SERVICE RESTORABILITY IN DEGREE-BASED WAVELENGTH DIVISION MULTIPLEXING NETWORKS

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ABSTRACT

Service restorability is a network-wide parameter for a specific failure scenario that is dependent on the physical topology of the network. Previously network topology generator models for generating random models were based on structural models. However, the Internet and most real world networks follow degree-based models. Service restorability in degree-based wavelength division multiplexing (WDM) networks is analyzed for single-link and dual-link failures for two degree-based models. The main finding is that degree-based WDM networks have very high restorability even under dual-link failures.

KEY WORDS

Degree-based models, wavelength division multiplexing.

1. Introduction

The Internet is a complex, distributed system with complex interactions and interdependencies within and among the disparate networks [1]. These interactions result in emergent behavior of the overall system that many times has adverse effects on the system. Better design strategies for the Internet are critical to achieve long-term national goals that depend on reliable, high confidence, distributed systems.

Service restorability is a network-wide parameter that corresponds to a specific failure scenario [2]. One definition of restorability is the average fraction of the failed working capacity that is restored for a specific failure scenario [3]. In this paper, the relationship between realistic network topologies and restorability is investigated.

Restorability depends on the physical topology of the network. Previously, structural models were used to generate real network topologies for simulation purposes [4], [5]. Then [6] demonstrated that real network topologies followed a power-law distribution. Network topology generators that follow a power-law distribution are called degree-based in [4].

In this work, the service restorability of degree-based models is analyzed because real networks tend to follow these models. There are many models, [7], [14], [17] and [18], which generate topologies that follow power-law distributions. In this work, topologies were generated using the models given in [7] and [17]. Both the models generate topologies using different properties. In [7], it is suggested that two features, incremental growth and preferential connectivity, are responsible for power-law scaling in real networks. The software *BRITE* topology generator generates topologies based on these two features [8]. In [17], the out-degree of nodes is used to guide the generation of topologies. Network manipulator (*nem*) generates topologies using the model in [17]. *BRITE* and *nem* are used to generate degree-based topologies in this work.

Given that network topologies have degree-based distributions, the problem is to identify the topologies that have a high restorability parameter. If the types of network topologies that have a higher restorability parameter can be identified, then the networks with higher availability can be constructed. Therefore, better design strategies for the Internet can be constructed.

Parallel recombinative simulated annealing (PRSA) is applied to degree-based WDM networks. PRSA is used to find low-cost wavelength assignments for the given traffic. The restorability metric measures the average amount of traffic that is restored for a specific failure scenario. The rest of the paper is organized as follows. In section 2, background is provided. In section 3, the experiments are discussed. Results are presented in section 4. Degree-based WDM networks have high restorability even under the dual-link failures.

2. Background

In this section, WDM networks, degree-based models, parallel recombinative simulated annealing algorithm, and service restorability are discussed.

2.1. Wavelength Division Multiplexing Networks

Wavelength division multiplexing (WDM) is a technology which multiplexes several optical carrier signals on a single optical fiber by using different wavelengths of laser light to carry different signals. A virtual channel can be established between any two nodes because of the multiple wavelengths [9]. The set of these virtual channels is called virtual topology. Because of multiple channels on each link, virtual topologies can be mapped onto a physical topology. At each node there are cross-connects that may or may not convert the wavelength of the incoming signal on its way to the output port. Based on this, there are essentially two types of cross-connects. Wavelength selective cross-connects (WSXC) do not convert the wavelength of the input signal while transmitting it to the output port. Wavelength interchange cross-connects (WIXC) may convert the wavelength of the input signal on its way to the output port. If WSXCs are used then there is a chance that a wavelength may not be assigned on a link between the source and the destination even if there are available wavelengths. If the traffic requirements are static then this problem is referred to as static lightwave establishment (SLE) network operation problem.

2.2 Degree-Based Vs. Structural Generators

The research community uses topology generators to generate realistic topologies for various simulations. There are many topology generators available in the literature. Waxman's topology generator was one of the first generators [10]. It generates a random graph based on the Erdos-Renyi model [11]. There are other topology generators that implement the hierarchical structure [12], [13]. These generators are called structural generators in [4].

These structural generators were used to generate realistic topologies for simulations until Faloutsos *et al.* published [6]. In [6], the authors demonstrated that the degree distribution of real network topologies followed power-law distributions. There are many topology generators that produce topologies with this power-law degree distribution [7], [14], [17], [18]. These topology generators are called degree-based generators in [4]. In [4], the authors showed that the topologies generated by degree-based generators exhibit a loose form of hierarchy similar to that of the Internet. This hierarchical structure is a result of long-tailed distribution of degrees.

In this work, topologies are generated using two different models described in [7] and [17]. Two different models are used for simulations because it is believed that simulations have to be done using topologies generated with different topology generators. The first model is Barabasi model, which is given in [7]. The scale-free power-law degree distribution in realistic network topologies is a consequence of two generic mechanisms, preferential connectivity and incremental growth [7]. Preferential connectivity is the tendency of new nodes connecting to nodes that are well connected. Incremental growth refers to continuous addition of nodes. In [15], the authors show that the aforementioned mechanisms are the key contributors for the success of a topology to resemble that of the Internet. *BRITE* topology generator [8] generates a degree-based topology based on the model proposed in [7]. The model described in [7], begins with a few isolated nodes either placed with a uniform or a long-tailed distribution. This is the backbone of the network. Next, at each time step it adds one node (this is incremental growth). All the new nodes that are added have fixed number of links, which are connected using preferential connectivity.

The *BRITE* topology generator was used to generate degree-based topologies as modeled in [7] in this work. The initial nodes were placed using a uniform distribution and the option to use incremental growth and preferential connectivity was selected. *BRITE* places the nodes on a plane with a selected size. The plane is sub-divided into inner planes whose size is selected. *BRITE* uses this information when placing nodes. Another parameter m refers to the number of links that each newly added node should have. The topology file generated with *BRITE* contains information about the position of each node in the plane and the edge distance, which is the distance between the source and the destination. In addition, *BRITE* can assign bandwidths to the links.

The second model used to generate topologies is called power law out degree (PLOD). This model is one of the models described in [17]. The out-degree of a node is used to generate topologies. Each node is assigned an out-degree value using the expression given below.

$$\beta x_i^{-\alpha}$$

The parameters α and β are chosen, but x_i is a random number that is generated between one and the number of nodes for each node i. Then edges are generated between nodes in the following way. Two nodes are picked randomly and connected if there is no edge between them and if their out-degree values are greater than zero. If there is already an edge between the chosen nodes or if the out-degree value on either node is zero, then the model will pick two other nodes randomly and the process is repeated. This is done until it can find two nodes where an edge can be placed between them. Whenever an edge is placed between two nodes, the out-degree on both the nodes is decremented by one.

The parameters α and β should be carefully adjusted to get the desired number of edges in the graph. Network manipulator (*nem*) software is used to generate topologies using the PLOD model. *Nem* can generate topologies in several output formats. Topologies are generated in the alternative format (format generated by gt-itm) and it is parsed for node and edge information. First β has to be chosen. Once β is fixed, α is varied until the desired number of edges is generated. In this work, α and β are chosen so that the topologies generated with the PLOD model and Barabasi model have an equal number of edges.

2.3 Parallel Recombinative Simulated Annealing

Parallel recombinative simulated annealing (PRSA) combines genetic algorithm (GA) and simulated annealing (SA) into a parallel algorithm [16]. The network operation problem for a WDM network consists of finding a routing and wavelength assignment for the given topology and traffic. If the traffic requirements are static, i.e., the wavelengths are fixed, and if the network only uses WSXCs then this problem is called SLE WSXC network operation problem [9]. In [9], PRSA is used to find low-cost wavelength assignments for SLE WSXC network operation problem.

PRSA takes as input the topology information file and traffic information file. The traffic file is generated randomly using a uniform distribution. Details of the topology file, traffic file, and traffic parcels are given in section 3. A traffic parcel is the number of wavelengths requested between each source and destination. PRSA outputs a file with wavelength assignments and the percentage of the requested wavelengths assigned. PRSA chooses the set of routes for each traffic parcel to minimize the total wavelength cost [9]. The cost is based on the distance between the source and destination. For more details on PRSA refer to [9]. The quality of solution depends on initial temperature, population size, and cooling coefficient. A higher cooling coefficient produces a better result, but it also requires more computations to converge. So there should be a tradeoff when choosing the cooling coefficient. Both a serial and parallel version of PRSA exist [16]. The serial version of PRSA for wavelength assignments is used in this work.

2.4 Service Restorability

Quality of service can be measured in many different ways such as signal quality, service reliability, service availability, and service restorability [2]. Service restorability is a network wide parameter that corresponds to a specific failure scenario in [2]. A definition of service restorability is the average fraction of failed working capacity that is restored for a specific failure scenario [3]. Service restorability in WDM mesh networks is studied in [3]. In this paper, restorability in degree-based WDM networks is analyzed. The restorability metric is derived to find restorability in degree-based WDM networks. PRSA is applied to WDM networks to assign wavelengths for the given traffic. PRSA gives the percentage of the requested wavelengths assigned for the given traffic. Service restorability is defined as the percentage of the requested wavelengths assigned by PRSA averaged over a specific failure scenario. A failure scenario can be a single-link failure or a dual-link failure in the network. A link here means a single optical cable. For example, let R_i be the percentage of requested wavelengths assigned by PRSA after the failure of link i. The average of R_i*'s* for all i*'s* is the service restorability for the single-link failure scenario. This restorability metric identifies networks with high restorability.

The traffic has to be scaled so that all the requested wavelengths are assigned when there are no link failures. This is required to begin with networks that are in fully working state without any link failures and that have high service restorability parameter.

3. Experiments

Several experiments were performed with single-link failures and dual-link failures for degree-based networks with different sizes. Networks with 10, 15, 20, 25, and 50 nodes were generated using the *BRITE* and *nem* tools for the Barabasi and PLOD models, respectively. Simulations were done on eight nodes of the local cluster computer. Networks with more than 50 nodes were not considered for simulations because of the resource and time constraints, and the very high number of simulations. This will be discussed in section 4 with results. In addition, a Waxman's random graph with 25 nodes was generated to compare the service restorability with the two degree-based models. Only single-link failures were simulated for the Waxman's model.

An example of a 10-node Barabasi degree-based network is shown in Fig. 1. Some nodes have just two links. This is because of the parameter m given to the *BRITE*. All the degree-based graphs were generated with $m = 2$. Random node placement strategy was used on a plane of size 100x100 with inner planes being of size 10x10. Preferential connectivity and incremental growth characteristics were used to generate these graphs.

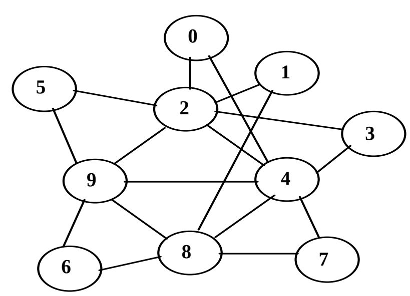

Fig. 1. Barabasi graph

The PLOD model was used to generate topologies with 10, 15, 20, 25, and 50 nodes. The parameters that are varied with this model are α and β. The parameters α and β are adjusted so that the topologies generated with this model have same number of links as that of the topologies generated with the Barabasi model.

The method for determining service restorability is shown in Fig. 2. The topology generated by *BRITE* is in the *BRITE* format whereas the topology generated with *nem* is in gt-itm's alternative format. However, PRSA takes the topology in a specific format where each line is in (source-node, destination-node, distance) format. Distance is the Euclidean distance between the two nodes (both *BRITE* and *nem* give this in the output file). The traffic file is generated randomly in a format required by

PRSA. The traffic file contains information about parcels. Each parcel is in the following format: (source-node, destination-node, number-of-wavelengths), where number-of-wavelengths is the number of wavelengths requested between the source and the destination.

The traffic has to be scaled so that 100% of the wavelengths are assigned when there are no failures. This is accomplished by modifying the scaling factor in the PRSA algorithm. Traffic for both the models is scaled separately. With this scaled traffic, single-link and dual-link failures are simulated. During single-link failure simulations, a link is deleted from the graph and PRSA algorithm is applied with the scaled traffic and the modified topology. For each single-link failure scenario, PRSA is applied to find a low-cost wavelength assignment and the percentage of failed working capacity that is restored is recorded. An average of the failed working capacity restored over all single-link failure scenarios is calculated. This number represents single-link failure service restorability of that network.

For each topology generated

1. Convert the topology file in *BRITE*/*nem* format to the format used by PRSA.
2. Generate random traffic for this topology.
3. Keep scaling the traffic until 100% of wavelengths are assigned by PRSA.
4. Once the traffic is scaled, delete one link at a time for single link failures (delete two links at a time for dual link failures) and run the PRSA algorithm.
5. Find the average fraction of the failed working capacity that is restored over all single link failure scenarios (dual link failure scenarios). This is the restorability parameter for single-link failures (dual-link failures).

End

Fig. 2. Method

For dual-link failure simulations all combinations of two links, one combination at a time, are deleted. After deleting each combination PRSA is applied again with the scaled traffic and the modified graph. An average of failed working capacity restored over all dual-link failure scenarios is calculated and this number represents dual-link failure service restorability.

The quality of solution given by PRSA depends on cooling coefficient, population size, number of generations required and initial temperature. Population size of 20 was used. A cooling coefficient of 0.9 was used to reduce the number of generations required. If 0.99 was used as the cooling coefficient for PRSA, then it would take 1500 generations to get the solution compared to 100 generations when 0.9 was used. This was required to reduce the time required to get the solution because of a large number of simulations involved in the experimentation. The way to calculate initial temperature and the number of generations for a given cooling coefficient is discussed in [9].

4. Results and Discussion

Results for single-link failures are given in Table 1 for graphs generated with both Barabasi and PLOD models. The numbers in the average column in Table 1 correspond to the average amount of traffic restored over all single-link failures for that model and size of the network. The standard deviation column is the standard deviation over all single-link failures again for the corresponding model and size.

Simulations are not done on graphs with more than 50 nodes. Table 4 gives, for each graph, the time required for one single execution of PRSA, the number of combinations of single link failures, and the number of combinations of dual-link failures. The time required for one single execution of PRSA for a 50-node network is 2 hours. To find restorability for single-link failures in a 50-node network requires 97 simulations. This is the reason for not considering networks bigger than 50 nodes.

The results in Table 1 suggest that the graphs generated with degree-based models have high service restorability under single-link failures. The values for the Barabasi and PLOD models in the average column are close. This suggests that, regardless of the type of model used, degree-based graphs have high restorability under single-link failures. The standard deviations are not very high. This means that there are not many single-link failure instances for which restorability is very deviant from the average.

Table 2 gives the service restorability values for dual-link failures in degree-based networks. The average and standard deviation are calculated over all dual-link failures of a network as discussed earlier. These numbers are only little lower than the corresponding values for single-link failures. This means that degree-based graphs have high restorability even under dual-link failures with respect to the service restorability metric used in this work. Again the models used to generate degree-based graphs are not significantly different.

Dual-link failures are not simulated for networks larger than 25 nodes. The number of dual-link failure combinations in a 50-node network is 4656 as given in Table 4. For each combination, the time required to run the PRSA is about 2 hours. The total time required for dual-link failure is over 9000 hours.

Table 1. Single-link failures for the Barabasi and PLOD models

Number of Nodes	*Number of Links*	*Average*		*Standard Deviation*	
		Barabasi	***PLOD***	***Barabasi***	***PLOD***
10	17	98.78	98.01	1.32	4.83
15	27	98.83	98.74	2.11	1.96
20	37	99.82	99.32	0.49	1.46
25	47	98.63	97.45	1.66	2.25
50	97	99.50	99.93	0.80	0.48

Table 2. Dual-link failures for the Barabasi and PLOD models

Number of Nodes	*Number of Links*	*Average*		*Standard Deviation*	
		Barabasi	***PLOD***	***Barabasi***	***PLOD***
10	17	97.32	97.05	4.58	6.53
15	27	96.38	98.16	3.34	2.88
20	37	98.91	98.32	1.88	2.11
25	47	97.72	95.83	2.39	2.88

All these simulations were done on the local cluster computer that has eight nodes. Even using this cluster it would still require very high computational power and time. For this reason, dual-link failures are not simulated for networks bigger than 25-nodes.

Finally, a comparison is made between the Waxman's model and the two degree-based models. All the three models have very similar restorability values under the restorability parameter given in this paper. The results of these experiments are given in Table 3. Only a 25-node graph is used to compare these three models for single-link failures. The results in Table 3 show that all the three models are highly restorable with respect to single-link failures.

Table 3. Waxman's model vs. degree-based models

Model	*Average*	*Standard Deviation*
Waxman's	98.42	2.15
Barabasi	98.63	1.66
PLOD	97.45	2.25

Table 4. Execution times and number of combinations

Number of nodes	**Time taken for each execution by PRSA**	**Number of executions (combinations)**	
		Single-link	**Dual-link**
10	40secs	17	136
15	2mins	27	351
20	6mins	37	666
25	12mins	47	1081
50	2hrs	97	4656

5. Conclusions and Future Work

In this paper, service restorability in degree-based models was analyzed. The restorability metric was used to determine service restorability. Two different models were used to generate topologies of varying sizes. Single-link failure and dual-link failure scenarios were simulated on these graphs and a comparison was made. In addition, a 25-node Waxman's graph was used to compare service restorability with 25-node degree-based models under single-link failures. The results presented indicate that degree-based networks have high service restorability even under the dual-link failures.

Networks greater than 50 nodes are not used because of the required number of evaluations. Larger networks and multiple link failures need to be investigated. However, even single-link failures are not easy to simulate for networks bigger than 50 nodes. In addition, it is not feasible to evaluate all combinations of multiple link failures because of the algorithm that assigns wavelengths.

Using statistical sampling, the number of simulations could be reduced so that all the simulations can be done with the available time and computational power. This would permit generating several networks of a given node size for a better comparison. In addition, degree-based network topologies are more sensitive to node failures than link failures because of the large node degrees of a few well-connected nodes. A study of node failures is planned.

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