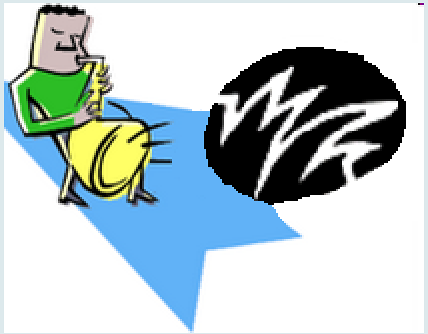

BATTLE OF THE BAND*width*S:

SPECTRUM MARKETS AND INTERFERENCE MANAGEMENT

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Spectrum Management

Policy

Economics

Communications Engineering

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Kellogg MEDS

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EECS

Outline

- Background
- Spectrum Markets
- Interference management

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

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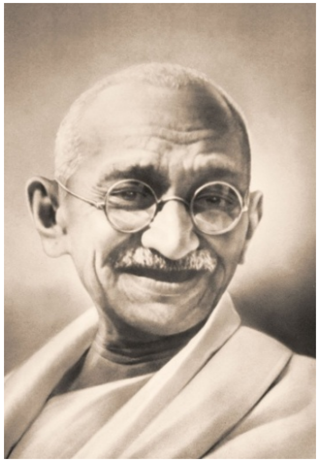

“Wise old man approach to spectrum allocation”

The Spectrum Paradox

- Spectrum is a scarce resource
- Spectrum is underutilized

Demand is Increasing

InternetNews.com >> Mobility

AT&T Faces 5,000 Percent Surge in Traffic

The nation's No. 2 carrier moves to address huge gains in data traffic, mirroring an industry-wide trend in wireless.

October 8, 2009
By Michelle Megna: *More stories by this author.*

AT&T's chief technology officer today highlighted how the recently maligned carrier is addressing skyrocketing demand for mobile data as it experiences a 5,000 percent surge in mobile data traffic.

As AT&T (NYSE: T), the exclusive carrier for the Apple (NASDAQ: AAPL) iPhone, has embraced smartphones and their applications as well as other devices including netbooks and e-readers, mobile data traffic has grown nearly 5,000 percent on the AT&T network over just the past three years, said AT&T CTO John Donovan, who was speaking at the CTIA IT & Entertainment conference.

Donovan outlined how AT&T is addressing this unprecedented challenge by investing $38 billion over two years on its wireless and wired networks. "AT&T is focused on delivering an ideal combination of more mobile data capacity and faster 3G speeds, with these capabilities being deployed over a very short timeframe to maximize customer benefit," said Donovan.

AT&T is 90 percent complete in its deployment of high-quality 850 MHz spectrum for 3G, which adds overall network capacity as well as improved in-building coverage.

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,
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Role of government should be to minimize transaction costs.

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

A Governor’s Proposal

Introduce property rights for senate seat, sell to highest bidder.

Rod Blagojevich
Former governor of Illinois

A Governor's Proposal

Introduce property rights for senate seat, sell to highest bidder.

Currently under federal investigation…

Rod Blagojevich
Former governor of Illinois

Current State of Affairs

- Large parts of the useful spectrum remain underutilized.
  - FCC has introduced secondary markets (2003).
- Restricted supply of spectrum for commercial (cellular) services.
  - Cellular spectrum is extremely expensive.
  - Service providers encouraged to build out national footprint.
  - Fosters the development of expensive (spectrally efficient) systems.
- Unlicensed systems are proliferating.

Spectrum Markets

Do we need them?

If so, then how should they be defined?

J. Bae, E. Beigman, R. Berry, MLH, H. Shen, R. Vohra, H. Zhou, “Spectrum Markets for Wireless Services”, Proc. Dyspan 2008

Do We Need Spectrum Markets?

A more fundamental question:
Is spectrum scarce or abundant?

- Spectrum is abundant → use Commons Model

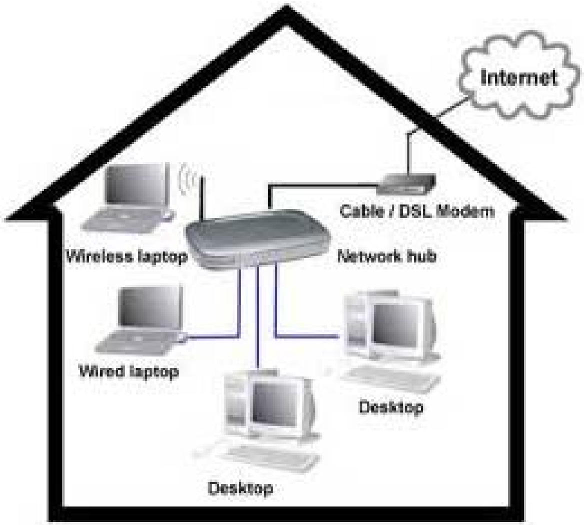
Do We Need Spectrum Markets?

A more fundamental question:
Is spectrum scarce or abundant?

- Spectrum is abundant → use Commons Model
- Spectrum is scarce: Commons model → "tragedy of the commons"

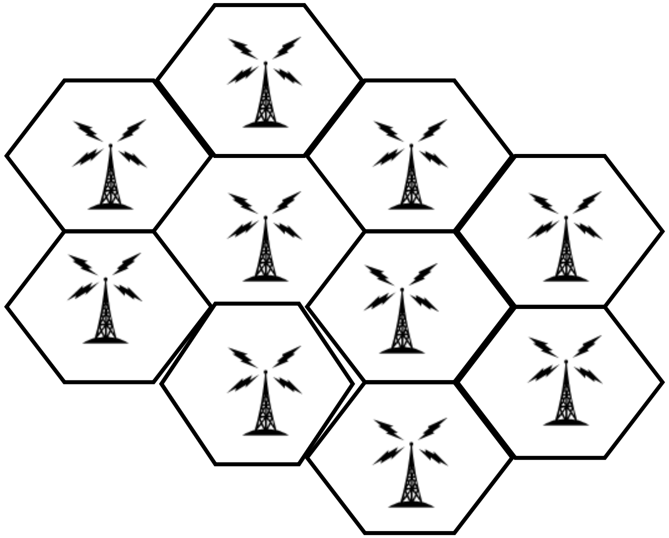
Do We Need Spectrum Markets?

A more fundamental question:
Is spectrum scarce or abundant?



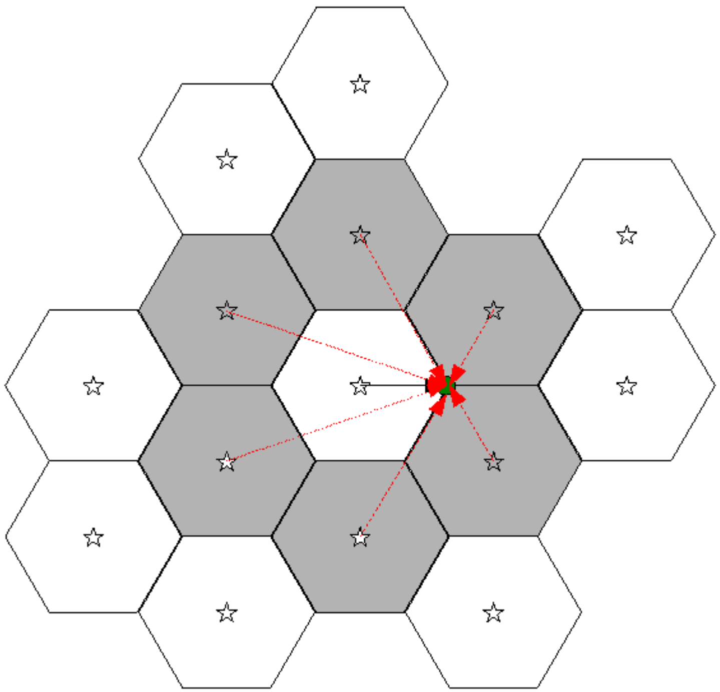
- For short-range communications (< 50 meters), spectrum is abundant (> 3 GHz).
  ➔ Commons model is appropriate.
- What about for longer-range communications?
  - Ultimately a technical question…

Rate Calculation



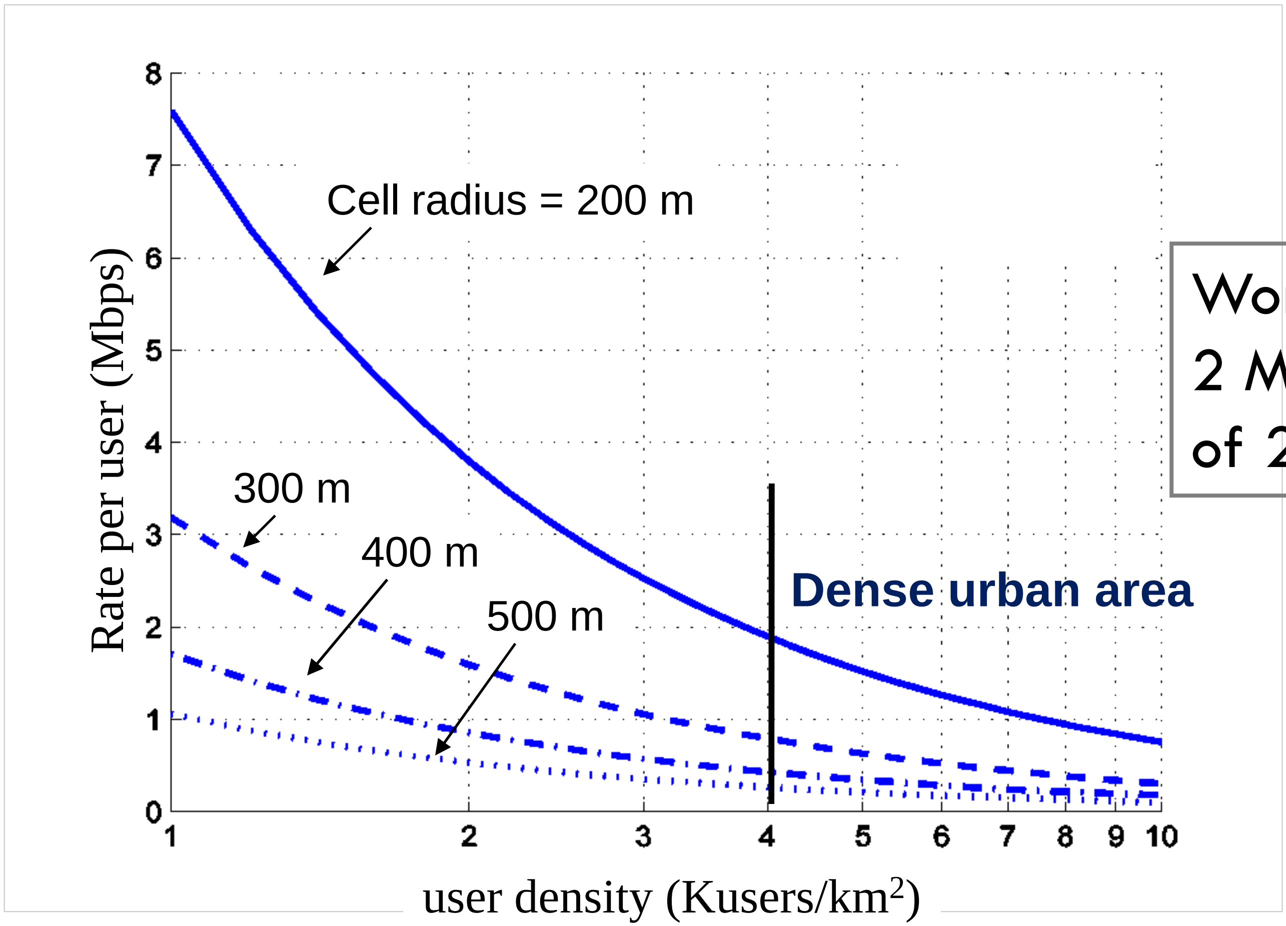
- Extensive spectrum sharing
  - Roughly 1 GHz between 150 MHz and 3 GHz
- Cellular Infrastructure
- System Assumptions
  - No intra-cell interference (time-division multiplexing)
  - Limited inter-cell interference.
  - All users are active all the time.

Rate Calculation: Assumptions



- User at cell boundary (worst-case)
- Standard large-scale propagation model
- Uniform power over frequency
- Shannon rate with 6 dB margin
- Frequency reuse optimized over each 1 MHz band

Achievable Rate per User

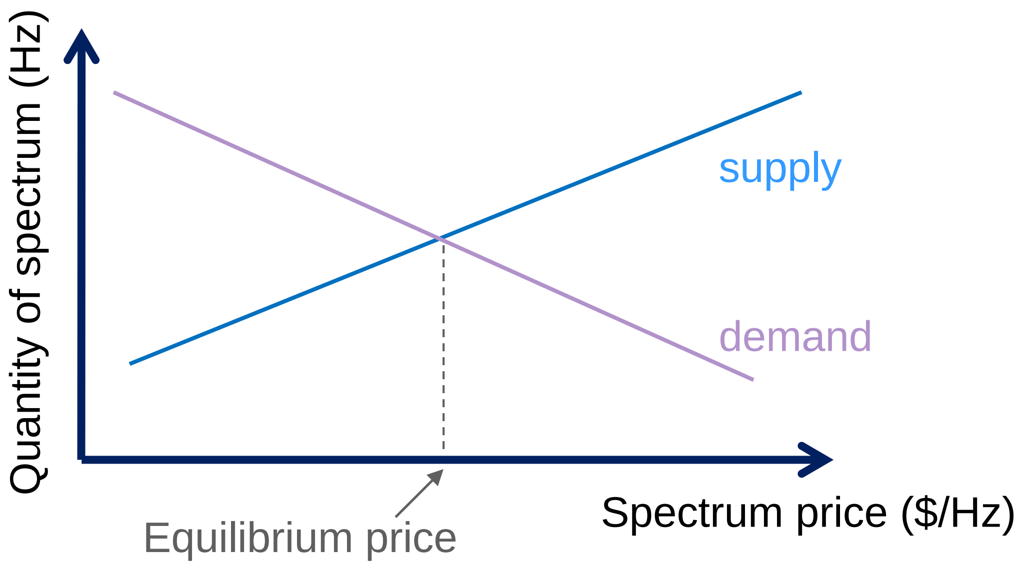


Worst-case rate is about 2 Mbps with cell radius of 200 m

Is Spectrum Scarce or Abundant?

- 2 Mbps per user seems like a lot, but recall the assumptions:
  - 1 GHz of shared bandwidth, no fading
  - Infrastructure of access points (200 m radius)
  - Optimized frequency reuse
  - Spectrally efficient modulation
- Also, less expensive spectrum encourages lower-cost, spectrally inefficient systems.

Spectrum Supply Curve



As the spectrum price goes to zero:

- The supply decreases due to the decrease in spectral efficiency.
- The demand increases due to introduction of new services.

Rate Calculations: Conclusions

- With extensive sharing and an extensive infrastructure the commons model may provide for an adequate range of near-term services, but interference is likely to become a problem in the long-term.
- Interference at lower frequencies is difficult to manage with a commons model.

Spectrum Asset (Property Right)

- Right to transmit up to specified power at specific time/frequency/location.
- Power limit should depend on frequency, antenna heights, proximity to other access points, time of day.
- Spectrum property rights can ultimately be defined by the market itself (Coasean bargaining).

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

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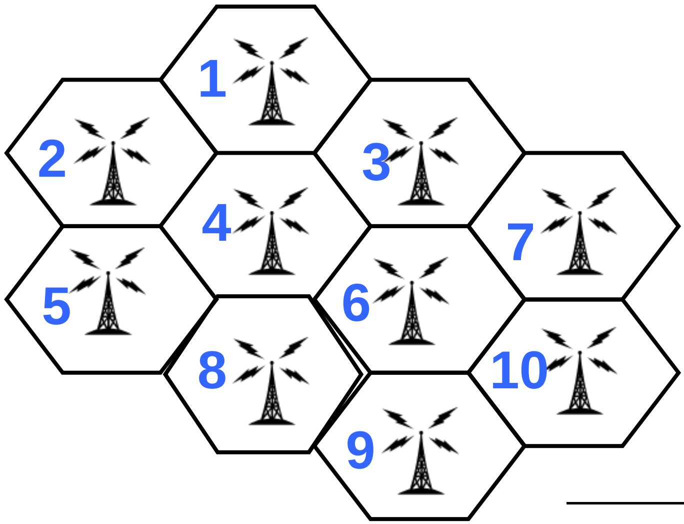
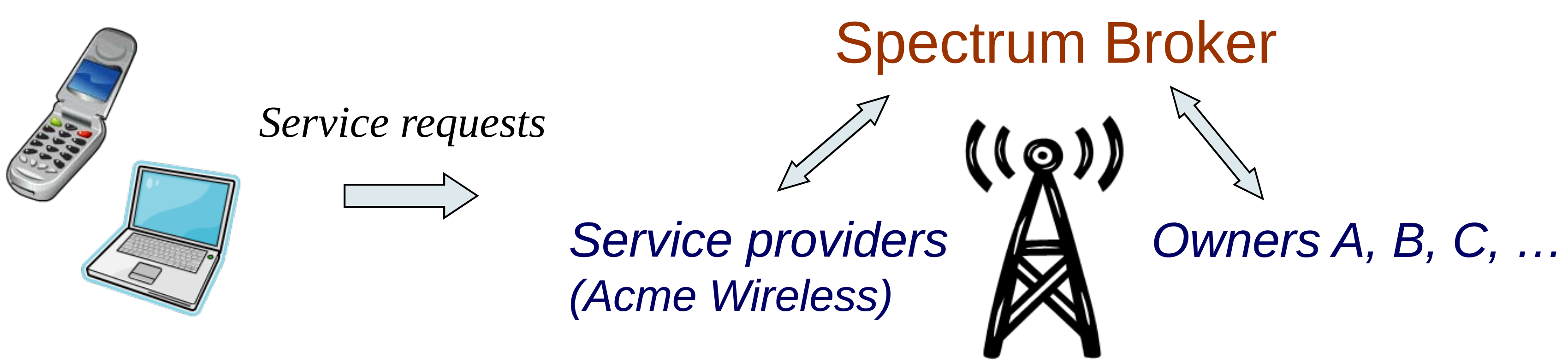
Owners can deploy services or rent / lease spectrum assets.
➔ Service providers need not be spectrum owners!

Two-Tier Spectrum Market

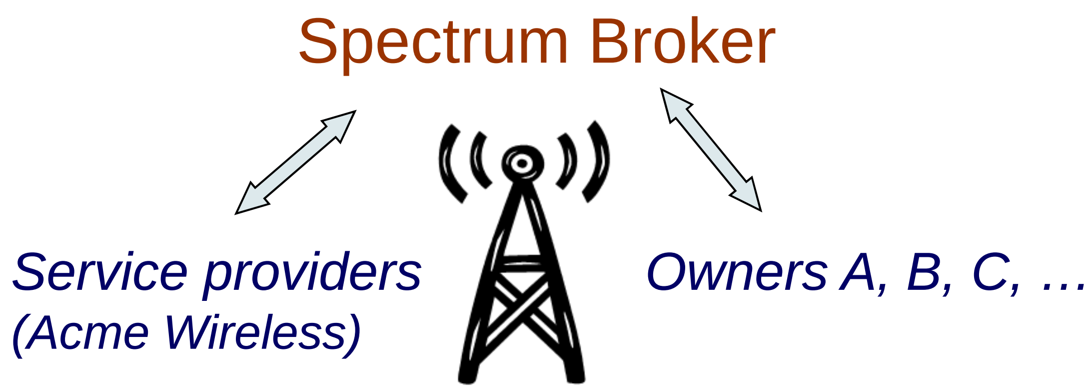


location	600 MHz	610 MHz	620 MHz
cell 1	Owner A	Owner B	Owner A
cell 2	Owner A	Owner B	Owner A
cell 3	Owner A	Owner C	Owner C

band



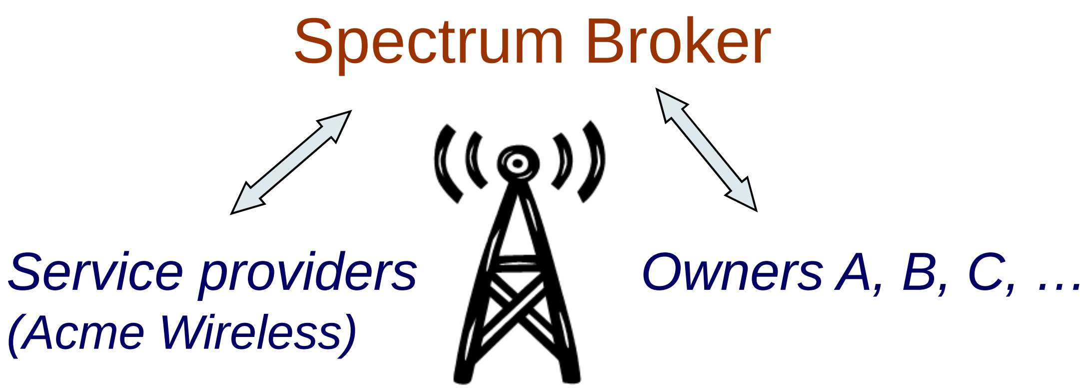
Lower-Tier Spot Market



Managed by spectrum broker

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

Lower-Tier Spot Market: Properties



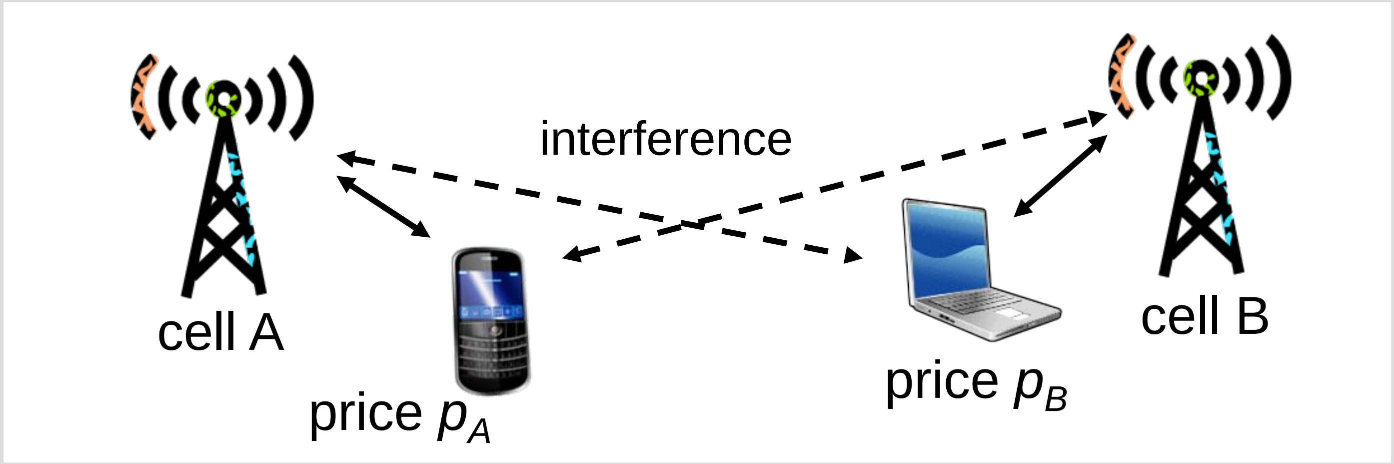
- Lowers entry costs
  - Could also rent radio equipment at each access point
- No need to build out large footprint
- Encourages introduction of new services

Interference Management

Incentives to aggregate spectrum (complementarities)
[H. Zhou, R. Berry, MH, R. Vohra, Allerton `09]

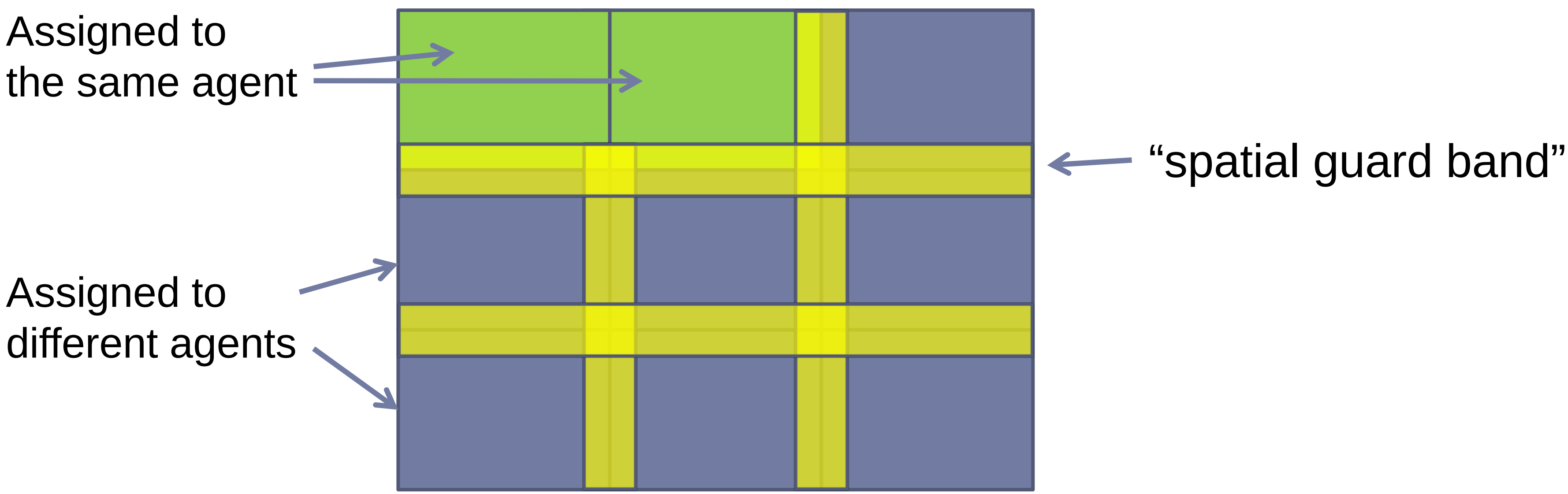
Local transactions
[J. Bae, E. Beigman, R. Berry, MH, R. Vohra, Dyspan `09]

Interference and Complementarities



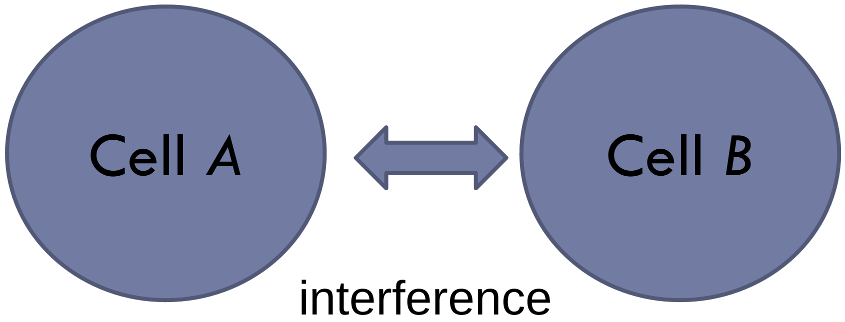
- Separate markets in each cell do not account for the externality due to interference; prices p_A and p_B may not be efficient
- Service provider may want to control interference by purchasing overlapping assets in adjacent cells.
- Spectrum assets exhibit complementarities: the combined value of adjacent assets exceeds the sum of their individual values.

Micro-cellular Network



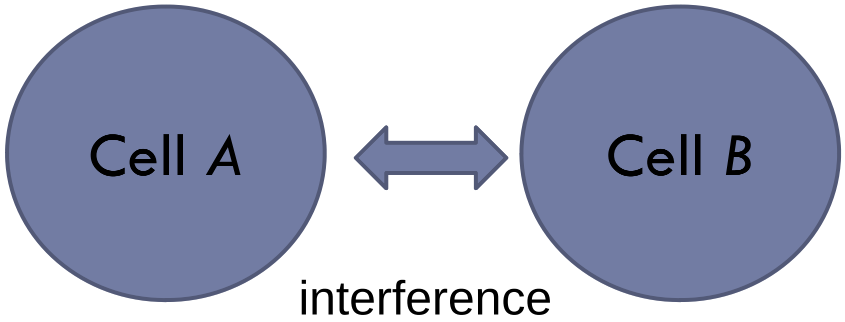
- Agents can purchase spectrum in adjacent cells to eliminate spatial guard bands.

Model: Two Adjacent Cells



- Each cell contains a single spectrum asset (same band).
- Each asset (cell) can be assigned to at most one agent.
- Agent i gets revenue r_{ij} from asset $j \in \{A, B\}$
- If A is assigned to agent i and B is assigned to agent $i' \neq i$, then i pays interference cost c^{i}_{AB} and i' pays $c^{i'}_{BA}$

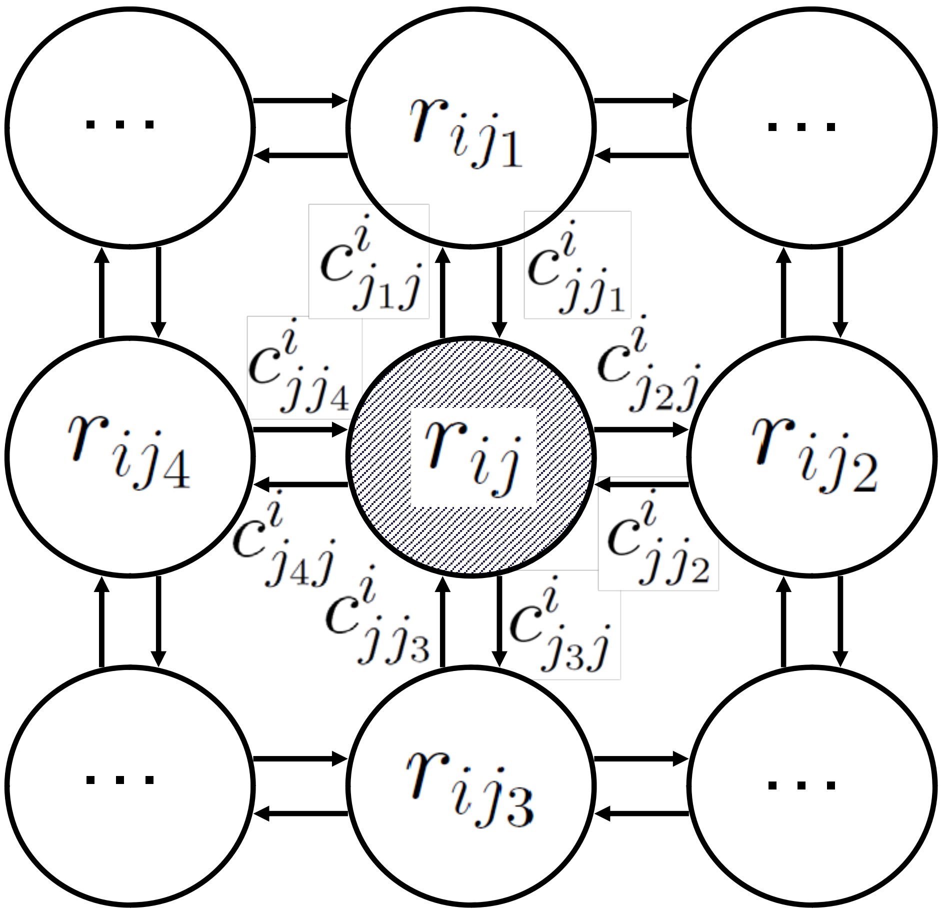
Model: Two Adjacent Cells



- A, B both assigned to i: Total revenue is $r_{iA} + r_{iB}$
- A assigned to i, B assigned to i':

  Total revenue is $r_{iA} + r_{i'B} - c^{i}_{AB} - c^{i'}_{BA}$

Lattice Model



Efficient Allocation

$$\max \sum_{i \in A} \sum_{j \in C} r_{ij} x_{ij} - \sum_{i \in A} \sum_{jj' \in E} c^{i}_{jj'} (x_{ij} - x_{ij'})^{+}$$

$$\text{S.t.} \sum_{i \in A} x_{ij} \leq 1 \quad \forall j \in C$$

$$x_{ij} \in \{0, 1\} \quad \forall i \in A, j \in C.$$

- x_{ij} = 1 if agent *i* is assigned asset *j*
- *A* is the set of agents, C is the set of assets,
- *E* = {(*j*,*j*'): *j* and *j*' are neighboring assets}

Properties

- The integer program is NP-hard.
  - Contains the max-independent set problem as a special case.
  - Linear Program (LP) relaxation may give fractional solution.

- LP relaxation does have integer solutions if:
  - Each agent *i* receives positive revenue for only one cell and

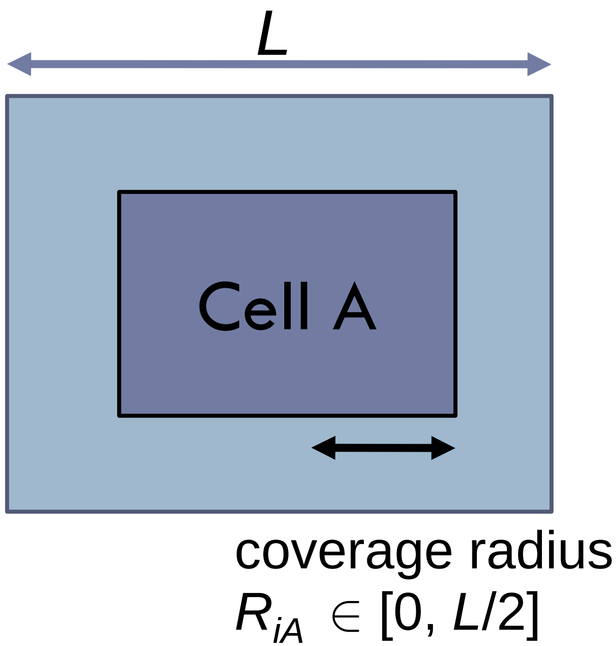
$$r_{ij} \geq \sum_{j':(j,j')\in E} c^i_{jj'} + \sum_{j':(j,j')\in E} \max_{i\in A} c^i_{j'j}$$

  - The underlying interference graph is a line.
    - Constraint matrix is *total unimodular*

Pricing Implications

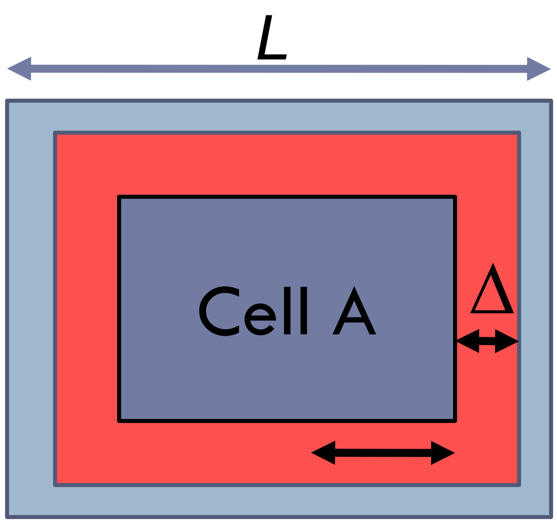
- To achieve efficiency it is necessary to price bundles of neighboring assets.
- Can announce prices as dual variables for relaxed LP, but users may report fractional demands.
- Rounding solution to relaxed LP approximates the optimal allocation.
  - Numerical examples show small loss in efficiency.

Radius Model



- Agent can adjust coverage radius by changing the power
- Revenue is proportional to area: $r_{iA} = 4w_{iA} R_{iA}^2$

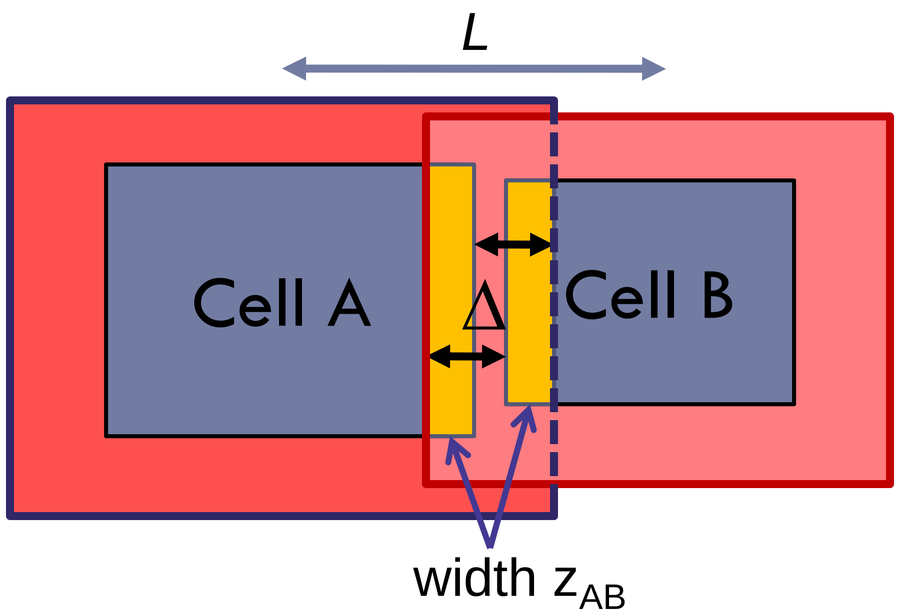
Interference Region



coverage radius
$R_{iA} \in [0, L/2]$

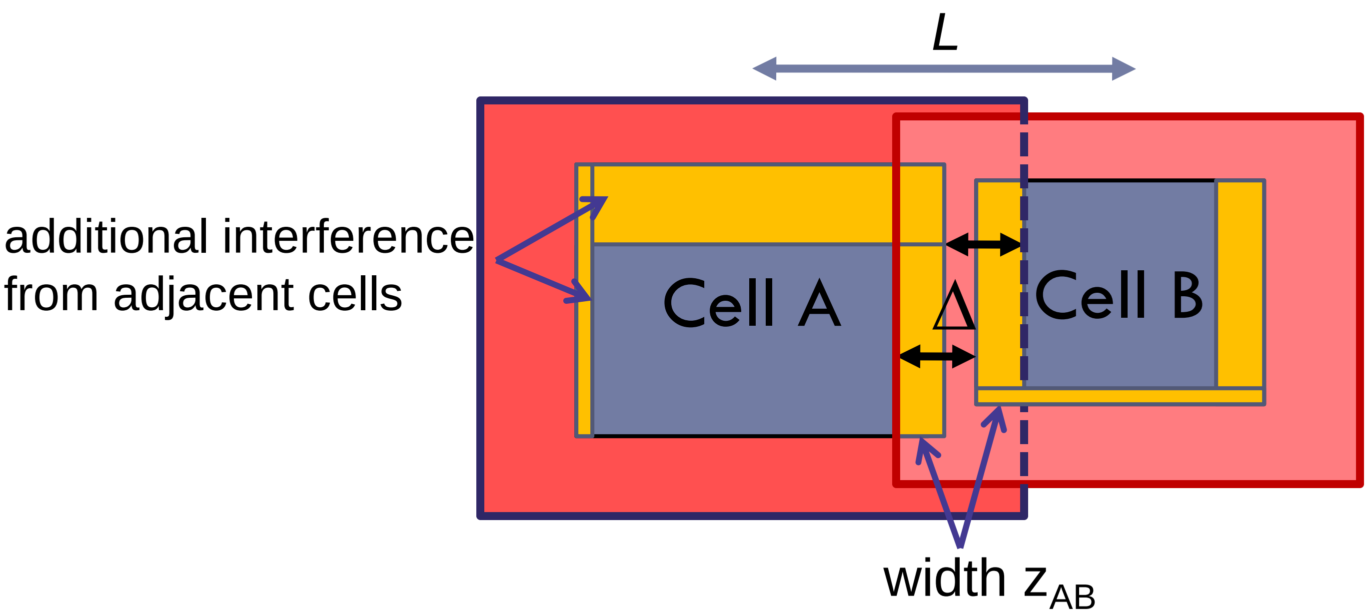
- Agent can adjust coverage radius by changing the power
- Revenue is proportional to area: $r_{iA} = 4w_{iA} R_{iA}^2$
- Interference region represents additional area over which the cell causes interference.

Radius Model: Two Adjacent Cells



- Agent *i*'s revenue in cell A: $r_{iA} = w_{iA}\,(4R_{iA}^2 - 2R_{iA}\,z_{AB})$
- Where $z_{AB} = [R_{iA} + R_{iB} - (L - \Delta)]^+$

Radius Model: Additional Interference



- Agent *i*'s revenue in cell A: $r_{iA} = w_{iA}\,(4R_{iA}^2 - 2R_{iA}\, z_{AB})$
- Where $z_{AB} = [R_{iA} + R_{iB} - (L - \Delta)]^+$

Optimization Over a Lattice

$$\max_{\mathbf{x},\mathbf{R},\mathbf{z}} \sum_{i\in A}\sum_{j\in C} 4w_{ij}R_{ij}^2 - \sum_{i,k\in A}\sum_{(j,j')\in E} 2w_{ij}R_{ij}z_{jj'}^{ik}$$

Subject to:

$$R_{ij} + R_{kj'} - z_{jj'}^{ik} \leq L - \Delta, \quad z_{jj'}^{ik} \geq 0$$

$$x_{ij}(L/2 - \Delta) \leq R_{ij} \leq x_{ij}L/2$$

$$\sum_i x_{ij} \leq 1, \quad x_{ij} \in \{0,1\}$$

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- *A* is the set of agents, C is the set of assets,
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Properties

- Mixed integer-quadratic program; can accurately approximate with a linear program for small Δ.

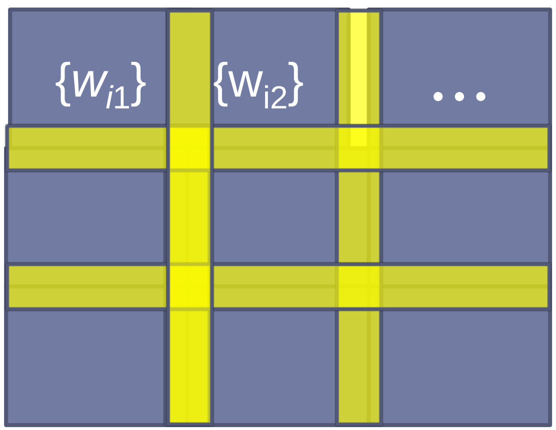
- Solution to mixed integer-LP:
  - Assign user i to cell j with the largest w_{ij}
  - Given the optimal assignment of users to cells $\{x_{ij}^*\}$, optimization of radii reduces to solving a linear program.
  - Each optimal radius $R_{ij}^* \in \{L/2 - \Delta, L/2 - \Delta/2, L/2\}$

Pricing: Naïve Approach

- Run 2nd price auction in each cell *j* to determine assignment of agent;
- Solve LP to determine radii
- Problem: not incentive compatible
  - Cell assignment influences radii → agents may have an incentive to lie about values (w_{ij}'s) to influence radii in adjacent (interfering) cells

Incentive Compatible Mechanism

Agents submit $\{w_{ij}\}$'s across **all** cells



Incentive Compatible Mechanism

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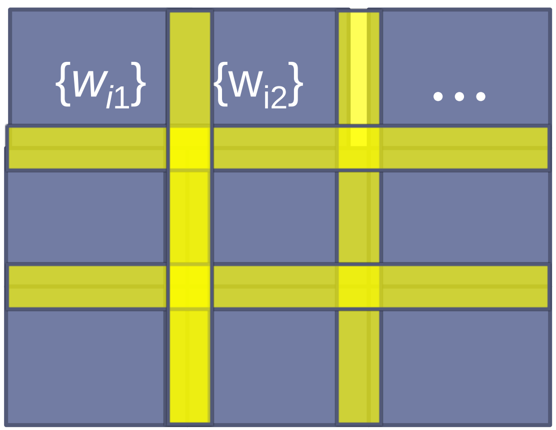
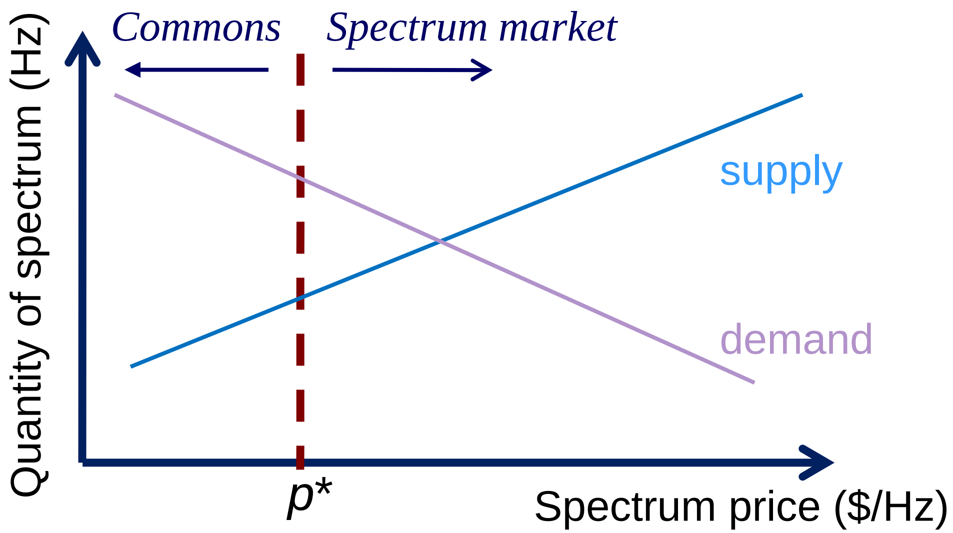


Auctioneer determines cell assignment, radii, and prices

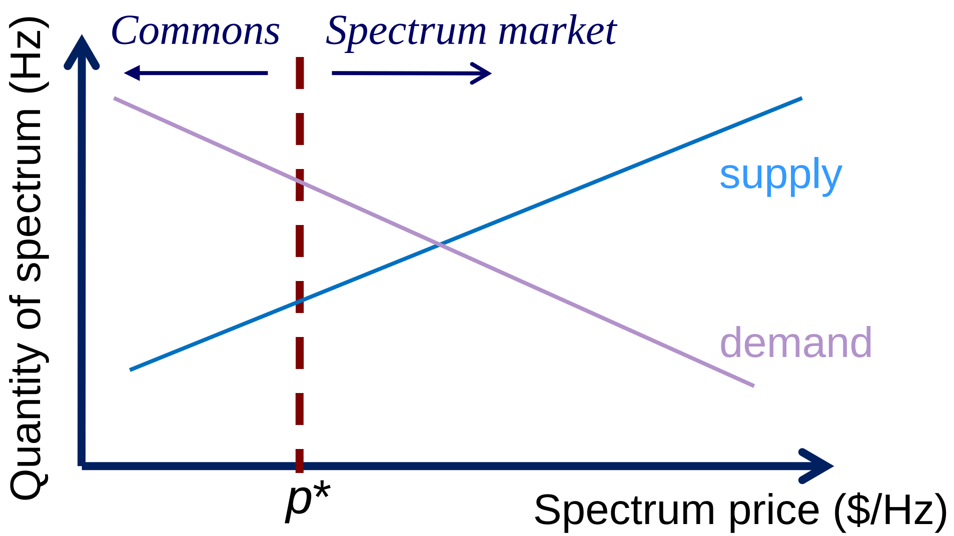
Prices for cells assigned to user *i* are determined by solving the optimization problem with user *i* removed. (Vickrey-Clarke-Grove mechanism)

Commons vs Market



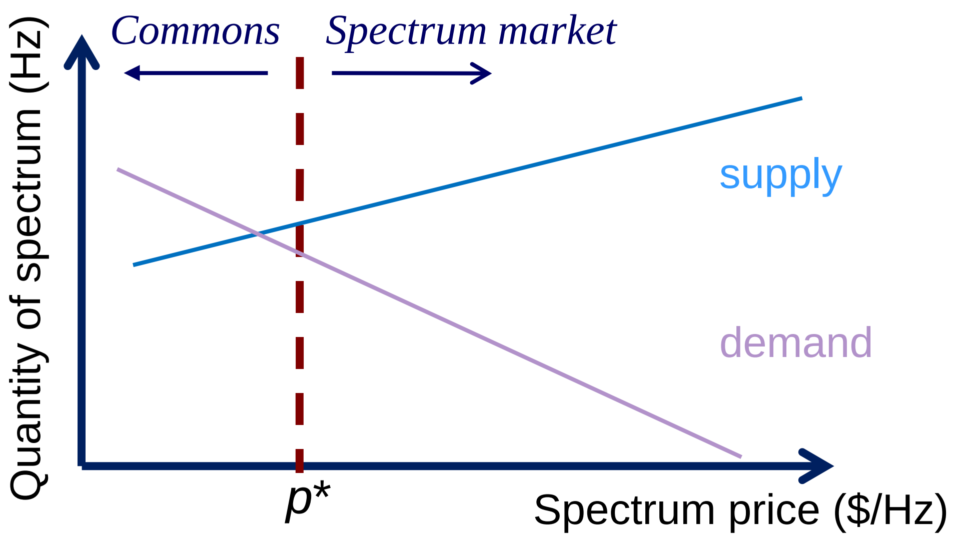
Commons/market boundary depends on associated costs.

Commons versus Market



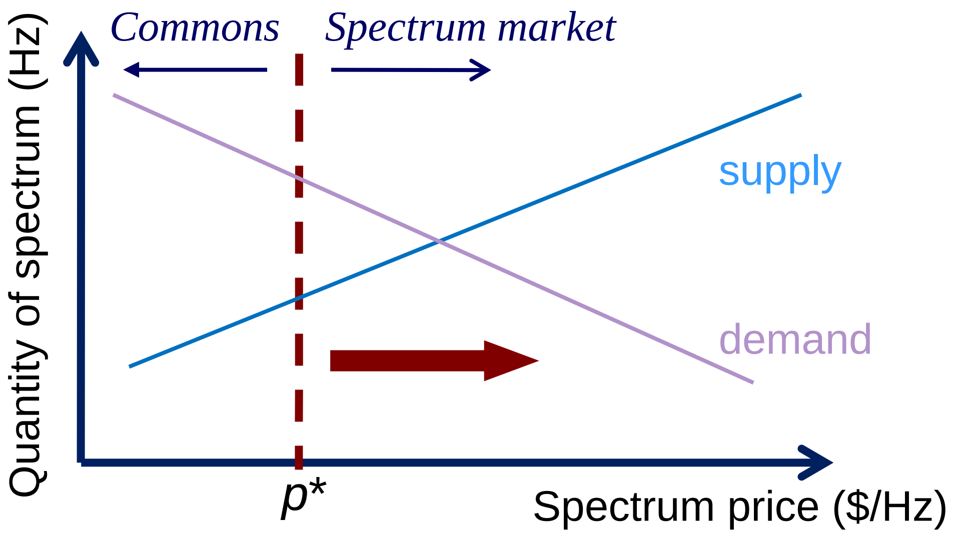
market transaction costs < cost of interference
➔ Set up spectrum market

Commons versus Market



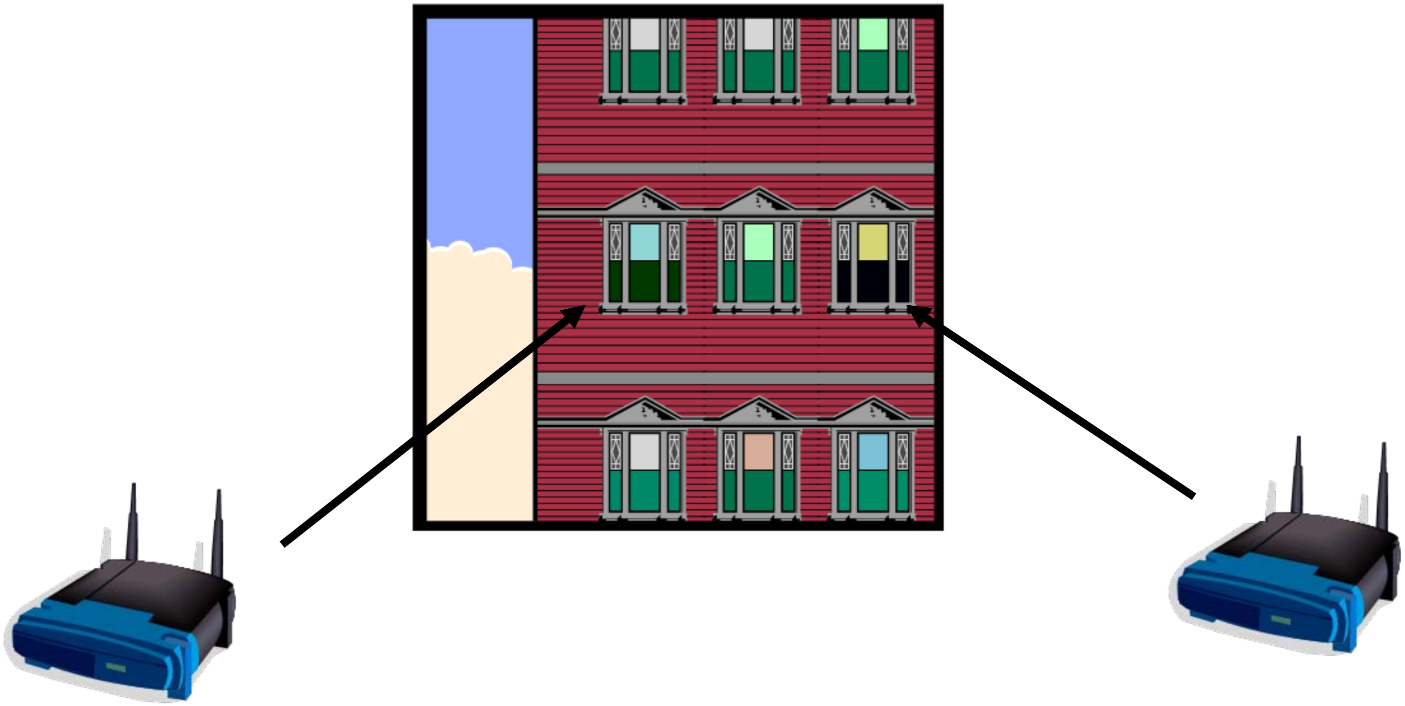
cost of interference < market transactions costs
➔ Use commons model

Commons vs Market



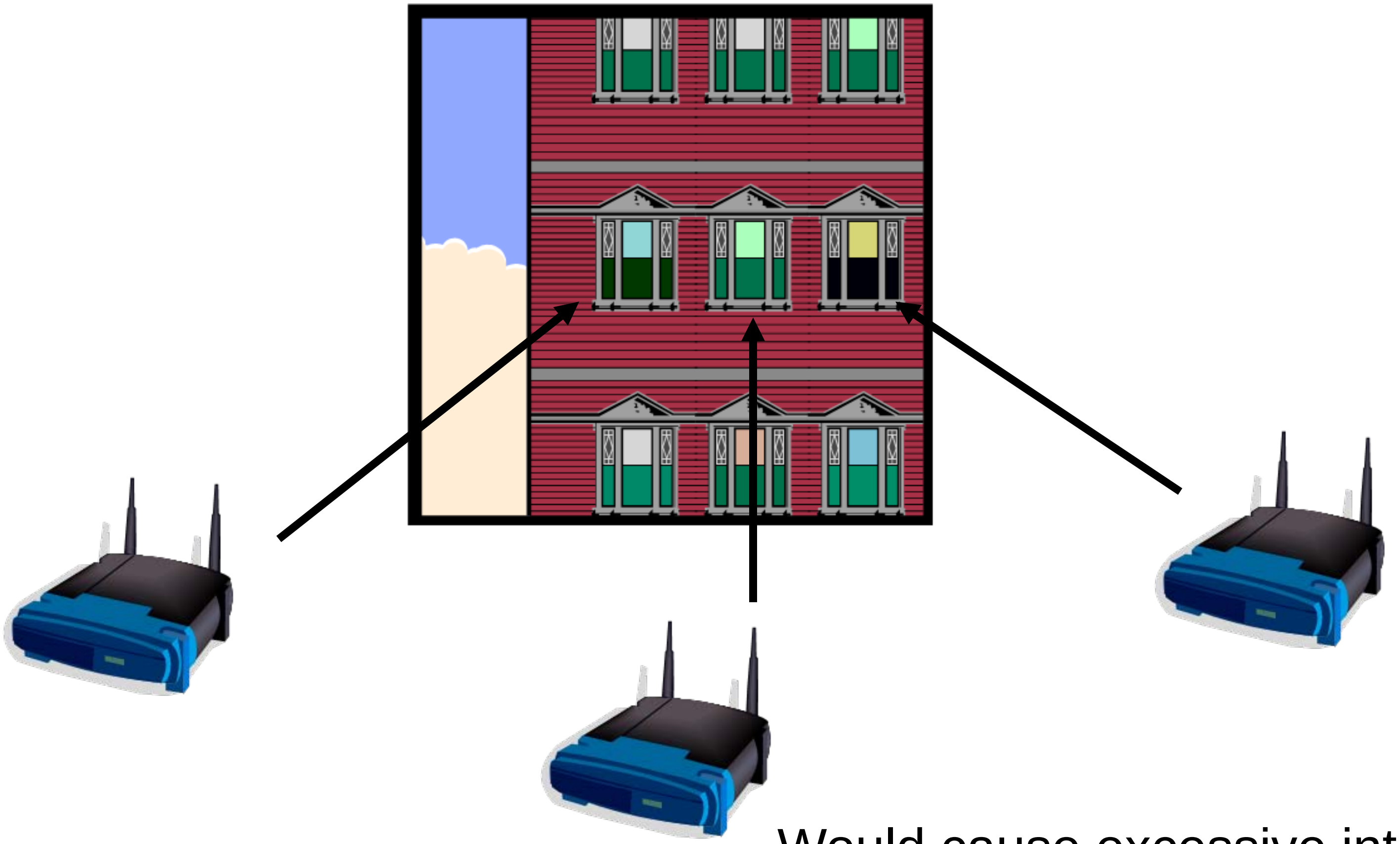
Can we shift the boundary to the right with distributed interference management schemes?

Local Transactions



Routers use the same channel, cause little interference

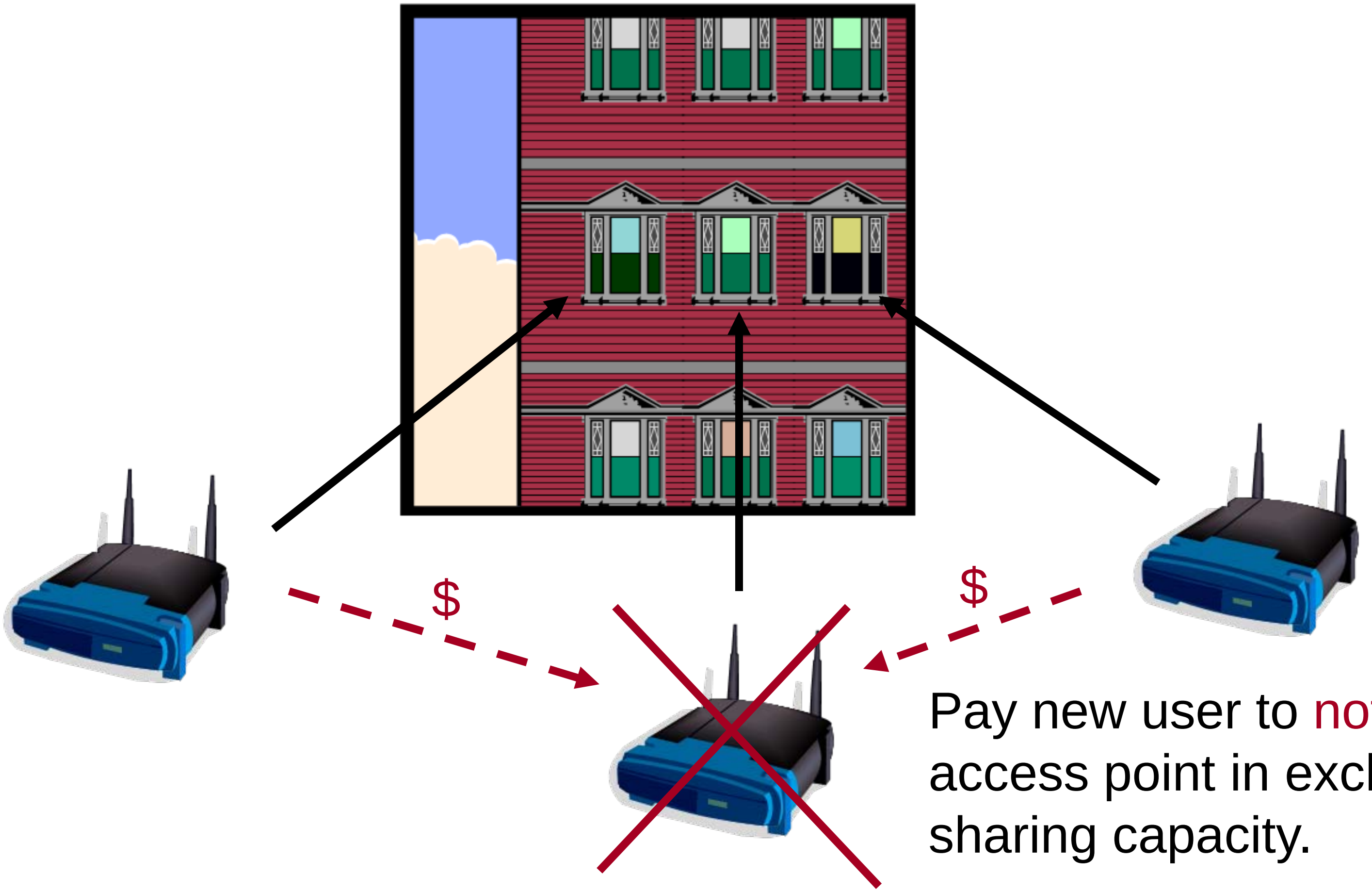
Local Transactions



Would cause excessive interference.

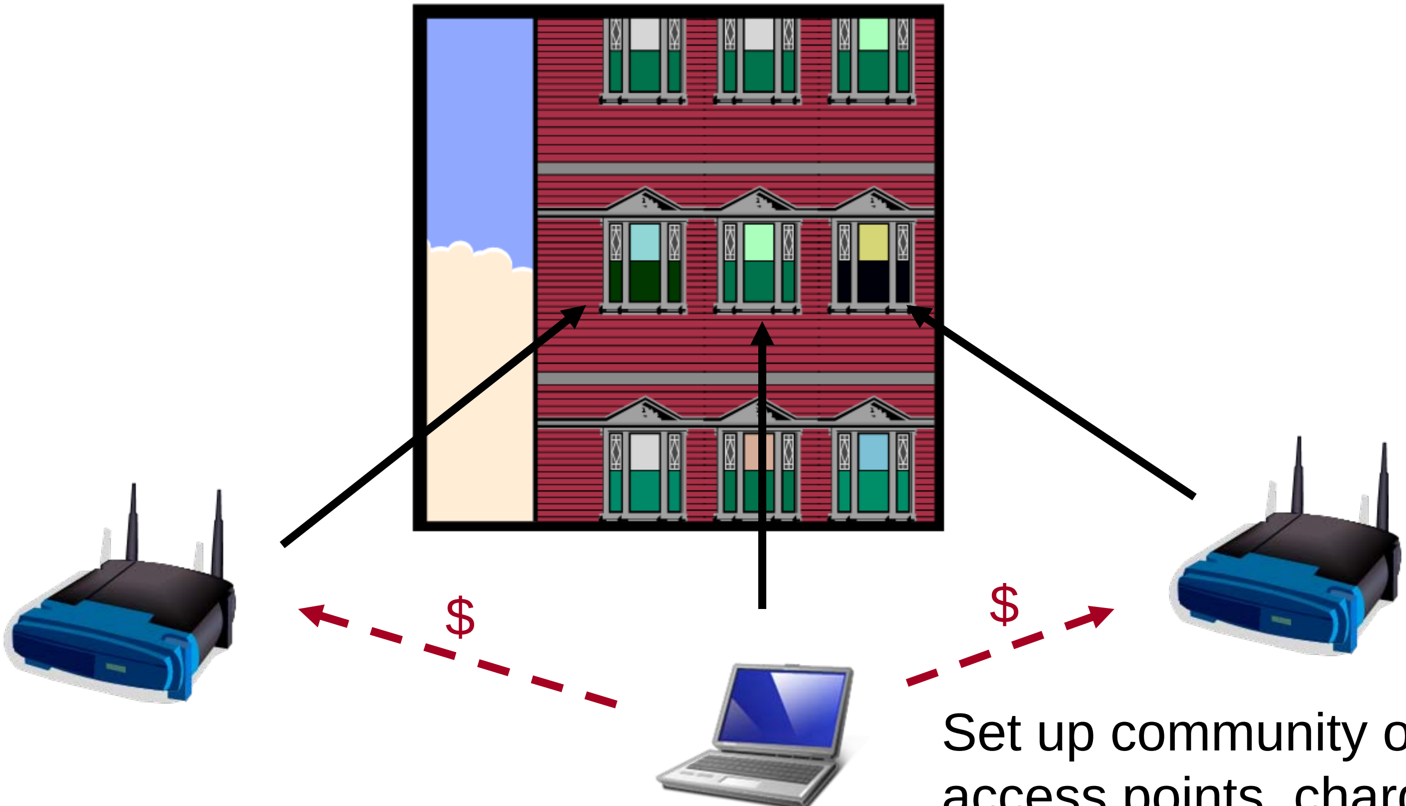
Meet Your Neighbor

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.

Concluding Remarks

- Many remaining challenges
  - Technical: interference management
  - Nontechnical: transition to markets (policy)
- What if spectrum is not so scarce?
  - More emphasis on power efficiency?
  - Minimize transaction costs
    - Automated, transparent mechanism for spot markets
    - Distributed interference management (local transactions)

Will Wireless Devices Become Generic Commodities?