Modelling the Internet

The Internet has become a critical infrastructure and its modelling has been a major research effort with some controversial findings. The primary focus has been on the logical aspects of the topology, since tools were developed to collect, measure, and analyse IP-layer properties of the Internet (e.g. Rocketfuel). On the other hand, physical level topologies provide the necessary connectivity to higher layers; thus defining physical connectivity is a major research challenge. Therefore, understanding the evolution of the Internet from a multilevel point of view is more realistic than examining its properties at lower levels.

Interdependencies Between Critical Infrastructures

Critical infrastructures such as the Internet and power grid increasingly become dependent on services of each other. Previously, we observed that the link connectivity of the physical topologies appear visually correlated with other critical infrastructures such as motorways and railways. We intend to provide insight into the evolution of the communication networks by generating the topology of the US interstate highway system and analysing its graph properties against the physical fibre topology and PoP (point of presence) level topology of two ISPs (Internet service providers).

Network Analysis Using Graph Spectra

The second major contribution of this study is to analyse the spectrum of the normalised Laplacian matrix for resilience properties. Collective analysis of graph metrics provides a good indication of the resilience of different topologies; however, it is difficult to infer sensible conclusions about the structure of a network or how similar two different networks are. Therefore, we redirect our attention to the spectra of traditional graph metrics. We show that traditional graph metrics are not sufficient for a comparative analysis of graphs with different numbers of nodes and links. Furthermore, we observe that the spectral radius of the normalised Laplacian matrix may be the ideal measurement for comparing connectivity of graphs with different order and size.

Topological Dataset and Visualisation

We study real networks (i.e. transportation and communication) that are geographically located within the continental United States. Furthermore, we have developed the KU-TopView (KU Topology Visualiser) using the Google Map API and JavaScript to visually present these topological maps. Unlike other visualisation tools, KU-TopView makes these data conveniently available in the universal form of an adjacency matrix along with the node coordinates. We have made these topologies publicly available (www.ittc.ku.edu/resilinet).

We have generated the interstate highway topology to represent the transportation network based on the American Association of State Highway and Transportation Officials (AASHTO) data as shown in Figure 1a. We use a US long-haul fiber-optic routes map data to generate physical level topologies as shown in Figure 1b. In this map US fiber-optic routes cross throughout the US and each ISP has a different coloured link to differentiate between other service providers. We project the cities to be physical node locations and connect them based on the map, which is sufficiently accurate for a national-scale map. The Rocketfuel-inferred AT&T and Sprint logical level topology are shown in Figure 1c.

Graph Metrics

Graph order: Number of nodes
Graph size: Number of links
Degree: Number of links incident to a node
Closeness: A measure of distance between a node and all other nodes
Clustering coefficient: A measure of how well a node’s neighbour’s are connected
Algebraic connectivity: Second smallest eigenvalue of the Laplacian matrix
Eccentricity of a node: Maximum distance between a node and all other nodes
Diameter: Largest eccentricity of a graph
Radius: Smallest eccentricity of a graph
Hopcount: Number of shortest paths
Betweenness: Number of shortest paths going through a node or a link

Graph Spectra

A graph can be represented by different matrices: adjacency, incidence, Laplacian, and normalised Laplacian

Given a matrix \( M \), eigenvalues \( \lambda \), and eigenvectors \( \mathbf{x} \)

Eigenvalues and eigenvectors satisfy: \( M \mathbf{x} = \lambda \mathbf{x} \)

Eigenvalues are roots of characteristic polynomial, \( \det(\mathbf{M} - \lambda \mathbf{I}) \) for \( \mathbf{x} \neq 0 \)

The spectrum of \( M \) is its eigenvalues and multiplicities: multiplicity is the number of occurrences of an eigenvalue

Eigenvalues of normalised Laplacian spectra: normalised according to degree of nodes

Range of normalised Laplacian eigenvalues: \( \{ \lambda_0 \leq \lambda_1 \leq \ldots \leq \lambda_n \leq 2 \} \)

Number of \( \lambda_0 \) represent number of connected components

Quasi-symmetric about 1

We calculate the relative cumulative frequency of these eigenvalues

Eigenvalue of 2 indicates bipartite ness of a graph

Eigenvalue 1 multiplicity indicates node duplications: nodes having similar neighbours

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