Enhanced Service Provisioning in Wireless Multi-hop Networks via Socially-driven Inverse Topology Control

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Evolutionary Design Loop - Motivation

- Physical networks, in which node associations correspond one-to-one in actual interactions among the entities and physical connectivity.

- Logical networks, involve logical associations and connectivity among peers. Such networks include, overlay and peer-to-peer (p2p) networks.

- Social networks, involves more complex interactions, that take into account mainly unpredictable/hidden social associations (activities).
Objective + Outline

Focus: on closing the loop between social and physical networking in the aforementioned design paradigm.

Exploit: how social knowledge and features of online social networks can be used in improving physical communication networks

Demonstrate: infuse the desired properties of online social structure (small-world effect, power-law like degree distribution) into the core structure of a wireless multi-hop network.

Use: Inverse Topology Control based techniques to modify topology in multi-hop networks (Edge Churn, Node Churn, Socially-aided Evolutionary Topology Modification (SETM))

Analyze: through a continuum-theory based framework

Evaluate: Identify performance gains and tradeoffs
Random Geometric Graphs RGG/Wireless Multi-hop Networks

- Constructed by allocating $N$ points uniformly and randomly over a plane region and linking two points separated by a distance of at most $r$

- Realistic model for actual multi-hop networks where a node may be connected with one or more nodes in its vicinity/range.

- Characterized by: high clustering, long average path length.

Idea: reducing average path length of wireless multi-hop networks, while not impacting clustering (its nature).
Clustering Coefficient

The **clustering coefficient** is a measure of direct connectivity between the neighbors of a node.

Quantifies how close its neighbors are to being a clique (complete graph)

\[
C = \frac{3 \times \text{number of triangles}}{\text{number of connected triples of vertices}} = \frac{\text{number of closed triplets}}{\text{number of connected triples of vertices}}.
\]

<table>
<thead>
<tr>
<th>#triangles</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>#connected triples</td>
<td>5</td>
</tr>
<tr>
<td>#closed triples</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>3/5</td>
</tr>
</tbody>
</table>
Small-world Networks

- Obtained evolutionary from ordered lattices
  - Start from an ordered lattice
  - Randomly rewire each edge with prob. $p$ excluding self-connections and duplicate edges
  - Arbitrary long-range edges maybe added
- Small average path length

**Examples:**
Social networks of relationships (short and long range connections), road maps, electric power grids, telephone call graphs, and social influence networks.
Preferential Attachment

\[
\text{Pref. Prob}(x) = \frac{W_x}{\sum_i W_i}
\]

- The probability that \( x \) participates in a process or takes a decision is proportional to a quantity \( w_x \) characterizing \( x \).

- Feature of social networks, \( w_x \) is usually the node degree.

- "cumulative advantage", "the rich get richer"

- Generates power law distributions.
  - Small percentage of nodes with great degrees
  - Majority of nodes with small degrees

\[
P(k) \sim k^{-\gamma}
\]
Topology Control (TC)- Inverse TC

- **Topology control** is a technique used mainly in wireless ad hoc and sensor networks in order to modify the initial topology of the network to save energy and extend the lifetime of the network.

- TC tries to achieve the balance:

  - Energy consumption
  - Node interference
  - Increase traffic carrying capacity
  - Connectivity
  - Cost at Delay, Path length

- **iTC**: Aims at achieving QoS performance benefits without impacting the energy consumption significantly.
Proposed Mechanism and Assumptions

- We propose edge churn, node churn and combinations based on iTC.

Assumptions:
- Not arbitrary increment of the transmission radius of each node (limited available energy of each wireless node).
- Connected network at any time (addition probability higher than deletion).
- Links between nodes: directional or bidirectional.
- Connections determined at physical/logical layer.
- $N$ nodes, in fixed locations.
- Homogeneous RGG initial network.
- Time $t$ is slotted.
- Distributed operation of the mechanism.
Edge Churn description

- The transmission radius of selected nodes increases thus extending their neighborhood and becoming more popular in the network.

- Each node can vary its radius between $R_{MIN}$ and $R_{MAX}$.

- Each time slot is characterized by two parameters $R_{min}$ and $R_{max}$.

- $R_c(i)$ is the radius of node $i$ at time step $t$.

- Initially we have a homogeneous RGG with transmission radius $R_f=R_{min}=R_{max}$.

- At each time step $R_{min}(t)=R_{max}(t-1)$ and $R_{max}(t)=R_{max}(t-1)+A$. 
Link
Addition

Initial bidirectional links

Added link of a previous step

Node i

New link

$K_i = 5$

$K_2 = 3$

$K_4 = 8$

$K_5 = 3$

$K_6 = 5$

$K_8 = 10$

$R_{\text{min}}$

$R_{\text{max}}$

$R_t$

$R_c(i)$
Link Rewiring

Deleted link from node j

Initial bidirectional links

New link

Node s chosen with pref. attach.

$K_s = 3$

$K_d = 8$

Added link of a previous step

$R_{c(i)}$

$R_f$

$R_{\text{max}}$

$K_e = 9$

$R_c(s) = R_{\text{max}}$

$K_s = 3$

$K_e = 5$
Link Deletion

Delete the forward direction of a link

Initial bidirectional links

Added link of a previous step

Node $i$
Edge churn processes (1)

- **Process \( p_1 \):** With probability \( p, 0 \leq p < 1 \), we add \( m_1, (m_1 < n) \) new links to \( m_1 \) selected nodes.
  First endpoint \( i \): selected with probability \( Q_1(k_i) \).
  Second endpoint \( j \): a randomly chosen neighbor in the area of the annulus bounded by \( R_{min}, R_{max} \) radii values of node \( i \).
  \( \text{Link formed} \quad i \rightarrow j \)

- **Process \( p_2 \):** With probability \( q, 0 \leq q < 1 \), we rewire \( m_2, (m_2 < n) \) links.
  First endpoint \( i \): randomly and uniformly selected among new nodes.
  Deleted endpoint \( j \): a randomly chosen neighbor of \( i \).
  \( \text{Link deleted} \quad i \leftrightarrow j \)
  Replacing endpoint \( s \): selected with probability \( Q_2(k_s) \).
  \( \text{Link formed} \quad i \leftrightarrow s \)
**Edge churn processes (2)**

- **Process $p_3$:** With probability $r$, $0 \leq r < 1$, we delete $m_3$, $(m_3 < n)$ links one from each of $m_3$ nodes selected with probability $Q_3(k_i)$.

  *Link deleted*  
  
  \[
  i \rightarrow j
  \]

### Equations

- **$Q_1(k_i)$**
  
  \[
  Q_1(k_i) = \frac{k_i + c}{\sum_{\text{all nodes } j} (k_j + c)}
  \]

- **$Q_2(k_s)$**
  
  \[
  Q_2(k_s) = \frac{k_s + 1}{\sum_{\text{all nodes } j \in A_{\max}^\infty R_c(i)(i)} (k_j + 1)}
  \]

- **$Q_3(k_i)$**
  
  \[
  Q_3(k_i) = \frac{N - k_i}{\sum_{\text{all nodes } j} (N - k_j)}
  \]

- **Inverse preferential attachment according to node degree**

- **Preferential attachment according to node degree**
Edge churn analysis via Continuum Theory

\[
\frac{dk_i}{dt} = pm_1 Q_1(k_i) - qm_2 \frac{1}{N} \frac{1}{k_i}
+ qm_2 \frac{1}{N} Q_2(k_i) - rm_3 Q_3(k_i)
\]

Approximation for average node degree

\[
\frac{dk_i}{dt} = pm_1 Q_1(k_i) - rm_3 Q_3(k_i)
\]
Node churn description- analysis

- **Process $p_4$: Node Addition**: With prob. $w$, $M_a$ nodes of the network are randomly and uniformly selected and each one of them invites a new node to join the network, by an analogy to a social network.
- The new nodes have increased radius compared to the original nodes in the network. In social network terms, this means that the friendship of a new node is extended to the majority of the friends of the inviting node and also that such node is more open to new friendships.

- **Process $p_5$: Node Deletion**: With prob. $v$, $M_d$ nodes are chosen, according to the inverse preferential attachment selection rule and deleted from the network.

- **Process $p_6$:** No change in the network topology.

Average node degree

\[
\frac{dk_i}{dt} = 2\pi M_a \frac{R_f^2}{L^2} + \pi w M_a \frac{(R_f + at)^2 - R_f^2}{L^2} - v M_d \pi \frac{R_f^2}{L^2}.
\]
Combined Mechanism-Demonstration
Socially-aided Evolutionary Topology Modification

\[ p+q+r+w+u+\text{Prob}(p_o)=1 \]
Combined Mechanism

Path length improved

![Graph showing average path length and clustering coefficient over steps of the simulation]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>750</td>
</tr>
<tr>
<td>L</td>
<td>2000</td>
</tr>
<tr>
<td>(p, q, r, w, v)</td>
<td>0.3, 0.1, 0.15, 0.3, 0.15</td>
</tr>
<tr>
<td>Steps</td>
<td>30</td>
</tr>
<tr>
<td>(R_{initial})</td>
<td>150</td>
</tr>
<tr>
<td>(Ma, Md)</td>
<td>5, 3</td>
</tr>
<tr>
<td>(m1, m2, m3)</td>
<td>10%N, 10%N</td>
</tr>
</tbody>
</table>

Clustered Coefficient like RGG
Node degree distribution

![Graph showing the node degree distribution for initial and final networks with density of degree on the y-axis and node degree on the x-axis. The graph includes two lines: one for the initial network (circles) and one for the final network (triangles).]
**Performance benefits**

**NS2 simulator:** 10 TCP connections for 10 randomly chosen pairs in initial and final topology and simulation of each topology for 300s. Average results over 5 different scenarios

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>250</td>
</tr>
<tr>
<td>$L$</td>
<td>800</td>
</tr>
<tr>
<td>$p, q, r, w, v$</td>
<td>0.3, 0.1, 0.15, 0.3, 0.15</td>
</tr>
<tr>
<td>Steps</td>
<td>19</td>
</tr>
<tr>
<td>$R_{initial}$</td>
<td>90</td>
</tr>
<tr>
<td>$Ma, Md$</td>
<td>5, 3</td>
</tr>
<tr>
<td>$m_1, m_2, m_3$</td>
<td>10%$N$, 10, 10%$N$</td>
</tr>
</tbody>
</table>
SETM leads to a mean radius less than Edge churn and higher than Node churn.
Energy consumed

![Bar chart showing energy consumed per node (in e.u.) for initial and induced network topologies. The chart indicates higher energy consumption for the induced network compared to the initial network.]
Conclusions

- We presented a socially inspired mechanism based on network churn aiming to improve the mean hop distance and as a result the performance metrics of a wireless multi hop network.

- The initial random geometric graph maintains its properties of clustering coefficient and approximated binomial distribution.

- The per node energy cost is affordable.

- By changing the process probabilities, it is possible to control the proposed mechanism at will.
Questions?

Thank you!