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Measuring the survivability of networks to geographic correlated failures

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ABSTRACT

Wide area backbone communication networks are subject to a variety of hazards that can result in network component failures. Hazards such as power failures and storms can lead to geographical correlated failures. Recently there has been increasing interest in determining the ability of networks to survive geographic correlated failures and a number of measures to quantify the effects of failures have appeared in the literature. This paper proposes the use of weighted spectrum to evaluate network survivability regarding geographic correlated failures. Further we conduct a comparative analysis by finding the most vulnerable geographic cuts or nodes in the network though solving an optimization problem to determine the cut with the largest impact for a number of measures in the literature as well as weighted spectrum. Numerical results on several sample network topologies show that the worst-case geographic cuts depend on the measure used in an unweighted or a weighted graph. The proposed weighted spectrum measure is shown to be more versatile than other measures in both unweighted and weighted graphs.

1. Introduction

Communication networks are one of the critical national infrastructures upon which society depends [1,2]. Hence it is imperative that communication networks be designed to adequately respond to failures and attacks. This has led to significant interest in the design and analysis of communication networks, which are able to survive failures. In particular, the survivability of WDM optical technology based backbone networks is of concern due to the high volume of traffic carried.

Network survivability originated from a military viewpoint and is defined as the property of a system, subsystem, equipment, process, or procedure that provides a defined degree of assurance that the named entity will continue to function during and after a natural or a man-made disturbance [3–5]. A communication network disturbance or failure is usually defined as a situation where the network is unable to deliver communication services. Thus a failure can be viewed as a disruption of service rather than degradation due to congestion. Typical failure events include cable cuts, hardware malfunctions, software errors, power outages, natural disasters (e.g., flood, fire, and earthquake), accidents, human errors (e.g., incorrect maintenance) and malicious physical/electronic attacks. Traditionally, network survivability analysis has focused on the effects of random failures. However, many real-world causes of failures/attacks happen at specific geographic locations (e.g. power outage, floods, and Electromagnetic Pulse attack [6]), therefore, the effect of such failures/attacks is geographically correlated.

Recently work has emerged from the critical infrastructure protection and network science communities studying

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the effects of correlated failures due to targeted attacks or geographically localized events (e.g., blackout and earthquake). This work typically models the network by a geographic coordinate based topological graph consisting of nodes and links. In the context of optical based wide area networks, the nodes are WDM access nodes or optical cross connects and links represent optical transmission systems consisting of long haul fiber and optical amplifiers. One of the main themes of the current literature is finding the geographic locations of disasters or attacks that will have the largest impact on the survivability of a network. Specifically the focus is on determining which geographic location for a specific failure scenario (e.g., node failure [7,2], geographic location of link cuts [8], and geographic circular shaped failure area [9]) has the greatest impact on the network. Alternatively this can be thought of as determining the weakest or the most vulnerable portion of a network topology for a specific type of geographic based event. Unfortunately, how to measure the *impact* of a failure is an open issue and a variety of measures have appeared in the literature primarily focusing on the graph connectivity. A weakness of many of the currently adopted measures is requiring the network topology graph be unweighted. However, in many cases it is desirable to study weighted graphs where the weights represent network topology characteristics (e.g., link capacity and link availability). Another drawback of existing measures is requiring the network graph to remain connected to or alternately be partitioned after the failures. In general, the lack of consistently used measures makes comparing and contrasting the existing literature difficult.

In this paper, we propose a new survivability measure applicable to both weighted and unweighted graphs. Further the proposed measure can be utilized to study connected and partitioned graphs. The measure is termed as the weighted spectrum (WS) and is based on the eigenvalues of the normalized Laplacian of a graph. Fay et al. illustrate the theory and application of WS to Internet topology analysis in [10]. They use the distribution of Weighted Spectrum to examine the mixing properties of networks, and to derive optimal parameterizations of synthetic Internet topology generators, but do not mention it as a measure to evaluate the network survivability. Here, we propose using the variation of the WS in the presence of a geographic correlated failure as a performance measure (*WS* is formally defined in Section 3) to assess the network survivability. Given a network topology with geographic coordinates of the nodes, we use the algorithm proposed in [8] to obtain a set of potential vulnerable geographic linear cuts. We designate as the worst-case cut, according to a given performance measure *X*, the one which causes the greatest variation in *X*. Note that more than one cut may result in the worst case variation in *X*. A comparative evaluation is conducted by contrasting the worst-case cut found by *WS* with the one(s) found by several other measures used in the literature. Additionally, we also find the worst-case node failure using *WS* and compare the result with other measures. We conduct numerical experiments on a variety of both unweighted and weighted real world optical backbone network topology graphs. The results show that the worst case cut depends on the measure adopted. Further, it is shown that the proposed Weighted Spectrum measure typically identifies a wider range of cuts of concern and can be used to study both weighted and unweighted network topology graphs for failure scenarios ranging from link/node failures where the topology is still connected to large scale disasters where the topology is partitioned.

The rest of the paper is organized as follows. We briefly discuss the related work in Section 2. In Section 3, we present theoretical background on the weighted spectrum and the network survivability evaluation model. In Section 4, the results of our numerical experiments are presented including a comparison of the different measures. We conclude and discuss future research directions in Section 5.

2. Related work

Spectral graph theory has been used to characterize the Internet topology. Fay et al. study the Weighted Spectral Distribution (WSD) to determine the level of underlying structural similarity between different graphs [10]. WSD can be used for topology tuning because of its low computational costs. It also can help investigate the evolution of the Internet graph and design future topology generators. However, [10] focuses on the graph comparison and does not mention anything about finding the vulnerable or the critical part of the network.

Fiedler in [11] defined the algebraic connectivity of a graph as the second smallest eigenvalue of the Laplacian matrix determined from the topology graph. The larger the AC, the more difficult it is to cut a graph into disconnected components [11]. Jamakovic and Uhlig propose to use the AC to provide a measure of properties such as robustness of a network to failures in [12]. Liu et al. [13] studied the use of AC in evaluating survivable network designs. The network topologies considered were unweighted and not geographically coordinate based.

Tizghadam and Garcia [14,15] propose the measure termed as network criticality (NC) to analyze the robustness of a network to unexpected changes. The network criticality is determined from the trace of the inverse of the Laplacian matrix and can be related to the node and link betweenness. The smaller the NC, the less sensitive the network is to changes in its topology and traffic [14]. Bigdeli et al. [16] compare the properties of NC with different measures (e.g., AC) and propose guidelines for designing and simplifying complex networks based on the desired network properties. Note that this work along with [14] did not study geographic coordinate based networks.

Neumayer et al. study the impact of geographical disasters on network robustness and survivability in [8,17]. They focus on the problem of geographical network inhibition (i.e., finding the most vulnerable cut of geographic line segment or circle) in optical layer backbone networks. The measures studied include node degree (ND), total expected capacity (TEC) and the average two terminal reliability (ATTR). ND [18] is defined as the number of direct neighbors of a node. The TEC is a form of node strength (NS) [19] which is the sum of weights of a node's connections in a weighted network. The average two terminal reliability is the fraction of node pairs that are connected by a path to each other.

Trajanovski et al. [9] extend the approach of [17] to identify the critical regions of a network topology. A critical