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Survivability Performance Evaluation of Slotted Multi-fiber Optical Packet Switching Networks With and Without Wavelength Conversion

تقييم أداء قابلية بقاء شبكة تحويل حزم البيانات متعددة ليف البصرية مشقوقة مع وبدون تحويل طول موجة

Fahad A. Al-Zahrani
Computer Engineering Department
Umm Al-Qura University
Makkah, Saudi Arabia
fahad1@uqu.edu.sa

الملخص: قابلية بقاء شبكة مُعَرَّفَةُ كقدرة شبكة لإبقاء مستوى مقبول من أداء الشبكة في وجود حالات الفشل. تحديد قابلية بقاء الشبكة خلال أداء الشبكة الصافي يميل إلى أن يكون متفائل منذ أن يُهمل توفر مصادر الشبكة في وقت الفشل. من الناحية الأخرى، يميل تحليل توفر صافي إلى أن يكون أيضاً محافظ منذ إعتبارات أداء لم يُؤخذ في الحسبان. في هذا البحث . تم إقتراح نموذج مركّب لقياس قابلية بقاء شبكة تحويل حزم البيانات متعددة الألياف البصرية المشقوقة بدقة. إنَ الأداء المتلاصق متعددة الليف شقت حزمة بصرية نقلت الشبكات بالإضافة إلى التوفر الثابت الرسمي للشبكة. هذان النموذجين تجمعان لبناء نموذج قابلية بقاء الشبكة. توضح الدراسة بأنَ إستعمال ترتيب شبكة ليف متعدد يُزوّدُ قدرة شبكة إضافية وتزيدُ قابلية بقاء الشبكة. أيضاً، من الواضح أن إستعمال تحويل طول الموجة يزيدُ قابلية البقاء بحل مشكلة طول الموجة.

Abstract:Network survivability is defined as the ability of a network to maintain an acceptable level of network performance in the presence of failures. Quantifying network survivability through pure network performance tends to be optimistic since it ignores the availability of the resources of the network at the time of failure. On the other hand, pure availability analysis tends to be too conservative since performance considerations are not taken into account. In this paper, a composite model to accurately measure the sur-vivability of slotted multi-fiber optical packet switching networks is proposed. The end-to-end performance of multi-fiber slotted optical packet switched networks as well as the steady-state availability of the network are modeled. These two models are combined to construct a hierarchical network survivability model. The study shows that the use of a multiple-fiber network configuration provides additional network capacity and increases network survivability. Also, it shows that the use of wavelength conversion increases survivability by resolving the wavelength contention problem.

1. Introduction

An all-optical network based on WDM technology becomes the technology of choice for use as a transport network due to its massive capacity, reliability, cost, and scalability. Using the conventional circuit-switched networks (wavelength-routed network), where a connection (light-path) between source-destination pair is established on top of the WDM multiplexing technology before data transmission begins, will result in ineffective use of the bandwidth provided by such technology. To overcome this inherent poor utilization of the WDM channels in wavelength-routed networks, the optical packet switching (OPS) network, which allows fast allocation of wavelengths on demand, is introduced.

The OPS architecture combines the massive bandwidth of the fiber cable provided by WDM with highspeed operation switching elements to allow fast allocation of wavelengths in an on-demand fashion [5]. Using multiple fibers on each link in OPS networks will enhance network performance by utilizing the space dimension of the same

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wavelength on different fibers to resolve the packets contention problem. This network environment can potentially transfer hundreds of terabits-per-second of data on each fiber link in the network, which results in better performance in the case of no failure. However, a single link failure in the multi-fiber OPS network may fail all fibers between the nodes simultaneously. The interruption of service for even short periods of time in the multi-fiber environment may have catastrophic and far-reaching consequences since a severe service loss as well as massive traffic interruption will occur. Thus, network survivability is considered a fundamental design factor for optical packet switching networks. In general, network survivability is defined as the ability of a network to maintain or restore an acceptable level of network performance in the event of failure scenarios to support a committed quality of service (QoS). By the use of passive connections and appropriate design of network topology, it is possible to provide multi-fiber connections among pairs of nodes via strands running in different cables. Such a design will carry with it the improved performance associated with multi-fiber design while also enhancing the survivability of the network. Wavelength conversion, if available, provides another mechanism for enhancing the end-to-end performance.

Wavelength convertible switches (WCS), optical switches (OSW) employing wavelength converters (WC), offer flexible light-path switching, contention resolution, and network interoperability as well as transparency of the optical layer. An important feature of WCSs is that they allow optical networks to be reconfigurable on a wavelength-by-wavelength basis to match changing traffic demands and to restore the network in case of failures. The major categories of WCSs are reviewed below. The dedicated WCS offers a wavelength converter for each outgoing wavelength allowing any incoming wavelength to be switched at a desired wavelength to the desired link [2], [3]. More cost-effective architectures use different converter-sharing mechanisms [3]. A share-per-node WCS offers all outgoing links a shared collection of converters that can be used by any channel on any link [2], [3].In the share-per-link WCS, the converters at the switching node are divided into a number of conversion banks. Each conversion bank is dedicated to one of the outgoing fiber links. The converters in a specific conversion bank can be accessed only by the incoming wavelengths that are destined for any wavelengths in the outgoing link that this conversion bank is associated with [1].

The assessment of network survivability performance has two facets: The assessment of the frequency of occurrence of abnormal conditions and the assessment of the impact of these conditions. Therefore, network survivability can be centered on 1) the frequency of failure events, 2) the duration of the outages, and 3) the impact of failure on the system. The first two items may be resolved by availability analysis when the system failure mechanisms are known. The third item can be handled by system failure impact analysis to find out the transient performance degradation when failure occurs. A quantitative approach for evaluating network survivability is proposed in [4], which analyzed wireless ad-hoc networks and is an example of a network survivability performance evaluation.

Both availability and performance are integral components of survivability. Therefore, a hierarchical sur-vivability model for multi-fiber OPS networks that consists of availability and performance analysis is proposed in this paper. A survivability comparison study between single-fiber and multi-fiber OPS environments is conducted in this research. The improvements in end-to-end blocking performance and survivability in multi-fiber OPS networks employing multi-fiber multi-hop architecture under different wavelength conversion scenarios are investigated.

Multi-fiber connectivity topology is proposed for the survivable multi-fiber WDM networks in Section 2. The performance analysis of the multi-fiber OPS network is presented in Section 3. In Section 4, the steady-state availability of the network is detailed. These two models are combined to construct a hierarchical survivability evaluation model in Section 5. Numerical results are discussed in Section 6. Section 7 concludes the paper.

2. Survivable Multi-Fiber OPS Networks Configuration

Our study is focused on a homogeneous multi-fiber network in which the number of fibers in each link is the same and the number of wavelengths in each fiber is the same. An easy extension and a similar analysis can be applied to more general multi-fiber networks. Having F parallel fibers on the same physical link that is connected by a pair of nodes in the multi-fiber WDM network provides a high blocking performance, but the survivability of this multi-fiber configuration is very low due to the failure of all fibers when a link failure occurs. Therefore, in survivable multi-fiber WDM networks, the multiple fibers between nodes have to be in different physical cables even though the fiber connectivity topology is shown as a direct connection between nodes. This may mean having a passive connection at the intermediate nodes between source and destination. Figure 1a shows a sample physical topology that provides two fibers between nodes. The fibers between nodes 1 and 4 are from two different cables, while nodes 2, 3, 5 and 6 could be passive connectors between these two nodes. If a link between nodes 1 and 4 fails, the traffic on this link can be restored using available fibers in other cables that connect these two nodes. Figure 1b illustrates the fiber connectivity between nodes 1 and 4 as three direct connections between these two nodes. The fiber connectivity topology is considered in the transient performance evaluation and availability analysis. Our results show that the multi-fiber connectivity topology provides better performance and higher surviv-ability for multi-fiber WDM networks

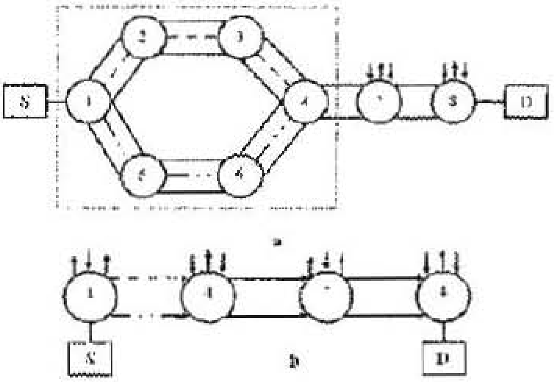

Figure 1 Fiber connectivity in survivable multi-fiber OPS networks a) Multi-Fiber Physical Topology. b) Multi-Fiber Connectivity Topology between S and D.

3. Multi-fiber OPS Networks Performance Analysis

In this section, a performance model [5], [1] for a multi-fiber OPS switch that operates in a slotted mode will be presented. In a slotted system, the incoming packets are synchronized at the inputs before they are processed. The developed model is a comprehensive model that can be used to evaluate the slotted OPS switch under different conditions and operation parameters such as number of wavelengths, number of fibers, number of converters, and different switch configurations. A symmetric OPS with N inputs, coming from different sources, and destined to N outputs links, each consisting of F parallel fibers, as shown in Figure 2, is considered.

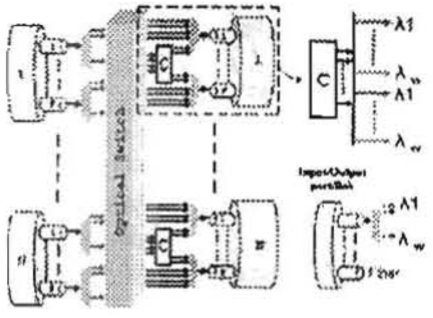

Figure 2.Slotted multi-fiber OPS switch architecture

The switch supports a WDM signal with w wavelengths per fiber and a conversion bank of C converters in case of convertible switch configuration. The packet length is assumed to be fixed for one time slot. The full derivation of this performance model was presented in [5], [1]. The aim is to use such a switch model to evaluate the degradation performance of the multi-fiber slotted OPS network under link failure condition. The network fiber connectivity topology, which is shown in Figure 1b, is considered to evaluate the end-to-end blocking probability of the network.

Also, the traffic at the input of the switch is assumed to be equally likely to be destined to any output port. Therefore, the number of packets competing for an output per wavelength in a given time slot and destined to the output link under consideration follows the binomial distribution for x = 0...NF, i.e.

$$P(X_i = x) = \binom{NF}{x}\left(\frac{p}{N}\right)^{x}\left(1-\frac{p}{N}\right)^{NF-x} \quad (1)$$

Where X; is a random variable representing the number of packets present at an output on A; in a given time slot. The probability that a packet arrives at an input in a given time slot is denoted by *p*, which corresponds to the normalized offered load. For a given time slot, if the number of arrivals per wavelength that are destined to the considered output is more than F packets, contention among them will occur. F packets out of the contending ones leave the switch directly using wavelength of interest X_u one on each fiber. Note that *direct* refers to packets that are directly routed from inputs to outputs without going through converters. The rest of these packets are forwarded to the conversion bank that belongs to the output port under consideration. The number of packets that are forwarded to the conversion bank from a single wavelength was derived in [5], [1] as follows:

$$P(Y_i = y | X_i > F) = \frac{P(Y_i = y \cap X_i > F)}{P(X_i > F)} \quad (2)$$

$$P(Y_i = y | X_i > F) = \binom{NF}{y+F}\cdot\left(\frac{p}{N}\right)^{y+F}\cdot \frac{\left(1-\frac{p}{N}\right)^{NF-y-F}}{1-\sum_{j=0}^{F} P(X_i = j)} \quad (3)$$

Let N_Y be a random variable representing the number of wavelengths that are competing for conversion resources. N_Y could take any value between *zero* to *w*. So the distribution of N_Y for $n_y = 0...w$ is as follows:

$$P(N_Y = n_y) = \binom{w}{n_y}\left(\sum_{i=F+1}^{NF} P(X = i)\right)^{n_y}\left(\sum_{i=0}^{F} P(X = i)\right)^{w-n_y} \quad (4)$$

The number of packets that can utilize conversion resources and leave the switch depends on the minimum of the total available wavelengths on all fibers at the output and the number of available converters. Since the packet length is fixed, all converters are available at the beginning of the time slot. Accordingly, the total number of wavelengths that are available on the output link after all direct packets are assigned to outgoing wavelengths has to be found. To find the available wavelengths on the output link for a given NY, B is defined as the random variable representing the total number of free wavelengths on the output link under consideration at any given time slot. The random variable B is simply the sum of the number of fibers in the port that have no direct packet on A. The random variable B could take any value between zero and F (w-ny). Therefore, for a given NY, the distribution of B is given by:

$$P(B = \beta | N_Y = n_y) = \begin{cases} 0 & n_y = w \\ \frac{1}{\beta!} H_B^{(\beta)}(z)|_{z=0} & \text{otherwise} \end{cases} \quad (5)$$

where HB (z) is the probability generating function of B. Packet loss takes place when all A;s are busy on all outgoing F fibers and the total number of packets forwarded to the conversion bank is greater than the minimum number of available converters and free wavelengths on the output. On the other hand, some of the rejected packets from the direct connection can be served by utilizing the available wavelengths and leave the switch by getting converted to one of the available channels on the output, provided there are free A,s on the output port under consideration. Accordingly, the average number of packets forwarded to the conversion bank, E {T}, which is equal to:

$$E\{T\} = \sum_{n_y=0}^{w} P(N_Y = n_y)\cdot(n_y \cdot E\{Y\}) \quad (6)$$

where E{Y}, is the average number of packets that are forwarded to the conversion bank per wavelength. Then, the average number of packets that will be dropped, E{d}, is calculated as the difference between the average of total forwarded packets to conversion bank, E{T}, and the average accepted packets for conversion, E{A}, as given by:

$$E\{d\} = E\{T\} - E\{A\} \quad (7)$$

The average number of packet arrivals per wavelength on the output under consideration is equal to F. ρ. Thus, the total expected arrival to the output link, shown in the denominator of equation 9, is given by:

$$E\{\xi\} = w \cdot F \cdot \rho \quad (8)$$

The switch-blocking probability, *Pb*, is then defined as the ratio of expected number of packets lost, E {d}, to the total number of arrivals of the output port, E {ζ}.

$$P_b = \frac{E\{d\}}{E\{\xi\}} \quad (9)$$

After obtaining the blocking probability for each individual switch on the path, the end-to-end packet loss probability of the fiber connectivity topology of a survivable multi-fiber slotted OPS network can be calculated as follows:

$$P_B = 1 - (1 - P_b)^H \quad (10)$$

where H denotes the number of hops along a path in fiber connectivity topology. In this model, all nodes along the path are assumed to have similar input traffic. These conditions describe the symmetric traffic nature of the optical packet switch in the network.

4. Multi-fiber OPS Networks Availability Analysis

In this section, the availability model that counts for failure-repair behavior of the path between pairs of nodes in the network fiber connectivity topology is developed. This model assumes the same number of fibers in all hops in the path between the source-destination pair of interest (S, D). Assume that there are F fibers available between nodes and the time to link failure and repair are exponentially distributed with mean i and i, respectively. Also assume that a single repair facility is shared by all the links. The availability model is then a homogenous CTMC with the state diagram shown in Figure 3.

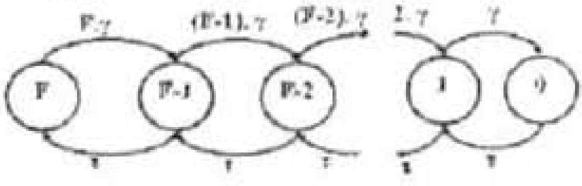

Figure 3 General availability model.

Here, the state index denotes the number of non-failed fibers in the network. The steady-state probability for the number of non-failed fibers in the network is given by:

$$\pi_{F-i} = \frac{F!}{(F-i)!}\left(\frac{\gamma}{\tau}\right)^i \pi_F, \quad i = 1, 2, \cdots, F \qquad (11)$$

where the steady-state system unavailability is:

$$\pi_F = \left[1 + \sum_{i=1}^{F-1} \frac{F!}{(F-i)!}\left(\frac{\gamma}{\tau}\right)^i\right]^{-1} \qquad (12)$$

5. Hierarchical Survivability Model

Studying the optical network survivability issues by quantifying the performance degradation of the network when different failures occur or by evaluating the resources availability for restoration after failure does not reflect the correct measure of the optical network survivability. Thus, as previously mentioned, network resources availability analysis and network failure impact analysis have to be considered as integral components of the survivability performance evaluation. In this section an accurate network survivability measure, which includes both performance and availability analysis of the network, is developed.

A gracefully degrading network may be able to survive the failure of one or more of its active components and continue to provide service at a reduced level. The hierarchical model is one of the most commonly used techniques for modeling of gracefully degradable networks. In this model, the availability model developed in the previous section is turned into a Markov reward model (MRM) [8].

The Markov Reward Model is a Markov chain with a reward rate assigned to each state. It is assumed that the system can be in one of a specified set of states. Each state is associated with a specific performance level as a reward rate. Therefore, for the general network survivability model, path availability between pairs of nodes in the network is modeled as general behavior of the network and the model is solved for the steady state probability that the path is up [8]. The steady state probability that there are i non-failed paths in the network is denoted by πi.

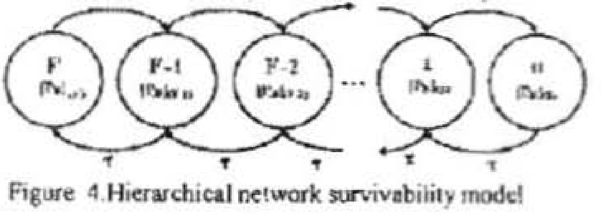

Figure 4.Hierarchical network survivability model

The reward rate for each state can be found using performance analysis of the network using Expression 10. The performance model depends on the number of fibers, routing algorithm, and number of converters in the system. This analysis could be carried as a Markov chain, analytical model, or as simulation modeling. Figure 4 illustrates the proposed general model of network survivability for multi-fiber slotted OPS networks.

By combining the availability model and performance of the network in the presence of failure as an MRM, we can find the survivability of the network. Attach a reward rate ri to the state i of the availability model and find the total loss due to unavailability of path(s) and also due to capacity constraints on the alternative F paths between nodes. Thus, the total loss of traffic at time of failure, susceptibility, is given by:

$$Susceptibility = \pi_0 + \sum_{i=1}^{F-1} P_{B_{(F-i)}} \pi_{F-i} \qquad (13)$$

In state0, there is no path available between the nodes; therefore, all the traffic is lost and the reward rate is 1 (r0 = 1). The network survivability can be calculated as follows:

$$Survivability = 1 - Susceptibility \quad (14)$$

6. Results

In this section, we discuss the network survivability improvements of an OPS network in the multi-fiber environment over the single-fiber case considering all network parameters. The survivability for the single fiber network environment, a single fiber in all hops between source and destination, is not zero because the network is not down all the time since failure-repair behavior of the network is considered, even though the down time of the network is taken into account when the survivability is evaluated. Therefore the network survivability should include system availability analysis to determine the cost due to system downtime, and system failure impact analysis to find out the transient performance degradation when failure occurs.

All results in this section considered the fiber connectivity topology of the OPS network shown in Figure 1b. If we assume there are 4 fibers available between the source-destination pair under consideration, the blocking probability for this case can be found using the expression 10 that was developed in Section 3. Using the same procedure, blocking probability for cases of 3 fibers to 1 can also be calculated. These results are used as the reward rate in expression 13 7T0, 7T1, 7T2, 7T3 and 7T4 can be found using expression 12 and 11. These results are combined to find the susceptibility and survivability of the network using expression 13 and 14. We assume a general network topology and single source-destination pair with a fixed routing algorithm between source and destination.

In Figure 5, the effect of availability on the survivability of the network is studied by changing the repair rate. In this figure network survivability is plotted as a function of offered load per wavelength for the multi-fiber case with 4 fibers, 4 wavelengths per fiber, 15 hops path lengths, and for different repair rates. In the first scenario, the performance of the network is used as a measure of network survivability without considering failure-repair behavior in the network, which indicates an availability of 100%. This scenario shows that using the performance measure as an indicator of network survivability is too optimistic. In scenarios 2 and 3, different repair rates (, 0.1 and 0.05) are considered, with Γ = 0.01. In these scenarios, the hierarchical survivability model is used to accurately calculate network survivability. As explained above, this survivability measure combines the performance and availability analysis at the time of failure to correctly measure network survivability. As the steady state availability decreases by decreasing the repair rate, the survivability of the network decreases. These results show that network survivability performance evaluation should include both network resources availability analysis and performance evaluation of the network.

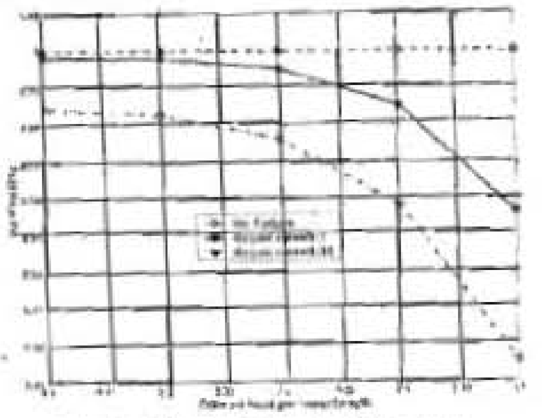

Figure 5 Steady state availability effect.

In Figure 6, the source-destination survivability is plotted as a function of the offered load for different numbers of fibers assuming same network performance parameters for all cases (H = 15, Γ = 0.01 and = 0.1, C = 2, w = 4). Having one fiber is denoted

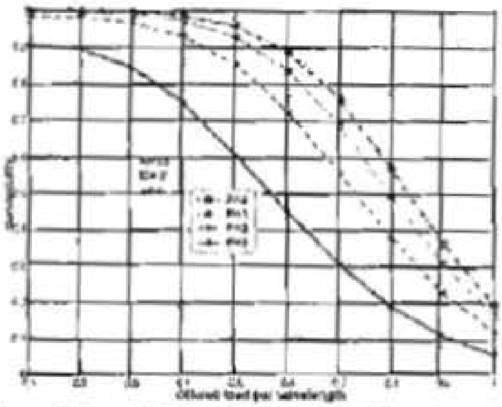

Figure 6 Survivability with respect to different number of fibers.

as F = 1, and F = 4 corresponds to four parallel fibers. More fibers between source and destination can provide additional routes between the nodes and increases the survivability of the network in case of failure. The survivability of the network can be significantly improved just by adding one additional fiber to the single-fiber environment. The significance of adding more and more fibers to the OPS network environment decreases as the number of added fibers increases due to the abundance of bandwidth that is introduced with every added fiber. This survivability behavior of the network will continue until it reach survivability saturation, where adding more fiber will not increase network survivability.

In Figure 7, the effect of wavelength conversion on the survivability of the network is explored. Using the wavelength conversion, the OPS network increases network survivability by resolving the wavelength contention problem. As can be seen in Figure 7, at 0.6 offered load, the survivability improvement for conversion case can reach 30%. This result shows the effect of the wavelength conversion on network survivability. However, using wavelength conversion increases cost, hardware complexity, and space requirements to the network, implying potential tradeoffs between survivability performance and the number of wavelength converters needed.

In Figure 8, the size of the network is increased by increasing the number of hops to study the effect of network reach on survivability. Increasing the number of hops decreases network survivability, as expected. But using wavelength conversion or adding more fibers can improve network survivability. This result shows the effect of multi-fiber network configuration on survivability and network size.

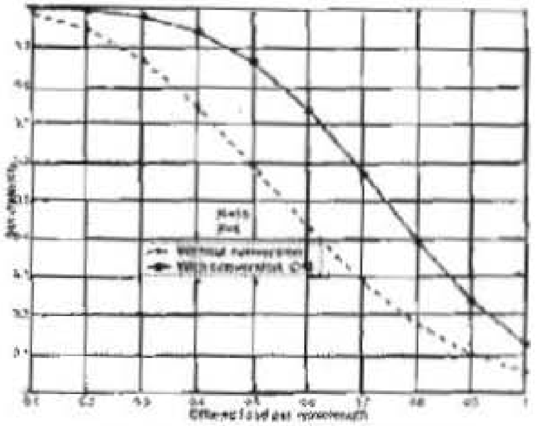

Figure 7. Survivability vs. offered load.

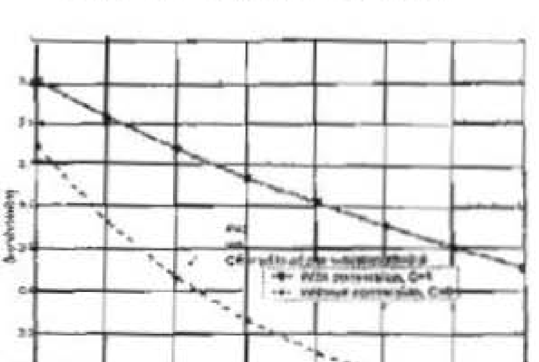

Figure 8. Survivability vs. number of hops.

7. Conclusions

A hierarchical model to evaluate system surviv-ability performance was developed. The end-to-end performance of multi-fiber OPS networks in multi-hop environments is modeled and evaluated with and without wavelength conversion. These models were utilized to evaluate performance degradation when a failure occurs. The performance degradation model and the availability analysis model were combined to construct a hierarchical network survivability evaluation model. We define network survivability as a composite measure that includes both failure duration and failure impact on the network.

The survivability of the OPS network decreases as steady state availability decreases. This result proves the hypothesis of this research: that is, the accurate survivability measure of the optical network has to consider both performance degradation during the time of failure and resources availability at the time of failure. A new approach for a more survivable optical network was presented and evaluated. This new approach provides multiple fibers between the nodes, but these fibers are not on the same physical link and have the intermediate nodes behaving as passive connectors.

The study showed that the use of multiple fibers at the connectivity topology level of OPS networks provides additional network capacity and increases network survivability by reusing the same set of wavelengths in multiple fibers in case of link failure. The use of wavelength conversion increases the survivabil-ity by resolving the wavelength contention problem. However, using wavelength conversion can increase cost, hardware complexity, and space requirements to the network, implying potential tradeoffs between the performance and the number of wavelength converters needed.

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