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Revealed-Preference Activity Rule in Combinatorial Clock Spectrum Auction: A Review and New Research Opportunities

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***Abstract*—Simultaneous Multiple Rounds Auction (SMRA) and Combinatorial Clock Auction (CCA) are two most dominant types of spectrum auctions in use today. CCA has potential to surpass SMRA as the standard for spectrum auctions. CCA's first practical implementations were the Trinidad and Tobago spectrum auction in 2005 and recently, Innovation, Science and Economic Development (ISED) Canada will held an auction for 600MHz licenses using CCA. New and improved auction format and rules emerged, led by advancement in auction theories and designs. The need of well understanding about CCA is a must in spectrum auction industry. CCA consist of Allocation Stage: Clock Rounds phase and Supplementary Round phase. This paper explain the road of CCA evolution and detailed focus in complexity in clock rounds phase. Two different activity-rules in clock rounds phase has been explain in this paper. We can conclude some of the future research in Combinatorial Clock Auction: the need of tools for clock rounds phase, the component tools to solve winner determination problem in supplementary round, and the pricing rule in CCA.**

Keywords: Combinatorial Clock Auction, CCA, Spectrum Auction, Spectrum Frequency Auction, Activity rule-based, SMRA

I. INTRODUCTION

Radio frequency is a limited and scarce resource. It has strategic values for both private users and communications service providers. Since this resource had strategic and economic values, its usage must be regulated and managed by government. Government could grant licenses using "first-come, first-serve", where the demand for such spectrum is not exceed the supply. In instances where the demand is high, competitive licensing process (such as an auction) is used. Therefore, mechanism of "frequency spectrum auction" becomes an alternative mechanism in frequency licenses request compliance.

In July 17-19 2018, The International Telecommunication Union (ITU) held the 4th Annual Asia Pacific Spectrum Management Conference in Bangkok, Thailand. This conference becomes an annual meeting point for all stakeholders of the ICT industry (regulators , operators, vendors, consultants and academics) to jointly discuss issues related to the management and coordination of spectrum policies in the Asia Pacific region as well as in the world. The Indonesian delegation from the Directorate General of Resource Management and Equipment Standard of Post And Information Technology (SDPPI) shares experiences on the success of Indonesia, especially the Directorate General of SDPPI Kemkominfo, in the auction process of 2.1 GHz and 2.3 GHz radio frequency spectrum bands conducted since 2006, 2009, 2011, 2013 and 2017 through various auction formats, beauty contest, and finally in 2017 through multi-round electronic auction method or commonly known as Simultaneous Multi Round Action (SMRA).

SMRA is one of dominant types of spectrum auctions in use today. The other is Combinatorial Clock Auction (CCA) by Cramton in [1]. CCA format was proposed in 2006 at FCC's Wye River Conference by Ausubel, Cramton and Milgrom [2], it has potential to surpass SMRA as a spectrum auction standard.

CCA first implemented at Trinidad and Tobago's spectrum auction (2005), and the UK's 10–40 GHz and L-Band auctions (2008). Recently, it has been applied for spectrum auctions in Austria, Australia, Canada, Denmark, Ireland, the Netherlands, Slovakia, Switzerland, and the United Kingdom. Table 1 below is a summary of the spectrum auction implementing countries.

Table 1 shows that Indonesia has not implemented CCA design in spectrum auction. According to Crampton [1], CCA is a widely used spectrum auction. This paper will discuss how the CCA works and how is implemented in spectrum auction in Canada as a case example. Canada has conducted many spectrum auctions, including using CCA as shown in Table 1 above [4]–[6]. Future planned auction for spectrum 600 MHz band will be held in May 2019 using CCA formats[7], [8].

This paper will be conducted in five sections: introduction, literature review, result and discussion, and conclusion.

II. THEORITICAL ASPECT

A. *Combinatoral Auction (CA)*

Auctions are combinatorial when bidders can place bids on a "package" of combination of auction-items. Expres-

siveness of bidding languages and algorithmic aspects of the underlying combinatorial problem, have attracted computer scientist. Idea of applying combinatorial optimization and mathematical programming to address the combinatorial problems in auctions, fascinated many researchers. Auctions have been widely studied by economists. As such, the emerging field of CA lies at the intersection of computer science, retrieval operations, and economics [9].

Table 1. Combinatorial Clock Auction, to date 2016 [3]

Country and auction	Year	Revenues
Trinidad and Tobago Spec. Auction	2005	USD 25.1 mill.
UK 10-40 GHz Auction	2008	GBP 1.43 mill
UK L-Band Auction	2008	GBP 8.33 mill
Netherlands 2.6GHz Spec. Auction	2010	EUR 2.63 mill.
Denmark 2.5GHz Spec. Auction	2010	DKK 1.01 bill.
Austria 2.6GHz Spec. Auction	2010	EUR 39.5 mill.
Switzerland Spec. Auction	2012	CHF 99.6 mill.
Denmark 800MHz Spec. Auction	2012	DKK 739 mill.
Ireland Multi-Band Spec. Auction	2012	EUR 492 mill.
Netherlands Multi-Band Spec. Auction	2012	EUR 3.80 bill.
UK 4G Spec. Auction	2012	GBP 2.34 bll.
Australia Digital Dividend Spec. Auctic	2013	AUD 1.96 bill.
Austria Multi-Band Spec. Auction	2013	EUR 2.01 bill
Slovakia 800MHz, 1.8 and 2.6GHz	2013	EUR 164 mill.
Canada 700MHz Spec. Auction	2014	CAD 5.47 mill
Slovenia Multi-Band Spec. Auction	2014	EUR 149 mill.
Canada 2.5GHz Spec. Auction	2015	CAD 755 mill.

The advantage of CAs is that bidders can more fully express their preferences. This is very important when the item complements. Items are complementary when a set of items has a utility that is greater than the number of utilities for each item (for example, a pair of shoes is worth more than the value of the left shoe plus the right shoe value). The auction designer also gets the value from the CA. Allowing bidders more fully to express preferences often leads to increased economic efficiency (allocating items to those who value them the most) and greater auction revenues.

After the bidding language is set, the question remains how to calculate the allocation, given a series of bids. This problem, called the winner determination problem (WDP) has received much attention in the literature. Lehmann, Müller and Sandholm provide precise formulations of problems and explore the properties of basic complexity [10]. The problem is this: Given a series of bids in a combinatorial auction, find the item allocation for the bidder, including the possibility that the auctioneer maintains several items, which maximizes the auctioneer's income. The problem, the most natural is represented as an integer program (IP), basically complex. In particular, it is NP-hard, which means that no polynomial-time algorithm is guaranteed to calculate the optimal allocation. Even worse, the problem is not uniform, in the following sense: there are no polynomial-time algorithms and constants which, for all inputs, produce answers that are at least 1/d of the correct optimal answer.

B. Combinatoral Clock Auction (CCA)

Ausubel and Baranov in [11] describe the CCA's evolution, including expected design innovations. Cramton in [1] outlines the SMRA flaws and argues how the CCA design solves them. Parkes [12], Ausubel and Milgrom [13], Day and Raghavan [14], Day and Milgrom [15] and Day and Cramton [16] have studied various pricing mechanisms for combinatorial auctions and their properties, including the pricing rules currently used for CCAs. Possible strategic manipulations for the CCAs are explored by Janssen and Karamychev [17] and Levin and Skrzypacz [18]. Experimental comparisons of the CCA design with other auction designs have been studied by Bichler et al. [19], [20]. From academic proposal in 2006 [2] to its implementation in 2012 to 2018, CCA has gained substantial momentum. Table 1 shows the use of CCA in spectrum auctions worldwide on three continents, allocating prime sub-1-GHz spectrum and raising approximately $20 billion in revenues.

The CCA is typically a two-stage auction, consisting of an allocation stage and, when generic licenses are used, an assignment stage. In the allocation stage, the number of generic licenses won by each bidder is determined. Then the assignment stage determines the specific blocks that are assigned to each winning bidder. The allocation stage of the auction determines the winning bidders as well as the number of licenses they have won. It is divided into two phases: the clock rounds and the supplementary round. This process and its rules are illustrated and described in Figure 1, a flowchart representing a CCA flow processes.

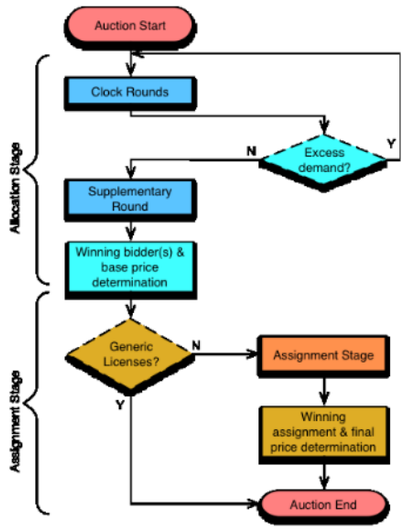

Figure 1. Flowchart of CCA process[5]

The first stage is clock rounds stage. This is a stage of series of rounds which the bidders bid the licenses they

want. The bid price will increase in every round. This round will continue until no bids from all of bidders, or numbers of bids are less than or equal with license categories. When there is no more bids in each licensing categories, clock round stage is finished and the process will enter the supplementary round. Like in clock rounds, bidders in supplementary round have one last bid. There are no series of rounds in supplementary round.

After supplementary round, all bids from clock and supplementary rounds are used to determine winning packages in a standard Winner Determination Problem (WDP). Bids combination that maximized the total values is determined as winning packages. Some constraints are set: each bidder has only one bid that can be selected as part of winning allocation and search item can be sold only once. Final pricing items founded by WDP are using second price method. Winning bidders should pay their winning packages according to those final prices. It is the end of allocation stages.

Assignment stage is a stage to assign all licenses offered and won in allocation stage. This stage won't be necessary if there are no generic licenses offered or won. This stage only should be done if there were any generic licenses offered and won in the allocation stage. In this assignment stage, final prices are found and winning assignments are determined in this assignment stage. The end of the auction will be different depends on this assignment stage.

The objective of the assignment stage is to simplify bidding in the assignment stage. These clock and supplementary rounds in the assignment stage treat several closely items as identical items. This assignment stage is used in the current practice.

In the European 800MHz band auction for example, the European digital dividend auctions offered six distinct licenses. During clock and supplementary rounds, bidders are asked to bid for quantities of 'generic' 800 MHz spectrum blocks. Winning allocations of the 'generic' spectrum are determined in the on allocation stage. In the assignment stage, bidders had a sealed-bid auction to compete for specific block assignments within 800 MHz band. This allocation stage will determine the mapping of generic licenses to physical frequencies.

C. *Evolution of the CCA*

Ausubel [11] discussed three evolutions of future CCAs: 1) Bidding Language, 2) Revealed-Preference Activity Rule, and 3) Iterative Pricing. The initial CCA, all bids are mutually exclusive, there for this initial CCA used a "XOR bids" bidding language The XOR bidding language is fully expressive, but non-compact. Ausubel introduced an "OR bids" bidding language in the supplementary round. This idea of OR bids made the significant change

The Canadian Government has adopted this enhancement in its 2500 MHz auction in January 2014. This is suitable for largest CCA in scale to date with 318 licenses, grouped into 106 categories.

The second evolution is CCA's Activity Rule. Activity rules in dynamic auctions are intended to prevent "bid sniping": a bidder must submit bids in early rounds in order to be allowed to continue to submit bids in later rounds. Spectrum auctions have traditionally required monotonicity in eligibility points. Various researchers have suggested activity rules based on revealed preference[21]. A bidder can switch from package x_s to x_t only if it has become relatively less expensive. Previous CCA using Weak Axiom of Revealed Preference (WARP) as revealed preference model.

In particular, Ausubel and Baranov [11] have advocated activity rules based on the Generalized Axiom of Revealed Preference (GARP). Given price-quantity pairs (x_i, p_i), $\dots, (x_t, p_t)$, package x_i is said to be revealed preferred to x_m if there is a sequence $j, k, \dots, l$ such that $p_i x_i \geq p_i x_j, p_j x_j \geq p_j x_k, \dots, p_l x_l \geq p_l x_m$. The data $(x_i, p_i), \dots, (x_t, p_t)$ are said to satisfy GARP if: x_i is revealed preferred to $x_m \Rightarrow p_m x_m \leq p_m x_i$.

The third evolution in CCA is Iterative Pricing. Previous CCA using iterative second-price, and it enhances to an iterative first-price auction.

III. COMBINATORAL CLOCK AUCTION IMPLEMENTATION

In this section we discuss how CCA works, focused in Allocation Stage. As mention above, allocation stage consists of clock rounds and supplementary round. In clock rounds, have revealed preference activity rule in two format WARP-based and GARP-based. We have Canadian Industry auctions as a case, since Canada Government have implemented so many spectrum auction using CCA.

A. *Spectrum Auction in Canada*

In Canada, auctions are held by Innovation, Science and Economic Development Minister in Canada (ISED). In the first auction that held in 1998, they used the SMRA auction format. In next six spectrum auctions, this SMRA auction are conducted in four of spectrum auctions. Not only Canada, many countries for over 15 years used the SMRA auction format. Italy, Germany, Mexico, Spain, the United States, as well as the Hong Kong Special Administrative Region are countries that have used SMRA auction format in recent their spectrum auctions.

After used the SMRA format for years, ISED selected CCA format for Canada 700 MHz auction and the upcoming 2500 MHz auction. CCA format, as a variation of the SMRA format, auctioned all licenses at the same time over multiple rounds. Like the SMRA format, the CCA format provides a simple bidding process, including the price discovery stage. There is significant difference between those two formats. SMRA format stated bidding for an individual license. CCA format forced bidders state their request for a license package.

Table 2 shows summary of the spectrum auction implemented in Canada.

The SMRA and CCA formats have been used in the auction, there are many blocks, some licensing areas are available and stakeholder needs to consider different combinations of each when bidding.

Table 2. Auction history of ISED Canada [4]

No	Auction of Spectrum	Auction Design	Year
1	Licenses in the 600 MHz Band	CCA	2018
2	Residual Spectrum Licenses in the 700 MHz, 2500 MHz, 2300 MHz and PCS-G Bands	Sealed-bid, second price	2018
3	700 MHz & AWS-3 (residual 2015)	Sealed-bid, second price	2015
4	2500-2690 MHz (2015)	CCA	2015
5	AWS-3 (2015)	Sealed-bid, second price	2015
6	700 MHz (2014)	CCA	2014
7	2300 & 3500 MHz (2009)	Sealed-bid, second-price	2009
8	Air-ground (2009)	Sealed-bid, second-price auction	2009
9	AWS-1 (2008)	SMRA	2008
10	2300 & 3500 MHz (residual 2004-05)	SMRA	2004
11	2300 & 3500 MHz (2004)	SMRA	2004
12	PCS - 2 GHz (2001)	SMRA	2001
13	24 and 38 GHz (1999)	SMRA	1999

ISED also uses sealed-bid auctions to make the spectrum available when there are multiple blocks available in a limited geographic area.

When proposing an auction format, the ISED should consider the benefits of an auction format versus the complexity and time required to run the auction. The proposed band plan and limited number of blocks mean no common blocks are available, so there is no benefit to running the CCA for this spectrum. Although the CCA and SMRA formats give stakeholders the advantage of price discovery through multiple rounds, this format is more complex and time-consuming for the stakeholders.

There are three auction formats being considered for the 600 MHz auction: Combinatorial clock auction, using the WARP-based activity rule, Combinatorial clock auction, using the GARP-based activity rule and Enhanced combinatorial clock auction (ECCA). We will focus in activity rules WARP-based and GARP-based.

B. Activity Rules-based Used in Spectrum Auction

In this section we will discuss an example of the activity rules. We use spectrum auction 600 MHz band for the purposes of this example. We have a bidder A, with initial eligibility of 20 points, which is interested in three (3) blocks of service areas (A, B, and C) which associated with the following eligibility points: A (15 points), B (10 points), and C (20 points), shown in table 3.

Examples of bidding history for bidder A, shown in table 4.

Table 3. Initial Eligibility points of bidder-A

Service Area	Eligibility
A	15 points
B	10 points
C	20 points

Table 4. Bidding history of bidder-A

Bidding history (bidder A)						
	Prices (thousands)				Activity (eligibility)	Bid amount (thousands)
Round	A	B	C	Bid		
1	$100	$100	$100	1 block A	15 (20)	$100
2	$100	$100	$110	1 block B	10 (15)	$100
3	$110	$100	$110	1 block C	20 (10)	$110

Activity rules analytics for bidder-A, described as follows:

1) WARP activity rules

To bid on C, the bid must satisfy revealed preference with respect to all eligibility-reducing rounds (Rounds 1 and 2), starting with the last round in which the bidder had sufficient eligibility to bid on C (Round 1).

$$\sum_{i=1}^{m}(Q_{t,i} \times (P_{t,i} - P_{s,i})) \leq \sum_{i=1}^{m}(Q_{s,i} \times (P_{t,i} - P_{s,i})) \ldots\ldots\ldots(1)$$

where:

$Q_{t,i}$: quantity of the i^{th} product bid in clock round t;

$Q_{s,i}$: quantity of the i^{th} product bid in clock round s;

$P_{t,i}$: clock-price of the i^{th} product bid in clock round t

$P_{s,i}$: clock-price of the i^{th} product bid in clock round s

With respect to Round 1:

$$C_{R_3} - C_{R_1} \leq A_{R_3} - A_{R_1}$$

(Price C in $R3$) − (Price C in $R1$) ⩽ (Price A in $R3$) − (Price A in $R1$)

With respect to Round 2:

$$C_{R_3} - C_{R_1} \leq B_{R_3} - B_{R_1}$$

(Price C in $R3$) − (Price C in $R1$) ⩽ (Price B in $R3$) − (Price B in $R1$)

Table 5. WARP constraint satisfaction for bidder-A

With respect to	WARP ($ thousands)	Satisfied?
Round 1	$110 - 100 \leq 110 - 100$ $10 \leq 10\ 0$	Yes
Round 2	$110 - 110 \leqslant 100 - 100$ $0 \leqslant 0$	Yes

The constraint is satisfied since, compared to round 2, the prices in round 3 have not increased for either A or C. Therefore the WARP-based activity rule would allow the bidder to submit a bid for one block of C in round 3.

2) GARP-based activity rule

To bid on C, the GARP-based activity rule requires that all of the bidder's bids, starting with the last round in which

the bidder had sufficient eligibility to bid on C (round 1) and ending in round 3 with a bid on C, must be consistent with truthful bidding for some implied valuations. Mathematically, these revealed preference constraints are calculated in the following way. There needs to exist values (V_1, V_2, and V_3) such that the following inequalities are satisfied:

$$V_j - \sum_{i=1}^{m} P_{k,i} \cdot Q_{j,i} \leq V_k - \sum_{i=1}^{m} P_{k,i} \cdot Q_{k,i} \ldots\ldots\ldots(2)$$

where:
$Q_{j,i}$: quantity of the i^{th} product in package Q_j of clock-round j;
$Q_{k,i}$: quantity of the i^{th} product in package Q_k of clock-round k;
$P_{k,i}$: clock-price of the i^{th} product in clock-round k;
V_j: bidder's implied valuation for package Q_j of clock-round j;
V_k: bidder's implied valuation for package Q_k of clock-round k;

for $j = 1, 2, 3$ and $k = 1, 2, 3$

$$\begin{aligned} &V_2 - B_{R_1} \leq V_1 - A_{R_1}; \\ &V_2 - 100 \leq V_1 - 100 \quad \Rightarrow V_2 \leq V_1 \\ &V_3 - C_{R_1} \leq V_1 - A_{R_1}; \\ &V_3 - 100 \leq V_1 - 100 \quad \Rightarrow V_3 \leq V_1 \end{aligned}$$

$$\begin{aligned} &V_1 - A_{R_1} \leq V_2 - B_{R_2}; \\ &V_1 - 100 \leq V_2 - 100 \quad \Rightarrow V_1 \leq V_2 \\ &V_3 - C_{R_1} \leq V_2 - B_{R_2}; \\ &V_3 - 110 \leq V_2 - 100 \quad \Rightarrow V_3 \leq V_2 + 10 \end{aligned}$$

$$\begin{aligned} &V_1 - A_{R_3} \leq V_3 - C_{R_3}; \\ &V_1 - 110 \leq V_3 - 110 \quad \Rightarrow V_1 \leq V_3 \\ &V_2 - B_{R_3} \leq V_3 - C_{R_3}; \\ &V_3 - 100 \leq V_3 - 110 \quad \Rightarrow V_2 \leq V_3 - 10 \end{aligned}$$

These inequalities imply $V_2 = V_3$ and that $V_2 = V_3 - 10$ which cannot hold simultaneously for any values.

C. Discussion

The results of the GARP-based activity rule differ from the WARP-based activity rules for two reasons:

1. the GARP-based activity rule goes back to the last round the bidder had sufficient eligibility to bid for the package and then calculates revealed preference with respect to all subsequent clock rounds and not just eligibility-reducing rounds (WARP).
2. the GARP-based activity rule calculates whether there are values that are able to satisfy all of the revealed preference constraints simultaneously and not just as individual pairs (WARP).

IV. CONCLUSION

A. Conclusion

This research conclude that:

1. Advancements in auction theory and design have led to new and improved auction formats and rules. CCA has potential to eclipse SMRA as the standard for spectrum auctions.
2. CCA has been used in several spectrum auction in many countries. ISED Canada used CCA two times in 2500-2690 MHz and 700 MHz spectrum auction (2014 and 2015) and continues to examine these new developments and is considering various options for the 600 MHz auction in 2018.
3. Benefit of CCA:
   a. significantly reduces one of the largest sources of risk to bidders (exposure risk) by the use of generic licenses and package bidding;
   b. encourages truthful bidding throughout the auction and provides bidders with useful information about the values of the offered licenses;
   c. the hybrid revealed preference/eligibility point activity rule provides bidders with greater flexibility to follow a straightforward bidding strategy
4. Complexity in CCA:
   a. Clock rounds phase needs revealed preference constraint in each rounds
   b. The need of define the winner in package bidding in supplementary rounds lead to winner determination problem (WDP)
5. Pricing rule at CCA has potential to further discussion

B. Future Research

As mention in introduction section, CCA has no been implemented in Indonesia. Since CCA has been an auction design, we need support and encourage Indonesia government to use this auction format in Indonesia spectrum auction management. This research will be continued focuses in:

1. how to develop a software tools for each stage in allocation stages in CCA,
2. how to develop a component tools to define various activity rule-based,
3. how define various methods to solve Winner Determination Problem in supplementary round,
4. how to define pricing rule and the tools to help the auctioneer

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