

# Revealed Preference in Bidding: Empirical Evidence from Recent Spectrum Auctions

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# Activity Rules

- 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
- In particular, Ausubel and Baranov (2014a,b,c) have advocated activity rules based on the Generalized Axiom of Revealed Preference (GARP)

# Revealed Preference

- Weak Axiom of Revealed Preference (WARP)

$$(p_s - p_t) \cdot (x_s - x_t) \leq 0, \text{ for } s < t$$

Verbally: A bidder can switch from package  $x_s$  to  $x_t$  only if it has become relatively less expensive

- Generalized Axiom of Revealed Preference (GARP)

Given price-quantity pairs  $(x_1, p_1), \dots, (x_t, p_t)$ , 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  $(x_1, p_1), \dots, (x_t, p_t)$  are said to satisfy GARP if:

$$x_i \text{ is revealed preferred to } x_m \rightarrow p_m x_m \leq p_m x_i$$

- Afriat's Theorem (1967): A finite set of data is consistent with utility maximization if and only if it satisfies GARP
- Note: When we say "GARP", we are generally referring to GARP + Quasilinearity

# Combinatorial Clock Auction (CCA)

- Proposed by Ausubel, Cramton and Milgrom (2006)
- Consists of a clock auction stage, a supplementary round and an assignment stage
- All bids are treated as true package bids—no provisional winners
- In the past few years, CCAs have been used for more major spectrum auctions worldwide than any other auction format

# Combinatorial Clock Auctions—History

Country and Auction	Year	Revenues
Trinidad and Tobago Spectrum Auction	2005	\$25.1 million (\$US)
UK 10 – 40 GHz Auction	2008	£1.43 million
UK L-Band Auction	2008	£8.33 million
Netherlands 2.6 GHz Spectrum Auction	2010	€2.63 million
Denmark 2.6 GHz Spectrum Auction	2010	DKK 1.01 billion

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<b>Switzerland Spectrum Auction</b>	<b>2012</b>	<b>CHF 996 million</b>
<b>Denmark 800 MHz Spectrum Auction</b>	<b>2012</b>	<b>DKK 739 million</b>
<b>Ireland Multi-Band Spectrum Auction</b>	<b>2012</b>	<b>€482 million</b>
<b>Netherlands Multi-Band Spectrum Auction</b>	<b>2012</b>	<b>€3.80 billion</b>
<b>UK 4G Spectrum Auction</b>	<b>2013</b>	<b>£2.34 billion</b>
<b>Australia Digital Dividend Spectrum Auction</b>	<b>2013</b>	<b>\$1.96 billion (\$AU)</b>
<b>Austria Multi-Band Spectrum Auction</b>	<b>2013</b>	<b>€2.01 billion</b>
<b>Slovakia 800, 1800 and 2600 MHz Spectrum Auction</b>	<b>2013</b>	<b>€164 million</b>
<b>Canada 700 MHz Spectrum Auction</b>	<b>2014</b>	<b>\$5.27 billion (\$CA)</b>
<b>Slovenia Multi-Band Spectrum Auction</b>	<b>2014</b>	<b>€149 million</b>

# Combinatorial Clock Auction (CCA)

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- Consists of a clock auction stage, a supplementary round and an assignment stage
- All bids are treated as true package bids—no provisional winners
- In the past few years, CCAs have been used for more major spectrum auctions worldwide than any other auction format
- Activity rules are particularly important for current CCAs, since current CCAs use a form of second pricing—and so bidders' payments are determined by their opponents' bids. If activity rules are too lax, it may be too easy for opponents to impose costs on a bidder
- Various recent CCAs have experimented with a variety of activity rules

# Outline of Talk

1. Premise for paper / available data
2. Narrow question: There has been considerable debate about the right constraint to place on supplementary bids in the CCA. To date, this has been based on theory and simulations. Here we attempt to assess using real data
3. Intermediate questions:
  - Is the GARP activity rule an overly stringent constraint—or do bidders in spectrum auctions typically satisfy it?
  - Conversely, to what extent is a check for GARP violations an effective automatic filter for detecting strategic behavior?
4. Broadest question: Are there minor relaxations of GARP that may be more robust to bidder error and to common-value learning, but which still largely accomplish the same goals as GARP?

# Premise for Paper

- There have been many spectrum auctions worldwide since the early 1990s, including:

<b>North America</b>	<b>Europe</b>	<b>Asia Pacific</b>
<b>US PCS—A and B blocks</b>	<b>UK 3G auction</b>	<b>Early New Zealand auctions</b>
<b>US PCS—C and F blocks</b>	<b>German 3G auction</b>	<b>Early Australian auctions</b>
<b>US 700 MHz</b>	<b>Swiss, Netherlands, Ireland 4G</b>	<b>Indian 3G/BWA</b>
<b>US AWS</b>	<b>German 4G auction</b>	<b>Thailand 3G auction</b>
<b>Canadian AWS</b>	<b>UK 4G auction</b>	<b>Australian digital dividend</b>
<b>Canadian 700 MHz</b>	<b>Austria, Slovakia, Slovenia 4G</b>	<b>Indian 900/1800 MHz</b>

# Premise for Paper

- Unfortunately (for this paper), many of these auctions were SMRA or ascending clock auctions with **provisional winners**. We would like to ask whether each submitted bid is a choice consistent with GARP, but if a bidder is obligated to stick with provisionally-winning bids, this is not a reasonable exercise (except with substitutes preferences):

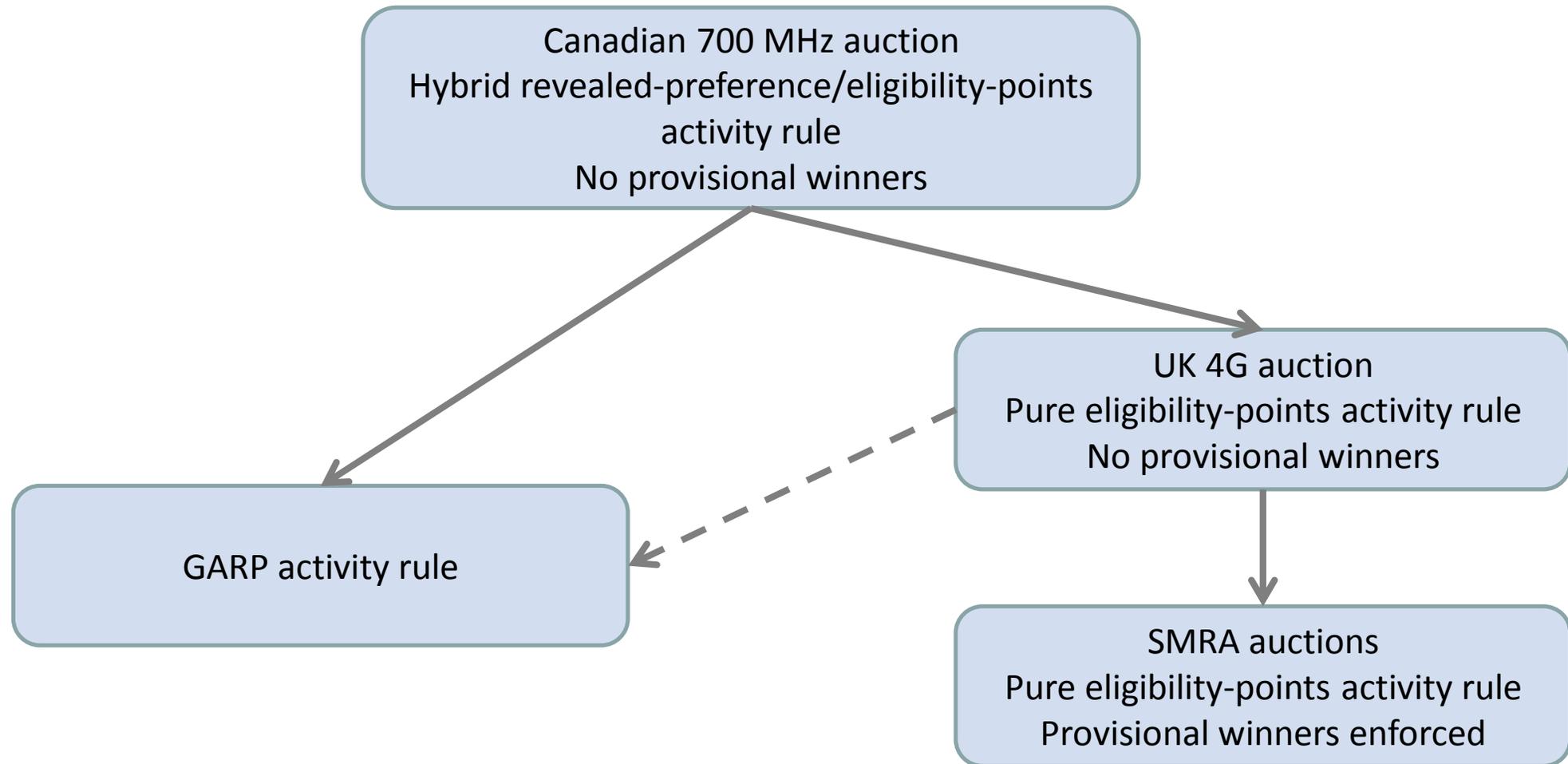
North America	Europe	Asia Pacific
US PCS—A and B blocks	UK 3G auction	Early New Zealand auctions
US PCS—C and F blocks	German 3G auction	Early Australian auctions
US 700 MHz	<b>Swiss, Netherlands, Ireland 4G</b>	Indian 3G/BWA
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# Premise for Paper

- Unfortunately (for research generally), the data from many of these auctions will never be publicly released:

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# Nesting of Activity Rules (least restrictive to most restrictive)



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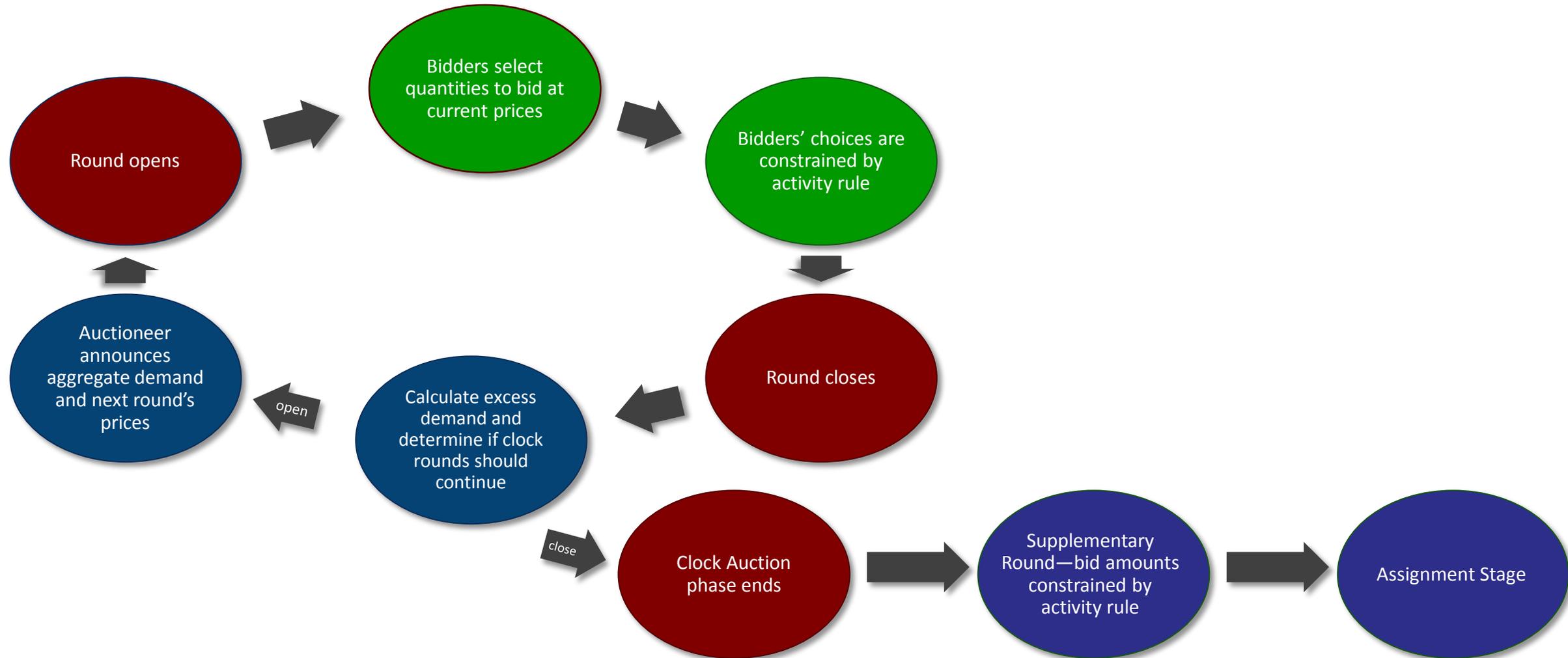
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# Premise for Paper

- As of today, the Canadian 700 MHz auction data has not yet been publicly released:

North America	Europe	Asia Pacific
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# Combinatorial Clock Auction—Process



# UK 4G Auction (2013): Summary

- **Licenses:** Supply of 4 A1 lots, one A2 lot, 14 C lots and 9 E lots
- **Endogenous Bandplan:** some of C lots might have been won as D1 or D2 lots
- **Bidders:** Vodafone, Telefonica, EE, Three, Niche(BT), HKT and MLL
- **Spectrum Floor:** provision (i.e. competition policy) that there should be at least 4 credible national competitors after the auction
- **Results:** all lots were sold; total revenue raised was around \$4 billion

Bidder	Vodafone	Telefonica	EE	Three	Niche
Package Won	2-A1, 4-C, 5-E	1-A2	1-A1, 7-C	1-A1	3-C, 4-E
Final Price	£ 803 mil	£ 550 mil	£ 589 mil	£ 225 mil	£ 202 mil

# Empirical Part 1 (Comparison of CCA Activity Rules): Background

- All empirical CCAs to date have enforced, in the supplementary round, at most a subset of the revealed preference constraints—WARP is enforced, relative to certain clock rounds
- The most common activity rule has been the “**relative cap**”: for each package, WARP is enforced relative to the last eligibility-reducing round in which the bidder was eligible to bid for the package (applied as telescoping inequalities)
- An additional constraint that has sometimes been imposed is the “**final cap**”: for each package, WARP is enforced relative to the final clock round
- Ausubel and Cramton (2011): With the final cap, in a CCA with no undersell in the tentative allocation of final clock round, the tentative allocation cannot change after the supplementary round

# Empirical Part 1 (Comparison of CCA Activity Rules): Background

- Ausubel and Cramton (2011): With the final cap, in a CCA with no undersell in the tentative allocation of final clock round, the tentative allocation cannot change after the supplementary round
- Pro: There is great stability between the clock phase and supplementary round
- Con: There is great stability between the clock phase and supplementary round
- Regulators' responses:
  - Ireland: Both the relative cap and final cap were imposed
  - UK and Australia: Only the relative cap was imposed
  - Canada: Both the relative cap and final cap were imposed, but the outcome of final clock round was not disclosed before the supplementary round

# Empirical Part 1 (Comparison of CCA Activity Rules): Question

- Regulators' responses:
  - Ireland: Both the relative cap and final cap were imposed
  - UK and Australia: Only the relative cap was imposed
  - Canada: Both the relative cap and final cap were imposed, but the outcome of the final clock round was not disclosed to bidders before the supplementary round
- Empirical exercise: How much uncertainty (or bid sniping opportunities) is left in the supplementary round under various activity rules in a realistic auction?
- Flip side of this: How much exposure (and scope for imposing costs on opponents) is there under various activity rules in a realistic auction?
- The following results also include an “intermediate cap”, which was used in Canada (but generally can be imposed with or without the final cap)

# Empirical Part 1 (Comparison of CCA Activity Rules): Results

Bidder (Final Clock Package)	Exposure Type	Relative Cap (UK)	Relative Cap + Intermediate Cap	Relative Cap + Final Cap (IRELAND)	Relative Cap + Intermediate Cap + Final Cap (CANADA)
Vodafone (2-A1, 3 - C)	<i>Exposure</i>	245%	184%	166%	166%
	<i>Net Exposure</i>	179%	118%	100%	100%
Telefonica (1-A2, 1 – D2)	<i>Exposure</i>	282%	206%	183%	183%
	<i>Net Exposure</i>	199%	123%	100%	100%
EE (9 - E)	<i>Exposure</i>	697%	438%	438%	438%
	<i>Net Exposure</i>	359%	100%	100%	100%
Niche(BT) (2 - C)	<i>Exposure</i>	1092%	616%	504%	504%
	<i>Net Exposure</i>	688%	212%	100%	100%
Three (4 - C)	..... Not Applicable—Opted in to the Spectrum Floor .....				

# Empirical Part 2: Violations of GARP

- The authors have advocated the practical use of activity rules based on the Generalized Axiom of Revealed Preference (GARP)
- In looking at empirical data, either of two perspectives can be taken
- Under one view, GARP violations exhibited in the bidding data may suggest that GARP-based activity rules are overly stringent and not viable in practice
- Under a second view, bidders' true preferences may be thought to be generally consistent with GARP—and violations may spotlight instances in which bidders were attempting to exploit strategic opportunities
- Ultimately, these two views are probably not empirically distinguishable
- Nonetheless, examining empirical bidding data for violations of GARP—and when they occur, seeing if there is a strategic reason—may shed some light on the issue

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# UK 4G Auction (2013): Details

- **Licenses:** Supply of 4 A1 lots, one A2 lot, 14 C lots and 9 E lots

Lot	Amt of Spectrum	Spectrum Band	Caveat	Eligibility Points	Reserve Price
A1	2 x 5 MHz	800 MHz		2250	£ 225 mil
A2	2 x 10 MHz	800 MHz	Coverage obligation	4500	£ 250 mil
C	2 x 5 MHz	2.6 GHz		150	£ 15 mil
E	1 x 5 MHz	2.6 GHz	Unpaired spectrum	1	£ 0.1 mil

- **Coverage obligation:** value of A2 lot < value of two A1 lots, due to coverage obligation
- **Reserve price:** gave the coverage obligation a discount of £ 200 million
- **One bidder:** tended to bid as if it discounted the coverage obligation by £ 31 million

# UK 4G Auction (2013): A Fine Institutional Detail

- **Spectrum cap:** On 800 MHz band, applicable to Vodafone & Telefonica, but not others:
  - Vodafone and Telefonica were each limited to two A1 lots (or one A2 lot)
  - EE and Three were not subject to any limits in the 800 MHz band
- **Only aggregate demand** was reported to bidders
- **Assumption** could be made that Vodafone & Telefonica would always bid for two blocks
- **However**, there are fairly dramatic pricing implications to Vodafone and Telefonica, depending on whether EE and Three are distributed as, say, 5 – 0 or 3 – 2, on the 800 MHz blocks
- **Neither EE nor Three** could bid individually on more than four A1 lots or one A2 lot
- **Hence**, there were reasons for bidders to strategically manipulate bids on A1 vs. A2

# GARP Violations — Niche (British Telecom)

- Generally, Niche (British Telecom) was bidding on subsets of prior bids throughout the clock auction phase. Such bidding would never violate GARP
- Niche violated GARP only once, in Round 41:

Round	Bid (C, E)	Price (C, E)
39	(3, 5)	(92 mil, 1.72 mil)
40	(3, 5)	(92 mil, 2.06 mil)
41*	(2, 8)	(92 mil, 2.47 mil)
42*	(2, 5)	(92 mil, 2.96 mil)

\* eligibility-reducing round

$$(p_{41} - p_{39})(x_{41} - x_{39}) = (2 - 3) * (92 - 92) + (8 - 5) * (2.47 - 1.72) = 2.25 \text{ mil} > 0$$

- If round 41 is deleted from Niche's bidding history, Niche satisfied GARP

# GARP Violations—Vodafone

- Vodafone triggered multiple GARP violations due to inconsistent switching between A2 lot and A1 lots

Round	Bid (A1,A2,C,E)	Price (A1, A2)	2A1-A2
19	(0, 1, 8, 7)	(316 mil, 608 mil)	24 mil
20	(2, 0, 8, 7)	(332 mil, 638 mil)	26 mil
21	(0, 1, 8, 7)	(349 mil, 638 mil)	60 mil
22	(2, 0, 8, 7)	(366 mil, 670 mil)	62 mil
23	(2, 0, 8, 7)	(384 mil, 670 mil)	98 mil
24	(2, 0, 8, 7)	(403 mil, 670 mil)	136 mil
25	(0, 1, 8, 7)	(423 mil, 670 mil)	176 mil

- Most likely, Vodafone was trying strategically to flush out information on A1 vs. A2
- If rounds 20, 22, 23 and 24 are deleted from Voda's bidding history, it satisfied GARP

# Vodafone and Revealed Preference

Round	Bid (A1,A2,C,E)	Price (A1, A2)	2A1-A2
38	(2, 0, 3, 9)	(423 mil, 815 mil)	31 mil
39	(0, 1, 3, 9)	(423 mil, 815 mil)	31 mil
40*	(2, 0, 3, 7)	(423 mil, 846 mil)	0 mil

\* eligibility-reducing round

- Vodafone revealed an indifference between A2 and A1 lots when the clock price difference was 31 mil
- In the supplementary round, Vodafone submitted 38 pairs of bids for various quantities of C and E lots expressing a difference of precisely 31 mil between A1 and A2 and also 9 pairs (for unlikely low quantities of C and E) expressing a difference of 0 mil between A1 and A2 lots.

# GARP Violations — Everything Everywhere

- EE triggered multiple GARP violations due to inconsistent switching between A2 lot and A1 lots

Round	Bid (A1,A2,C,E)	Price (A1, A2)	2A1-A2
2	(4, 0, 4, 0)	(236 mil, 263 mil)	209 mil
4	(2, 1, 4, 0)	(248 mil, 290 mil)	206 mil
...	...	...	...
18	(0, 1, 6, 0)	(316 mil, 579 mil)	53 mil
21	(2, 0, 6, 0)	(349 mil, 638 mil)	60 mil
22	(2, 0, 6, 0)	(384 mil, 670 mil)	62 mil
23	(2, 0, 6, 0)	(403 mil, 670 mil)	98 mil

- Most likely, EE was trying strategically to conceal information on A1 vs. A2

# GARP Violations — Everything Everywhere

- EE triggered multiple GARP violations by not switching back to C lots from E lots that become relatively expensive late in the auction.
- EE was prevented from switching back by the monotonicity requirement.

Round	Bid (A1,A2,C,E)	Price (C, E)	Size of Violation
37	(0, 0, 8, 0)	(87.6 mil, 1.194 mil)	
38*	(0, 0, 0, 9)	(92 mil, 1.43 mil)	
...	...	...	...
45	(0, 0, 0, 9)	(92 mil, 5.11 mil)	0.044 mil
46	(0, 0, 0, 9)	(92 mil, 6.4 mil)	11.645 mil
...	...	...	...
52	(0, 0, 0, 9)	(92 mil, 24.4 mil)	173.654 mil

# GARP Violations — Hutchinson 3G (Three)

- H3G triggered multiple GARP violations due to inconsistent switching between A2 lot and A1 lots.

Round	Bid (A1,A2,C,D2,E)	Price (A1, A2)	2A1-A2
10	(1, 1, 10, 1, 5)	(248 mil, 410 mil)	106 mil
...	...	...	...
16	(3, 0, 10, 1, 5)	(316 mil, 525 mil)	107 mil
17	(3, 0, 10, 1, 5)	(316 mil, 551 mil)	81 mil
...	...	...	...
24	(3, 0, 10, 1, 5)	(403 mil, 670 mil)	136 mil

- Most likely, H3G was trying strategically to conceal information on A1 vs. A2

# GARP Violations — Hutchinson 3G (Three)

- H3G triggered another GARP violation by switching from A1 lot to E lots that become relatively more expensive.
- Potentially, can be explained by a budget constraint (bids made in rounds 24 and 25 are the highest bids made by Three in the auction)
- In round 26, Three dropped an A1 lot that was not increasing in price.

Round	Bid (A1,A2,C,D2,E)	Price (A1, E)	Size of Violation
25	(1, 1, 10, 1, 5)	(423 mil, 0.322 mil)	
26*	(0, 1, 10, 1, 7)	(423 mil, 0.338 mil)	0.032 mil
27	(0, 1, 10, 1, 7)	(423 mil, 0.355 mil)	0.066 mil

# Other Bidders — No GARP violations

- Telefonica did exhibit some degree of substitution between C lots and E lots, but the moves were fully consistent with GARP
- Telefonica never substituted A2 lot for A1 lots during clock rounds like other major bidders. This is also consistent with their supplementary bids that revealed a slight preference for winning A2 lot versus A1 lots
- Two small bidders, HKT and MLL, also did not violated GARP during the clock stage. They were bidding for E lots only (as in a homogeneous auction). GARP Clock Rule and monotonicity in eligibility points are equivalent in homogeneous auctions, so they would not have been able to violate GARP had they wanted to

# Extra Analysis: Simulating clock rounds using reported values

- Vodafone's and Niche's supplementary bids appear to be consistent with their clock round bidding; there are slight delays in dropping lots, but this is consistent with the actual use of eligibility points
- Telefonica bid for many C lots during clock rounds, but failed to express any value for them during the supplementary round
- EE bid for 20 MHz of sub-1GHz spectrum for many clock rounds, but demanded only 10 MHz in the supplementary round. Also, see discussion on next slide
- H3G overstayed on 15 MHz of sub-1GHz spectrum for 15 rounds, but was relatively truthful starting from round 30

# Empirical Part 2 (GARP Violations): Conclusions

- The bidding of Telefonica, HKT and MLL was fully consistent with GARP
- With deletion of round 41, Niche was consistent with GARP
- With deletion of rounds 20, 22, 23 and 24, Vodafone was consistent with GARP
- With deletion of rounds 16, 24 and 25, H3G was consistent with GARP
- EE's near-final bidding exhibited two inconsistencies with its supplementary bids:
  - In round 37, EE would have been expected to revert from 8-C to 2-A1 and 9E (but couldn't do this, since it would have required increase in eligibility points from 1200 to 4509!)
  - In round 50, EE would have been expected to revert from 9-E to 8-C (but couldn't do this, since it would have required increase in eligibility points from 9 to 1200!)
- In short, if anything, a GARP activity rule would have been **less restrictive** than the pure-eligibility-point activity rule that was used

# Empirical Part 3: Inessential relaxations of GARP

- The authors previously showed that GARP satisfies a “No Dead-Ends” property; after any bidding history consistent with GARP, the bidder has a legal nonzero bid in every round
- Using a reasonably tight activity rule is beneficial, since it limits bidders’ exposures
- Some concerns have been expressed that one should use minor relaxations of GARP that may be more robust to bidder error and to common-value learning
- We consider several ways to relax GARP. Any relaxation ought to be formulated so as to maintain the “No Dead-Ends” property

# Relaxed GARP — Budget-constrained bidder

- Quasilinear GARP can get in the way of straightforward bidding by a participant who faces a budget constraint
- GARP can be relaxed in a way that will allow bidders to claim being budget-constrained
- The revealed (or claimed) budget level can be used to constrain bidders in future rounds (to discipline bidders who decide to violate GARP, claiming to being budget-constrained)

# Relaxed GARP — Previous-Bid Safe Harbor

- Under GARP, it is possible that a bidder's previous clock bid becomes infeasible in the current round. This makes bidding more difficult and less predictable
- GARP can be relaxed to allow bidders to remain on their previous package (or reduce to a subset) even if remaining would create a GARP violation
- Intuitively, such relaxation will make future bidding much more predictable without introducing any apparent opportunities for strategic manipulation
- This also allows for some degree of forgiveness to bidders who made mistakes in earlier rounds

# Relaxed GARP — Subsequence

- A requirement is imposed that there exists a **reasonable subsequence** of clock round bids that will satisfy full GARP.
- A reasonable subsequence should not exclude too many rounds (a limited number of violations) and possibly should not allow for violations to be clustered (a limited number of consecutive violations)
- For example, the requirement for a reasonable subsequence might be at least every other round, or at least every 4<sup>th</sup> round
- Intuitively, such a relaxation allows a limited number of rounds to be inconsistent with GARP
- Empirically, in the UK auction, a standard of requiring the subsequence to include at least every 4<sup>th</sup> round has all bidders except EE satisfying subsequence GARP

# Relaxed GARP — Near Optimality

- GARP requires the existence of values rationalizing the bids made in the clock rounds
- Under “near optimality”, a small discount is implicitly applied to the bidder’s past choices
- This reduces the burden of identifying the optimal package in every round
- It might be reasonable to allow a bigger discount (i.e., greater distance from optimality) in earlier rounds and gradually reduce the discount as the auction progresses

# Conclusions

1. Answer to narrowest question: The empirical data suggests that the final price cap in the CCA makes a fairly dramatic reduction in bidders' exposure calculations. The biggest impact appears to fall on the smallest bidders
2. Answers to intermediate questions:
  - In the UK auction, most bidders were broadly in compliance with a GARP activity rule
  - Most GARP violations either involved an informational issues relating to the A1 and A2 lots, or were forced by the actual activity rule (based on eligibility points)
  - One advantage of GARP is that it avoids the need to set eligibility points. In the UK auction, the eligibility point ratio between A and C lots was set at 15-to-1. The price ratio ended up at about 4-to-1; and, in order to avoid constraining bidders from straightforward bidding, it appears to have been needed to be set at only 2-to-1!
3. Answer to broadest question: Several possible relaxations of GARP may be more robust. One new possible approach is a subsequence condition