ESF Research Conference
Future Internet & Society:
A Complex Systems Perspective

Interactions among physical, logical and social viewpoints:
An evolutionary design loop

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Complex Networks

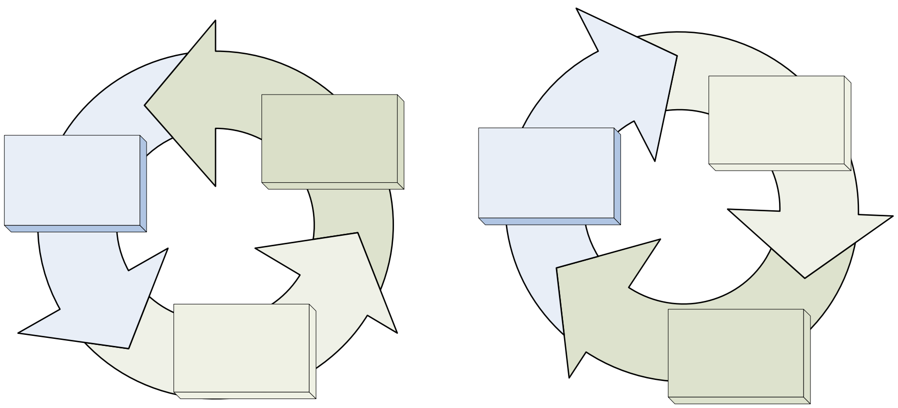
- Network: A collection of (nodes, agents, components, objects, services …) that collaborate to accomplish actions, gains, …that cannot be accomplished with out such collaboration
- It is all about Interactions that keep increasing and become more complex
- Trade-off: gain from collaboration vs. cost of collaboration
- Complex Networks (CNs): Describe wide range of systems of interacting entities
- Complex Network Analysis
  - Models
  - Properties/features
  - Behavior

Complex Network Taxonomy

Communication, infrastructure, technological networks	Social and economical networks	Biological networks
Designed and/or engineered	Human initiated, Spontaneous growth	Spontaneous evolution

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

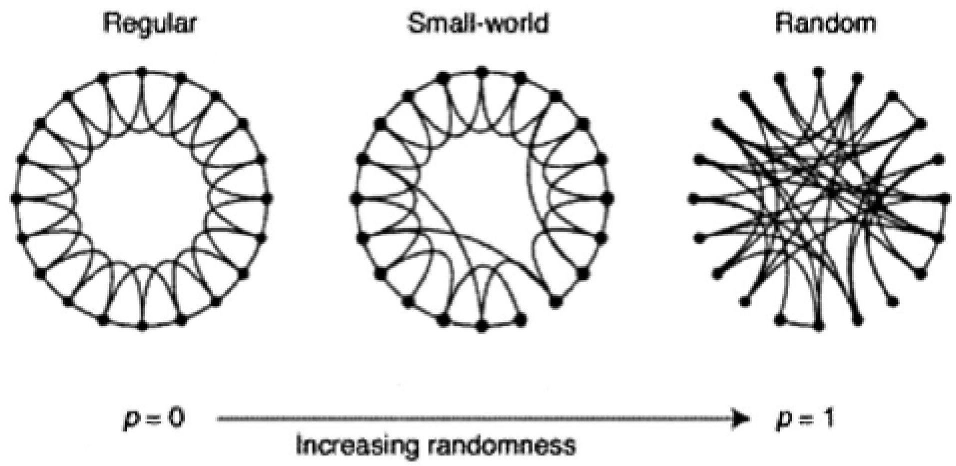
- Many graphs as abstractions
- Collaboration graph – or a model of what the system does (behavior)
- Communication graph – or a model of what the system consist of (structure)
- Challenge 1: Given behavior, what structure (subject to constraints) gives best performance?
- Challenge 2: Given structure (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.

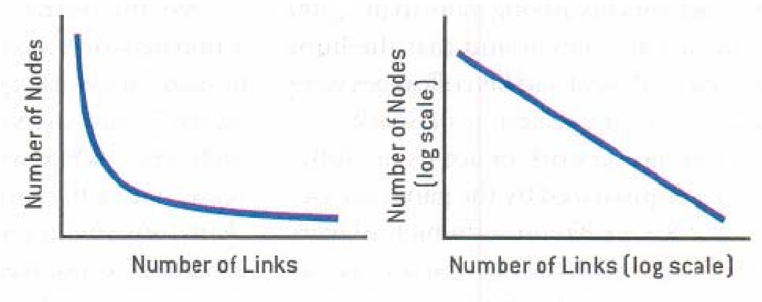
Small-world Networks

- 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 $P(k) \sim k^{-\gamma}$
  - Small percentage of nodes with great degrees
  - Majority of nodes with small degrees

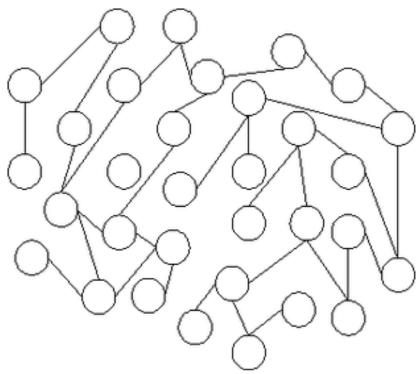


- Obtained by growth + preferential attachment

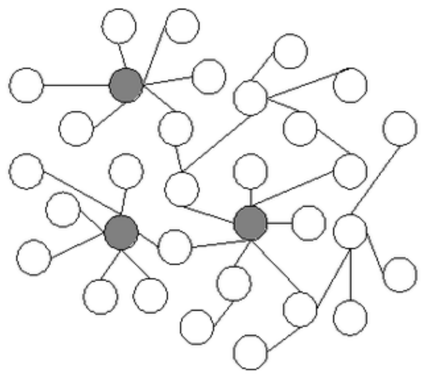
$$\Pi(k_i) = \frac{k_i}{\sum_j k_j}$$

- Many empirically observed networks appear to be scale-free $\rightarrow$ seems the most natural emerging network structure

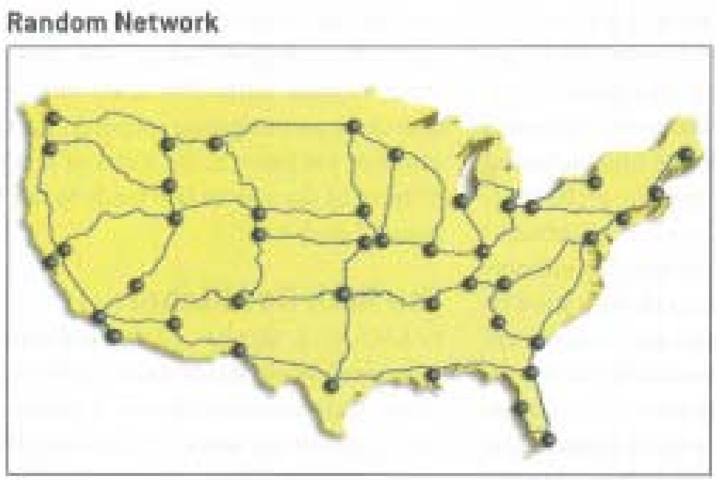
Examples of Scale-free Networks

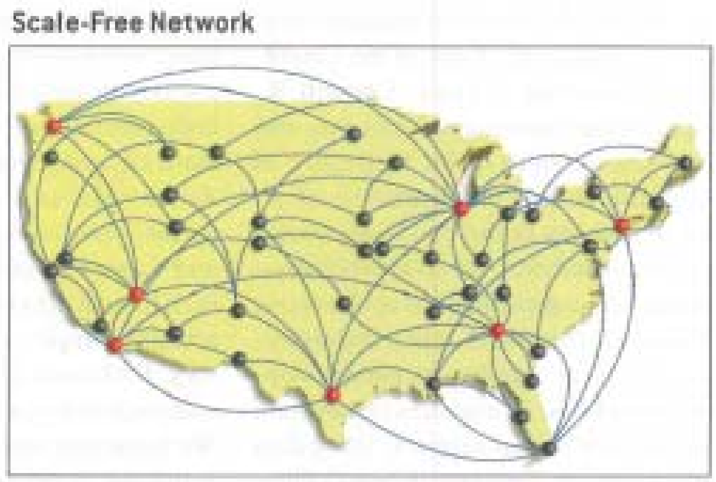


(a) Random network



(b) Scale-free network



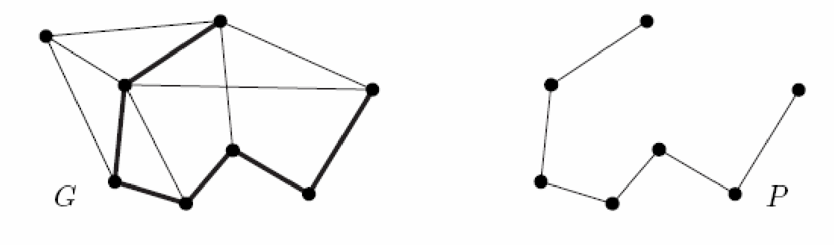


Applications of Scale-free Networks

- 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: $l_G = \frac{1}{n*(n-1)} * \sum_{i,j} d(v_i, v_j)$
  - 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 $\rightarrow$ 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)

Description

- 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

$$\frac{dk_i}{dt} = pm_1Q_1(k_i)$$

- $Q_1(k_i)$: determined by one of the three scenarios

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)

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

- 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

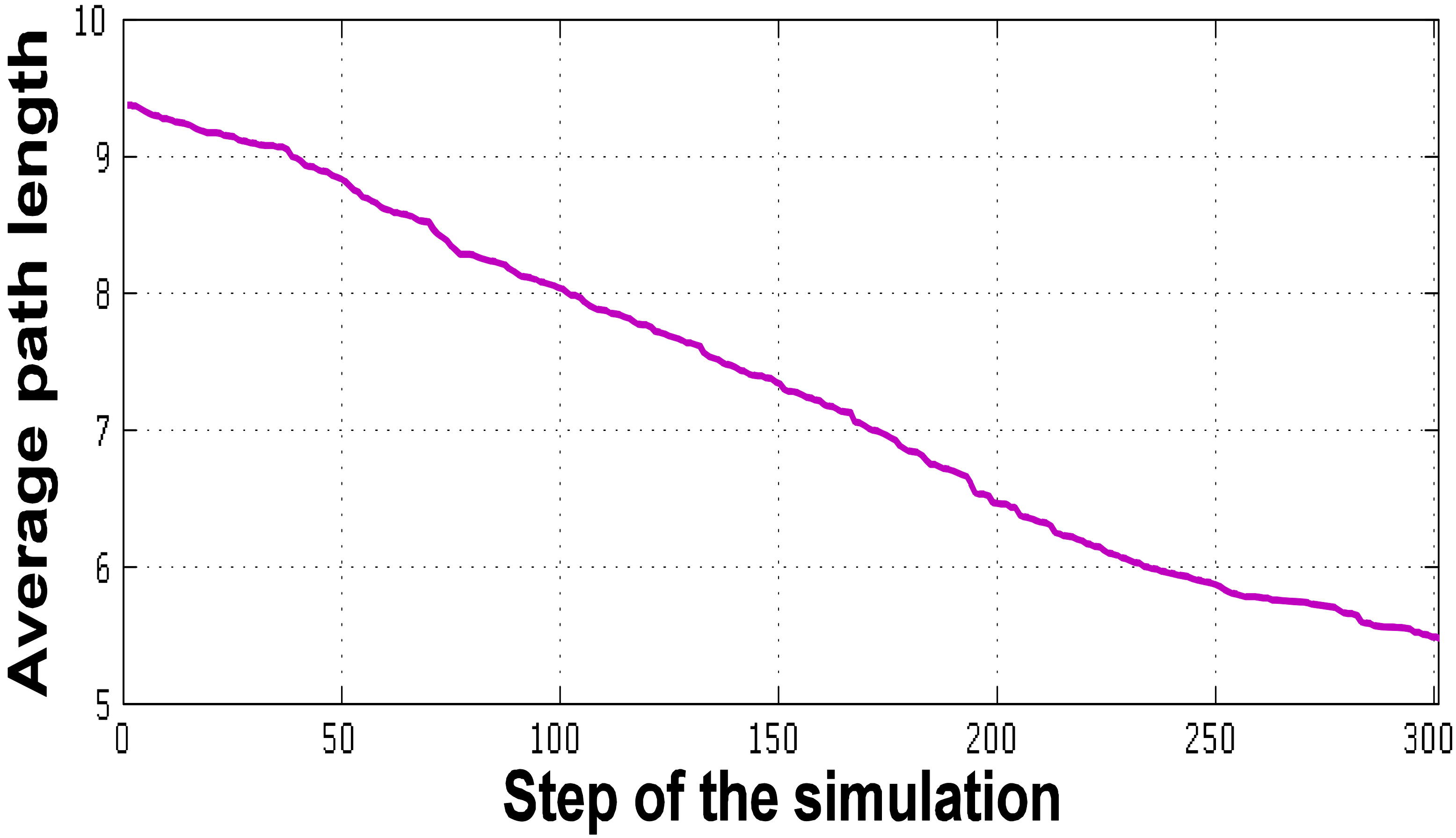
- ***Main difference:*** The transmission radius increases at both the selected node and the nodes to which the initiating nodes connect to

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

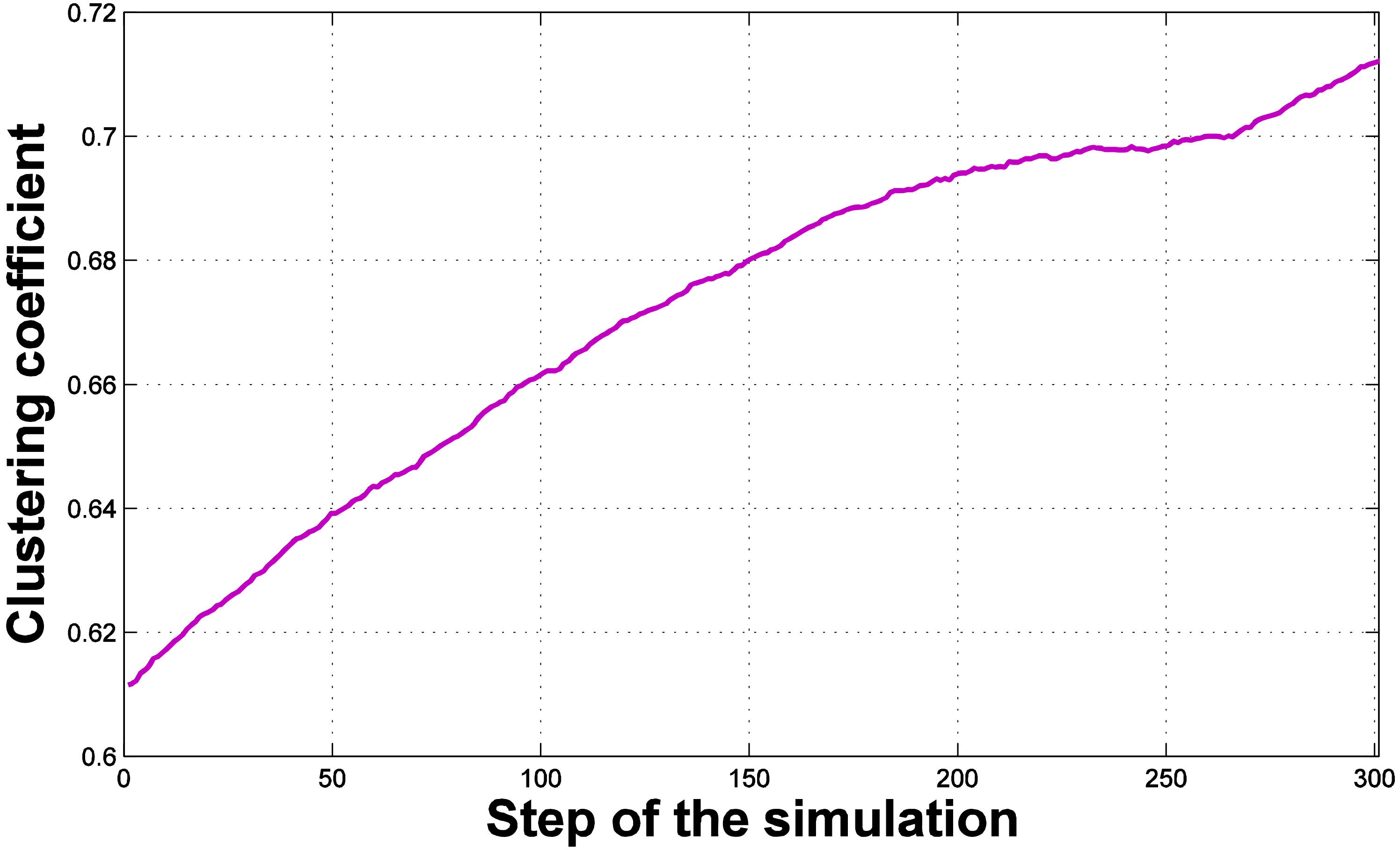
Evaluation – Numerical Results

- 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.
- $Rmax$=150m to 450m.

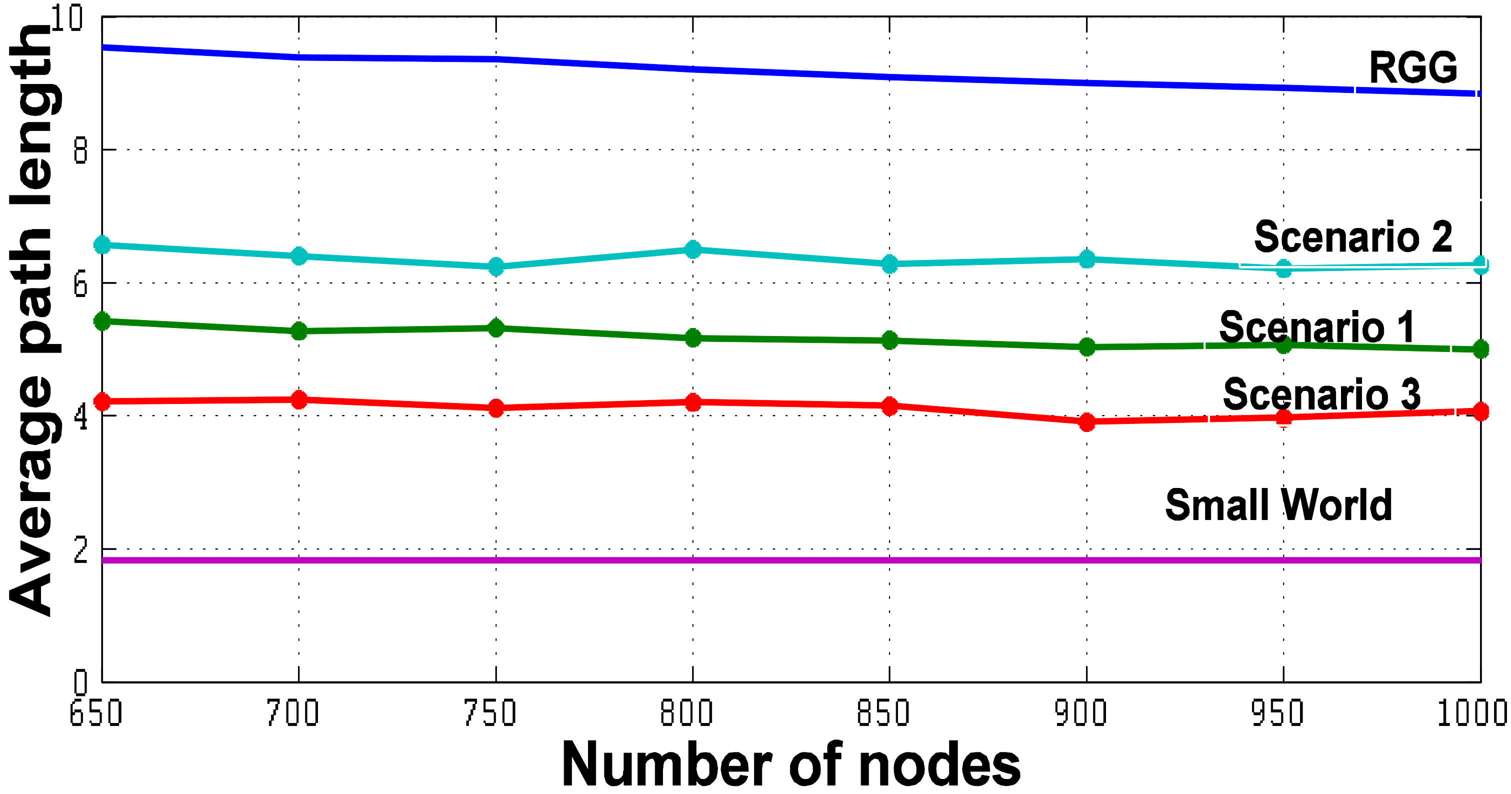
Reduction of Average Path Length



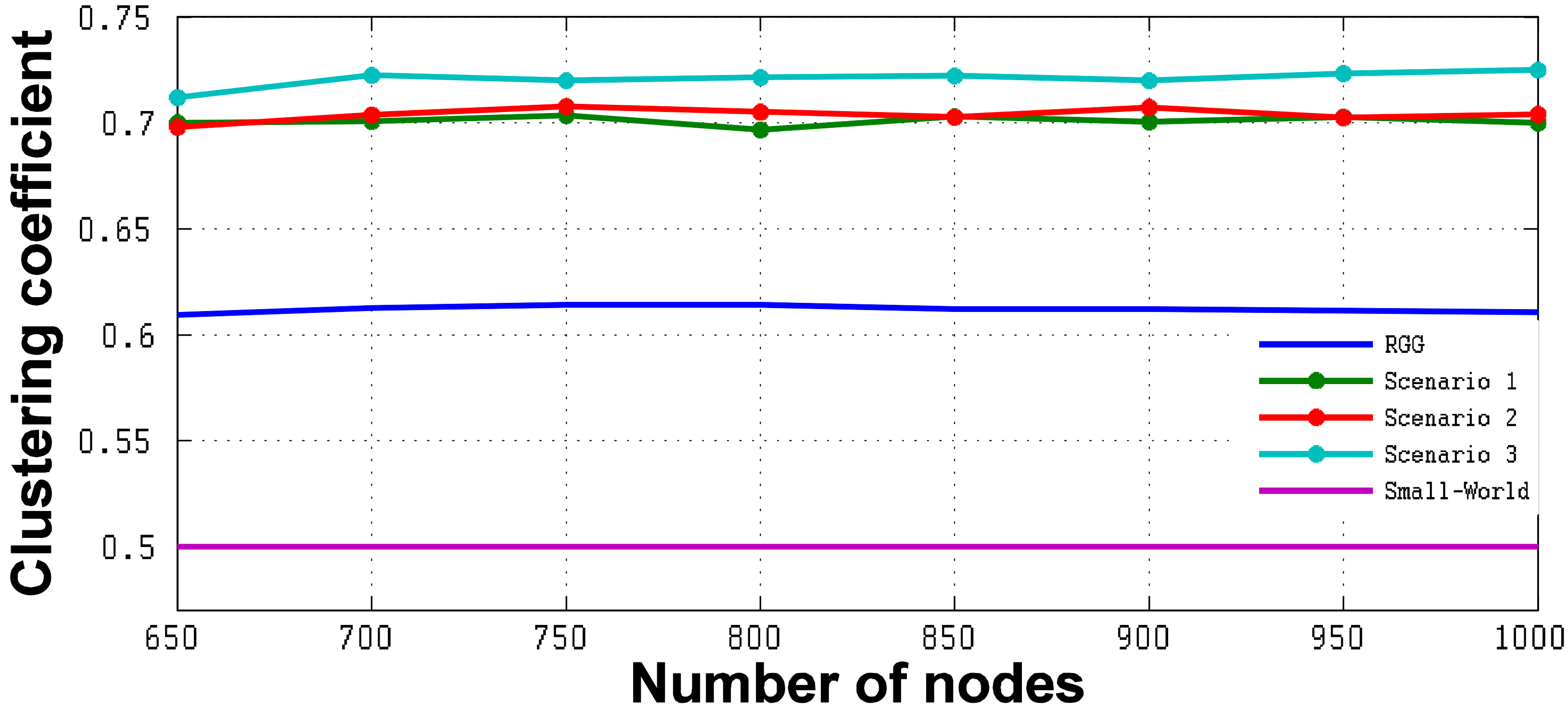
Increase of the Clustering Coefficient



Comparison of Average Path Length



Clustering coefficient comparison



Some recent (2010) relevant publications:

- E. Stai, V. Karyotis and S. Papavassiliou, “Socially-inspired Topology Improvements in Wireless Multi-hop Networks”, in Proc. of Social Networks Workshop of IEEE International Conference on Communications (ICC), May 2010.
- E. Stai, V. Karyotis and S. Papavassiliou “Enhanced Service Provisioning in Wireless Multi-hop Networks via Socially-driven Inverse Topology Control”, in Proc. of the 4th IEEE Workshop on Enabling the Future Service-Oriented Internet: Towards Socially-Aware Networks, of IEEE Global Communications Conference (GLOBECOM), December 2010.
- E. Stai, V. Karyotis and S. Papavassiliou, “Topology Enhancement in Wireless Multi-Networks: A Top-down Approach”, IEEE Trans. on Parallel and Distributed Systems (under review), 2010.
- V. Karyotis, A. Manolakos and S. Papavassiliou, “On Topology Control and Non-Uniform Node Deployment in Ad Hoc Networks”, in Proc. of Sixth IEEE PerCom Workshop on Pervasive Wireless Networking (PWN 2010), April 2010.
- V. Karyotis and S. Papavassiliou, “Mobility-induced Capacity-Delay Tradeoff in Wireless Multihop Networks”, Cluster Computing and Multi-Hop Network Research, Nova Publ., 2010.

Thank you for your attention

Questions?