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Modeling reliability constraints in modern Optical Network Simulation Environments

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Abstract

Simulation is widely recognized as an extremely effective option to avoid the implementation of costly and sophisticated testbed infrastructures for testing, validation, and assessment of control plane protocols and algorithms in large-scale optical network scenarios. Its primary goal is to provide sustainable, realistic, and accurate models for analyzing specific system properties by resulting in an approach that becomes more effective with the growth of both the size of the infrastructure of interest and the observation timespan. However, the absence of optical network simulation environments that adequately address complex constraints such as node and link reliability represents a significant gap in current simulation research and development efforts. Accordingly, in this work, we present our modeling experience concerning the impact of potential physical-level failures involving network nodes and communication links in network-wide state information and operations. The model has been implemented in our existing SimulNet simulation environment in order to include reliability-related concerns in the routing and wavelength assignment framework. This results in a modern optical network simulation framework adopting a flexible network model, and capable of considering also specific failure probability constraints in the lightpath selection process.

Keywords: Optical Network Simulation; Reliability Modeling; MTBF

1. Introduction

Simulation is now considered a crucial element in the design of network infrastructures since it offers an extremely cheap but effective way of analyzing and exploring in advance the functionality and performance of new protocols or architectures. This assumes paramount importance in the deployment of large-scale optical network infrastructures, involving plenty of sophisticated and expensive wavelength division multiplexing, and optical switching equipment. In these scenarios, the preliminary validation of new design choices or extension/upgrades becomes indispensable, in order to avoid significant economic losses as well as functional or performance problems.

Indeed, the availability of reliable simulation environments obviates the need for sophisticated network testbeds, implying the acquisition and management of complex optical devices and communication links. In addition, even in presence of fully-equipped testbeds, the implementation, testing, and evaluation of new architectural schemes or protocols, can pose significant challenges, due to the limited scale of communication links used in typical testbeds and to the limited time horizon characterizing testbed experiments.

For example, estimating the effect over time of a specific technological improvement involving a specific class of devices, as well as of a topological change implying the creation of traffic diversions over new paths with very different physical features in terms of communication links and optical devices traversed, can become extremely difficult, if not impossible.

On the contrary, realistic simulation environments, based on accurate models for describing the system properties of interest, can provide a more flexible and complete approach for coping with optical network problems involving architectures characterized by expensive links and equipment, and/or requiring observation over longer timespans. Thus, their use can result in more accurate design choices or management decisions, mainly when the analysis involves space and time scales and perspectives that cannot be affordable on an evaluation testbed. Indeed, simulation allows the study of networks comprising hundreds of elements and wavelengths, minimizing the risk of underestimations or errors in the analysis. In addition, despite simulated devices may exhibit limited functionalities, sometimes deviating from real-world behavior, simulation results, especially when properly oriented to the representation of specific architectural elements of interest, are easier to interpret than testbed-related data, greatly facilitating network-wide behavioral analysis and problem diagnosis.

Starting from the previous considerations, in this work we deal with modeling and simulation of link and equipment-related reliability properties in modern wavelength-switched optical network environments. In particular, by considering that almost all the available optical network simulation solutions do not take into account the impact of physical-level failures involving network nodes and communication links in network-wide state information and operations, we properly extended our former SimulNet optical simulation tool (Palmieri et al., 2009) to incorporate comprehensive models for several kinds of optical devices and transmission link reliability.

This results in a modern simulation framework adopting a highly flexible network model, and accommodating heterogeneous WDM equipment, wherein the number and type of lambdas can vary across each link. It features fully dynamic and customizable path selection schemes that support sub-wavelength bandwidth allocation and accounts for multiple factors such as cost, performance, reliability, and resource limitations inherent in different types of optical switching devices or circuits. In particular, it can now intelligently weight the path selection process according to specific failure probability constraints. These constraints are pivotal factors in the design, deployment, and operation of modern optical networks, where path reliability becomes a fundamental concern together with the more traditional performance and network engineering objectives. By fostering a deeper understanding of the interplay between reliability and engineering constraints (bandwidth, latency, QoS) in optical network infrastructures, the resulting advanced simulation environment can support the development of innovative network architectures, protocols, and management strategies that meet the evolving demands of modern communication systems.

2. State of the art: existing optical simulation environments

Several optical network simulation environments are available, but none of them specifically supports the reliability of the involved network elements in its overall routing and wavelength assignment engine.

ns-3 (Network Simulator 3) is a widely used discrete-event network simulator that can model various types of networks, including optical ones (Riley and Henderson, 2010). Despite offering a rich set of functionalities and leveraging the contributions of a large community of users, its support for optical-specific features and protocols, including reliability-related ones is quite limited. In addition, it may require extensive customization and development of additional modules to accurately model complex optical network scenarios.

ONS (Costa and Drummond, 2019) is a simple but effective discrete event-based optical network simulation environment totally written in Java and fully available in source format. It supports a wide range of fully optical and hybrid electric-optical network features (grooming, wavelength conversion etc.), as well as it provides different kinds of modulations and spectrum-level visibility. However, it does not consider the reliability properties of the involved devices and hence may require some substantial customization for introducing such concepts into its overall framework.

OMNeT++ (Objective Modular Network Testbed in C++) is a modular, flexible and extensible component-based simulation framework (Varga, 2010) extremely suitable for modeling and simulating various types of networks, including optical ones. It also supports parallel simulations and provides a large library of existing models and components. However, like ns-3, OMNeT++ lacks built-in support for specific optical network features and protocols, requiring users to develop or integrate custom models for coping with new features and parameters. This can clearly lead to complexity and steep learning curves for beginners.

OptSim (Haefner et al., 2013) is a commercial product by Synopsys offering a comprehensive set of features for modeling and simulating optical communication networks. It provides specialized tools for supporting design and optimization studies as well as available models of advanced modulation schemes, impairments, and signal processing algorithms. However, being a proprietary tool, it implies licensing costs and does not make its source code available for customization or extension such us the one needed in modeling reliability issues.

GloMoSim (Global Mobile Information System Simulator) is an open-source parallel discrete-event simulator developed specifically for wireless and wired network simulation, including optical networks (Bajaj et al., 1999). It offers support for modeling complex network topologies, mobility patterns, and communication protocols. Unfortunately, since it is mainly focused on the wireless and mobile environments, it results in limited features and capabilities for modeling optical-specific devices and technologies.

The Complex Elastic Optical Network Simulator (CEONS) (Aibin and Blazejewski, 2015) is another open-source simulation environment mainly focusing on optical network operations visualization starting from different topologies, routing algorithms, traffic dynamics, etc. It allows geographical mapping of topologies and allows real-time observation of resource usage at the intermediate node or link level. Despite it provides extended visibility of equipment features and operation it does not take into consideration at all reliability and failure-related concepts.

NetSim (McGrath et al., 2004) is another commercial network simulator supporting several network flavors including optical ones, with a rich range of pre-built models and components. Like other commercial simulators, it may come with licensing costs, and however due to its generality its dedicated capabilities for optical network simulation are limited with respect to dedicated optical network simulators. In addition, customizing or extending the simulation environment may be challenging.

These are just a few examples of the available options for simulating optical networks. The choice of simulator depends on factors such as the specific requirements of the simulation, the available resources, the desired level of detail and accuracy, and the expertise of the users. Researchers and practitioners should carefully evaluate the features, capabilities, and limitations of each option before selecting the most suitable simulator for their needs.

3. Reliability issues in optical infrastructures

Considering the reliability of optical devices and links is essential for building robust and resilient optical networks that meet the requirements of modern communication systems. Effective reliability engineering practices, proactive maintenance strategies, and advanced monitoring and diagnostic tools play key roles in achieving high levels of reliability in optical networks.

Optical devices encompass a wide range of components such as regenerators, amplifiers, optical switches, and transceivers. The reliability of these devices directly impacts the overall performance and uptime of optical networks. Over time, these optical devices may experience performance degradation or wear-out due to factors such as material aging, fatigue, and cumulative stress. Analogously, fiber optic cables, with the associated connectors, splices, and passive components are susceptible to damage from bending, twisting, stretching, and crushing. Predictive maintenance and lifecycle management strategies help mitigate the impact of damages or aging effects on device reliability that however must be considered a first-class parameter during the path selection process involved in building new network lightpaths.

In this direction, the Mean Time Between Failures (MTBF), representing the average time between failures, combined with the service lifetime of the involved devices becomes the most effective reliability metric that can be used for driving route and wavelength assignment activity at the control plane level.

4. Modeling component reliability in optical network environments

In real-world optical networks, node and link failures can occur due to various factors such as hardware malfunctions, fiber cuts, or power outages. Simulating these scenarios accurately is crucial for evaluating network resilience and designing effective fault-tolerant mechanisms. However, many existing simulation environments overlook or oversimplify reliability considerations, leading to unrealistic assessments of network performance and robustness. Thus, integrating these features into existing simulation platforms can enhance their utility for studying diverse applications and scenarios, ranging from mission-critical optical telecommunications networks to emerging technologies like smart grids. For this purpose we properly improved our Simulnet (Palmieri et al., 2009) optical simulation environment, by adding network component reliability issues in its overall Routing and Wavelength Assignment (RWA) framework. Simulnet has been built as an object-oriented application that fosters modular interaction among functional entities, facilitating easy extension and encapsulation. It already features a fully dynamic and customizable SPF-based lightpath selection scheme that supports sub-wavelength bandwidth allocation (grooming) by keeping into account several intricate factors such as cost, performance, and resource limitations inherent in different types of optical switching devices.

In detail, the simulator meticulously models network nodes, optical fibers and wavelengths per link, ensuring flexibility across diverse networks. Additionally, it offers extensive configuration options for topology definition, supporting node-specific conversion capability, lambda types, bandwidth, and propagation delay per link.

In order to condition the path selection process, with the aim of maximizing reliability, we need to introduce such a property as an alternative weighting option to be managed at the control-plane level within the context of modular, platform-agnostic, and expandable architectures. Each simulated optical network element x is associated with its fault probability $F_x(\sigma_x, \varphi_x)$ that can be seen as a function of the service life σ_x and of a constant failure rate φ_x (expressed in 1/time units) that are specific for the element x. According to (Birolini, 2013)(O'Connor and Kleyner, 2012), we modeled this probability by using an exponential distribution:

$$F_x(\sigma_x, \varphi_x) = 1 - e^{-\varphi_x \sigma_x}. \tag{1}$$

The constant φ_x is directly related to the Mean Time Between Failures (*MTBF*) μ_x characterizing the equipment x as $\mu_x = \frac{1}{\varphi_x}$ and hence we can substitute φ_x in eq. (1):

$$F_x(\sigma_x, \mu_x) = 1 - e^{\frac{-\sigma_x}{\mu_x}}. \tag{2}$$

An aggregate fault probability $F^s_{(x,y)}(\cdot, \cdot)$, represents the chance of a cut or a total degradation occurring after a service time $\sigma_{(x,y)}$ of the strand of fibers $s_{(x,y)}$ that realize the connection link between nodes x and y. Also, we can model as $F^{(x)}_{(x,y)}(\cdot, \cdot)$ and $F^{(y)}_{(x,y)}(\cdot, \cdot)$ the fault probabilities of the interfaces side x and side y, respectively, associated with each strand on the link (x, y). In addition, each link (x, y) can be equipped with $r_{(x,y)}$ technologically homogeneous optical regenerators and $a_{(x,y)}$ technologically homogeneous optical amplifiers, whose fault probabilities are modeled respectively as $F^a_{(x,y)}(\cdot, \cdot)$ and $F^r_{(x,y)}(\cdot, \cdot)$, also depending, as in the previous cases, on the service lifetime σ_z and on the *MTBF* μ_z referring to the specific regenerator or amplifier z. We finally assume that the fault probabilities of all the involved equipment are statistically independent.

The individual *MTBF* values μ_z for the most typical optical network components have been taken from (Vasseur et al., 2004) as reported in table 1.

Table 1. MTBF values for optical network components

Device	MTBF (hours)
Bidirectional Optical Amplifier	$5 \cdot 10^5$
Bidirectional Regenerator	$5 \cdot 10^5$
Bidirectional WDM Line System	$5 \cdot 10^5$
WDM OXC	$1 \cdot 10^5$
ROADM	$1 \cdot 10^5$
Router	$1 \cdot 10^5$
Interface Card	$1 \cdot 10^4$
Terrestrial Fiber optic Cable CC (km)	450

By using the Terrestrial Fiber optic Cable Cut (CC) metric, representing the average size of cable section on which at least an individual interruption can be observed yearly, we can calculate the *MTBF* of a single fiber strand (x, y). More precisely, if $l_{(x,y)}$ is the length of the fiber strand implementing the connection (x, y), then we can calculate $\mu_{(x,y)}$ as:

$$\mu_{(x,y)} = \frac{CC \cdot 365 \cdot 24}{l_{(x,y)}}. \tag{3}$$

Clearly, in our optical network simulation environment we need to estimate the fault probability associated to each link in order to eventually consider it in the metric used by the control plane protocols in the Routing and Wavelength Assignment (RWA) process. Thus, by simplifying the notation without indicating the functional dependencies of each component on its specific lifetime and *MTBF* we can model the fault probability of a connection (x, y) between two nodes x and y as:

$$F_{x,y} = 1 - \left[(1 - F^{(x)}_{(x,y)})(1 - F^{(y)}_{(x,y)})(1 - F^{s}_{(x,y)})a_{(x,y)}(1 - F^{a}_{(x,y)})r_{(x,y)}(1 - F^{r}_{(x,y)})\right] \tag{4}$$

Finally, the above fault-related component $F_{x,y}$ of the link-level metric, combined with the fault probabilities F_x of the individual nodes traversed contributes to the determination of the fault probability associated with each lightpath resulting from the RWA activity. Thus, by considering the lightpath (a.k.a. wavelength switched path) $\lambda(\pi)$ characterized by the use of the common wavelength λ on all the fiber strands involved in the path whose traversed links (x, y) are provided in the list π, its fault probability is modeled as:

$$F_{\lambda(\pi)} = 1 - \left[\prod_{(x,y)\in\pi} (1 - F_{x,y}) \cdot \prod_{x|(x,y)\in\pi \vee (y,x)\in\pi} (1 - F_x)\right] \tag{5}$$

The estimated fault-related probabilities can be used as costs metrics driving an online single-step shortest path routing scheme, so that the overall lightpath reliability, as the statistical complement of its fault probability (Bazovsky, 2004), is the final optimization objective.

5. Validation

The validation of a simulation model involves implementing well-known algorithms and benchmarking the results in real-word scenarios, in order to demonstrate its efficacy and reliability. To validate the aforementioned reliability modeling schemes within our SimulNet (Palmieri et al., 2009) simulation environment we realized a specific real-world proof-of-concept scenario and meticulously observed its behavior in terms of realism and coherence.

SimulNet is a discrete-event optical network simulation framework entirely implemented in Java® as an object-oriented application, and characterized by a fully modular design, that accommodates control-plane characteristics of wavelength-routed networks and features a suite of network traffic generators and control plane protocols. In particular, it provides an Open Shortest Path First-based routing protocol engine leveraging metrics based on link cost, hop count, as well as link nominal and dynamic residual capacity. The underlying Dijkstra algorithm implementation has been optimized with a Fibonacci heap (Fredman and Tarjan, 1987), achieving a $O(|N| \log |N| + |E|)$ complexity (Cormen et al., 2009).

The simulator meticulously models a significant number of optical nodes as well as optical fibers and wavelengths per link, supporting node-specific conversion capability, intermediate amplification/regeneration capabilities lambda types, and granular bandwidth demands/allocations (grooming), ensuring flexibility across diverse networks. Additionally, it offers extensive configuration options for topology and experimental trial definition, fostering modular interaction among different functional entities, and facilitating its extension and evolution.

The validation scenario has been crafted over the well-known Geant2 (Koster and Kutschka, 2011) network topology, which has been chosen also due to the significant number of long-haul connections, allowing a more significant evaluation of fiber strand reliability properties.

The Geant scenario provides 34 internal transport nodes (the backbone facility) each co-located with an edge node for originating and terminating optical connections. The sizes of fiber strands range from 8 to more than 800 Kms, each composed of 1 to 4 fibers.

The wavelength switches have been modeled to manage from 1 to 64 wavelength channels, characterized by a maximum bandwidth varying from 1 to 192 optical carrier (OC) units.

Nodes located in network core aggregate more fibers, channels and bandwidth capacity, with respect to termination nodes which essentially have the role of connecting their own payloads (radio access antennas, edge/fog or cloud facilities) to the infrastructure.

All the topological details are reported in figure 1. MTBF values for all the components reflect table 1 whereas all the devices have been assigned the same service lifetime.

Regenerators and amplifiers, all of the same type have been systematically deployed on the link depending on their size (an amplification device every 70 Kms and a regenerator every 4 amplifiers.

The requests for optical lightpaths have been generated randomly based on a Poissonian arrival distribution, and the associated origins and destinations have been uniformly distributed among randomly located sources/destinations. Each request is characterized by a bandwidth demand randomly selected in a set of $\{1, 3, 12, 24\}$ optical carrier units.

Individual simulation trials involving increasing traffic demands (number of end-to-end lightpath requests) have been repeated 100 times and all the achieved results have been averaged for reliability purposes. As performance metrics, we observed both the blocking factor (connection not allowed due to congestion) and fault probabilities. The different RWA strategies involved were all based on OSPF, differentiating in the use of distinct metrics (i.e., hop count, nominal bandwidth, residual capacity, link reliability).

We can see from figures 2 and 3 that the implemented model is effective in capturing the effects of link reliability and influencing, when needed (if the reliability metric is used for driving path selection), the overall RWA framework. Indeed, it can be immediately appreciated how the use of reliability metric in path selection is able to control the blocking factor better than the minimum hop or nominal bandwidth ones, achieving however blocking results that are comparable with the ones involving the use of the minimum residual bandwidth metric that is the best traffic-engineering option between them.

Instead, by observing fault probability in fig. 3 we see that reliability-sensitive RWA achieves significantly better results than the ones driven by the other metrics, as expected, substantially improving the overall network reliability. We can also notice that the use of the hop count metric can reduce the average fault chances since a minor number of network components are traversed within the resulting lightpaths. Also, the above evidence suggests that the proposed fault-awareness model is able to realistically depict and describe the reliability-related dynamics.

6. Conclusions

Simulation environments serve as invaluable tools for predicting the behavior of network devices within complex networks, leveraging internal models unique to the simulator. While simulators may not precisely replicate real-world events, they employ a set of transformation routines to guide the simulated network toward a final state resembling reality as closely as possible. By encapsulating relevant information and abstracting unnecessary details, simulation models streamline both simulation and network analysis activities, facilitating scalability in size and complexity. Hence, the careful selection of parameters for representation and abstraction is crucial.

Starting from these premises, by considering that almost all the available optical network simulation solutions do not take into account the impact of physical-level failures involving network nodes and communication links in network-wide state information and operations, we properly extended our former SimulNet optical simulation tool to incorporate comprehensive models for several kinds of optical devices and transmission link reliability.

This results in a modern simulation framework adopting a highly flexible network model, and accommodating heterogeneous WDM equipment, wherein the number and type of lambdas can vary across each link. Such a framework can provide a more flexible and complete approach for coping with optical network problems that also involve specific architectural aspects such as the reliability and continuity of service as a priority.

Moreover, integrating these features into existing simulation platforms can enhance their usefulness for studying diverse applications and scenarios, ranging from mission-critical telecommunications networks to emerging technologies like the IoT and smart grids.

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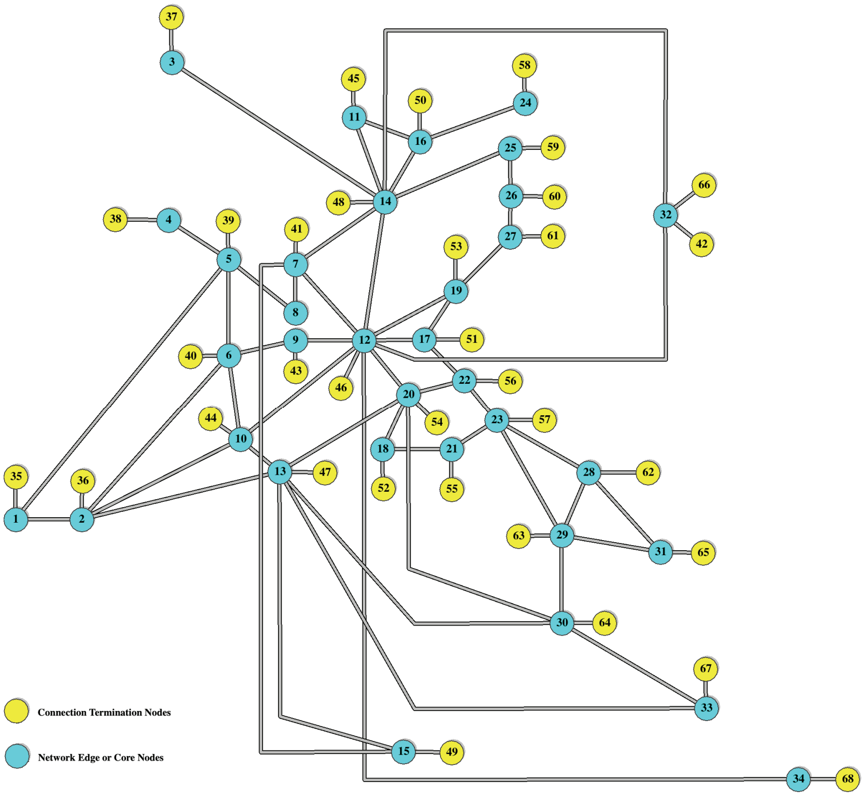

(a) Topology: 68 nodes (34 edge, 34 core).

src	dst	*len*	*#fib*	#λ	*bu*
15	49	263	1	32	48
5	39	263	1	32	48
5	8	77	4	64	192
16	50	263	1	32	48
10	44	263	1	32	48
17	51	263	1	32	48
11	45	263	1	32	48
16	11	728	2	32	192
19	53	263	1	32	48
19	17	23	1	16	192
20	54	263	1	32	48
25	59	263	1	32	48
18	52	263	1	32	48
20	18	51	4	64	192
24	58	263	1	32	48
16	24	77	4	64	192
4	38	263	1	32	48
4	5	58	2	32	192
22	56	263	1	32	48
17	22	28	4	64	192
20	22	263	4	64	192
26	60	263	1	32	48
25	26	51	1	16	192
2	36	263	1	32	48
10	2	11	2	32	192
27	61	263	1	32	48
27	19	36	1	16	192
26	27	51	1	16	192
21	55	263	1	32	48
18	21	86	3	48	192
34	68	263	1	32	48
32	42	263	1	32	48
32	66	263	1	32	48
29	63	263	1	32	48
28	62	263	1	32	48
28	29	836	1	8	48
31	65	263	1	32	48
29	31	15	1	8	48
28	31	17	1	8	48
14	48	263	1	32	48
16	14	46	2	32	192
11	14	58	2	32	192
14	25	29	1	16	192
14	32	8	1	8	48
12	46	263	1	32	48
12	10	17	4	64	192
17	12	751	2	32	192
19	12	623	1	16	192
12	20	23	1	16	192
12	34	8	1	8	48
32	12	8	1	8	48
12	14	636	2	32	192
6	40	263	1	32	48
5	6	77	3	48	192
10	6	28	3	48	192
6	2	712	1	16	192
3	37	263	1	32	48
3	14	11	1	4	12
9	43	263	1	32	48
12	9	23	1	4	12
9	6	51	1	4	12
30	64	263	1	32	48
30	20	10	1	16	192
29	30	23	1	8	48
1	35	263	1	32	48
1	5	16	1	8	48
2	1	623	1	8	48
23	57	263	1	32	48
23	22	686	3	48	192
21	23	51	2	32	192
23	29	19	1	2	3
23	28	19	1	4	12
33	67	263	1	32	48
30	33	26	1	2	3
13	47	263	1	32	48
13	15	39	1	1	1
10	13	36	3	48	192
13	20	17	2	32	192
2	13	9	1	1	1
13	30	23	1	16	192
13	33	12	1	2	3
15	7	121	1	1	
8	7	86	4	64	192
7	14	539	2	32	192
7	12	723	3	48	192
7	41	263	1	32	48

(b) Links details (Source, Destination, Length, Number of fibers, Number of wavelengths, Bandwidth Units).

Figure 1. The simulated Geant layout.

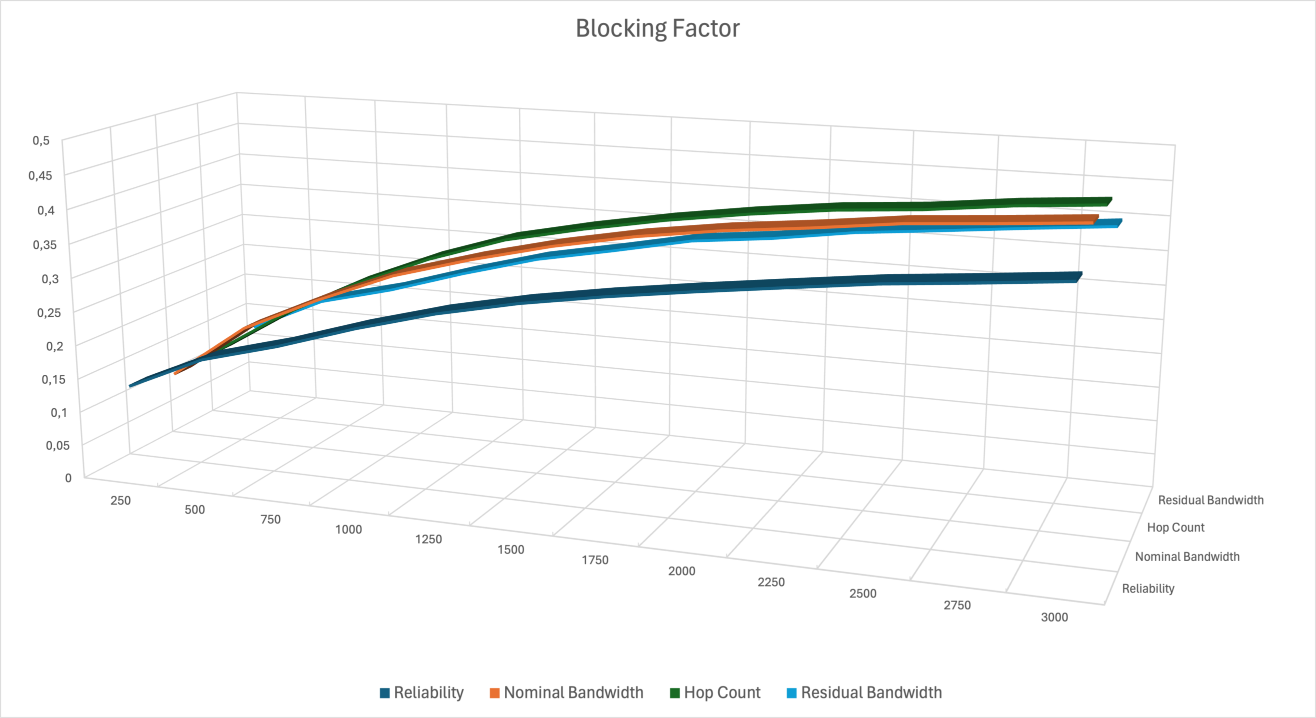

Figure 2. Average Blocking Probability with varying network load (connection requests).

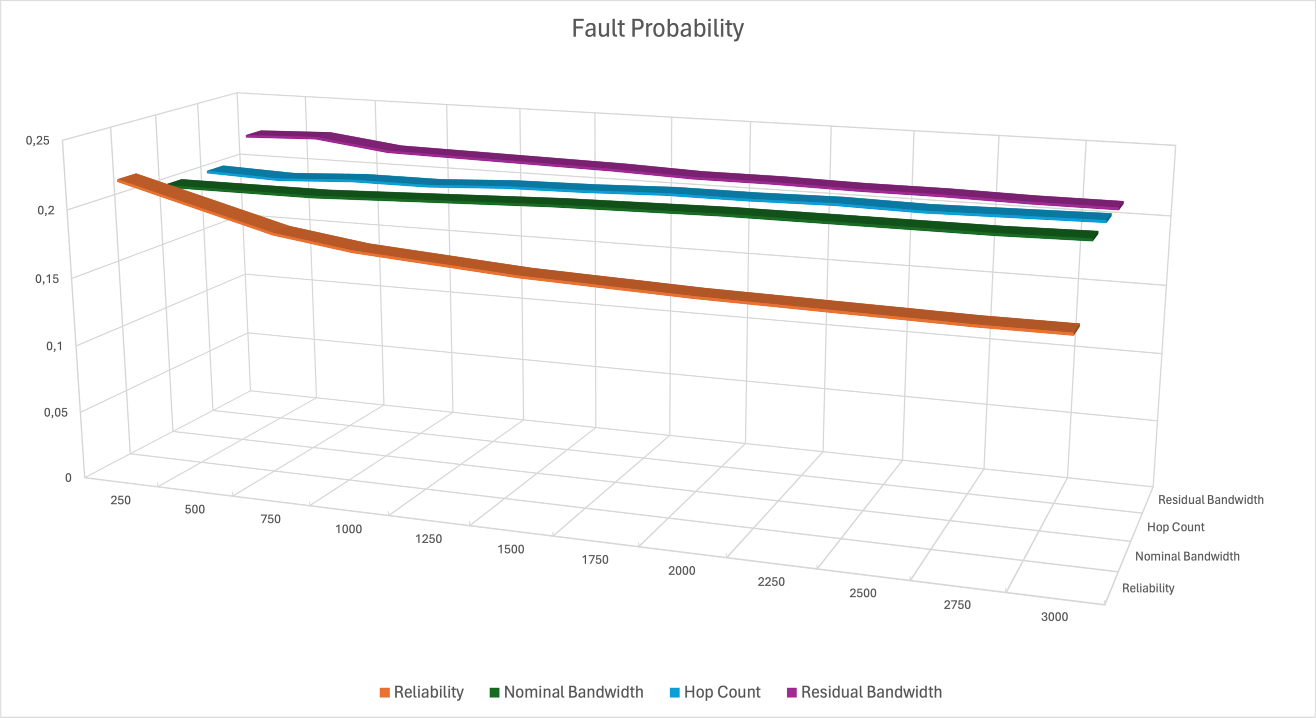

Figure 3. Average Failure Probability with varying network load (connection requests).

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