SPECTRUM MARKETS

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Spectrum Management

Policy

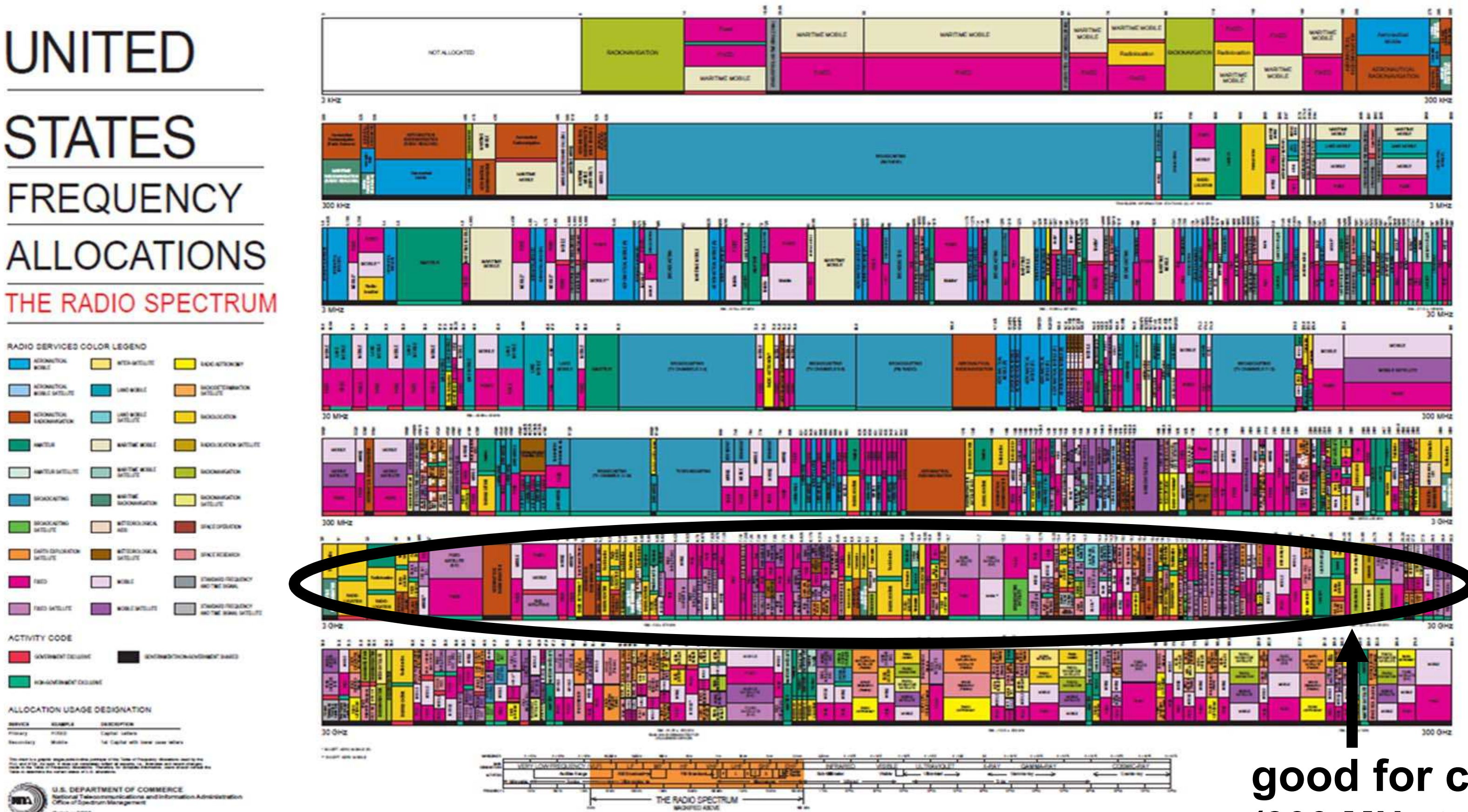
Economics

Communications Engineering

Why This Tutorial?

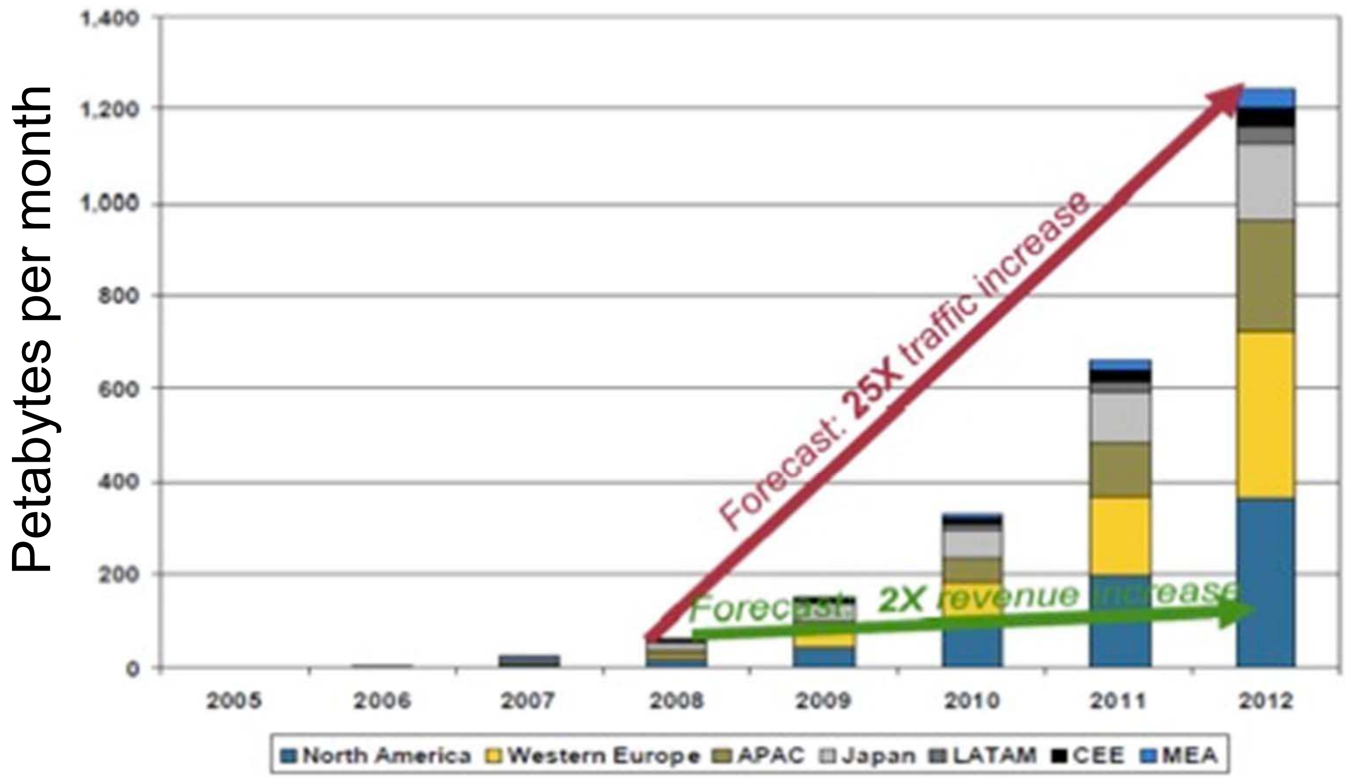
- Timely and relevant
  - New policies are needed for spectrum allocation.
  - Markets are natural policy candidates.
- Markets for spectrum pose unique challenges/questions.
  - Definition of property rights, interference externalities
  - Efficiency, incentives, wireless system design
- Interplay between economics and engineering issues

Limited Supply of Spectrum



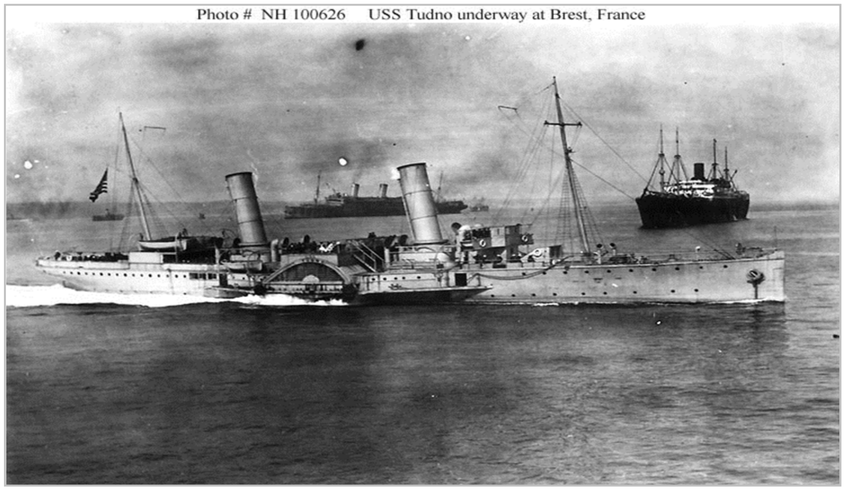
good for cellular
(300 MHz to 3 GHz)

Spectrum "Crunch"



Sources: Cisco, from Operators' network data and Analysts, 2008; Informa, 2008; and Pyramid, "Mobile data revenue will double by 2012," Dan Locke, Analyst Insight, 4/2008.

Regulation Prior to 1927: Open to All



Earliest uses of wireless for ship-to-ship, ship-to-shore communications.

Broadcast radio begins in 1921.

Licenses issued by the Department of Commerce.

Regulation since 1927: "Command and Control"

- Federal Radio Commission (FRC) established in 1927.
- Federal Communications Commission (FCC) established in 1934.
- Maintains authority to
  - Grant / renew / deny licenses for spectrum use.
  - Assign applications to particular frequencies.
  - Police content and use

An Economist's Proposal

R. Coase, "The federal communications commission," *J. Law and Economics*, pp. 1–40, 1959.

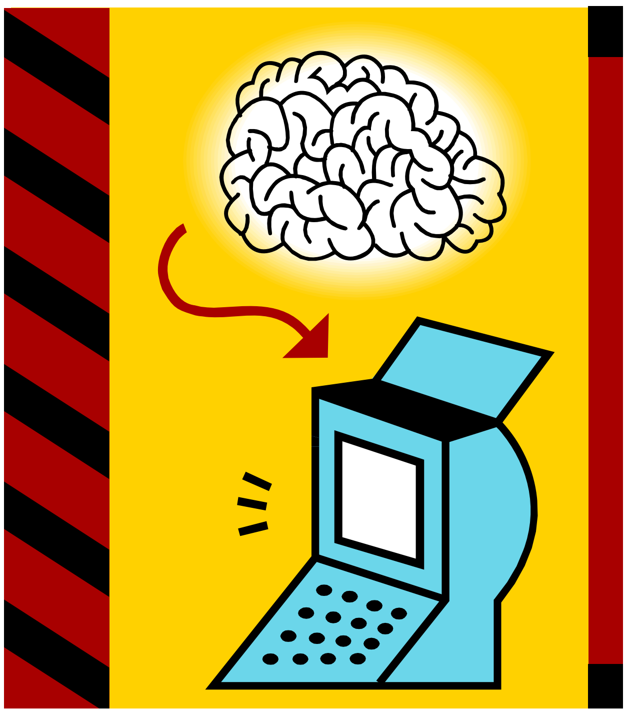
Introduce spectrum property rights, sell to highest bidders, do not restrict use.

Coase's "Theorem": In the absence of transaction costs, spectrum owners will trade rights so that the outcome allocates spectrum to best use.

Ronald Coase,
1991 Nobel Laureate in Economics

Spectrum auctions finally introduced in the 1990s. Restrictions on use remain.

Engineering Approach to Spectrum Crunch



Cognitive Radio
Mitola and Maguire (1999)

- Add intelligence to mobile devices
  - Frequency agility
  - Wideband sensing
  - Interference avoidance
  - Adaptive quality of service (context aware)
- Enables spectrum scavenging

Spectrum Sharing Models

- Exclusive use
- Commons
- Hierarchical

Exclusive Use

- Spectrum owned by government
  - Licensed to particular application, service provider
  - Rigid use rules
- Spectrum is private property
  - Applications, technical constraints decided by markets
- "Liberal" licenses
  - Spectrum publicly owned, but licenses can be transferred, liberal use rules
  - Secondary markets (2003)

Spectrum Commons

- Unlicensed
- Requires etiquette rules for sharing

- State-regulated
  - Spectrum owned by government
  - Etiquette rules part of industry standard (802.11)
- Privately owned
  - Owner sets rules, polices band
  - Revenue from selling approved equipment

Hierarchical

- Primary and secondary users
- Secondary users must not disrupt primary users
- Relies on cognitive radio

- State-regulated
  - Spectrum owned by government
  - Use rules for secondary users part of standard (802.22)
- Private contracts with "spectrum scavengers"
  - Interference levels/payments set by mutual agreement

Market Design

Asset Design

Market Mechanisms

Examples

Focus

- Designing a *dynamic* market for spectrum.
  - "Short-term" allocations done in "real-time"
  - "Small" spatial-scale

- Consider one entity responsible for leasing/selling spectrum to multiple agents.

Does Market Design Matter?

- Coase's theorem states that given no transaction costs and well-defined property rights, owners will bargain and reach an Pareto efficient outcome.

- Do we need to worry about designing a market?

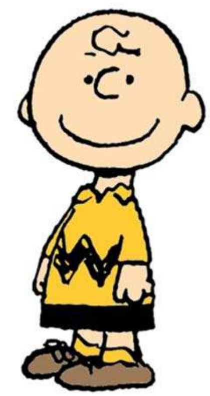
Caveats

- Non-zero transaction costs
- Multilateral externalities
- Private information

Private Information

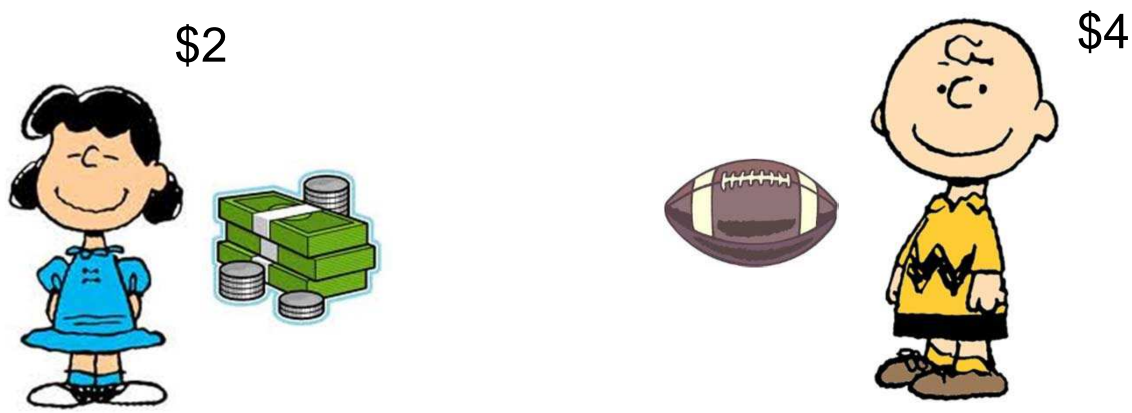
$2

$4



- If Lucy knows Charlie's value $\Rightarrow$ can make an offer to sell at \$4 - ϵ.

Private Information



- If Lucy knows Charlie's value $\Rightarrow$ can make an offer to sell at \$4 - ϵ.
- Efficient outcome.

Private Information

$2

$4

- Suppose Lucy only knows that Charlie's value is uniformly distributed on [0,10].
- Then she would expect to get $5 from any transaction ⇒ no trade.

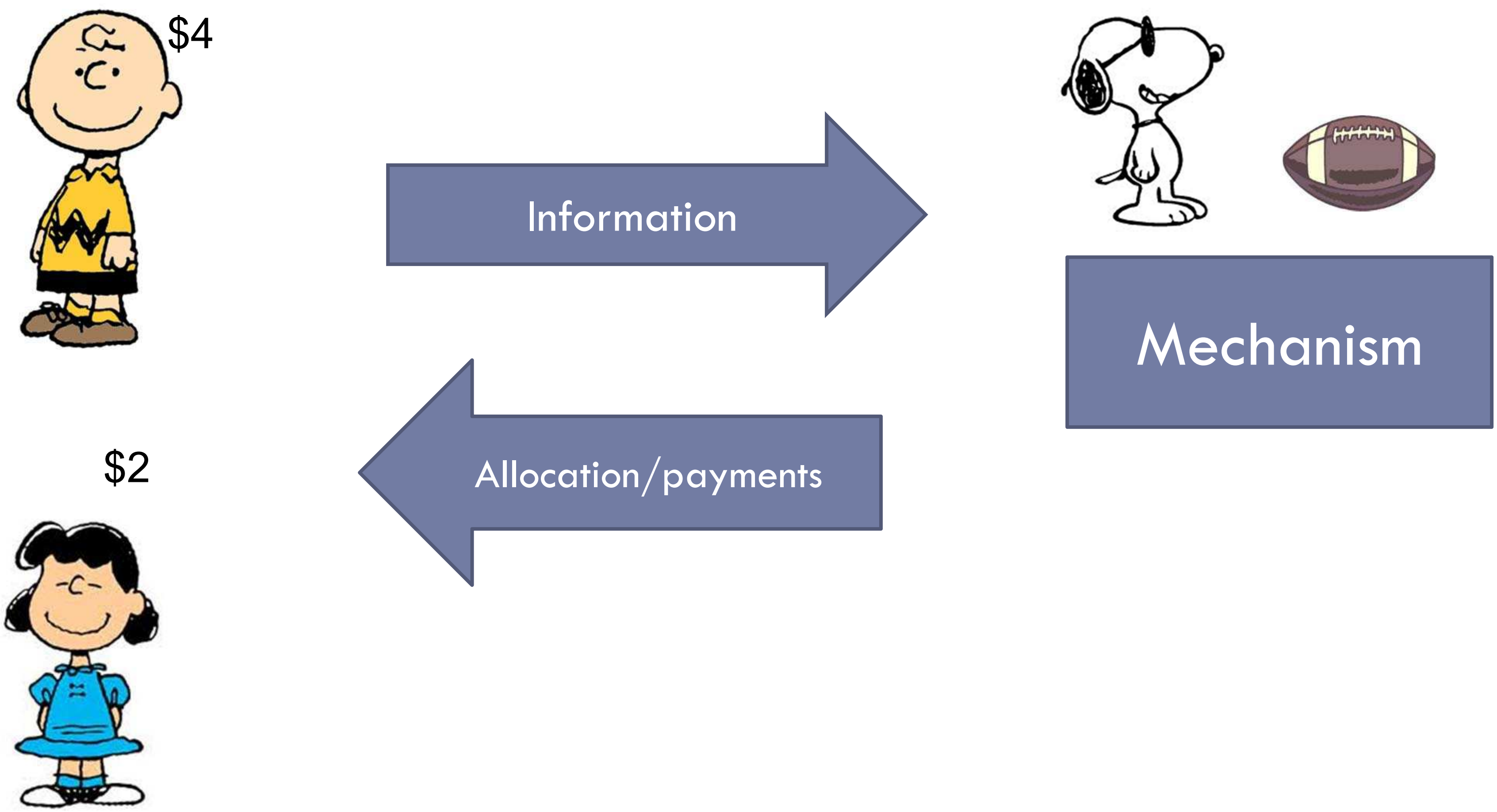
Pathological Example?

- No.
- Myerson-Satterthwaite theorem shows that with private information, under very general conditions there is no way for two parties to trade that is *efficient* and *individually rational*.
- Suggests market design matters.

Markets

- Market design has a long history in economics.
  - Intellectual foundations are mechanism design/game theory.

Mechanisms



Mechanism Design Problem

- Need to design
  1. Rules for soliciting information
  2. Allocation/payment rule

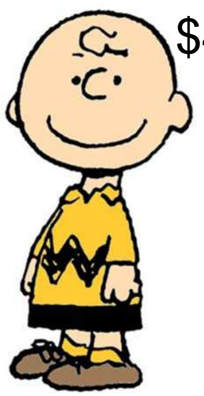
- Objectives:
  - Social welfare
  - Revenue

Example: 2nd Price Auction

- Mechanism:
  - User's submit bids.
  - Mechanism allocates good to highest bidder
  - User's pay 2nd highest bid.

- User's can be viewed as playing a non-cooperative game.
  - Use equilibrium concepts from game theory to study performance.

Optimal Bids?



$4

$4

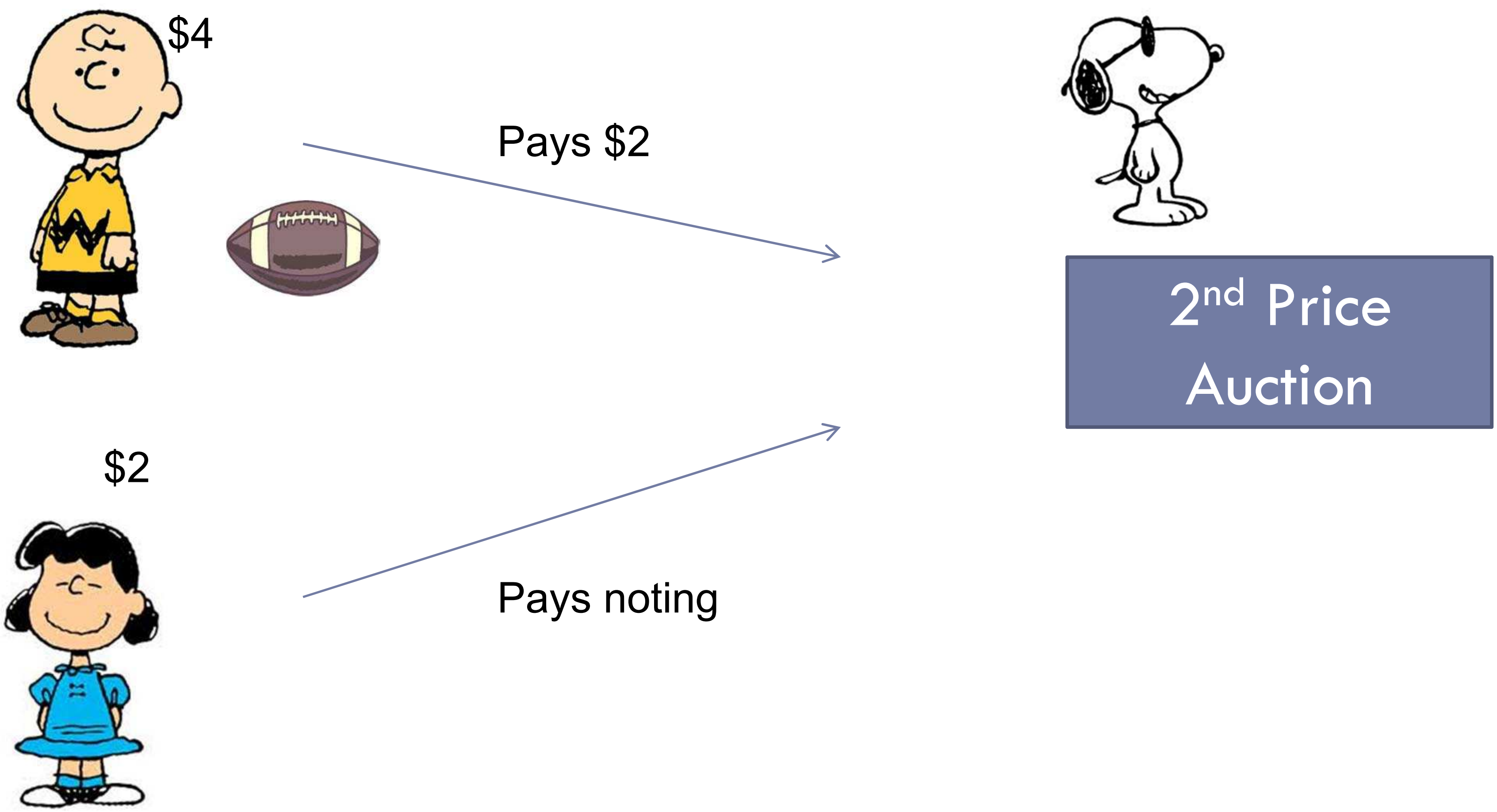
2nd Price Auction

$2

$2

Weakly dominant strategy.

Outcome



Multiple Goods

- For a single indivisible good, 2nd price auction gives efficient outcome.

- Unless we are allocating all spectrum to one user, we need to deal with multiple goods.

Vickrey-Clarke-Groves (VCG)

- VCG mechanisms generalize 2nd price auction to arbitrary "goods."

Incentive compatible, direct revelation mechanism with the efficient outcome.

VCG Mechanism

- Let A = set of alternative allocations.
- Each agent i submits valuation $v_i(a)$ for each $a \in A$.
- Mechanism chooses alternative to maximize $\sum v_i(a)$.
- Charge user i the marginal cost they impose on other players:

$$\max_b \sum_{j \neq i} (v_j(b) - v_j(a))$$

Can modify payments by adding terms that only depend on other player's valuations.

Issues with VCG

- **Complexity:** VCG requires solving N+1 optimization problems for allocating goods to N agents.
- **Overhead:** Required bids may have a high communication costs.
- Requires agents to know values for all alternatives.
- May be susceptible to collusion.

Market Design

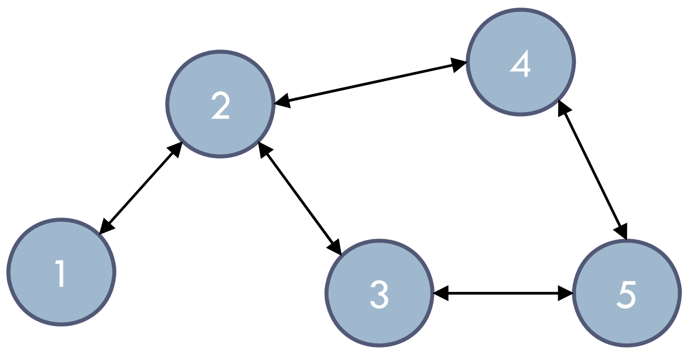
Asset Design

Market Mechanisms

Examples

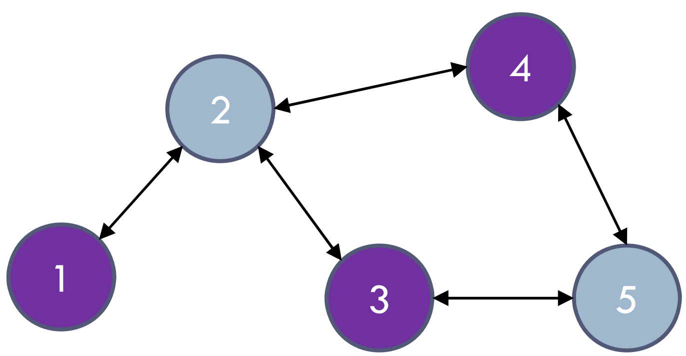
Basic Model

- Consider the allocation of C *spectrum assets* to A *agents*.
  - Each asset is right to transmit in given spatial region over a given frequency band for fixed time period.
  - Model Interference among assets via an *interference graph*.



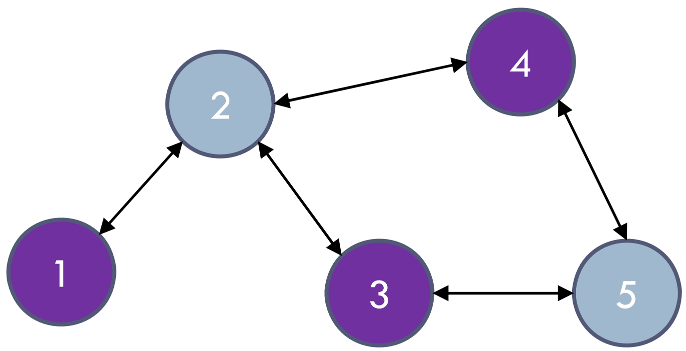
Static Interference Free Allocation

- Pick a fixed set of *non-interfering assets*.
  - Only allocate these.
- If agents valuations of different assets are additive ⇒ can allocate each using second price auctions.



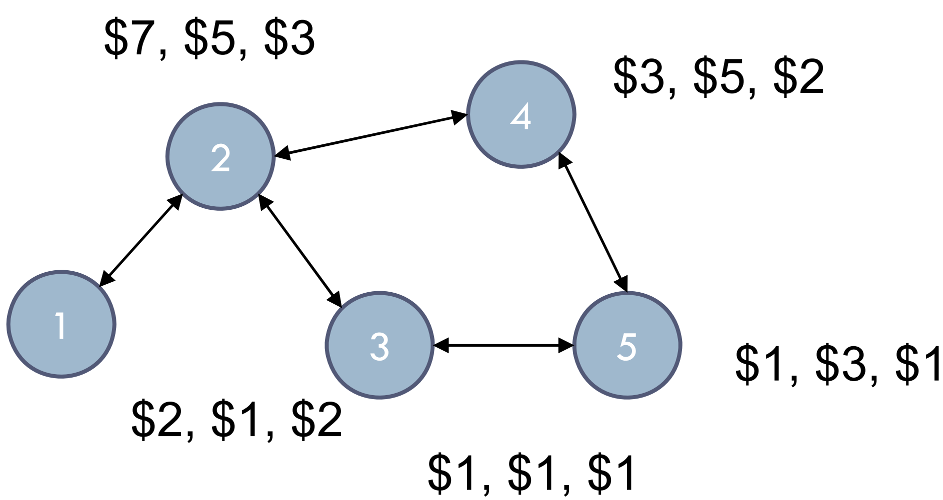
Static Interference Free Allocation

- Overhead: linear in number of assets.
- Complexity: O(CA log(A))
- Issues?



Dynamic Interference Free Allocation

- Let agents bid on *every* asset.
- Allocate an interference free set of assets with the highest bids.



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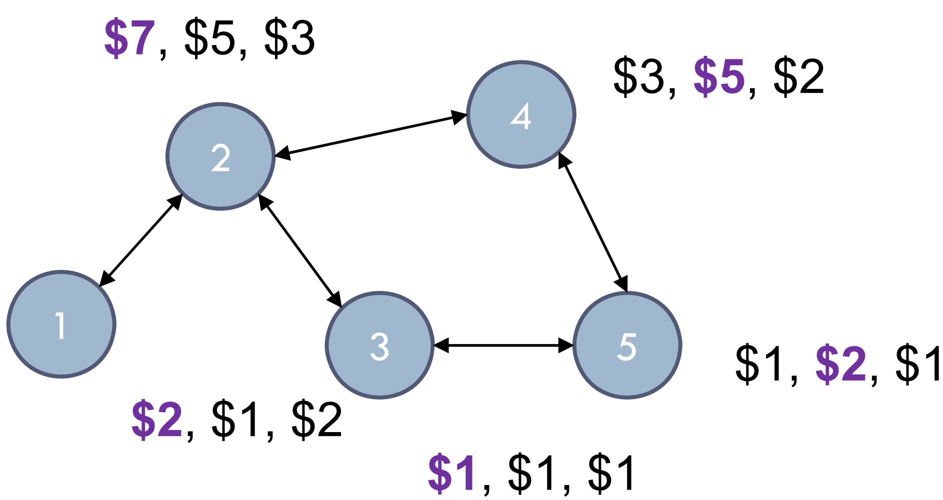
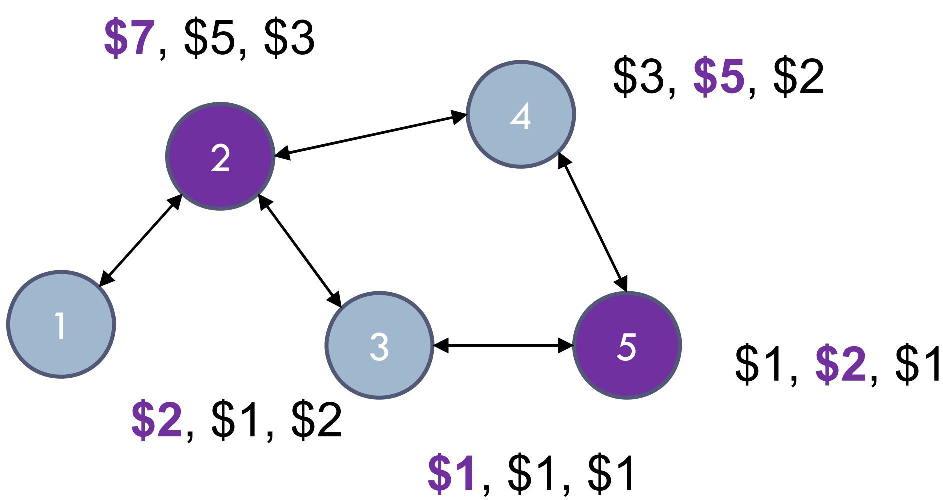


Dynamic Interference Free Allocation

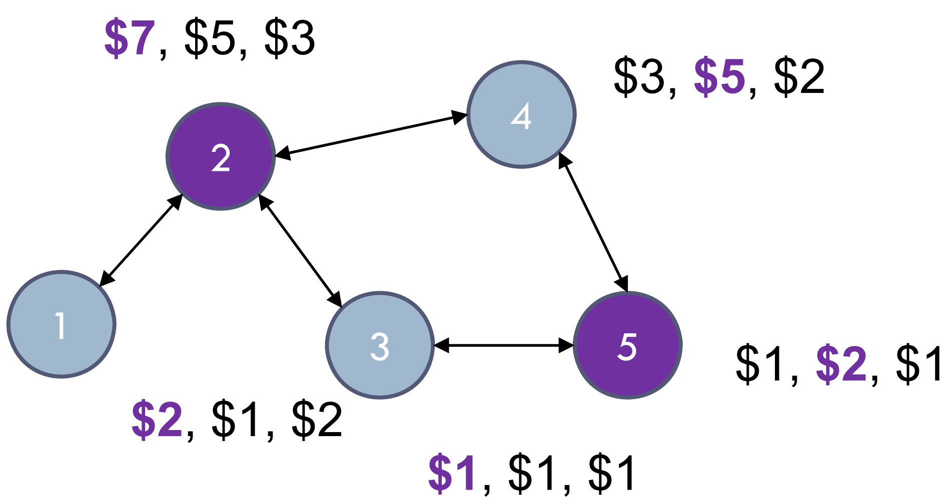
- Let agents bid on *every* asset.
- Allocate an interference free set of assets with the highest bids.

  ⇒ Maximum weight independent set.



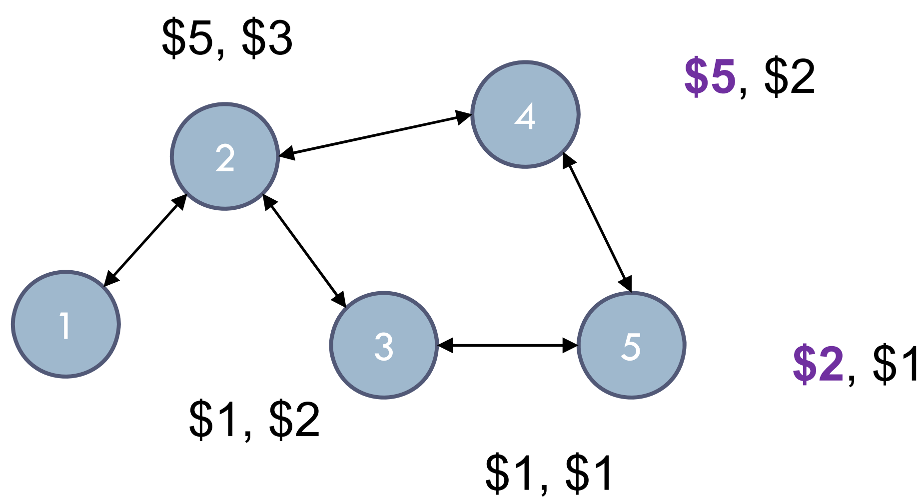
VCG payments

- Consider Agent 1?



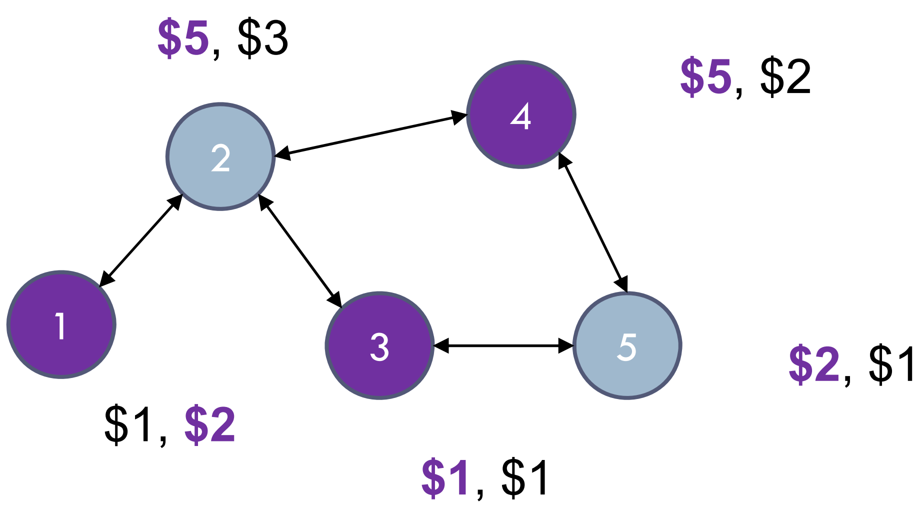
VCG Payments

- Consider Agent 1
- Remove Agent's bids



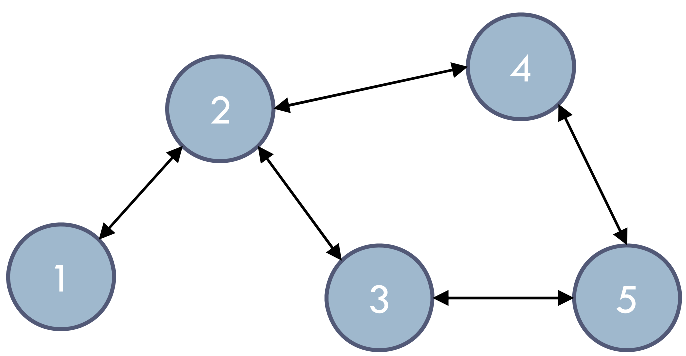
VCG Payments

- Consider Agent 1
  - Remove Agent 1's bids
  - Re-calculate allocation
  - Payment = (6-2) + (2-0) = $6



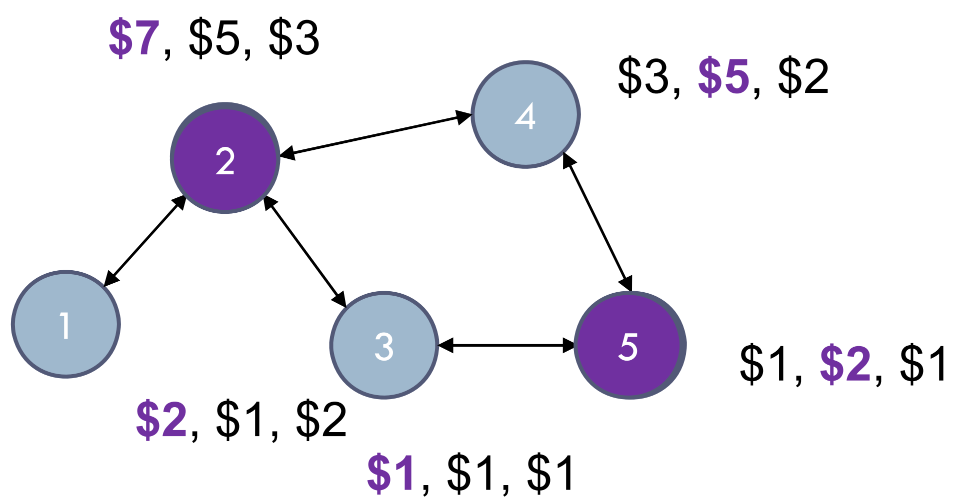
Dynamic Interference Free Allocation

- Overhead: linear in number of assets.
- Complexity: NP-hard!
  - Need to find multiple maximum weight independent sets.



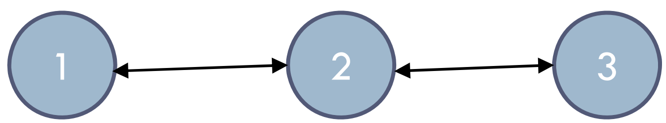
Approximations

- Consider a greedy approximation:
  - Order assets by bids and assign from highest to lowest if possible.



Greedy Approximation

- No longer Truthful!
  - Truthful bids ⇒ Agent 1 gets Assets 2
  - Suppose Agent 2 increases bid on 1 to $4
    - Agent 2 gets Assets 1 and 3 and pays $3
    - Pay-off = $4- $3.



True values	$1, **$2**	**$3**, $1	$1, **$2**
New bids	$1, **$4**	**$3**, $1	$1, **$2**

Market Organization

Market structures

Competitive Behavior

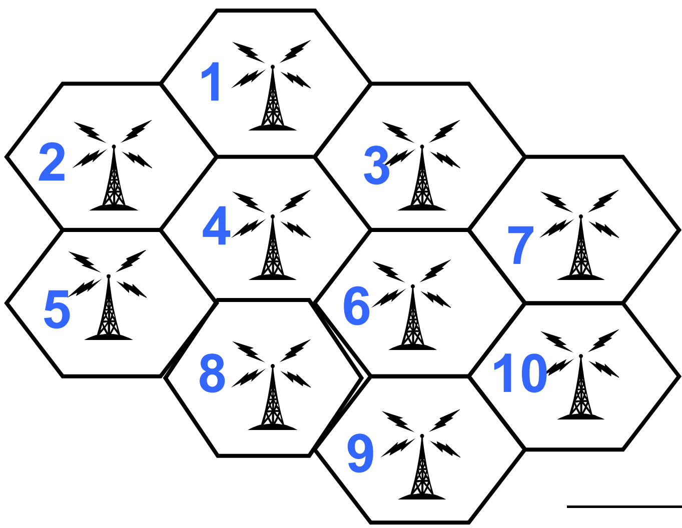
Owning vs Leasing

Owned spectrum asset has unlimited time duration;
traded as property (e.g., land).

Leased spectrum asset has limited time duration;
available through local spot market

Owners can deploy services or rent / lease spectrum assets.
➔ Service providers need not be spectrum owners!

Two-Tier Spectrum Market

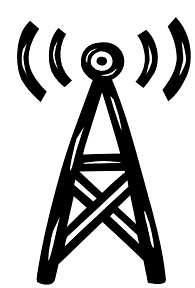


location	band 3.5 GHz	3.6 GHz	3.7 GHz
cell 1	Owner A	Owner B	Owner A
cell 2	Owner A	Owner B	Owner A
cell 3	Owner A	Owner C	Owner C

Service requests

Spectrum Broker

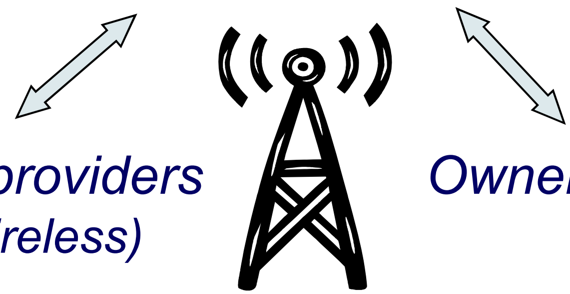
Service providers (Acme Wireless)



Owners A, B, C, □

Lower-Tier Spot Market

Spectrum Broker



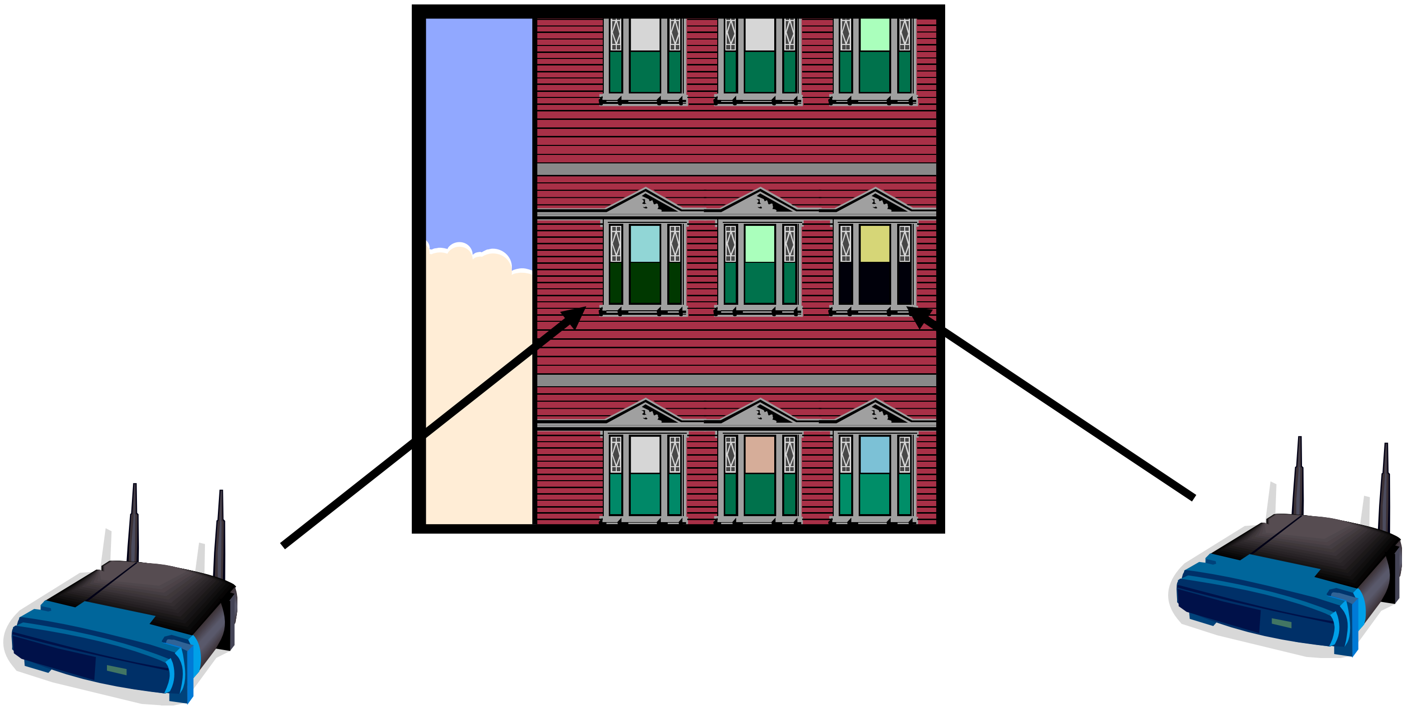
Service providers
(Acme Wireless)

Owners A, B, C, □

Managed by spectrum broker

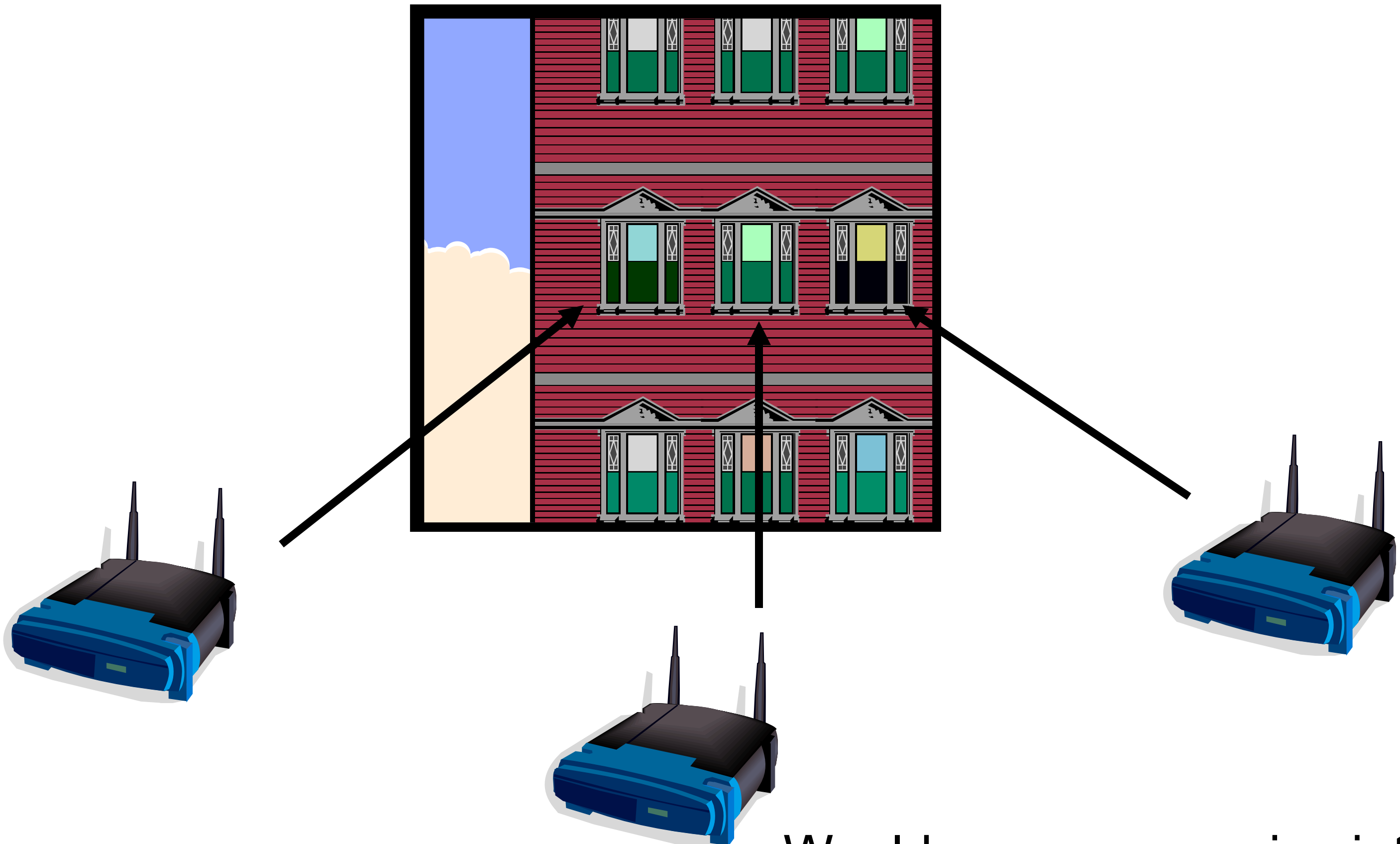
- Sets prices, attempts to clear market
- Auction mechanism: collects bids; determines allocation
- Can be automated ("spectrum server")

Local Transactions



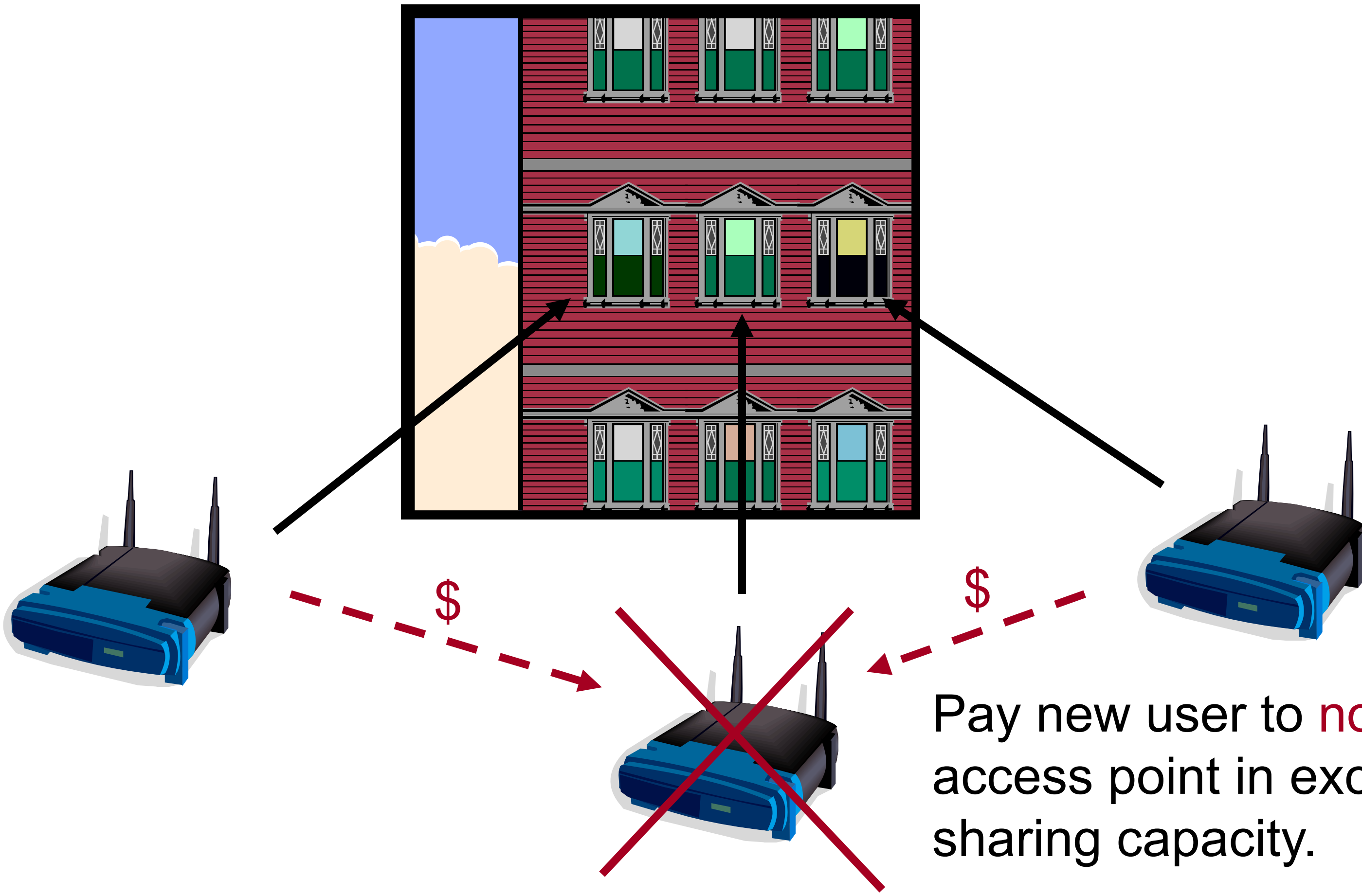
Routers use the same channel, cause little interference

Local Transactions



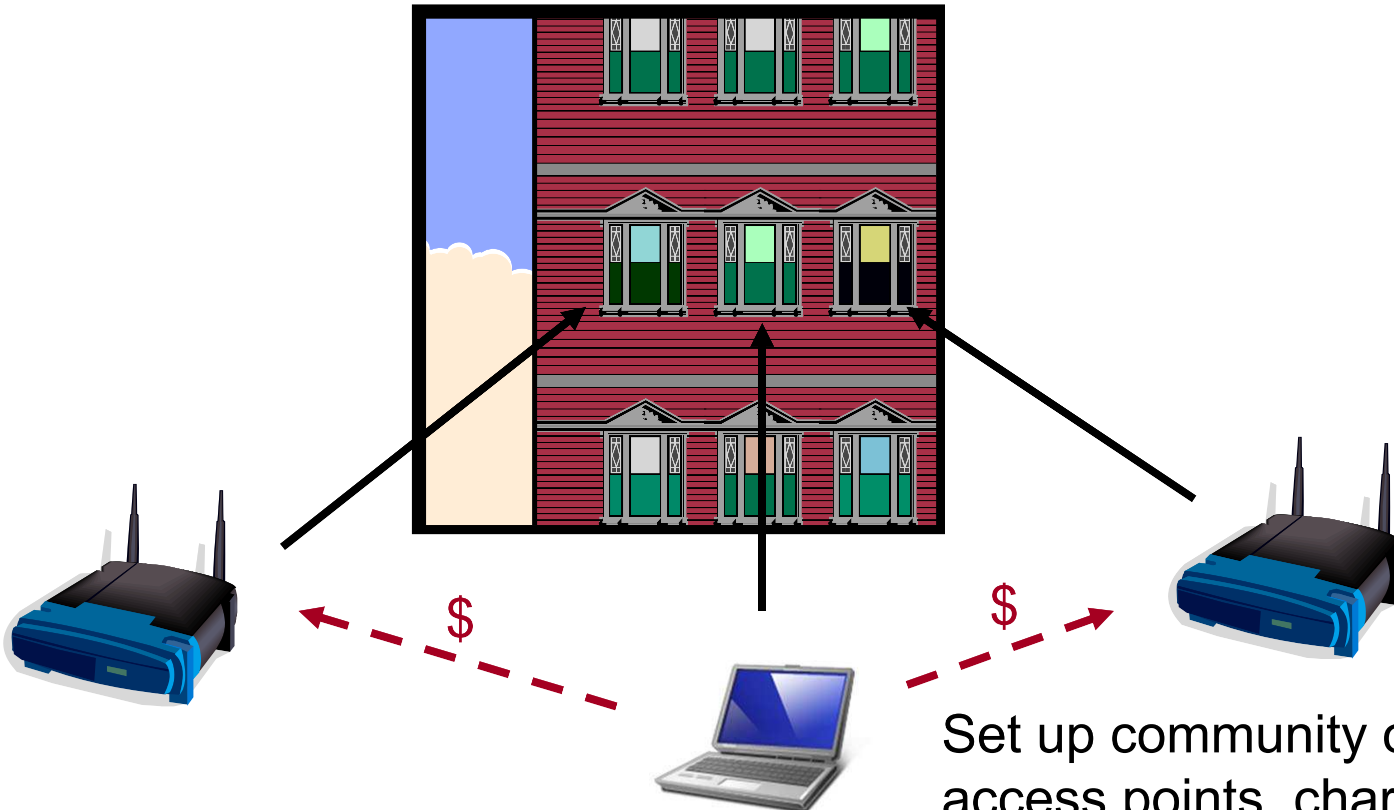
Would cause excessive interference.

Deterence Price



Pay new user to not setup access point in exchange for sharing capacity.

Usage Price



Set up community of access points, charge fee for sharing capacity (Fonera).

Pricing and Efficiency

- Deployment game: each user decides whether or not to setup an access point given a fixed deterrence price from neighbors.
- Deterrence pricing can substantially increase efficiency, mitigate interference [Bae et al, DySPAN `09] .