Thou Shalt Be a Selfish Overlay Neighbor
Implications of Selfish Neighbor Selection on the Design and Performance of Overlay Networks

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On the importance of neighbors

☑ Neighbor selection is a key building block for many applications – e.g., selecting
   - inter ISP peering relationships as in BGP
   - intra ISP router topology
   - neighbors in proxy caching networks
   - neighbors in P2P applications as in Bittorrent

☑ Performance depends largely on the quality of one’s neighborhood.

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Love thy neighbor as thyself...

... unless you can afford to move!

☑ In cyberspace, changing one’s neighborhood is cheap – just rewire!

☑ Especially true for overlay networks.

☑ Implications?

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Example uses of overlays as ...

☑ Routing Networks (e.g., Skype):
   - Send unicast traffic from one overlay node to another
   - Node’s objective is to minimize its average (or maximum) routing cost to all destinations

☑ Broadcast Networks (e.g., MS update):
   - Send data from one node to all nodes in the overlay
   - Node’s objective is to minimize its average (or maximum) broadcast cost to all destinations

☑ Query Networks (e.g., Gnutella):
   - Find content available in some (unknown) overlay node
   - Node’s objective is to query the most number of overlay nodes using scoped flooding

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Choosing thy neighborhood game

☑ Given an established overlay network
   - A node evaluates the advantage (if any) from picking a different set of neighbors
   - If rewiring is warranted, the node changes its (outbound) neighbors accordingly
   - This rewiring may trigger more rewiring by other nodes

and the “Selfish Neighbor Selection” (SNS) game goes on...

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How we depart from prior work?

- **Selfish routing**
  - Game input: Fixed network topology
  - Game outcome: Selfishly constructed source-based routes over the topology

- Our SNS work:
  - Game input: Shortest-path routing
  - Game outcome: Selfishly constructed network topology

† References: [Roughgarden & Tardos, JACM’02] [Qiu et al, Sigcomm’03]

SNS Game: Interesting questions

- What is the optimal strategy for playing the SNS game?
- How does it compare to empirical ones (e.g., random, nearest neighbor, ...)?
- Under what conditions will neighborhoods stabilize (i.e., reach Nash-like equilibrium)?
- What do the resulting Nash-equilibrium overlay structures look like?
- What is the impact of partial/incomplete knowledge on optimal strategies?
- What is the price of anarchy?

SNS Game: Interesting questions

- What is the effect of node churn on stability and performance?
- What is the effect of changing costs due to changes in physical network?
- What if some (most) nodes are naïve? malicious? adversarial?
- How does this all scale with the size of the network?
- Could answers to the above questions inform systems/protocol design?
- ...

Formulation of SNS for routing

- Notation:
  - $S_i$ is the residual wiring graph defined by the local wirings of all nodes except node $v_j$
  - $S$ is the global wiring graph obtained by adding $v_i$'s choice of neighbors $s_i$ to $S_j$

  $$S = S_j \cup \{s_i\}$$

Defining an overlay neighborhood

- Assumptions by prior works
  - No cap on number of neighbors
    - Impractical – think about implications on scoped flooding in P2P, link state for routing, OS socket overheads, up-link bandwidth fragmentation, ...
  - Neighbor relationships are symmetric
    - Presumptuous – communication is directed and costs are often asymmetric

- Our assumptions:
  - Nodes have a small bounded-degree $k \ll n$
  - Neighboring relationship is directed

Selfish Neighbor Selection (SNS)

- Players:
  - The set of overlay nodes, $V = \{v_1, ..., v_n\}$

- Strategies:
  - A strategy $s_i \in S_i$ for $v_i$ amounts to selecting $k_i$ outgoing overlay links; $|S_i| = (n-1)$ choose $k_i$

- Outcome:
  - $S = \{s_1, ..., s_n\}$ is the “global wiring” composed of all “individual wirings” $s_i$
Formulation of SNS for routing

- The objective of node \( v_i \) is to find the local wiring \( s_i \) that minimizes
  \[
  C_i(S) = C(S_{-i} \cup \{s_i\}) = \sum_{y \in S_{-i}} p_{ij} d_x(v_i, v_j)
  \]
  where
  - \( p_{ij} \) is the preference of \( v_i \) for \( v_j \) as destination
  - \( d_x(v_i, v_j) \) is the cost of routing from \( v_i \) to \( v_j \) in \( S \)

How we depart from prior work?

- Prior work assume undirected links, unbounded degree, and uniform destination preferences
  - In [Fabrikant et al., PODC'03], a node may "buy" as many undirected links as it wants, each at cost \( \alpha \), so as to minimize the purchase + access cost
  \[
  C_i(S) = \alpha |s_i| + \sum_{v \in S} d_x(v_i, v_j)
  \]
  - In [Chun et al., Infocom'04], effect of non-uniform link costs \( \alpha_{ij} \) is empirically evaluated.
- Appropriate for telecom networks, but not overlays; results in preferential attachment...

Neighbor selection strategies

- Best-Response (BR) is the optimal local neighbor selection strategy for node \( v_i \):
  - BR leverages knowledge of topology and link costs of residual graph \( S_{-i} \) to minimize \( C_i(S) \)
- Empirical local strategies that do not use global information:
  - \( k \)-kandom does not use any link information
  - \( k \)-closest uses only local information

BR for SNS (for routing) is NP hard

- Theorem:
  Under uniform overlay link weights (e.g., hop-count), finding the BR to \( S_{-i} \) is equivalent to solving the asymmetric \( k \)-median on \( S_{-i} \) with reversed distance cost.

Game theoretic results for SNS†

- Theorem:
  All games with uniform node preference, node degree, and link costs have pure Nash equilibria (stable graph).
  - In any such stable graphs, the cost of any node is at most \( 2 + k^{-1} + O(1) \) that of any other node.
  - The diameter of the stable graph for a uniform game is \( O(q(n \log n)) \).

- Theorem:
  There exist non-uniform games with no pure Nash equilibria.

Empirical evaluation of SNS (routing)

- Obtain BR wiring for SNS game as follows
  
  \[
  \text{start with an arbitrary wiring ; until wiring is stable or within threshold } \{ 
  \text{BR}(v_i) \leftarrow \text{heuristically}^1 \text{ solve asymmetric k-median; } \}
  \]

- Vary problem inputs/parameters and evaluate resulting wirings w.r.t. topological features, individual node cost, and overall social cost

  \( ^1 \) Two heuristic implementations:
  - ILP using Simplex method (Cplex Tomlab toolbox)
  - Local search (with \( r \)-link swap, \( r = 1, 2, \ldots, k \); \( O(nr) \) complexity)

Results under complete uniformity

- Under unit link costs and uniform routing preference to all destinations, we know that a Nash-equilibrium exists.

- What are the characteristics of the resulting wiring graphs?
  - Are they random?
  - Do they exhibit a uniform in-degree distribution?

Results under complete uniformity

- Not uniform, but skewed in-degree distribution
- Selfishness yields preferential attachment to "accidentally" popular nodes
- Phenomenon more evident for small \( k/n \) – why?

Effect of skewed routing preference

- Preferential attachment to "inherently" popular nodes satisfies selfishness' need for popular nodes for small \( k \)
- What happens with larger \( k \) ?

The two sources of in-degree skew

- Skew

Why is node 13 popular?

Effect of heterogeneous link costs

- Link cost generation
  1. Synthetically using BRITE:
     - Barabasi-Albert (BA) model with heavy-tailed 2D placement
     - Euclidean distance used to derive cost of overlay links
  2. Empirically from PlanetLab:
     - 300-node PlanetLab topology
     - All-pair ping traces used to derive cost of overlay links
  3. Empirically from AS-level maps
     - 12/2001 Rocket-Fuel data of the Internet topology
     - AS-level hop-count used to derive cost of overlay links

- Control parameter
  - Bound on out-degree (\( k \)) ≈ link density (\( \beta \))
Experimental setting

- Neighbor selection strategy
  - a. The $k$-random heuristic
  - b. The $k$-closest heuristic, a.k.a. greedy
  - c. SNS Best Response (BR) wiring using ILP

- Experiments done in nine permutations
  - Three strategies for a new comer, each assuming residual graph was wired using one of the three strategies

- Performance metrics
  - Individual Cost = Average cost for a newcomer
  - Cost ratio for strategy $x = \frac{C(x)}{C(BR)}$
  - Social Cost = Sum of cost for all nodes
  - Social Cost ratio for strategy $x = \frac{SC(x)}{SC(BR)}$

SNS over random residual networks

- BR is dominant, with $k$-closest decidedly better than $k$-random. BR’s benefit pronounced for small $k$ – why?

SNS over greedy residual networks

- BR is dominant, with $k$-random slightly better than $k$-closest – why?

SNS over selfish residual networks

- BR is dominant, but not by a significant margin, with $k$-closest being quite competitive – why?

Social cost benefit from SNS

- Adopting BR as a neighbor selection strategy results in a significant reduction in the social cost (by 30-60%) over naive (random/greedy) approaches.

Almost Utopia!

- Not much difference between social cost of SNS wiring and that of a Utopian wiring over wide ranges of preference skew and link density.

The network is better off with selfish nodes!

The network is almost a utopia with selfish nodes!
EGOIST: SNS prototype

EGOIST Demo at: http://csr.bu.edu/sns

EGOIST: Implementation

Protocol for EGOIST overlay node $i$:
1. Bootstraps by connecting to arbitrary neighbors
2. Joins link-state protocol to get residual graph
3. Measures cost to candidate neighbors
4. Wires according to chosen strategy (default: BR)
5. Monitors and announces overlay links

† We have also implemented a light-weight version of this protocol, in which steps 2, 4, and 5 are implemented on a central server.

EGOIST: Features

- Supported metrics:
  - Delay (actively/passively monitored with ping/pyxida)
  - Available bandwidth (monitored with pathChirp)
  - Node load (monitored with loadavg)

- Supported wiring strategies:
  - $k$-random
  - $k$-closest
  - $k$-regular
  - Best-Response (Delay and AvailBw formulations)
  - Hybrid Best-Response (subset of links donated to the network)

- BR Computation:
  - By using the full residual graph
  - By sampling the residual graph

EGOIST: Baseline results (n=50)

- Passive approaches deliver comparable results (across strategies) with much less overhead!
- Greedy indistinguishable from random; regular

EGOIST: Other metrics

- Significant gains possible with BR
- Greedy’s performance is lagging – why?
EGOIST: Re-wiring frequency

- Overlay fairly stable, especially for small k
- Re-wirings increase quite rapidly with k – why?

EGOIST: Marginal utility of re-wiring

- Most of the benefit achieved with k ~ 3-4
- Re-wirings could be reduced using "lazy" BR

EGOIST: Effect of churn

- HybridBR delivers much of the efficiency of BR
- Greedy strategy less susceptible to churn than random and regular strategies

EGOIST: Effect of churn

- BR dominates non-BR wirings strategies
- At very high churn, using HybridBR pays off

EGOIST: Vulnerability to abuse

- Free riders avoid being chosen as neighbors by inflating cost of their outgoing links (* above)
- EGOIST is robust to abuse by free riders (not the case with greedy neighbor selection)

EGOIST: Effect of partial knowledge

- Sampling rate affects BR and greedy strategies
- Topology-based biased random sampling significantly improves BR's performance
Other SNS objectives

- **Routing Networks (e.g., Skype):**
  - Send unicast traffic from one overlay node to another
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  - Send data from one node to all nodes in the overlay
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The $n$-way broadcast problem

- Each node needs to send a file to all others
  - Exchange of large scientific data-sets in grid computing
  - Distribution of traffic log files for network-wide IDS
  - Synchronization of distributed databases
  - Distributed backup

- Use swarming to reduce link stress
  - How do we create the underlying torrent topology?
  - Could SNS lead to better overlay on which to swarm?
  - What would constitute a selfish objective?
    - Maximize the average bandwidth over all nodes
    - Maximize the minimum bandwidth across all nodes

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Swarming over SNS overlays

<table>
<thead>
<tr>
<th>File ID</th>
<th>Node ID</th>
<th>Delivery Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random</td>
<td>Greedy</td>
<td>Selfish (min-max)</td>
</tr>
</tbody>
</table>

† Thou shalt swarm over selfishly-constructed overlays!

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Query routing over SNS overlays

† Thou shalt query over selfishly-constructed overlays!

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Take home messages

- Performance of overlays depends highly on neighbor selection strategy
- Framing neighbor selection as a strategic game yields highly optimized overlays
- Implementing SNS is practical and yields overlays that are robust to churn/abuse

⇒ Papers, demos, traces, and code available from [http://csr.bu.edu/sns](http://csr.bu.edu/sns)

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Publications

"EGOIST: Overlay Routing using Selfish Neighbor Selection"  
Georgios Smaragdakis, Vassilis Lekakos, Nikolaos Laoutaris, Azer Bestavros, John W. Byers and Mema Roussopoulos.  
ACM CoNEXT 2008.

"Swarming on Optimized Graphs for $n$-way Broadcast"  

"Implications of Selfish Neighbor Selection in Overlay Networks"  
Nikolaos Laoutaris, Georgios Smaragdakis, Azer Bestavros and John W. Byers.  