA choose to auction licenses in ascending order with sealed information. By implementing sealed bidding, NRA can prevent the market from collusive behavior and thus increase chances of new entrants to enter the markets (Klemperer, 2004).

- **Vickrey auction:** This type of auction is based on fact that winner does not pay his final bid but the second highest bid. The purpose of this design is simple – to avoid the winner's curse while using sealed bid auction. The use of this type of auction is not present in the dataset consisted of 108 licenses auctioned in 18 countries, which is used for empirical analysis in next chapter.

- **FPSB auction:** The abbreviation stands for "first-price sealed-bid" auction. Straightforwardly, the bidders have just one round to bid without any information about the other bidders or their bids. This auction is seen as a discriminating since the incumbents can use strength of their position in the market and place higher bid (Klemperer, 2002).

- **Reverse auction:** Reverse auction is not a common type of auction for spectrum assignment but in last years there is a tendency to introduce this design also to this sphere. Reverse auctions are based on the fact that in rural areas there is a need for subsidies in universal services. Since the auctioned items would be subsidized, NRA announces a reverse auction where the winner is a company that requires the lowest subsidies from NRA. The result is not evaluated by the amount of revenues but by the amount of expenditures (lower is better). Reverse auction is widely used in United States for various types of auctioned services, but it is not a method that is used for spectrum auctions (Wallsten, 2008). However this design is interesting to be used, we can expect several issues. Firstly the condition of well functioned reverse auction is that the participants need to be subsidized. If the incumbent are independent of state, the idea of subsidies does not make sense. Also when there are entrants that need subsidies and incumbents that do not, NRA can create even stronger barriers to entry by conducting reverse auction. A case study of Western Europe of Ozanich, Hsu, & Park (2004) shows the auctions generally appear to create the barriers to entry since the incumbents that are heavily set in the market have paid uneconomic prices for spectrum licenses.

Even though these designs were developing for a long time, the use of auctions in spectrum assignment is not an old concept. The spectrum auction was conducted for the first time more than 30 years ago in 1990 in New Zealand. It was a second-price sealed-bid auction. Then Australia and United States followed, Australia in 1993 with first-price sealed-bid auction and USA in 1994 with simultaneous multiple round auction. Thanks to the revenues generated in United States the spectrum auctions started to be popular there (Genty, 1999).

4.3 Europe

Even though the idea of empirical analysis of spectrum auctions come from the paper constructed to analyze spectrum auctions in United States, this study concentrates on smaller countries, including European states as substantial part. The

reason is that countries with large area conduct spectrum auctions individually for their smaller regional units. Even though spectrum auction is one for whole country, the result is more complex since every company can choose for which regions it will bid. This is for example a case of United States, Australia or India. In the end we have *x* regions, *y* bidders and *z* licenses, where each bidder can bid on particular license in particular region. The purpose of this thesis is to concentrate on the study of states where the license is auctioned for whole country as one region. It is assumed that the nature of such auction is different from the one mentioned for United States or Australia. In this thesis we assume that the focus on the smaller countries that have more in common among each other can make the results more precise. Due to this fact and the accessibility of data, European countries form a bigger part of the analysis, specifically 73 % of the dataset.

As it is written in Klemperer (2002), European regulators have two major issues when speaking about auctions. Encouraging new entrants and preventing collusive behavior in auction. Both situations were already discussed and the impact of auction design on them was presented. As in other countries, European NRAs can avoid both problems by setting the auction design properly. To avoid collusive behavior, we can expect European regulators to conduct auctions with sealed bidding, where participants do not get the information about their competitors during the auction. This however raises the problem of winner's curse. To enhance competition in the telecommunications market, it is necessary to set the number of licenses well. It is expected that the number of bidders will be higher than the number of licenses to be assigned. However as it will be showed in next chapter, the cases, in which it was on the contrary and the number of bidders was higher, were not an exception. The Dutch auction of 3G licenses is heavily judged since the number of licenses auctioned and the number of bidders was five for both (Klemperer, 2002). The economists argued that this is an unfavorable situation for new entrants whose chances to win a license are lowered rapidly and as a result, the Dutch auction also generates low revenue (Van Damme, 2002). The case can be also that the companies applied for participation in auction, but they did not fulfill the conditions to become successful applicants despite the fact that NRA made the spectrum auction attractive. Also it should be mentioned that spectrum auctions are not used in Europe for a long time. Even radio frequencies intended for technology of second generation (2G) were assigned by beauty contests in six countries in Europe including Finland, Sweden or France. Spectrum auction was a method selected just by 8 European countries. Of course, the most used design was English auction (e.g. Germany, Netherlands) which can also be seen when looking at the data. But also Anglo-Dutch (UK and Greece) or

SPSB (Denmark) design was used, which shows the spectrum auction design is not minor aspect of radio spectrum assignment.

4.4 Auctions in practice

Up to this point the thesis was based on theoretical background and prepared the reader to the empirical study that will follow in fifth chapter. The fourth chapter acquaints reader with auctions and different designs. What can one feel missing is the practical execution and conduction of auctions. As every other regulatory issue managed by some national regulatory authority, conducting auction takes a lot of time, even if it is time restricted. This is something everybody should have in mind.

When collecting the data from spectrum auctions all around the world, some pitfalls were observed. First of all, NRA announces the auction will take a place. This is generally done half a year before the auction takes place. After the announcement of auction the interested companies apply. After some time (it differs from country to country and according to the auction design) NRA announces successful candidates that fulfilled the conditions to participate in the auction. Next step is preparation of the auctioning documents such as information memorandum, bidder forms and training documents. Between the preparation and start of the auction there is a period for different subjects to raise comments, objections or proposals for change in public hearings. It is not an exception for NRA to organize more of them. In this phase the auction design can be changed dramatically. Then the phase of public hearings is closed and the training period commence. Participants have to go through the courses where simulation of auction is done. After that the auction can start. The auctions nowadays are conducted by software prepared directly for the auction. After the condition of ending the auction is fulfilled, computer ends the auction. But it still does not mean the licenses are assigned right away. It takes time for winners to get the licenses. First of all NRA has to issue a declaration document to state who will receive the access to which license. Also some licenses are auctioned prior they are free and available and they are auctioned while some company still holds them. In such case there is a date set in advance that states when the licenses will be available. And we should not forget about the technical interconnection of NRA's spectrum and technical base of the winner.

For NRA to be able to say the auction was successful, there are some issues that has to be kept in mind. Firstly, in the beginning, there has to be a base formed by candidates for bidders. Companies (sometimes conglomerates) that apply for

participation in the auction are then examined according to rules and conditions set by NRA, by same manner as it would be for example beauty contest. The number of companies can be then dramatically lowered. As a result there can be fewer companies – bidders – than licenses to be assigned. Unfortunately, as it was mentioned before, this situation was a reality in few European countries and it will be discussed in next chapter. NRAs have this situation in mind and they often prepare a "backup design" in case of unwanted number of bidders. Sometimes the auction would not take place or the auction format would be modified to substitute competition. If the auction takes place even so, the expected gain in form of revenue from the bidding is decreased by the fact that bidders are not forced to interfere and it is assumed the final price will be the same as the reserve price. This was a case for example in Nigeria in 2007 where the auction was canceled and the license was assigned to the only participant for a reserve price. Another problematic aspect of auction for NRA is its length. When auctioning the radio spectrum without setting a time restriction, the length of the process is not completely in hands of NRA. As it happened in Finland in 2013, the auction lasted 993 rounds within 170 days. The rules had to be revised and auctioning software had to be renovated in the last quarter of auction. With this length of auction it is hard to predict what will be the economic situation in a country after many days. Also the bidding companies have to adapt their business plans to new situation and it can change their behavior in auction. In times of crisis or instable economic situation, this can cause major issues either for NRA or for bidders. As a result the bidding can slow down but not stop. As a part of the empirical analysis the impact of length of the auction will be also examined.

5 Model of spectrum auctions

As a key part of this thesis the empirical model will be evaluated in this chapter. As a base and inspiration the paper from Cramton et al. (1997) was used. The authors are well known for designing spectrum auctions for FCC in United States and consequently consulting around the world in other countries that are trying to implement auctions in telecommunications. However the study done in the paper is focusing on United States and its special concept of spectrum auctions where the licenses are assigned per states as regional units. This complicates the analysis a bit more and thus does not allow the reader to compare the results with other countries so easily. In multiple auctions such as those in USA, the bidders have to bid for multiple licenses if they want to gain licenses in more regions. As it is explained in Cramton et al. (1997), bidders are then exposed to higher risk that they would not achieve their goals and the bidding strategy is mild without any aggressive moves. This situation can result in low revenues. Also when searching for empirical studies about spectrum auctions in telecommunications, only analyses concerning United States were found. This is also a reason why the study on final price of auctions all around the world is done in this chapter. Firstly the empirical study of Cramton et al. (1997) will be presented in detail. The data collected for the purpose of this analysis will follow in next subchapter where also the differences with the base study will be discussed. Constructed model of spectrum auctions will be showed afterwards and it will be followed by the evaluation of results and comments. The empirical study is mainly focused on finding whether the following stated hypotheses were true:

1. *Number of bidders has positive influence on the final price.*
   As it was already discussed before and validated by various economists, increase in number of bidders enhances competition in the market. As a result bidders have to fight more for the licenses and thus the price is growing faster than in situation, where few bidders are not forced to interact with each other.

2. *When new entrant is present, the final price is getting higher.*
   One of the pitfalls the economists stressed when speaking about tasks of NRAs is making the auction attractive for newcomers. If NRA fails, it can cause the final price to be low and revenues not sufficient. As already discussed in previous chapter, when new entrant is present, the price is much likely to be higher.

3. *When the bids are revealed in the auction, the final price is not as high as when the bids are sealed.*
   Also this hypothesis is based on the theory presented in previous chapter. The idea behind is that when the information about bidding is closed to the participants, the bidders are more likely to overestimate the value of auctioned license and bid higher than in the situation of revealed bidding. According to this idea the final price (and thus the revenues) should be higher in case of sealed-bid auction design.

5.1 Essential paper

When speaking about the spectrum auctions, there are few economists that are essentially connected to this topic such as Peter Cramton, Lawrence M. Ausubel, R. Preston McAfee or John McMillan and Paul Klemperer. And first four economists are those who wrote the article *"Synergies in wireless telephony: Evidence from the broadband PCS auctions"* that studies US spectrum auctions (Cramton et al., 1997). The article is written by the most competent specialists since they are consulting and giving recommendations to NRAs around the world. The study examines the bid data from first two broadband PCS spectrum auctions in United States. The final output of the paper is a study of presence of synergies in the market after the auction. However this is not a topic connected to this thesis considering the synergies is large issue by itself and deserves more attention.

The data collected for the study were presented in detail in Cramton (1997). Design of the auctions in USA was the same as used around the world, simultaneous multiple-round auction with ascending bidding and revealed information about the prior rounds. The final price was expressed in winning dollar bid per population in 1994 ($/pop). Nowadays the results of auctions are generally stated in dollar bid per population divided by the bandwidth ($/MHz-pop) to include the amount of frequencies sold in auction. To keep the study comparable with today studies the final price is expressed also in $/MHz-pop. The results show all six variables have significant influence on final price on 5 % level of confidence. These variables are:

- Eligibility (number of bidders eligible to bid for particular licenses)
- Population density
- Expected population growth

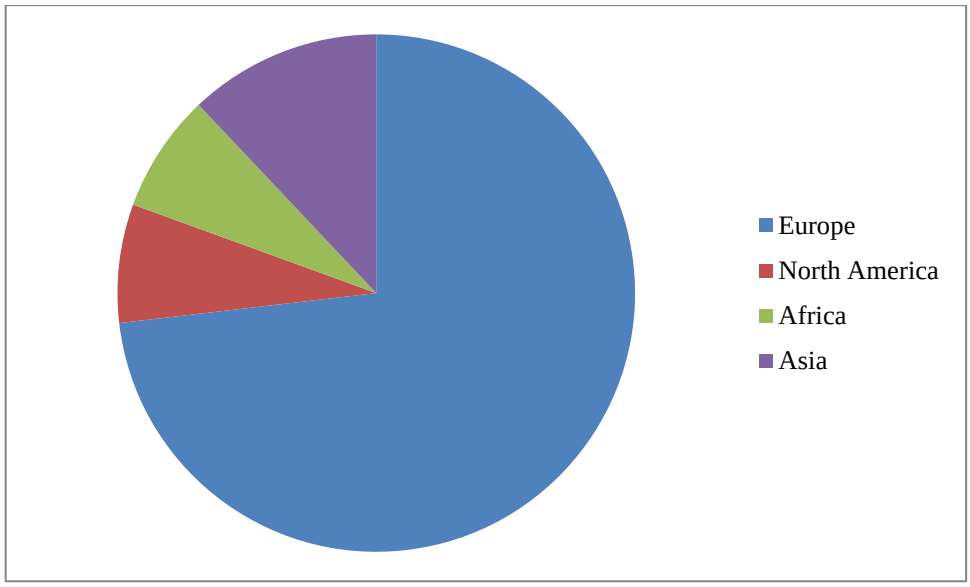
- Microwave links (existing microwave links increase costs of reallocating users)
- Population
- Household income (fraction of households with annual income exceeding $35,000)

5.2 Dataset

To analyze spectrum auctions around the world the dataset was constructed especially for this purpose. Data consist of 108 observations from 31 auctions from 18 countries. Particular observations are the licenses offered in auctions, not overall auctions because during the auctions the licenses can be auctioned with different conditions. The data were found on the websites of particular NRAs of the countries in the official documents and press releases, completed with information directly from the personnel of NRA. Country specific information such as population or GDP growth was collected from the databases of OECD and United Nations. All the sources are specified in the Appendix B.

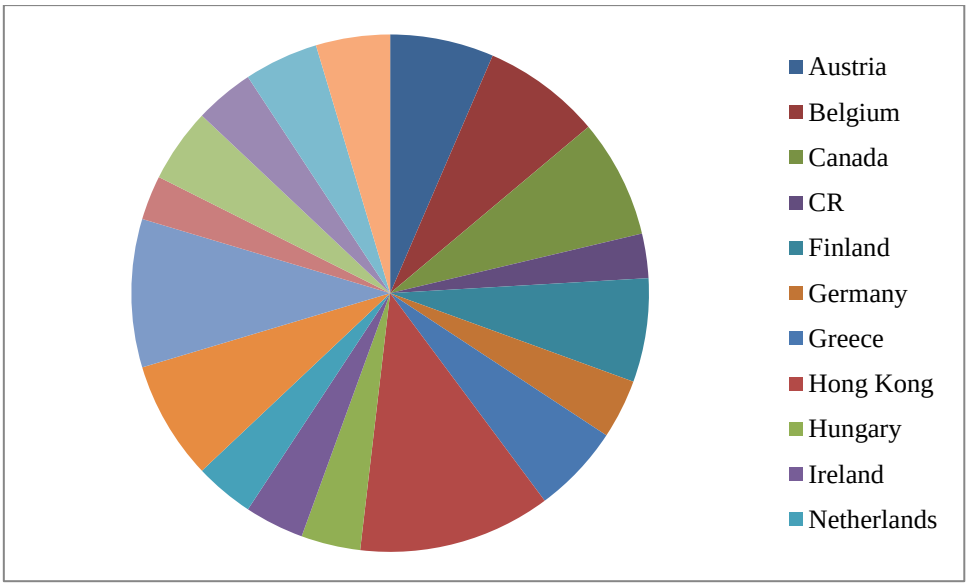
Diversity of data in dataset was an issue because auctions started to be used in telecommunications just about 30 years ago and definitely not every country started to conduct spectrum auctions. As it can be seen in figure 2, Europe is the major part of the dataset. The reason is that spectrum auctions are mostly conducted in developed and developing countries. This caused the observations from South America and Africa (only Nigeria is present in the dataset) is missing. The absence of data from Australia is explained by the concept of auctions which is similar to US spectrum auctions, where licenses are auctioned per regions. To keep the data diversified at level of countries, every country is represented by 3 to 13 observations with mean equal to six. Concrete distribution can be seen in figure 3. Even though it looks like the dataset is unbalanced, the author of the thesis is confident these are the most representative cases of spectrum auctions that were conducted within past 20 years as this method of spectrum assignment is not used widely across the world for spectrum auctions in mobile services.

Figure 2: Representation of regions in dataset



Source: Author's calculations from collected data

Figure 3: Representation of countries in dataset



Source: Author's calculations from collected data

5.3 Model

In table 3 we can see characteristics concerning auctions that were collected. These properties were used as variables for model of spectrum auctions with final price as a dependent variable. We can see the database does not include all characteristics of spectrum auctions. At first sight, the information whether the auction was conducted with simultaneous or sequential bidding is missing, as well as if the winning bidder was paying his bid or the second highest one. These specifications are not included however the information was collected. All auctions were conducted with simultaneous bidding and the bidder paid his final bid. This show not all the auction designs are generally used by NRAs.

Table 3: Model variables

Final price ($/MHz-pop)	Population density
Population growth	Reserve price
GDP growth	Gap between the number of bidders and number of licenses auctioned
License duration	If an entrant is participating
Number of rounds	Revealed x sealed bid auction design

Even though the model is based on the model of (Cramton et al., 1997) and on their variables, changes have been made to fit them to our model.

- Final price (*finp*): As it was already said before, the result of auctions is today measured in currency divided by MHz bandwidth and population. It is generally assumed the price should be more or less constant when cleared of bandwidth and population size. This idea was used also in Cramton et al. (1997) but the authors used final price as $/pop only which does not correspond to nowadays approach.

- Population density (*popdens*): The final price in the auction is not the final price for spectrum license. The companies have to take into account costs such as establishing technical background or building base transceiver stations (BTS). If the country is large with the population living all around the country in small communities, the costs of building the transceivers are high and the return does

not have to be sufficient. If the population is living mainly in big cities with higher concentration, the companies can save money by building BTS only in the inhabited areas which leaves them more resources to be spent in the auction. That is why the population density is an important part of the model.

- Population growth (*popgr*): When bidders are deciding how much they are willing to spend in the auction, their decision is influenced by near future as well as far future. Their revenue from the license depends among other things on the number of customers he will have since they bring money to the company. If there is a prediction of having more potential customers in future, in model we expect the bidders will be willing to bid higher and then the final price will be higher than in the situation of lower (or no) population growth.

- GDP growth (*gdpgr*): The companies are undoubtedly influenced by the economic situation of the country. To include this factor in our model, GDP growth is present in the equation as a proxy for welfare of a country. During time of high GDP growth, companies are willing to invest more as they assume the investment will be returned in form of revenues. Thus higher GDP growth should positively influence the final price in auction.

- Revealed x sealed bid auction design (*rev_seal*): This is a dummy variable which has a value of 1 when the information about bidding is revealed and 0 when the information is closed. In chapter 4 we discussed what the influence of the factor on the final price was and now we will empirically test it in the model. In accordance to the prior findings, the hypothesis is: if the auction is designed as an auction with revealed bidding, it will have negative influence on the final price as there is no winner's curse phenomenon present.

- License duration (*licdur*): Another characteristic which was varying for different auctions was the duration of license auctioned. Generally the duration varies from 5 to 20 years with mean 16 years. In the model we expect to see the final price is increased with higher license duration.

- Number of rounds (*rounds*): The influence of this variable is not as straightforward as the others can seem. The assumption is that the number of rounds is not exogenously given by the rules of auction set by NRA (in reality none of the auction in the sample had a maximum number of rounds stated), but it is a result of behavior of bidders. If the bidders are willing to participate in additional rounds, it means that they are competing for the license and

competition means increase in final price. By doing this reasoning we expect the variable *rounds* will have positive impact on final price.

- Gap between the number of bidders and number of licenses auctioned (*comp*): To include an element of competitiveness of the telecommunication in the model, a proxy was used. Variable *comp* is expressing how many additional bidders were in the auction in comparison to the number of licenses auctioned. To maintain competitive environment NRA should target high number of bidders, definitely higher than number of licenses assigned by the auction. If NRA fails, the bidders will not be forced to compete and they will simply split the licenses.

- Reserve price (*resp*): Reserve price is a value of spectrum license stated by NRA in advance, usually in Information Memorandum. It is a value of spectrum that is minimum revenue for the license NRA is willing to accept. When the auction starts, in the first round, minimum bid is a reserve price. Since the variable *comp* for competition environment shows there is weak competition, using reserve price is reasonable (DotEcon Ltd, 2012). Thus we can expect the lower the reserve price is the lower the revenue from the auctioned license will be since weak competition means bidders will not be competing for spectrum.

- If an entrant is participating (*entrant*): The variable *entrant* is another variable that is expected to have a large influence on the final price. Telecommunications are originally monopoly industry that is now changing. As any other monopoly structure, every incumbent is afraid of newcomers and adjust its strategy to this fact. When the new entrant is participating in the auction, the final price is expected to increase.

The model used in this chapter will be constructed from the variables presented above. But before putting data together to get the equation, it has to be mentioned the dataset is specific since 108 observations were collected from 18 countries. Due to this fact the efficiency of the model would be overestimated. To correct this condition another variable has to be added and it is the variable that assigns a numbers to the observations according to the country. This variable was named *country* and functions as a cluster variable for a cluster analysis that improves the model. Country assigns each observation number from range 1 to 18 as the dataset consists of 18 countries.

Equation 1 shows the theoretical form of the model. All the variables specified above are included in the equation as it is expected they all will have significant

effect on final price expressed in $/MHz-pop. To estimate the coefficients correctly the data had to be modified compared to the source data. The original variables expressed in currencies were not collected having the same currency since the countries did not recalculate them in dollars. Thus first step was to convert the values to dollars with an exchange rate of the end day of the particular auction. To make the results comparable it was necessary to convert the values to constant prices. In accordance with Larson, Butzer, Mundlak, & Crego (2000) from World Bank firstly the conversion to current dollars was done and then the values were transformed to constant prices in year 2005 which is a base year generally used by institutions such as World Bank or Organization for Economic Co-operation and Development (OECD).

Equation 1: General model equation of final price in spectrum auctions

$$finp = \alpha + \beta_1 popdens + \beta_2 popgr + \beta_3 gdpgr + \beta_4 rev_{seal} + \beta_5 licdur + \beta_6 rounds + \beta_7 resp + \beta_8 comp + \beta_9 entrant + u$$

Before the estimation of the model will be done, here is a summary of the expected impact of particular variables on the final price (finp):

- Increase in population density (popdens) should have a positive effect on final price since the population is living more concentrated.
- With higher population growth (popgr) final price should be also higher as the expected revenue in future periods is increased.
- GDP growth (gdpgr) is expected to work the same way as population growth above.
- The fact in the particular auction revealed bidding is present (then value of 1) is assumed to have negative effect on the final price (no winner's curse).
- Regarding license duration (licdur) we expect to see the final price increasing in license duration rising.
- Number of rounds (rounds) is expected to have positive impact on final price.

- Gap between the number of bidders and number of licenses auctioned (comp) is the variable that is expected to positively influence final price with strong significance.
- The lower the reserve price (resp) is the lower the revenue from the auctioned license will be due to weak competition.
- If an entrant is participating (entrant) in the auction, the final price is expected to increase.

In table 4 there are the summary statistics of particular variables. They will be further studied in next chapter where the model and its results are evaluated.

Table 4: Summary statistics of variables

Variable	Mean	Min	Max
popdens	893.193	3.500	6741.000
popgr	0.741	-0.496	11.200
gdpgr	1.708	-8.539	6.828
rev_seal	0.435	0.000	1.000
licdur	16.190	5.000	20.000
rounds	76.944	1.000	993.000
finp	0.470	0.014	4.711
resp	0.139	0.000	0.885
comp	0.546	-4.000	8.000
entrant	0.676	0.000	1.000

Source: Stata output

5.4 Evaluation of model

The data collected especially for this model allows us to examine range of different aspects of spectrum auctions, the country and the auction specifics. The method used to study the effects of variables is OLS improved by cluster analysis. Table 5 shows the results of the basic OLS analysis that does not take into account the restriction of 18 countries in the dataset yet. We can observe that already in this model, without any improvements and corrections, some coefficients are not

significant. This is the most notable in case of *rev_seal* variable that determines if the spectrum licenses were auctioned with revealed or sealed bidding. On the other hand very significantly the coefficients came out for population growth (*popgr*), reserve price (*resp*), the presence of competition (*comp*) and an entrant (*entrant*) in the auction.

Table 5: Econometric analysis, first step

Variable	Coef. (Std. Err.)	P-value
popdens	-0.000	0.121
	(0.000)	
popgr	-0.100	0.000
	(0.025)	
gdpgr	0.029	0.046
	(0.014)	
rev_seal	0.027	0.776
	(0.096)	
licdur	-0.038	0.057
	(0.020)	
rounds	0.000	0.095
	(0.000)	
resp	0.775	0.001
	(0.220)	
comp	0.348	0.000
	(0.024)	
entrant	0.457	0.000
	(0.098)	
constant	0.493	0.150
	(0.340)	

Source: Stata output

Even though the analysis looks right at first sight, it has to be kept in mind there is an issue in number of observations. The number of observations, which is 108, is the number of licenses auctioned during 31 auctions collected around the world, but mostly from Europe. These 31 auctions were from 18 countries. When speaking about country specific variables, we have population density, population

growth and GDP growth. Due to the fact the auctions took place in different years, GDP growth is a variable whose values are not so linked to the country specifics. And the range of years the data were collected from is from 2001 to 2014. That means years of crisis are included and this makes the variable GDP growth varying a lot in the dataset and thus does not devalue the data. But the problem starts with variables population density (*popdens*) and population growth (*popgr*). As we can see in the table 6, population density and population growth are variables strongly linked to their country. Especially population density is varying a lot. In table 6 the means and the variance of means is showed. This table 6 is a base for reasoning cluster analysis as an important part of the empirical study. We can see the variance within a country is small, but the variance among the countries is large. This phenomenon supports the idea of clustering variables according to countries to get the estimates of coefficients more efficient.

Table 6: Country specific variables and their analysis

		Mean_popdens	Var_popdens	Mean_popgr	Var_popgr
1	Hong Kong	6 604,25	18 736,25	0,30	0,02
2	Canada	3,50	0,00	1,00	0,00
3	Nigeria	52,93	5 225,01	5,53	24,12
4	Norway	11,85	0,00	0,58	0,00
5	Finland	15,85	0,00	0,40	0,01
6	Sweden	20,50	0,00	0,77	0,00
7	Ireland	64,80	0,00	0,85	0,00
8	Greece	83,50	0,00	0,10	0,00
9	Romania	91,20	0,00	-0,32	0,00
10	Austria	98,43	1,49	0,44	0,01
11	Hungary	106,80	0,00	-0,50	0,00
12	Slovakia	110,70	0,00	-0,08	0,00
13	Portugal	114,80	0,00	-0,22	0,00
14	Czech Republic	133,70	0,00	0,42	0,00
15	Germany	232,50	0,00	-0,20	0,00
16	UK	242,70	0,00	0,33	0,00
17	Belgium	359,73	0,05	0,44	0,00
18	Netherlands	401,70	0,00	0,14	0,00
	Variance:	**2 344 378,26**		**1,71**	

Source: Author's calculations from collected data

In OLS estimation the heteroskedasticity in the data is often present. For this purpose White's test for homoskedasticity was done to find out if this is the case too. The result of the test is showed in table 7 below. As it is seen in the results of the test

with p-value 0.0203, we can assume an issue of heteroskedasticity. This problem will be corrected by using robust standard errors in next step.

Table 7: Homoskedasticity test

White's test for Ho:	homoskedasticity
against Ha:	unrestricted heteroskedasticity
P-value:	0.0203

Source: Stata output

To correct heteroskedasticity and to include the information about different countries, model is improved by cluster analysis with robust standard errors. For this purpose new variable (*country*) was created, assigning one number to each country. The results can be seen in table 8. Although the coefficient estimates stayed the same, efficiency of the model improved. We can see that compared to the previous model, all p-values increased but one did not, which is *rounds*. Also, given significance level on 5 %, we see there are more variables that do not have an effect on final price.

We achieved a nice result in coefficient of *popgr*. Significant impact of population growth rate on final price indicates the companies participating in spectrum auctions are taking the future development of country into account. On the other hand GDP growth is not a factor that concerns them. This may be caused by the volatility of GDP growth which makes it harder to include it into the decision making while bidding in the spectrum auction. Also population density, another country specific variable, is not considered as a significant variable. The explanation suggested by author is the microwave links are already built and thus it is not considered by the bidders as another cost added to the final price of the auction.

Hypothesis no. 3 stated in the beginning was the auction design matters, especially if the licenses are auctioned in revealed or sealed bidding. The expected result was the variable *rev_seal* would have strong impact on the final price. As we can see in the table 8, this aspect does definitely not have significant impact on price achieved in spectrum auction. It can be understood also in a way the bidders were sufficiently aware of the competitors. Also, as it can be seen in the table 4, where there is a summary of data, the variable competition is varying from -4 to 8 with mean approximately 0.55. So, most of the time there was few of the bidders, the additional bidders to the number of licenses were not so numerous and they were not

competing for licenses. As a result of this they were not threatened and thus did not bid aggressively.

Interesting result can be seen when looking at variable *licdur* which records duration of spectrum license permit. This variable was assumed to strongly form the final price since the bidder can receive money as the time goes and thus it forms its revenues. It was even regarded by the author to be so significant that the final price, dependent variable, should be divided by the number of years the license was to be assigned for. Surprisingly it seems license duration does not matter for the bidders. But the reason is obvious when one thinks about the fastness of progress in telecommunications. As it is written in chapter 2, telecommunications sector is growing really fast and we can see in table 1 that between 1G and 2G technologies there were just 7 years, between 2G and 4G the telecommunications had just 10 years and it lasted 8 years since 4G started after 3G. In the table 4 we can see the license duration varies from 5 to 20 years with mean approximately 16.19, which shows most of the time licenses are assigned for longer time than it can be expected, new generation technology will be invented. This can be the reason why the bidders do not take the license duration into account.

On 10 % significance level, the number of rounds came out as having impact on final price. This supports our thoughts made in subchapter 5.3 where the variable *rounds* is assumed to have a significant coefficient. On the other hand, *resp* came out strongly insignificant in comparison to the previous model without clustering. This indicated that reserve price does not have any impact on final price.

Our hypothesis no.1 speaks about competition having the impact on final price. We took the gap between the number of bidders and the number of licenses auctioned as a proxy and called it *comp*. Clearly we did not reject our hypothesis of comp having positive influence on final price in the auction. This means having additional bidders in the auction increases the final price formed by the auction.

Our last hypothesis, stated as second one, is about having a new entrant in the auction. As we can see in table 8, when new entrant is present, it has a significant positive impact on the final price which definitely supports our hypothesis.

Table 8: Econometric analysis, cluster included

Variable	Coef. (Std. Err.)	P-value
popdens	-0.000	0.191
	(0.000)	
popgr	-0.100	0.001
	(0.025)	
gdpgr	0.029	0.140
	(0.019)	
rev_seal	0.027	0.864
	(0.158)	
licdur	-0.038	0.335
	(0.039)	
rounds	0.000	0.093
	(0.000)	
resp	0.775	0.145
	(0.507)	
comp	0.348	0.000
	(0.069)	
entrant	0.457	0.016
	(0.172)	
constant	0.493	0.430
	(0.610)	

Source: Stata output

In table 9 we can see the test for skewness and kurtosis. The hypothesis of the normality was not rejected by this test. In table 10 we can see the summary statistics of residuals. We cannot reject the null hypothesis of error term having zero population mean. These two tables thus support the assumption of having normally distributed error term, even though the results of skewness and kurtosis test is not really convincing. What may be the cause of it is the sample has only 108 observations, which is not too much to speak about the normality without any doubts.

For further examination of the assumptions of the model, the reader can find the appendix A useful. For example in table A5 it can be seen, that the residuals, stated as *res* in this table, are not correlated with any variable. The table A5 thus shows the assumption of having no correlation of any variable with error term holds.

Also correlation matrix can be found in the appendix A in the table A6 and shows there is no multicollinearity in the data.

Table 9: Cameron & Trivedi's decomposition of IM test

Source	P-value
Heteroskedasticity	0.0203
Skewness	0.0535
Kurtosis	0.1203
Total	0.0051

Source: Stata output

Table 10: Summary statistics of residuals

	Mean	Std. Err.
Residuals	-5.17e-11	0.041

Source: Stata output

5.5 Findings

As it was said before, the empirical study done in subchapter 5.4 may function for the national regulatory authorities as a base of analyzing the effect of spectrum auctions on the telecommunications sector and state treasury. The reasoning for using spectrum auctions mainly composes from two main ideas. Firstly, spectrum auctions assign the license to those who value it the most and are willing to pay the highest price for it. Secondly, the auctions work in a way the price does not have to be set by the regulator who does not have means to evaluate it and the bidders create the price by themselves competing for it, which means final price is often higher than in a situation without spectrum auction. It means NRA can expect high revenue into the state treasury. But to really get the revenue high, NRA has to set the specifications of spectrum assignment properly. In chapter 4 we specified the theory of auctions and all the components that make the auction what it is. NRA decides what will be the design of the auction by setting if the auction will use revealed or sealed bidding, if the price will be ascending or descending, if the winner pays the final or the second highest price, if the bids are submitted sequentially or simultaneously or if the bidding will take place for more rounds or just one. These and more things were

included in the model presented in subchapter 5.3 to find out which components of the auction have impact on the final price. Also, as important characteristics to be included in the model the country specifics were added. We should not forget the countries that were chosen to be examined are auctioning licenses on the national level, not regional. Thus our results stand for these countries.

For NRA to predict the final price according to country specifics, population growth can be taken into account as a reputable variable. With higher population growth the final price can be expected to increase. On the contrary of the theory, speaking about the impact of revealed/sealed bidding design on the final price and thus revenue for state, the fact if the license is auctioned with revealed or sealed bidding does not make a difference for countries similar to those in our analysis. But, since the theory is supported by several economists, as shown in chapter 4, NRA should take into account the situation where the competitors are few and they have the information needed to bid moderately. But, on the other hand, lower final price can mean the market is saturated and no other licenses are needed by the companies. This phenomenon is captured in a book of Buigues & Rey (2004) where it is said that high prices of licenses can mean there is high demand on spectrum and the number of licenses auctioned is not sufficiently high.

One of the surprises in the model was a variable *licdur* that speaks about the number of years the license is assigned for. This component came out insignificant, meaning number of years does not have an impact on final price. Possible reason that was discussed is the technology is changing rapidly and in few years there will be new technology. Noam (1997) concludes the implication for NRAs to shorten the period for which the licenses are auctioned. As a result the licenses will be free in the future to be offered for more modern technology that would be invented.

Another fact that NRA can influence and that has an impact, although with not so strong significance, is number of rounds. For regulatory authority, if it wants to keep the price higher, number of rounds should not be restricted. Of course, if the bidders do not want to compete, the price will not increase. But if the competition is present and the bidders want to raise the price constantly, there should be the possibility. Here we have two extremes. The auctions where only one round took a place and the auction that lasted for almost whole year and reached almost 1000 simultaneously conducted rounds. First extreme, with only one round in the auction, was observed in 22 auctioned licenses. From these 22 observations exactly 50 % were the cases where final price was higher than the reserve price. If the number of rounds was restricted, NRA could have gained more when leaving the bidders to

compete. Second extreme, the long spectrum auction, took place in Finland. The spectrum auction started on 24th January 2013 and ended on 30th October the same year after 993 bidding rounds. As it was discussed in subchapter 4.4, such a long auction comes across a pitfall in a form of unstable prediction of economic situation of either country or company. It is up to NRA to set the design of the auction in correspondence to the current circumstances. What is important for the regulators to keep in mind, is that in each country in different time NRAs are standing in front of different problems and even though it is comfortable for spectrum auction designer to just take a design from another auction, it would not be adjusted to the special circumstances (Binmore & Klemperer, 2002). Due to this fact it is not recommended to NRAs to copy a design from another situation without considering the country and time specifics. For example in Nigeria, one of the countries included in our dataset, the circumstances encompassed low transparency and objectivity in country. Other selection methods, administrative ones, failed due to the political situation in country. When the auction took place for the first time, the result was a success (Doyle & McShane, 2001).

Last two recommendations to national regulatory authorities concern the level of competition in spectrum auctions. The economists around the world see one of the worst problems of nowadays regulatory authorities in inability to attract newcomers to telecommunications. This was already discussed in subchapter 4.3 with support of the article of Klemperer (2002). By the empirical study we confirmed the importance of having a competition and new entrants participating in the spectrum auction. In recommendation to NRAs we can stress the substance of attracting new entrants to participate in auction, because it was empirically observed the presence of entrant increase the final price. Also from theory of monopolies it is generally known that higher number of competitors increase the consumer surplus. First hypothesis stated in the beginning of this chapter speaks about presence of additional bidders. Again, it was empirically confirmed that with higher positive gap between the number of bidders and the number of licenses the final price increases too. That is the reason why the last recommendation to NRAs is to attract not only new entrants but also any company that could be interested. According to our model results, when NRA succeeds in these two aspects, it can expect higher revenues to state treasury from the spectrum auction. How to achieve high competition in auction? This is another issue worthy of its own work. As it is written in Binmore & Klemperer (2002): "*Tackling such problems sensibly requires high-quality market research that keeps pace with developments in an industry that can change its clothes with bewildering rapidity.*"

6 Conclusion

Telecommunication sector is one of the most developing in last 20 years. The speed of the progress in inventing new technologies has to be balanced by proper radio spectrum management since radio spectrum is a scarce resource. The methods of assignment used in past such as beauty contests or lotteries are no longer those that rule the sector. To keep pace with new technologies, spectrum auctions were presented as a new method that ensures the best results for state. Since the companies are competing for the licenses, final price is getting higher and thereby higher revenues go to the state treasury. In this thesis the behavior of final price in the spectrum auctions was examined. Firstly, the author performed a literature overview in chapter 4. Secondly, an empirical analysis was conducted with respect to the findings of previous works as the main part of the study. In the end of the work, recommendations to NRAs were presented to conclude the results of the empirical examination. To summarize the findings, national regulatory authorities should take into account not only the specifics of the telecommunication sector and its volume, but also country characteristics, namely population growth. When speaking about the auction design, with higher number of rounds conducted in the auction the price is increasing. But what is the most important for regulators to achieve is high number of bidders. When there is a number of bidders higher than number of licenses auctioned participants are willing to compete with each other to get the desired license and thus the final price is increasing. Another factor playing role in success of spectrum auctions is a presence of new entrant, working in the same way as an additional bidder.

Even though the empirical analysis tried to explain as many aspects of spectrum auctions as it is possible, there are still questions of regulators to be answered. One of the issues is attracting newcomers in the telecommunication sector. Historically telecommunication industry was formed by state-owned institution. Now, as there is a tendency to bring competition to telecommunications, the structure of the market changed. For national regulatory authorities it is not easy to come up with strategies how to make telecommunications more competitive since historically this was not an issue. For the future we can only hope the attempt will succeed and the regulators will have more opportunities to conduct successful spectrum auctions.

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8 Appendix A: Model evaluation

Table A1: Summary statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
popdens	108	893.1926	2115.507	3.5	6741
popgr	108	.7409537	1.882126	-.496	11.2
gdpgr	108	1.707658	3.20546	-8.538612	6.828398
rev_seal	108	.4351852	.4980926	0	1
licdur	108	16.18981	2.711793	5	20
rounds	108	76.94444	167.7464	1	993
finp	108	.4693589	.8655054	5.72e-06	4.711421
resp	108	.1387537	.2146308	0	.8845263
comp	108	.5462963	2.10644	-4	8
entrant	108	.6759259	.4702098	0	1

Table A2: Econometric analysis – first step

Source	SS	df	MS
Model	60.2770391	9	6.69744879
Residual	19.8766252	98	.202822706
Total	80.1536643	107	.749099666

Number of obs	108
F(9, 98)	33.02
Prob > F	0.0000
R-squared	0.7520
Adj R-squared	0.7292
Root MSE	.45036

finp	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
popdens	-.0000375	.000024	-1.56	0.121	-.0000851	.0000101
popgr	-.1002031	.0246136	-4.07	0.000	-.1490479	-.0513583
gdpgr	.0290011	.0143609	2.02	0.046	.0005024	.0574999
rev_seal	.027299	.0955169	0.29	0.776	-.1622513	.2168492
licdur	-.0384344	.0199847	-1.92	0.057	-.0780934	.0012247
rounds	.0004948	.0002939	1.68	0.095	-.0000885	.0010781
resp	.7750783	.2196177	3.53	0.001	.3392541	1.210903
comp	.3477672	.0242442	14.34	0.000	.2996554	.3958791
entrant	.4574427	.0981866	4.66	0.000	.2625947	.6522908
_cons	.4931389	.3396817	1.45	0.150	-.1809484	1.167226

Table A3: Econometric analysis, cluster included

```
Linear regression                               Number of obs =     108
                                                F(  9,    17) =   29.10
                                                Prob > F      =  0.0000
                                                R-squared     =  0.7520
                                                Root MSE      =  .45036

                                   (Std. Err. adjusted for 18 clusters in country)
------------------------------------------------------------------------------
             |               Robust
        finp |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     popdens |  -.0000375   .0000275    -1.36   0.191    -.0000956    .0000206
       popgr |  -.1002031   .0253242    -3.96   0.001    -.1536324   -.0467737
       gdpgr |   .0290011   .0187231     1.55   0.140    -.0105011    .0685034
    rev_seal |    .027299   .1575421     0.17   0.864    -.3050858    .3596838
      licdur |  -.0384344   .0387011    -0.99   0.335    -.1200865    .0432177
      rounds |   .0004948   .0002784     1.78   0.093    -.0000927    .0010823
        resp |   .7750783   .5068118     1.53   0.145    -.2942011    1.844358
        comp |   .3477672   .0685691     5.07   0.000     .2030991    .4924354
     entrant |   .4574427   .1715373     2.67   0.016     .0955306    .8193549
       _cons |   .4931389   .6099522     0.81   0.430    -.7937478    1.780025
------------------------------------------------------------------------------
```

Table A4: Summary of residuals

```
Mean estimation                 Number of obs    =       108

------------------------------------------------------------------------------
             |       Mean   Std. Err.      [95% Conf. Interval]
-------------+----------------------------------------------------------------
         res |  -5.17e-11   .0414732     -.0822158    .0822158
------------------------------------------------------------------------------
```

Table A5: White's test for homoskedasticity

```
White's test for Ho: homoskedasticity
         against Ha: unrestricted heteroskedasticity

         chi2(42)     =     62.82
         Prob > chi2  =    0.0203

Cameron & Trivedi's decomposition of IM-test

---------------------------------------------------
              Source |       chi2     df      p
---------------------+-----------------------------
Heteroskedasticity |      62.82     42    0.0203
            Skewness |      16.71      9    0.0535
            Kurtosis |       2.41      1    0.1203
---------------------+-----------------------------
               Total |      81.94     52    0.0051
---------------------------------------------------
```

Table A6: Correlation matrix with residuals

	popdens	popgr	gdpgr	rev_seal	licdur	rounds	resp	comp	entrant	res
popdens	1.0000									
popgr	-0.0962	1.0000								
gdpgr	-0.1156	0.2525	1.0000							
rev_seal	0.2186	-0.1784	-0.0604	1.0000						
licdur	-0.2617	-0.0844	-0.0533	-0.1482	1.0000					
rounds	-0.1313	-0.0734	-0.1143	-0.0889	0.3493	1.0000				
resp	-0.0315	-0.1467	-0.1421	0.2204	0.1970	0.2200	1.0000			
comp	0.1872	0.0688	0.0745	-0.1485	0.3711	0.1091	-0.0112	1.0000		
entrant	-0.1627	0.0820	0.0772	-0.0706	-0.0466	-0.2583	-0.0677	-0.0366	1.0000	
res	-0.0000	0.0000	0.0000	-0.0000	-0.0000	0.0000	0.0000	-0.0000	-0.0000	1.0000

Figure A1: Histogram of residuals

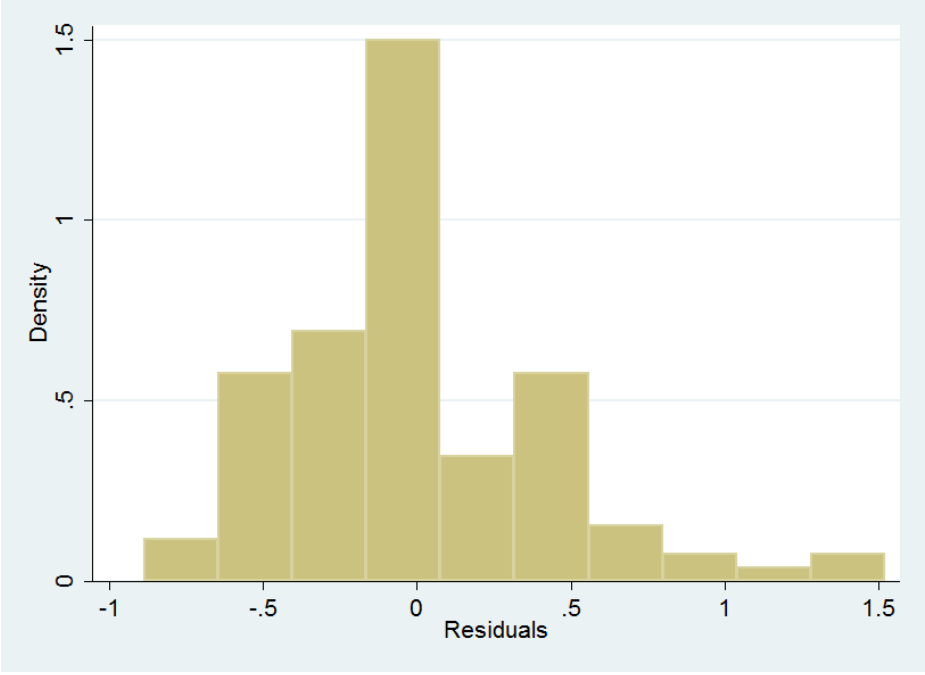
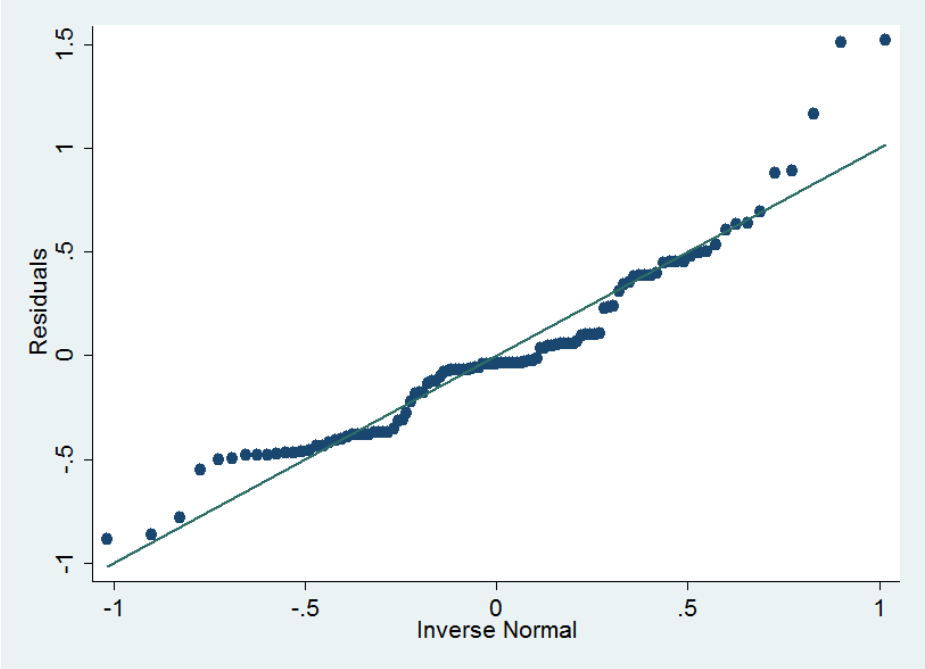


Figure A2: Q-Q plot of residuals



9 Appendix B: List of countries in dataset and websites of NRAs

1	Hong Kong	http://www.ofca.gov.hk/en/home/index.html
2	Canada	http://www.crtc.gc.ca/eng/home-accueil.htm
3	Nigeria	http://www.ncc.gov.ng/
4	Norway	http://eng.npt.no/
5	Finland	http://www.lvm.fi/en/home
6	Sweden	http://www.pts.se/en-GB/
7	Ireland	http://www.comreg.ie/
8	Greece	http://www.eett.gr/opencms/opencms/EETT_EN
9	Romania	http://www.ancom.org.ro/en/
10	Austria	https://www.rtr.at/en
11	Hungary	http://english.nmhh.hu/
12	Slovakia	http://www.teleoff.gov.sk/
13	Portugal	http://www.anacom.pt/render.jsp?languageId=1
14	Czech Republic	http://www.ctu.cz/
15	Germany	http://www.bundesnetzagentur.de/cln_1412/EN.html
16	UK	http://www.ofcom.org.uk/
17	Belgium	http://www.ibpt.be/en
18	Netherlands	https://www.acm.nl/en/