A Multi-Level Approach for Evaluating Internet Topology Generators

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Motivation

Why Topology Generators?

- Generate representative network topologies of different sizes
- Used for experiments to design protocols, predict performance, and understand robustness and scalability of the future Internet
- Unfortunately, many fail to capture static and evolutionary properties of today’s Internet, e.g., assume average path length and clustering coefficient constant

Our goal:

- Determine how to quantitatively assess a generator through a multi-level hierarchy of graph, node and link measures
- Focus on 2 popular generators: Orbis [SIGCOMM06] and WIT [INFOCOM07]
- Validate using different views of the Internet: data (traceroute), control (BGP tables), and management (WHOIS) planes
<table>
<thead>
<tr>
<th>Generators</th>
<th>Process</th>
<th>Model Type</th>
<th>Topology</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIT</td>
<td>Random-walks</td>
<td>Parametric</td>
<td>AS</td>
</tr>
<tr>
<td>RSurfer</td>
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<td>Orbis</td>
<td>Optimization</td>
<td>Data-driven</td>
<td>AS &amp; RL</td>
</tr>
<tr>
<td>HOT</td>
<td></td>
<td>Parametric</td>
<td>RL</td>
</tr>
<tr>
<td>Mod. HOT</td>
<td></td>
<td>Parametric</td>
<td>AS</td>
</tr>
<tr>
<td>AB</td>
<td>Preferential</td>
<td>Parametric</td>
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<td>BRITE</td>
<td>Attachment</td>
<td>Data-driven</td>
<td>AS &amp; RL</td>
</tr>
<tr>
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<td></td>
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<td>AS</td>
</tr>
<tr>
<td>GLP</td>
<td></td>
<td>Parametric</td>
<td>AS</td>
</tr>
<tr>
<td>SWT</td>
<td>Geometry</td>
<td>Parametric</td>
<td>AS &amp; RL</td>
</tr>
<tr>
<td>GT-ITM</td>
<td></td>
<td>Parametric</td>
<td>AS &amp; RL</td>
</tr>
</tbody>
</table>
Series of measures based on degree correlations

The first few $dK$ distributions are:

- $0K$ (average degree)
- $1K$ (degree distribution: $P(k) = n(k)/n$)
- $2K$ (joint degree distribution: $P(k_1, k_2) = m(k_1, k_2)\mu(k_1, k_2)/(2m)$, where $\mu(k_1, k_2) = 2$ if $k_1 = k_2$, otherwise 1)
- $3K$ (wedges and triangles), etc.

Fails to capture global characteristics

$d$ must be small in practice due to increasing complexity

Relies on rescaling technique; inaccurate as topology becomes larger
Captures the “wealth” of ISPs over time

Multiplicative stochastic process, \( u_i(t) = \lambda_i(t) u_i(t - 1) \), where \( u_i(t) \) is the unscaled wealth and \( \lambda_i(t) \) is an independent random variable

\( w_i(t) \) is the normalized wealth for node \( i \), and \( z_i(t) = C \cdot d_i(t) \) is the expense

In each iteration,
- If \( w_i(t) - z_i(t) > C + T \), place a link between the node \( i \) and an arbitrary node by randomly walking \( l \)-steps from \( i \)
- If \( w_i(t) - z_i(t) > -T \), remove a random link of node \( i \)

Threshold \( T \) is carefully chosen to avoid oscillation
Orbis versus WIT

- WIT attempts to model the evolution of the AS topology
  - Fails when the underlying process and growth of the Internet change
- Orbis generates topologies that preserve a set of measures
  - Fails if the set of characteristics is incomplete w.r.t. the actual AS topology
- What is the best representative set of local and global measures?
# Network Properties

<table>
<thead>
<tr>
<th>Measure</th>
<th>Importance in Computer Networks</th>
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<tbody>
<tr>
<td><strong>LOCAL</strong></td>
<td></td>
</tr>
<tr>
<td>Degree</td>
<td>Fault tolerance, local robustness</td>
</tr>
<tr>
<td>Assortativity</td>
<td></td>
</tr>
<tr>
<td>Clustering coefficient</td>
<td>Path diversity, fault tolerance, local robustness</td>
</tr>
<tr>
<td><strong>GLOBAL</strong></td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>Scalability, performance, protocol design</td>
</tr>
<tr>
<td>Betweenness</td>
<td>Traffic engineering, potential congestion points</td>
</tr>
<tr>
<td>Eigenvector</td>
<td>Network robustness, performance, clusters/hierarchy, traffic engineering</td>
</tr>
</tbody>
</table>
Measures Used

The order of evaluation measures in terms of the difficulty of preservation is:

\[ \text{Link} \geq \text{Node} \geq \text{Graph} \]

**Graph Measures**
- Traditional: Average degree, Assortativity coefficient, Average clustering and Average distance, etc.
- Additional: largest singular value \((\lambda_1)\), Network conductance \((\lambda_1 - \lambda_2)\), radius, and diameter, etc.

**Node Measures**
- Traditional: Degree distribution, Clustering coefficient, distance, eccentricity, betweenness, etc.
- Additional: Network values, Scree Plots, K-walks, K-core, etc.
Measures Used (cont’d)

Link Measures
- Order of the nodes with respect to the magnitude of their coordinates along the principal direction
- The closest $k$-approximation of the topology

Community measures
- Louvain’s modularity
Quantitative Measures

- **Graph based:**
  - The normalized root-mean-square error (NRMSE)

\[
D_{NRMSE}(\vec{x}, \hat{\vec{x}}) = \frac{\mathbb{E}[(\vec{x} - \hat{\vec{x}})^2]}{\max(\vec{x}, \hat{\vec{x}}) - \min(\vec{x}, \hat{\vec{x}})}.
\]

- **Node based:**
  - **Kolmogorov-Smirnov (KS):** 
    \[
    KS(F_1, F_2) = \max_x |F_1(x) - F_2(x)|.
    \]
  - **Kullback-Leibler (KL) divergence:**

\[
D_{KL}(P \parallel Q) = \sum_i P(i) \ln \frac{P(i)}{Q(i)}.
\]
Learning Graph Measures [ReFeX, SIGKDD 2011]

Instead of selecting a set of graph measures, we automatically learn a set of graph measures recursively.

1. **Base set of measures.** The process starts by computing degree (in/out/total edges) and egonet measures (in/out egonet).
   - egonet includes the node, its neighbors, and any edges in the induced subgraph on these nodes.

2. **Aggregate measures.** The existing measures of a node are aggregated to create additional measures by taking the sum/mean of the neighbors (done in a recursive fashion). One simple measure is the mean value of the degree among all neighbors of a node.

3. **Prune correlated measures.** At each iteration, we test for redundant measures using a simple correlation test, and remove all measures that are highly correlated.

4. **Stopping Criteria.** Repeat steps 2-3 until no new measures are retained.
Evaluation Strategy

1. Given $G^*_n$ of size $n$, generate same size graph $G_n$ s.t. $M(G_n) \approx M(G^*_n)$

2. Given $G^*_n$ of size $n$, generate $G_m$ of size $m$ where $m \geq n$ s.t. $M(G_m) \approx M(G^*_n)$

3. Given an ordered sequence $G^*_t$ for $t = 1, 2, \ldots, m$, generate a corresponding sequence $G_t$ for $t = 1, 2, \ldots, m$ s.t. $G_t$ is the same size as $G^*_t$ and $M(G_t) \approx M(G^*_t)$
Datasets for Validation

- Skitter traceroute
- RouteViews’ BGP tables (RV)$^1$
- RIPE’s WHOIS
- HOT
- RocketFuel

$^1$AS-level subgraphs for 2004-2012
Results: Graph Measures

(a) Average Degree

(b) Average Clustering

(c) Assortativity

(d) Characteristic Path Length

(e) Diameter

(f) Largest Eigenvalue
Results: Node Measures

(a) Degree

(b) Clustering Coefficient

(c) Distance

(d) K-cores
Results: Node Measures

(a) Scree plot

(b) Network values
Results: Link Measures

(a) WHOIS

(b) HOT

(c) RocketFuel

(d) Orbis (WHOIS)

(e) Orbis (HOT)

(f) Orbis (RocketFuel)
Results: Quantitative Measures

<table>
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<tr>
<th></th>
<th>Deg.</th>
<th>CC</th>
<th>Ecc.</th>
<th>Kcores</th>
<th>PR</th>
<th>EigDiff</th>
<th>Net-Value</th>
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<tr>
<td>Hot</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.078</td>
<td>0.067</td>
<td>0.588</td>
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<td><strong>0.450</strong></td>
<td>0.000</td>
<td>0.088</td>
<td><strong>0.215</strong></td>
<td>0.629</td>
<td>0.680</td>
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<td>Whois</td>
<td>0.059</td>
<td><strong>0.480</strong></td>
<td><strong>0.224</strong></td>
<td>0.060</td>
<td><strong>0.536</strong></td>
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<td>0.009</td>
<td><strong>0.342</strong></td>
<td>0.096</td>
<td>0.182</td>
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</table>
## Results: Community Measures

Table: Evaluating the Community Structure of the Topologies.

<table>
<thead>
<tr>
<th></th>
<th>Communities</th>
<th>Q</th>
<th>Nodes</th>
<th>Edges</th>
<th>Degree</th>
<th>CC</th>
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<tbody>
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<td>5.60</td>
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<table>
<thead>
<tr>
<th></th>
<th>Communities</th>
<th>C-path</th>
<th>Radius</th>
<th>Diameter</th>
</tr>
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<tbody>
<tr>
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<tr>
<td>RouteViews</td>
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<tr>
<td>Orbis</td>
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<tr>
<td>WIT</td>
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<td>3.44</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>
Results: Selected versus Learned Measures

(a) Selected Measures

(b) Learned Measures
Results: Learned Graph Measures

(a) RV (Internet)  (b) Orbis  (c) WIT
Conclusions

- We propose a multi-level framework for understanding Internet topologies, and evaluating generators (focus on Orbis, WIT)
- We leverage both macro measures (graph) and micro measures (node and link measures) to accurately compare topologies
- We show that the existing generators fail to capture static and evolutionary properties of the Internet AS topology
- Data-driven generators generate static topologies with little or no variance
- Parametric generators typically cannot accurately model Internet evolution
Future Directions

- Investigate additional topology generators
- Develop a parameter estimation technique for WIT and analyze its behavior with the refined parameters
- Study Internet evolution and investigate causes for the changes we observed
Thank you.
Questions?