Redundancy and Robustness of the AS–level Internet topology and its models

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Abstract: A comparison between the topological properties of the measured Internet topology, at the autonomous system level (AS graph), and the equivalent graphs generated by two different power law topology generators is presented. Only one of the synthetic generators reproduces the tier connectivity of the AS graph.

Introduction: Simulation plays an important role in the development of the Internet, as it can be used to compare and analyze new network protocols. In these simulations it is crucial that the topology generators capture the key topological properties of the Internet. For example, Labovitz *et al* [1] showed that the topology of the Internet has a major impact on the delayed BGP routing convergence.

If each autonomous system (AS) of the Internet is represented by a node in a graph, Faloutsos *et al* [2] discovered that the link connectivity between these nodes follows the power law $P(k) \propto k^{-\gamma}, \gamma \approx 2.2$, where k is the number of links a node has. A good model of the AS-level Internet topology not only has to reproduce the power law link connectivity but also the connectivity of the core of the network. Tier 1 of the AS graph is the core of the network which consists of a set of nodes which are very rich in links and are densely interconnected with each other, we called this set of nodes the rich–club [3]. This letter shows that a power law topology generator without a rich–club could under–estimate network redundancy and over–estimate network robustness of the Internet.

TABLE I

NETWORK PROPERTIES

	AS graph	IG graph	FBA graph
Number of nodes, N	11122	11122	11122
Number of links, L	30054	33349	33349
Power–law exponent, γ	2.2	2.22	2.255
Maximum k	2839	842	1793
Maximum K_t	7482	4962	1191
Average K_t	12.7	10.0	0.6

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Methodology: We compared the traceroute AS graph [4] measured on the 1st of April 2002 against the synthetic networks generated by the Fitness Barabási–Albert (FBA) model [5] and Interactive Growth (IG) model [6]. The two models create networks using a node growth mechanism, where a new node attaches to other nodes and prefers to attach itself to nodes that have large numbers of links. The FBA model is an example of a generator where the preferential attachment is controlled by a fitness parameter. This parameter adjust the node's ability of acquiring connections with other nodes. The IG model is an example of a generator where a new node attaches itself to other nodes and also creates new links between nodes that already exist on the network. As shown in table 1, these two topology models generate networks that have similar sizes and power law degree distributions as the AS graph.

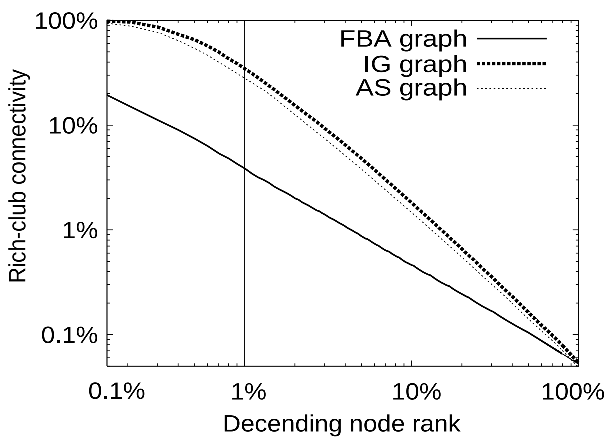

Fig. 1. Rich–club connectivity.

Each node in a network is sorted in decreasing number of the links that the node contains. The node rank r is the position that a node has on this ordered list. The position is normalized by the total number of nodes N. The rich–club are the nodes with rank less than r (e.g. 1%). The core connectivity of the network (tier 1) is measured using the rich–club connectivity, which is the ratio of the actual number of links between the members of the rich–club to the maximum possible number of links (fully connected). Figure 1 shows that the IG graph closely matches the AS graph's rich–club connectivity. For example, the 1% best connected nodes have 35% of the maximum possible number of links, whereas in the FBA graph they only have 4% of the maximum possible number of links.

In a network a circuit of length three is called a triangle. The number of alternative routes in a network increases with the number of triangles. The triangle coefficient K_t of a node is defined as the number of triangles that share the node. Figure 2 and table 1 show that the AS graph and the IG graph have significantly more triangles than the FBA graph. Hence the FBA model produces networks that are less flexible to traffic routing and have a lower degree of network redundancy.

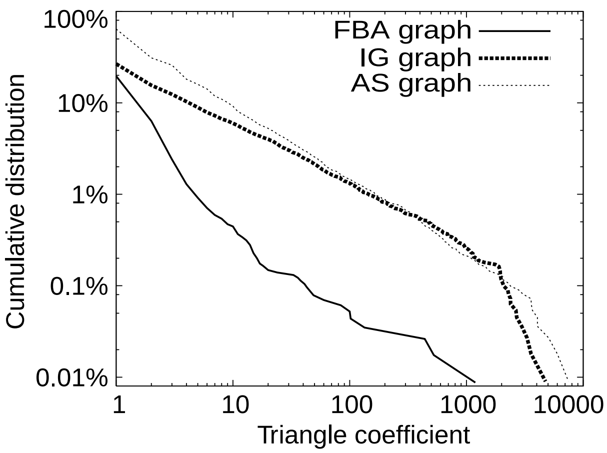

Fig. 2. Cumulative distribution of triangle coefficient.

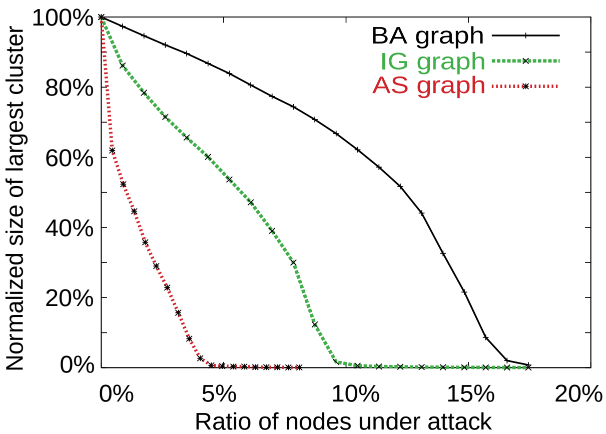

Fig. 3. Network robustness under node attack.

The removal of the best connected nodes from a network is called node attack. This resembles the Internet scenario where a node, AS or router, is out of service due to severe traffic congestion or infection by a malicious virus. Figure 3 shows that the AS graph and the IG graph are extremely fragile under node attack. The removal of only a few of the AS graph's richest nodes can break down the network integrity. By comparison, the FBA graph is not so vulnerable and shows higher degree of resilience to node attack.

Conclusion: The AS graph have a densely interconnected core structure, which plays a dominant role in the network. The rich–club acts as a super traffic hub providing a large selection of shortcuts. Realistic models of the Internet should reproduce this core structure to avoid under–estimating the network redundancy and over–estimating the network robustness.

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