How Does Computer Science Inform Modern Auction Design?

Case Study: The 2016-2017 U.S. FCC Incentive Auction

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F.C.C. Backs Proposal to Realign Airwaves

The New York Times

September 28, 2012 **By EDWARD WYATT**

WASHINGTON — The government took a big step on Friday to aid the creation of new high-speed wireless Internet networks that could fuel the development of the next generation of smartphones and tablets, and devices that haven't even been thought of yet.

The five-member Federal Communications Commission unanimously approved a sweeping, though preliminary, proposal to reclaim public airwaves now used for broadcast television and auction them off for use in wireless broadband networks, with a portion of the proceeds paid to the broadcasters.

The initiative, which the F.C.C. said would be the first in which any government would pay to reclaim public airwaves with the intention of selling them, would help satisfy what many industry experts say is booming demand for wireless Internet capacity.

Mobile broadband traffic will increase more than thirtyfold by 2015, the commission estimates. Without additional airwaves to handle the traffic, officials say, consumers will face more dropped calls, connection delays and slower downloads of data.

FCC Incentive Auction

Broadcast Television Incentive Auction (3/16-3/17):

- Reverse Auction: buy TV broadcast licenses
  - Final tally: ≈\$10 billion cost
- Forward Auction: sell wireless broadband licenses.
  - Final tally: ≈\$20 billion revenue
- Revenue to cover auction costs, fund a new first responder network, reduce the deficit (!)
  - "Middle Class Tax Relief and Job Creation Act"

The Reverse Auction

Reverse Auction Format

"Descending Clock Auction":

[Milgrom/Segal 14] (extending [Moulin/Shenker 01],[Mehta/Roughgarden/Sundararajan 09])

- each round, each broadcaster offered a buyout price (decreases over time)
  - declined => exits, retains license
  - accepted => moves to next round
- different prices allowed for different broadcasters

Milgrom

Segal

The Stopping Rule

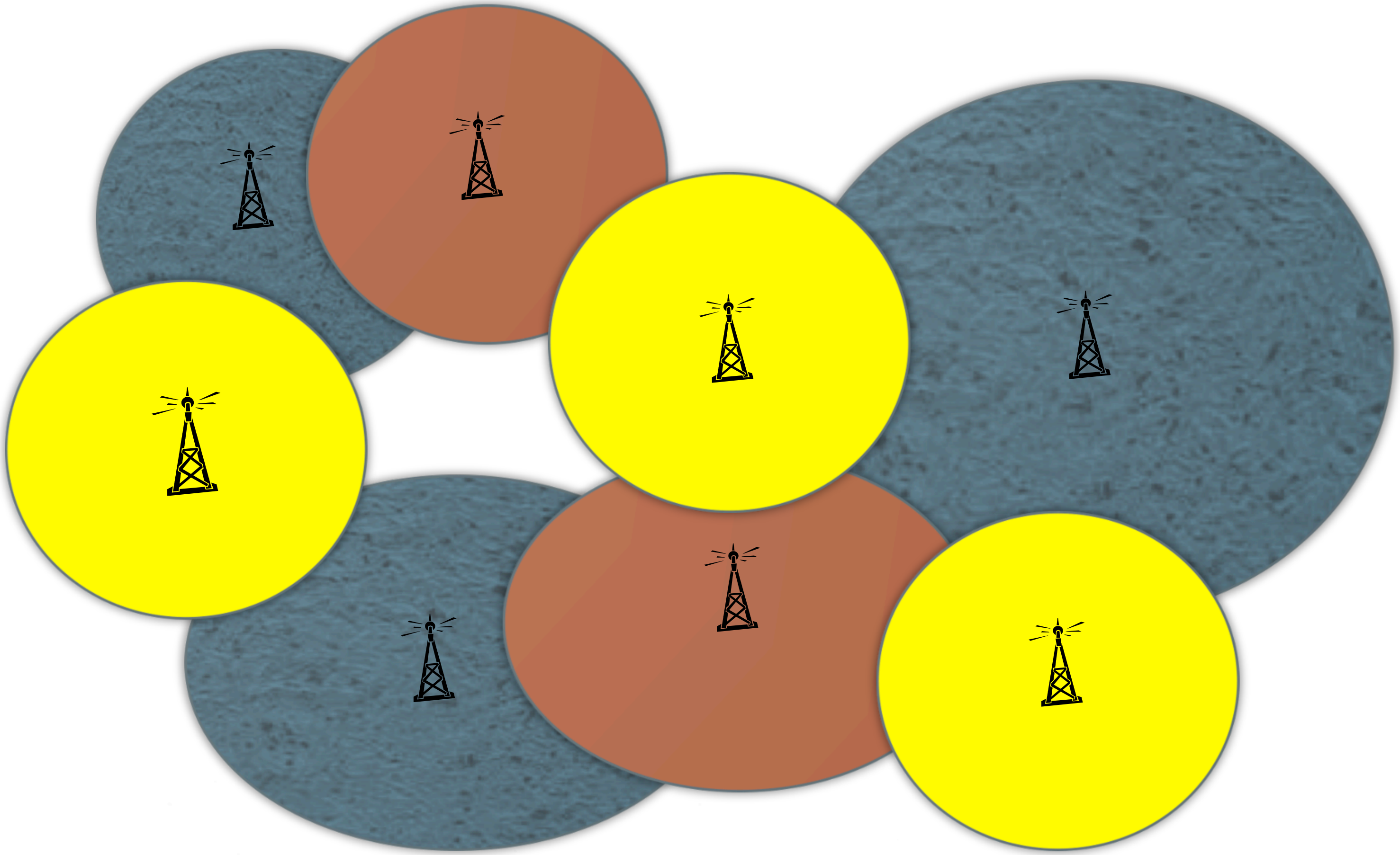
Intuition: stop auction when prices are as low as possible, subject to clearing enough spectrum.

Example goal: from channels 38-51, clear 10 of them nationwide.

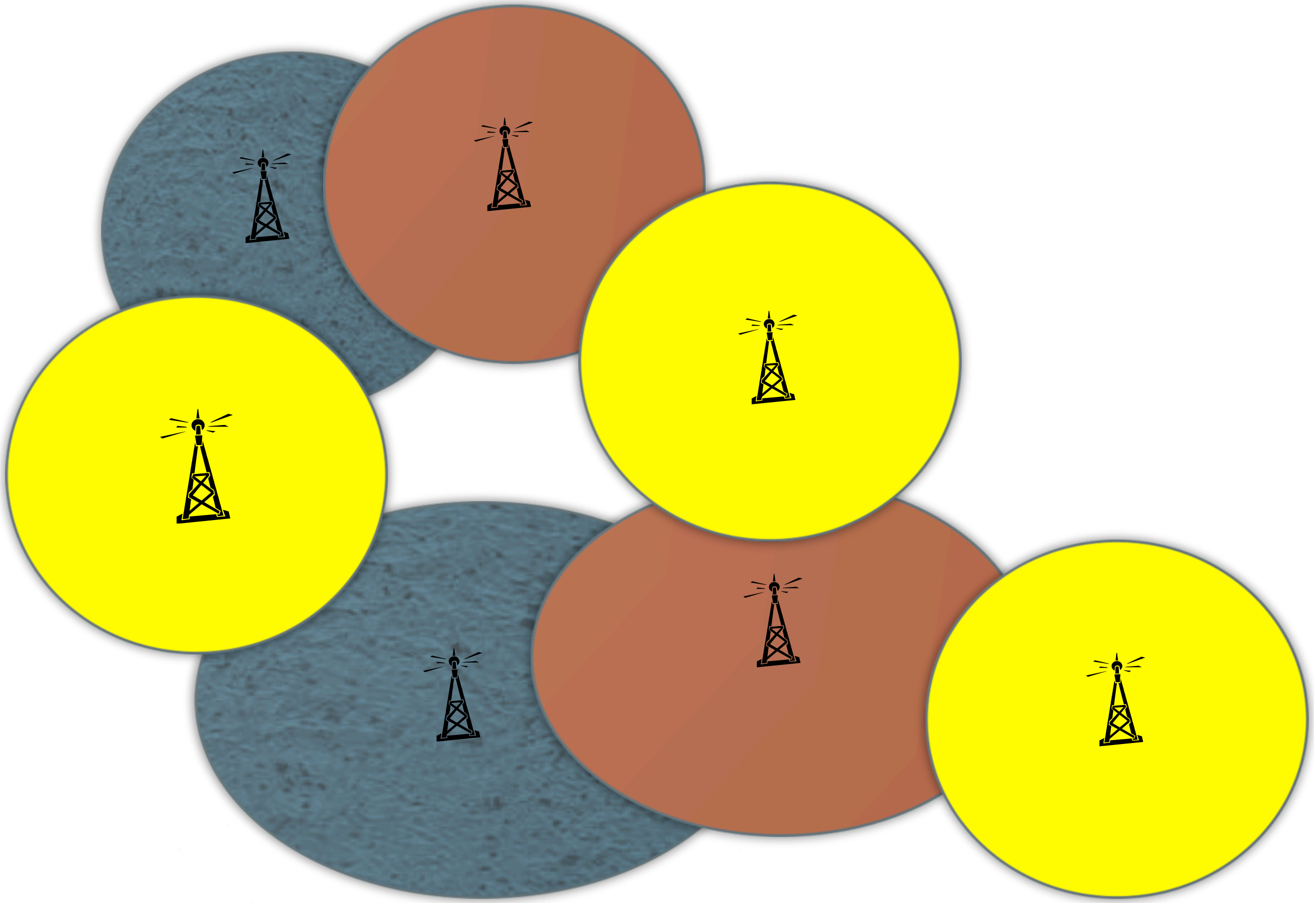
Issue: buyouts scattered across channels.

Solution: repack remaining TV stations into a smaller subset of channels (e.g., 38-41).

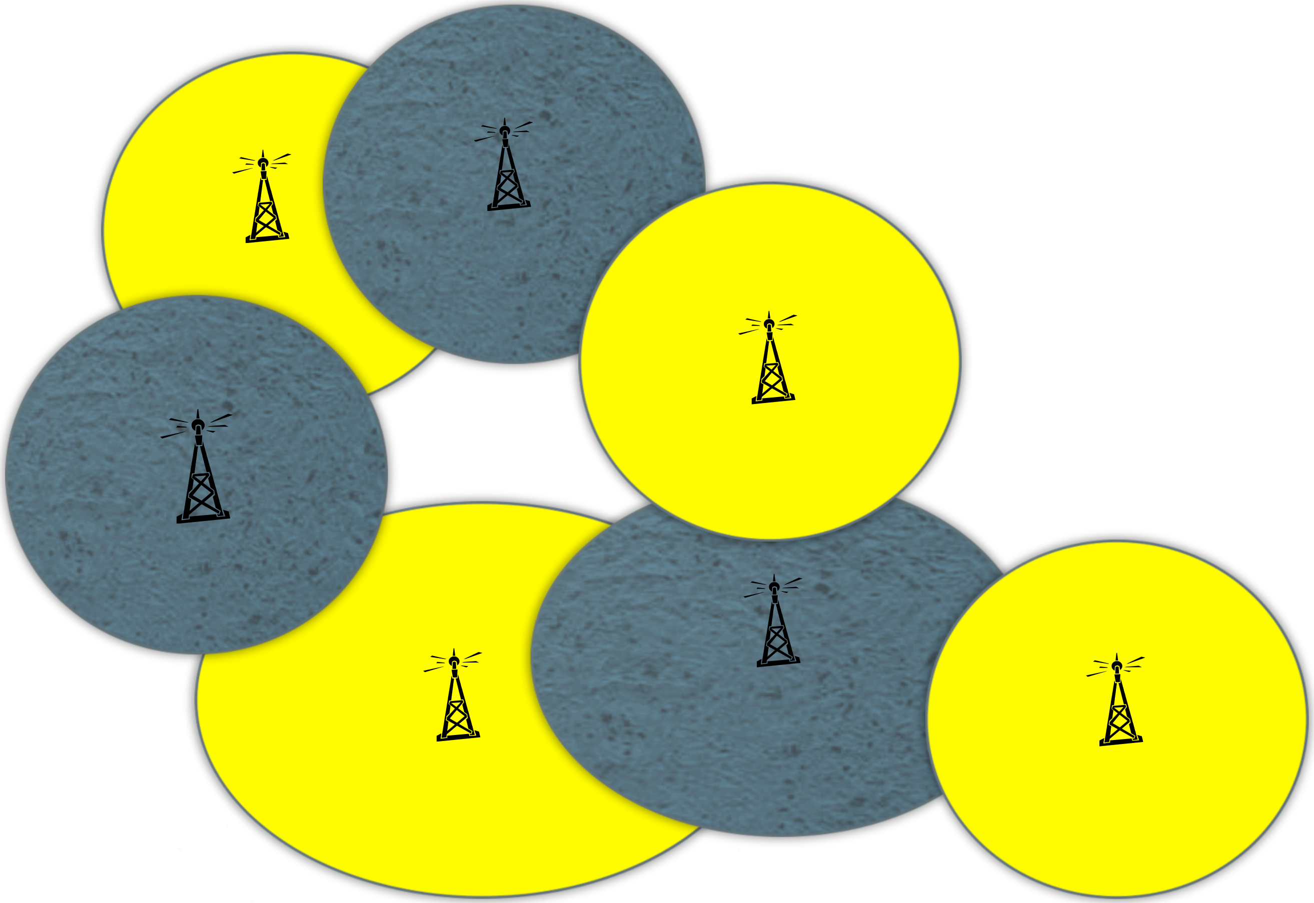
The Repacking Problem



The Repacking Problem



The Repacking Problem



The Need for Algorithms

Cool fact: state-of-the-art algorithms for solving NP-complete problems both necessary and sufficient to solve repacking problem quickly.

Leyton-Brown

[Leyton-Brown et al. 13, 14, 17]

- encode as satisfiability (SAT)
- use presolvers, solver configuations tuned to interference constraints, caching tricks

Reverse Greedy Algorithms

Theorem: [Milgrom/Segal 14] to be implemented as a descending iterative auction, necessary and sufficient to use a *reverse greedy algorithm.*

- example: still optimal in matroids

Results: [Dütting, Gkatzelis, Markakis, Roughgarden 14, 17]

- reverse version of a good greedy algorithm can be bad
- but there are novel reverse greedy algorithms for graph matching, scheduling, polymatroids, etc.

The Forward Auction

Bad Designs Cost Billions

New Zealand, 1990:

- simultaneous sealed-bid 2nd-price auctions for 10 interchangeable TV broadcasting licenses
  - creates tricky coordination problem
- projected revenue: 250M; actual = 36M
- often huge difference between top two bids

US, 2016: 10s of billions at stake.

Forward Auction Format

First cut: [McAfee, Milgrom-Wilson 93] *simultaneous ascending auctions* (one auction per license).

- usually works decently, but:

Issue #1: *demand reduction.*

- bidder buys fewer licenses to get a cheaper price

Issue #2: *exposure problem.* (with item synergies)

- example: 2 licenses; bidder #1 has value 6 for *both* licenses, bidder #2 wants one license, value = 5

Practical Rules of Thumb

Folklore belief #1: without strong complements, simple auctions work pretty well.

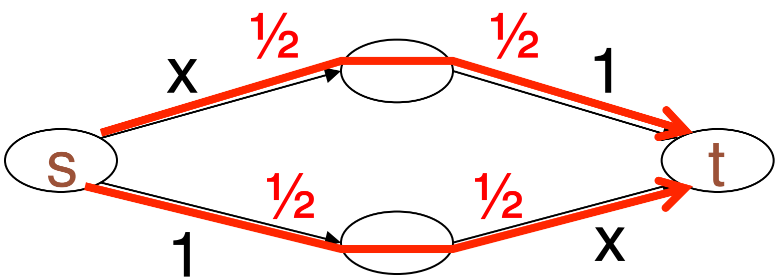
- *loss in outcome quality appears small*
- *demand reduction exists, but not a dealbreaker*

Folklore belief #2: with strong complements, simple auctions aren't good enough.

- loss in outcome quality could be big
- exposure problem exists, and is a dealbreaker

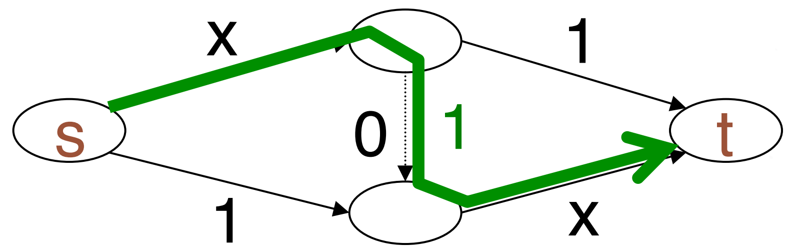
The Price of Anarchy (circa 2000)

Initial Network:



Cost = 1.5

Augmented Network:



Cost = 2

Price of anarchy = 4/3 in augmented network

- [Koutsoupias/Papadimitriou 99], [Roughgarden/Tardos 00], …

The Formal Model

- n bidders (e.g. telecoms), m items (e.g. licenses)
- bidder i has private nonnegative *valuation* $v_i(S)$ for each subset S of items [≈2^m parameters!]
- bidder i wants to maximize $v_i(S_i)$ – payment
- *social welfare* of allocation $S_1, S_2, \ldots, S_n$: $\sum_i v_i(S_i)$
  - in a perfect world, want to maximize this

The Price of Anarchy (circa now)

Theorem(s): without strong complements, all equilibria of simple auctions are approximately optimal.

[Christodoulou/Kovacs/Schapira 08], [Bhawalkar/Roughgarden 11,12], [Hassidim/Kaplan/Mansour/Nisan 11], [Feldman/Fu/Gravin/Lucier 13], [Syrgkanis/Tardos 13], [de Keijzer/Markakis/Schaefer/Telelis 13], [Duetting/Henzinger/Starnberger 13], [Babaioff/Lucier/Nisan/Paes Leme 14], [Devanur/Morgenstern/Syrgkanis 15], [Feige et al. 15], [Feldman/Immorlica/Lucier/Roughgarden/Syrgkanis 16], ...

Primary proof technique: extension theorems for smooth games. [Roughgarden 09]

When Do S1A's Work Well?

Subadditive valuations: $v_i(S+T) \leq v_i(S)+v_i(T)$ all S,T.

Theorem: [Feldman/Fu/Gravin/Lucier 13] every equilibrium of a *simultaneous first-price auction (S1A)* has welfare at least 50% of the maximum possible.

- applies more generally to "Bayes-Nash equilibria"
- 63% when valuations are submodular [Syrgkanis/Tardos 13]

Take-away: without strong complements, simple auctions work pretty well.

Practical Rules of Thumb

Folklore belief #1: without strong complements, simple auctions work pretty well.

- loss in outcome quality appears small
- demand reduction exists, but not a dealbreaker

Folklore belief #2: with strong complements, simple auctions aren't good enough.

- *loss in outcome quality could be big*
- *exposure problem exists, and is a dealbreaker*

Lower Bounds for Simple Auctions

Theorem: [Hassidim/Kaplan/Mansour/Nisan 11] With general valuations, S1A's can have equilibria with welfare arbitrarily smaller than the maximum possible.

Theorem: [Roughgarden 14] With general valuations, *every simple auction* can have equilibria with welfare arbitrarily smaller than the maximum possible.

- "simple" = subexponential (in m) number of bids per player

Take-away: with strong complements, simple auctions aren't good enough.

From Protocol Lower Bounds to POA Lower Bounds

Theorem: [Roughgarden 14] Suppose:

- (hardness assumption) no nondeterministic subexponential-communication protocol approximates the welfare-maximization problem to within a factor better than α.

Then worst-case POA of mixed Nash equilibria of every "simple" auction is at least α.

  - "simple" = sub-doubly-exponential number of actions per player
  - fine print: actually for ε–equilibria, where ε can be as small as inverse sub-exponential in n and m

Point: reduces lower bounds for equilibria to lower bounds for nondeterministic communication protocols.

Applying the Theorem

Theorem: [Nisan 02] No nondeterministic subexponential protocol approximates welfare with general valuations to any constant factor (as # of items goes to infinity).

Theorem: [Dobzinski/Nisan/Schapira 05] No nondeterministic subexponential protocol approximates welfare with subadditive valuations better than a factor of 50%.

Corollary: S1A's = *optimal* simple mechanism for subadditive valuations!

- open: true also for submodular valuations?

Proof of Theorem

Suppose worst-case POA of ε-MNE is $\rho < \alpha$:

Input: game G s.t. either (i) OPT $\geq$ W* or (ii) OPT $\leq$ W*/ α

$\rightarrow$

Protocol: advice = small-support ε-MNE x (exists by sampling argument [LMM03]); players verify it privately

$\rightarrow$ if E[wel(x)] > W*/ α then OPT > W*/ α so in case (i)

$\rightarrow$ if E[wel(x)] $\leq$ W*/ α then OPT $\leq$ (ρ / α)W* < W* so in case (ii)

Key point: every ε-MNE is a short, efficiently verifiable certificate for membership in case (ii).

How Computer Science Informs Auction Design

- Reverse auction format extends previous designs that were motivated by computational constraints
- SAT solvers for fast solution of repacking problems
- Descending iterative auctions as reverse greedy algs
- "Price of anarchy" toolbox proves that simple auctions work well without complements
- Communication complexity explains why simple auctions perform poorly with strong complements