Impact Evaluation of Physical Length of Shared Risk Link Groups on Optical Network Availability Using Monte Carlo Simulation

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***Abstract*—In optical networks a group of logically distinct links can unintentionally share a physical resource (e.g. a cable or a duct). Such a group, called shared risk link group (SRLG), introduces a situation where a single failure of common resource can cause multiple failures. Failure of common resource usually occurs due to physical force (e.g. digging or earthquake) and causes failures of multiple links. Specifically, such a failure can cause both working and spare wavelength path of a logical connection between two edge nodes to fail at the same time, leaving them disconnected until a repair is done. The usual approach to solving this problem consists of introducing more spare capacity to the network and also using a routing algorithm that takes SRLGs into account when computing paths. Such a routing algorithm avoids creating working and spare path pairs that have links contained in the same SRLG, to minimize the negative impact of SRLG failure on logical connection availability. In this paper the impact of physical length of the SRLGs on network availability is evaluated using Monte Carlo simulation. New simulation model for availability evaluation is implemented by discrete-event network simulator ns-3. Implementation approach is discussed, and an overview of model features is provided. For simple cases, Monte Carlo simulation results obtained by using the model are compared to analytical results. The availability results for the general case are obtained using Monte Carlo simulation and discussed.**

***Index Terms*—optical networks, failure modeling, Monte Carlo simulation, network simulation, network simulator, ns-3, availability, shared risk link groups**

I. INTRODUCTION

The rapid growth of the Internet traffic, supported by rapid increase of capacity of optical transport networks makes network resilience a requirement that has to be taken care of in the process of designing the network. The failure of a network element (e.g. a fiber in a cable or a cross-connect at a node) can cause a failure of many lightpaths, leading to data and revenue losses.

In case of a failure of a component of a path used by logical connection in the network, an alternative path (called spare path) has to be used until the component of working path is repaired. Schemes dealing with such challenges can be classified by time of operation, on protection and restoration, by routing type, on link-based and path-based schemes, and by criteria of spare resource sharing, on dedicated and shared. In comparison with protection based schemes, restoration based schemes generally need longer recovery time, but give better performance in case of multiple time-overlapping failures of network components [1]. Path-based schemes offer better performance compared to link-based at higher runtime cost.

Two path-based protection schemes are used: shared path protection (SPP) and dedicated path protection (DPP). Both approaches provide a link-disjoint spare path for each working path in the network. DPP scheme is simpler than shared protection and offer better performance in case of multiple failures, but also require more spare bandwidth than SPP scheme. Better performance of DPP scheme is a result of dedicated spare path resources for each working path, which is not the case with SPP scheme.

Shared risk link group (SRLG) [2] is a group of links in a network that share a physical location. This can be a cable, a duct or an exit at a node. (Example of the last case is shown in Figure 1.) All links contained in the SRLG have a probability of being damaged in case of physical damage to one link in the part contained in the SRLG. Such physical damage introduces a situation where a multiple logical failures in the network occur due to a single physical failure, and is therefore in general more damaging than two uncorrelated time-overlapping single failures.

AT&T's experience indicates that a link may belong to over 100 SRLGs, each corresponding to a separate fiber group. In addition, in a large network it is very hard to maintain accurate SRLG information [3]. Common approach is to avoid SRLGs in the path routing stage, namely by making working and spare paths SRLG-disjoint. If the network has enough capacity, this leads to complete restorability in case of failure [4]. However, such a restorability increases costs and also is not always a necessity, as there is a possibility of dropping best-effort traffic in case of failure. Furthermore, common approaches rarely take SRLG weights (lengths and capacities) into account when doing route computation.

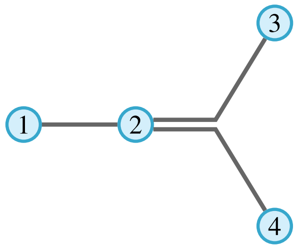

Figure 1. SRLG example with two cables sharing a common exit at a node.

In this paper we evaluate the effect of physical lengths of SRLGs on network availability. Since the failure dependency induced by SRLGs makes analytical computation of availability hard except in trivial cases, we use Monte Carlo simulation utilizing a new model implemented by network simulator ns-3 [5] to obtain results.

We expect that physically longer SRLGs will have higher failure probability, and more negatively impact logical connection and network availability. Since SRLG elimination is in general costly, it is useful to know the impact of partial elimination (shortening the physical length of SRLG). While the exact results are hard to obtain analytically due to the model complexity, it is possible to model an optical network containing SRLGs and use Monte Carlo simulation to get approximate results.

The paper is organized as follows: in Section II we cover related work, in Section III we present our model, in Section IV we compare the results obtained by simulation to results using analytical methods, in specific cases, and then present results obtained by simulation for general case. Finally, in Section V we conclude and suggest some directions and plans for future work.

II. RELATED WORK

While the protection and restoration of wavelength paths in case of dependent component failures in optical networks has been studied by researchers for a long time, very few works are concerned with estimating the probability range and effects of such failures. One of the earliest papers explaining why dependent failures should be considered is [6], arguing with the assumption that all failures are independent. Lam and Li [7] study the dependence between link failures in communication network and propose an event-based reliability model. In the proposed model dependent failures are the effect of independent events. Single failures of components occur with certain probabilities and cause failures of other components sharing the common equipment.

SRLG introduces dependence between link failures [8], [4], [2], since it is a set of links that share a common physical resource, such as conduit, cable or duct. Usual assumption is that correlation between failures is deterministic, implying that failure of one link in a SRLG always causes failure of all other links contained in it. In reality, this is not necessarily the case, so probabilistic models in which the links contained in the SRLG are damaged with a certain probability in case of failure have been studied in [9], [10]. Lapčević et.al. [9] studied the impact of dependency between failures (including SRLGs) on network availability, and concluded that it is significant.

Various approaches to path provisioning, and more specifically routing and wavelength assignment (RWA) in optical networks containing SRLGs have been studied [11], [12], [13], [14] with the common goal of avoiding the failure of working and spare path at the same time. RWA problem can be expressed as an integer linear program. Since it is in general NP-hard, heuristics are often used [15], [16]. Lee and Mondiano [10] developed more general probabilistic SRLG framework for studying correlated failures, and formulated a problem of finding paths with minimum failure correlation as a non-integer linear program. An approach utilizing colored graphs (graphs containing colored vetrices or edges) for modeling shared risk resource groups, an unifying concept for both SRLGs and shared risk node groups has been proposed in [17], [18], [19]. Multicast routing utilizing path protection in presence of SRLGs has also been studied [20].

Somewhat related to our work are the papers studying geographically correlated failures [21], [22], which do not address SRLGs specifically, but focus on a broader set of link failures due to accidents and attacks affecting regions. A comprehensive network reliability framework is proposed in [23] and its implementation in network simulator is described in [24]. The framework includes SRLGs as a special case, but does not consider their effects specifically.

III. OPTICAL NETWORK AVAILABILITY ANALYSIS

In our previous work [25], we analyzed existing simulation models for optical transport network and found that none of the existing implementations fit the requirements, so we developed our own model basing on the infrastructure provided by network simulator ns-3 [5]. Taking into account the feature functionality of ns-3 network simulator at the time, we had to identify the specific areas where it was to be extended to support simulating optical WDM network. We considered the differences between the networks that have existing models in ns-3, which operate almost entirely in the electronic domain, and the optical WDM networks, which operate in both the optical and electronic domain. We opted for model based on components since it is easier to develop, test, verify and validate, and also because the implementation of feature functionality can happen iteratively, first implementing a feature and then testing the implementation. In addition, code reusability inherent in object-oriented design reduces the time needed to develop a similar model.

Components of ns-3 are modules, which consist of one or more classes which together make one or more models of real world communication devices, communication channels, network protocols etc. Abstract base classes used implemented by every model of a physical network in ns-3 are `NetDevice` and `Channel`. `NetDevice` describes a network interface card at a network node; `Channel` interconnects two or more network cards and contains delays, losses etc. Models of complex networks (e.g. WiFi, WiMAX, LTE) frequently separate PHY layer of the network card from its MAC layer to allow combining various MAC devices and PHY devices and facilitate code reuse.

Our optical network model implementation consists of models for common optical transport network components: edge network devices (class `WdmEdgeNetDevice`), core network devices (classes `WdmOxcNetDevice`, `WdmMuxNetDevice` and `WdmDemuxNetDevice`), physical interfaces (classes `WdmInputPhy` and `WdmOutputPhy`) and channels (class `WdmUnidirectionalChannel`). Detailed description of these classes can be found in [25].

We opted for centralized control paradigm instead of distributed, due to the centralized nature of a network simulation. The model uses DPP scheme, and uses Dijkstra shortest path algorithm to find both working path and spare path when creating logical connections.

A. *Model description*

In addition to models for optical network components, our implementation also supports analysis of availability. For the present requirements of our research, we implemented models for additional physical objects and software entities.

`WdmNetworkCable` is a class modeling a physical cable containing one or more fibers. It has a physical length, measured in meters or kilometers, and it contains information about positions of zero or more unrepaired cable cuts. We assume that cable cut affects all the fibers in the cable.

`SharedRiskLinkGroup` is a class modeling a group containing parts of two or more cables that share a physical location. If the part of the cable that gets hit by a failure is contained in the SRLG, other cables in the same group will also fail at a certain probability. Our model allow configuration of this probability, ranging from 0 to 1. In case it is 0, the cables failures will occur independently, while in case it is 1, each failure affecting SRLG will cause failures of all cables contained in it.

`WdmWavelengthPath` is a class modeling a wavelength path passing through one or more network devices, physical interfaces and fibers. In case any of these becomes faulty, `WdmWavelengthPath` instance is notified about it and it changes its state from working to failed. Upon repair of a previously failed network device, physical interface or fiber, it is also notified and changes its state back to working.

`WdmLogicalConnection` is a class modeling a logical connection that has working and spare wavelength path. In case of failure of working path, spare path is activated, and connection remains in working state. In case of failure of both paths, connection changes its state to failed. Upon repair of at least one path, logical connection switches to it and changes its state back to working.

`WdmLogicalConnectionManager` is a class that manages logical connections present in the network, establishing and tearing down connections on demand.

`WdmConnectionAvailabilityTracker` is a class that tracks uptime and downtime of logical connections in the network. It is used for getting simulation results.

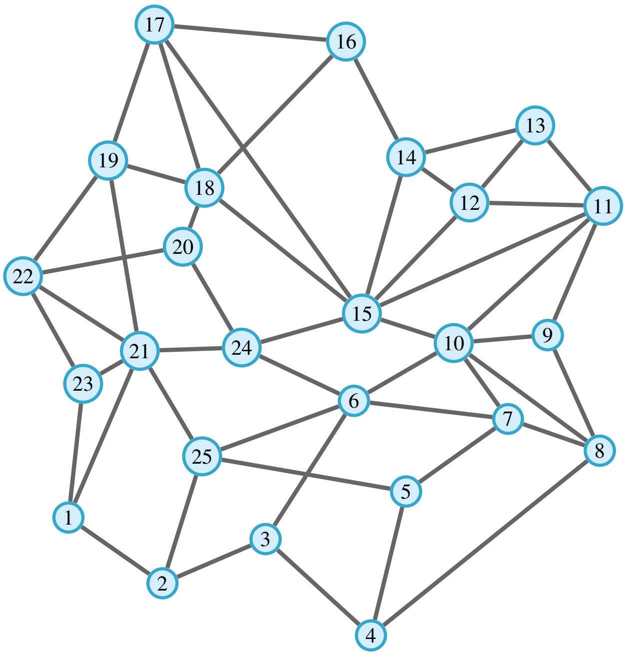

Figure 2. Test network topology containing 25 nodes and 50 spans [12].

IV. ANALYTICAL COMPUTATION OF NETWORK AVAILABILITY AND COMPARISON TO SIMULATION RESULTS

Network availability A is a probability that a repairable system will be in operating state at a random moment in time. Network operators frequently aim for "five nines" (99.999%) availability, which translates to less than 5.26 minutes of network outage per year.

For the evaluation we use the network with 25 nodes and 50 links that can be seen in Figure 2. The link length is taken to be Euclidean distance between nodes, resulting in mean distance of 129.40 km with standard deviation of 47.63 km. The total length of cables in the network is 6470.38 km.

A. *Comparison of simulation and analytical results*

Logical connection is considered to be in working state if at least one of working or spare path is in working state, and in failed state otherwise. Path is considered to be in working state if all the links it contains are in working state, or equivalently, none of the links contained in the path are in failed state.

Cables are considered to have failure rate of 114 FIT per kilometer, which translate to mean time to failure (MTTF) of approximately 1000 years per kilometer, which equals 8 760 000 hours [26]. We take mean time to repair (MTTR) to be 6 hours. Finally, we take the nodes to be ideal (have availability equal 1).

We did not specifically consider optical amplifier failures. However, one could simply include optical amplifiers in computation by considering the cable lengths to be larger. Namely, as optical amplifier is considered to have 2850 FIT [27], it has the same failure rate as 25 km of cable. As we assume one amplifier per 100 km of cable, a cable 150 km long has one

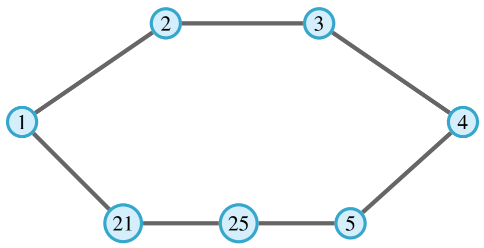

Figure 3. Part of the test network used by working and spare paths between nodes 1 and 4 (case without SRLGs).

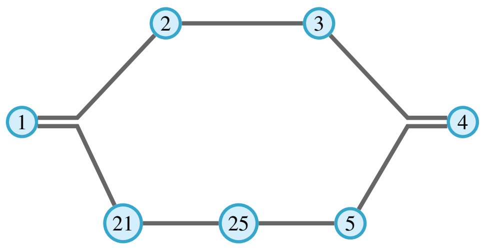

Figure 4. Part of the test network used by working and spare paths between nodes 1 and 4 (case with SRLGs).

optical amplifier and will have the same failure rate as the cable that has 175 km.

To compare analytical availability results to results obtained by using Monte Carlo simulation, we evaluate the availability of the following two logical connections:

- logical connection between nodes 1 and 4, having working path going over nodes 2 and 3, and spare path going over nodes 21, 25, and 5 (shown in Figure 3);
- logical connection between nodes 8 and 18, having working path going over nodes 10 and 15, and spare path going over nodes 7, 6, 24 and 20.

We denote availability of logical connection between nodes i and j by A^{conn}_{i-j}, availability of working (spare) path between nodes i and j by A^{work}_{i-j} (A^{spar}_{i-j}), and availability of physical link between nodes i and j by A_{i-j}.

Using the analytical approach we obtain availabilities for logical connections as follows.

$$\begin{aligned}
A^{conn}_{1-4} &= A^{work}_{1-4} + A^{spar}_{1-4} - A^{work}_{1-4} \cdot A^{spar}_{1-4} = \\
&= A_{1-2} \cdot A_{2-3} \cdot A_{3-4} + A_{1-21} \cdot A_{21-25} \cdot A_{25-5} \cdot A_{5-4} - \\
&- A_{1-2} \cdot A_{2-3} \cdot A_{3-4} \cdot A_{1-21} \cdot A_{21-25} \cdot A_{25-5} \cdot A_{5-4} \\
&= 0.999999911055623
\end{aligned}$$

$$\begin{aligned}
A^{conn}_{8-18} &= A^{work}_{8-18} + A^{spar}_{8-18} - A^{work}_{8-18} \cdot A^{spar}_{8-18} = \\
&= A_{8-10} \cdot A_{10-15} \cdot A_{15-18} + A_{8-7} \cdot A_{7-6} \cdot A_{6-24} \cdot \\
&\cdot A_{24-20} \cdot A_{20-18} - A_{8-10} \cdot A_{10-15} \cdot A_{15-18} \cdot A_{8-7} \cdot \\
&\cdot A_{7-6} \cdot A_{6-24} \cdot A_{24-20} \cdot A_{20-18} = \\
&= 0.999999902632511
\end{aligned}$$

We now consider the case in which working and spare paths contain coincident SRLGs. Due to complexity of analytical computation for arbitrary failure dependency between cables contained in SRLG, we study the specific case with failure dependency equal to 1. For analytical approach, such failure dependency implies that one computes availability of an SRLG as it was a single cable. Furthermore, the SRLG is in series availability structure with the rest of the cables in the path.

We take two coincident SRLGs to be present at links incident to source and termination node of logical connection, each 5 km long. Specifically,

- logical connection between nodes 1 and 4 passes through SRLG that contains parts of links $1-2$ and $1-21$ and through SRLG that contains parts of links $3-4$ and $5-4$ (shown in Figure 4),
- logical connection between nodes 8 and 18 passes through SRLG that contains parts of links $8-10$ and $8-7$, and through SRLG that contains parts of links $15-18$ and $20-18$.

By A^{srlg}_i we denote the availability of SRLG at node i, and by A^*_{i-j} we denote the availability of the part of the cable between nodes i and j that is not contained in the SRLG.

$$\begin{aligned}
A^{conn}_{1-4} &= A^{work}_{1-4} + A^{spar}_{1-4} - A^{work}_{1-4} \cdot A^{spar}_{1-4} = \\
&= A^{srlg}_{1} \cdot (A^*_{1-2} \cdot A_{2-3} \cdot A^*_{3-4} + A^*_{1-21} \cdot A_{21-25} \cdot \\
&\cdot A_{25-5} \cdot A^*_{5-4} - A^*_{1-2} \cdot A_{2-3} \cdot A^*_{3-4} \cdot A^*_{1-21} \cdot \\
&\cdot A_{21-25} \cdot A_{25-5} \cdot A^*_{5-4}) \cdot A^{srlg}_{4} = \\
&= 0.999993065984851
\end{aligned}$$

$$\begin{aligned}
A^{conn}_{8-18} &= A^{work}_{8-18} + A^{spar}_{8-18} - A^{work}_{8-18} \cdot A^{spar}_{8-18} = \\
&= A^{srlg}_{8} \cdot (A^*_{8-10} \cdot A_{10-15} \cdot A^*_{15-18} + A^*_{8-7} \cdot A_{7-6} \cdot \\
&\cdot A_{6-24} \cdot A_{24-20} \cdot A^*_{20-18} - A^*_{8-10} \cdot A_{10-15} \cdot \\
&\cdot A^*_{15-18} \cdot A^*_{8-7} \cdot A_{7-6} \cdot A_{6-24} \cdot A_{24-20} \cdot \\
&\cdot A^*_{20-18}) \cdot A^{srlg}_{18} = \\
&= 0.999993057590914
\end{aligned}$$

By doing 1000 runs[1] of Monte Carlo simulation having 10^9 hours of simulated time per run, we get the the availabilites shown in Table I. We set the requirement for both standard deviation and absolute difference between analytical result and simulation result mean to be lower than 10^{-5}, which is the threshold for "five nines" availability. Since the standard deviation is in order of magnitude of 10^{-8} in case without SRLGs and 10^{-7} in case with SRLGs, we consider the number of runs was sufficient. Comparing simulation mean and analytical results results in absolute difference below

[1] For doing multiple runs of a single simulation scenario, our model uses high-level interface provided by ns-3 (description can be found in [28]). For the purpose of pseudorandom number generation, ns-3 provides built-in MRG32k3a [29] generator. MRG32k3a provides $1.8 \cdot 10^{19}$ independent sequences of random numbers, each containing $2.3 \cdot 10^{15}$ subsequences. Each subsequence has period $7.6 \cdot 10^{22}$.

Table I
DIFFERENCE BETWEEN SIMULATION AND ANALYTICAL RESULTS.

Logical connection between nodes	**Simulation availability result**	**Standard deviation of availability**	**Absolute difference between simulation and analytical result**
Nodes 1 and 4 (no SRLGs)	0.999999910399	1.916×10^{-8}	6.56×10^{-10}
Nodes 8 and 18 (no SRLGs)	0.999999903363	1.988×10^{-8}	7.30×10^{-10}
Nodes 1 and 4 (with SRLGs)	0.999993075031	2.1123×10^{-7}	9.047×10^{-9}
Nodes 8 and 18 (with SRLGs)	0.999993060931	2.0268×10^{-7}	3.340×10^{-9}

10^{-5} by five orders of magnitude (four in case with SRLGs). Therefore we consider our model used in simulation validated, and have reasonable confidence it is suitable for general use.

B. Simulation results for network unavailability

For the case study, we evaluate the scenario where all pairs of nodes have bidirectional logical connections. As the test network has 25 nodes, 300 bidirectional connections are established. The working and spare paths for each logical connection are made to be both link and SRLG-disjoint if possible, and link-disjoint otherwise.

We used the following two measures of network availability:

- s,t-availability, defined as the minimum of all logical connection availabilities,
- g-availability, defined as the probability that all logical connections in the network are in working state at a random time.

Unavailability U is a complement of availability defined as

$$U = 1 - A.$$

Since availability values are often very close to 1, it is easier to do comparisons of simulation results based on the order of magnitude difference in unavailability. Therefore, to ease the evaluation of the effect of various simulation scenario settings on network availability, we additionally define s,t-unavailability and g-unavailability as complements of s,t-availability and g-availability (respectively).

We simulate the scenarios with 20, 40, 60 and 80 SRLGs present in the network, each containing two cables. For each of these numbers of SRLGs in the network we simulate scenarios with SRLG mean lengths of 1.0 km, 2.0 km, 3.0 km, 4.0 km and 5.0 km. For each combination we do 1200 runs of Monte Carlo simulation having 10^9 hours of simulated time per run.

Based on real data presented in [30], [9], we set failure dependency between cables contained in the same SRLG to be 0.7. The consequence of this failure dependency is that, on average, 70% of the time a failure of a part of cable contained in SRLG will affect both cables, and the rest of the time will affect only one. Also, we assume that upon repair, both cables will be repaired in the common part.

Table II
LINE COEFFICIENTS OBTAINED USING LEAST SQUARES METHOD.

Simulation case	**Line slope**	**Line y-intercept**	**Sum of residuals**
20 SRLG s,t-unavailability	5.403×10^{-7}	1.268×10^{-7}	9.891×10^{-16}
20 SRLG g-unavailability	9.203×10^{-7}	5.117×10^{-6}	4.03×10^{-15}
40 SRLG s,t-unavailability	1.56×10^{-6}	4.06×10^{-8}	1.314×10^{-15}
40 SRLG g-unavailability	4.428×10^{-6}	4.973×10^{-6}	4.063×10^{-14}
60 SRLG s,t-unavailability	2.315×10^{-6}	-8.769×10^{-9}	3.231×10^{-15}
60 SRLG g-unavailability	1.006×10^{-5}	4.832×10^{-6}	1.147×10^{-13}
80 SRLG s,t-unavailability	3.025×10^{-6}	-7.743×10^{-8}	1.01×10^{-14}
80 SRLG g-unavailability	1.691×10^{-5}	4.772×10^{-6}	1.641×10^{-13}

We evaluate the availability of the network in terms of both s,t-unavailability and g-unavailability. The unavailabilities obtained by Monte Carlo simulation are shown in Figure 5, along with "Five nines" availability threshold line.

Simulation results show that linear increase in mean SRLG length causes linear increase both in s,t-unavailability and g-unavailability for all numbers of SRLGs evaluated. We used the least squares method for obtaining line coefficients that fit simulation results. The coefficients obtained are shown in Table II. This results in sum of residuals is in each case below y values by seven or more orders of magnitude, so we consider the line to fit our results well.

All this gives us a reasonable confidence to consider our hypothesis to be true, given the conditions we stated.

It's also worth noting that standard deviation also increases with increase in number and mean length of SRLGs. Such an increase in standard deviation can be explained by larger variety of scenarios that can happen. Namely, in case with more and longer SRLGs, the probability that failure of a cable in the network will hit an SRLG also increases, but still does not equal 1 so SRLG will not be by every failure.

V. CONCLUSIONS AND DIRECTIONS FOR FUTURE WORK

We expected that physically longer SRLGs will more negatively impact logical connection and network availability. To evaluate this, we developed a new model of optical network components and implemented it in network simulator ns-3. We validated our model in specific cases by comparing Monte Carlo simulation results for availability analysis to analytical results. Results fulfilled our expectations.

In more complex cases other factors impacting network availability could be studied. Physical factors such as geographical location, altitude and urbanization level of the area can be taken into account as well as network characteristics such as routing and wavelength assignment algorithm and traffic demand patterns.

Since elimination of all SRLGs is costly, partial elimination in terms of shortening physical length and reducing the number

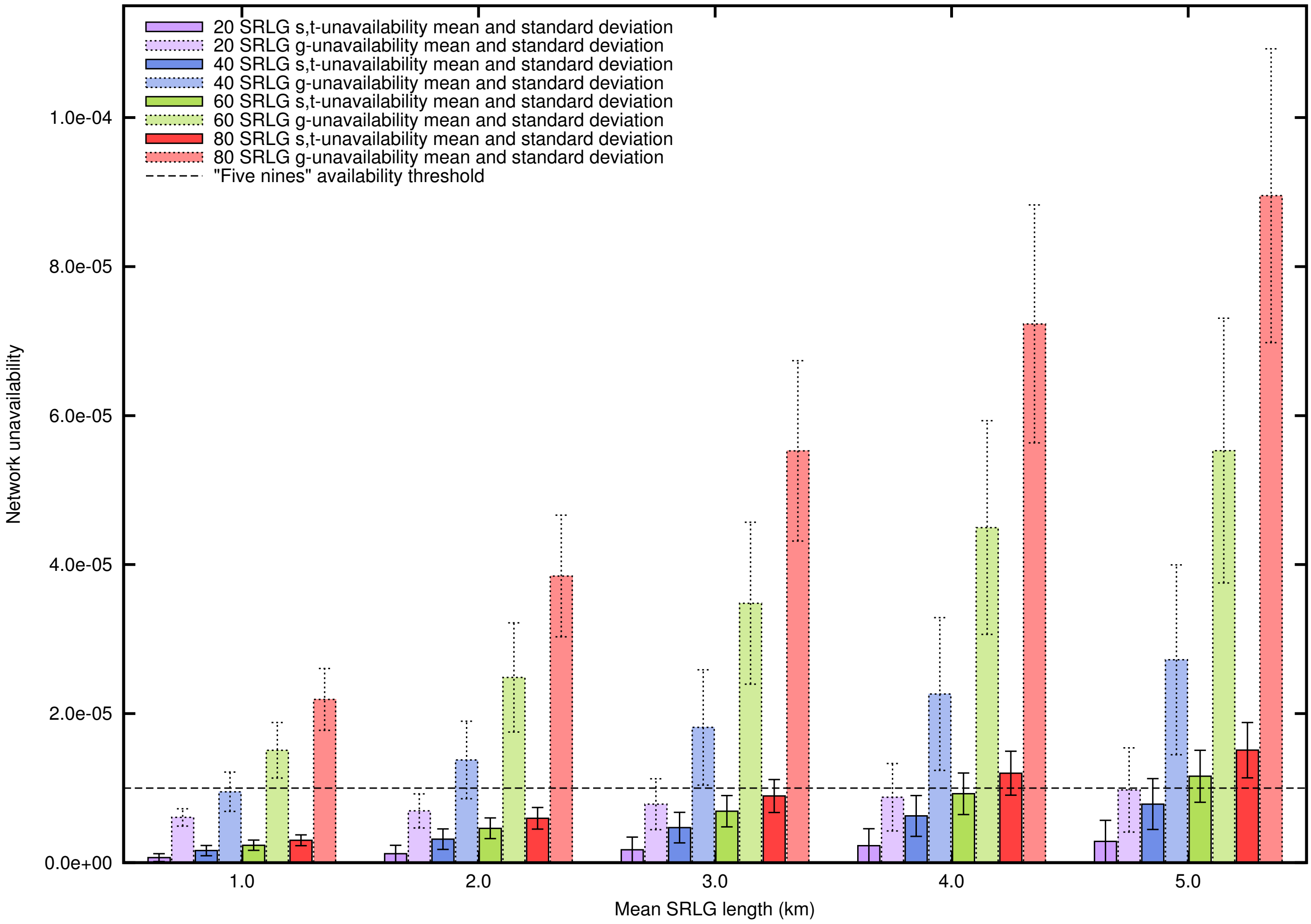

Figure 5. Monte Carlo simulation results for network unavailability for varying number of SRLGs and varying mean of SRLG physical length.

of SRLGs can be a viable alternative. While the exact network availability results are hard to obtain analytically, it is possible to use Monte Carlo simulation to get approximate results and evaluate different possible improvements.

Finally, in sprit of free open source software, we plan to write detailed documentation describing the features our model and submit our code for review and inclusion as a part of ns-3 source code distribution.

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