NSF-SES-1247988: Market Mechanisms for Allocation of Spectrum

Eiichiro Kazumori, SUNY

October 8, 2013.

Good Morning!

- Name: Eiichiro Kazumori
- Affiliation: State University of New York
- Research area: auction theory, finance, and industrial organization.
- Software projects:
  - METI-IPA Frontier Software Project: Tokyo Financial Market Research Database (TRDS)
    - Offers from Bloomberg for index data distributions
  - T-tree (Tokyo Toolbox for Readymade Economic Experiments)
- Main reference: Preston McAfee (Google and Caltech, preston@mcafee.cc)

Acknowledgements

- First of all I would like to express my sincerest gratitude for the support from the NSF EARS program and the advice and guidance from Dr. Clegg and Dr. Reksulak.

I. Introduction and Summary

Wireless Communication and Mobile Internet

- Wireless communication and mobile internet are *general purpose technologies* that deliver
  - Pervasive and wide adoption
  - Productivity growth
  - Innovation-spillover
- Their impacts have been compared to those of automobile and electricity.

Building the Economic Infrastructure for the Future

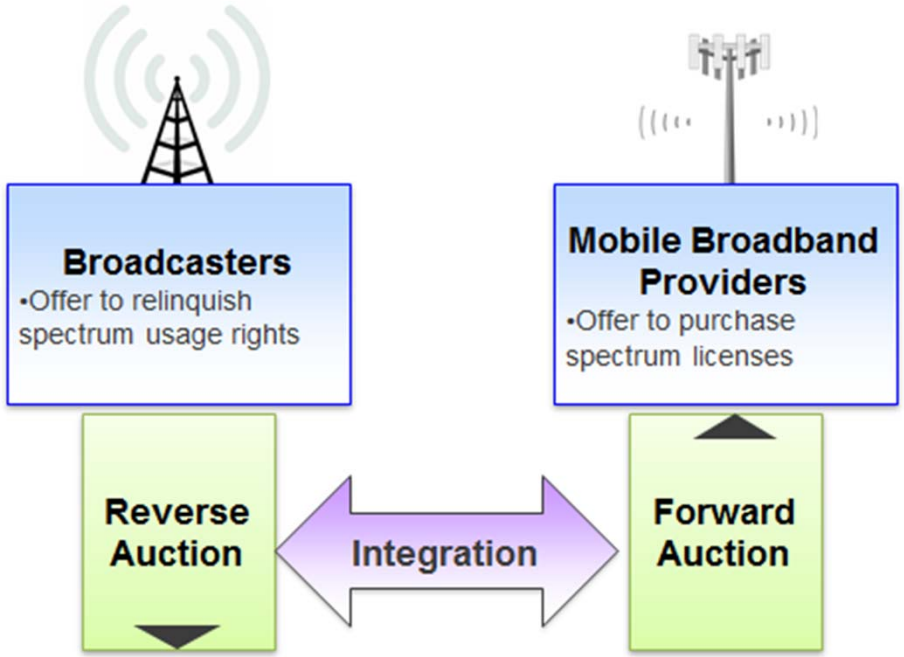
- New technology requires new economic infrastructure to realize the full potential of these innovations
- “How can we develop an economic/social/legal mechanism to actually realize these innovations?”

Enhancing Access to Radio Spectrum

- The key challenge is an efficient use of spectrum.
- Near-term: property right approach, incentive auctions
- Long-term: spectrum sharing, dynamic spectrum access
- It is an interdisciplinary challenge:
  - Technological challenge: spectrum sensing, interference, coexistence,…
  - Economic challenge: usage rights, pricing, incentives,…

An Objective of this Study = FCC Incentive Auctions

- We focus on the FCC incentive auctions that consist of
  - voluntary relinquishments of spectrum by TV broadcasters.
  - making the spectrum available for mobile network operators and whitespace users



Why Study Incentive Auctions?

- *Economic/social value proposition*: incentive auctions improves efficiency of spectrum use
- *A step toward enhancing access to spectrum*: the economic mechanisms can be extended for the future dynamic spectrum access and sharing

Incentive Auctions Design Question

How can we design the economic mechanism that

- *Provide incentive for TV stations and mobile operators to participate in the auctions?*
- *Transfers spectrum efficiently?*
- *Raises revenues to meet the congressional mandate?*
- *Develops competitive mobile communication and TV broadcasting industries?*

We study this problem from the perspective of the auction theory, algorithm design, and public policy.

Deliverables: 4 Direct Outputs

1. Kazumori, E., and Y. Belch (2013a). "On the Design of Reverse Auctions with Multiple Bid Options for the US Incentive Auctions: Generalized Heuristic Threshold Auctions," Working Paper.
2. Kazumori, E., and Y. Belch (2013b). "Descending Clocks, Ascending Clocks, and Closing Rule: An Open-Source Prototype Software for Incentive Auctions," Working Paper.
3. Kazumori, E., and Y. Belch (2013c). *Incentive Auctions Prototype Software*.
4. Kazumori, E. (2013a). “Simultaneous Deferred Acceptance Heuristics Auctions," Working Paper.

5 Papers Related to the Project

1. Kazumori, E. (2013b): Deleveraging, Liquidity Risk, and Asset Prices: Evidences from US and Japanese Stock Markets, 1977-2009.
2. Kazumori, E. (2013c): “What Drives Stock Returns of Apple, Google, Microsoft and Oracle? Industry Structure and Stock Returns in the US Computer Industry, 1965-2012.,” Working Paper.
3. Kazumori, E. (2013d): “Double Auction Markets with Interdependent Values: An Asymptotic Equivalence Approach,” Working Paper.
4. Kazumori, E. and Tchuindjo, L. (2013a): “Primary Dealers, Indirect Bidders, and Direct Bidding: A Structural Model of US Treasury Auctions,” In Preparation.
5. Kazumori, E. and Tchuindjo, L. (2013b): “Treasury Inflation Protected Securities: The Role of Margin Requirements,” In Preparation.

8 Referred Conference Presentations

1. 2013 North American Winter Meeting of the Econometric Society, San Diego (Presentation, Discusstant)
2. The University of Tokyo: Empirical Microeconomics Workshop (Presentation)
3. 2013 Second Cambridge Area Economics and Computation Day, MIT. (Presentation)
4. 5th Israel Game Theory Conference, Tel-Aviv. (Presentation)
5. 2013 North American Summer Meeting of the Econometric Society, USC (Presentation)
6. 2013 Stony Brook Game Theory Conference (Presentation)
7. 2013 Midwest Theory Conference, Michigan (Presentation)
8. 2014 North American Winter Meeting of Econometric Society, Pennsylvania (Planned, Presentation, Discusstant)

Contribution of the Project

- The theoretical results = provide game-theoretic foundations of incentive auctions design
- The software = the first public implementation of the incentive auctions algorithms
- These results validate the incentive auctions design proposed by FCC.

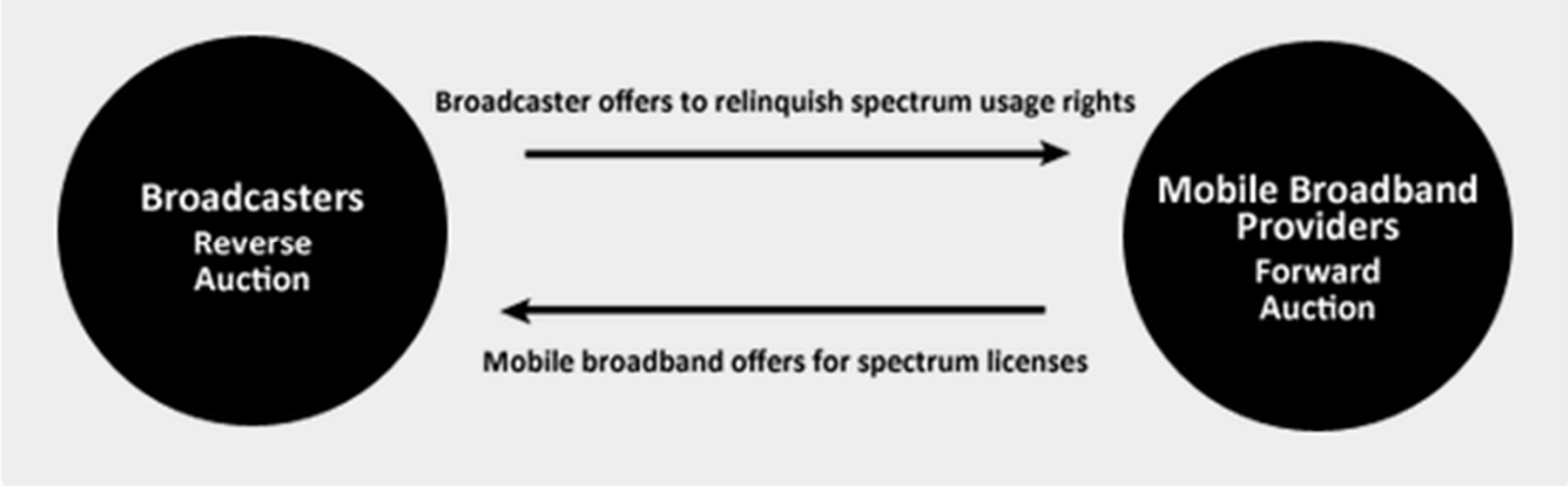
Today's Presentation

- Kazumori (2013c) = the design of reverse auctions algorithm
- Kazumori and Belch (2013b) = prototype software of incentive auctions

II. The Design of Reverse Auctions Algorithm: Simultaneous Deferred Acceptance Heuristic Threshold Auctions

Fundamental Structure of Incentive Auctions

- Reverse auctions=TV broadcasters relinquish the spectrum usage rights in exchange for payments
- Repacking=Reorganize the television band into blocks of spectrum for flexible use
- Forward auctions=Mobile operators bid for usage rights of repurposed spectrum

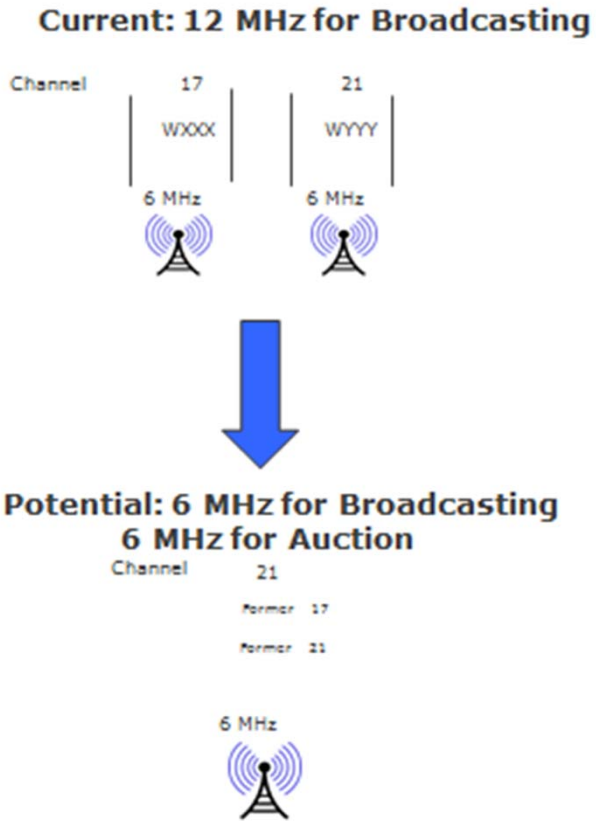


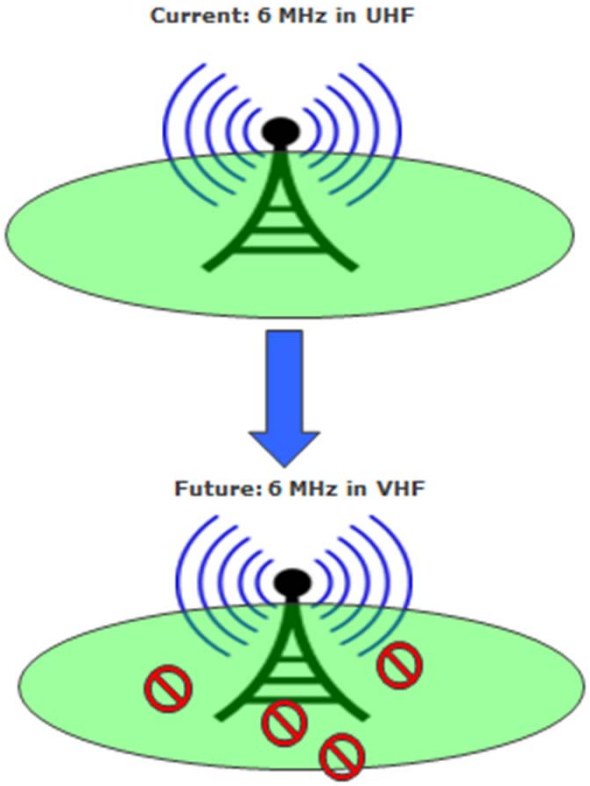
Deferred acceptance heuristic auctions algorithm (Milgrom and Segal (2013))

- TV stations submit offers to relinquish the usage rights
- Expensive offers will be rejected and stations will be repacked into the UHF band
- As the price goes down, more stations will be repacked.
- The auction ends when the band is full.
- Unassigned stations with lower offers will sell the usage right to FCC
- They will receive the threshold price.
  - Threshold price=maximum offer possible to sell
- The theorem: *when sellers are single-minded and make only one offer, the auction mechanisms are strategy-proof.*

TV Broadcasters Multiple Relinquishment Options

- Spectrum Act 6403(a)(2) states that reverse auctions shall provide 3 bid options for participants: Going off the air, switching to the VHF band, and Channel sharing





Research Question=Generalization of the Milgrom-Segal Algorithm

- Milgrom and Segal consider single minded bidding where TV stations can place only one bid.
- The research question is to extend the algorithm to accommodate these options
  - Potentially nontrivial (Lehmann, O'Callaghan, Shoham (2002)).

Why Consider this Question?

- Allowing multiple options to relinquish spectrum instead of only one can increase TV broadcaster participation in reverse auctions.

Our Approach: Integration with Tried and True Algorithms.

- We integrate the Milgrom-Segal algorithm with
  - Deferred acceptance algorithm (Gale and Shapley (1962), Roth(1984), Nobel Prize 2012)
  - Simultaneous ascending auctions algorithm (Milgrom (2000, 2004))

Simultaneous Deferred Acceptance Heuristic Auctions Algorithm

- TV stations submits offers for multiple options.
- FCC evaluates interference constraints using the scoring functions.
- FCC calculates the threshold prices
- The FCC buys from a TV station with an option that makes a highest positive provisionally profit (=threshold prices - costs) .
- The TV station receives the compensation equal to the threshold price.

Strategy-Proofness

- Theorem: *In the reverse auctions economic environment, simultaneous deferred acceptance heuristics auctions are strategy-proof.*
- Interpretations
  - In this auction algorithm, it is the best interest of the participants to offer according to their true valuations
  - Thus, auctions are incentive compatible and efficient subject to interference constraints
- Intuition:
  - The threshold pricing rule=a seller's offer cannot influence the price.
  - A seller has an incentive to offer truthfully to obtain the highest possible profit from the auction.

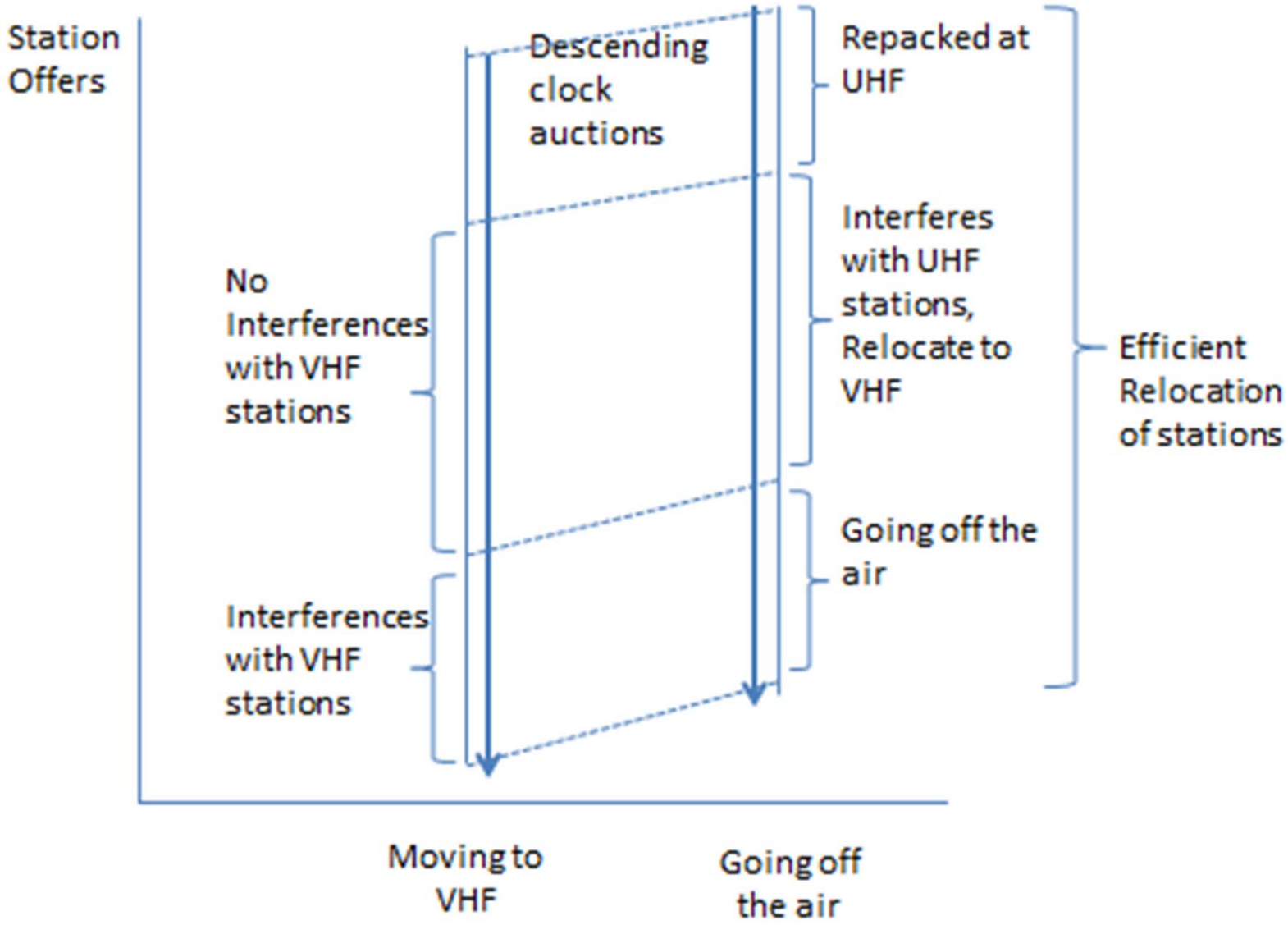
Significances of Strategy-Proofness

- Strategy-proofness (dominant strategy equilibrium) implies that it is a best response for a TV station to participate and report the value truthfully, whatever other TV stations do.
  - Reduce concerns on collusions.

Descending Clock Auctions Algorithm

- TV stations report their offers to the proxy agent.
- The proxy agent make an actual offer on the option that provides the highest profit for the seller
- FCC chooses the provisional allocations with the minimum acquisition costs and satisfies interference constraints.
- Rejected TV stations make counteroffers.
- The auction ends when the proxy agents exhaust all possible offers.
- The key point:
  - Proxy bidding to simply the bidding process
  - Personalized prices for threshold pricing

Efficient Relocation of Stations



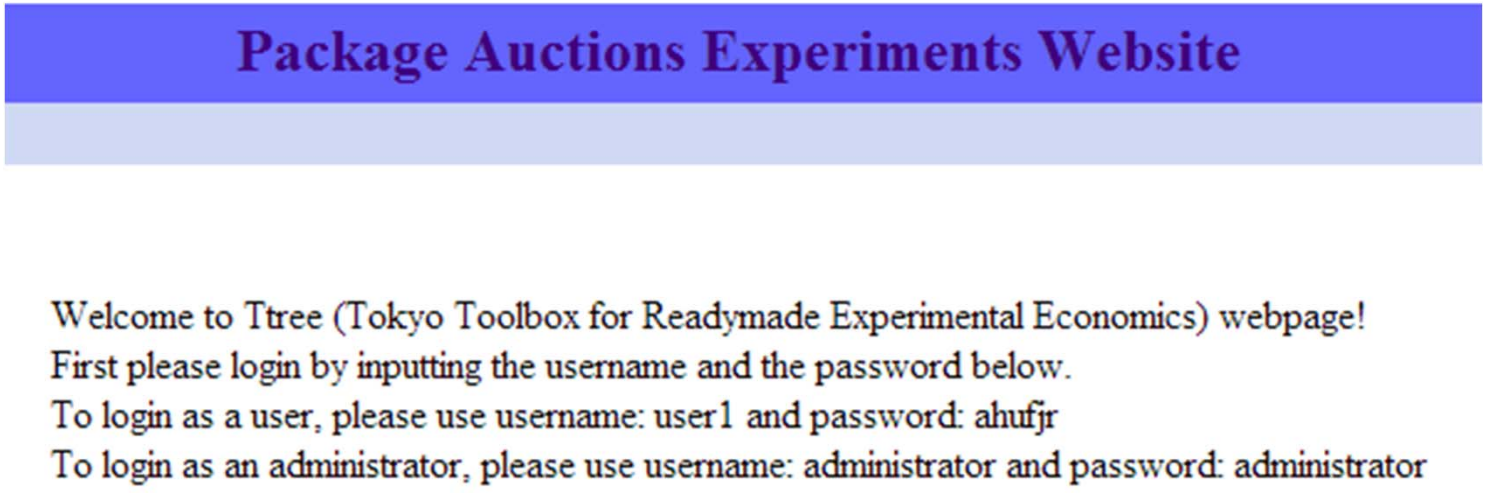
III. Software Implementations

Importance of the Prototype Software

- Kwerel (2004): *The elegance and the coherence of the proposal were not sufficient to make it an easy sell at the FCC. Many staff had little taste for taking the chance on an auction design that had never been used and seemed far more complex than any auction they had heard of. Chairman Reed Hundt's legal advisor, Diane Cornell, argued that the mechanism, especially the activity rule, was much too difficult for bidders to understand.*
- Kwerel (2004) and Rosston (2000): *As one senior FCC official put it, "it [the CalTech backup and checking during the first auction] is like flight insurance. If the airplane doesn't crash, you are annoyed that you wasted your money, but you get over it."*

Software Developments

- Continuation of the previous T-tree software



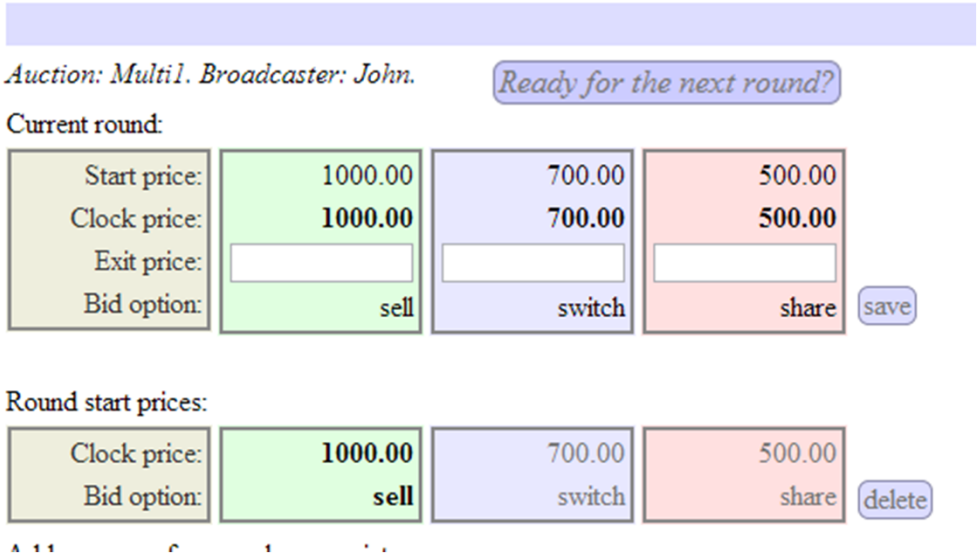
- Use lp-solve to deal with feasibility constraints.
- Reverse auctions implementations have some limitations for the number of licenses and broadcasters
- Forward auctions implementations have less limits.

Our Implementations

- A prototype software organizes these auctions with the price clocks
  - Descending Clock UHF Band Reverse Auctions
  - Descending Clock VHF Band Reverse Auctions
  - Ascending Clock Forward Auctions.
  - Closing Rule.
- This is the first publicly available implementations of the incentive auctions.

A. Reverse Auctions Implementation Step 1: Beginning of the Round

- Consider a following simple demo (Auction id: Multi1, User id: John, Password: qwerty)
- FCC wants to choose one station into the band.
- At the beginning of the round, FCC announces the starting offer price for each bid option.
- Broadcaster can input the exit price for each options.
  - Can allow intra-round bidding



Step 2: Inputting the Exit Prices

Auction: Multi1. Broadcaster: John.

Current round:

Start price:	1000.00	700.00	500.00	
Clock price:	~~1000.00~~	~~700.00~~	~~500.00~~	
Exit price:	800	500	200	
Bid option:	sell	switch	share	save

Round start prices:

Clock price:	**1000.00**	700.00	500.00	
Bid option:	**sell**	switch	share	

Reject 'sell' at price 800:

Clock price:	800.00	**560.00**	400.00	
Bid option:	~~sell~~	**switch**	share	

Reject 'switch' at price 500:

Clock price:	714.29	500.00	**357.14**	
Bid option:	~~sell~~	~~switch~~	**share**	

Reject 'share' at price 200:

Clock price:	400.00	280.00	200.00	
Bid option:	~~sell~~	~~switch~~	~~share~~	delete

#assume uniform clock speed
#when the price goes down to 800 the bidder 1 will exit from the selling option

Step 3: Outcome of the Auction

Auction: Multi1. Broadcaster: John.

Provisional outcome: exit ==> ch1

Current round:

Start price:	400.00	280.00	200.00	
Clock price:	~~400.00~~	~~280.00~~	~~200.00~~	
Exit price:	800	500	200	
Bid option:	sell	switch	share	save

Reject 'sell' at price 800:

Clock price:	800.00	**560.00**	400.00
Bid option:	~~sell~~	**switch**	share

Reject 'switch' at price 500:

Clock price:	714.29	500.00	**357.14**
Bid option:	~~sell~~	~~switch~~	**share**

Reject 'share' at price 200:

Clock price:	400.00	280.00	200.00	
Bid option:	~~sell~~	~~switch~~	~~share~~	delete

#The second station was willing to sell at 350 and it was cheapest for FCC to buy from the second station.

Step 4: Reverse Auctions with Multiple Stations with Various Bid Options

Auction: MultiX. Broadcaster: Anton.

Current round:

Start price:	1000.00	700.00	500.00	
Clock price:	**1000.00**	**700.00**	**500.00**	
Exit price:				
Bid option:	sell	switch	share	save

Round start prices:

Clock price:	**1000.00**	700.00	500.00	
Bid option:	**sell**	switch	share	delete

Auction: MultiX. Broadcaster: Benny.

Current round:

Start price:	1000.00	700.00	
Clock price:	**1000.00**	**700.00**	
Exit price:			
Bid option:	sell	switch	save

Round start prices:

Clock price:	**1000.00**	700.00	
Bid option:	**sell**	switch	delete

Auction: MultiX. Broadcaster: Claus.

Current round:

Start price:	700.00	500.00	
Clock price:	**700.00**	**500.00**	
Exit price:			
Bid option:	switch	share	save

Round start prices:

Clock price:	**700.00**	500.00	
Bid option:	**switch**	share	delete

Auction: MultiX. Broadcaster: Daniel.

Current round:

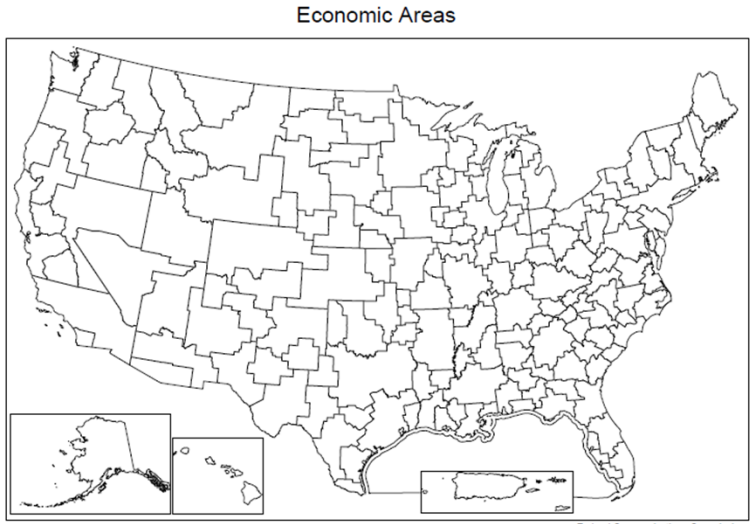
Start price:	1000.00	500.00	
Clock price:	**1000.00**	**500.00**	
Exit price:			
Bid option:	sell	share	save

Round start prices:

Clock price:	**1000.00**	500.00	
Bid option:	**sell**	share	delete

B. Forward Auctions= Selling Generic Licenses

- The forward auction sells generic licenses of repurposed spectrum to potential users based on the Band Plan.
- The Products offered for sale will include generic licenses for paired spectrum in each of the 176 Economic Areas (EAs).
- Generic licenses provide the right to a specific amount of spectrum in a specific area, but not to particular frequencies.
- The assignment to frequencie



Milgrom-Ausubel-Levin-Segal Algorithms

- The FCC announcing prices in each round (the ascending prices are referred to as price “clocks”) for each category of generic licenses in each geographic area, and bidders responding with the quantities of licenses of each type they seek at those prices.
- Prices will rise in a round if there is excess demand for the product in the preceding round or if the closing conditions have not been satisfied.
- When there is a round with no excess demand for any product, the closing conditions will be checked.
- When the auction closes, winners pay the final clock prices for each product.

Intra-Round Bidding: An Example at MALS P.15.

- Consider a following simple demo (Auction id: fwd-A, User id: Anton, Password: abc)
- FCC announces for each Product the amount by which its price may increase during the round.
- The price before the increase is called as “start-of-round” price.
- The price after the increase is called as “end-of-round”

Bidder: Anton. Auction: fwd-A.

New bid:	License-A	License-B	License-C	License-D
Start (0%):	100.00	150.00	150.00	100.00
End (100%):	120.00	180.00	180.00	120.00

Intra-Round Bidding: Bidder 1

- An intra-round bid specifies how a bidder would like to adjust its demand as prices increase toward their end-of-round levels.
- For example, a bidder could specify a demand decrease of 1 for Product A at a "price point" of 50%, meaning the bidder wants to reduce its demand for Product A by one unit when all prices have increased 50% of the way from

Bidder: Anton. Auction: fwd-A. *Round 1* *Ready for the next round?*

New bid:	License-A	License-B	License-C	License-D
Start (0%):	100.00	150.00	150.00	100.00
End (100%):	120.00	180.00	180.00	120.00
50.00 %	110.00	165.00	165.00	110.00
add	-1			
Current Demand:	8	8	4	0
Excess Demand:	3	7	7	3

Intra-Round Bidding: Bidder 2

- A bidder could specify a demand decrease of 1 for Product B and a demand increase of 1 for Product C at a price point of 75%.
- Such a bid would specify a switch of demand from Product B to C when prices have risen 75% of the way from start-of-round to end-of-round levels.

Bidder: Benny. Auction: fwd-A. *Round 1* *Ready for the next round?*

New bid:	License-A	License-B	License-C	License-D
Start (0%):	100.00	150.00	150.00	100.00
End (100%):	120.00	180.00	180.00	120.00
75.00 %	115.00	172.50	172.50	115.00
add		-1	+1	
Current Demand:	0	4	8	8
Excess Demand:	3	7	7	3

Bid Processing

- After intra-round bids are submitted, they are processed sequentially.
- The intra-round bids are processed starting with the lowest price point and continuing upward.
- An intra-round bid is allowed so long as the requested demand adjustment(s) do not cause the Aggregate Demand for any Product to fall below the Supply of that Product.

Moving to the Next Round

Round 2 *Ready for the next round?*

Bidder: Anton. Auction: fwd-A.

Round 1	License-A	License-B	License-C	License-D
50.00%	110.00			
Δ	-1			
New bid:	License-A	License-B	License-C	License-D
Start (0%):	120.00	180.00	180.00	120.00
End (100%):	144.00	216.00	216.00	144.00
100.00 %	144.00	216.00	216.00	144.00
add				
Current Demand:	7	8	4	0
Excess Demand:	2	6	8	3

#Bidder 1's demand for License A is reduced by one unit since bidder 1 decreased the demand by one unit.

#Excess demand for License B is reduced by one unit since bidder 2 decreased the demand by one unit.

#Excess demand for License C has increased by one unit since bidder 2 switched the demand from License B to C.

Multiple Intra-Round Bids

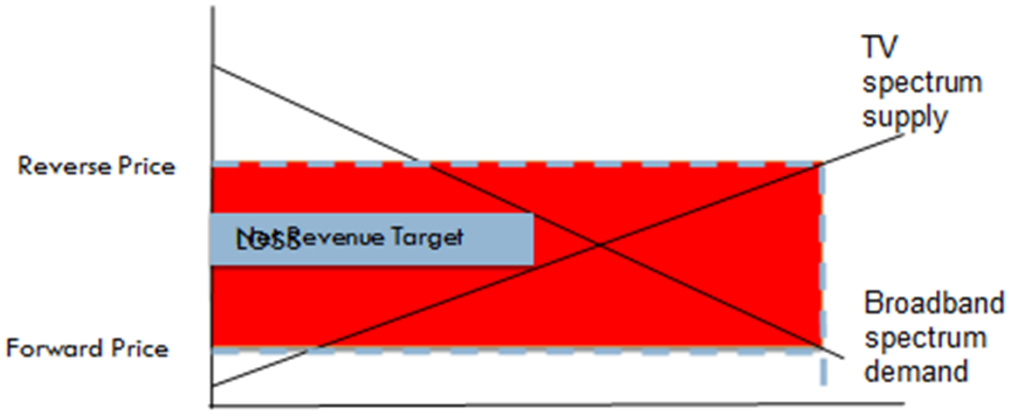
Bidder: Benny. Auction: fwd-A.

Round 1	License-A	License-B	License-C	License-D
40.00% delete		162.00 -1		
60.00% delete	112.00 -1		168.00 +1	
80.00% delete				116.00 -1
New bid:	License-A	License-B	License-C	License-D
Start (0%):	100.00	150.00	150.00	100.00
End (100%):	120.00	180.00	180.00	120.00
100.00 % add	120.00	180.00	180.00	120.00
Current Demand:	0	4	8	8
Excess Demand:	3	7	7	3

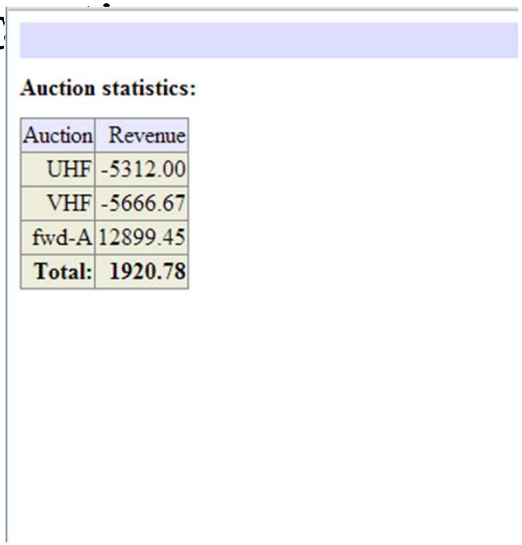
#The program can deal with multiple intra-bids by the same bidder.

C. Closing Rule: Integrating Two Auctions

- A Closing Condition would be satisfied when the Net Revenue Target is reached or exceeded and there is no excess demand for any products.
- If the Net Revenue Target cannot be reached using the current provisional Clearing Target, then the provisional Clearing Target would be reduced by one channel and the Forward and Reverse auctions would c



Credit: Milgrom-Segal



Auction statistics:

Auction	Revenue
UHF	-5312.00
VHF	-5666.67
fwd-A	12899.45
Total:	**1920.78**

IV. Conclusion

What is this Project About?

- This objective of this project = contribute to the public agenda of developing the spectrum infrastructure by studying the design of incentive auctions.

What are the Deliverables of this Project?

- 3 papers
- 1 software
- 5 related papers
- 8 conference presentations

What are the Contributions of the Project?

- The theoretical results provide game theoretical foundations of incentive auctions.
- The software is the first public implementations of the incentive auctions process.
- These results provide validations of the incentive auctions design proposed by FCC.

What are the Next Steps of the Project? - Toward a Spectrum Future

- Economic analysis of exchange of spectrum between buyers and sellers in incentive auctions.
  - Design of exchange mechanisms with technological constraints such as interferences.
- Extension to general spectrum sharing and dynamic spectrum access mechanisms.
  - Develop realistic economic methods for spectrum access and usage.
  - Field experiments for spectrum sharing.

Thank you!