Games Ad Hoc Networks Play

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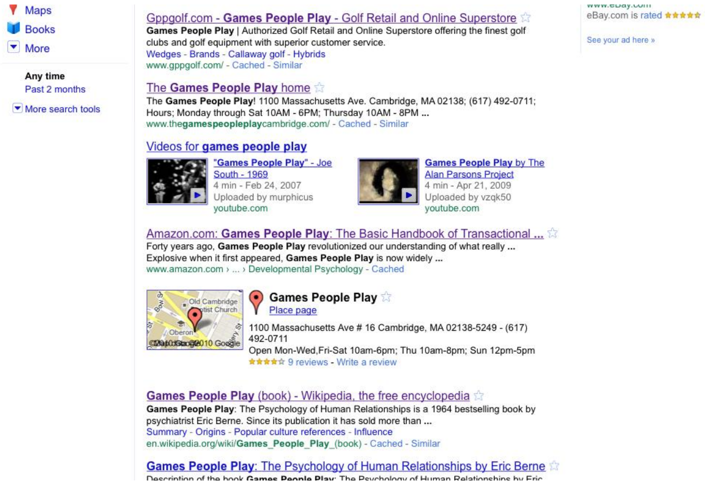
Games People Play



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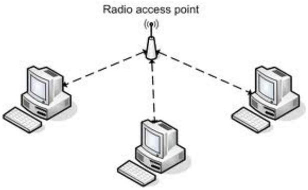
The Role of Game Theory in Ad Hoc Networks

- von Neumann, Morgenstern, Nash, Vickrey, ...
- “The Internet is an equilibrium, we just have to find the game” – Scott Shenker.
- Algorithmic game theory
- PPAD and related complexity classes
- Algorithmic mechanism design
- Selfish routing
- Pricing and resource allocation in communication networks
- Spectrum auctions

The Role of Game Theory in Ad Hoc Networks

- Since the early 00s, an explosion of research.
- Games have been defined at every resource allocation point of the entire protocol stack.
- Multiple-access schemes:
  - Contention resolution, power control, rate selection
- Packet scheduling and routing:
  - Incentives and pricing
- Topology control:
  - Transmission range selection and network formation
- Network security:
  - Jamming, network immunization

A framework for a basic multiple-access game



- Users sharing a multiple-access channel.
- Each user has exactly one packet to transmit, and wants to minimize delay.
- A strategy is simply an algorithm that decides whether to transmit given the past history.
- Nash equilibria: Uniqueness, efficiency, and realizability.

Efficiency and equilibria

- Suppose k users are contending for the channel.
- Optimal symmetric protocol:
  - Set transmission probability $p_k = 1/k$ since it minimizes $kp_k(1 - p_k)^{k-1}$.
- Not in equilibrium for $k \geq 2$ since each would gain by transmitting with probability 1.
- In fact, a (symmetric) equilibrium strategy for more than two players: continuously transmit.
  - Infinite price of anarchy!

Seeking more efficient equilibrium protocols

- Consider symmetric time-independent protocols.
  - Symmetry: The equilibrium strategy of every player is the same.
  - Time-independent: Action not dependent on current time step, but may depend on number of remaining packets.
  - Continuously transmitting is an example of a symmetric time-independent protocol that is in equilibrium.
- Suppose in equilibrium, each user transmits with probability p_k when there are k packets remaining.
- Clearly, $p_1 = 1$.
- What is p_2?

Calculating p_2

- Suppose A transmits with probability p and B with p_2.
- Expected number of steps before any success is

$$\frac{1}{(1-p)p_2 + p(1-p_2)}.$$

- Probability that the successful user is B is

$$\frac{(1-p)p_2}{(1-p)p_2 + p(1-p_2)}.$$

- Therefore, in equilibrium, p_2 is the value of p that minimizes

$$\frac{1}{(1-p)p_2 + p(1-p_2)} + \frac{(1-p)p_2}{(1-p)p_2 + p(1-p_2)}.$$

- Unique solution $p_2 = 1/\sqrt{2}$.

A new equilibrium

- In fact, there is a unique symmetric time-independent non-blocking equilibrium: p_k is $\Theta(1/\sqrt{k})$. [Fiat-Mansour-Nadav 2007].
- While more efficient than continuous transmission, Aloha with $p_k = \Theta(1/\sqrt{k})$ is highly inefficient.
- Probability that a transmission succeeds is

$$\frac{1}{p_k}\left(1 - \frac{1}{p_k}\right)^k \leq \Theta\left(\frac{1}{\sqrt{k}e^{\sqrt{k}}}\right).$$

- Expected time for n transmissions is $\Omega(ne^{\sqrt{n}})$.
- Why is this equilibrium protocol inefficient?
    - There is not much incentive for a user to be nice (transmit with low probability).

Enforcing good behavior in equilibrium

- Delay with k users not much different than with $k-1$ users, so no incentive to transmit with low probability.
- Need to make the protocol time-dependent.
- Suppose we impose a hypothetical deadline D for two users A and B, and assign a huge cost for not meeting the deadline.
- At time D and $D-1$, the equilibrium strategy is to transmit with probability 1.
- At time $D-2$, the equilibrium strategy will set the transmission probability so as to maximize the probability of a successful transmission: $1/2$.

An incentive-compatible efficient protocol

- Introduce a deadline of $\Theta(n)$ steps with a threat that after the deadline, all players switch to the time-independent protocol (with exponential delay).
- Very close to the deadline, every player will adopt the almost-always-transmit behavior.
- When deadline within reach, the (expected) future cost with $k-1$ users much lower than that with k users.
- "Pre-deadline" behavior: transmit with probability $\Theta(1/k)$ for k users.
- In equilibrium strategy, all users complete within linear steps with very high probability [Fiat-Mansour-Nadav 2007].

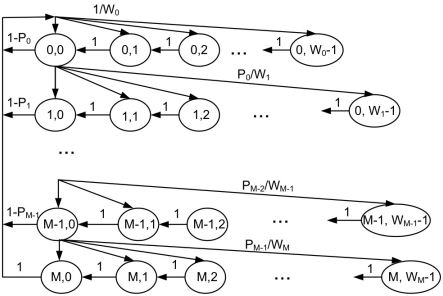
Contention resolution games: Summary

- Highly inefficient equilibria exist, but incentive-compatible protocols can be designed.
    - When there are transmission costs, but in a stronger feedback model [Christdoulou, Ligett, Pyrga 2010].
    - Stochastic framework with much simpler strategy space, but with pricing [Altman, El Azouzi, Jimenez 2004].
- Future directions:
    - Eliminate knowledge of n.
    - Consider general packet generation models.
    - Non-symmetric equilibria that capture heterogeneous nodes.

Adversarial multiple-access games

- Players of this game are of two types: users and jammers.
- All users follow a protocol and their utility is given by the performance of the whole system, e.g., *system throughput*.
- Jammer may not follow the protocol, and its utility decreases with system throughput.
  - Minimize throughput subject to average power constraint.
  - Decreasing function of both throughput and power consumed.
- Even games involving one user and one jammer can be complex: best response is difficult to compute.
  - Optimal jamming against 802.11 MAC [Bayraktaroglu et al 2008].

Markov chain model for 802.11 MAC under jamming



- Jammer is channel-aware and omniscient, i.e., aware of the internal state of the protocol.

Steady-state occupancy probabilities

- Let $b_{i,j}$ be probability that a node has backoff value j in stage i.

$$b_{i,j} = \begin{cases} b_{i,j+1} + P_i b_{i-1,0}/W_i & i > 0, j < W_i - 1 \\ P_i b_{i-1,0}/W_i & i > 0, j = W_i - 1 \neq 0 \\ b_{0,j+1} + b_{M,0}/W_0 & i = 0, j < W_0 - 1 \\ b_{M,0}/W_0 & i = 0, j = W_0 - 1 \end{cases}$$

- Given failure probabilities P_i, the above equations together with the condition that $b_{i,j}$s sum to 1, yield the $b_{i,j}$ values.
- Steady state transmission probability $\tau = \sum_{i=0}^{M} b_{i,0}$.

Analysis of best-response jamming

- Jamming vector: $(q_0, q_1, q_2, \ldots, q_M)$, where q_i is the probability of jamming when user is in backoff stage i.
- Success probability:

$$n \sum_{i=0}^{M} b_{i,0}(1 - P_c)(1 - q_i).$$

- The optimal jammer, constrained by jamming rate R, solves the following

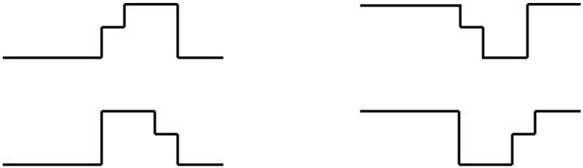
$$\text{minimize} \quad \frac{Ln(1-P_c)\tau}{(1-(1-\tau)^n)T_{tr}+(1-\tau)^n\sigma} - \frac{LR}{w}$$

$$\text{subject to}$$

$$\sum_{i=0}^{M} \frac{nwb_{i,0}(1-P_c)q_i}{(1-(1-\tau)^n)T_{tr}+(1-\tau)^n\sigma} = R$$

Characteristics of an optimal jammer

- Complex non-linear program that does not appear to admit a closed-form solution.
- **Theorem:** For one user, there exists an optimal jammer of the form $(q, 1, 1, \ldots, 0)$ or $(1, 1, \ldots, q)$.
- **Conjecture:** For more users, the jamming vector always has one of the following forms.



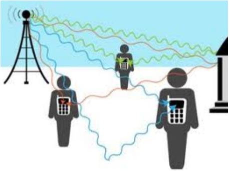
Equilibria in jammer games

- Jammer's strategies include permissible jamming vectors and user's strategies include variants of 802.11 MAC.
    - For instance, having interleaved instances of 802.11 running in "parallel", and switching across them [Liu et al 2007].
    - This transforms an "optimal" jammer to one whose jamming vector is identical across all backoff stages.
    - Resulting equilibrium improves throughput by 20-30% [Bayraktaroglu et al 2008].
- Zero-sum and non-zero sum stochastic games defined by [Altman et al 2005, 2007].
- An alternative is to design jammer-resistant protocols and bound their performance directly [Awerbuch-Richa-Scheideler 2008, Richa et al 2010]

Stochastic games for power control

- Focus thus far largely on defining the strategy space using algorithms/decisions on when to transmit.
- There are a number of stochastic game-theoretic formulations over the power control strategy space.
  - Distributed power control in CDMA systems.
  - Power control games for fading multiple-access channels [Lai, El Gamal 2005].
  - Jamming games [Altman, Avrachenkov, Marquez, Miller 2005].
  - Spectrum sharing [Etkin, Parekh, Tse 2005].

A spectrum sharing game



- Suppose n users are sharing a spectrum of bandwidth W, with the channel model described as

$$y_i(t) = \sum_{j=1}^{n} \sqrt{h_{ji}} x_j(t) + z_i(t).$$

where $x_i(t)$ is the transmitted signal of i and h_{ji} is the channel cross-gain, and $z_i(t)$ is the noise at user i.

Strategy space and utility

- The strategy space is the set of power spectral density functions: $p_i(f)$ subject to an average power constraint.

$$\int_0^W p_i(f)df \leq P_i.$$

- Utility is the maximum achievable rate given by the Shannon capacity theorem.

$$R_i = \int_0^W \log\left(1 + \frac{h_{ii}p_i(f)}{N_0 + \sum_{j\neq i} h_{ji}p_j(f)}\right).$$

Properties of equilibria

- Nash equilibria of one-shot games may be very inefficient, under high SNR environments.
  - A common theme among multiple-access games.
- An equilibrium strategy is to spread: $p_i(f) = P_i/W$.
- Consider two users with equal power constraint P, $N_0 = 1$, and cross channel gain coefficients $1/4$.
- The utility of each user is $\log(1 + P/(1 + P/4))$ is at most a constant, independent of P.
- If the two users partitioned the spectrum, they get a utility of $\log(1 + 2P)/2$, which is increasing with P.

Incentive-compatible spectrum sharing

- If the interaction is set up as a repeated game, and other operating points of the capacity region can be realized as equilibria [Etkin, Parekh, Tse 2005].
- Idea: If any player deviates from the desired operating point in a step, then the other players will adopt the highly inefficient equilibrium allocation.
- Requires perfect information and, hence, ways to make the mechanism truth-revealing.
- Similar results have also been derived for time-varying channels [Lai, El Gamal 2005].

Multihop network games

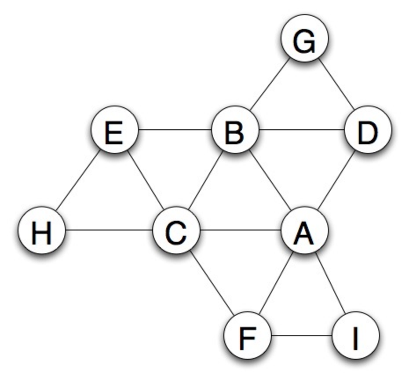
- Network formation games: Each node determines its neighbors so as to maximize some connectivity-based utility.
  - Costs on edges [Fabrikant, Papadimitriou, Shenker 2003; Moscibroda, Schmid, Wattenhofer 2006; Demaine et al 2010].
  - Bounds on degree [Laoutaris et al 2008].
  - Biateral contracts [Corbo, Parkes 2005; Arcaute et al 2006]
- Routing games: Each node decides the fraction of resources to allocate for forwarding other nodes' packets.

Network immunization game

- Each node decides whether to protect itself from viruses that may spread from neighboring nodes.
- [Aspnes et al 2006], [Moscibroda, Schmid, Wattenhofer 2006], [Kumar et al 2010], [Chen, David, Kempe 2010]
- Simple game-theoretic model:
  - Contact graph: $G(V, E)$.
  - Strategies: install anti-virus software or not, $a_i \in \{0, 1\}$.
  - Security cost/infection cost: C_i, L_i.
  - Individual cost: $a_i C_i + (1 - a_i) L_i \Pr[\text{infection under } \overline{a}]$.
  - Local infection model: infection initiated at a node transmits over at most d hops in the contact graph.

An example with $d = 2$

Example



- Infection and protection costs:
  - Very low infection costs for nodes D through I.
  - Nodes A through C protect themselves only if more than 7 reachable unprotected nodes within neighborhood.
- No pure Nash equilibrium.

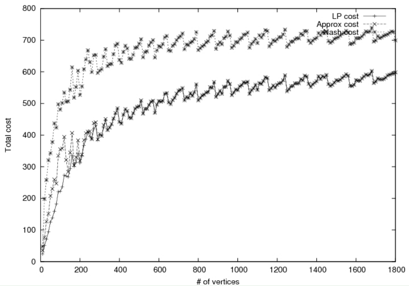
Existence and efficiency of equilibria

	$d = 1$	$1 < d < \infty$	$d = \infty$
existence of pure NE	Yes	No/NP-complete	Yes
price of anarchy	$\Delta + 1$		$O(1/\alpha(G))$
approx social opt	2	2d	$O(\log n)$

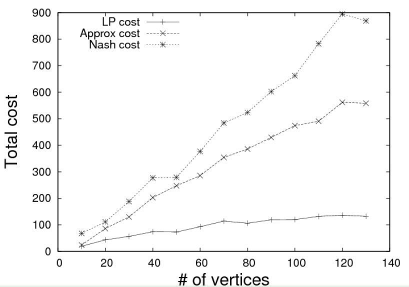
- Δ is the max degree in the contact graph.
- $\alpha(G)$ is the vertex expansion of the contact graph.
- A socially optimal action set is NP-hard to find.

Efficiency of equilibria in random geometric graphs

$d = 1$



$d = \infty$



- LP cost is a lower bound on the social optimum.
- Approx cost is the social cost of 2-approx algorithm.

Concluding remarks

- Multiple-access games:
  - Very high price of anarchy but low price of stability.
  - Incentive-compatible efficient protocols can be designed.
  - May require perfect information or repeated game framework.
- Jammer games:
  - Specialized models, often hard to compute.
  - Design of strategy spaces plays a key role.
- Multihop network games:
  - Equilibria may not exist or may be hard to reach.
  - Very simplistic models.

Potential impact and future work

- A game-theoretic study may explain a certain phenomenon: e.g., unfair allocation, inefficiencies.
- May be able to extract macro guidelines for protocol design.
- Incorporate imperfect information and locality into game formulation.
- Incorporate multiple types of players (altruistic, Byzantine, selfish, etc.)
- Incorporate mobility and changing sets of players.
- Other solution concepts such as Stackelberg equilibria could model hybrid networks.