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Selfish neighbor selection: thou shalt be a selfish overlay neighbor

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Boston University

Thou Shalt Be a Selfish Overlay Neighbor

Implications of Selfish Neighbor Selection on the Design and Performance of Overlay Networks

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<http://www.cs.bu.edu/groups/wing>

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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!

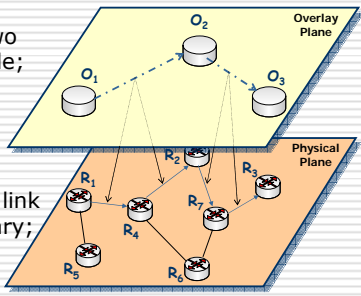
- In cyberspace, changing one's neighborhood is cheap – just rewire!
- Especially true for overlay networks.
- Implications?



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Overlay networks

- Communication between any two nodes is possible; any node is a candidate as a neighbor
- Cost of overlay link could be arbitrary; e.g., delay, physical hops, distance, ...



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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]

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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?

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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?
- ...

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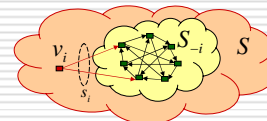
Formulation of SNS for routing



Notation:

- S_{-i} is the residual wiring graph defined by the local wirings of all nodes except node v_i
- S is the global wiring graph obtained by adding v_i 's choice of neighbors s_i to S_{-i}

$$S = S_{-i} \cup \{s_i\}$$



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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

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Selfish Neighbor Selection (SNS)



Players:

The set of overlay nodes, $V = \{v_1, \dots, v_n\}$

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:

$S = \{s_1, \dots, s_n\}$ is the "global wiring" composed of all "individual wirings" s_i

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Formulation of SNS for routing



- The objective of node v_i is to find the local wiring s_i that minimizes

$$C_i(S) = C_i(S_{-i} \cup \{s_i\}) = \sum_{v_j \in V_{-i}} p_{ij} \cdot d_S(v_i, v_j)$$

$$|s_i| \leq k$$

where

- p_{ij} is the preference of v_i for v_j as destination
- $d_S(v_i, v_j)$ is the cost of routing from v_i to v_j in S

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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 α , so as to minimize the purchase + access cost

$$C_i(S) = \underbrace{\alpha \cdot |s_i|}_{\text{Purchase Cost}} + \underbrace{\sum_{v_j \in V_{-i}} d_S(v_i, v_j)}_{\text{Access Cost}}$$

- In [Chun *et al*, Infocom'04], effect of non-uniform link costs α_{ij} is empirically evaluated.

- Appropriate for telecom networks, but not overlays; results in preferential attachment...

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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

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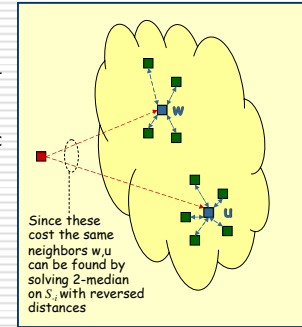
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BR for SNS (for routing) is NP hard



- 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



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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

- Corollaries:

- BR is NP hard; constant approximation for *metric* k -median does not apply
- $O(1)$ -approximation with $O(\log n)$ blow-up in number of medians [Lin and Vitter, '92] is possible

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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 $O(\sqrt{n \log_k n})$.

- Theorem:

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

[†] Proofs, constructions, and more results in Laoutaris, Rajaraman, Sundaram, Teng. "A bounded-degree network formation game", from arXiv-CoRR cs.GT/0701071.

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Empirical evaluation of SNS (routing)

- Obtain BR wiring for SNS game as follows


```

start with an arbitrary wiring ;
until wiring is stable or within threshold {
  for each node  $v_i$  {
    BR( $v_i$ ) ← heuristically† solve asymmetric k-median;
  }
}
```
- Vary problem inputs/parameters and evaluate resulting wirings w.r.t. topological features, individual node cost, and overall social cost
 - Two heuristic implementations:
 - ILP using Simplex method (Cplex Tomlab toolbox)
 - Local search (with r -link swap, $r = 1, 2, \dots, k$; $O(n^r)$ complexity)

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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?

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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?

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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 ?

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The two sources of in-degree skew

Why is node 13 popular?

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Effect of heterogeneous link costs

- Link cost generation
 - Synthetically using BRITE:
 - Barabasi-Albert (BA) model with heavy-tailed 2D placement
 - Euclidean distance used to derive cost of overlay links
 - Empirically from PlanetLab:
 - 300-node PlanetLab topology
 - All-pair ping traces used to derive cost of overlay links
 - 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) \approx link density (β)

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Experimental setting

Neighbor selection strategy

- The k -random heuristic
- The k -closest heuristic, a.k.a. greedy
- 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

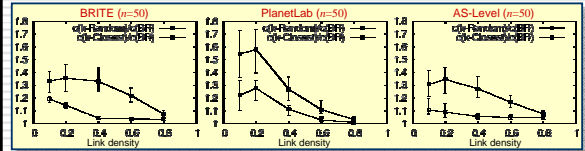
- Individual Cost = Average cost for a newcomer
→ Cost ratio for strategy $x = C(x)/C(BR)$
- Social Cost = Sum of cost for all nodes
→ Social Cost ratio for strategy $x = SC(x)/SC(BR)$

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SNS over random residual networks



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

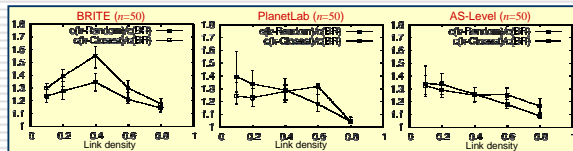
If your neighbors are naive, it pays to be selfish

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SNS over greedy residual networks



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

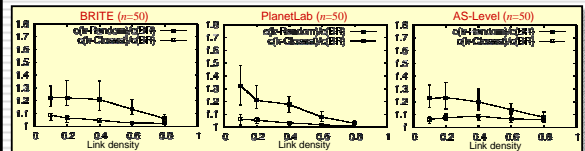
If your neighbors are greedy, it pays to be selfish

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SNS over selfish residual networks



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

If your neighbors are selfish, it's OK to be naive

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Social cost benefit from SNS

	$\beta = 0.1$		$\beta = 0.2$	
	k -Random/BR	k -Closest/BR	k -Random/BR	k -Closest/BR
BRITE	1.44	1.53	1.52	1.84
PlanetLab	2.23	1.48	1.75	1.23
AS-level	2.04	1.90	1.83	1.61

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

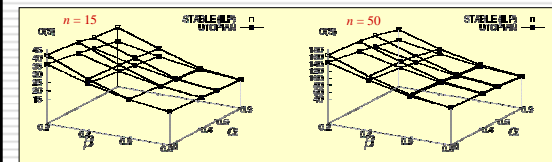
The network is better off with selfish nodes!

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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 almost a utopia with selfish nodes!

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EGOIST: SNS prototype

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

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EGOIST: Implementation

Protocol for EGOIST overlay node v_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.

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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

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EGOIST: Baseline results (n=50)

Metric: Delay (via ping)

k	k-Random	k-Regular	k-Closest	Full mesh
2	4.0	3.0	2.5	0.7
3	3.0	2.5	2.0	0.7
4	2.5	2.0	1.5	0.7
5	2.0	1.8	1.5	0.7
6	1.8	1.6	1.5	0.7
7	1.6	1.5	1.5	0.7
8	1.5	1.5	1.5	0.7

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EGOIST: Active vs. passive

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

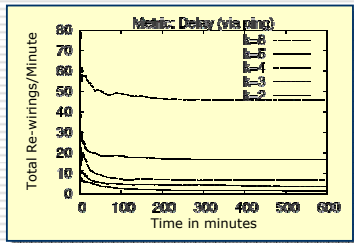
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EGOIST: Other metrics

- Significant gains possible with BR
- Greedy's performance is lagging – why?

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EGOIST: Re-wiring frequency



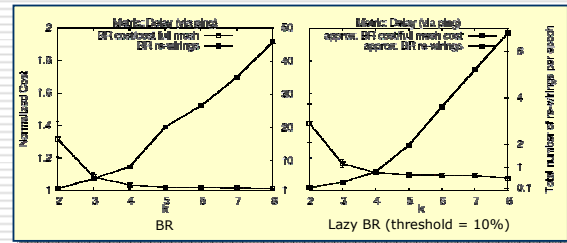
- Overlay fairly stable, especially for small k
- Re-wirings increase quite rapidly with k – why?

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EGOIST: Marginal utility of re-wiring



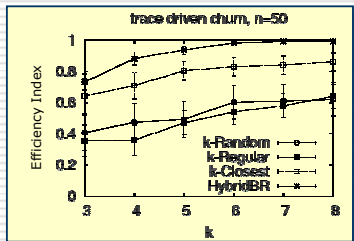
- Most of the benefit achieved with $k \sim 3-4$
- Re-wirings could be reduced using “lazy” BR

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EGOIST: Effect of churn



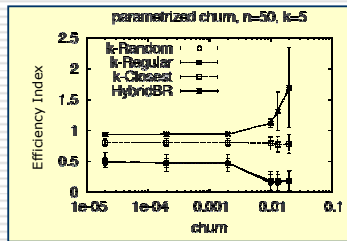
- HybridBR delivers much of the efficiency of BR
- Greedy strategy less susceptible to churn than random and regular strategies

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EGOIST: Effect of churn



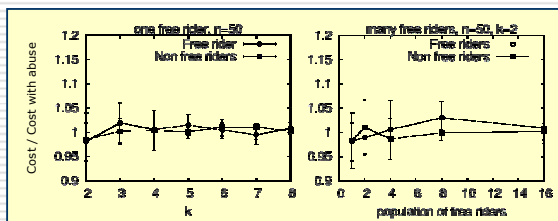
- BR dominates non-BR wirings strategies
- At very high churn, using HybridBR pays off

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EGOIST: Vulnerability to abuse



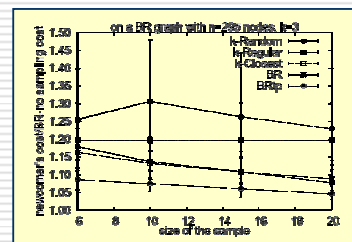
- Free riders avoid being chosen as neighbors by inflating cost of their outgoing links (*2 above)
- EGOIST is robust to abuse by free riders (not the case with greedy neighbor selection)

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EGOIST: Effect of partial knowledge



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

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Other SNS objectives



- **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 updates):**
 - Send data from one node to all nodes in the overlay
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- **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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The n -way broadcast problem



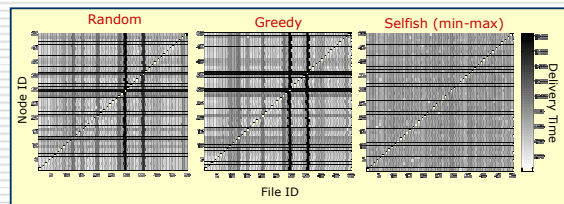
- **Each node needs to send a file to all others**
 - Exchange of large scientific data-sets in grid computing
 - Distribution of traffic log files for network-wide IDS
 - Synchronization of distributed databases
 - Distributed backup
- **Use swarming to reduce link stress**
 - How do we create the underlying 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



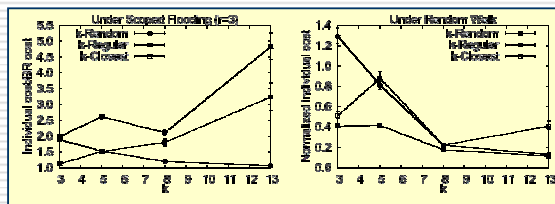
Thou shalt swarm over selfishly-constructed overlays!

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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>

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Publications



- "[EGOIST: Overlay Routing using Selfish Neighbor Selection](#)"
Georgios Smaragdakis, Vassilis Lekakis, Nikolaos Laoutaris, Azer Bestavros, John W. Byers and Mema Roussopoulos.
ACM CoNEXT 2008.
- "[Swarming on Optimized Graphs for \$n\$ -way Broadcast](#)"
Georgios Smaragdakis, Nikolaos Laoutaris, Pietro Michiardi, Azer Bestavros, John W. Byers and Mema Roussopoulos.
IEEE INFOCOM 2008.
- "[Implications of Selfish Neighbor Selection in Overlay Networks](#)"
Nikolaos Laoutaris, Georgios Smaragdakis, Azer Bestavros and John W. Byers.
IEEE INFOCOM 2007.

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