Modelling IP Network Topologies by Emulating Network Development Processes

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Abstract: **Recent developments in Internet mapping and metrification as well as research into scale-free networks has given us an insight into modelling inter-connected IP networks. A number of topology generators have emerged which attempt to generate topologies which follow the power laws discovered in Internet topologies but don't consider the causes of the power laws. They tend to concentrate on creating a topology that follows the power laws on a macroscopic scale. In this paper we present a generalisation of a topology generator which emulates microscopic network growth decisions to generate macro-scale topologies which may follow power-laws. The microscopic decisions are examined further and their effect on the macroscopic result demonstrated. The design of these schemes and the possible impact of the underlying transport network is also briefly considered.**

1 Introduction

When studying aspects of networks and the effect of various ideas such as routing strategies, network dimensioning and the like, one very large variable is the topology of the network. For simplicity, regular topologies are often used such as uniform grids of nodes or rings or more random graphs like a uniformly randomly connected network. Real network topologies aren't usually like this and this can have a large impact on results [15][16]. Recent studies [1] have shown that the Internet topology isn't one of these regular patterns or a totally randomly connected set of nodes but rather a network which follows an emergent topology which exhibits a number of power-laws. Other networks have exhibited similar patterns, such as WWW page connectivity [2][3] and telephone call graphs [4]. The source of these power laws has been speculated [1][19] and has been often attributed to the fact that these networks grow in size and make active connectivity decisions. A good approximation to the processes behind the network's creation is essential if all of its characteristics are to be captured. In this paper we will propose a simple model for network growth and identify the micro-scale processes involved in growing networks and their effect on the macroscopic scale.

The microscopic growth process has a fundamental effect on the resulting network. An example of the effect of topology decisions on network research was the work by Albert et al. which showed that scale-free topologies are resistant to random failure but sensitive to deliberate attack [5][8]. On the other hand, uniformly randomly connected networks are both sensitive to attack and failure.

2 Network Modelling

To model the IP networks we must first have some kind of an idea of what they look like. The design goals and principles of the Internet are known at various levels. In the core the networks may be classified as either stub networks where traffic flows are sourced and sinked or transit networks which carry flows between stub networks [11]. The end-to-end IP network can pass through a hierarchy, with most users being on LANs which are interconnected within cities by MANs, which are in turn connected by WANs. Those are aspects of macro scale physical layer structure. From an emergent structure perspective, a number of empirical power laws were also found to exist in topologies of the core of the Internet at various levels. These laws cross the boundaries between routing protocols (the inter/intra network routing protocol boundary) and hold true for router level and autonomous system domain topologies.

2.1 Power Laws in Internet Topologies

Faloutsos et al. discovered four power laws [1] in three instances of inter-domain topologies and one instance of a node-level topology. The following four laws were found to hold at both the node-level and the BGP AS-level:

Power-Law 1 (rank exponent): The outdegree (connections from a node) was found to be proportional to the rank of a node, to the power of a constant. The rank being the position of the node in a table sorted (numerically decreasing) by the outdegree of the node.

Power-Law 2 (outdegree exponent): The frequency of an outdegree is proportional to the outdegree to the power of a constant.

Power-Law 3 (hop-plot exponent): The total number of pairs of nodes within *h* hops of each other, is proportional to the number of hops to the power of a constant. This is more of an approximation since it only holds for value of *h* which are much less then the network diameter.

Power-Law 4 (eigenvalue exponent): The sorted eigenvalues (decreasing order) of the adjacency matrix (an N node by N node matrix which is 1 when the two nodes are

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connected and 0 otherwise) are proportional to the index into the list, to the power of a constant. The power law was shown to hold for only the top 20 eigenvalues.

The cause of the power laws is a matter of some speculation – even though there are well defined discontinuous structural rules in the Internet there are still some large scale emergent patterns. The structural rules aren't the only ones: IP is a network level technology and therefore must be carried by a variety of heterogeneous transport networks all of which have their own implications on IP network planning. It is these macro-scale properties which we try model by emulating the microscopic actions in the various network layers.

3 Topology Generators

To properly investigate IP networks models are required which can generate topologies which are representative of real networks. Many topology generators have already been proposed in literature [6][10][11][12][13][14], some consider the known structure of the network being modelled such as the two tier architecture of the Internet, clustering and sub-nets while others consider random graphs and create more generic topologies.

3.1 Random Graph Models

Topologies of uniformly randomly connected nodes, first examined by Erdös and Rényi [13] are commonly used to generate test networks. They have a few shortcomings, such as the lack of internal structure, and this leads to characteristics like an average network diameter that is independent of the number of nodes and that all nodes have the same average degree.

Uniformly Random networks however do not exhibit power laws or have specific micro-scale decisions. There are a number of ways of generating power-law graphs but they generally rely on preferential attachment of nodes according to existing connectivity. Nodes connect to other nodes, preferring to connect to the already more connected nodes [5][19]: such that the probability of connecting to a node i, of j nodes in the network, with k_i links already is $P(k_i) \sim k_i / \Sigma k_j$. Such a network model creates networks that follow all four powers laws. It has been widely shown [19] that not only preferential attachment is necessary but also growth for the graph to conform to the power laws.

3.2 Current Topology Generators

A number of topology generators exist, most concentrating on different aspects of the Internet. Waxman [6] first proposed a topology generator in his examination of multicast routing trees. The generator used the euclidean distance between nodes to govern their connectivity: $P(u,v) = \beta e^{-d(u,v)/L\alpha}$, where $P(u,v)$ is the probability of linking nodes u and v, $d(u,v)$ is the euclidean distance between u and v, L is the euclidean diameter of the network and β and β are parameters. The use of euclidean distance now makes the geographic distribution of nodes a factor in the topology.

Other topology generators include Transit-Stub [11] and Tiers [10] which try to emulate different aspects of Internet structure such as transit network or hierarchical topologies. More recently the BRITE [12] topology generator was created to investigate the source of power laws in Internet topologies. BRITE borrows a number of modelling techniques to investigate network topologies. BRITE can generate Waxman topologies and also has a model for creating scale-free (power-law) networks. The scale-free model BRITE uses is the Barabasi-Albert [19] model which uses incremental growth and preferential attachment to create topologies which conform to the four power laws. In the Barabasi-Albert model at every time epoch a new node is added (incremental growth) and it is linked to exactly m existing nodes (preferring the more connected nodes – preferential attachment). This model, while producing results that match power laws, isn't very representative of the real processes involved in creating a network. The result is a network which has an average degree of $2m$ [19] and the lowest degree is m, which may not be the case with real networks. The result is good for performing experiments on the core of the Internet like those described in the introduction but we cannot model how the network will react to changes in environment or growth in demand or changes in transport layer topology.

4 Proposed Topology Generator

To be able to model reactive network growth a new method for creating topologies is proposed. In it we add a reactive step which can respond to the changed state of the network. We could now cater for reactive mechanisms such as those postulated by Faloutsos et al. [1] as one of the causes of the power laws.

The proposed process of creating the final topology has two growth stages to it: node and link growth. At every time epoch a node is added and linked to an existing node with some scheme (referred here as the "new node link scheme"). The scheme could be preferential attachment, or it could be dependant on distance or any other linking process. Then after the new node is added a certain number of new links are created between existing nodes in the network. For each new link a start node is chosen according to some scheme (referred to as the "source node scheme") and the end node is also chosen with some scheme (the "destination node scheme"). This is three step process is repeated for every new link that must be added. The number of links added is governed by a tally which is incremented by a certain amount (the link growth rate) at every epoch. The link growth rate is a real number which can be < 1.0 since the tally accumulates over epochs. Therefore if the growth rate is 0.5, one new link is added between existing nodes for every two new nodes. If the growth rate is 3.0 then three links are added between existing node pairs for every new node. The algorithm is as follows:

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i.    $N_l = G_l$;
ii.   Add a node. Connect it to only one other node according to the "new node link scheme".
iii.  If floor($N_l$) < 1.0 jump to step vii.
    iv.   Choose a source node according to the "source node scheme", and a destination node according to the "destination node scheme", and link the two.
    v.    $N_l = N_l - 1.0$;
    vi.   Jump to iii.
vii.  $N_l = N_l + G_l$.
viii. Jump to step ii. until the network contains the required number of nodes.
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Where N_l is a tally (just an internal counter) and G_l is the link growth rate (the number of links the network must grow by (not including the link added with the node) ever time a node is added). *floor(…)* is a function which returns the first integer value less than the argument value. At every time epoch a link is added from the new node and G_l links between existing nodes. As the network becomes large the number of links (average degree) per node approaches G_l +1.

The use of three schemes differentiates processes which can often be rather different. The node growth doesn't necessarily follow the same process as the link growth.

4.1 Link and Node Schemes

The schemes used to choose the destination of the link from the new nodes and the end-points of the new link are the microscopic decisions which must mimiced to emulate real network growth. The schemes used are dependent on the level (LAN, WAN or MAN) and the type of network (transit or stub network [11]) we are modelling. For example in a campus backbone network the "new link scheme" may be as simple as "connect to the nearest (Euclidean distance) existing node". The schemes which choose the endpoints for network link growth could initially be "choose a random node favouring the more connected nodes" - the preferential connectivity which is seen in so many power-law topology generator [20][7]. The reasoning behind this is that the more connected nodes are the nodes which carry more traffic and therefore must increase their connectivity to satisfy demand, or for resilience purposes.

4.1.1 Existing Connectivity based schemes

Here the endpoint node is chosen according to its existing connectivity. Power-law topology generators commonly use this method for choosing endpoints [19][4]. The more connected nodes are usually chosen in this way to create super-nodes which have been found to exist in internet topologies. In our scheme however we could examine the effect of network growth on the infrastructure by putting realistic limits on the number of ports a node has, something which current generators disregard.

4.1.2 Underlying Transport Network based schemes

IP networks must use an underlying transport network for their connectivity requirements. These transport networks can impose limitations and cost functions that must be expressed in the schemes.

- Euclidean Distance

Waxman [6] used the Euclidean distance between node pairs to generate a probability for there to be a link between them. This is an implicit form of transport network connectivity cost. The cost isn't however always a function of simple distance but also of the carrier network. The use of euclidean distance makes the geographic location and distribution of nodes an issue [9].

- Co-location

Geographically IP nodes usually appear at locations where there are transport network nodes such as SDH ADMs or WDM fibre endpoints. This can cause the grouping of IP nodes and affect the connectivity decision. IP node location could therefore be influenced by legacy network configuration.

- Network Structure

Depending on the type of underlying network the probability of a link can change - a series of nodes connected over a switched ethernet segment could have identical connectivity probabilities. Such ethernet segments in LANs may be modelled by schemes which generate star shaped networks with the exterior router as the hub or by full meshes.

- Network Performance

The performance of the network can also influence the location and connectivity of nodes. Certain links in the IP network may require resilience which is only available between certain locations or diverse physical layer paths.

The emulation of the growth processes in such a way is quite a powerful method to model networks – since there are three separate schemes for various aspects of the growth we have a lot of control over the process. The schemes don't have to necessarily be constant throughout either – they can change over time to simulate the effect of legacy networks or can be adaptive to the existing network.

5 Experiments

To demonstrate our method of topology generation we devised two example experiments:

- AS Topology Simulation.

The first experiment attempted to emulate the growth of the AS topology to reach the Int-04-98 instance described by Faloutsos et al [1].

- Campus Backbone

This experiment examined the effect of a few basic connectivity rules on the topology. Rather than aiming toward the power-law topologies of the Internet core this was an attempt to model the result of a growing campus backbone at the edge of the Internet.

5.1 AS Topology Simulation

Faloutsos et al. examined three instances of BGP Autonomous System connectivity. Here we examine the instance referred to as Int-04-98 that contained 3530 nodes and had an average degree of 3.65. To attempt to emulate this preferential connectivity schemes were used for the new node link and the growth link endpoints. Therefore every new node was linked to an existing node (just one) with a probability of $P(k_i) \sim k_i/\Sigma k_j$. Where $P(k_i)$ is the probability of linking to a node with k_i links and Σk_j is the sum of all the degrees of the nodes. The source nodes for the added links were chosen in the same way, as were the destination nodes. The new links cannot connect two already connected nodes and cannot have the same node for both endpoints. For a desired average degree of 3.65 the link growth parameter, G_l, was specified as 2.65 (since one link is automatically added with new nodes).

The outdegree rank can be seen in Figure 1 and the outdegree frequency distribution can be seen in Figure 2.

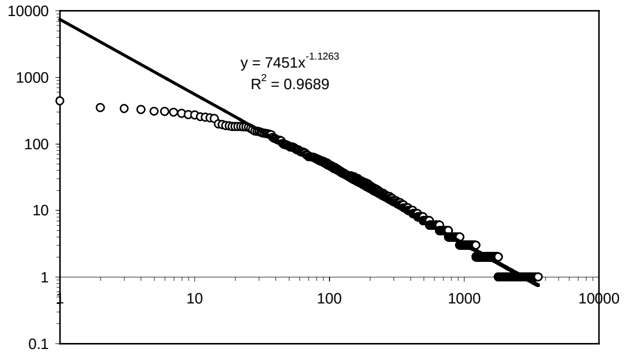

Figure 1 The outdegree vs. the rank (in decreasing order of outdegree) (power-law 1) for the AS Topology Simulation

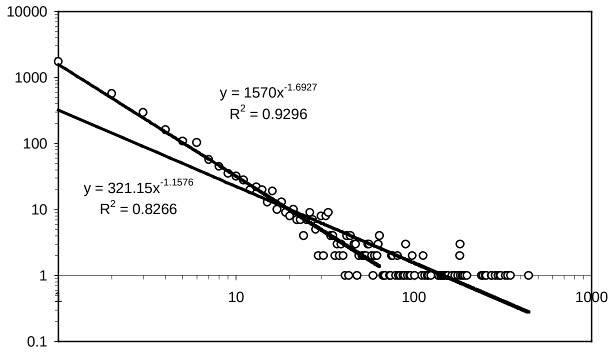

Figure 2 The frequency of an outdegree versus the outdegree (power law 2) for the AS Topology Simulation

The rank plot has a distinct drop at the highest ranks (lowest figure rank, highest connectivity) which is less predominant with smaller network sizes. This implies the highly connected nodes aren't increasing their connectivity as much as in the Barabasi-Albert model. Direct comparison of the exponents to BRITE Barabasi-Albert is inaccurate since the average outdegree (dictated by the link parameter *m*) is limited to integer values.

Table 1 Exponents and correlation co-efficients for BRITE Barabasi-Albert topologies

	M	Exponent	R^2
Outdegree Rank	3	0.5658	0.9851
	4	0.5545	0.9907
Outdegree Frequency distribution	3	1.9811	0.8727
	4	1.9658	0.8585

In both the proposed model and the Barabasi-Albert model there were quite a few extraneous points in the outdegree frequency plot at the high connectivity end of the graph which disfigure the trait and result in only a 0.83 correlation co-efficient where a 0.93 would be possible in our model. The values measured from the Int-04-98 instance were 0.82127 for the rank exponent and 2.16356 for the outdegree frequency exponent.

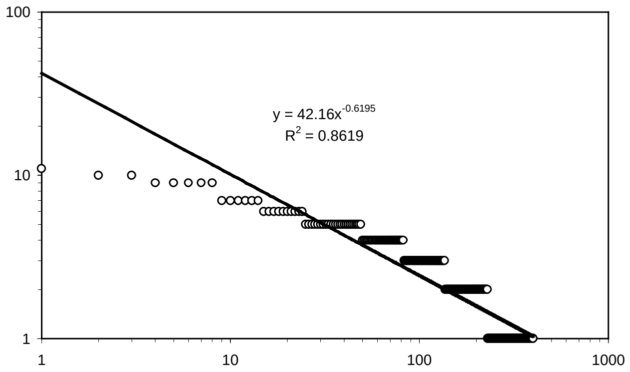

Figure 3 The outdegree vs. the rank (in decreasing order of outdegree) (power-law 1) for the Campus Backbone

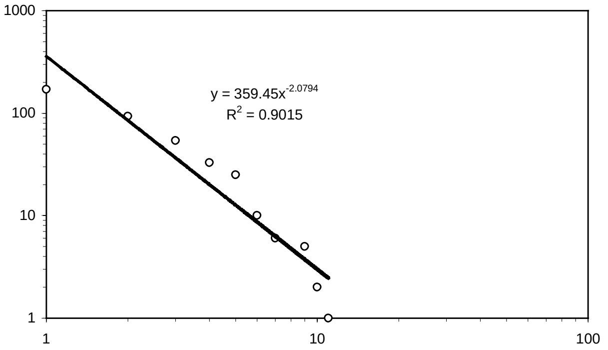

Figure 4 The frequency of an outdegree versus the outdegree (power law 2) for the Campus Backbone

5.2 Campus Backbone

Here we attempt to grow a hypothetical campus network. All new nodes used a link scheme which would link them to the nearest (Euclidean distance) existing node. For every 5 new nodes a link was added. The source was chosen preferring the more connected nodes as in the AS simulation but the destination was chosen using the Waxman equation to favour the nearer nodes (nearer to the source).

An unrealistically high final network size of 400 nodes was chosen to allow the degree traits to settle. While this creates a smoother plot it also influences the shape. The nodes were randomly distributed rather than with a heavy tailed distribution.

Precise power law topologies aren't expected as preferential connectivity isn't used throughout. A correlation co-efficient of 0.8619 for the rank exponent suggests a leaning toward a power law. This was caused by the implicit use of incremental growth (the node adding stage of the algorithm) which by itself can create topologies which approach power laws [19]. The outdegree frequency distribution approaches a power law but has already started to develop a "knee" element.

Comparison to a real topology is difficult in this case but the plots have confirmed a tendency toward power laws from the incremental growth aspect of the generator.

6 Conclusions and Discussion

The use of a growth and reactive stage in topology generation while initially not producing perfect results opens up a large gamut of control and emulation precision which isn't possible in simple growth and preferential attachment generators [19] or other macroscale generators [10][11]. The AS topology simulation presented above is more realistic than a simple Barabasi-Albert model because AS domains often add links between existing domains for resilience and to increase their traffic carrying capabilities.

The ability to control aspects of growth and impose limitations such as those from transport layer systems opens a new area of research into the sources of power-laws. The effect of the transport layer on IP networks is currently unknown. The non-linear heterogeneous nature of the transport layer can dramatically affect the topology of the IP network. Similarly the demands of the IP networks on the transport layer will cause it to re-configure in what is really a feedback system. The transport network feeds back through available bandwidth and therefore link load and therefore affects dynamic IP layer routing metrics.

In reality it is also improbable to connect any two nodes based simply on their connectivity as they will be affected by connection availability, which is dictated by the underlying transport network. This could be factored into the connection schemes.

Faloutsos et al. postulated [1] that the power laws could be the result of co-operative and antagonistic forces and that the network must reconfigure itself to cope with demand. Effectively they proposed a feedback system *within* the IP layer. This reactive topology generator could certainly investigate that but also the feedback into the transport layer. With the heterogeneous nature of the transport layer we may postulate that it forms a self-organising system [17] with the IP network. In systems that achieve self-organising criticality heterogeneity is actually a requirement [18] and with the diverse transport technologies it is certainly present.

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