Interactions among physical, logical and social viewpoints:

An evolutionary design loop

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Complex Networks

- Network: A collection of (nodes, agents, components, objects, services ...) that collaborate to accomplish actions, gains, ...that cannot be accomplished without such collaboration
- It is all about Interactions that keep increasing and become more complex
- Trade-off: gain from collaboration vs. cost of collaboration
- Complex Networks (CNs): Describe wide range of systems of interacting entities
- Complex Network Analysis
  - Models
  - Properties/features
  - Behavior
## Complex Network Taxonomy

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication, infrastructure</td>
<td>Designed and/or engineered</td>
</tr>
<tr>
<td>technological networks</td>
<td></td>
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<tr>
<td></td>
<td>Social and economical networks</td>
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<td></td>
<td>Human initiated, Spontaneous growth</td>
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<tr>
<td>Biological networks</td>
<td>Spontaneous evolution</td>
</tr>
</tbody>
</table>
Networks: Different Views

- Network Science employs a three level consideration:
  - 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).

- Evolutionary Design Loop: Interactions among different Layers
Control vs. Communications

- Many graphs as abstractions
- **Collaboration** graph – or a model of what the system does (behavior)
- **Communication** graph – or a model of what the system consist of (structure)
- Challenge 1: Given behavior, what structure (subject to constraints) gives best performance?
- Challenge 2: Given structure (and constraints) how well behavior can be executed?
- Topology modification – topology formation/ transformation
Objective

- **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 the characteristics of physical communication networks.
- **Demonstrate**: infuse the desired properties of an 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 properly add communication links in a multi-hop network.
- **Analyze**: through a continuum-theory based framework.
- **Identify**: underlying research challenges that need to be addressed for a more holistic treatment and exploitation of the proposed evolutionary design vision.
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
Scale-free (Exponential) Networks

- Power-law distributed small-world network
  - Small percentage of nodes with great degrees
  - Majority of nodes with small degrees

\[ P(k) \sim k^{-\gamma} \]

- Obtained by growth + preferential attachment

\[ \Pi(k_i) = \frac{k_i}{\sum_j k_j} \]

- Many empirically observed networks appear to be scale-free → seems the most natural emerging network structure
Examples of Scale-free Networks

(a) Random network

(b) Scale-free network
Applications of Scale-free Networks

- Internet/WWW
- Science collaboration graphs
- Hollywood co-starring graphs
- Cellular networks
- Citation networks
- Road maps
- Food chains
- Electric power grids
- Neural networks
- Voter networks
- Social influence networks
- Human sexual contacts
Average Path Length

- Path $\rightarrow$ sequence of vertices traversed in a network
- Geodesic path $\leftrightarrow$ shortest path (topology)
  - shortest path through a network from a vertex to another
- Network diameter $\rightarrow$ length of longest geodesic
- Definition:
  $$ l_G = \frac{1}{n \times (n - 1)} \times \sum_{i,j} d(v_i, v_j) $$
  - Un-weighted graph
  - Total # nodes is $n$,
  - $d(v_i, v_j)$ geodesic length of $v_i$ from $v_j$
- The actual path length experienced on average by a user
- The lower $l_G$ is, the better it is in general
  - Information dissemination
  - Lower cost
Clustering Coefficient

- Measure of degree → graph nodes tend to cluster together
  - Global
    \[ C = \frac{3 \times \text{number of triangles}}{\text{number of connected triples of vertices}} = \frac{\text{number of closed triplets}}{\text{number of connected triples of vertices}}. \]
  - Local
    \[ C_i = \frac{|\{e_{jk}\}|}{k_i(k_i - 1)} : v_j, v_k \in N_i, e_{jk} \in E. \]
    - quantifies how close its neighbors are to being a clique (complete graph)

- (Network-wide) Average Clustering Coefficient
  - Average of the local clustering coefficients of all vertices
    \[ \bar{C} = \frac{1}{n} \sum_{i=1}^{n} C_i. \]
Inverse Topology Control

• **Therefore:**
  - infuse the scaling behavior of the small-world average path length to a multi-hop network
  - exploit Topology Control
  - propose various mechanisms for topology modification
  - use Continuum Theory for the analysis

• **Main objective**: basic features of mechanisms to improve selected properties of RGGs making them resemble the behavior of small-world networks (motivated by social network features and processes)

• Advantage in real-time applications: average packet delay (video streaming) and packet loss (QoS)
At each time step we increase the radius of $m_1$ selected nodes to a value of $R_{max}$

We employ the model at T time steps

$R_{max}, R_{min}$: parameters of the network characterizing each time step

$R_{max}(t+1) = R_{max}(t) + A$

$R_{min}(t+1) = R_{max}(t)$
Processes

• **Process \( p_1 \):** With probability \( p, 0<p<1 \), we add \( m_1, (m_1<n) \) new links to selected nodes

• First endpoint: probability \( Q_1(k_i) \)
  
  Second endpoint: one of the new neighbors in the area of the annulus bounded by \( R_{min}, R_{max} \) values of node \( i \)

  
  Probability that a node is selected as the endpoint of the connection:

  \[
  R(t) = \pi \frac{R_{max}^2(t) - R_{min}^2(t)}{L^2}
  \]

• **Process \( p_2 \):** With probability \( (1-p) \), no change in a node's transmission range

• \( Q_1(k_i) \): determined by one of the three scenarios

\[
\frac{dk_i}{dt} = pm_1Q_1(k_i)
\]
Scenario 1

Preferential attachment to popular nodes

- Starting point of the chosen link: one of the nodes with highest node degree (emergence of node-hubs similarly to scale-free networks)

\[ Q_1(k_i) = \frac{k_i + 1}{\sum_{all\_nodes\_i} (k_i + 1)} \]

- Preferential attachment regime: nodes favor connections to popular nodes

- Aim: Reduction of the average path length by connecting nodes of high degree with even more nodes \(\rightarrow\) Better traffic dissemination

- Concept: based on the scale-free topological nature of most social networks such as the WWW, the networks of scientific paper citations, actors in Hollywood, etc.
Scenario 2
Clustering based on popularity and proximity

- Initial endpoint of a new connection chosen regarding: the degree of the node (proportionally), the distance from the center of the deployment area (inversely proportional)

\[ Q_2(k_i) = \frac{k_i + 1}{\sum_{all\_nodes\_i} (k_i + 1)} \frac{1}{\sum_{all\_nodes\_i} d_i} \]

- Both popularity and spatial proximity exploited
- Social analogue: the tension followed by groups of people to cluster on the basis of popularity and geographic proximity
Scenario 3
Preferential attachment with bidirectional links

- Concept similar to Scenario 1 with bidirectional new links added

- **Main difference:** The transmission radius increases at both the selected node and the nodes to which the initiating nodes connect to

- Bidirectional links lead to higher energy consumption in the whole network but to a larger reduction of the average path length than Scenario 1
Evaluation – Numerical Results

- Number of nodes $N=750$.
- Selected nodes at each time step $m_1=10\% \ N=75$
- Number of steps=300.
- Radius increment at each time step=1m.
- Square deployment area $L=2000m$.
- Initial Radius=150m.
- $R_{max}=150m$ to 450m.
Reduction of Average Path Length

![Graph showing the reduction of average path length over the steps of the simulation.](image-url)
Increase of the Clustering Coefficient
Comparison of Average Path Length

- RGG
- Scenario 2
- Scenario 1
- Scenario 3
- Small World

Average path length vs. Number of nodes
Clustering coefficient comparison
Some recent (2010) relevant publications:


Thank you for your attention

Questions?