Optical Switching and Networking 14 (2014) 95–106

Contents lists available at ScienceDirect

Optical Switching and Networking

journal homepage: www.elsevier.com/locate/osn

A comparative analysis of geometric graph models for modelling backbone networks

Egemen K. Çetinkaya [a,d,*,1], Mohammed J.F. Alenazi [a,b], Yufei Cheng [a], Andrew M. Peck [a], James P.G. Sterbenz [a,c]

[a] Information and Telecommunication Technology Center, The University of Kansas, Lawrence, KS 66045, USA
[b] College of Computer and Information Sciences, Department of Computer Engineering, King Saud University, Riyadh, Saudi Arabia
[c] School of Computing and Communications, Lancaster University, Lancaster LA1 4WA, UK
[d] Department of Electrical & Computer Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA

ARTICLE INFO

Article history:
Received 16 January 2014
Accepted 4 May 2014
Available online 2 June 2014

Keywords:
Backbone network
Physical level graphs
Graph metrics
Graph spectra
Network cost model
Gabriel graph
Geometric graph
Geographical threshold graph
Waxman graph
Population weighted graph
Resilience
Connectivity

ABSTRACT

Many researchers have studied Internet topology, and the analysis of complex and multilevel Internet structure is nontrivial. The emphasis of these studies has been on logical level topologies, however physical level topologies are necessary to study resilience realistically, given the geography and multilevel nature of the Internet. In this paper, we investigate the representativeness of the synthetic Gabriel, geometric, population-weighted geographical threshold, and location-constrained Waxman graph models to the actual fibre backbone networks of six providers. We quantitatively analyse the structure of the synthetic geographic topologies whose node locations are given by those of actual physical level graphs using well-known graph metrics, graph spectra, and the visualisation tool we have developed. Our results indicate that the synthetic Gabriel graphs capture the grid-like structure of physical level networks best. Furthermore, given that the cost of physical level topologies is an important aspect from a design perspective, we also compare the cost of synthetically generated geographic graphs and find that the synthetic Gabriel graphs achieve the smallest cost among all the graph models that we consider. Finally, based on our findings we propose a graph generation method to model physical level topologies, and show that it captures both grid and star structures ideally.

1. Introduction and motivation

Internet modelling has been the focus of the research community for decades [1–4]. The Internet can be examined at the physical, IP, router, PoP (point of presence), and AS (autonomous system) level from a topological point of view [5]. At the lowest level we have the physical topology, which consists of components such as fibre and copper cables, ADMs (add drop multiplexers), cross-connects, and layer-2 switches. The logical level consists of devices operating at the IP-layer. The primary focus of previous studies has been on the logical aspects of the Internet, since tools were developed to collect, measure, and analyse IP-level properties of the Internet (e.g. Rocketfuel [6]). However, given that physical networks provide the means of connecting nodes in the higher levels, the study of physical connectivity is an important area of research [7–9]. Moreover, geography is an

* Corresponding author at: Department of Electrical & Computer Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA.

E-mail addresses: ekc@ittc.ku.edu, cetinkayae@mst.edu (E.K. Çetinkaya), malenazi@ittc.ku.edu, mjalenazi@ksu.edu.sa (M.J.F. Alenazi), yfcheng@ittc.ku.edu (Y. Cheng), apeck@ittc.ku.edu (A.M. Peck), jpgs@ittc.ku.edu, jpgs@comp.lancs.ac.uk (J.P.G. Sterbenz).

[1] Work performed primarily at The University of Kansas.

http://dx.doi.org/10.1016/j.osn.2014.05.001
1573-4277/

important aspect to consider during the design and analysis of networks [10,11], in particular modelling area-based challenges on networks, such as power failures and severe weather [12].

Physical level topologies are *necessary* and *important* for studying the structure and evolution of the Internet holistically [13]. Unfortunately, in an effort to maintain intellectual property and competitiveness, many providers are unwilling to disclose their physical topologies. We generate adjacency matrices of physical level graphs of four commercial service providers based on a third party map [14], and then make use of the publicly available Internet2 research network and the synthetic CORONET fibre topology. Using the node locations of the physical topologies, we generate synthetic *geographical* graphs of these topologies utilising the Gabriel, geometric, geographical threshold, and Waxman graph models. We analyse the structural properties of the synthetically generated geographical graphs using the KU-TopView (KU Topology Viewer) [15] visualisation tool, well-known graph metrics, and graph spectra and find that the Gabriel graph model most closely captures the grid-like structure of the physical networks.

Another important aspect of modelling physical graphs is the *cost* of networks, which is particularly important to consider when designing physical level networks. Moreover, from a network design perspective, it is important to design networks that are *resilient* yet *less costly*. Unfortunately, these two objectives fundamentally oppose one another. We compare the synthetically generated geographical graphs based on a cost model and our results indicate that Gabriel graphs are also the best among the ones we consider in terms of minimising cost. Additionally, amongst all of the synthetically generated graphs we find that there are some whose costs are two orders of magnitude greater than their corresponding physical graphs. To the best of our knowledge, there are no other studies that provide structural- and cost-based comparisons of geographic graph models applied to graphs with node locations that are constrained to those of actual physical graphs. Furthermore, we discuss how one might develop a better synthetic graph generator that incorporates the strengths of two of the geographical graph models that we study.

The rest of the paper is organised as follows: the properties of graphs we analyse are presented in Section 2. We describe the synthetic geographical graph models in Section 3. We analyse the structural properties using well-known graph metrics and graph spectra, as well as the cost incurred to design these graphs in Section 4. We discuss how one might develop a better alternative geographical graph model to capture graph structural properties in Section 5. Finally, we summarise our study as well as propose future work in Section 6.

2. Properties of networks

In this section we present characteristics of networks in terms of graph metrics, graph spectra, and network cost. We also provide visual representation of backbone networks.

2.1. Topological dataset

We study physical level communication networks that are geographically located within the continental United States. Therefore, we only include the 48 contiguous US states, the District of Columbia, and exclude Hawaii, Alaska, and other US territories. We use US *long-haul fibre-optic routes* map data to generate physical topologies for AT&T, Level 3, and Sprint [14]. In this map, US fibre-optic routes cross cities throughout the US and each ISP has different coloured links. We project the cities to be physical node locations and connect them based on this map, which is sufficiently accurate on a national scale. We use this data to generate adjacency matrices for each individual ISP. To capture the geographic properties as well as the graph connectivity, cities are included as nodes even if they are merely a location along a link between fibre interconnection. Finally, we also make use of the publicly available TeliaSonera network [16], Internet2 [17], and CORONET [18,19] topologies. CORONET is a synthetic fibre topology designed to be representative of service provider fibre deployments. Moreover, we have developed the KU-TopView (KU Topology Map Viewer) [20] to visually present the topologies we study. The topologies we studied are shown in Fig. 1 and they are publicly available [15] (see Table 1).

2.2. Graph properties

The graph metrics provide insight on a variety of graph properties, including distance, degree of connectivity, and centrality. We calculate a number of well-known graph properties using the Python NetworkX library [21]. Network diameter, radius, and average hop count provide distance measures [7]. Clustering coefficient is a measure of how well a node's neighbours are connected [7]. Eccentricity of a node is the longest shortest path from this node to every other node; the largest value of eccentricity among all nodes is the diameter and the smallest eccentricity is the radius. Closeness centrality is the inverse of the sum of shortest paths from a node to every other node [22]. Betweenness is the number of shortest paths through a node or link and provides a centrality or importantness measure [23]. In Table 1 we list a number of relevant quantities for each of the provider networks. A detailed analysis of graph metrics for the given physical networks was presented in our earlier work [24]. We observe from the node and link counts that AT&T, Level 3, and Sprint are the larger among the networks. Moreover, all of the physical topologies have an average degree between 2 and 3. In our previous work, we noted that the average degree of these physical topologies was much smaller than the average degree of their corresponding logical topologies due to the difficulty involved in connecting nodes in a physical topology, where one must physically lay down fibre between nodes [24–26].

2.3. Spectral properties

In this section we provide the necessary background on network spectra, discuss how to analyse spectral plots, and present spectra of physical level networks. We note that