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A review of radio spectrum combinatorial clock auctions

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ABSTRACT

This paper surveys a decade of Combinatorial Clock Auctions (CCAs) to allocate radio spectrum licenses from their inception to 2016. Although all CCAs share a common structure (first an allocation stage and then, an assignment stage), regulators have tailored key variables depending on their spectrum policies and market structures. We identify these variables, such as: spectrum packaging policy, reserve price, demand limit, activity rule, transparency and pricing rule. We also analyze the different ways in which regulators can design them along with their implications. This theoretical work is accompanied by a review of the practical implementation decisions in each actual auction and final outcomes. Although all the information is public, it is not easy to find because it is highly disaggregated. Finally, after having identified advantages and disadvantages in this auction model, we present some proposals to improve the actual mechanism.

Keywords:
Combinatorial clock auction (CCA)
Spectrum auction
Spectrum packaging policy
Reserve price
Demand limit
Activity rules
Transparency
Pricing rule

1. Introduction

The Combinatorial Clock Auction (CCA) was presented for the first time by Ausubel, Cramton and Milgrom, (2006). Two years later, in 2008, the communications regulator in the UK (Ofcom) adopted this mechanism for two award processes. Since then, many other countries have implemented CCAs as the mechanism to award available spectrum, displacing Simultaneous Multiple Round Auctions (SMRAs).

The CCA is a hybrid auction with two stages. First, there is an allocation stage in which the number of lots each bidder wins and the base prices are settled. Then, an assignment stage is run to determine which specific lots are awarded to each winning bidder. The allocation stage is a two stage bidding process. First is the clock stage, composed of multiple rounds in which prices increase until there is no excess demand for any item. In each round, bidders submit a single bid for a package of items at the current prices. Following the clock phase is the supplementary phase, which is a single round process in which bidders can submit multiple bids both to improve their clock bids and to bid for new packages. With all the clock and supplementary bids submitted, the Winner Determination Problem (WDP) is solved finding the value maximizing combination, using the XOR bidding language in which all bids are mutually exclusive. Finally, the allocation price for each winning bidder is calculated using a second price rule.

All CCAs recently conducted in different countries share this general structure. Nevertheless, each regulator has tailored key rules such as setting reserve prices, demand limits, and rules related to activity, transparency or pricing. These practical implementation decisions, together with the structure of each market and the spectrum packaging policies, have had a significant impact on the final outcome.

This paper surveys a decade of spectrum CCAs from their inception to 2016. While all the information is public, it is not easy to find because it is highly disaggregated. The goal in this paper is twofold: first, to gather all information about the final design in each

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country to observe how different regulators have adapted CCAs to their specific market structures; second, to compare and analyze the differences in order to understand its impact on the final outcome.

This paper is structured in the following way. Section 2 includes a brief review of the most relevant works related to CCAs. Section 3 highlights key rules that need to be tailored in any CCA, such as spectrum packaging policies, reserve prices, demand limits, activity rules, transparency, price increments and pricing rules. The description of these practical implementations is accompanied by a historical overview of the decisions taken in the CCAs performed up to the present.

Section 4 summarizes the main features and results of the auctions analyzed. The advantages and disadvantages identified in this auction model over the years are discussed in Section 5. The paper ends with Section 6, in which the conclusions and possible future approaches are described.

2. State of the art

Due to the relevance of this allocation mechanism, there are previous works that have analyzed the CCA's advantages and limitations, proposed future improvements and included references to real spectrum auctions. A summary of the most relevant ones is included below.

Ausubel and Cramton (2011) propose activity rules that combine revealed preference and eligibility point monotonicity. For the clock phase, they present a hybrid revealed preference/eligibility point approach. Bids in the supplementary phase must satisfy the revealed preference constrain with respect to the last clock round and all eligibility reducing rounds in which the bidder's eligibility was below the eligibility of the affected package bidding. This is known as the simplified revealed preference cap. Section 3.4 includes a complete list of the activity rule used in each CCA. The authors' suggestion for the clock phase was implemented in four auctions and only two CCAs included the proposed activity rule for the supplementary phase.

Cramton (2013) shows how the CCA solves many of the SMRA's problems while maintaining its strengths. Among the advantages, he highlights enhanced substitution and the encouragement of price discovery and truthful bidding, given the pricing and activity rules. This paper includes references to UK CCAs.

Bichler, Shabalin, and Wolf (2013) perform a lab experiment to compare the SMRA and the CCA in terms of bidding behavior, efficiency and revenues. They highlight some important aspects regarding bidding behavior under certain activity rules. A straightforward bidding strategy in the clock round is not always possible if a simple eligibility point rule is used. In the supplementary phase, bidders could have incentives to submit spiteful bids to increase their rival's prices without any risk if the revealed preference constrain with respect to the last clock package must be satisfied. Section 3.4 shows that all but four CCAs have used the simple eligibility point rule in the clock phase. In the supplementary phase the activity rule with respect to the last clock package was settled only in three auctions.

Janssen and Karamychev (2013) describe a bidding behavior in CCAs in which bidders care about the price competitors have to pay and are budget constrained. They show that CCAs present many strategic gaming possibilities in both the clock and supplementary phases.

Ausubel and Baranov (2014a) review critical decisions for implementing the CCA, such as the following: treating reserve prices as a lower bound or a minimum incremental cost; accommodating technological choice; setting activity rules; price increments in the clock phase; competition policies and the bidding language. How to customize these details can prove decisive for the final result of the auction. There are references to real CCAs throughout their work. Section 3 of the present work describes some of these variables, such as: reserve price; activity rules; price increment; and competition policies. Furthermore, final implementations in each CCA are included.

Ausubel and Baranov (2014b) analyze both the advantages and limitations of CCAs and describe how these auctions have been implemented in different countries. Ultimately, the authors recommend the following improvements to be done in future: combining non mutually exclusive bids ("OR bids") and mutually exclusive bids ("XOR bids"); introducing activity rules based on the General Axiom of Revealed Preference (GARP); and transforming the CCA into an iterative first price auction.

Levin and Skrzypacz (2014) describe ex post equilibria in three different scenarios. The first is focused on the standard allocation problem. In the second scenario, bidders have the incentive to make their rivals pay more. In the third scenario, bidders try to raise each other's price by relaxing the activity rule constraints on their final bids. Neither efficient allocation nor truthful Vickrey prices are achieved in any of these scenarios. These authors also include an analysis of the UK spectrum auctions in 2008 and 2013 as well as the Austrian 4G auction (2013).

More recently, Janssen, Karamychev and Kasberger (2015) explore the CCA properties when bidders are budget constrained in two scenarios. In the first scenario, with "standard" preferences, bidders only care about the items they win and the price they pay. In the second scenario, bidders also care about the rival's price and the lots earned.

Finally, Bichler, Goetzendorff and Kroemer (2016) have analyzed bidding behavior in CCAs. These authors state that although from a theoretical point of view bidders have the incentive to bid straightforwardly, in real auctions, bidders deviate significantly from straightforward bidding. The results come from both lab experiments and real spectrum auctions analysis (the UK multi band spectrum auction in 2013 and the Canadian 700 MHz auction in 2014). The authors conclude that a strong activity rule based on the GARP, which tests bidding consistency throughout the entire history, could be a solution. Price discovery and truthful bidding are analyzed in Section 5.2. of the present work.

Table 3.1
Spectrum CCAs up to 2016.
Source: Compilation based on information from regulator websites and other public information. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

Year	Country	Total reserve value (million $)	Reserve value allocated items (million $)	Final payment (million $)	Price increment (%)[a]
2016	Mexico	166.11	162.67	165.78	2
2015	Canada	199.98	193.86	599.78	209
2014	Canada	820.00	819.74	4816.62	488
2014	Slovenia	143.53	134.48	204.02	52
2013	Australia	2971.33	2013.23	2017.08	0
2013	Slovakia	187.02	187.02	215.13	15
2013	Austria	725.18	725.18	2680.94	270
2013	UK 4 G	2195.62	2195.62	3820.60	74
2012	Netherlands	619.55	619.55	4924.61	695
2012	Ireland	278.61	262.62	605.81	131
2012	Denmark	44.01	44.01	125.14	184
2012	Switzerland	680.02	657.66	1083.80	65
2010	Austria	9.88	9.88	51.36	420
2010	Denmark	3.53	3.44	182.98	5216
2010	Netherlands	2.54	1.74	3.52	102
2008	UK L Band	1.87	1.87	16.40	777
2008	UK 10 40 K	1.59	1.59	2.79	75

[a] The price increment is calculated by dividing the final payment by the reserve value allocated items.

3. Practical implementations in CCAs: theory and history

Since CCA was introduced by (Ausubel et al., 2006), it has been used in 17 spectrum auctions in 11 countries and has yielded very different outcomes. Table 3.1. recapitulates spectrum CCAs up to 2016.[1] The results through the years have greatly differed. Some auctions, such as the Dutch 2.6 GHz (2010) auction, had a spectacular price increment. In others, such as in Mexico (2016) and Australia (2013), the final prices were very close to reserve values.

Although the CCA was used in all these award processes, lots of different bands and size were offered, generating great diversity. Market structure and competition per country also have an important impact on the final outcome. Furthermore, each regulator tailored key variables, such as spectrum packaging, reserve price, demand limit, activity rule, transparency and price. In the following sub sections, we discuss different ways of designing these variables, and we describe the decisions made in each case.

3.1. Spectrum packaging policy

One of the main advantages of CCAs is the ability to auction heterogeneous lots in a single auction. Accepting bids for complete packages eliminates the exposure problem or risk faced by bidders when complement items are auctioned if they only win some (but not all) items included in the demanded package.

Many regulators have chosen to perform multi band auctions, where spectrum of different bands is offered in the same process. In other cases, a spectrum of the same band is auctioned, but lots are grouped according to variables such as size, paired/unpaired, with/without coverage obligations, interferences, and licensing terms. Table 3.2. depicts CCAs per band and the total spectrum available per auction.

Regulators must make multiple decisions regarding spectrum packaging, such as how to manage the competing demands from different technologies (service neutrality versus dedicated licenses), the size of lots, licensing terms, coverage obligations, how much paired and unpaired spectrum to offer, roaming or network sharing. Table 3.3. shows the distribution in each country between paired and unpaired spectrum offerings, along with the lot size settled. The trend suggests that paired spectrum offerings are grouped in 2×5 MHz or 2×10 MHz blocks, while unpaired spectrum offerings are frequently grouped in 5 MHz blocks.

3.2. Reserve prices

Setting the reserve price or opening bid is not a trivial decision, as any choice involves certain risks. On the one hand, the establishment of a high reserve price may discourage small players, decreasing the competition level and increasing the chances of having unsold lots. On the other hand, setting a low reserve price exposes the regulator to low revenues and may incentivize collusive behavior among participants.

In recent years, regulators have made very different decisions regarding reserve price policies, as we found a great dispersion.

[1] Ausubel and Baranov (2014a) mention that the first CCA with an assignment stage was conducted in Trinidad and Tobago in 2005. Nevertheless, the rules were not found at the website of the Telecommunications authority of Trinidad and Tobago, so it is not included in this work.

Table 3.2
CCAs per spectrum band.
Source: Compilation based on information from regulator websites and other public information.

Year	Country	Spectrum band	Total MHz
2016	Mexico	1700 MHz	80.0
2015	Canada	2500 MHz across 61 service areas	6360.0
2014	Canada	700 MHz across 14 service areas	952.0
2014	Slovenia	800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz	500.0
2013	Australia	700 MHz and 2500 MHz across 11 service areas	1630.0
2013	Slovakia	800 MHz, 1800 MHz and 2600 MHz	290.8
2013	Austria	800 MHz, 900 MHz and 1800 MHz	280.0
2013	UK 4 G	800 MHz and 2600 MHz	250.0
2012	Netherlands	800 MHz, 900 MHz, 1800 MHz, 1900 MHz, 2100 MHz and 2600 MHz	359.6
2012	Ireland	800 MHz, 900 MHz and 1800 MHz	560.0
2012	Denmark	800 MHz	60.0
2012	Switzerland	800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz	605.0
2010	Austria	2600 MHz	190.0
2010	Denmark	2500 MHz and 2010 MHz	205.0
2010	Netherlands	2600 MHz and 2010 MHz	199.7
2008	UK L Band	1400 MHz	39.7
2008	UK 10 40 K	10, 28, 32, 40 GHZ	5832.0

Table 3.3
Spectrum packaging per CCA.
Source: Compilation based on information from regulator websites and other public information.

		Paired		Unpaired	
Year	Country	Lots size (MHz)	Total MHz	Lots size (MHz)	Total MHz
2016	Mexico	2×5	80		
2015	Canada	2×10	5460	25	900
2014	Canada	2×6 and 2×5	784	6	168
2014	Slovenia	2×5, 2×10 and 2×15	430	5	70
2013	Australia	2×5	1630		
2013	Slovakia	2×5, 2×0.4, 2×0.6, 2×1,2×1.2 and 2×2.2	240.8	5	50
2013	Austria	2×5	280		
2013	UK 4 G	2×5 and 2×10	200	5	50
2012	Netherlands	2×5	290	14.6 and 5	69.6
2012	Ireland	2×5	560		
2012	Denmark	2×5 and 2×10	60		
2012	Switzerland	2×5 and 2×10	540	5 and 15	65
2010	Austria	2×5	140	5	50
2010	Denmark	2×5	140	5 and 15	65
2010	Netherlands	2×5	130	5 and 9.7	69.7
2008	UK L Band			1.7 and 12.5	39.7
2008	UK 10 40 K	2×10, 2×112, 2×126 and 2×250	5832		

Table 3.4.a
Reserve Price in $/MHz-pop for sub 1 GHz bands.
Source: Compilation based on information from regulator websites and other public information.

Year	Country	700 MHz	800 MHz	900 MHz	Licensing term (years)
2014	Canada	0.3602			20
2014	Slovenia		0.2503	0.3125	15
2013	Australia	1.3963			15
2013	Slovakia		0.4609		15
2013	Austria		0.5026	0.4696	16 & 14
2013	UK 4 G		0.4824		20
2012	Netherlands		0.2704	0.2233	17
2012	Ireland		0.2265	0.2265	15
2012	Denmark		0.1312		22
2012	Switzerland		0.2898	0.2898	16 & 15
Average reserve price		0.7092	0.2997	0.2928	

Table 3.4.b
Reserve price in $/MHz-pop for 1.4 2.6 GHz bands.
Source: Compilation based on information from regulator websites and other public information.

Year	Country	1400 MHz	1700 1800 MHz	2010 2100 MHz	2500 2600 MHz	Licensing term (years)
2016	Mexico		0.0196			15
2015	Canada				0.0734	20
2014	Slovenia		0.1596	0.0408	0.0395	15, 7 & 15
2013	Australia				0.0308	15
2013	Slovakia		0.0535		0.0248	13 & 15
2013	Austria		0.2293			14
2013	UK 4 G				0.0279	20
2012	Netherlands		0.0319		0.0090	17
2012	Ireland		0.1132			15
2012	Switzerland		0.1129	0.1129	0.1129	18
2010	Austria				0.0008	15
2010	Denmark			0.0011	0.0033	20
2010	Netherlands			0.0004	0.0008	20
2008	UK L Band	0.0008				15
Average reserve price		0.0008	0.0767	0.0068	0.0129	

Table 3.4.c
Reserve price in $/MHz-pop for bands above 10 GHz.
Source: Compilation based on information from regulator websites and other public information.

Year	Country	10 GHZ	20 GHZ	32 GHZ	40 GHZ	Licensing term (years)
2008	UK 10 40 K	0.000016	0.000005	0.000007	0.000002	15

Tables 3.4.a. 3.4.c. show opening bids measured in $/MHz pop.[2]The last column of the table shows the number of years each license lasts.[3] In cases where different bands have different durations, the license years have been included in the order of the band. There are some specific cases worth mentioning:

- Australia 2013: All licenses last 15 years, except in two service areas in the 2.5 GHz band.
- Austria 2012: The 900 MHz band includes licenses for 12 and 14 years. The table includes only the reserve value for 14 years. In the same way, the 1800 MHz band includes licenses for 10, 12 and 14 years, but the table only includes the reserve price for 14 years.
- Ireland 2010: Two time slides were auctioned for each spectrum band (until 2015 and until 2030). The table only reflects the values for licenses until 2030.
- Switzerland 2012: The 1800 MHz band includes 15 and 18 years' licenses. The 2.1 GHz band included licenses for 15 and 18 years. The table only incorporates values for 18 years.

Setting the value of the opening bid is not the only decision regulators have to make with respect to this variable. They also have to decide the implications for the final price calculation[4]:

- Bundle reserve prices option (knows as "bounds only"): The final price of a package must be at least the sum of the starting price of all lots included in the package.
- Incremental reserve prices option (knows as "reserve bidders"): The incremental price of winning an additional lot is at least the reserve price of that lot. To implement this option, the seller submits a reserve bid for each lot that is included both in the allocation process (WDP) and when computing final prices.

At first, CCAs chose the bounds only option, but recently, the reserve bidder option has dominated: Ireland (2012), Austria (2013), Australia (2013), Slovenia (2014), Canada (2014 and 2015) and Mexico (2016). When the reserve bidder option is settled, the bounds only option is also satisfied, but not vice versa.

[2] To perform a more rigorous comparison, we recommend following the data treatment in DotEcon and Aetha (2012), in which reserve prices are adjusted with GDP, license term and inflation. It would also be good to know the spectrum characteristics in terms of coverage obligation, interferences, roaming and technology.
[3] For some CCAs, the exact licensing term was not found, so the term expiry date is given instead. In these cases, we have assumed that the licenses are available from the year after the auction and have counted the licensing duration.
[4] Ausubel and Baranov (2014a, 2014b) describe some implications of these options.

3.3. Demand limits

Traditionally, regulators set limits on the bidders' demand with the aim of diversifying the number of winners. While these tools tend to lessen competition during the auction (and potentially reduce final prices), they also incentivize the entry of new participants, thus reducing market concentration. Next, main the mechanisms are described[5]:

3.3.1. Spectrum caps

The maximum amount of spectrum a bidder can get can be set in different ways:

- For a specific spectrum band or an overall cap across bands.
- It can be applied only to licenses obtained in that auction or accumulated on previous holdings.
- Can be symmetrical for all bidders or asymmetrical, i.e., incumbent operators subject to lower caps, known as virtual set aside.

The cap setting can have an important effect on the final outcome. If a cap is set too low, bidders might not have the option to acquire the spectrum needed for feasible business cases, which will discourage participation. If the cap is too high, it might become non binding and will have no effect. It could also happen that, according to the cap and the market structure, demand matches supply, killing competition.

3.3.2. Spectrum set aside

One or more blocks of spectrum are reserved for a type of bidder. Usually incumbents are excluded from bidding on those blocks, and only new entrants can demand them.

From the incumbent's point of view, having set aside spectrum implies a reduction of the available spectrum, which increases competition and the final prices for non set aside blocks. This tool encourages small players participate, as it increases their chances of getting spectrum at lower prices. Obviously, when set aside spectrum is settled, it generates a gap in final prices paid per type of bidder.

The demand limit tools set up in each CCA are summarized in Table 3.5. On decisions made over the years, we highlight the following:

- Canada 2014: In addition to the overall cap, the regulator imposed a specific cap for large wireless service providers (virtual set aside).
- Austria 2013: The regulator offered two frequency blocks in the 800 MHz band for a new entrant in the pre auction, but because there was no demand, it was finally allocated in the main auction.
- UK 2013: A set aside block was settled in each band, leaving the market to resolve which of them would finally be the set aside spectrum.
- Netherlands 2012: The regulator fixed a set aside block in the 800 MHz and 900 MHz bands plus a cap on the maximum number of reserved frequencies to be acquired by newcomers.

3.4. Activity rules

The allocation stage is the first phase of all CCAs, in which winners of generic lots and base prices are determined. This allocation process is comprised of a clock phase and a supplementary phase. To encourage price discovery and truthful bidding, activity rules are set between clock rounds and between the clock and supplementary phases. Also, activity rules can prevent sniping, i.e., bidders dropping in early rounds and bidding on later ones, therefore not revealing information.[6]

3.4.1. Activity rule in the clock phase

Two activity rules can be implemented in the clock phase: an eligibility point rule and a simplified revealed preference /eligibility point hybrid rule.

- Eligibility point rule

The point based approach limits the size of the packages in which a bidder can bid in each round based on the previous rounds. Bidders start the auction with a given level of Eligibility Points (EPs), and in each round, the current eligibility is calculated by adding the EP of the lots they bid on. The rule states that a bidder can never bid for a larger package, in terms of EP, than in the previous round.

The main advantage of this rule is that it is very easy to implement and understand. However, it has two major drawbacks. First, the effectiveness of this rule will depend on how the regulator grants the EP. Second, under this rule, the best strategy a bidder can follow is to bid for the largest package that is still profitable, but a truthful bidder could be sharply constrained in the supplementary

[5] Cramton, Kwerel, Rosston, and Skrzypacz (2011) analyze different tools that encourage competition and improve market outcomes.

[6] To understand the activity rules in more detail, we recommend the papers presented by Ausubel and Cramton (2011), Cramton (2013) and Bichler et al. (2013).

Table 3.5
Demand limits implemented.
Source: Compilation based on information from regulator websites and other public information.

Year	Country	Caps	Set-aside
2016	Mexico	Yes	No
2015	Canada	Yes	No
2014	Canada	Yes	No
2014	Slovenia	Yes	Yes
2013	Australia	Yes	No
2013	Slovakia	Yes	No
2013	Austria	Yes	Yes
2013	UK 4 G	Yes	Yes
2012	Netherlands	Yes	Yes
2012	Ireland	Yes	Yes
2012	Denmark	Yes	No
2012	Switzerland	Yes	No
2010	Austria	Yes	No
2010	Denmark	Yes	No
2010	Netherlands	Yes	No
2008	UK L Band	No	No
2008	UK 10 40 K	No	No

phase because of the activity rules.

- Simplified RP/Eligibility Point hybrid rule

Ausubel et al. (2006) proposed an activity rule based on the Revealed Preference (RP) constraint, which allows bidders to bid on packages that have become less expensive, even if they are larger. A bidder is allowed to bid on package q^t if satisfies the RP constraint with respect to the package bid in round l for $l < t$:

$$q^t(p^t - p^l) \leq q^l(p^t - p^l), \tag{1}$$

where pt is the vector of clock prices for round t.

The main advantage is that if, during the clock phase, bidders bid straightforwardly, they would be able, in the supplementary phase, to bid the full value for every package.

However, this rule has an important risk. If valuations are not entirely consistent or change during the clock phase, the rule can lead to a dead end. In a certain round, it can fail to draw any bid that meets the RP constraint, so the bidder will have to drop out of the auction.

To avoid this situation, Ausubel and Cramton (2011) propose the simplified revealed preference with an eligibility point safe harbor rule (Simplified RP/Eligibility Point Hybrid rule). Under this rule, bidders can bid for a larger package if it meets the RP constraint with respect to any previous package in which there was a reduction of their EP. These are known as anchor packages. Likewise, bidders may always bid on packages with the same or a lesser EP than their actual eligibility.

3.4.2. Activity rule in the supplementary phase

In the supplementary phase, there is no limit on the bid amount for the last clock round (LCR) package. However, all other bids will be capped by the clock phase.

According to the initial proposal (Ausubel et al., 2006), supplementary bids must also meet the RP constraint. The bid amount for package q, $b(q)$, must satisfy the following constraint with respect to round t:

$$b(q) \leq b(q^t) + (q - q^t)\ p^t, \tag{2}$$

where $b(q^t)$ is the final bid for package q^t demanded in round t.

The RP can be implemented in the following ways:

- Relative cap

The bid $b(q)$ must satisfy RP with respect to the last clock round in which the bidder had sufficient eligibility to bid on this package.

- Intermediate cap

The bid $b(q)$ must satisfy RP with respect to the last clock round in which the bidder had sufficient eligibility to bid on this package and all subsequent eligibility reducing rounds (anchor rounds).

- Final cap

Table 3.6
Activity rules implemented for each CCA in each phase.
Source: Compilation based on information from regulator websites and other public information.

Year	Country	AR Clock	AR Supplementary
2016	Mexico	EP	Relative
2015	Canada	Hybrid	Simplified RP
2014	Canada	Hybrid	Simplified RP
2014	Slovenia	EP	Relative
2013	Australia	Hybrid	Relative
2013	Slovakia	EP	Relative
2013	Austria	EP	Relative (may relax or eliminate)
2013	UK 4 G	EP	Relative
2012	Netherlands	EP	Relative
2012	Ireland	Hybrid	Relative+Final
2012	Denmark	EP	Relative
2012	Switzerland	EP	Relative
2010	Austria	EP	Relative (may relax or eliminate)
2010	Denmark	EP	Relative
2010	Netherlands	EP	Relative
2008	UK L Band	EP	Relative
2008	UK 10 40 K	EP	Relative

The bid $b(q)$ must satisfy RP with respect to the LCR.

- Simplified revealed preference cap

Intermediate and final caps are combined, so the bid $b(q)$ must satisfy RP with respect to:

- The last clock round in which the bidder had sufficient eligibility to bid on this package and all subsequent eligibility reducing rounds (anchor rounds);
- LCR.

Table 3.6. shows a summary of the activity rules implemented in each phase of the CCAs. Austria is the only case in which the auctioneer reserves the right to relax the limits set by the RP constrain in the supplementary phase or even eliminate them.

Both Final Cap and Simplified Revealed Preference Cap activity rules set the limit with respect to the LCR, so the following hold (Ausubel & Cramton, 2011)[7]:

1. Stable allocation: If demand equals supply in the LCR, the final award would be the same as the LCR because supplementary bids cannot change the allocation.
2. Safe bids: If there are unsold items in the LCR, a bidder can ensure winning his last clock package by increasing the bid for that package by the value of the unsold lots at the final round prices and by not bidding on a package not containing his LCR package.
3. Pick up bids: If there are unsold items in the LCR, but at least one bidder submits the highest permitted supplementary bid for a package including his LCR allocation and the set of unallocated items, then in the final allocation, each bidder will get his LCR package, and one bidder will also obtain the unallocated lots. If instead of bidding on the complete set of unallocated items bidders bid on an incremental set, unallocated items can be distributed among different bidders.

Stability among both phases encourages truthful bidding throughout the clock phase, as bidders never know which will be the last round. However, many regulators thought that the rule resulted in too much stability and decided not to implement it. So far only Canada and Ireland have established constraints with respect to the LCR, and only the Irish regulator would release to each bidder information about the aggregate demand in the last clock round. Hence, in the Canadian auction, the LCR allocation was not guaranteed because bidders had to make guesses about unsold items in the LCR.

To analyze the stability between both phases, we have compared LCR and final allocation in the CCAs where the information is public.

- Mexico (Relative Cap):
  - Final allocation was the same as LCR. Telcel was already bidding his maximum amount in the LCR according to its cap (six lots), so it could not have submitted safe or pick up bids. ATT decided not to submit a pick up bid including the unsold lot, although it only asked for two lots. In the final allocation, there was one unsold item.
- Canada 2500 (Simplified Revealed Preference Cap):

[7] Assuming that a strict version of the revealed preference constraint with respect to the final clock round (T) is satisfied: $b(q) < b(q^T) + (q - q^T)\, p^T$.

- 318 licenses were auctioned, and the LCR ended with 38 unsold lots. Despite not knowing what the unsold lots were because the auctioneer did not provide information on aggregate demand in the LCR, all bidders maintained their final package. In addition, five bidders submitted successful pick up bids, which increased their LCR packages. Corridor Communications Inc., despite having a zero package in the LCR, obtained 16 items of the unallocated ones in the LCR. In the final outcome, there were still 16 unsold lots.

- Canada 700 (Simplified Revealed Preference Cap):
  - The Industry of Canada auctioned 98 licenses, and there were six unsold lots in the LCR. Again, no information about aggregate demand was provided in the LCR, and one bidder did not keep his last package. Telus lost two and won three licenses that were not in the LCR award. Others maintained their LCR packages. Bell added four licenses to this LCR package. At the end of the auction, there was one unallocated item.
- UK 4 G (Relative Cap):
  - The UK regulator offered 29 licenses, 22 of which were allocated in the LCR. However, only two bidders (Niche and Vodafone) won a larger package than their LCR one. Others got a different package with respect to the LCR. EE won 35 MHz, H3G lost 30 MHz and Telefonica, being most affected, lost 40 MHz. In the final allocation, all lots were awarded.
- UK L Band (Relative Cap):
  - The 17 licenses offered were entirely awarded to Qualcomm both in the LCR and the final allocation. This bidder only submitted a supplementary bid for the whole package, increasing his LCR bid amount.
- UK 10 40 K (Relative Cap):
  - 27 licenses were auctioned, and all except one were awarded at the end of the clock stage. However, four of the ten winners did not keep their LCR packages. There were also two bidders who, although they had sent a zero package in the LCR, won some licenses in the end. Three players won the same package as the LCR, and only one obtained a larger one. At the end of the process, there were no unallocated items.

3.5. Transparency

Another variable to decide is the amount of information provided to bidders during the process. A transparent model allows bidders to adapt as they observe their rivals' behavior, thus favoring price discovery. However, a less transparent design prevents collusive behavior that may generate lower profits, and it is even more important when competition is low.

Information provided between clock rounds and at the end of the clock phase is especially relevant in CCAs. Bidders always have full information on their own bids but none on their rivals, as anonymous bidding prevents coordination and encourages participation. The only information about the opponents' behavior is usually released through the aggregate demand (AD) per category after each clock round. However, not even this rule has been applied across all auctions. Table 3.7 shows a summary of the policy in each CCA.

Providing information on aggregate demand in the LCR is especially relevant if the activity rule settled upon depends on the LCR because bidders can guarantee winning their LCR package. However, these two conditions have only been given in the Irish auction.

Auctioneers must also decide which information should be released after the auction is completed. Only regulators from Canada, UK and Mexico (marked in bold) have made public full bid history.

Table 3.7
Aggregate information release per CCA.
Source: Compilation based on information from regulator websites and other public information.

Year	Country	AD release after each clock?	AD release in LCR?
2016	**Mexico**	**Yes**	**Yes**
2015	**Canada**	**Yes**	**No**
2014	**Canada**	**Yes**	**No**
2014	Slovenia	Yes	Yes[a]
2013	Australia	Yes	Yes
2013	Slovakia	Only at the end of the day	Yes[a]
2013	Austria	At its discretion (they did it publicly after round 39)	At its discretion
2013	**UK 4 G**	**No, only mention if there is excess demand**	**No**
2012	Netherlands	Yes	Yes
2012	Ireland	Yes, but only for non-set-aside lots	Yes
2012	Denmark	Yes	Yes[a]
2012	Switzerland	Yes	Yes[a]
2010	Austria	No	No
2010	Denmark	Yes	Yes[a]
2010	Netherlands	Yes	Yes
2008	**UK L Band**	**Yes**	**Yes**
2008	**UK 10 40 K**	**Yes**	**Yes**

Only regulators from Canada, UK and Mexico (marked in bold) have made public full bid history.

[a] If information offered after the LCR is not specified, we assume it is the same as at the end of each clock round.

Table 3.8
Price increment in clock phase settle per CCA.
Source: Compilation based on information from regulator websites and other public information.

Year	Country	Max price increment per round
2016	Mexico	Most likely between 3% and 10% and never above 30%
2015	Canada	Between 1% and 20%
2014	Canada	Between 1% and 20%
2014	Slovenia	Most likely between 2% and 20% and always between 1% and 50%
2013	Australia	Not available
2013	Slovakia	Max increase 30%
2013	Austria	Between 2% and 15%
2013	UK 4 G	Most likely between 5% and 15% and never above 100%
2012	Netherlands	Max increase 100%
2012	Ireland	Max increase 20%
2012	Denmark	Max increase 100%
2012	Switzerland	Max increase 100%
2010	Austria	Between 2% and 15%
2010	Denmark	Max increase 100%
2010	Netherlands	Max increase 100%
2008	UK L Band	Max increase 100%
2008	UK 10 40 K	Max increase 100%

3.6. Price increment in clock phase

Between rounds, the auctioneer increases prices for those categories where there is excess demand. This increase can be:

- A fixed rate for all categories
- A different increment depending on the excess demand.

In all CCAs studied, the price increment between clock rounds is set at the auctioneer's discretion and may vary across categories and across primary rounds. Regulators usually give a range or a maximum possible increment. Table 3.8. shows these ranges or maximum increments.

3.7. Pricing rule

The pricing rule of all CCAs is established on a second price basis, in which each winning bidder pays an amount equal to the opportunity cost of the awarded items: the Vickrey Clarke Groves (VCG) mechanism. The main advantage is that it is incentive compatible, i.e., truth telling is the dominant strategy for all bidders. However, it also has important drawbacks (Ausubel et al., 2006). Vickrey prices may be too low because of complement items, and the final payment may not be in the core. In other words, there may be a coalition of bidders who would strictly prefer an alternative allocation, including the seller. To solve this problem, some authors have proposed a core selecting mechanism (Day and Milgrom, 2008; Day and Raghavan, 2007), but the bidder optimal core prices are usually not unique. To date, all CCAs have implemented a core selecting mechanism, and most of them have selected the Vickrey nearest core pricing presented by Day and Cramton (2012).[8]

4. CCA result history

As noted in the previous section, each regulator has customized CCAs according to their market structure and expectations, yielding different outcomes. The main results are summarized below.

4.1. Mexico 1710 1780 MHz /2110 2180 MHz (2016)[9]

The Instituto Federal de Telecomunicaciones (IFT) of Mexico auctioned 80 MHz, with a total of 8 lots split into three categories (A, G and J). An additional 2×5 MHz A lot was included in the auction to be reallocated for contiguity purposes, as it was partially held by Telcel (10.1%) and AT & T (89.9%). A cap for A lots plus an overall cap among categories was settled. The main problem of this auction was that Telefonica, one of the three incumbents expected to be involved, finally decided not to participate, so there was no competition. Furthermore, AT & T chose to submit the minimum possible bid, according to the caps, that would ensure the auction would end in the first round. Although there was an unsold lot in the LCR, AT & T did not bid for it in the supplementary stage. Telcel was already bidding the maximum amount in the first and unique round. Table 4.1. shows the final outcome. The MHz

[8] Mochon, Saez, Gomez-Barroso, and Isasi (2012) analyzes the implications of selecting a particular pricing rule on combinatorial auctions.
[9] Auction rules are in Instituto Federal de Telecomunicaciones IFT (2015) and both bids and final results are in Instituto Federal de Telecomunicaciones IFT (2016).

Table 4.1
Mexico 2016 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)
Telcel	60	108.02	111.13
AT & T	20	54.65	54.65
Unsold	10	3.44	
Total	90	166.11	165.78

2015 Mexico population was obtained from www.worldpopulationstatistics.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

acquired includes an A lot that was previously held by Telcel and AT & T. Nevertheless, the value of this contributed spectrum is not included in the reserve price or in the final price.

4.2. Canada 2500 MHz (2015)[10]

Industry of Canada offered 318 licenses across 61 service areas. A 40 MHz cap per area, including previous holdings, was settled, which mainly affected two of the incumbents: Bell and Rogers. Despite the cap, competition was strong during the 39 clock rounds. Nine of the eleven bidders ended up winning licenses. The average final price was well above the reserve (209% price increment) although there was a significant deviation between bidders, see Table 4.2. The LCR served as the reference for the final allocation, but it did not help in terms of price discovery. Every bidder kept the LCR package, and some of them added new lots by submitting pick up bids. Nevertheless, there were important discounts in the final payment with respect to the LCR prices (See Appendix A). The auction ended with 16 unallocated licenses. The starting price was 0.0734 $/MHZ pop and the auction final price was 0.229 $/MHZ pop.[11]

4.3. Canada 700 MHz (2014)[12]

Industry of Canada auctioned seven licenses (five paired and two unpaired) in 14 service areas, a total of 98 licenses. A cap of two paired lots per area was fixed plus an aggregate cap for large wireless service providers (virtual set aside). Competition was very intense among the ten qualified bidders throughout the auction with final prices 488% above reserve. In total, 106 clock rounds were needed to eliminate the excess demand. Seven of the eight winners obtained their LCR package, and Bell even managed to obtain four additional licenses. Telus was the only bidder that failed to maintain the LCR package. The clock phase was not helpful in terms of price discovery, there were significant discounts in the final payment respect to LCR prices, See Appendix A. Table 4.3. displays the final prices and price increments. As observed, there were important differences in the final prices paid per bidder. The average starting price was 0.3602 $/MHz pop and the final price 2.117 $/MHz pop. There was only one unsold item in the final allocation.

4.4. Slovenia 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz (2014)[13]

In the 2014 Slovenia auction, 55 lots grouped into ten categories were auctioned. The auctioneer imposed caps per category and across categories. Additionally, the Slovenian market agency enforced a set aside in which it reserved up to two 2×5 MHz blocks of 800 MHz spectrum for new entrants and small players. Three out of four of Slovenia's mobile operators took part in the auction, and all became winners. The clock phase lasted for 55 rounds, and in the final allocation there were three unsold: 20 MHz in the 1800 MHz band and 10 MHz in the 2100 MHz FDD band. Tušmobil benefitted from caps and set aside, winning spectrum at approximately the reserve value. Others competed for licenses auctioned, so the final prices were 52% above reserve. For more details, see Table 4.4.

4.5. Australia 700 MHz and 2.5 GHz (2013)[14]

The 2013 Australian auction offered 9 national lots of 2×5 MHz in the 700 MHz band and 14 lots of 2×5 MHz in the 2.5 GHz band across 11 regions. The auction only lasted 3 rounds, and already in the first round, there was no excess demand for the 700 MHz band. Although the Australian Communications and Media Authority settled high caps (50 MHz in the 700 MHz band and

[10] Industry Canada (2015a, 2015b) document collects the auction rules. Final results and full bid history can be found in Industry Canada (2015a).
[11] Given the combinatorial nature of the CCAs in which a final price for the whole package is obtained, we have only calculated the $/MHz-pop per bidder in single band auctions.
[12] Industry Canada (2013) describes the auction mechanism. Final results and full bid history can be found in Industry Canada (2014).
[13] Auction rules are in Agency for communication networks and services of the Republic of Slovenia AKOS (2013), where results can also be found. More information about the final outcome can be found at Mourad (2014).
[14] Australian rules can be found in two documents: Australian Communications and Media Authority ACMA (2012, 2013a, 2013b). Public information about the results can be found in Australian Communications and Media Authority ACMA (2013b).

Table 4.2
Canada 2015 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
Bell	1020	13.71	23.01	68
Bragg	220	2.81	3.83	36
Corridor	260	1.83	1.83	0
MTS	40	1.78	1.78	0
Rogers	820	13.29	19.13	44
TBayTel	40	0.34	1.37	308
Telus	2440	106.25	380.19	258
Videotron	360	42.05	148.44	253
Xplornet	840	11.81	20.20	71
Unsold	320	6.11		
Total	6,040	199.98	599.78	209[a]

Canada population was obtained from the original rules. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.
[a] The price increment is calculated by dividing the final payment by the reserve value allocated items.

Table 4.3
Canada 2014 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
Feenix	10	0.26	0.26	0
MTS	10	2.92	8.02	174
Bragg	40	7.51	18.55	147
Telus	264	201.63	1044.50	418
Videotron	70	134.58	213.23	58
Bell	274	183.05	516.98	182
Sasktel	10	2.52	6.91	174
Rogers	264	287.27	3008.19	947
Unsold	10	0.26		
Total	952	820.00	4816.62	488[a]

Canada population was obtained from the original rules. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.
[a] The price increment is calculated by dividing the final payment by the reserve value allocated items.

Table 4.4
Slovenia 2014 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
Simobil	225	48.27	87.61	82
Telekom Slovenije	195	58.36	88.06	51
Tušmobil	50	27.84	28.35	2
Unsold	30	9.05		
Total	500	143.53	204	52[a]

Slovenia 2014 population was obtained from http://countryeconomy.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.
[a] The price increment is calculated by dividing the final payment by the reserve value allocated items.

80 MHz in the 2.5 GHz band), 30 MHz of the 90 MHz offered in the 700 MHz band (worth approximately $1 billion) went unsold. Table 4.5. shows that bidders paid marginally above reserve for the acquired lots. Most likely, high reserve prices were the main reason for the low competition and the disappointing result.

4.6. Slovakia 800 MHz, 1800 MHz and 2600 MHz (2013)[15]

In 2013, the Slovakian regulator (TUSR) offered 38 licenses in a multiband auction and established a cap per band to encourage

[15] Auction rules are in Regulatory Authority for Electronic Communications and Postal Services (2013a, 2013b) and results are published at Regulatory Authority for Electronic Communications and Postal Services (2013c). Telefonica (2014) includes more information about the auction.

Table 4.5
Australia 2013 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
Optus Mobile	460	666.46	666.46	0.00
Telstra	920	1332.91	1336.76	0.29
TPG Internet	220	13.86	13.86	0.00
Unsold	30	958.10		
Total	1630	2971	2017	0.19[a]

Australia 2013 population was obtained from www.acma.org. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

[a] The price increment is calculated by dividing the final payment by the reserve value allocated items.

Table 4.6
Slovakia 2013 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
Orange	89.6	61.33	73.68	20
Slovak Telekom	150	66.72	79.85	20
SWAN	30	8.67	8.67	0
Telefonica	21.2	50.30	52.93	5
Total	290.8	187.02	215.13	15

Slovakia 2013 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

new players. In the 800 MHz band, 60 MHz was auctioned and a 2×10 MHz cap was settled. The three incumbent bidders won the maximum spectrum without competition as there was no new entrant participation, most likely because of the high opening bid. In the 1800 MHz band, only Swan (alternative telecommunications service provider) was allowed to bid on the 2×5 MHz lot because of the cap, turning this spectrum into a set aside that Swan acquired at reserve. Finally, the entire spectrum was awarded, and the final average price was 15% above reserve. Table 4.6. shows the final outcome per bidder.

4.7. Austria 800 MHz, 900 MHz and 1800 MHz (2013)[16]

Before the auction, the Austrian regulator offered set aside spectrum for new entrants in the 800 MHz band, but because it was not taken, all spectrum was auctioned in the main auction. A total of 28 licenses were offered in the multi band process and caps were set up per band and across bands although they turned out to be especially lax. This CCA had two implementations that differ from others:

- The relative cap activity rule was settled in the supplementary phase but the regulator reserved the right to relax and increment the max bids in the supplementary phase and even to suspend the limits entirely.
- The regulator did not disclose information on aggregate demand until round 39. Then, due to high prices, transparency was increased to facilitate coordination among the bidders.

According to Austrian Telekom Control Kommission TKK (2013a, 2013b), the bidders bid aggressively during the clock phase, which lasted 72 rounds. Spectrum valued at LCR prices was approximately $2.6 billion, and with no supplementary bids, the final revenue would have been approximately $1 billion. Nevertheless, in the supplementary phase, bidders bid aggressively to increase their rivals' prices in packages unlikely to win. Hence, the final prices were surprisingly high, 270% above reserve (see Table 4.7).

4.8. UK 4 G 800 MHz and 2.6 GHz (2013)[17]

Ofcom offered 60 MHz in the 800 MHz band and 190 MHz in the 2.6 GHz band. The auction started with seven qualified bidders. To encourage the entry of a new entrant in the market, Ofcom included caps (overall and sub 1 GHz) and set aside spectrum. Although the clock phase lasted 52 rounds and final prices were 74% above reserve, the auction revenues were below expectations. The LCR did not provide helpful information about the final outcome. The relative cap activity rule was settled and only two out of

[16] Rules were summarized from Austrian Telekom-Control-Kommission (2013a)
[17] Office of Communications (2012a, 2012b) include the process rules. Auction results and bidding history are available at: Office of Communications (2013).

Table 4.7
Austria 2013 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
A1 Telekom	140	380.36	1,370.64	260
T-Mobile	90	258.18	871.02	237
Hutchison	50	86.64	439.29	407
Total	280	725.18	2,680.94	270

Austria 2013 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

Table 4.8
UK 2013 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
H3G	10	532.37	950.00	78
EE	80	362.98	362.98	0
Niche	55	73.40	325.13	343
Telefonica	20	403.31	887.28	120
Vodafone	85	823.56	1,295.21	57
Total	250	2,195.62	3,820.60	74

UK 2013 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

five winning bidders kept their LCR package. Bidders also had an important discount respect to LCR prices, between 39% and 49% (See Appendix A). In the LCR, there were seven unallocated items that were sold in the final award. Table 4.8. summarizes the final outcome per bidder.

4.9. Netherlands 800 MHz, 900 MHz, 1800 MHz, 1900 MHz, 2100 MHz and 2600 MHz (2012)[18]

In 2012, the Radiocommunications Agency Netherlands auctioned 359.6 MHz from six different spectrum band divided in 41 lots. There were five qualified bidders but only four of them were winners. The Dutch regulator decided to set aside two sub 1 GHz licenses for newcomers that benefit Tele2 that end up paying lower prices respect to other bidders in the 800 MHz band. Nonetheless, incumbents bid aggressively and one failed to win any 800 MHz spectrum. Final prices were 695% above reserve, see Table 4.9.

4.10. Ireland 800 MHz, 900 MHz and 1800 MHz (2012)[19]

In the Ireland auction, ComReg offered 560 MHz divided in 56 licenses grouped into two time slides:

- 28 licenses in time slice 1: available from 2013 until 2015.
- 28 licenses in time slice 2: available from 2015 until 2030.

The regulator fixed tight spectrum caps for each time slide and established set aside spectrum only for specific bidders (party specific lots). During the clock phase, eligibility was calculated separately for each time slice, and transfer among them was not possible. In the supplementary phase, both relative and final caps were settled. Furthermore, bidders were informed about aggregate demand in LCR, so each bidder could guarantee the LCR package even if there were unsold lots. Table 4.10 summarizes the auction results, in which the bidding was intense and resulted in final prices 131% above reserve.

4.11. Denmark 800 MHz (2012)[20]

In 2012, the Danish Business Authority auctioned 2×30 MHz in the 800 MHz band and set a 2×20 MHz cap. This auction had an

[18] Rules are included in Staatscourant (2012). Results are published at Radiocommunications Agency Netherlands (2012). KPN (2012) makes a further analysis of the auction.
[19] Irish Commission for Communications Regulation (2012a, 2012b, 2012c) includes the auction rules, and the results can be accessed in Irish Commission for Communications Regulation (2012a, 2012c)
[20] Auction rules in Danish Business Authority (2012). Auction outcome and other related documents are available at Danish Business Authority (2013)

Table 4.9
Netherlands 2012 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
KPN	120.0	192.35	1,749.82	810
Vodafone	90.0	187.81	1,787.36	852
T-Mobile	129.6	148.79	1,179.06	692
Tele 2	20.0	90.60	208.37	130
Total	359.6	619.55	4,924.61	695

Netherlands 2012 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

Table 4.10
Ireland 2012 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price[a] (million $)	Price increment (%)
Hutchison	80	37.57	64.31	71
Meteor	120	69.95	182.08	160
O2	110	69.96	157.12	125
Vodafone	160	85.14	202.29	138
Unsold	90	15.98		
Total	560	278.61	605.81	131[b]

Ireland 2012 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.
[a] Usage fees not included in final price.
[b] The price increment is calculated by dividing the final payment by the reserve value allocated items.

Table 4.11
Denmark 2012 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
TDC	40	33.86	106.28	214
TT-network	20	10.16	18.87	86
Total	60	44.01	125.14	184

Denmark 2012 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

innovative component: bidders could bid for regional exemptions from the coverage obligation imposed by default. Three bidders were involved, but only two of them acquired spectrum. TT network won 20 MHz plus the exemption from the coverage obligation. Table 4.11. shows the outcome per bidder. Although the final prices were 184% above reserve, the final revenues were low. The opening bid was 0.1312 $/MHz pop, the lowest of all CCAs analyzed and 0.373 $/MHz pop the final value, still below the reserve fixed in some other auctions.

4.12. Switzerland 800 MHz, 900 MHz, 1.8 GHz, 2.1 GHz and 2.6 GHz (2012)[21]

The Swiss regulator ComCom auctioned 605 MHz across several bands with difference license terms. There was substantial amount of spectrum available and only the three incumbent operators participated, all of them won spectrum. Caps per band as well as overall caps were settled. The clock phase lasted many rounds and although final prices were 65% above reserve, final revenues were not as high as in other countries. An interesting outcome was the significant difference in the final prices paid per bidder.

[21] Swiss Federal Communications Commission (2011a, 2011b) describes the auction mechanism. Results included in Swiss Federal Communications Commission (2011b)

Table 4.12
Switzerland 2012 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
Orange	160	657.66	168.29	
Sunrise	160		524.04	
Swisscom	255		391.46	
Unsold	30	22.36		
Total	605	680.02	1,083.80	65[a]

Switzerland 2012 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

[a] The price increment is calculated by dividing the final payment by the reserve value allocated items.

Sunrise paid 211% more than Orange for the same spectrum and 34% more than Swisscom for 95 MHz less, see Table 4.12 (reserve price per bidder could not be calculated, because the specific band allocation was not found).

4.13. Austria 2.6 GHz (2010)[22]

In the 2.6 GHz band auction 24 licenses were offered and allocated among the four participants. Caps that differed per operator were established depending on whether they had previous holding on the 900 MHz or 1800 MHz band. Although the final prices were well above reserve, the auction outcome was relatively small compared to those of other countries as reserve prices were settled very low: 0.0008 $/MHz pop. The final average price was 0.004 $/MHz pop, below the reserve price for the same band of some other auctions, probably because of the strict roll out obligations. Table 4.13 summarizes the final outcome.

4.14. Denmark 2500 MHz and 2010 MHz (2010)[23]

The Danish regulator offered 140 MHz of paired spectrum and 50 MHz of unpaired spectrum in the 2500 MHz band. Moreover, one lot of 15 MHz was offered in the 2010 MHz band that was unsold. The auction saw high competition as the four incumbents fought for 2×20 MHz of paired spectrum (matching the cap for that category) until Hi3G dropped the demand to 2×10 MHz. The process generated high benefits and final prices were 5,216% above reserve. The starting price was 0.003 $/MHz pop and the final price 0.174 $/MHz pop, for the 2500 MHz band. Table 4.14. shows the final results.

4.15. Netherlands 2.6 GHz and 2010 MHz (2010)[24]

In the 2010 Netherlands auction, supply in the 2010 MHz band was on a lot of 9.7 MHz that was unsold. Supply in the 2.6 GHz band was 190 MHz, of which 55 MHz was unallocated. To promote new entrants, bidders were capped depending on their current spectrum holdings. However, caps on incumbents for paired spectrum were set very tightly, so there was not enough demand to increase prices above reserve. Vodafone and Tele2 got their packages at reserve, and Tele2 won and additional 5 MHz block (guardband). Due to the lack of competition and the low reserve prices, the final revenues were not as high as expected. In the 2500 MHz band, the starting price was 0.0008 $/MHz pop and the final price was only 0.0016 $/MHz pop. Table 4.15. shows the result for the five bidders involved in the auction.

4.16. UK L Band MHz (2008)[25]

In the UK L Band auction, Ofcom auctioned 39.7 MHz divided in 17 licenses in the 1400 MHz band. No spectrum caps were settled. The clock phase lasted 33 rounds, and although there were 8 qualified bidders, all lots were allocated to Qualcomm.

Allocation in LCR remained after the supplementary phase. Final prices were 777% above reserve (Table 4.16) although the winner obtained 55% discount respect to LCR prices (See Appendix A).

4.17. UK 10, 28, 32, 40 GHz (2008)[26]

This auction was Ofcom's first CCA, in which 10 players were involved and 5832 MHz were offered grouped in 27 lots. No spectrum caps were settled. After 17 clock rounds, there was no excess demand, and bidders submitted their supplementary bids. All

[22] Rules and results are available at the regulator website: Austrian Telekom-Control-Kommission (2010a, 2010b)
[23] National IT & Telecom Agency (2010b) collects the rules, and results can be found at National IT & Telecom Agency (2010a)
[24] Rules are in Staatscourant (2009) and results can be found at Radiocommunications Agency Netherlands (2010)
[25] Office of Communications (2008c) include the auction rules. Bidding history and results are available at Office of Communications (2008b).
[26] Rules can be found in Office of Communications (2007). Bidding history and results are available at Office of Communications (2008a).

Table 4.13
Austria 2010 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
A1	65	3.38	17.21	410
T-Mobile	40	2.08	14.61	603
Orange	20	1.04	5.20	400
Hutchison	65	3.38	14.33	324
Total	190	9.88	51.36	420

Austria 2010 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

Table 4.14
Denmark 2010 outcome.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
Hi3G	45	0.82	1.28	58
TDC	40	0.72	60.38	8,233
Telenor	50	0.91	60.38	6,567
Telia	55	1.00	60.93	6,015
Unsold	15	0.09		
Total	205	3.53	182.98	5,216[a]

Denmark 2010 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.
[a] The price increment is calculated by dividing the final payment by the reserve value allocated items.

Table 4.15
Netherlands 2010 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
Vodafone	20	0.27	0.27	0
Zigo	40	0.54	1.35	152
T-Mobile	10	0.13	0.15	9
KPN	20	0.27	1.22	355
Tele2	45	0.54	0.54	0
Unsold	64.7	0.80		
Total	199.7	2.54	3.52	102[a]

Netherlands 2010 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.
[a] The price increment is calculated by dividing the final payment by the reserve value allocated items.

Table 4.16
UK L-Band 2008 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
Qualcomm	39.7	1.87	16.40	777

UK 2008 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

bidders won a package, but the LCR allocations and final awards were not the same. Final revenues were 75% above reserve but still lower than expected (Table 4.17.). All bidders got a discount between 69% and 83% respect from LCR prices (Appendix A) and some of them paid reserve prices.

Table 4.17
UK 10 40 K 2008 outcome.
Source: Compilation based on information from regulator websites and other public information.

Bidder	MHz	Reserve price (million $)	Final price (million $)	Price increment (%)
Arqiva	448	0.45	0.62	40
BT	252	0.23	0.53	127
Digiweb	40	0.23	0.51	117
Faultbasic	224	0.12	0.36	205
Orange	504	0.17	0.35	99
T-Mobile	1,164	0.23	0.23	0
Transfinite	224	0.04	0.08	95
UKBB	2,000	0.06	0.06	0
MLL	752	0.04	0.04	0
Red-M	224	0.02	0.02	0
Total	5,832	1.59	2.79	75

UK 2008 population was obtained from www.google.com. Prices were converted from local currencies into USD using www.xe.com exchange rates at the auction date.

5. Pros and cons of CCAs: evidence of actual cases

5.1. CCA advantages

The CCA has proven to be a good allocation mechanism that solves many of the problems found in previous models. First, it enables the offering of heterogeneous lots (substitutes and complement items), eliminating the exposure problem, as all bids are made for complete packages, thus avoiding the risk of winning only part of the demanded lots.

Setting generic and technology neutral lots allows bidders to substitute items and enables the auction itself to determine how the spectrum is organized. Thus, regulators no longer have to present fixed band plans, which could result in inefficiency.

With the clock phase, bidders solve the package discovery problem, because as the price increases, bidders can discover their own demand and substitute lots according to relative prices.

The supplementary phase allows bidders to fully express their preference, as they can increase their bids for packages they already bid on in the clock phase and can bid for new packages. Finally, in the assignment stage, specific lots are awarded to winning bidders, allowing regulators to allocate contiguous lots.

5.2. Advantages that did not work as expected

However, from a theoretical point of view, the CCA has two fundamental qualities that, in practice, have been threatened: price discovery and truthful bidding.

5.2.1. Price discovery

One of the great advantages of the clock phase is that, combined with an effective activity rule, it favors price discovery. However, an argument against CCAs is that LCR prices do not always provide helpful information about final prices, because the second price rule is implemented.

This is what has happened in many of the auctions conducted. Table 5.1. shows final price discounts with respect to LCR for those auctions in which full bidding information is available. Except for Mexico, where there was only one round, the auctions experienced discounts of between 29% and 79%. This table shows the discounts grouped for all bidders per auction, but when the analysis is performed per bidder, the dispersion is even greater. For example, in the 2015 Canadian auction, TBayTel paid LCR prices, while Corridor's discount was 83.32%. Appendix A includes the discount per bidder in these auctions.

5.2.2. Truthful bidding

Another expected advantage of CCAs is that bidders have the incentive to bid truthfully in the clock phase (because of the activity

Table 5.1
Final payment discounts with respect to LCR prices.
Source: Compilation based on information from regulator websites and other public information.

Year	Country	N° rounds	LCR value sold (million $)	Final payment (million $)	Discount (%)
2015	Canada	39	1,368.57	599.78	56
2014	Canada	106	6,797.72	4,816.62	29
2013	UK 4 G	52	6,565.89	3,820.60	42
2008	UK L Band	33	36.66	16.40	55
2008	UK 10 40 K	17	13.28	2.79	79

Table 5.2
Average number of supplementary bids submitted per auction.
Source: Compilation based on information from regulator websites and other public information.

Year	Country	N° bidders	N° SP bids	Average number of SP bid
2016	Mexico	2	6	3
2015	Canada	11	1332	121
2014	Canada	10	1209	120
2013	UK 4 G	7	277	39
2008	UK L Band	8	34	4
2008	UK 10 40 K	10	712	71

rules) and in the supplementary phase (because of the second price rule).

However, in the clock phase, many of the real cases only implemented the eligibility point activity rule causing some bidders to be unable to bid according to their true valuations in some rounds.

Moreover, if the revealed preference activity rule with respect to the LCR is implemented in the supplementary phase, supplementary bids cannot modify the LCR allocation if:

- there is no excess demand in the LCR,
- there is excess demand in the LCR but bidders are informed about unallocated items and submit safe bids.

Therefore, if the allocation is fixed, according to the second price rule, a bidder's payment only depends on the bids of the others. Then bidders could have incentives to deviate from truthful bidding and instead engage spiteful bidding to try to increase their rivals' prices without risk. Among the authors who analyze how bidding behavior deviates from truthful bidding, both in theoretical and experimental work and with reference to real auctions, we highlight (Bichler et al., 2013; Kroemer et al., 2016; Levin and Skrzypacz 2014). Hence, truthful bidding is not an attribute in CCAs.

Some of these authors also mentioned the "missing bids" problem, as the data reveal that bidders tend to make fewer supplementary bids than they would if they had really been following their preference structure. This has a negative impact on revenues. Furthermore, Scheffel et al. (2012), report on laboratory experiments comparing the Combinatorial Clock auction, the Hierarchical Package Bidding format, and an auction format with pseudo dual prices in large value models with 18 items. They found the limited number of packages that bidders evaluate to be the greatest barrier to efficiency, much more so than differences in the auction formats.

Table 5.2. indicates the average number of supplementary bids submitted in each CCA for which bidding history information is available.

To solve the missing bids problem, Ausubel and Baranov (2014b) proposed combining mutually exclusive and non mutually exclusive bids (XOR and OR bidding language). The goal with this innovation is to enable bidders to bid easily for a higher number of packages. This option is particularly relevant in countries with regional licenses, such as Australia and Canada, where there are a large number of items. The OR bidding option can be implemented as the possibility that bidders have to specify various OR bids as increments on top of their final clock package. Nevertheless, in order to guarantee the success of this option, it is important to incorporate various controls over the OR bids submission, such as: total size limit or total budget limit. Furthermore, an appropriate activity rule for OR bids must be designed. The combination of XOR and OR bids was implemented in 2015 in Canada, but only 3 of the 11 bidders used the OR option, and a total of 5 OR collections were submitted.

5.3. Other reviews

One common critique to CCAs is that this auction mechanism violates the "law of one price", as bidders do not pay the same price for identical lots, resulting in frequently embarrassing outcomes. Some examples are presented below:

- Canada 2014: Important differences can be found when comparing the results of the three incumbents bidding on all areas. Rogers paid $3,000 million for 264 MHz of paired spectrum. For the same amount of spectrum (180 MHz paired plus 84 MHz unpaired), Telus paid 65% less. Bell paid 83% less than Rogers for 190 MHz paired and 84 MHz unpaired.
- Switzerland 2012: Orange and Sunrise won 160 MHz across bands, but Sunrise paid 3.1 times more than Orange. Swisscom was awarded 255 MHz and paid 25% less than Sunrise for a package that included significantly more 1800 MHz and 2.1 GHz spectrum.
- Netherlands 2010: Thirteen lots of 2×5 MHz were allocated in the 2.6 GHz band. Vodafone, T Mobile and Tele2 won two, one and four lots, respectively, at approximately reserve. Zigo and KPN obtained four and two lots, paying 1.5 and 3.5 times reserve, respectively.

Finally, another problem that has been highlighted in some countries is that, if only the Relative Cap activity rule is implemented, there may be a large difference between final and LCR allocation. This creates a feeling of lack of control, as bidders do not have the option to react after the supplementary phase. The UK 2013 and UK 2008 10 40 K auctions are clear examples.

6. Conclusions

After a decade since the CCA was first presented, it is time to analyze the results. Over previous designs, the CCA has proven to be an innovative model that solves many of the problems identified. This mechanism has many of the desired advantages in these processes: bidders have the ability to set the band plans as generic, and natural technology lots can be offered; it mitigates the exposure problem that appears when auctioning complements items; the clock phase helps with the package discovery problem; and the assignment stage allows contiguous lots to be awarded.

However, the experience of recent years also indicates that the model has important weaknesses. A main concern, under certain activity rules, is that the allocation of the last clock round cannot be changed with supplementary bids. Thus, with a second price rule, instead of the desired truthful bidding behavior, bidders are incentivized to engage spiteful bidding to increase their rivals' prices without any risk (or very low). Price discovery has also been a missing attribute in many cases as large discounts can been found in final prices with respect to LCR as well as significant differences among bidders.

It is also important to remark that, as in any auction, details matter, and the final outcome will be largely affected by the design of key variables such as spectrum packaging policy, reserve price, demand limits, activity rules, transparency, price increment and pricing rules. All these practical implementations along with the market structure of each country will have a strong impact on the results.

Given this situation, some authors have already begun to present modifications to improve the actual model and overcome the disadvantages found. Ausubel and Baranov (2014b) propose an evolution of the CCA with three main innovations. First, OR bids are combined with XOR bids. Second, the activity rule is based on the Generalized Axiom of Revealed Preference (GARP) instead of the Weak Axiom of Revealed Preference (WARP). Finally, an iterative first price rule is implemented. In the iterative pricing format the exposure calculation is computed in each round as the maximum amount that a bidder could ever have to pay to win a package if this were the final clock round of the auction. The main advantages of this approach are that it would reduce the tension between strict activity rules and second pricing and it reduces the importance of bidders' budget constraints.

DotEcon (2016) proposed a new auction format, the Combinatorial Multi Round Ascending Auction (CMRA), which combines an iterative 'pay your bid' approach with a combinatorial bidding framework. This mechanism replaces the supplementary phase with an opportunity for bidders to submit bids for alternative packages during the clock phase, subject to constraints that link these new bids to the previous clock prices. In May 2016, the Danish Energy Agency published a draft indicating that this auction mechanism will be implemented to allocate 2×64.9 MHz in the 1800 MHz band.[27]

Finally, led by professor Paul Milgrom, the United States Federal Communications Commission (FCC) has implemented the ambitious "incentive auction". This is a completely novel approach in the market. It buys back spectrum from television stations (reverse auction) and repackages it, releasing new spectrum available for auction to the telecom industry (forward auction). First, an initial clearing target is decided. Then, prices fall in the reverse auction until the supply equals the clearing target. Finally, prices rise in the forward auction. This exceptional auction design allows bidders to exchange spectrum at the same time that the band plan is organized.

Spectrum allocation mechanisms are evolving, and sophisticated solutions are being developed. Market designers are working hard to discover new processes that accomplished all the needs of this complex market and regulators' spectrum policies. Future research will be required in order to validate these new proposals.

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Appendix A. Final payment discounts respect to LCR prices

This section present the discount obtained for each bidder in their final payment respect to the LCR values. Table A.1. shows data for the auctions held in Canada, in which significant differences can be found among bidders.

Table A.2. displays the same information for the UK auctions in which differences among bidders in the same auctions are not that significant. It can be argued that while the clock phase did not help disclose information on final prices, it served as indicator on relative prices.

This analysis has only been done for these auctions in which the full bidding history is available.

[27] http://www.ens.dk/auktion-frekvenser-1800-mhz-baandet (last accessed on 26 Jun 2016).

Table A.1
Final payment discount respect to LCR prices in the Canadian auctions.
Source: Compilation based on information from regulator websites and other public information.

Bidder	CANADA 2015	CANADA 2014
Bell	62.34%	60.0%
Bragg	60.13%	47.7%
Corridor	83.32%	
MTS	14.07%	19.2%
Rogers	67.22%	16.3%
TBayTel	0.00%	
TELUS	53.89%	26.8%
Videotron	57.52%	50.2%
Xplornet	60.50%	
Feenix		17.9%
Sasktel		36.6%

Table A.2
Final payment discount respect to LCR prices in UK auctions.
Source: Compilation based on information from regulator websites and other public information.

Bidder	UK 2013	UK 2008 L Band	UK 2008 10 40 K
EE	44.81%		
H3G	46.81%		
Niche	49.36%		
Telefonica	34.99%		
Vodafone	39.91%		
Qualcomm		55%	
Arqiva			81.58%
BT			69.19%
Digiweb			71.74%
Faultbasic			76.92%
Orange			77.09%
TMobile			83.02%
Transfinite			79.38%
UKBB			80.13%
MLL			75.97%
Red-M			72.97%

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