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Use of Auctions in Spectrum Awards

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Abstract

In my thesis I explore how to best award spectrum licenses to mobile network operators. During the last twenty years governments have shifted their preferred method of awarding spectrum from comparative awards to auctions. The praised VCG mechanism does not apply well to auctioning spectrum and instead simultaneous multiple round auction, clock auction, and combinatorial clock auction models are used. These models have flaws causing bidders to lack an unambiguous dominant strategy and practice demand reduction. Each spectrum auction is different and there exists no one-size-fits-all solution. Thus, the auction design process carries tremendous weight when attempting to organize a successful spectrum award.

Contents

1 Introduction

The goal of this thesis is to explain the difficulty associated with allocating spectrum licenses to mobile networks operators. It acts as a summary of the challenges regulators face when designing spectrum auctions and is meant to act as guidance to policy makers in pointing out the central issues a regulator needs to address when auctioning spectrum. I focus on auctions since they are currently the best way for national regulators to allocate spectrum licenses. There exist unsolved problems, such as demand reduction and lack of equilibrium, that plague the allocation process even when using auctions. I analyze the role of spectrum auction design, which consists of product design, mechanism choice and rule design, as possible means to overcome some of these issues.

The outline of the thesis is as follows. In the rest of introduction I explain in detail the characteristics of spectrum as an awardable good and why the topic is relevant. In the second section I explain governments' objectives in spectrum awards as well as cover the relatively short history of spectrum awards, arguments for using auctions, and the role of the aftermarket. In the third section I introduce VCG mechanism as an efficient mechanism for allocating goods and explain why it is not used to auction spectrum. Fourth section introduces popular spectrum auction models and the theory behind them. Fifth section reviews the challenges left unaddressed by spectrum auction models while the sixth section explores the spectrum auction design process as a possible answer to these challenges.

Throughout this thesis I will keep referring to specific spectrum auctions, their regulations[1] and their results. These are listed in appendix A. I will refer to an auction by country name and the year the auction was held in. For example, *Finnish 2013 auction* will refer to Finnish 800 MHz auction held in 2013. I use years to identify different auctions to avoid confusion as some spectrum has already been auctioned twice.

1.1 Characteristics of spectrum as an awardable good

People have long joked about government making money by putting a price on the air that its citizens breathe, but one might argue that by selling spectrum licenses, governments are doing exactly that. There seems to be no shortage of demand for air either. The German

[1] Auction regulations are official texts which include information on the auction. They usually cover the goods sold, the auction model used and the rules imposed.

telecommunications regulator, Bundesnetzagentur, managed to raise €5.1 billion in a spectrum auction that concluded after three weeks of bidding on 19.7.2015. The ones buying are mobile network operators, henceforth referred to as MNOs, who require spectrum to provide services to consumers.

The invisible electromagnetic waves, known as electromagnetic spectrum or simply spectrum, are the key to transmitting data wirelessly. Every phone call we make and text message we send on our mobile phones is possible thanks to this unique scarce good. Unlike natural resources such as fossil fuels, the amount of spectrum available for use stays constant. It simply exists in the atmosphere where it cannot be destroyed, nor can new spectrum be created. Spectrum cannot be stolen, but it is possible to cause interference and diminish its value to other users. Therefore all governments and several international organizations such as International Telecommunications Union, which is a United Nations specialized agency for information and communication technologies responsible for coordinating spectrum use globally, attempt to control the use of spectrum by licensing it.

In the aforementioned German auction Bundesnetzagentur sold licenses for 270 MHz of spectrum, but this is only a fraction of the approximately 300 GHz of spectrum currently available for use. Most of the spectrum has been either allocated for government specific purposes ranging from space research to maritime radios or is unprofitable to use with current technologies. Since spectrum in government's use is awarded through political decision making, and not auctions, it is of no interest to us. The benefits of assigning a larger share of spectrum licenses through market forces, and how it should be accomplished, are possible research questions for the future. This thesis focuses solely on spectrum used by mobile network operators to provide services such as mobile telephone calls, text messaging, and mobile internet connections.

Despite the coordination efforts by ITU, licenses and spectrum maps, which are the result of spectrum planning and indicate for what use the entirety of spectrum has been allocated, differ greatly between continents and even countries. For example, in Europe the spectrum licenses assigned to MNOs are always sold as nationwide licenses while in the U.S. and Australia they are fragmented into state, county and city-sized licenses. This thesis focuses on European spectrum awards[2], although most of the theory and concepts covered are applica-

[2]The use of auctions to award spectrum licenses has mostly been pioneered by the U.S. regulator FCC. A large part of the literature cited is written by economists and other staff who have worked with the FCC

ble to spectrum auctions everywhere.

Most of the technicalities of spectrum will be omitted in this thesis, but there are few key characteristics essential to the mechanism design discussed later that are worth mentioning. Spectrum is mapped using frequencies which range from 0 to 300 GHz, with more interesting frequencies existing in the lower end of the range. Lower frequencies are always more valuable than higher frequencies as signals travel farther and pierce walls better when sent on lower frequencies (Rappaport, 1996). The distance traveled and piercing capability approximately halve when the frequency doubles, so licenses for spectrum in 1400 MHz band are worth approximately half as much as those for spectrum in 700 MHz band. Due to higher frequencies being worth less in general, there are more of them available for MNOs to use. Thus higher frequencies are often used for carrying capacity[3] in densely populated areas, while lower frequencies are used for providing coverage in rural areas.

Spectrum is divided into bands, which are divided into blocks, which are then awarded to MNOs. Each block can be seen as a license to use spectrum on specific frequencies and thus terms *block* and *spectrum license* will be used interchangeably in this paper. The size of blocks can vary, but the most recent technology makes best use of 5 MHz blocks making it the most common block size used in recent spectrum awards. Three different types of blocks can be awarded. Most relevant bands such as the 700, 800, 900 and 1800 MHz bands are commonly awarded as FDD[4] blocks. Some bands are dedicated to TDD[5] blocks, which use a newer technology which is not yet as widely spread. Third type of blocks awarded contain supplementary downlink frequencies (SDL for short), which only grants extra downlink capacity. Downlink is generally regarded as more valuable than uplink since customers tend to download significantly more than they upload. The importance has increased lately due to rising popularity of various internet streaming services, such as YouTube, Netflix and

in the past. Such literature sometimes emphasizes issues which might be absent in Europe due to different spectrum planning.

[3]Carrying capacity is the amount of data that can be transferred wirelessly. It is often more important than coverage in densely populated areas such as cities.

[4]Frequency Divided Duplex, or FDD for short, technology separates uplink (traffic from mobile phone to the base station) and downlink (traffic from base station to mobile phones) by using blocks separated by a spectrum gap. FDD blocks always contain two blocks, one for uplink and one for downlink, making the size of a usual FDD block 2*5 MHz

[5]Time Divided Duplex, or TDD, technology separates uplink and downlink traffic using different time slots, enabling both channels to operate within the same block.

Spotify, which are often used on mobile devices.

FDD1	FDD2	FDD3	FFD4	FFD5	FDD6	Spectrum Gap	FDD1	FDD2	FDD3	FFD4	FFD5	FDD6
703 – 708 MHz	708 – 713 MHz	713 – 718 MHz	718 – 723 MHz	723 – 728 MHz	728 – 733 MHz	733 – 758 MHz	758 – 763 MHz	763 – 768 MHz	768 – 773 MHz	773 – 778 MHz	778 – 783 MHz	783 – 788 MHz

Figure 1: Licenses in the 700 MHz band.

Figure 1 has an example of six FDD blocks in the 700 MHz band that will be awarded in Finland in 2016. Each block has a specific location in the band marked by exact frequencies said block is allowed to use. As stand-alone products these six blocks are, in principle, substitutes to each other. In fact, blocks within any band are, in principle, substitutes to other similarly sized blocks within the same band. Blocks within nearby bands, for example 700 MHz and 800 MHz bands, can also be thought of as near-perfect substitutes. However, since higher frequencies such as 1800 MHz often serve a different purpose, these can be thought of as complements to the blocks on using frequencies below 1000 MHz.

Unfortunately reality is more complicated than this. The current technology enables MNOs to benefit greatly from acquiring contiguous blocks. Two contiguous block provide more carrying capacity than two separate blocks, even if they are all situated in the same band. Combining this with the multi-unit demand present in most spectrum awards makes blocks such as FDD1 and FFD2 in the above picture complements, while FDD1 and FFD3-6 remain substitutes. This poses a great challenge to policy makers, since having operators operate with non-contiguous blocks can be seen as inefficient use of spectrum. This is one of the essential differences between spectrum auctions and other multi-unit auctions, such as treasury bond auctions, which often can assume bidders having decreasing marginal utility for additional goods obtained.

1.2 Relevance of the topic

Historically television broadcasting has taken up a large number of spectrum bands in the very valuable below 1 GHz area. Due to technological innovations that allow television broadcasting to operate with less spectrum, some of the spectrum has recently been freed up to be repurposed for other uses. This freed spectrum, which has been dubbed the digital dividend, has in most countries been assigned to wireless internet use and thus needs to be awarded to MNOs who can then use it to provide the required services to consumers. Besides the technological innovations, there is an enormous outside pressure towards governments to assign more spectrum to wireless internet use. The evolution of smartphones and tablets, combined with the emergence of streaming services, has caused the amount of data transferred wirelessly to skyrocket. In Finland the amount of data transferred wirelessly has increased 1728 fold between years 2007 and 2014, from 154TB to 266107TB (FICORA, 2015). It is expected to keep rising as more and more people adopt the smartphone technology and the quality of wireless services, most importantly video streaming, increases.

In addition to the aforementioned allocation of digital dividend, a new wave of technology is in the making. Globally dubbed as *5G*, it is said to benefit traditional spectrum users as well as make completely new parties interested in obtaining spectrum by enabling internet of things, which has various applications in all kinds of industries. Such applications are, for example, self-driving cars and self-monitoring machines. The applications for machine-to-machine technologies seem endless and only time will tell how many industries will make use of them. Researchers claim one of the current bottlenecks related to the anticipated revolution of internet of things is lack of spectrum, ensuring that we will see spectrum awards being held in the future as well.[6]

The search for the best way to allocate spectrum is now at its height and will remain a hot topic for an unforeseeable future. National regulators are on the lookout for a fast and legally robust way to allocate spectrum efficiently. They agree almost unanimously on auctions being the superior way to allocate spectrum, but there is no consensus on which auction format is the best. Instead, both in academic literature and in policy articles (see for example Klemperer (2002) and RSPG (Forthcoming 2016)), most parties are emphasizing that every spectrum auction has to be designed from scratch for the specific market and type of spectrum sold. Furthermore, a large number of failed spectrum auctions, latest happening in 2015, highlights the need to further research spectrum auction design.

[6]These points were emphasized in Finnish 5G-seminar organized by Finnish Communications Regulatory Authority on October 22nd 2015. Seminar presentations can be found at `https://www.viestintavirasto.fi/5gseminaari2015/index/ohjelmajaesitykset.html` (Accessed on May 5th 2016).

2 Spectrum award objectives and how to fulfill them

Objectives of spectrum awards are defined by governments and international laws and agreements. Radio Spectrum Policy Group, which is appointed by European Commission and represents all European regulators, has listed the most common objectives in their forthcoming Report on Awards (RSPG, Forthcoming 2016). The most important objectives, which have also been emphasized by Binmore and Klemperer (2002) who advised British government, are using and allocating spectrum efficiently and promoting competition.

Efficient use of spectrum involves technology more than economics. Technology allows spectrum to be used more efficiently when the user has access to two contiguous blocks as compared to a scenario where he has two separate blocks in the same band. Efficient use also includes the obvious case that all available spectrum should be awarded as long as there is demand for it [7]. Thankfully these objectives are unambiguous and hence often easier to achieve than those mentioned below.
In economics efficient allocation is often assumed to refer to Pareto efficiency which can be defined as follows (Jehle and Reny, 2006)

A feasible allocation $x \in X$ is Pareto efficient if there is no other feasible allocation $x' \in X$ such that $x'_i \succeq^i x_i$, $\forall i \in I$, with at least one preference strict.

However, in mechanism design theory the term efficiency has a narrower meaning than Pareto efficiency as it only takes into account the preferences of those $N \in I$ agents participating in the mechanism (Milgrom, 2004). This poses a problem to the policy maker, as he would like to maximize the overall utility, taking into account also those not participating in the mechanism. Jehiel and Moldovanu (2003) note that selling licenses to a new entrant affects the profits of incumbents negatively, but allowing an incumbent operator to have monopoly power in a market can seriously harm the consumers. Figuring out how the market can decide which alternative is better, and at which prices for licenses, is one of the central questions in spectrum awards.

Promoting competition, which is the objective emphasized in literature, springs from the willingness to maximize social surplus. It is understood as attracting new entrants and safe-

[7] There is an example from Romanian spectrum auction in 2013 which resulted spectrum being unawarded due to flawed rules that resulted in bids on previous rounds ceasing to be binding in the subsequent rounds.

guarding existing competition. The goal is often stated as to at least roughly preserve the ratios of market shares of current MNOs while at the same time encouraging new competitors to enter the market. The simplest way to attract new entrants is setting aside spectrum for them. However, this is often not enough since an operator needs a large and diversified basket of spectrum licenses to be fully competitive. Thus additional means, such as allowing roaming on other operators' networks at a regulated price, have also been applied (Binmore and Klemperer, 2002).

While it is emphasized to focus on attracting new entrants and promoting competition, there is actually a different trend present in the European telecommunications markets. In many European countries the key spectrum licenses are divided between three different MNOs[8]. In Europe's largest market, Germany, a switch from four to three operators happened in 2014 and despite serious effort the country failed to attract new entrants in the spectrum auction it held in 2015. In both France and Britain, the next two largest markets, there are currently news about takeovers which, if approved by the regulators, will result in three player markets. One reason for this trend could be that telecommunications markets are in fact natural oligopolies (Valletti, 2003), a topic that in my view is worth researching further. Whatever the case, reducing the number of participants to three has increased the difficulty, and the importance, of spectrum auction design.

Other common, but not as vital from an award design perspective, objectives that RSPG lists are increasing broadband penetration and enhancing coverage in rural areas. Since providing services in rural areas is often economically irrational, governments add requirements for the blocks they sell. These can for example oblige the buyer to reach a certain milestone in coverage and/or penetration within a given time period. Often these requirements reduce the value of the blocks they are attached to, potentially making the block less perfect of a substitute to other blocks on sale.

Revenue can be one of the goals for a government holding a spectrum auction, but it is usually subjected to achieving other goals first (Klemperer, 2002). Most governments refrain of mentioning revenue as a goal, but for example U.S. Federal Communications Commission (henceforth FCC) mentioned lost revenue as one of the failures of awarding spectrum through

[8]There are also cases where operators form joint ventures before auctions. In Sweden for example, there are four operators but only three companies have won spectrum in recent auctions.

other means than auctions. Spectrum auction literature does not cover revenue maximizing mechanisms and similarly these will not be covered in this thesis.

Governments are also known to value award processes that are fast, cheap, and, preferably, as transparent as possible to increase their legal robustness. One has to wonder how, for much of the last century, the award processes were in fact the exact opposite.

2.1 Development of spectrum awards

When the use of radio spectrum was first mastered in 1897 there was an abundance of spectrum and the licenses were awarded, then with efficiency, by a first come, first serve basis. In the 1920s the broadcasting industry started to be considered a unique industry requiring regulation, which lead to governments deciding on to whom the spectrum licenses should be awarded to. However, it was not until the 1950s when the topic of assigning the rights to this scarce resource through the use of market forces was brought to attention first by Leo Herzel (Herzel, 1951) and then by Ronald Coase (Coase, 1959), who argued that it would be fairer to allocate the resource through the use of an auction instead of comparative hearings.

Still, for two decades following Coase's article, Federal Communications Commission and the regulators in other countries kept awarding spectrum licenses mainly through administrative processes which are also sometimes referred to as beauty contests. In 1981 the FCC finally acknowledged the inefficiencies of assigning non-regulated spectrum licenses by beauty contests and opted to use lotteries instead. It is somewhat a mystery to economists why even after so long the regulator did not opt for auctions. It turned out lotteries also had several problems, most notable one being the massive loss of revenue for the government, which was estimated at $46 billion for the 1980s alone (McMillan, 1994). Instead of government coffers, this potential revenue went to the large amount of opportunistic speculators attending the lotteries. Their goal was to sell any licenses they managed to win to MNOs, making large zero-risk profits in the process.

Three possible hypotheses have been proposed as to why auctions were not employed, with a few exceptions, before 1990s (Hazlett, 1998)[9]. The first hypothesis is what Hazlett calls error

[9] In his article Hazlett also covers much of the history of spectrum awards in the United States. He emphasizes how using market prices to determine the spectrum access was proposed to FCC over two dozen times between 1927 and 1992 without much effect.

theory, where the government and the regulator are assumed to simply have had erroneous beliefs. Second hypothesis, the so called public trustee theory, says that letting the market assign spectrum licenses would diminish government control over key outputs. Last hypothesis, the franchise rent theory, claims that the government was eager to protect broadcasters' rents for the return of some authority over them.

Hazlett concludes his article by noting that none of these theories are convincing, adding that the spectrum awards before 1990s were not only an inefficient but also an illogical accident in the history. The discussed award procedures not fulfilling all of the aforementioned objectives for spectrum awards strengthens his argument. It is also supported by the fact that the decision to award spectrum licenses through auctions, which took place in 1993 when the U.S. Congress tasked FCC to encourage "efficient and intensive use of electromagnetic spectrum", was propelled not by new economic theories, but instead by a change in the political climate. It is also probable that evolving computational technologies, which made arranging large scale auctions significantly easier, was one of the factors behind Congress' decision. Following FCC's successful spectrum auction in 1994 many European governments adapted auctions as the primary way to award spectrum copying the best practices from the U.S..

2.2 Arguments in favor of using auctions

The first argument usually mentioned when discussing auctions as a mean to award spectrum is efficiency. There exist mechanisms (e.g. VCG mechanism) which can be shown to lead to an efficient allocation under rather general assumptions. However, allocation efficiency is not the only goal that matters. Jehiel and Moldovanu (2003) list six other goals that might, depending on the setting, encourage the use of auctions as a tool for allocating goods. The five that are of interest to a policy maker tasked with awarding spectrum are revenue-maximization, valuation and price discovery, transparency and fairness, speed and low administrative costs, and promotion of competition.

The importance of revenue-maximization is arguable, as most policy makers distance themselves from the idea by explicitly stating that they do not wish to maximize revenue(Binmore and Klemperer, 2002). Still, auctions ending at low prices can cause criticism towards the regulator. When a second price auction is used and the winning bidder bids several times more than the highest losing bidder, as was the case in New Zealand's spectrum auction in 1990 (McMillan, 1994), the regulator can get a fair share of unpleasant inquiries on the subject. Of course, had the regulator not published the final prices there might not have been such a large public backlash.

The fact that governments consistently opt to use reserve prices in spectrum auctions[10] indicates that there might be at least some sort of a revenue related goal, although there are other benefits to reserve prices which will be discussed in section 4.4.2. While not the trend, some regulators (e.g. Swiss regulator) have explicitly stated that they expect to obtain a "reasonable return" for selling their scarce public resources. I will assume that, while not the top priority, spectrum auction designers also want to receive a certain amount of revenue from the auction.

It is impossible for the policy maker to know the exact value for the spectrum licenses he is awarding and thus he cannot engage in first degree price discrimination requiring each operator to pay their full valuation (assuming policy maker would be interested in maximizing revenue). Additionally, the value cannot be determined when awarding the licenses through negotiations as operators have clear incentives to understate their value when negotiating with the policy maker. Hence we need a mechanism like auctions to incentivize the buyers to tell their willingness to pay to the policy maker, who would like to know the real values regardless of revenue related goals as such knowledge allows him to allocate the goods efficiently.

Dynamic auctions can also benefit the bidders by enabling price discovery. Cramton (2013) writes that while bidders do a lot of analysis on the expected values of spectrum licenses there is still much uncertainty regarding said values. He uses the European 3G auctions[11] as an example where the bidding was based more on the situation in the stock market (which was affected by IT bubble at the time) than the actual value of licenses. This example probably says more about the difficulties operators have predicting the values of licenses than the actual benefits of price discovery, as the 3G licenses were generally sold in dynamic auctions which enabled price discovery, yet the prices paid by operators were way above the realized

[10] There has not been a spectrum auction in Europe during the last 5 years which didn't employ reserve prices. Curiously, France put the reserve price (416 000 000€) for its 700 MHz licenses higher than the final prices (166 000 000€) were in German auction just half a year earlier.

[11] 3G auctions were held to allocate the then newly available spectrum in 900 MHz and 1800 MHz bands. They were held in Europe in the late 90s and early 00s.

values of the licenses won. However, in a case where only one operator (as opposed to the whole industry like in the early 2000s) has heavily overvalued the licenses price discovery could be seen as having beneficial effects for said operator.

Comparative awards are often cumbersome for the policy maker and feel unfair for the losing participants as it is rarely clear as to why exactly they lost. They also tend to lead to costly litigation processes that could drag on for years (Kwerel and Felker, 1985). Hence one of the most widely accepted benefits of using auctions for awarding spectrum is their transparency and fairness. In auctions, the rules are set in advance and are the same for every participant. Thus when a participant is left without a license it is considerably harder to sue the policy maker for an unfair result. Kwerel and Felker also mention that it took both comparative awards (mostly due to litigation) and lotteries (due to a massive amount of participants) over a year on average to award spectrum licenses. Auctions generally take much less time even when accounting for the time it takes the policy maker to prepare the auction. A faster award process is generally also cheaper, further encouraging the use of auctions.

Promoting competition is by definition one of the central tasks for regulators and hence a good argument for using auctions. Optimally the regulator would want to ensure (i) competition during the market entry process, which in this case would be the spectrum award, and (ii) sufficient competition in the consumer market after the spectrum has been awarded. Comparative awards tend to favor well established companies[12] and make it more difficult for new companies to enter the market. As such they generally do not fulfill the first goal. Auctions on the other hand can fulfill both these goals. While achieving the first goal is fairly obvious, the second one requires the regulator to impose additional rules. Without them the incumbents could for example engage in predatory bidding to deter entry. There have been several policy instruments used by FCC to ensure sufficient competition in consumer market (Cramton et al., 2011) but only two, set-asides and spectrum caps, have been popular in Europe.

When set-asides are used, some spectrum is made available only to certain operators, usually new entrants. Set-asides are probably the easiest way to increase the competition in the

[12] These companies are often domestic making it especially difficult for international companies to enter the market. Whenever spectrum is awarded through comparative awards governments might act in a protectionist manner.

consumer market as they guarantee at least some spectrum blocks for newcomers no matter how much the incumbents are willing to pay. Set-asides have the downside of decreasing competition in the auction and might cause an inefficient allocation where a less efficient operator is awarded spectrum simply because he is a newcomer. Set-asides are less common of the two instruments, but they have nevertheless been used successfully for example in United Kingdom's 3G auction in 2000, where part of the success can probably be attributed to there being many potential entrants competing for the set-aside license. In most 3G auctions obtaining a single license could allow a company to become a successful mobile network operator. However, this is no longer the case in auctions involving several bands of spectrum where using set-asides is much more complicated as the policy maker would have to estimate the exact portfolio of spectrum licenses a newcomer requires in order to successfully facilitate his entry to the market.

The more popular option (in fact so popular that it is used in almost every European spectrum auction, regardless of other instruments applied) is to impose a spectrum cap, which limits the amount of spectrum a single operator can win in an auction. Spectrum caps are usually imposed as a MHz based limit on the amount of spectrum an operator can win in an auction or own in certain bands[13]. The latter also takes into account the possible ownership of spectrum licenses awarded before the auction and thus inflicts a more significant restriction on incumbent operators. Spectrum caps foster competition in the consumer market while still enabling reasonable competition in the auction itself. They also enable the actual allocation to be determined within the auction while set-asides usually offer a predetermined block to the entrant. Hence a spectrum cap is usually the more appealing option.

2.3 The role of the aftermarket: does the award procedure matter?

People criticizing auctions have claimed that the award procedure does not matter and that lotteries are fine as long as resale of licenses is allowed. These critics usually cite Coase theorem to strengthen their argument. Coase never properly defined this theorem in his article *The Problem of the Social Cost* (Coase, 1960), but it is commonly understood as follows (Posner, 1993):

[13] For example, a popular spectrum cap limits the amount of MHz of spectrum an operator can own below 1 GHz. The operator is then free to choose, subject to for example a 60 MHz cap, whether he wants to buy licenses in the 700 MHz, 800 MHz or 900 MHz bands.

'If transaction costs are zero, the initial assignment of a property right – for example, whether to the polluter or to the victim of pollution – will not affect the efficiency with which resources are allocated.'

According to the theorem, regardless of how the spectrum licenses are allocated initially, as long as there are clearly defined property rights, the agents will ensure the licenses end up in an efficient allocation by trading in the aftermarket. The reason for this is that as long as there is inefficiency, agents will have an incentive to sell, buy, and swap. While trading can improve inefficiency, the critics forget several weaknesses of the Coase theorem.

To start with, the assumption that transaction costs are zero is far from realistic. If nothing else, it costs the agents time and manpower to come to an agreement. Furthermore, Milgrom (2004) lists other assumptions of the Coase theorem that may fail in the aftermarket trading, such as agents' values reflecting social values, agents having unlimited budgets, and licenses not having externalities. Milgrom further argues that to counter the critics' arguments one only needs to apply two well-known propositions. First, one can show that there exists no mechanism that will reliably fix the inefficient allocation. To see this one can use Myerson-Satterthwaite theorem (Myerson and Satterthwaite, 1983) to show that inefficiencies are inevitable in bargaining if the initial allocation is inefficient and the participants have private information. Second, one can show that there exist auction mechanisms which, under certain assumptions, result in an efficient allocation for any number of licenses.

This by no means indicates that the aftermarket is useless. In such a fast evolving industry the value licenses have to different companies can change rapidly. Since licenses are usually awarded for more than a decade at a time, allowing resale can help correct some inefficiencies. While spectrum licenses being traded is still a rather rare event in Europe, a very recent example is available. In 2015, British telecommunications regulator Ofcom approved a large trade of 40 MHz worth of licenses in the 1500 MHz band (Ofcom, 2015). Two operators, Vodafone and Hutchison, bought the spectrum licenses from Qualcomm, an equipment manufacturer, after new technologies enabled profitable applications of said spectrum..

3 Vickrey-Clarke-Groves mechanism

While this paper focuses on modern spectrum auction models and their shortcomings, it is necessary to be familiar with Vickrey-Clarke-Groves mechanism[14] since it is a cornerstone for the more applied models used in spectrum auctions. It is built around the key article by William Vickrey (1961) and has been later reinforced by Clarke (1971) and Groves (1973). I focus on its virtues by showing proofs that, under general assumptions, VCG mechanism can be used to efficiently allocate multiple goods to multiple bidders. Although quite different from the models used in recent European spectrum auctions, VCG mechanism essentially aims at the same objective: to maximize the social surplus. The reasons why VCG mechanism is not used in practice will be covered at the end of this section.

I now introduce the mechanism formally and show that it expands well into a multi-unit case such as an auction for spectrum licenses. My notation is as follows. We are in an environment with N agents, mobile network operators, with private types $\theta_i \in \Theta_i, i \in N$, indicating their values for the spectrum licenses sold. The private types assumption means that the type of agent i does not depend on types of other agents. Formally we can write that for all $i \in \{1, ..., N\}$

$$v_i(x, \theta_i, \theta_{-i}) = v_i(x, \theta_i, \theta'_{-i}) \quad for \quad each \quad \theta_{-i}, \theta'_{-i} \in \Theta_{-i}.$$

I assume all agents know their own type. There is a set of possible decisions by the principal (assumed to be the policy maker) X where individual decisions x also include the cases where multiple licenses are sold to multiple buyers. I denote the vector of goods (e.g. spectrum licenses) on offer as $\bar{x}$. Then $v_i(x_i, \theta)$ can be understood as bidder i's value for any non-negative vector of goods x_i. For now, all licenses are assumed to be homogeneous and the bidders are assumed to have monotonically non-increasing marginal values for the licenses.

I assume the simple case where the good sold has no value to the principal whose value is denoted $v_0 = 0$, and where transfers are only made between the principal and the agents, meaning $t_0 = \sum_i t_i$. The first is a realistic assumption in a spectrum auction setting as spectrum has essentially no value to the government but has a lot of value to the MNOs, who

[14]Mechanisms exist in games where one player, usually called principal and which can be thought of as the auctioneer in the context of this paper, conditions his behavior on information sent to him by other players. A mechanism dictates how said information affects the outcome of the game. Hence mechanism design is often used to affect the way players behave in the game.

make transfers only to the government. Lastly, I assume that agents $i \in N$ have quasi-linear utilities. Hence we can write

$$u_i((x,t),\theta) = v_i(x,\theta) - t_i.$$

In the VCG mechanism each bidder $i \in N$ reports his value $\hat{v}_i(x_i,\theta_i)$ to the principal who then computes a value maximizing allocation according to the following allocation rule:

$$x^\star \in \arg\max_{x \in X} \sum_{i=1}^{N} \hat{v}_i(x_i,\theta_i)$$

$$\text{subject to} \quad \sum_{i=1}^{N} x_i \leq \bar{x}$$

In VCG mechanisms transfers paid by agent i are not affected by his actions. This removes the incentive to report non-truthfully. Vickrey auction belongs to the group of pivot mechanisms where agent i is pivotal if $x^*(X,N,\theta_i) \neq x^*(X,N_{-i},\theta_{-i})$, i.e. if his participation changes the outcome allocation. In pivot mechanisms the transfers made by agent i are determined as follows

$$t_i = \tau_i - \sum_{j \neq i}^{N} \hat{v}_j(x_j^\star,\theta_j)$$

where

$$\tau_i = \max_{x \in X} \sum_{j \neq i}^{N} \hat{v}_j(x_j,\theta_j)$$

$$\text{subject to} \sum_{j \neq i}^{N} x_j \leq \bar{x}$$

In spectrum auctions this means that if a bidder wins two licenses, he pays the opportunity cost of winning those two blocks; namely the sum of the two highest rejected bids. This payment is also equal to his marginal contribution to social surplus.

In addition to agent's payments only depending on the actions of other agents, pivot mechanism is characterized by only the pivotal participants making or receiving non-zero transfers, which in our context means that all the operators who do not receive spectrum licenses are not pivotal and thus make no payments. In reality agents have to pay a registration fee which is meant to keep out the non-serious bidders. The fee however is constant and thus does not affect the behavior in the mechanism itself. Instead, it is a sunk cost and affects the participants decision to enter the auction in the first place. There is a chance that his payoffs will be negative, violating the individual rationality constraint[15]. This usually affects only non-serious bidders as spectrum cap usually guarantees the incumbents at least some spectrum, and thus positive utility. The registration fees tend to also be quite small, having little to no effect on operator's decisions.

The beauty of VCG mechanism is that being truthful is always optimal and, additionally, being truthful is a dominant strategy. A dominant strategy is always a best response regardless of strategies played by other agents $j \neq i, j \in N$ and there is no other strategy that has the same property. The next two theorems and proofs largely follow theorems 1 and 2 presented in Ausubel and Milgrom (2006).

Theorem 1. *Truthful bidding is a dominant strategy for each bidder $i \in N$ in a VCG mechanism and when all bidders bid truthfully the outcome is efficient in a sense that it maximizes total value.*

Proof. Start by fixing the bids $\hat{v}_j(x_j)$ for all other bidders $j \neq i$. Next suppose that i bids truthfully $v_i(x_i)$ and this bid results in an allocation $x^\star$ and transfers $t^\star$. If i instead bids non-truthfully $\tilde{v}_i(x_i)$ this results in allocation $\tilde{x}$ and transfers $\tilde{t}$. i's payoff from reporting $\tilde{v}_i(x_i)$ is then

$$\begin{aligned} v_i(\tilde{x}) - \tilde{t}_i &= v_i(\tilde{x}) + \sum_{j \neq i}^{N} \hat{v}_j(\tilde{x}_j) - \tau_i \\ &\leq \max\{v_i(x_i) + \sum_{j \neq i}^{N} \hat{v}_j(x_j)\} - \tau_i \\ &= v_i(x_i^\star) + \sum_{j \neq i}^{N} \hat{v}_j(x_j^\star) - \tau_i \\ &= v_i(x_i^\star) - t_i^\star \end{aligned}$$

It can easily be seen that truthful reporting is always optimal. To see that it is a dominant strategy, it is enough to assume that all reports are potentially pivotal (Milgrom, 2004). This means that for all $j \in N$ and $\theta_j, \tilde{\theta}_j \in \Theta_j$, where $\tilde{\theta}_j$ is j's false report, there exists a $\theta_{-j} \in \Theta_{-j}$ such that

$$\sum_{i=1}^{N} \hat{v}_i(\tilde{x}(X, N, \tilde{\theta}_j, \theta_{-j}), \theta) < \sum_{i=1}^{N} \hat{v}_i(x^*(X, N, \theta_i), \theta).$$

[15]Individual rationality constraint (sometimes also called the participation constraint) states that an agent entering an auction has to except being better off entering than staying out.

Then all reports have a positive probability of being pivotal and when false reports are they lead to a worse payoff than a true report and are thus dominated by truthful reporting.

Furthermore, by construction, VCG mechanism leads to an efficient outcome since the auctioneer is choosing allocation that maximized total value. □

In the assumed case where agents have independent private values, meaning that agents i's value does not depend on θ_{-i}, where principal's value for the good is zero, and where all transfers go to the principal, it follows that

$$x^*(\theta) \in \arg\max_x \sum_i v_i(x, \theta) = \arg\max_x \sum_i v_i(x, \theta_i)$$

meaning that the efficient outcome is also Pareto efficient.

If we impose an additional assumption, we can use Holmström's Theorem (Holmström, 1979)[16] to show that VCG mechanism is actually a unique direct incentive-compatible mechanism that has dominant strategies, always leads to an efficient outcome, and has zero transfers made by losing bidders. The assumption we need is that the set of possible value functions V is smoothly path connected meaning that for any two value functions $v(x, 0)$ and $v(x, 1)$ there exists a path $\{v(x, \theta)|\theta \in [0, 1]\}$ between them.

Theorem 2. *Supposing value functions V are smoothly path connected and contain the zero function, then VCG mechanism is a unique direct revelation mechanism for which truthful reporting is a dominant strategy, the outcomes are always efficient, and there are no transfers made by losing participants.*

Proof. I prove this by showing that there can be no other mechanism with same properties and a different transfer rule. First fix the values for all bidders but i and consider any mechanism satisfying the assumptions. In case i reports a zero function his payoff is zero as he is not being allocated anything. I denote the total value maximizing allocation when i reports $v_i(x)$ by $x^*(\theta)$ defined as above. Then $V_i(\theta)$ is i's payoff in the VCG mechanism and it can be denoted as

$$V_i(\theta) = v(x_i^*(\theta), \theta) - t_i(\theta).$$

Using the envelope theorem in integral form we can write (Milgrom and Segal, 2002)

$$V_i(\theta) = V_i(0) + \int_0^\theta v_i''(x^*(s), s)ds.$$

[16] One can also use theorem by Green and Laffont (1979) for this proof.

Now assume a different transfer rule $\hat{t}(\theta)$ in another direct revelation mechanism with truthful reporting being a dominant strategy, with always efficient outcomes, and where losing participants make no transfers. Denote the payoffs in this other mechanism as $\hat{V}_i(\theta)$. Then using envelope theorem as above we can write

$$\hat{V}_i(\theta) - \hat{V}_i(0) = \int_0^\theta v_i''(x^*(s), s)ds = V_i(\theta) - V_i(0).$$

We can write $\hat{V}_i(0) = V_i(0) = 0$ as there are no transfers by losing participants, then

$$v_i((x^*(\theta), \theta) - \hat{t}_i(\theta) = \hat{V}_i(\theta) = V_i(\theta) = v_i((x^*(\theta), \theta) - t_i(\theta)$$

which shows that the transfer rule has to be the same as in VCG mechanism, making VCG mechanism the unique direct revelation mechanism for which truthful reporting is a dominant strategy, the outcomes are always efficient, and there are no transfers made by losing participants. □

VCG mechanism is the optimal mechanism to allocate goods in a setting where the auctioneer cares only about surplus maximization and not about his own revenues. Another virtue of the VCG mechanism Ausubel and Milgrom (2006) point out is that the assumptions made are extremely general. For example the constraint $\bar{x}$ can be replaced with any constraint $\hat{x} \in X$ which proves to be useful in accomplishing certain objectives set by the policy maker, such as ensuring competition in the consumer market by setting spectrum caps in the auction.

3.1 Issues with VCG mechanism when auctioning spectrum

Why then, as Ausubel and Milgrom put it, is VCG mechanism so *lovely but lonely*, never used to auction spectrum? The main reason VCG mechanism has not seen any significant use in practice is the vastly complicated nature of spectrum auctions which results both from the characteristics of spectrum as well as government's objectives for the award.

VCG mechanism's allegedly general assumptions still assume, for example, participants having independent private values that are known to them and bidders not having budget constraints. The assumption that the auctioneer is only maximizing total surplus is also questionable. Unless all goods auctioned are substitutes, the revenue can be very low or even zero. Ausubel and Milgrom (2002) shows that most of these assumptions are violated when auctioning spectrum.

Mobile network operators are generally very similar firms offering an almost identical product to consumers, who are often free to switch between service providers with minimal inconvenience[17]. Hence it is probable that their values for a set of homogeneous goods are in some part correlated forcing us to work with interdependent values. Furthermore, MNOs tend to have imperfect information since the values of licenses are generally not known to operators as it is difficult to predict how the technology will evolve in 20 years. Value estimation is further complicated by the indistinct and slow diplomatic process through which the spectrum bands are allocated to their respective uses.

Ausubel (1999) discusses VCG mechanism in a setting where bidders have interdependent values. He shows that when assuming single-dimensional signals there exists a generalized Vickrey auction which yields efficiency even when bidders have interdependent values. In a generalized Vickrey auction the seller allocates goods according to an efficient assignment rule which maximizes total surplus similar to the standard Vickrey auction. The payment rule calculates bidder payments using the minimum bid a bidder could have reported to still win the object(s) instead of actual bids. While generalized Vickrey auction is theoretically plausible, Ausubel notes that it is inferior to efficient ascending-bid auction which assumes less information available to the auctioneer. Furthermore, while accounting for interdependent values generalized Vickrey auction still suffers from the same issues as the standard Vickrey auction.

Spectrum auctions usually involve complementary goods as both contiguous licenses and licenses across to distant bands are complements. Hence allowing package bidding is often favored by auctioneers. However, this can make the VCG mechanism lead to low or zero revenue for the auctioneer. If two bidders bid a on one of two licenses respectively and a third bidder bids $b \leq a$ on a package of two licenses the VCG payment rule results in zero payments. While this is a very special example, it can be shown that there are more fundamental issues where payoff outcome is not in the core. This will be discussed along the combinatorial clock auction model in the next section.

[17] The inconvenience can vary between countries. Tie-in sales, which often bind the consumer to a service provider for a lengthy one of two year period, are nowadays quite rare in Finland.

Ausubel and Milgrom (2002) further note how VCG mechanism is susceptible to shill bidding and collusion even by the losing bidders when the goods sold have synergies. While shill bidding is practically impossible in present day spectrum auctions, tacit collusion can not be ruled out. Another drawback of a VCG mechanism, especially when applied in public auctions, is the mechanism's use of explicit price discrimination. Two bidders might end up paying different prices for identical allocations. This can be illustrated with an example using two bidders and two goods. Each bidder bids a for the first item and b and c respectively for a second item. The second bidder has larger marginal value for an additional license and hence $c > b$. Assuming $a > c$, both bidders get one good, but bidder one pays c while bidder two pays strictly less: $b < c$.

Lastly, assuming that bidders are not budget constrained might not hold in large spectrum auctions where licenses worth several billions are auctioned simultaneously. Thus, while the VCG mechanism is undeniably great in theory, it is almost never being used in practice. Instead, models purposefully built for auctioning spectrum, which are more or less based on the theory presented here, have been used.

4 Spectrum auction models

Models used in European spectrum awards are Simultaneous Multiple Round Auction (SMRA), Clock Auction (CA), and Combinatorial Clock Auction (CCA) RSPG (Forthcoming 2016). I start by introducing these models one by one, focusing on their unique features and their general outlook. Since the models are essentially based on the same theory, I cover most of the theory simultaneously by focusing on common characteristics between models and how the models differ from VCG mechanism. I finish the section by comparing the models and analyzing their key differences.

4.1 Simultaneous Multiple Round Auction

Simultaneous Multiple Round Auction (henceforth SMRA) was introduced by Federal Communications Commission (McMillan, 1994) in 1994 for the specific purpose of auctioning spectrum licenses. It is essentially a multi-unit generalization of the classic English auction. SMRA can last for several rounds and each round bidders bid on their desired blocks. As long as there has been a new bid on *any* block during a given round, a new round will commence, meaning that the auction only ends after no new bids whatsoever have been announced (hence the term simultaneous auction). If the blocks are homogeneous and the minimum increments by which the bids can be increased are sufficiently small, then SMRA resembles a uniform price auction.

In a uniform price auction each of the k winning bidders pay the highest losing bid, the $k + 1^{th}$ bid. It is clear that in uniform price auctions the transfers made by the winning bidders are not affected by their own bids, and that losing bidders make no transfers. Hence a uniform price auction is strategically equivalent to a VCG mechanism the same way English auction is strategically equivalent to a second price sealed-bid auction as the bidders' optimal strategy is to keep bidding until the price equals their valuation.[18]

SMRA format was by no means perfect when first introduced and it has received several modifications at the hands of national regulators and economists as they have attempted to tailor the model to better suit their needs, and to overcome its obvious faults. Modifying is especially common when the blocks sold are not homogeneous and/or blocks are complements, as then the auction ceases to be equivalent to a uniform price auction. A case of heterogeneous blocks often occurs in countries which lie on the border of a unified spectrum policy zone. European spectrum map differs from the Russian one, causing disruptions on some frequencies (effectively making licenses for these frequencies less valuable) in countries bordering Russia.

Blocks sold are complements in practically every auction involving multi-unit demand, forcing auctioneers to augment the original model to avoid fragmentation risk[19]. In both Finnish (2013) and Swedish (2010) spectrum auctions this was tackled with augmented switching rule which allowed the standing high bidder to switch his bid to another block. Some other countries have attempted to achieve the same goal by allowing combinatorial bidding. When we can assume homogeneous blocks a much simpler solution involving the use of abstract blocks can be used. I will further discuss the effect of complementarity on auction models in 5.2. More thorough theoretical review of SMRA can be found in Milgrom (2000).

[18]This holds assuming bidders have single unit demands. When multi-unit demands are present, the strategic equivalence between uniform price auction and a VCG mechanism longer holds.

[19]Fragmentation risk realizes when a bidder is not awarded contiguous blocks of spectrum.

4.2 Clock Auction

Clock auction is essentially a variation of SMRA introduced for spectrum selling purposes by Ausubel (2004) where the auctioneer sets a price for each product and all participants inform the auctioneer whether they want to buy the product(s) at the listed price or not. If there is excess demand on any product, the auctioneer increases the price on products with excess demand and a new round begins. The bidding ceases simultaneously on all blocks after there is no excess demand on any block. Winning bidders pay the final price while losing bidders make no transfers. This format works especially well in a setting where there is continuous bidding and no market power where it has been shown to lead to an efficient outcome (Ausubel and Cramton, 2004).

When auctioning spectrum the above assumptions made by Ausubel and Cramton obviously do not hold, but clock auction format has other virtues as it is both strategically and mechanically extremely simple when the auctioneer is selling only homogeneous goods. Such was the case in the 2015 French spectrum auction where six blocks of spectrum in the 700 MHz band were auctioned. All a bidder had to do was to express his demand (in blocks) each round and the auction ended when aggregate demand was equal to six blocks. After the main auction an assignment phase is held where the, until now abstract, spectrum blocks are assigned exact frequencies. This can be done by arranging a single round sealed bid auction where bidders pay for the right to choose first or allowing the operators to come up with an allocation themselves.

A problem might arise when two or more bidders reduce their demand simultaneously[20]. This can lead to aggregate demand falling below aggregate supply and the auction ending with one or more unsold blocks. This happens because bids on each round are separate, meaning that the bids are not binding. While this helps to mitigate issues like exposure problem, it is an issue regulators need to address if they want to use clock auction.

A large chunk of clock auction's charm is lost when the policy maker is simultaneously auctioning blocks across multiple bands. A bidder might value combinations *(one 700 MHz block, three 1500 MHz blocks)* and *(two 700 MHz blocks, one 1500 MHz block)* equally, but clock auction format does not allow him to express both these demands simultaneously. If the two bands were auctioned one after another in sequential clock auctions the bidders could

[20]This happened in Romanian spectrum auction in 2013.

compensate the lack of blocks won from the first auction in the second one. However, policy makers should always attempt to sell all the blocks simultaneously as will be explained in section 4.4.1. Therefore the use of combinatorial clock auction presented below should be considered.

4.3 Combinatorial Clock Auction

Combinatorial Clock Auction[21] (henceforth CCA) is a three phase auction model where the first phase is essentially a clock auction, the second phase consists of a supplementary bidding round, and the last phase is an assignment phase like the one described above. CCA is the newest and most complicated of the three models introduced here. It has also lately become the most popular model used in European spectrum auctions. Hence it will be analyzed in considerably more detail than the previous two models.

Besides clock auction, CCA is the only package auction model used in recent spectrum auctions. CCA differs from clock auction by introducing an additional phase which is a single round sealed bid auction where bidders are allowed to submit bids at the prices of their choosing (subject to certain a priori known limitations, such as the activity rule[22] and a spectrum cap) for all possible combinations of licenses the bidder is interested in. This phase takes places between the clock auction phase and the assignment phase. During this second phase the bidder is revealing his whole demand curve to the auctioneer. The auctioneer then proceeds to find the revenue maximizing combination with the help of combinatorial optimization.

CCA format is currently the most popular auction format used in European multi-band auctions(RSPG, Forthcoming 2016). It has been developed over the course of several research articles (See for example Ausubel et al. (2006), Day and Milgrom (2008), and Erdil and Klemperer (2010)) and one of the key issues during its development was coming up with an efficient payment rule. Due to bidders being allowed to bid for packages, a simple

[21]The auction has also been referred to by other names, especially in academic texts. A common name for early versions of this auction was *Clock Proxy Auction*, but the regulators and more recent researchers refer to it by the name used in this paper.

[22]CCA has an activity rule different from SMRA and clock auction as bidders have to maximize the value they are allowed to bid for in the supplementary round already in the clock rounds. Hence instead of bidding straightforwardly they need to bid on the largest package that is still profitable on each round. More thorough discussion on activity rule in CCA can be found in Ausubel et al. (2011).

second-price payment rule wouldn't work as the prices would not necessarily be in the core, which means that the allocation could be improved.

It is easy to show[23] that a traditional second-price payment rule does not necessarily result in a core outcome when products are complements[24] and package bids are allowed. Imagine a sealed-bid auction with three bidders, two indivisible products A and B for sale, and an allowance to make bids on both products A and B as well as the package AB. Goods A and B are complements, but the strength of the complementary effect depends on the bidder. Each bidder is allowed to make separate bids for each product individually as well as a package bid for both products. Now imagine the bidders having the following bid portfolios $\{A, B, AB\}$. Bidder one bids $\{20, 8, 30\}$, bidder two bids $\{6, 22, 30\}$, and bidder three, who assumes strongest complementarity between the goods, bids $\{8, 10, 34\}$. The auctioneer then searches for the combination of bids that has the highest value. This combination consists of bidder one's bid for product A, which was 20, and bidder two's bid for product B, which was 22. The combined value is 42, which is more than the package bid by bidder three. Following the familiar second-price payment rule, each bidders pays the opportunity cost he has inflicted on the highest losing bid. Hence bidder one pays 8 (three's bid on product A), and bidder two pays 10 (three's bid on product B). The total payment is then 18, but bidder three was actually willing to pay 34 for the package AB meaning that the outcome is not in the core. The main problem is that the second-price payment rule says nothing about package bids, forcing researchers to come up with a new payment rule for the model to work.

A proposed solution to this problem is using a core-selecting auction. A version of such auction was first proposed by Day and Raghavan (2007) who acknowledged the problem described above and proposed using constraint generation to determine the core payments. However, unless the point consisting of Vickrey prices is in the core, this method does not usually determine the optimal payment point but instead a group of points, referred to as Minimum Revenue Core (MRC), that are all bidder-optimal[25] core prices. Day and Milgrom (2008) refined this solution by proposing that the optimal payment point be de-

[23]Cramton (2013) first used a similar example to demonstrate Vickrey-nearest-core pricing rule. However, he used five bidders in his example.

[24]This problem does not arise when goods are substitutes.

[25]Bidder-optimality refers to all participating bidders being satisfied with the result. This essentially follows from no bidder being willing to pay any more than the clearing prices to obtain the goods auctioned. In other words, bidder optimal price point is in the core.

termined by choosing the point in the core that minimizes the Euclidean distance between it and the Vickrey payment point. This is referred to as Vickrey-nearest-core, or sometimes closest-to-Vickrey core, pricing. Since the core is convex and the Vickrey prices are unique, Vickrey-nearest-core rule results in a unique point that maximizes incentive to bid truthfully (Cramton, 2013).

To illustrate this pricing rule with a figure I will return to the above example with two products and three bidders. The Vickrey payment point was determined to be $\{8, 10\}$ and not in the core.

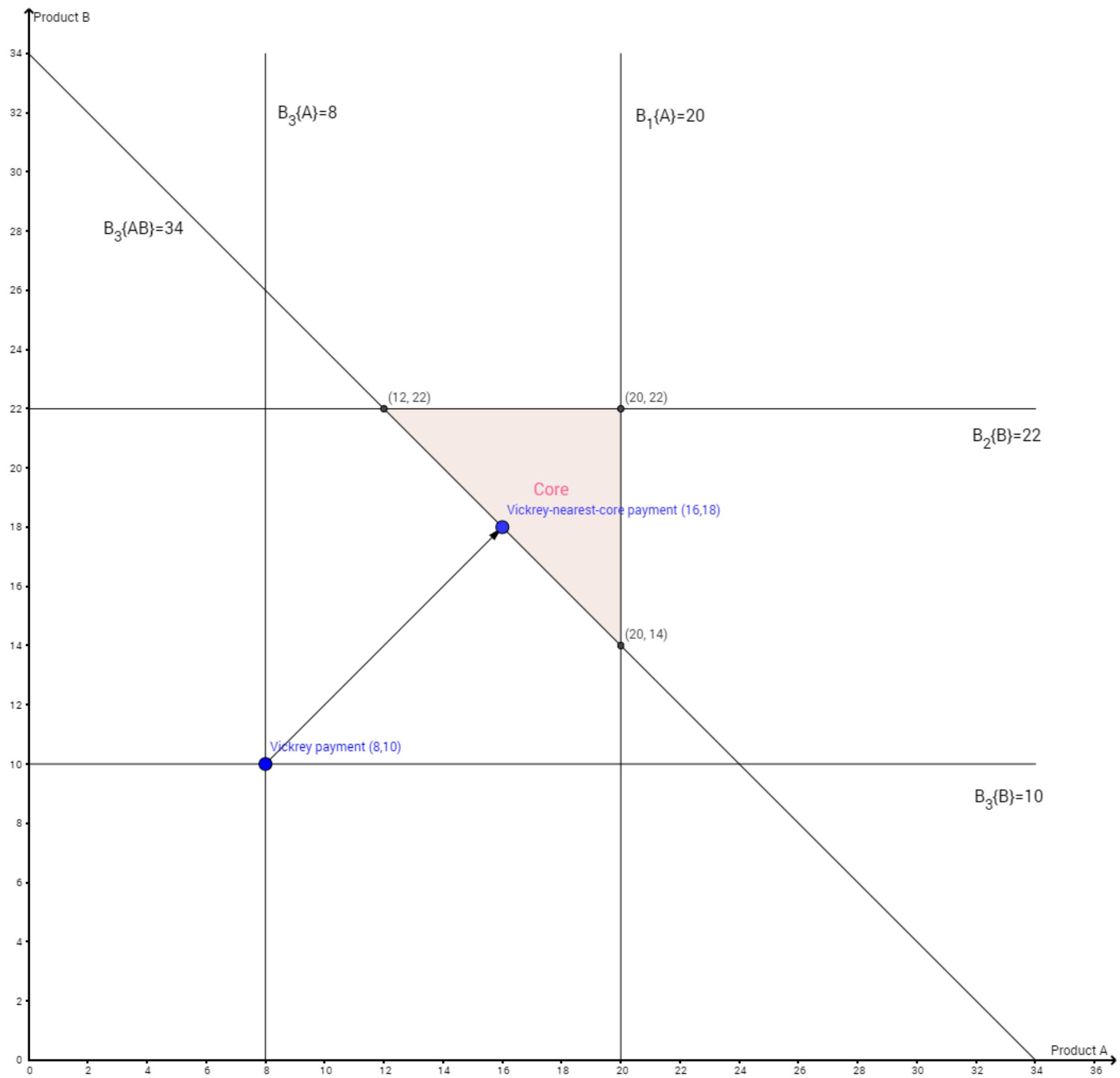

Figure 2: Illustration of Vickrey-nearest-core payment rule.

We can see how in this example core is determined by the winning bids and a package bid. Without the package bid, or if the package bid was small enough, the core would be the same as in a standard Vickrey auction and the Vickrey payment would be the optimal one. In our example the package bid affects the core, hence we need Vickrey-nearest-core payment rule to determine a bidder-optimal unique price point $(16, 18)$.

However, when a mechanism is altered by changing the payment rule, then so are inevitably also the characteristics of said mechanism, and hence the ways bidders behave. In section 3 I discussed VCG mechanism and how truthful bidding is a dominant strategy. Furthermore, when goods are substitutes VCG mechanism produces a unique outcome that is always in the core. A sealed-bid auction employing a Vickrey-nearest-core payment rule (henceforth referred to as VNC auction), which the last phase of a CCA auction represents, is not equivalent to a VCG mechanism. Goeree and Lien (2016) point out that the Vickrey-nearest-core payment rule results in a unique price point which is in the core, but only with respect to bidder's *reported* values instead of bidder's true values. If the reports are not truthful, the outcome is no longer necessarily in the core with respect to bidders true values. Using a VNC auction in the case where auctioneer is selling complementary goods can be seen as a trade-off between stability and fairness in a VNC auction and strict incentive constraints in a VCG mechanism. Furthermore, they prove that whenever an auction is core-selecting it is necessarily identical to the VCG mechanism. If VCG mechanism does not result in a core outcome, no mechanism will.

Goeree and Lien prove their result by first defining VNC auction, VCG mechanism and the cores for both of them separately, and then by showing how any core-selecting auction is ex post payoff equivalent to a VCG mechanism. They use a relaxed version of the VCG mechanism, as instead of dominant-strategy equilibrium Goeree and Lien's model assumes Bayesian Nash equilibrium, and instead of losing bidders making no payments the model assumes that outcome is in the core. Especially this second relaxation's would be troublesome for spectrum auctions, but Proposition 1 in Goeree and Lien's paper states that all core-selection auctions are ex-post payoff equivalent to the VCG mechanism. A corollary is then that if VCG mechanism is not core-selecting, no other core-selecting auction exists. Another corollary of the above result is that any auction resulting in a competitive equilibrium is ex-post payoff equivalent to a VCG mechanism.

The outcome of a VCG mechanism was in the core when goods are substitutes (Ausubel and Milgrom, 2002). In such a case the outcome of the combinatorial clock auction would also be in the core with respect to bidders true values. When goods are not substitutes the auctioneer has to be aware of the trade-off between a core-selecting VNC auction and a VCG mechanism. I look into this and other issues the spectrum auctions models face in section 5.

4.4 Common characteristics

Ever since FCC introduced SMRA as the first auction model specifically tailored for auctioning spectrum, all subsequent variations and new models have shared certain characteristics that are widely accepted by both the academia and the national regulators as being essential in spectrum auctions. Hence the models discussed resemble each other in ways presented below.

4.4.1 Simultaneous ascending design

All of the models are either ascending-bid auctions or, in the case of CCA, have an ascending-bid phase. McMillan (1994) states the reasons behind FCC favoring an ascending auction over the other alternative, a sealed-bid auction. The first reason is simplicity. Nalebuff and Bulow (1993) pointed out that understanding the pricing rule can prove complex to some bidders who are not familiar with economic theories. Kagel et al. (1987) showed in their study that bidders indeed acted in a more optimal way in an English auction as compared to a sealed-bid auction. In this study bidders had affiliated private values, an assumption which could very well hold in a spectrum auction setting. They reached a similar conclusion of sealed-bid auction leading to sub-optimal behavior in their newer experiment involving auctions with synergies and multi-unit demands (Kagel and Levin, 2005).

The second argument in favor of using ascending-bid auction format also involves affiliated values and winner's curse[26]. Milgrom and Weber (1982) showed that open auction is better at reducing the force of winner's curse by arguing that rational bidders anticipate the winner's curse and bid too low, and that providing more information makes bidders less cautious resulting in higher average bids.

[26]Winner's curse is a phenomenon where the winner of the auction is the bidder that has most overvalued the object on sale. Its discovery is attributed to Wilson (1969).

Ascending auction format has received further praise for enabling price discovery, the importance of which I already pointed out in section 2.2. Auction theory usually assumes that bidders have full knowledge of their own type and are only uncertain about the types of other bidders. In practice, however, this usually does not hold as figuring out ones own values can be rather difficult (Jehiel and Moldovanu, 2003). Cramton (2013) writes that economists generally tend to ignore this issue and thus end up favoring sealed-bid auctions. Price discovery can be seen as especially beneficial when auctioning licenses for multiple bands simultaneously, as it helps to determine the relative values between bands. For the same reason it is also a valuable feature when auctioning regional licenses, which is the norm in many countries outside Europe.

In my view Cramton's emphasis on the importance of price discovery is well-founded. Mobile network operators bidding for the spectrum licenses have only educated guesses about the technology available to them in five years time, and with licenses being handed out for decades at a time, this results in a severe lack of information about the license's value over the whole relevant time period. In a sealed bid auction, such as the previously introduced VCG mechanism, bidders only have this educated guess to work with and thus might severely over- or undervalue the licenses. In more recent auctions, thanks to a change in legislation in certain countries such as France, price discovery has also allowed bidder to asses roaming opportunities. If roaming on other operators' networks is allowed then an operator can prefer to drop out of the auction when the prices become high and instead rent the spectrum from other operators.

A lack of price discovery can also cause mistakes by the bidders where they underestimate the competition in the case when the number of bidders is not known. This happened in Norway where one of the incumbent operators, not knowing a fourth operator had decided to participate in the auction, severely underestimated the price for the licenses and ended up without any spectrum, essentially forcing the company, Tele2, to sell all its assets in Norway. This is quite a unique scenario (it has happened only once in Europe during the last five years) and it can equally well be blamed on the Norwegian regulator for using a first price sealed bid auction which created an incentive for the bidders to severely understate their values. Nevertheless, it would have been avoided if an ascending-bid format was used.

The majority of price discovery is made irrelevant if bidders are allowed to stay inactive for most of the auction, only to start bidding later when the auction is drawing to a close. If all bidders act this way the auction could also take an unnecessarily long time to complete. To ensure price discovery and to end the auction in a reasonable time, activity rules, devised by Milgrom and Wilson, have been used (McAfee and McMillan, 1996). In their simplest form they simply state that a bidder cannot increase his demand during an auction. After the first round of an auction, each bidder can only bid on the same amount, or less, licenses as he bid in the first round. Such rule ensures that bidders are showing their truthful demand across the whole duration of the auction[27].

Ascending-bid format is not without its critics. Klemperer (2002) argues that (i) ascending auctions are very vulnerable to collusion[28] and (ii) ascending auctions are very likely to deter entry. Much of the issues that relate to collusion pointed out by Klemperer have already been accounted for in recent auctions. One of the main innovations regulators have come up with has been reducing information available to bidders (e.g. hiding bidder identities and the amount of bidders) to make punishment strategies harder to execute. Further still, regulators no longer allow bidders to submit their own bids (as this allowed bidders to send numerical messages to each other within the auction software) but instead have to either choose from a menu of predetermined increments or, in the case of clock auctions, the price increase is set by the auctioneer.

It is not enough that licenses are offered for sale simultaneously. To function properly, and to live up to its name, a simultaneous auction requires a simultaneous stopping rule which allows bidding to continue on each license until there is no excess demand on *any* license. This allows bidders to flexibly change their demanded licenses as prices evolve. When a price on certain license rises too high, a bidder is free to start competing for a different, cheaper license that has so far been uninteresting to bidders.

Simultaneous auction is superior to its alternative, auctioning each license sequentially (McMillan, 1994). Particularly when auctioning spectrum licenses, sequential auctions impede aggregation and use of backup strategies. A firm might have been willing to bid more

[27] Without an activity rule the revealed demand curve could look upward sloping: an operator started by bidding on a single license but after the prices of other licenses went up he increased his demand!

[28] The advantages of a sealed-bid auction in the case where bidder collusion is anticipated was already pointed out in McMillan (1994)

(or less) for early licenses had it seen how bidders behave in the later stages. Predatory bidding is possible as bidders might drive the prices for first licenses up making the winners unable to compete for later products[29]. Regret is also a problem, since the final prices often vary from auction to auction[30] and there will probably be a bidder that ended up paying more than necessary for one of the earlier goods.

A short theoretical and non-strategic analysis of simultaneous ascending auctions will be provided here. The theory concerns the convergence of prices and quantities towards a competitive equilibrium in a similar fashion as Walrasian tatonnement[31]. The introduced notation will be used later to illustrate the various issues that prevent simultaneous ascending auction models from reaching a competitive equilibrium. The notation is somewhat similar to one used in previous section and follows that used in Milgrom (2004). Assume there are still N bidders and that L is a set of available licenses with a typical subset S. Bidder i can be seen as receiving an allocation x_i which is a vector consisting of $0's$ and $1's$ describing some subset S. Bidder's payoff is then the value of licenses acquired minus the transfer paid for said licenses, just as in the VCG setting. The difference is that now the transfers $t_i(x_i)$ are the determined by bidder i's bids. The payoff can be written as $v_i(x_i) - t_i(x_i)$ and hence the problem bidder faces each round can be written as bidders demand correspondence $D_i(t) = argmax_{x_i} v_i(x_i) - t_i^{kn}(x_i)$. The transfer $t_i^{kn}(x_i)$ is a personalized price for bidder i at round n on license k. It is the high bid if bidder i is the standing high bidder on said license, or the high bid plus one increment $\epsilon > 0$ otherwise. A bidder is said to bid straightforwardly if during each round he bids according to his demand correspondence.

Milgrom (2004) shows that under general conditions the auction outcome will be an almost competitive equilibrium, with the difference between the final outcome and the competitive equilibrium being at most one bid increment ϵ. The underlying condition for the above to hold is that goods are substitutes for bidder i, meaning that increasing the prices of other

[29]Binmore and Klemperer (2002) wrote about a tragicomic example of this. In the Turkish 3G spectrum auction two equal licenses were sold sequentially and bidders were allowed to only obtain one license each. The problem arose when officials ruled that the reserve price on the second auction will be set at the clearing price of the first. This resulted in one operator bidding more than anyone else could afford on the first license, resulting in the second license going unsold and the winner of the first license receiving a monopoly.

[30]Salant (2014) discusses this in chapters 6 and 7 of his book.

[31]Léon Walras suggested that an equilibrium can be achieved through "trial and error" (which is the translation of tatonnement from French). Different prices would be posted by auctioneer, which would be met by different demands, but no transactions would be made until supply was equal to demand.

goods l ($l \neq k$) does not decrease the demand of good k. Formally, this condition can be written as $(k \in D_i(t), t^k = t'^k, t'^l \geq t^l) \Rightarrow k \in D_i(t')$. Straightforward bidding is a feasible strategy for a bidder in each round of the auction if and only if the goods are substitutes for said bidder. If the substitute condition holds true and all bidders bid in a straightforward manner, the auction also ends in a finite number of rounds after no new bids are made. The last condition needed to ensure that an almost competitive equilibrium exists is that bidders have strictly positive marginal values.

4.4.2 Reserve prices

The importance of seller revenues is a controversial topic in spectrum auction design. Most governments deny having revenue goals in spectrum auctions or subject them to fulfilling other, efficiency related, goals first (Klemperer, 2002). Still, setting the right reserve price is essential.

First, the reserve price can have drastic effects on seller revenues. Whenever there is uncertainty in the number of bidders the reserve price should be set close to the predicted sales price. A disastrous example of not doing so was seen in Swiss 3G spectrum auction in 2000. The number of bidders turned out to be much less than anticipated and only four bidders participated to bid for four licenses. It goes without saying that the auction ended after the first round. In recent spectrum auctions the amount of bidders has also typically been low as a result of consolidation in the market and reserve prices often dictate the sale price.

Setting reserve prices too low also increases the incentives for predation and incentivizes collusion that might otherwise not be profitable. Incentives created by a low reserve price can be demonstrated with a simple example. Assume there are six identical licenses for sale and three bidders. Two bidders demand two licenses each, but there is a third bidder that would like to have three licenses. Two bidders value each license at 35. The third bidder each license at 50. Constant marginal utilities are assumed for simplicity here. In the first case, auctioneer has set the reserve price at 10. Bidder three then has two choices. He can settle for two licenses, in which case the auction ends immediately and he receives a net benefit of $2 * (50 - 10) = 80$, or he can outbid one of the other two bidders for third license. Since the licenses are identical, bidding for a third license also increases the prices for all other licenses sold in the auction. Bidder three has to bid at least 35 on three licenses to obtain them, resulting in a net benefit of $3 * (50 - 35) = 45 < 80$. He would then be much better off not competing for the last license.

Let's now look at case two, where the auctioneer has attempted to predict bidder values and set the reserve price at 30. Doing the same calculations as before, settling with two licenses gives bidder three a net benefit of $2 * (50 - 30) = 40$ while competing for a third license results in $3 * (50 - 35) = 45 > 40$. Depending on the reserve price, bidder three behaves differently and the auction ends in a different allocation, the latter being the efficient one. This phenomenon is more generally called demand reduction and goes beyond depending simply on reserve prices. It will be discussed further in section 5.1.

Setting reserve prices too high has the obvious drawback of resulting in unsold spectrum. It is also important that the auctioneer can commit to the reserve prices it sets. If the prices are high and the commitment is weak, bidder could strategically withdraw from bidding in a hope that the unsold licenses will be re-auctioned at lower prices. This is especially risky when bidders know the total number of bidders participating in the auction and when each bidder is guaranteed spectrum in the auction.

4.4.3 Other rules

Adding to the above, there are a number of other rules that, while almost universally employed in spectrum auctions, might differ a bit between auctions. Cramton (2002) lists these as spectrum cap, payment rules, bid increments and bid information. These have varying effects on spectrum auctions depending on how they are implemented.

Spectrum caps limit the amount of spectrum a single bidder can win. They are used almost universally[32], although they might differ from auction to auction. The benefits of spectrum cap are all related to post-auction competition between MNOs and hence they need to be chosen differently for different markets. For the auction process itself, they are burden. First of all, spectrum caps forcibly "cut off" the tails of participants' demand curves making them unable to bid according to their true demand on all the available licenses. Focusing only on the auction and ignoring any welfare gains from added competition in the consumer market, this rule might violate the efficiency of the outcome.

[32]The only exceptions involve auctioning high frequency spectrum which is far less valuable, for which there is significantly less demand, and which could not unbalance the competition in consumer market

Another possible issue is that a low spectrum cap can make the whole auction process obsolete. This issue can be demonstrated in a situation where six licenses are auctioned to three bidders[33]. If the auctioneer wants to encourage equal competition in the telecom market he will set the spectrum cap at two licenses. However, unless the licenses differ from each other, such a cap causes the auction to end immediately. Spectrum caps also often guarantee bidders at least some spectrum, which can incentivize demand reduction, to be discussed later.

Two kinds of *payment rules* have been used in spectrum auctions. In the first one the winning bidders have to pay the license fee in full within a short time following the concluded auction. The second type has the winners making their payments in several installments, usually over several years. Paying over time allows for winning MNOs to use more resources on building infrastructure needed to roll out their service. It also reduces the risk that bidders will be budget constrained in an auction. However, these positive qualities have a negative side as well. Would be budget constrained firms could be risky ventures. Moving a significant part of the payments into the future also probably increases the final prices in the auction, as the discounted present value of the payments is lower than the value of winning bids. These two combined can lead to winners defaulting on their payments[34].

How *bid increments* are chosen can play a vital role in the auction. In the first spectrum auctions bidders were allowed to decide on their own bids. This lead to bidders tacitly colluding with each other using for example bids ending in specific numbers as messages. Tacit collusion[35] can be a severe problem in spectrum auctions and it is closely linked to the strategic demand reduction. Parties engaging in tacit collusion often aim at keeping the licenses prices low by avoiding (unnecessary) competition.

Free choice of bid increments also allowed bidders to stall the auction at will by using very

[33] This is becoming the standard in Europe, where 700 MHz band, which will be auctioned next, is divided into six licenses and most of European countries currently have three active operators.

[34] FCC (1995) arranged an auction to encourage entrepreneurship by setting the payment period to 10 years. \$10 billion worth of licenses were sold, but \$8.2 billion worth of those were affected by default (Campbell, 2013).

[35] Explicit collusion, which takes the form of negotiating with other bidders over the strategies exercised in the auction, is prohibited under the competition law in practically all countries much the same way as forming cartels is prohibited.

small increments to outbid each other. Mainly for these two reasons more recent spectrum auctions have opted for either giving bidders a menu of bids they can choose from, say a choice of outbidding standing high bidder by 5%, 10% or 15%, or the auctioneer calls the prices altogether. The latter is used both in clock auction as well as in its combinatorial variant.

Hiding *bidder's information* during an auction serves a similar purpose as predetermining the bid increments: it reduces the possibility for bidders to collude with each other (Klemperer, 2002). By hiding the standing high bidder's identity it becomes considerably harder to, for example, execute punishment strategies. It is also common to hide the number of bidders participating in an auction to create uncertainty among bidders whether they are guaranteed to obtain a certain amount of spectrum or not. Such uncertainty makes it riskier to engage in activities like demand reduction. When no information about the numbers or identities of bidders is disclosed, the simultaneous ascending auction provides minimal information and is strategically equivalent to a VCG mechanism (Milgrom, 2004). However, by doing this auctioneer also hampers price discovery. Hence this rule is a trade-off between collusion avoidance and price discovery. Hence different auctioneers have opted for different rules. For example German regulator published practically all information in its 2015 auction, while Finnish regulator chose to hide all information regarding the number and identity of bidders in its 2013 auction. Said choices can be explained by observing the auctioned licenses. Price discovery was probably more important in the German auction where four, two of which completely new, different bands of spectrum were on sale simultaneously.

5 Issues unsolved by spectrum auction models

Even though the models presented in previous section address certain shortcomings of the Vickrey auction, they are not by any means perfect. I will now present issues that the auctioneer has to address or at least acknowledge when organizing a spectrum auction. I explain what causes these issues and whether they can be mitigated.

Multi-unit auctions can be divided into two categories based on participants having single-unit [36] or multi-unit demand. Most spectrum auctions involve participants with multi-unit

[36]Single-unit demand can be real or artificial. An example of an artificial single-unit demand is the UK 3G spectrum auction where spectrum cap was set to one block per participant, essentially leading to them

demands, creating challenges to the policy maker.

In the case of single-unit demand, no synergies, and homogeneous goods a spectrum auction is relatively simple to arrange since a uniform price auction is efficient. Each bidder has a dominant strategy of placing a bid equal to his value for the item sold (Milgrom, 2004) since, in a VCG fashion, their bids don't affect their payments. Enforcing single-unit demands allows auctioneer to focus on issues like facilitating entry, and can thus sometimes be beneficial (Binmore and Klemperer, 2002). The reason enforced single-unit demands are rare in modern spectrum auctions is auctioneers' willingness to allow MNOs to choose their own allocation. Especially in multi-band auctions it is practically impossible for the auctioneer to know the exact packages the bidders demand, hence preemptively packaging the licenses would partly destroy the purpose of running the auction.

5.1 Strategic demand reduction

Complications arise when bidders demand more than one unit even when assuming homogeneous goods. In auctions with multi-unit demand bidders generally express the amount demanded at each given price or, alternatively, bid separately for each subsequent unit. The most notable problem is the lack of unambiguous dominant strategy, as even in a uniform price auction the bidder might not want to express his true demand curve due to a phenomenon called strategic demand reduction.

Strategic demand reduction occurs when a bidder finds it beneficial to shade his real demand. It is commonplace in uniform price auctions, but also occurs in simultaneous ascending auctions where goods do not have to be identical. As long as bidders demand multiple units and have non-increasing marginal values there is an incentive to bid less than bidders' value on said units (Milgrom, 2004). More precisely, in every undominated equilibrium of a uniform price auction bidders bid their real value on the first unit, but shade their bids on every subsequent unit (Krishna, 2009).

Strategic demand reduction has become increasingly important issue in European spectrum auctions where the amount of bidders attending the auctions has been steadily falling

having single-unit demand.

throughout the 21^{st} century. In early 00s spectrum auctions could involve as many as six bidders, allowing policy makers to set a spectrum cap of one license, effectively forcing bidders into a single unit demand setting. Nowadays the telecom markets commonly involve only three or four competing operators. At the same time the amount of spectrum available to MNOs has increased, making demand reduction a valid strategy for profit maximizing bidders.

Ausubel and Cramton (2002) show that not only do bidders with multi-unit demand have an incentive to reduce demand, but this demand reduction also necessarily leads to inefficiency where, with positive probability, every equilibrium of a uniform price auction is ex-post inefficient. Ausubel and Cramton illustrate their inefficiency theorem using a simple example with two identical licenses and two bidders with independent private values x_1 and x_2 for each license. Bidder one demands only a single license while bidder two demands up to two licenses with constant marginal value x_2. x_1 and x_2 are drawn from a uniform distribution $[0, 1]$. The auction in question is $k + 1^{th}$ price auction where k refers to the number of licenses sold. In the case of this example this results in the winner paying the third highest bid.

As stated above, it is a weakly dominant strategy to bid one's true value on the first license. Hence we need to analyze bidder two's bid on the second license. Bidder two's expected profit can be written as a function of his bid on the second license b_2.

$$\pi(b_2) = (x_2 - b_2)(1 - b_2) + \int_0^{b_2} 2(x_2 - s)ds$$

Where the first part represents bidder two's payoff when winning one license (the probability of this happening is $1 - b_2$) and the second part represents payoff from winning the second license. Solving the integral and rearranging gives

$$\begin{aligned}\pi(b_2) &= (x_2 - b_2)(1 - b_2) - b_2(b_2 - 2x_2) \\ &= x_2 - x_2 b_2 - b_2 + b_2^2 - b_2^2 + 2x_2 b_2 \\ &= x_2 - b_2(1 - x_2)\end{aligned}$$

Taking a derivative with respect to b_2 gives

$$\frac{\partial \pi(b_2)}{\partial b_2} = x_2 - 1 \leq 0 \quad \text{since} \quad x_2 \leq 1$$

Setting $b_2 = 0$ maximizes bidder two's payoff regardless of his value. Bidder two then only bids on one license, resulting in both bidders winning their license free of charge and the auctioneer receiving zero profit. In this rather extreme example the auction fails not only in generating profit but also in efficiency, as it could very well be that $x_2 > x_1$ yet bidder two would still only want to bid on one license.

While Ausubel and Cramton analyze uniform price auctions where bidders express their demand curves, they emphasize that the results are applicable in general to auctions that have an equilibrium with a uniform price character. Hence we can generalize their results to auctions like SMRA and Clock Auction, which while not perfect uniform price auctions, have historically resulted in equilibria with similar blocks clearing at almost identical prices. Demand reduction is most severe when when the number of bidders is small compared to the number of licenses sold (Krishna, 2009). Hence the impact from demand reduction decreases as the number of bidders grows.

One way to address demand reduction would be to design the auction in a way that forces bidders to have a single unit demand. We will see that this in fact solves a good number of issues presented in this section, but does so at possible expense of an efficient allocation, substitutability and price discovery.

5.2 Complementary goods and their implications

Spectrum blocks can be thought of as being complements in two ways. First, due to current technology, two contiguous blocks provide operators with more capacity than two separate blocks, making contiguous blocks on the same band complements while other blocks remain substitutes. Second, especially in large spectrum auctions involving many spectrum bands, blocks from different bands can be thought of as complements. This can generally be assumed to apply to all operators who attend spectrum auctions. Since Vickrey originally assumed monotonically non-increasing marginal values in his original case of multiple homogeneous goods (Ausubel and Milgrom, 2006), this complementary between goods violates the assumptions behind VCG mechanism.

Furthermore, since only contiguous blocks are complements we cannot simply assume that acquiring additional blocks would make all other blocks increasingly more valuable. We have to instead assume that acquiring additional *contiguous* blocks is makes all other *contiguous* more valuable. This currently applies to blocks on all bands. For the policy maker complementary goods imply several problems, which are discussed below.

5.2.1 Exposure risk

Exposure risk[37] refers to a situation where a bidder is left with only one license after bidding more than his value on it in order to capture significant synergies for obtaining numerous licenses (Kagel and Levin, 2005). Exposure risk can only appear when the products sold have synergies, bidders demand multiple units, and bidding for packages is not allowed. An extreme example is a situation where some minimum amount of spectrum is required to operate profitably, but the bidder has been outbid on all other licenses except for one or two. Since withdrawing bids is not usually allowed the bidder is stuck with unwanted licenses for as long as someone overbids him. Such extreme exposure risk is less common in Europe where licenses are nationwide and often auctioned one or two bands at a time, in which case they act as extra capacity to incumbent operators and are not essential for staying in business. Large multi-band auctions, such as the German spectrum auction in 2015[38], where practically all licenses on all bands are auctioned simultaneously form an exception to this.

A less extreme, and much more common, situation is one where operators are attempting to obtain two or more contiguous licenses in an auction that does not allow bidding for packages. A simple example can be used to illustrate the problem. Lets assume an ascending bid auction where a bidder one demands two products that have synergies. His utilities are $U_1(A) = a$, $U_1(B) = b$, and $U_1(AB) = a + b + c$. A situation could arise where bidder one is standing high bidder on A with a bid of a, and bidder two has a standing high bid b on license B. It would be rational for for bidder one to overbid bidder two on license B by bidding $b + 0.5c$ since he values combination AB at $a + b + c$ and at a combined price of $a + b + 0.5c$ his payoff would be $0.5c$. However, after overbidding bidder two, he might himself get overbid on license A by someone bidding $a + c$ or more on it. In such a situation bidder one no longer finds it profitable to bid for license A since bidding anything over $a + c$ would make his payoff negative despite the synergies. However, he is stuck paying $b + 0.5c$ for license B even though he values said license at b. Unless someone overbids him, he will receive a negative payoff from the auction due to realized exposure risk. This example is closely tied to the fact that no competitive equilibrium exists in the case of synergies as I

[37] The exposure risk is often referred to as aggregation risk in regulatory texts.

[38] To cope with exposure risk German auctioneer allowed bidders to withdraw bids. Bidder that withdrew bids was required to pay the difference between the realized final price and his own bid prior to withdrawal, if it difference was negative.

explain below in section 5.2.2 .

Even this less extreme type of exposure risk is regarded as a serious problem. Hence it has often been addressed by either allowing withdrawal of standing high bids or by enabling standing high bidders to flexibly switch their bids to other licenses. (Cramton, 2006). Switching between licenses solves the issue when synergy comes from obtaining contiguous blocks as it can prevent the bidder from being stuck on separated licenses.

5.2.2 Lack of competitive equilibrium

In section 4.4.1 I wrote how simultaneous ascending auctions can achieve an *almost* competitive equilibrium under general conditions. The underlying assumption for the proofs was that the auctioned licenses should be substitutes to each of the bidders for them to bid straightforwardly. If this is not the case, Milgrom (2000) shows that the existence of competitive equilibrium cannot be guaranteed. While the proof will be omitted here, Milgrom offers a simple example that provides intuition for his result.

Start with a setting with two bidders and two licenses. Assume again that there is one bidder for whom the licenses are complements, i.e. $U_1(A) = a$, $U_1(B) = b$, and $U_1(AB) = a + b + c$, where $c > 0$. For the second bidder the goods are substitutes and his values are assumed as $U_2(A) = a + 0.6c$, $U_2(B) = b + 0.6c$, and $U_2(AB) = a + b$. If we suppose there exists a competitive equilibrium both goods go to bidder one since the allocation must be efficient. However then the prices $p_A \geq a+0.6c$ and $p_B \geq b+0.6c$ which implies $p_{AB} \geq a+b+1.2c$. At this price p_{AB} bidder one is not willing to buy the package and hence competitive equilibrium prices do not exist.

The above example is also tied to the idea of *no regret* that exists only when licenses are substitutes. As long as there is no complementarity a bidder following a straightforward bidding strategy will never face a situation where he would regret a bid he made previously. With complementarity involved bidder might regret his previous bids and this effectively removes the guarantee of a competitive equilibrium existing. If in the above example bidder one tried competing against bidder two by bidding straightforwardly he would have to bid over a or b on the respective licenses. However, he will never be willing to bid more than $a + 0.6c$ and $b + 0.6c$ on both licenses. By bidding straightforwardly auction would end with both bidders getting one license and bidder one having a negative payoff. Straightforward bidding is thus unfeasible and this severely complicates bidder's strategy and introduces uncertainty.

5.2.3 Ensuring contiguous allocation

The original Simultaneous Multiple-Round Auction used to auction spectrum did not allow standing high bidders to switch their bids. This lead to problems dubbed as exposure risk and fragmentation risk[39].

Fragmentation risk, while similar to exposure risk, refers to a more specific situation where a bidder obtains spectrum licenses that are not contiguous. As this is inefficient use of spectrum, it is in direct conflict with one of the main objectives of the auctioneer. Pareto improvements could be made by simply switching around the licenses between winners, but fragmentation often occurs in situations where only one of the bidders has incentives to change allocation while other two are completely satisfied with their current licenses and hence indifferent (or sometimes reluctant) to switch. Such a scenario is depicted in figure 3 with three bidders bidding on six licenses. Each color represents the licenses bidders acquired in the final allocation. Only the green bidder (and the auctioneer) is unhappy with the allocation.

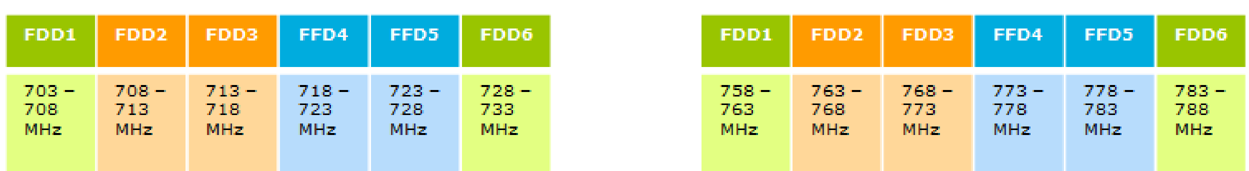

Figure 3: Fragmented allocation of licenses.

To achieve efficient use of spectrum, and to allow bidders to reap the benefits of complementarity, policy makers want to ensure that contiguous allocation of spectrum blocks will be achieved during an auction. The spectrum auction designers have approached this issue in four different ways.

First way is to auction the licenses as generic blocks, assuming them to be identical during

[39]These risks were already identified in the original SMRA model, but were accepted as necessary due to lack of tools to overcome them (McMillan (1994) and McAfee and McMillan (1996)).

the auction. This approach is by far the most simple and effective, but can only be used without downsides when the licenses on sale are similar enough. Still, its use is advised whenever possible (Cramton, 2013). Small differences can be accounted for in the assignment round, which is often held after the number of licenses each bidder wins has been determined in the initial auction. Assignment rounds are single round sealed-bid second price auctions where the highest bidders gets to choose their allocation first while paying the second highest bid. When the licenses sold are identical the assignment round can be replaced with the auctioneer choosing the final allocation by himself. This was the case in German 2015 spectrum auction[40].

Second way is to allow the participating bidders to switch their standing high bids from one license to another during an auction round. It helps prevent bidders from getting "stuck" on separated blocks. This so called augmented switching rule is often used in SMRA auctions that involve heterogeneous licenses and hence cannot be run using generic blocks. Multi-band auctions involve by definition such licenses and thus augmented switching rule is common in those. It also allows bidders to better substitute their planned licenses for another similarly valuable package which might be cheaper at a time, a feature important especially in multi-band auctions. Allowing standing high bidder to switch his bid to other license can create new problems for the auction. Hence a regulator should carefully analyze the need for such rule.

Third way is to allow bidders to bid for packages, in which case they either receive the package they bid for or nothing at all. Both clock auction and combinatorial clock auction models incorporate this in a sense that bidders are expressing their demand for the licenses separately each round. Hence if the auctioneer raises prices to a point where neither a package nor an individual license is longer attractive, bidders can simply choose to exit the auction. Same applies to the supplementary round in CCA model, where bidders can express their demands for different packages simultaneously. As was discussed in 4.3, allowing package bids when complementarity is present can result in the auction outcome being outside core.

Fourth way is to preemptively package the licenses, or set the spectrum cap, in a way that

[40]German regulator actually gave operators one month to decide the allocation by themselves. Having failed to achieve a consensus the regulator then assigned the licenses to them.

bidders are left with a single unit demand, hence essentially removing the need to worry about fragmentation and exposure risk altogether. This is a good choice when the auction participants and the final allocation can be predicted with near certainty. While predicting the final allocation is not easy, there are certain cases where it rather obvious assuming that all licenses are sold. First it should be noted that predicting is easier in the case of single band auctions below 1000 MHz. These usually have six licenses for sale. In an example of four bidders and with bidders capable of obtaining only two licenses, the only possible allocation is for two bidders to obtain two licenses and the remaining two obtaining only one. In such a case the auctioneer can design the auction in a way that there are only four licenses on sale, and each participant is allowed to obtain at most one license. Such an approach was taken with good results by Ofcom in the UK 3G auction (Klemperer, 2002).

By preemptively packaging the licenses the auctioneer does not only fix the issues regarding contiguous allocation but also a majority of other issues such as ensuring the outcome being in the core and the auction having a competitive equilibrium. It does however reduce substitution among licenses and can lead to a different, potentially inefficient[41], outcome. Unless the licenses are homogeneous, the auctioneer probably cannot know which bidder wants which frequencies. A situation might arise where a bidder is willing to get two licenses and thus would want to bid for the larger package, but at the same time he would prefer to have the frequencies sold as smaller package. Regardless of his willingness to pay, auction design prevents him from receiving a satisfactory allocation. Nevertheless, enforcing a single-unit demand upon the participants should always be considered.

5.3 Common values and imperfect information

It is rational to assume that in spectrum auctions bidders have common values since spectrum has the same properties for each auction participant. However, some differences in bidder values may occur based on the previous holdings of spectrum the bidders have. For example, high frequency spectrum might be more valuable to a bidder who previously has obtained mostly low frequencies and would want to provide more capacity in densely populated areas. In such case we talk about bidders having almost common, or interdependent[42],

[41] The concept of efficiency can become messy at this point. The outcome of an auction with preemptively packaged licenses might be efficient on its own, but the outcome might differ from an auction where all minimum-sized licenses are made available. Only smallest effective license sizes should be considered when discussing efficiency of an allocation.

[42] A bidder with interdependent values has a common component and a private component.

values.

In addition to common or interdependent values bidders probably have imperfect information in regards to their own values. Predicting the value of the licenses is difficult due to them being awarded for a long period of time in an industry that is constantly evolving. Hence bidders might have different ex-ante values, even if the values end up being same ex-post. A particularly sad example of MNOs misvaluing licenses was seen in the German 3G spectrum spectrum auction in 2000 where two winners, Mobilcomm and Group3G, never used the spectrum they paid $8 billion for as they found that investing in infrastructure would no longer be profitable due to changes in technology (Salant, 2014).

In common value auctions with imperfect information, such as the German example above, winners are those that are most optimistic about the values. Since bidders tend to realize this, they adjust their bidding accordingly. As mentioned earlier as an argument for using open ascending auctions, the effects of winner's curse can be corrected when more information is made available during the auction itself.

Interdependent values cause problems to auction mechanisms that according to Krishna (2009) can be insurmountable especially in a multi-unit case. Most notable Morgan (2001) has shown that when there are three or more bidders whose values are interdependent an ascending auction (or a Vickrey auction for that matter) need not result in an efficient allocation.

5.4 Budget constrained bidders

When bidders face binding budget constraints the dominant strategy property of sealed-bid second price auction such as the VCG mechanism and the supplementary phase of CCA no longer necessarily hold[43]. Ausubel and Milgrom (2002) demonstrate the issue through an example where there are three bidders and two goods. Bidder 1 demands two goods at price 10 each and has a budget constraint of 12, while bidder 2 demands one good at price 8. Bidder 3 demands either one good at a price of 11 or nothing at all. Bidder 3's decision

[43]The effects of budget constraints on sequential multi-unit auctions are analyzed extensively in Jean-Pierre Benoît (2001). In sequential auctions bidders can have an incentive to attempt to deplete other bidder's budget in order to obtain goods cheaper in later auctions. However, since sequential auctions are not used to auction spectrum, more detailed analysis will be omitted here.

depends on exogenous factors.

Due to budget constraint limiting bidder 1's bid for the package at 1.2, bidder 1 has no dominant strategy in such a situation. Instead, bidder 1's optimal bid depends on the decision made by bidder 3. Assume that bidder 2 bids 8 according to his optimal strategy. If bidder 3 bids 11, bidder 1 wants to bid more than 8 on a single good to obtain it. If instead bidder 3 does not bid anything, bidder 1 would want to bid less than 4 for a single license and 12 for the package. In both cases bidder 1 would end up paying a total of 8, yet his strategies are inconsistent.

Ausubel (2004) has devised an efficient ascending bid auctions, dubbed Ausubel auction, which mitigates issues caused by budget constraints. Ausubel auction has no simultaneous ending rule. Instead, licenses are awarded whenever they are "clinched". In a six license auction, bidder i clinches a license whenever total demand excluding i drops below six. Hence, even if bidder i would end up bidding less on the remaining five licenses, he would still be guaranteed at least one. Ausubel auction results in the same outcome as VCG mechanism when bidder values are private, and may still result in an efficient outcome when bidder values are interdependent. However, it never gained popularity among spectrum auctioneers. Possible explanation could be that said model only works for identical goods. Furthermore, regulators might actually not consider budget constraints a problem.

This is because in reality bidders participating in spectrum auctions are rarely truly budget constrained, or at very least their budget constraint does not bind. Even in Poland's case, where the highest grossing European spectrum of this decade concluded in 2015, it is doubtful that budget constraints were an issue for the bidders. Orange Poland, which obtained most licenses in the auction, paid PLN 3.2 billion ($\approx$ €0.75 billion) for them. Orange Poland's operating income of PLN 1.0 billion means they could pay for the 20 year license investment in almost three years all by themselves. Here I don't even consider the fact that Orange Poland is a part of multinational Orange Group which had operating income of €4.7 billion, which in amounts for PLN 20.2 billion. Even the smaller national MNOs were hardly taking a huge risk, since Cyfrowy Polsat, which spent PLN 2.2 billion in the auction, had operating profit of PLN 1.4 billion in year 2014[44].

[44]These numbers were taken from Orange Poland's financial statement (Poland, 2014), Orange groups financial statement(Group, 2014), and Cyfrowy Polsat financial statement (Polsat, 2014)

The case for non-binding budget constraint is even stronger in other European spectrum auctions. For example, in Finnish 2013 spectrum auction six licenses were auctioned for €16.67 - €22.2 million euros each while smallest of the winning MNOs, DNA, had an operating profit of €43.7 million in the same year (DNA, 2013). In essence, DNA could have financed the auction with operating profits from the same year.

In some countries (e.g. Finland) regulators have attempted to further loosen any possible budget constraints by allowing the winners to pay their winning bids over time. This can eliminate situations where a bidder would have to drop out due to not having enough money to pay for the license immediately after the auction while regarding winning at current prices profitable over time. However, it is arguable that this could ever be an issue since companies should be able to get funding for a profitable investment.

Acknowledging the above we can assume that bidders participating in European spectrum auctions are probably not budget constrained and hence it should not be taken into too much consideration when designing the auction.

5.5 Facilitating competition

Attracting enough participants is essential for every auction designer and it was the most important goal for early European spectrum auction designers (Klemperer, 2002). Not only does an auction with too few bidders run a risk of being unprofitable (Bulow and Klemperer, 1996), but it might end up in an inefficient allocation due to demand reduction. Additionally an auction with few bidders certainly results in a market with few companies possibly forming socially inefficient oligopolies[45].

Attracting participants is not easy. Ascending auctions are especially poor in facilitating competition as they often contribute to entry deterrence and predatory behavior and thus discourage participation. Furthermore, entering a telecom market is not only about acquiring spectrum, but entrants are required to invest heavily in the infrastructure as well. Thus incumbents have a large advantage regardless of auction used and participating might be unprofitable for outsiders, even when they are guaranteed spectrum through set-asides and

[45] As stated previously, telecommunications industry might in fact be a natural oligopoly (or even a monopoly) due to overlapping infrastructure requirements.

spectrum caps.

Nevertheless, the rewards for successfully attracting entrants are considerable. First, it can reduce the possibility for bidders exercising demand reductions. It also allows the auctioneer to simplify the auction in manners discussed above. Second, revenue oriented governments will profit much more from an auction with four or more participants. Due to the way spectrum is divided into licenses, European spectrum auctions experience a considerable price increase when moving from three to four bidders.

The common way to compare final prices between countries is through a Price per MHzPop measure. This measure is obtained by standardizing the final prices to make comparisons between countries feasible. Price per MHzPop is obtained by dividing the total clearing price of an auction by the product of country's population and the total MHz of spectrum sold. Formally

$$\text{Price per MHzPop} = \frac{\text{Total clearing price}}{\text{Total MHz sold} * \text{Country's population}}$$

Even after accounting for different populations, comparing prices in different auctions is not straightforward. Almost every auction depicted here is different despite same or similar products being sold. For example, potential revenue for MNOs can differ from country to country based on things like population density (low density increases infrastructure costs), GDP per capita (poorer citizens have less money to spend on wireless services), and auction model used. In figure 4 we can observe that the model used seems to have no significant effect on the revenue, although with so few observations the results are vague at best. The amount of observations (the number of spectrum auctions in Europe) is still insufficient to conduct proper empirical analysis that would yield statistically significant outcomes for relevant variables. The upcoming wave of spectrum auctions where licenses from 700 MHz band will be awarded might change this and make analyzing factors that affect final prices in spectrum auctions feasible in the future.

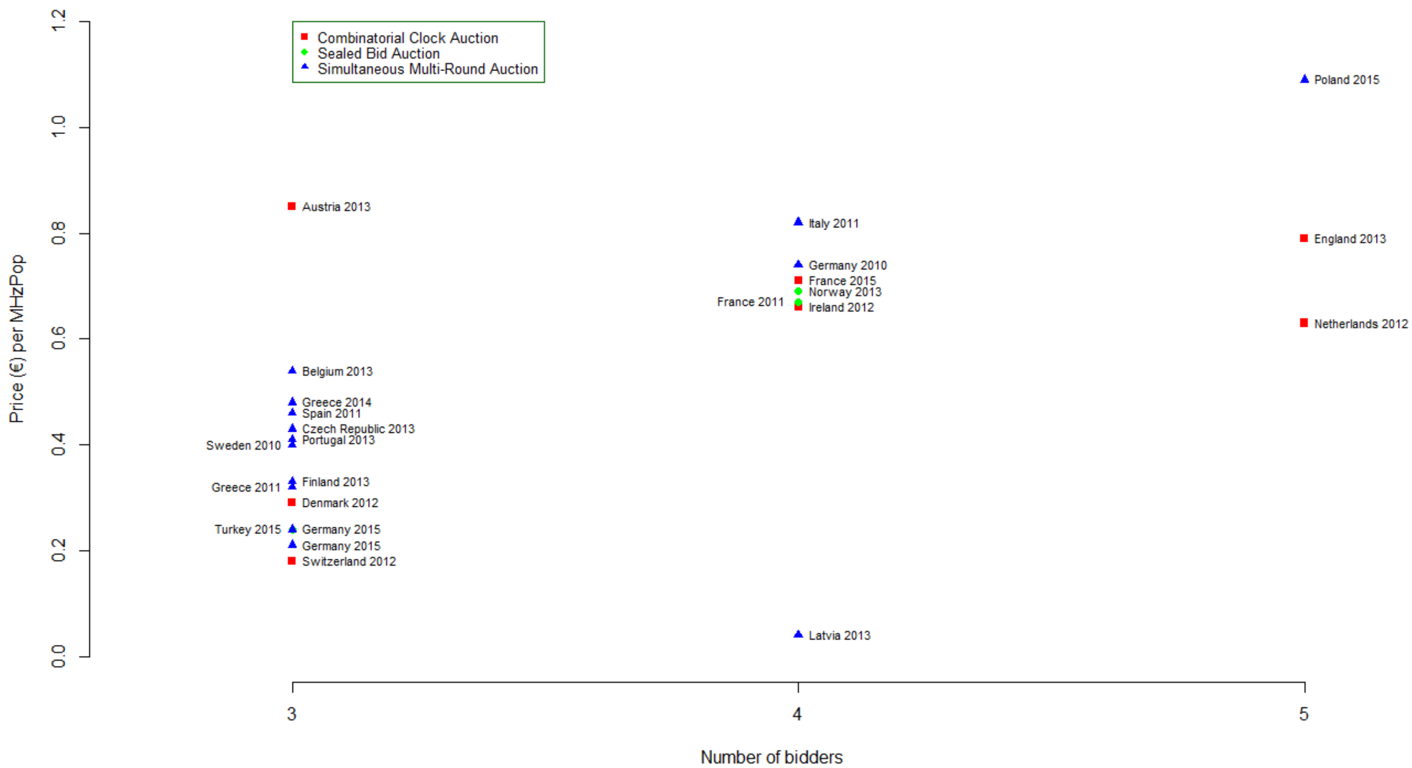

Figure 4: Final prices of recent European 700, 800 and 900 MHz spectrum auctions.

Still, the positive effect that additional bidders have on final prices of an auction seems evident. Figure 4[46] shows the clearing prices of recent comparable[47] European spectrum auctions for different amounts of bidders. There is huge price variation in auctions with 3 bidders, but almost none when there are 4 or 5. Latvian auction is a clear outlier, but it can be explained by the fourth bidder registering but not actually bidding in the auction.

The price variation can probably be explained by the nature of the auctions and the major role rules play when auction has only three participants. Auctions for 700 MHz and 800 MHz spectrum bands that are included in the above figure were auctions of six licenses, a number which is nicely divisible by number three. Hence it is meaningful to assume that demand

[46]The data on which the figure is based can be found in Appendix B.

[47]Auctions involving the sale of 700, 800 and 900 MHz licenses, which are considered technologically similar, are included in the figure. Some CCA auctions included involved other bands as well. Clock auctions are included under CCA auctions in case where licenses from a single band were auctioned.

reduction has been an attractive option for bidders. It is possible that it was further helped by strict spectrum caps which made competing for larger share difficult or impossible. As was stated earlier, bidders are eager to engage in demand reduction only when they know they are guaranteed at least some spectrum.

Thus the price increase when jumping from three to four bidder can be explained by bidders having less chances to engage in demand reduction. In addition, bidders more clearly compete for a dominating market position as some bidders will inevitably gain a larger share of spectrum than others. Since bidders are thought to have almost common values and declining marginal values (ignoring here that contiguous blocks are complements), we can illustrate the price increase with a hypothetical example where all bidders have same values. If we assume that bidders value the first license they receive at 5 and second at 2, having two bidders in a three license auction would yield prices $\{2+\epsilon, 2+\epsilon, 2\}$ where $\epsilon > 0$ represent the minimum bid increment in an ascending auction. Having a third bidder would increase the price on third license to $2+\epsilon$ and having a fourth bidder would increase prices on all licenses to 5, essentially almost tripling the seller revenue.

Additional bidders then increase the revenue for the auctioneer (a positive effect on social surplus) while increasing the prices bidders pay (a negative effect on social surplus). While this surplus contribution of an entrant has been studied by (Milgrom, 2004) among others, what really should interest the auctioneer is effect an entrant has when also taking into account entrant's effect on consumer market competition. Due to heavy infrastructure requirements the industry has, this effect is ambiguous.

6 Auction design process

Organizing a spectrum auction consists of much more than simply choosing the mechanism, yet most literature on the subject focuses on the characteristics of different mechanisms and how bidders behave in them. In this section I review the auction design process as a way to make the mechanism design itself easier. A well designed auction could by itself fix many of the issues discussed previously and thus help achieve the objectives of awarding spectrum.

I start by presenting the auction design process widely followed by European spectrum auction organizers. I analyze the process focusing on how it succeeds at fixing and preventing the shortcomings of the aforementioned spectrum auction models. I then follow a similar approach taken by Salant (2014) and review different cases of spectrum auctions held in Europe to distinguish auction-improving choices from those that hinder the allocation process.

6.1 Overview of the process

The main objective of the spectrum auction design is to achieve the goals set by the government. These were discussed in section 2 and often include efficient use and allocation of spectrum, promoting competition, and promoting broadband penetration. In addition, these goals should be achieved in a manner that is fast, cheap and transparent.

The process as presented here is often taught to policy makers by international economics consulting agencies[48] and followed by most auctioneers. Its roots lie in the academic papers written about the topic during the 90s and early 00s, all of which were already discussed in this paper. It involves lawmaking, designing the products sold, choosing the auction model, and lastly tailoring the model so that it best fits the setting it will be used in. Since all spectrum awards are different the challenges faced by the auctioneer also differ from award to award. By designing the auction properly the auctioneer can reduce the number of issues he might encounter during the auctions itself. However, the auctioneer should also be careful when attempting too clever designs, as these often complicate the auction and lead to unforeseen, and often negative, outcomes.

The first spectrum auction design process has been thoroughly recorded by McMillan (1994). Another thorough coverage of auction design process has been written by Klemperer (2002). He discusses the 3G spectrum auction held in the United Kingdom in 2000. The UK policy maker faced challenges different from the U.S. spectrum auctions held by the FCC, such as the issue of promoting competition. A more recent paper has been written by Cramton and Ockenfels (2014) who analyze the successfulness of mechanism design in the German 4G auction held in 2010.

The design process itself starts with government identifying a need to award spectrum and choosing what spectrum will be awarded. The regulator, who acts as the auctioneer, needs to acknowledge what will be awarded and what goals the government wants to achieve. The

[48] Presentations by NERA economic consulting and Copenhagen Economics both advised similar design. Presentations were held in IRG training workshop on Spectrum in August 25. - 27. 2015

regulator has to be aware how different goals can require different mechanisms to be fulfilled. For example, emphasizing monetary goals could radically change the auction design as compared to putting emphasis only on efficiency. National laws also need to be taken in to account as they dictate regulator's ability to award spectrum. Hence while not always a part of the process, lawmaking can be essential to the auctioneer. Some of the recent failed auctions resulted from a combination of bad laws and auctioneer not making their auction robust to them.

The process can be divided into three distinctive steps. The first step involves analyzing the quality of the spectrum and choosing how to present it in the auction. This process is called product design. There are a number of choices the auctioneer can make and they mainly affect how contiguous allocation is achieved. First, auctioneer can choose the size of a license. Technology dictates the most efficient license size[49], but the auctioneer is free to choose how many of these minimum sized licenses he ties together. This can be particularly useful when it is possible to force the auction into a single unit demand setting as explained in section 5.2.3.

Auctioneer can also choose whether to auction the licenses as concrete or as generic blocks of spectrum. When the goods are almost identical, using generic licenses can significantly simplify the process by allowing the use of a uniform price auction where bidders are only required to submit the number of licenses demanded, with final allocation chosen in a separate process. Almost no additional rules are required when licenses are auctioned as generic.

The second step is choosing the auction model. Given the product design, auction model choice is often straightforward. The first and most important factor is the number of spectrum bands present in the auction. When several bands are auctioned simultaneously it can be beneficial to allow bidding for packages to avoid exposure risk. In such cases combinatorial clock auction is the leading option. If exposure risk is deemed insignificant due to for example strict spectrum caps guaranteeing each participant enough spectrum, SMRA can also be used. However while seemingly simple, SMRA can be strategically very complex to participants as they are unable to express their demands for different combinations of licenses simultaneously.

[49] The newest technology, 4G, best exploits two paired spectrum blocks sized 5 MHz.

Since CCA, and more specifically the Vickrey-nearest-core payment rule it employs, has downsides it should not be used in other than multi-band auctions where exposure risk is significant. When only a single band is auctioned the regulator can choose between SMRA and clock auction. These two mechanisms lead to almost identical outcomes. However, when goods sold are identical clock auction is both faster and simpler than SMRA (with generic blocks) as bidders only express their amount demanded at different prices instead of actually bidding on individual licenses. Furthermore, clock auction will end in uniform prices while in SMRA prices could differ by at most one bid increment (Milgrom, 2004).

When licenses are heterogeneous and clock auction is used, the bidders have to express their demand for each license individually just like in SMRA. The two models are sometimes difficult to distinguish from each other since most regulators using SMRA have moved to predetermining bid increments as in a clock auction. The only difference will be that in clock auction bids are often not binding for future rounds. Hence auctioneer has a trade-off between fixing exposure risk (clock auction) and reducing the probability that licenses end up unsold (SMRA).

Auction design process is finalized by deciding on auction rules. This third step is focused on bridging any gaps left over by the previous two steps. These include both universally applied rules which were discussed in section 4.4 as well as situation specific rules such as the augmented switching rule. Additional rules are often required when auctioning heterogeneous goods, hence they are more common in SMRA than other two models.

An important rule that is often omitted is one that makes offers binding in the broad meaning of the word. While a bid is by definition usually[50] binding for the round it is placed on it might cease to bind in the following rounds for two reasons. First one was touched upon earlier and is related to how clock auction treats each round separately. If not addressed by limiting bidder's ability to reduce demand during the auction it might result in unsold spectrum. The second reason follows from allowing the standing high bidder to switch his bid onto another license in an SMRA model. When an augmented switching rule is in place it is essential to make bids binding.

[50] There are cases where even this was not completely true. Polish 2014/2015 and Czech 2012/2013 auctions are two examples.

A common way[51] to achieve this is to make bidders who switch or withdraw their bids pay the difference between the final price and their former bid, if the difference is positive. A bidder who once bid a on a license and then switched or withdrew his bid would have to pay $max\{a-b,0\}$, where b is the final price for said license, as compensation. A lack of such rule can make price discovery impossible and in the worst case allow the auction to continue indefinitely.

6.2 Experiences from European spectrum auctions

Recent European spectrum auctions provide examples of spectrum auction design process and how it can affect the outcome of a spectrum award. I analyze the auctions based on auction regulation released by the national regulators (who acted as auctioneers) as well as the auction outcomes and whatever other public information has been made available. Theory and concepts covered earlier in this paper will be cited when analyzing the cases and no new theory will be introduced. I focus on the design of the auction, specifically the product design, model choice, and rules.

I present examples where through good product and rule design and a proper mechanism choice the regulator managed to successfully reach their objectives. I also analyze auctions where some objectives were not achieved and discuss how to avoid similar issues in the future. The regulations and results for these auctions can be found in appendix A.

6.2.1 Austrian 2013 and Swiss 2012 auctions

Austrian 2013 multi-band auction acts as a model example of an appropriate mechanism choice as well as well designed spectrum cap which enabled flexible substitution between different license packages. I will analyze it together with Swiss 2012 auction. Both auctions were very similar to each other with several bands being auctioned at the same, both using combinatorial clock auction model to run the auction, and both having three bidders attending the auction. Despite notable similarities these two auctions ended up in two very different allocations and raised a very different amount of revenue.

[51] Applied both in German 2015 auction and Australian 2016 auction

I argue that the reason for different outcome was the spectrum cap, which was more lax in the Austrian case. Austrian regulator ruled that a single bidder can obtain at most 2x35 MHz in the spectrum bands below 1000 MHz while the Swiss regulator capped bidders from obtaining more than 2x25 MHz of spectrum below 1000 MHz. Another minor difference was that in the Swiss auction two additional bands were auctioned as operators had a chance to bid for spectrum on 2100 MHz and 2600 MHz bands.

Lax spectrum cap meant that bidders were much more free to compete for their desired packages and the final allocation had two biggest MNOs, Telekom Austria and T-mobile, share the most valuable 800 MHz band just between themselves. In Swiss case spectrum cap forced bidders to end up with 20 MHz each on the 800 MHz band as attempting to gain more would have forced them to forfeit licenses on almost equally important 900 MHz band. The effect on social surplus of having one stronger (Telecom Austria received 43 % of total spectrum) and two a bit weaker (T-mobile received 30 % and Three received 26 %) operators is ambiguous. However it is inline with the theory of auctions that the bidder who can best utilize the licenses, and thus willing to pay the most, receives the most licenses. In my view the differences in spectrum shares post-auction is not large enough to considerably hinder the competition in the consumer market.

What is not ambiguous is the effect the lax spectrum cap had on auction revenue. As was shown in figure 4 the two auctions represented the opposite ends of the revenue raised in auctions with three bidders. This can partly be explained by Swiss auction including cheap high frequency spectrum. Due to the auction running the CCA model we cannot separate the values for different bands. Hence the Price per MHzPop in the Swiss case has been inflated by additional 250 MHz in the denominator. Still, even if we assume that the price paid for this high frequency spectrum was zero and calculated the Price per MHzPop without it, we would only be at 0.35 Price per MHzPop while the Austrian auction raised 0.85. The remaining difference can be attributed to additional competition during the auction. The benefits from slightly more even competition post-auction would need to be extremely high to justify the several hundred million difference in auction revenue.

6.2.2 French 2015 auction

In the French 2015 auction six licenses from 700 MHz band were for sale and four bidders attended the auction. Since the licenses were nearly identical the national regulator Arcep opted to use clock auction supplemented by an assignment round where bidders bid for the right to choose their frequencies first. Hence each round the bidders only had to express their demand in number of licenses. However, there remained the downside of the clock auction where some spectrum might be left unsold.

Arcep fixed this problem by imposing an additional rule which (i) did not allow a single bidder to contract his demand by more than one block per round and (ii) required the bidder contracting his demand to post a price which was above the price he bid in $n-1^{th}$ round but below the n^{th} round list price at which he would still be willing to buy the block. Therefore in the case where two bidders simultaneously contract their demands the one posting the higher price would get the block at said price. Such rule works especially well when there is no exposure risk, meaning that an operator is happy with any number of licenses he will receive and does not demand a minimum amount to operate profitably.

6.2.3 Finnish 2013 auction

In 2013 Finland auctioned six licenses from 800 MHz band. SMRA was chosen as the auction model and the spectrum cap was set at three licenses. This allowed bidders to flexibly compete with each other. To reduce the possibility of collusion the regulator did not disclose the number of participants during the auction. To improve substitutability and to ensure that operators could receive contiguous licenses the regulator used an augmented switching rule which allowed standing high bidders to switch their bids to another license. Bids were in general binding but when switching their bid bidders weren't required to compensate the possible drop in prices.

This prolonged the auction and made price discovery impossible. The auction lasted for nine months yet the final prices were close to reserve prices. Finnish auction is an example of how attempting to fix inefficiencies can lead to worse problems when not done with extreme care. While the most obvious fix would have been to pay more attention to bindingness of bids, it might not have been the best one. Some of the licenses sold in the Finnish auction were very similar to each other, allowing for at least some to be sold as generic blocks, hence possibly eliminating the need for the augmented switching rule altogether.

6.2.4 Polish 2015 auction

Polish 2015 auction, which was supposed to take place a year earlier but was canceled due to faults in auction rules, probably has the most to teach among latest European spectrum auctions.

First lesson to learn is the importance of proper laws. Polish legislation is such that bids made during auction were not binding save for a tiny deposit the bidders had to pay in order to participate in the auction. At any point during and after the auction a bidder could simply opt out and decline to pay his bid, losing only said deposit. This lead to abnormally high prices that prolonged the auction and made others question whether the bidders would even pay the final prices[52]. The risk was realized in February 2016 when, already after handing operators the spectrum, NetNet, which was one of the bidders, relinquished its license.

Second lesson is the importance of appropriate reserve price and bid increments. Polish reserve price was set extremely low at 250 million zloty (12% of the final prices) which, coupled with minimum bid increment of 1%, resulted in an auction lasting over nine months. While a minimum bid increment of 1% is not bad per se, the auctioneer should always consider maintaining at least some control over the bid increments during the auction. This way the auctioneer can control the pace at which the auction evolves. For example, the auctioneer can announce certain range of bid increments which it will follow. Such solution has been applied in Germany and Finland among others.

Third lesson we can learn from the Polish auction is the importance of designing a proper ending rule. The combination of lessons one and two forced the Polish regulator UKE to end the auction prematurely. The regulator decided that the auction would terminate on the 115^{th} round of bidding which would be followed by a sealed-bid round where bidders were free to bid any amount. This decision was made rather hastily during the auction and caused some bidders to threaten to sue the regulator if auction was ended prematurely. Regulators should include the ending rule in the auction regulation to avoid controversy of changing the rules during the auction itself.

[52] A similar issue was seen in Czech 2012 auction, which was canceled and rerun in 2013.

7 Conclusions

Auctions are currently the best way to allocate scarce spectrum to mobile network operators. The previous method of awarding spectrum through administrative process was unintelligible, slow, and costly for the administrator. These so called beauty contests probably also resulted in inefficient allocations as it was impossible for the government to figure out the valuations of different MNOs. In addition to addressing these flaws auctions also bring the benefits of promoting competition and raising revenue for the government. Hence their popularity has been steadily increasing for the past twenty years with most governments nowadays awarding spectrum through auctions.

Among economists the most celebrated auction is the second-price sealed bid auction which is a variation of the VCG mechanism. Given a set of general assumptions, VCG mechanism has truthful bidding as a dominant strategy and always results in an efficient outcome. However, a number of issues arise when trying to apply VCG mechanism in spectrum awards. The two most significant violations of the assumptions result from bidders having almost common values and constrained budgets. VCG mechanism also has a tendency to result in zero or low revenues when goods auctioned are not substitutes. Hence other mechanisms have been created for use in spectrum auctions.

In Europe, three commonly used spectrum auction models are simultaneous multiple round auction, clock auction and combinatorial clock auction. All three are ascending bid auctions where bidding on all goods ceases simultaneously. SMRA is the oldest and most versatile of the three and can be used in almost all situations. Clock auction works well in a single-band auctions where licenses are homogeneous. CCA is a variant of clock auction created for multi-band auctions. It enhances an ascending auction with a sealed bid round with package bids and a variation of a second price payment rule to allow bidders to simultaneously express their demands for all different combinations of licenses.

A number of issues remain even when using auction models specifically tailored for spectrum auctions. One of the most prevalent is strategic demand reduction which can occur whenever bidders have multi-unit demand. It causes bidders to lack unambiguous dominant strategy. Another issue is exposure risk and lack of competitive equilibrium caused by licenses being complementaries. Both contiguous licenses and licenses on different bands are complements with each other. Hence package bidding has been favored especially in multi-band auction as a way to nullify exposure risk.

Bidders having common values and imperfect information pose problem in spectrum auction models, although the negative effects are smaller than in a VCG mechanism. Bidders being budget constrained is an issue in theory, but it is doubtful that these constraints are binding in European spectrum auctions. Facilitating competition is regarded as an important objective since it can help fix many of the problems encountered. Furthermore, increased competition in the consumer market most likely increases social surplus. However, ascending auctions are particularly punishing for new entrants and hence additional measures such as setting set-asides and spectrum caps are often required to attract them.

Regulators can address some issues through good auction design. Since every spectrum auction is different, there does not exist any one-size-fits-all solution. Hence the design process plays an important role. It usually consists of three steps. First the auctioneers designs the product, then chooses the spectrum auction model, and lastly adds rules to improve the efficiency of the model. Auctioneers have had varying success with their auction design. In best case good auction design can indeed improve the efficiency of the auction - but too eager tinkering with the rules can lead to complete failure.

Appendices

Appendix A

Spectrum auction regulations and results

Australian 700 MHz and 2500 MHz Auction (2013)
Auction regulation:http://www.acma.gov.au/~/media/Spectrum%20Licensing%20Policy/Information/pdf/Auctionguide%20pdf.pdf
Auction results: http://www.acma.gov.au/Industry/Spectrum/Digital-Dividend-700MHz-and-25Gz-Reallocation/digital-dividend-auction-results

Australian 1800 MHz Auction (2016)
Auction regulation: http://www.acma.gov.au/~/media/Spectrum%20Licensing%20Policy/Information/pdf/Auction%20guide%20_1800%20MHz%20spectrum%20auction%20pdf.pdf
Auction results: http://www.acma.gov.au/sitecore/content/Home/Industry/Spectrum/Spectrum-projects/1800-MHz-band/1800-mhz-band-auction-strong-result-reveals-high-demand

Austrian 800 MHz, 900 MHz and 1800 MHz Auction (2013)
Auction regulation:https://www.rtr.at/en/tk/multibandauktion_AU/27890_2013-03-26_F1_11_Tender_Document_Multiband_Auction_2013.pdf
Auction results: http://cdn1.telekomaustria.com/final/de/media/pdf/TKA_acquires_austrian_spectrum_Presentation.pdf

Czech 800 MHz, 1800 MHz and 2600 MHz auction (2012)
Auction regulation (in Czech): http://www.ctu.cz/vyhlaseni-vyberoveho-rizeni-na-kmitocty-v-pa
Auction results: Auction cancelled http://www.ctu.eu/main.php?pageid=342

Czech 800 MHz, 1800 MHz and 2600 MHz auction (2013)
Auction regulation (press release):http://www.ctu.eu/164/download/Press_releases/pr25_08042013_an.pdf
Auction results: http://www.ctu.eu/164/download/Spectrum%20Auction/2013/invitation_to_tender_15_08_2013_summary_auction_results_20_11_2013.pdf

Finnish 800 MHz Auction (2013)

Auction regulation (in Finnish): https://www.viestintavirasto.fi/attachments/maaraykset/Viestintavirasto642012M.pdf
Auction results: https://www.viestintavirasto.fi/en/ficora/news/2013/endof4gspectrumauction.html

French 700 MHz Auction (2015)
Auction regulation (in French): http://www.arcep.fr/uploads/tx_gsavis/15-0825.pdf
Auction results: http://www.arcep.fr/index.php?id=8571&tx_gsactualite_pi1[uid]=1806&tx_gsactualite_pi1[annee]=&tx_gsactualite_pi1[theme]=&tx_gsactualite_pi1[motscle]=&tx_gsactualite_pi1[backID]=26&cHash=7e1d824a1659bb2e7723a117bffbff80&L=1

German 700 MHz, 900 MHz, 1500 MHz and 1800 MHz Auction (2015)
Auction regulation: http://www.bundesnetzagentur.de/SharedDocs/Downloads/EN/BNetzA/Areas/Telecommunications/TelecomRegulation/FrequencyManagement/ElectronicCommunicationsS
DecisionP2016_pdf.pdf?__blob=publicationFile&v=3
Auction results: http://www.bundesnetzagentur.de/EN/Areas/Telecommunications/Companies/FrequencyManagement/ElectronicCommunicationsServices/MobileBroadbandProject2016/project2016_node.html

Polish 800 MHz and 2600 MHz Auction (2015)
Auction regulation (in Polish): http://uke.gov.pl/files/?id_plik=17709
Auction results: https://en.uke.gov.pl/files/?id_plik=20951

Swiss 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz Auction (2012)
Auction regulation and results: http://www.news.admin.ch/NSBSubscriber/message/attachments/26004.pdf

Appendix B

Data on European spectrum auctions

Auction (Country/Year/Bands)	Model	Participants	Total price (€)	Population	Price per MHzPop	Pop. density (pop/km2)	GDP/capita ($)
Austria 2013 800/900/1800 2013	CCA	3	2 014 000 000	8 500 000	0,85	100	51306
Belgium 2013 800	SMRA	3	360 000 000	11 200 000	0,54	355	45383
Czech Republic 2013 800	SMRA	3	269 000 000	10 500 000	0,43	134	27344
Denmark 2012 800	CCA	3	99 000 000	5 500 000	0,30	131	56147
England 2013 800	CCA	5	3 067 000 000	64 500 000	0,79	255	35334
Finland 2013 800	SMRA	3	109 000 000	5 500 000	0,33	16	43492
France 2011 800	SBCA	4	2 639 000 000	66 000 000	0,67	114	44747
France 2015 700	CCA	4	2 799 000 000	66 000 000	0,71	114	44747
Germany 2010 800	SMRA	4	3 576 000 000	80 600 000	0,74	229	47589
Germany 2015 700	SMRA	3	997 000 000	80 600 000	0,21	229	47589
Germany 2015 900	SMRA	3	1 341 000 000	80 600 000	0,24	229	47589
Greece 2011 900/1800	SMRA	3	380 500 000	10 800 000	0,32	82	29635
Greece 2014 800	SMRA	3	309 000 000	10 800 000	0,48	82	29635
Ireland 2012 800/900/1800	CCA	4	855 000 000	4 600 000	0,66	65	51356
Italy 2011 800	SMRA	4	2 962 000 000	60 000 000	0,82	202	35823
Latvia 2013 800	SMRA	4	4 700 000	2 000 000	0,04	89	21381
Netherlands 2012 800/900/1.8/2.6	CCA	5	3 800 000 000	16 800 000	0,63	407	48223
Norway 2013 800/900/1.8	SBCA	4	212 000 000	5 000 000	0,71	16	97013
Poland 2015 800	SMRA	5	2 100 000 000	38 500 000	1,09	123	23275
Portugal 2013 800/900	SMRA	3	300 000 000	10 400 000	0,41	115	21408
Spain 2011 800	SMRA	3	1 300 000 000	47 000 000	0,46	92	31946
Sweden 2010 800	SMRA	3	233 000 000	9 600 000	0,40	22	43986
Switzerland 2012 800/900/1.8/2.1/2.6	CCA	3	800 000 000	8 200 000	0,18	198	67560
Turkey 2015 800	SBCA	3	1 116 000 000	77 500 000	0,24	101	19610

Figure 5: Information on recent European spectrum auctions

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