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Blocking performance of extended pruned vertically stacked optical banyan structure under different link failure conditions

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ABSTRACT

The blocking performance of extended pruned vertically stacked optical banyan (VSOB) networks under different link failure conditions has been analyzed in this paper. We applied plane fixed routing with linear search and plane fixed routing with random search algorithms to route the optical data through the network in our simulation. Our simulation results show that adding one or two extra planes to the pruned VSOB network reduces the blocking probability significantly. Beyond two extra planes, the decrease of blocking probability is not so significant. A close approximation of the minimum number of planes required to make the extended pruned vertically stacked optical banyan networks nonblocking has been presented.

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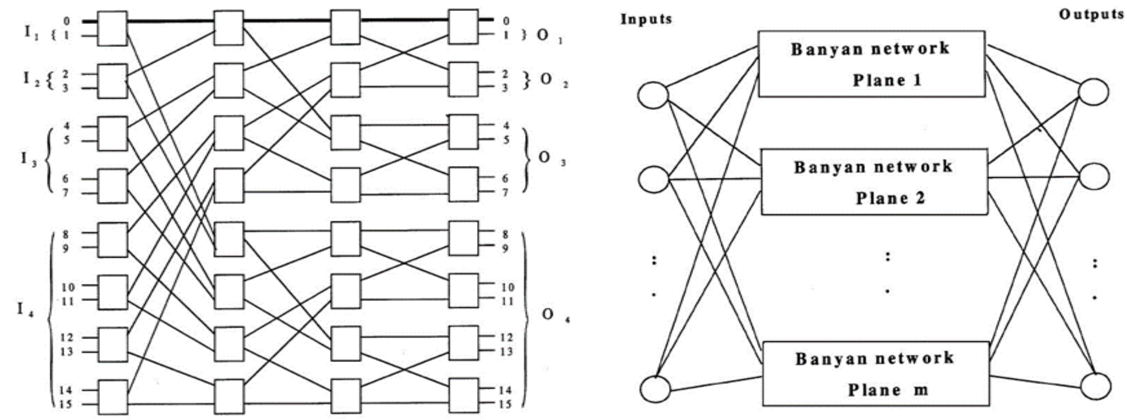
1. INTRODUCTION

With technological advancements in schools, business, banking, government, media, as well as the rising dominance of computer and modern data analyzing tools, there is a never-before-seen surge in demand for higher and much more dynamic bandwidth requirements. Optical fiber, a new blessing of modern technology, has been developed to satisfy this requirement. A switching network is an important section of an optical communication system. It is comprised of a huge number of basic switching elements. A directional coupler (DC) is the most common switching element used in optical switching networks. It is an electro-optical switching system made by bringing two-channel waveguides together [1]. Cross and bar are the two states of a 2×2 switching element (SE) having switch features identical to that of it [2]. DCs can accommodate signals with different wavelengths and a speed of several terabits per second. The DC has a built-in flaw of crosstalk [1], [3] and this can be eliminated easily by not allowing two optical signals through the same DC instantaneously [3]. Directional couplers can be used to make banyan networks. Banyan, omega, baseline, and shuffle-exchange, [4]-[8] are examples of banyan networks. There are $\log_2 N$ stages in a standard N×N banyan network. Each stage in a banyan network has N/2 2×2 switches, and the butterfly interconnection pattern is used to create links between neighboring stages repeatedly, as seen in Figure 1.



(a) (b)

Figure 1. VSOB networks are shown: (a) a 16×16 banyan network and (b) a VSOB network

On the other hand, only one path exists from every input to every output in the banyan network. All of the inputs cannot be linked to all of the outputs whenever they want. Consequently, the network becomes a blocking network. If several copies of similar networks are stacked in a vertical direction, the probability of blocking can be minimized to null [7]. Such a network is known as a vertically stacked optical banyan (VSOB) network. To maintain the non-blocking behavior of a network, the minimum required planes have been evaluated in many studies [9]-[13]. According to those researchers, vertically stacking will minimize the probability of blocking while significantly increasing the hardware cost. To deal with this situation researchers proposed pruned VSOB network (P-VSOB) [14] where the number of switching elements is less than that of the original VSOB network. Sultana *et al.* calculated a pruned vertically stacked optical banyan network's probabilities of blocking with disconnected paths in their study [15]. P-VSOB networks have lower hardware expenses and probability of blocking than that of VSOB networks, but their probability of blocking is too large for some ultrahigh performance applications. Extended pruned vertically stacked optical banyan (EP-VSOB) networks were presented by Khandker *et al.* as a solution to the problem [16]. The EP-VSOB network's blocking probabilities under various link failure conditions were estimated in our study.

2. RESEARCH METHODOLOGY

A large number of switching elements (SEs) organized in multiple stages, as well as optical links ordered in a specific pattern act as the constituents of an optical switch. In optical switching systems, a directional-coupler (DC), which is composed of two waveguides that are similar to each other, generally acts as the basic 2×2 switching element [1], [17]. A collection of appealing switching structures that are used to construct DC-based optical switches are the banyan networks (e.g., banyan, omega, baseline and shuffle-exchange) [3], [18]-[20]. Banyan networks are considered blocking networks because of having only one connection between an input and an output. To stack several copies of a banyan network in a vertical direction [21]-[23] is an efficient way to render the entire network non-blocking. This method is appealing, but it would dramatically raise hardware costs. The least number of planes needed for a non-blocking VSOB network with no disconnected path was estimated by Khandker *et al.* [14] using a packing technique. As a wide mesh wavelength division multiplexing (WDM) network requires fault-tolerant optical switches, analyzing the performance of the VSOB network with the possibility of disconnected paths is becoming extremely significant for the realistic implementation of VSOB networks in modern internet applications. Sultana *et al.* [15] calculated the VSOB networks' probability of blocking with disconnected paths.

2.1. Pruned-VSOB or P-VSOB (N, T) networks

A pruned VSOB network has T planes, each accepting N/T links from N as (1). If P_i is an inputs' set assigned to the i plane and $X_i \in I_j$ is an element belonging to the set, then

$$P_i = \{ X_i \mid X_i \in I_j, 0 \leq j < N/T \} \quad (1)$$

A uniform distribution of N inputs among T planes is visible in (1). I input would be activated as N/T connections are set at their respective inputs in the plane; the others will be idle. As a result, input switches attached to unused inputs, as well as switches in subsequent stages connected to that inputs are redundant. The unnecessary switching components are removed [16]. Figure 2 depicts the concept.

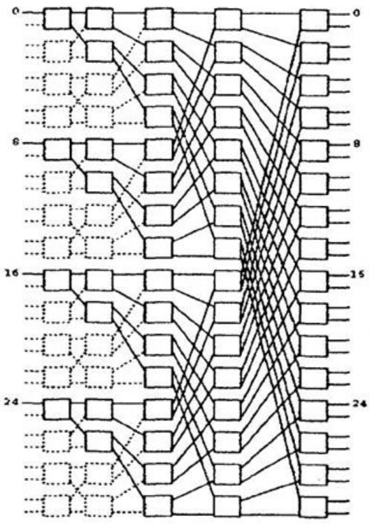


Figure 2. A pruned VSOB network, dashed lines represent redundant SEs

2.2. Extended pruned-VSOB or EP-VSOB (N, T+K) networks

Pruned and standard, two types of banyan planes are used in an extended pruned vertically stacked optical banyan (EP-VSOB) structure as per researchers' [16], [24] suggestion. Since some of SEs are never included in the system, they are removed from the pruned plane. Both pruned and non-pruned banyan planes are stacked in a vertical direction, similar to [16]. Here, the number of pruned banyan planes is $\sqrt{N}$ ($\sqrt{2N}$, when $\log_2 N$ is odd). The standard (non-pruned) banyan planes are also known as K extra planes. A pruned plane and K extra planes are linked for each input. If a path cannot be located by an input in its pruned planes, it is given only one chance to scan the additional planes. With three extra planes, this technique greatly decreases the blocking probability. So, the complexity of time is nearly similar to O ($\log_2 N$). Expenses on hardware can be reduced as well by pruning banyan planes. The structure of an extended pruned vertically stacked optical banyan (16, 8+2) structure is shown in Figure 3.

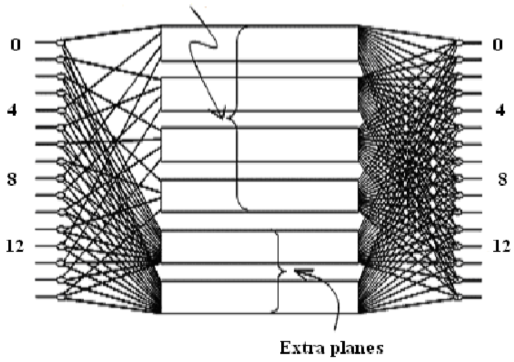


Figure 3. An extended pruned vertically stacked optical banyan (16, 8+2) network's structure

2.3. Plane fixed routing (PFR)

A single input is chosen from each input group and attached with VSOB (N, T) network's plane in the PFR algorithm. The inputs associated with a plane are separated into groups. An example of a probable plane assignment strategy using the PFR algorithm is given below. To begin, for an input set I={0, 1,..., N−1}, the subsets can be defined as:

$$g_i = \{i, i+T, i+2T, \ldots, i+(N/T-1)T\}, 0 \le i \le T-1.$$

The vertically stacked optical banyan (N, T) network's plane i (assume the planes are numbered 0, 1,..., T−1) is connected to every input in the set g_i. For instance, for the VSOB (16, 4) network, the subsets g_i

$(0 \leq i \leq 3)$ are g_0 = { 0, 4, 8, 12} , g_1 ={ 1, 5, 9, 13} , g_2 ={ 2, 6, 10, 14} ,and g_3 ={ 3, 7, 11, 15}. Figure 4 shows the assigned inputs for various planes. In a self-routing switching network, the route of an input signal to its destined output is determined by the address of the destination, irrespective of other links' destination addresses. The vertically stacked optical banyan (N, T) structure using the PFR scheme is self-routing because all planes of such a network are self-routing banyan structures. Every input-output pair in the VSOB (N, T) network has only one route. As a result, the time complexity for routing is O (log_2N) in a VSOB (N, T) network using the PFR scheme, which is proportional to the networks' number of stages. As establishing a route in a log_2N-stage banyan network takes minimum O (log_2N) time, the time complexity is optimal [25]. Although the PFR scheme in a VSOB (N, T) network ensures nonblocking behavior in the prior half stages, still there is a probability of blocking in the latter half stages. Nevertheless, a large VSOB (N, T) network using the PFR scheme has a significantly small probability of blocking as shown in the results. To establish a link quickly in an extended pruned VSOB (N, T+K) network, we have proposed two routing algorithms, PFR with linear search and PFR with random search, based on their methods of selecting a plane from the extra planes.

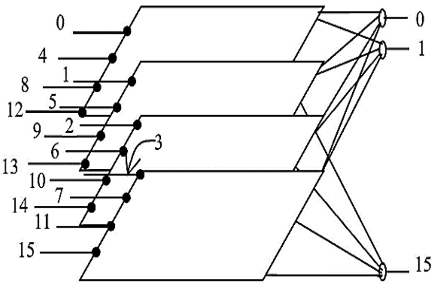


Figure 4. Inputs are assigned to the VSOB (16, 4) network's planes using the plane fixed routing algorithm

2.3.1. PFR with linear search (PFR_LS)

Each link has (1+K) possibilities of being formed via the network for the PFR_LS algorithm in an extended pruned VSOB (N, T+K) structure. When a request is received at an input, the input's assigned plane is its primary destination. An unused plane is searched by that input among the K extra planes whenever the connection is not developed in the assigned plane. The search proceeds from the first plane to the last one in a logical order, with each plane being checked only once by an input. It is called a blocked request whether an unused path is not found among the K extra planes by the link request. When K has a constant value and the value of T is much larger compared to K, the PFR_LS algorithm's time complexity is O (log_2N).

2.3.2. PFR with random search (PFR_RS)

Each link gets two opportunities to be developed across the network for the PFR_RS algorithm in an extended pruned VSOB (N, T+K) network. Connecting with the assigned plane is its prior choice. A possibility of being formed via one of K extra planes chosen at random still exists whether the link request is rejected in its assigned plane. It is called a blocked request when the link request is not created via the chosen plane at random. The PFR_RS algorithm's time complexity has always been the optimum O (log_2N).

2.4. Description of the simulator

We developed the network simulator to calculate the blocking probabilities. As there is no output conflict in a permutation, the request for permutation is treated as traffic in this case, and therefore only gives the switch network's actual probability of blocking. All link requests have equal possibilities of being blocked because of the pruned vertically stacked optical banyan (N, T) network's symmetric architecture. The link request of input-output pair 0-0 is set in simulation, and the probability of blocking of the link request is solely examined. The network simulator consists of six modules as given:

- Module 1: Depending on the workload r, this module produces a permutation request for the VSOB (N, T) network at random (here the probability of occupancy of a port is called workload r).
- Module 2: Disconnected paths are produced depending on the assigned pfr (the possibility of a connection to be collapsed or damaged) and these failures are then assigned to various connections at random.
- Module 3: A permutation request is used to activate the switches in this module.
- Module 4: This module tries to select different planes for different link requests. It only takes into account the plane in which the designated route is located. It attempts to locate the designated route in the chosen plane. If the designated route is not formed, then it tries assigning other links in its chosen planes.

- Module 5: The designated route is considered to be established in the extra planes (along with any other links that are not established in their chosen plane) whether it is not formed in the chosen plane yet. The search proceeds from the first plane to the last one in a logical manner for the plane fixed routing linear search algorithm. It is called a blocked request if an unused plane is not found. On the other hand, a plane is chosen at random from the extra planes for the plane fixed routing random search algorithm. The request is blocked again if the designated route is not formed via the chosen plane at random.
- Module 6: The blocking probability is calculated in this module. It is obtained by dividing the number of link requests blocking the 0-0 request by the sum of total link requests produced.

The network simulator's block diagram is depicted in Figure 5.

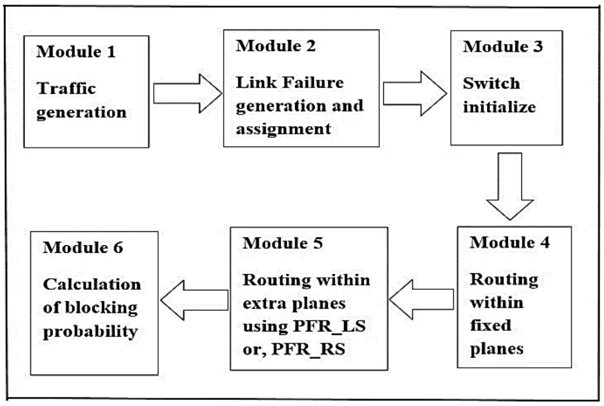


Figure 5. Network simulator's block diagram

3. RESULTS AND ANALYSIS

In our simulation, we have considered the size of network N=128, load=100% as default values. A network containing 6% link failure indicates a very badly degraded and vulnerable network. We have also considered this link failure probability as the highest value in our simulation to get a clear but wide idea of the blocking behaviour of the network.

3.1. Blocking probability using PFR_LS algorithm

Figure 6 shows the simulated result showing blocking probability vs link failure probability of an extended pruned VSOB network without any extra plane and with a single extra plane. As link failure probability rises, a sharp and almost linear increase in blocking probability is evident from this figure. If only 6% link fails to transmit light then about 60% call can be blocked. From the figure, it is also clear that adding an extra plane can make a dramatic change to the blocking probability of the whole network. For a 6% link failure, the blocking is now reduced to 33% which is about 40% less than the blocking of the network without an extra plane.

Figure 7 gives us a comparative study of the three independent simulation results. The addition of another extra plane (a total of two planes) can make the network reliable enough for most of the applications. This result indicates that two extra planes though demand some more switching elements, can reduce blocking to only 17% and which is 71% less than the first case of Figure 6. The third plane can eliminate some blocking significantly. This time for 6% link failure probability, blocking probability is only 8.1%. This is an 86% reduced figure of the initial value (blocking probability without an extra plane). From Figure 7, it is evident that another extra plane (a total of four planes) reduced blocking probability from 8.1% to 4.9%, which means adding this extra plane although can reduce some blocking, it is not so significant compared to the previous cases.

3.2. Blocking probability using PFR_RS algorithm

Figure 8 shows the results obtained from simulation of an extended pruned vertically stacked optical banyan network including disconnected paths and applying plane fixed routing random search algorithm. Both algorithms, plane fixed routing linear search and plane fixed routing random search, exhibit similar blocking behaviour without an extra plane and a single extra plane. Figure 8 demonstrates the effects of extra planes 2, 3 and 4. The probability of blocking increases almost linearly with the probability of link failure, as seen in this graph. For 1% link failure conditions with two extra planes, blocking probability is 3%. Following a roughly linear curve blocking is reached to 20% for a 6% link failure probability. The addition of another extra plane reduced the blocking probability by only 5%. For a link failure probability of 1%, its blocking is 2.6% and for 6% link failure probability, it is elevated to 15%. It is evident from this figure that for a 1% link failure probability with four extra planes, blocking is 1.7% and for maximum link failure probability of 6%, it reaches 10%. It is also seen from the figure that blocking increases linearly with link failure and at some points, it reduces and increases again.

Figure 9 gives us a comparison between plane fixed routing linear search and plane fixed routing random search algorithms. It is clear from the figure that the first algorithm is superior to the latter one. For an equal number of extra planes, the use of the plane fixed routing linear search algorithm can reduce blocking enormously. At the initial point of the figure, we see that for 0.5% link failure probability, blocking probability is 1.8% for the PFR_RS algorithm and it is only 0.2% for the PFR_LS algorithm. For the PFR_RS algorithm blocking is increased more sharply than that of the PFR_LS. If we concentrate at the peak points of both curves then we see that for 6% link failure probability blocking is 14.9% for the PFR_RS algorithm and 8.1% for the PFR_LS algorithm which ensures the first statement again. We can also see in Figures 6-9 that for some ranges of disconnected paths, the probability of blocking reduces prior to an increase afterward. This occurs because there are certain disconnected paths on the route of possible blocking connections that do not conflict with the designated route, allowing the designated route to successfully build the connection.

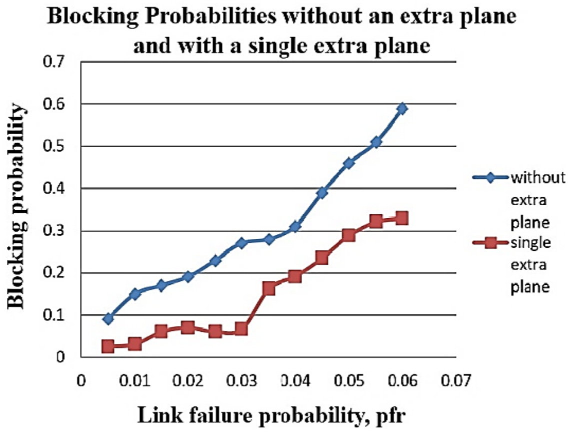


Figure 6. Simulated results showing blocking probability vs link failure probability of an extended pruned VSOB network without an extra plane and with a single extra plane

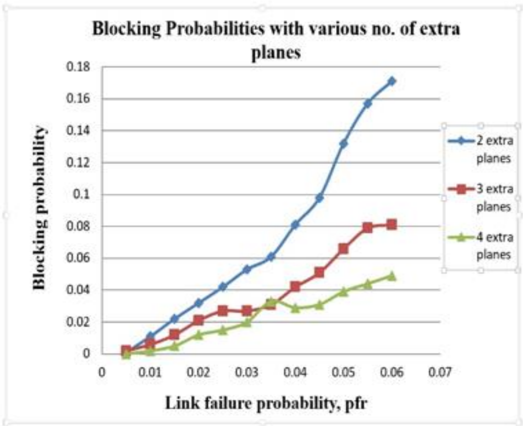


Figure 7. Simulated results showing blocking probability vs link failure probability of an extended pruned VSOB with two to four extra planes

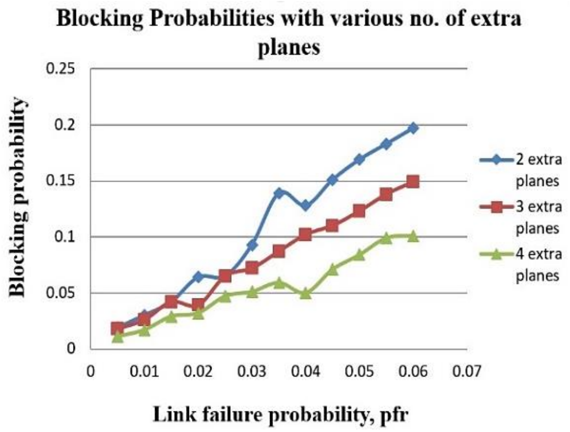


Figure 8. Simulated results showing blocking probability vs link failure probability of an extended pruned VSOB with two to four extra planes

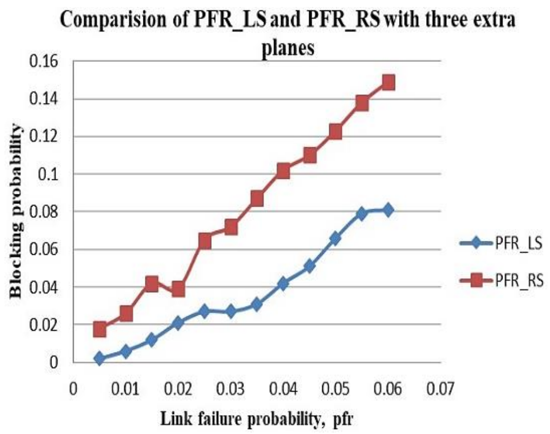


Figure 9. Simulated results showing a comparison of blocking probability vs. link failure probability observed from plane fixed routing linear search and plane fixed routing random search algorithms with three extra planes

4. CONCLUSION

In this research work, the probability of blocking for an extended pruned vertically stacked optical banyan network including connection failure conditions has been investigated. Two algorithms, PFR_LS and PFR_RS, were used for routing optical data. We have simulated five independent simulations for each routing algorithm. When there is no extra plane or a single extra plane, blocking probabilities are the same whether the routing algorithm is PFR_LS or PFR_RS. The rate of falling decreases for the no. extra planes EP>2. So it is clear that adding extra planes will not be an advantageous step excluding some special cases where a reduction of 1% blocking can make a great benefit. From our simulation results, we observed that blocking probability usually increased with link failures but at some points blocking decreased with the increasing link failure conditions. This may happen for the reason that at those points most of the input requests demand those paths where most link failure occurs. Our simulation shows that, despite having a greater number of switching components, the EP-VSOB network has a higher level of fault tolerance than the P-VSOB network. We also observed that the PFR_LS algorithm outperforms the PFR_RS algorithm significantly. This paper will help the optical switching network manufacturer to provide a network with better performance and less vulnerability.

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