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Analyzing the performance of optical multistage interconnection networks with limited crosstalk

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Abstract Analytical modeling techniques can be used to study the performance of optical multistage interconnection network (OMIN) effectively. MINs have assumed importance in recent times, because of their cost-effectiveness. An $N \times N$ MIN consists of a mapping from N processors to N memories, with $\log_2 N$ stages of 2×2 switches with $N/2$ switches per stage. The interest is on the study of the performance of unbuffered optical multistage interconnection network using the banyan network. The uniform reference model approach is assumed for the purpose of analysis. In this paper the analytical modeling approach is applied to an $N \times N$ OMIN with limited crosstalk (conflicts between messages) up to $(\log_2 N - 1)$. Messages with switch conflicts satisfying the constraint of $(\log_2 N - 1)$ are allowed to pass in the same group, but in case of a link conflict, the message is routed in a different group. The analysis is performed by calculating the bandwidth and throughput of the network operating under a load l and allowing random traffic and using a greedy routing strategy. A number of equations are derived using the theory of probability and the performance curves are plotted. The results obtained show that the performance of the network improves by allowing limited crosstalk in the network.

Keywords Bandwidth · Banyan network · Crosstalk · OMIN

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1 Introduction

Multistage Interconnection Networks (MINs) are very popular in switching and communication applications and have been used in telecommunication and parallel computing systems for many years. This network consists of N inputs, N outputs, and n stages ($n = \log_2 N$). Each stage has $N/2$ switching elements (SEs); each SE has two inputs and two outputs connected in a certain pattern [1]. The most widely used MINs are the electronic MINs. With growing demand for bandwidth, optical technology is used to implement interconnection networks and switches [18, 22]. In electronic MINs electricity is used, where as in optical MINs (OMIN) light is used to transmit the messages.

The electronic MINs and the optical MINs have many similarities [24], but there are some fundamental differences between them such as the optical-loss during switching [7, 23] and the crosstalk problem in the optical switches [15, 18]. In this research, we focused on a network called the banyan network [24]. To transfer messages from a source address to a destination address on an optical banyan network without crosstalk, we need to divide the messages into several groups, and then deliver the messages using one time slot (pass) for each group, which is called the time division multiplexing (TDM) [1, 21]. In each group, the paths of the messages going through the network are crosstalk free [9, 12]. So, from the performance aspect, we want to separate the messages into groups such that no message conflicts arise with each other in the same group as well as to reduce the total number of the groups [9, 18]. In other words, the fewer passes the messages take to get transferred, the better the performance of the optical network. Previous research work was completely concentrated on allowing no crosstalk in the optical network [12, 17, 21].

But in this paper we propose a very interesting idea of allowing some crosstalk (limited crosstalk) in the optical network. Because as optical technology advances day-by-day (reduced noise leakage, noise re-correction devices), limited crosstalk can be tolerated, the need arises for studying this type of architecture from different angles and the performance evaluated. We will only allow switch conflicts [21] and check that there are no link conflicts [26], even when crosstalk is permitted in the proposed optical network. The link conflicts are not allowed because two messages cannot traverse along the same link at the same time [14, 18]. We will evaluate the performance of such an optical network (network with limited crosstalk) by doing probabilistic analysis to find out the bandwidth and throughput of the network by varying the load and allowing random traffic and using a greedy routing strategy.

Analytical modeling is a cost effective technique used to study the performance of a computer system. However, any real system is too complex to be modeled exactly. To make an analytical model tractable, certain assumptions are necessary [3]. “MINs have assumed importance in recent times because of their cost-effectiveness”. They allow a rich subset of one to one and simultaneous mappings of processors to memory modules, while reducing the hardware cost to $O(N \log N)$ in contrast to $O(N^2)$ for crossbar networks [4]. An $N \times N$ MIN consists of a mapping from N processors to N memories. For N a power of two, it employs $\log_2 N$ stages of 2×2 switches with $N/2$ switches per stage. Many significant MINs, such as banyan, generalized cube, baseline etc., have been proposed [6, 20]. However, most of these networks are similar except for the interconnection between the adjacent stages [2]. The switch size in an MIN need not be restricted to 2×2. In fact, the butterfly parallel processor connects N inputs to N outputs using 4×4 crossbar switches and $\log_4 N$ stages with $N/4$ switches per stage. A Delta network can connect $M = a^n$ inputs to $N = b^n$ outputs through n stages of $a \times b$ crossbar switches [7]. The generalized shuffle network (GSN) is capable of connecting any $M = m_1 \times m_2 \times \cdots \times m_r$ inputs to $N = n_1 \times n_2 \times \cdots \times n_r$ outputs through r stages of switches. The ith stage employs $m_i \times n_i$ crossbar switches and is preceded by a generalized shuffle interconnection that is essentially a super set of the omega and delta interconnections. This is the most generalized version of an MIN that allows different input and output sizes, and all the other networks can be obtained by choosing the m_is and n_is, appropriately. For example, when $m_i = a$, $n_i = b$ for all is, it is a delta network; $m_i = n_i = 2$ for all is gives an omega network; $r = 1$ gives a crossbar; and $M = M \times 1$ and $N = N \times 1$ provides a shared-bus connection.

In this paper we study the performance of unbuffered optical multistage interconnection networks by using the banyan network [5, 8, 20]. Many significant MINs, such as the banyan, generalized cube, baseline, and delta are similar except for the interconnection between the adjacent stages [7, 10, 16]. Hence it is sufficient to study the performance of any one of these networks. We consider the packet-switching networks built of switches connected by unidirectional lines. A p input, q output ($p \times q$) switch can receive packets at each of its q output ports. A network is a directed graph where nodes are of the following three types [10]:

(1) Source nodes which have indegree 0;
(2) Sink nodes which have outdegree 0;
(3) Switches which have positive indegree and outdegree.

Each edge represents only one line (link) going from a node to a successor [6]. A banyan network is defined by Goke and Lipovsky [8, 20] to be a network with a unique path from source node to each sink node. This condition implies that the set of paths leading to a node in the network forms a tree and that the set of paths leading from a node also forms a tree. A multistage network is a network in which the nodes can be arranged in stages, with all the source nodes at stage 0, and all the outputs at stage i connected to inputs at stage $i + 1$. If all the sink nodes of a multistage network are at stage $n + 1$ then we have an n-stage network. A uniform network is a multistage network in which all switches at the same stage have the same number of input ports and the same number of output ports. A square network of degree k is a network built of $k \times k$ switches.

2 Assumptions made for the analysis

Most of the interconnection network analyses assume identical processors and a uniform reference model (URM). The URM implies that, when a processor makes a memory request to the global memory, the request will be directed to any one of the M memory modules with the same probability $1/M$. That is, the destination address of a memory request is uniformly distributed among M memory modules. For the MIN the M memory modules are the M inputs of an $M \times N$ interconnection network. This assumption provides us with the symmetric property, significantly simplifying the modeling.

The performance of the n-stage banyan square networks discussed in this paper is analyzed under the following assumptions [7, 10, 16]:

(1) Fixed size packets are generated by the modules at each source node.

(2) Arrival of packets at the network inputs are independent and identical Bernoulli processes.
(3) Each processor generates with probability p at each cycle a packet, and sends a generated packet with equal probability to any sink node. We assume that the network is synchronous, so that packets can be sent only at time t_c, $2t_c$, $3t_c$, where t_c is the network cycle time.
(4) The network is fault-free and all the switches in the network are synchronized by a single clock.
(5) A connection between two switches (link) can carry one packet in each clock cycle.
(6) If two packets arriving at two distinct network inputs require the use of a common link between two stages, one of the packets is discarded.
(7) The switches and links have no internal buffers to temporarily store an incoming packet that cannot be forwarded in the current cycle [11].
(8) There is no blocking at the output links of the network. This means that the output links have at least the same speed as the internal links.

The uniqueness of paths in banyan networks implies the following result which is implicitly used in the performance analyses of all these networks.

Lemma Let packets be generated at the source nodes of a banyan network by independent, identically distributed random processes, which uniformly distribute the packets over all the sink nodes. Assuming that the routing logic at each switch is "fair," i.e., conflicts are randomly resolved, then

(1) The patterns of packets arrivals at the inputs of the same switch are independent.
(2) Packets arriving at an input of a switch are uniformly distributed over the outputs of that switch.

Moreover, if the network is uniform, then for each stage in the network, the patterns of packet arrivals at the inputs of that stage have the same distribution. While banyan networks are very attractive in their simplicity, other considerations such as performance or reliability sometimes dictate the use of more complicated networks. We consider packet-switching networks built of 2×2 unbuffered switches with the topology of an n-stage square banyan network [8, 19, 20]. When several packets at the same switch require the same output, a randomly chosen packet is forwarded and the remaining packets are deleted. An 8×8 banyan network is shown in Fig. 1.

3 Analysis

In OMINs, at any instant of time we can only send one message through any switch to avoid the effect of crosstalk. But here in this paper for an $N \times N$ network we allow limited crosstalk's up to $C = (\log_2 N - 1)$ (where 'C' is a parameter dependent on technology). The number of stages for such a network is given by $n = \log_2 N$. Hence for the banyan network shown in Fig. 1 we can allow crosstalk in switches at two stages out of the three stages in the network. Hence in this paper we can have switches where 0, 1 or 2 messages can be allowed at the same time. In other words a switch can be 2-active, 1-active or 0-active. Both 0-active and 1-active switches do not allow any crosstalk where as the 2-active switch produces optical conflicts and hence could potentially contribute to crosstalk. We are most interested in analyzing the performance of a banyan network allowing limited crosstalk. For instance, one of the best ways for analyzing the performance is to calculate the bandwidth (BW) and the throughput of the $N \times N$ banyan network operating under a *load* l [13, 20]. Load is defined as the probability, that an input is active. Thus, the expected number of active inputs at load l for an $N \times N$ banyan network is Nl.

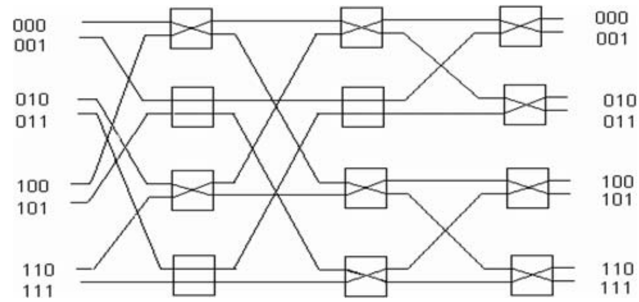


Fig. 1 An 8×8 banyan network

We derive some equations to find the bandwidth and throughput of such a banyan network built with 2×2 unbuffered switches. Let $P(j)$ be the probability that a request exists at an input link of a switch in stage j, and let $P(j+1)$ be the probability that an output link of this switch is used for routing a request. The analysis involves the iterative computation of $P(j+1)$ in terms of $P(j)$, starting with $P(1)$. For an n-stage network, the probability of acceptance, P_A is given by $P(n)$ [25]. The crucial step in the analysis of each network is the recurrence relation to specify $P(j+1)$ in terms of $P(j)$. The recurrence relation depends on the network topology and the routing algorithm. Since we are dealing with a banyan network with 2-active, 1-active or 0-active switches, for each stage j $(1 \le j \le n)$, we define:

$P_2(j) =$ probability that a given switch is 2-active.

$P_1(j) =$ probability that a given switch is 1-active.

$P_0(j) =$ probability that a given switch is 0-active.

Given the definition of load at stage 1, for the switches shown in Fig. 2 the following equations are derived:

1. If both inputs are active for a switch and are operating under load l, then according to the theory of probability, both inputs are selected and $P_2(j)$ is given by:

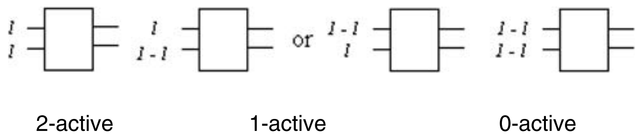


Fig. 2 Various combinations of load at stage 1

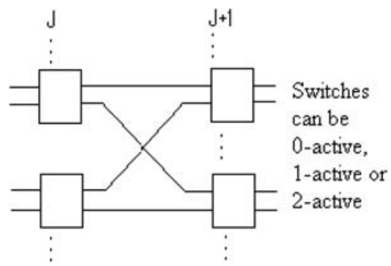


Fig. 3 Interconnection of switch pairs in two adjacent stages

$$P_2(j) = l \times l = l^2. \tag{1}$$

2. If only one input is active and the other is not, then one input is operating at load l and the other input is operating at load $(1-l)$. Hence according to the theory of probability, $P_1(j)$ is given by:

$$P_1(j) = l(1-l) + (1-l)l = 2l(1-l). \tag{2}$$

   We get a multiplier of two because any one of the inputs can be at load l and the other at $(1-l)$, and therefore we have to consider both the combinations while calculating the probability.
3. If both inputs are not active for a switch, then they are operating at load $(1-l)$, and according to the theory of probability, both inputs are not selected and $P_0(j)$ is given by:

$$P_0(j) = (1-l) \times (1-l) = (1-l)^2. \tag{3}$$

To proceed from one stage j to the next stage $j+1$ $(1 \le j \le n)$ in the banyan network, let us consider the two pair of switches in the two stages that are connected as shown in Fig. 3.

The equations for the next stage of a network always depend on its previous stage except for the first stage, which in turn depends on their previous stages. The following equations can be derived at the next stage for the connection pattern in Fig. 3.

1. For a switch to be 2-active at stage $j+1$ then the 2 switches in stage j from which the present switch gets its two inputs must be both 2-active, both 1-active or one of them be 2-active and the other be 1-active. No switch can be a 0-active switch in stage j because this combination of a 0-active with a 1-active or a 2-active switch at stage j does not lead to a 2-active switch combination at stage $j+1$. Hence according to the theory of probability, $P_2(j+1)$ is given by:

$$\begin{aligned} P_2(j+1) &= P_2(j) \times P_2(j) + \frac{P_1(j)}{2} \times P_2(j) \\ &\quad + P_2(j) \times \frac{P_1(j)}{2} + \frac{P_1(j)}{2} \times \frac{P_1(j)}{2} \\ &\Rightarrow P_2(j+1) = P_2(j)^2 + P_1(j)P_2(j) \\ &\quad + \frac{P_1(j)^2}{4}. \end{aligned} \tag{4}$$

2. For a switch to be 1-active at stage $j+1$ then the 2 switches in stage j from which the present switch gets its two inputs must be both one active, one of them 0-active and the other 1-active, one of them 0-active and the other 2-active or one of them 1-active and the other 2-active. Both switches in stage j of the network cannot be 2-active because this combination leads to a situation where in stage $j+1$ we will have a 2-active switch instead of the intended 1-active switch. Also both the switches in stage j cannot be 0-active because this combination leads to a situation where in stage $j+1$ we will have a 0-active switch instead of the intended 1-active switch. Hence according to the theory of probability, $P_1(j+1)$ is given by:

$$\begin{aligned} P_1(j+1) &= P_0(j)\frac{P_1(j)}{2} + \frac{P_1(j)}{2}P_0(j) + P_0(j)P_2(j) \\ &\quad + P_2(j)P_0(j) + \frac{P_1(j)}{2}P_2(j) \\ &\quad + P_2(j)\frac{P_1(j)}{2} + \frac{P_1(j)}{2} \times \frac{P_1(j)}{2} \\ &\Rightarrow P_1(j+1) = P_0(j)P_1(j) + 2P_0(j)P_2(j) \\ &\quad + P_1(j)P_2(j) + \frac{P_1(j)^2}{4}. \end{aligned} \tag{5}$$

3. For a switch to be 0-active at stage $j+1$ then the 2 switches in stage j from which the present switch gets its two inputs must be both 0-active, both 1-active or one of them 0-active and the other 1-active. No switch in stage j can be 2-active because this combination leads to a situation where in stage $j+1$ we will have at least a 1-active switch instead of the intended 0-active switch. Hence according to the theory of probability, $P_0(j+1)$ is given by:

$$\begin{aligned} P_0(j+1) &= P_0(j) \times P_0(j) + P_0(j)\frac{P_1(j)}{2} \\ &\quad + \frac{P_1(j)}{2}P_0(j) + \frac{P_1(j)}{2} \times \frac{P_1(j)}{2} \\ &\Rightarrow P_0(j+1) \\ &= P_0(j)^2 + P_0(j)P_1(j) + \frac{P_1(j)^2}{4}. \end{aligned} \tag{6}$$

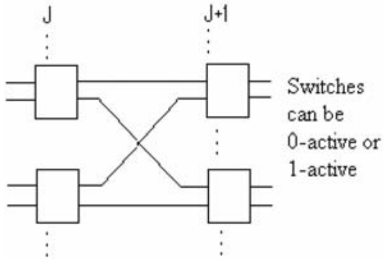


Fig. 4 Interconnection of switch pairs in two adjacent stages of an OMIN

For an n-stage banyan network the equations at the output are given by:

$$P_2(n) = P_2(n-1)^2 + P_1(n-1)P_2(n-1) + \frac{P_1(n-1)^2}{4}. \quad (7)$$

$$P_1(n) = P_0(n-1)P_1(n-1) + 2P_0(n-1)P_2(n-1) + P_1(n-1)P_2(n-1) + \frac{P_1(n-1)^2}{4}. \quad (8)$$

$$P_0(n) = P_0(n-1)^2 + P_0(n-1)P_1(n-1) + \frac{P_1(n-1)^2}{4}. \quad (9)$$

These equations are good for a network when we have all types of switches i.e.; 0-active, 1-active and 2-active. But if we do not allow any crosstalk in an optical multistage interconnection network, we can only have 1-active or 0-active switches because 2-active switches lead to crosstalk. To proceed from one stage j to the next stage $j+1 (1 \le j \le n)$ in the optical banyan network, let us consider the two pair of switches in the two stages that are connected as shown in Fig. 4.

1. For a switch to be 1-active at stage $j+1$ then the 2 switches in stage j from which the present switch gets its two inputs must be both one active or one of them 0-active and the other 1-active. No switch in any stage of the network can be 2-active, because this leads to switch crosstalk in the network. Also both the switches in stage j cannot be 0-active because this combination leads to a situation where in stage $j+1$ we will have a 0-active switch instead of the intended 1-active switch. Hence according to the theory of probability, $P_1(j+1)$ is given by:

$$P_1(j+1) = P_0(j)P_1(j) + \frac{P_1(j)^2}{4}. \quad (10)$$

2. For a switch to be 0-active at stage $j+1$ then the 2 switches in stage j from which the present switch gets its two inputs must be both 0-active, both 1-active or one of them 0-active and the other 1-active. No switch in stage j of the network can be 2-active because this combination leads to a situation where in stage $j+1$ we will have at least a 1-active switch instead of the intended 0-active switch. Hence according to the theory of probability, $P_0(j+1)$ is given by:

$$P_0(j+1) = P_0(j)^2 + P_0(j)P_1(j) + \frac{P_1(j)^2}{4}. \quad (11)$$

For an n-stage optical banyan network the equations at the output are given by:

$$P_1(n) = P_0(n-1)P_1(n-1) + \frac{P_1(n-1)^2}{4}. \quad (12)$$

$$P_0(n) = P_0(n-1)^2 + P_0(n-1)P_1(n-1) + \frac{P_1(n-1)^2}{4}. \quad (13)$$

4 Analytical results

"The Eqs. (1) to (13)", are utilized for the purpose of achieving some analytical results. The bandwidth of an n-stage banyan network ($N = 2^n$ is the network size) is given by:

$$BW = P(n) \times 2^n.$$

The value of $P(n)$ can be obtained from the probabilistic Eqs. (1) to (13).

Figure 5 shows the comparison of BW of a banyan network operating at a load $l = 0.9$ for different network sizes.

Figure 5 clearly illustrates that for a given load as the network size increases the bandwidth increases.

Figure 6 shows the BW of a banyan network operating under different loads of $l = 0.95$, $l = 0.9$, $l = 0.85$ respectively for different sizes of networks.

From Fig. 6 it is clear that for small network sizes, the bandwidth is nearly equal for different loads, but as the size of the network becomes large, the graph clearly illustrates that load plays a dominant factor on the bandwidth. At higher loads for a given load as the network size increases the bandwidth increases.

Figure 7 shows the BW of an optical banyan network to a non-optical banyan network operating at a load $l = 0.9$ for different network sizes. In optical banyan network we do not allow switch conflicts and hence the network does not contain any 2-active switches.

From Fig. 7 it is clear that as the network size increases the bandwidth increases. Also from Fig. 7 we observe that the bandwidth of a non-optical network is much more than

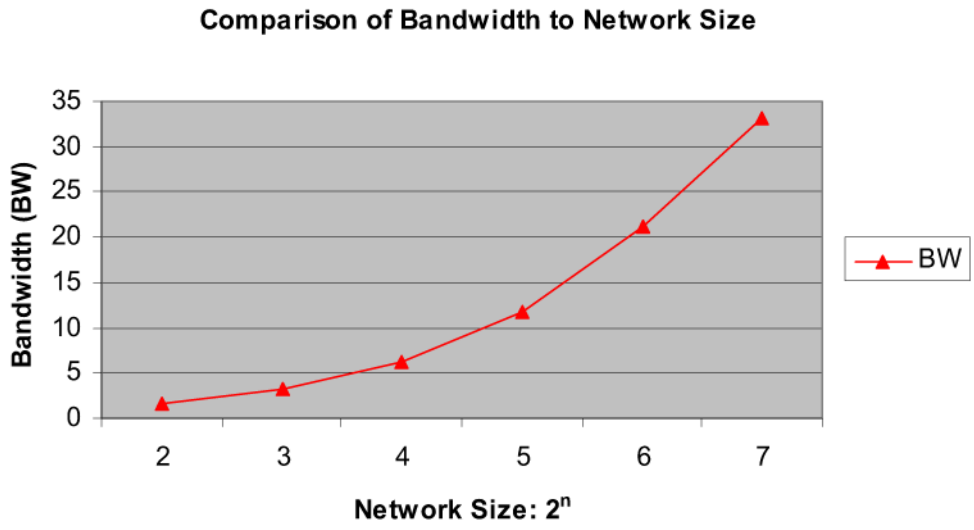


Fig. 5 Comparison of bandwidth to the network size

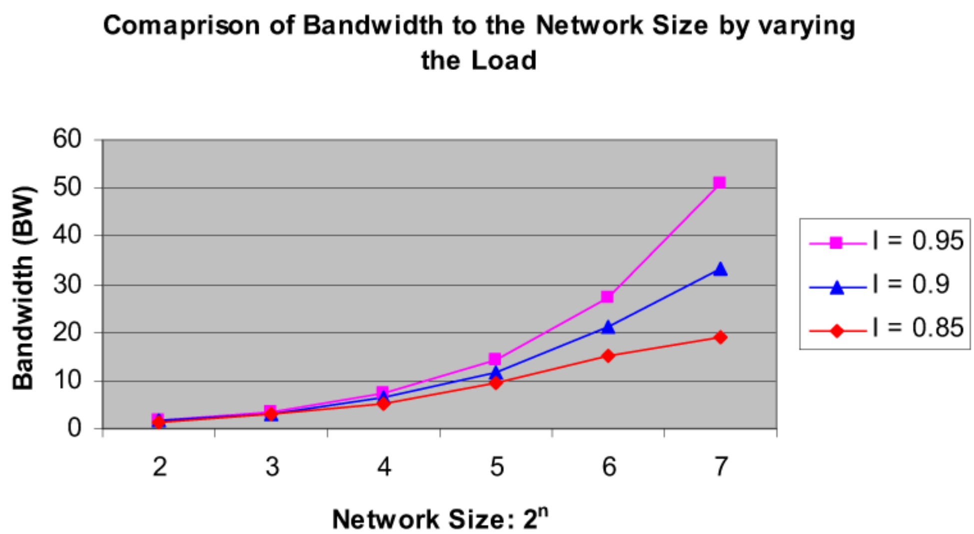


Fig. 6 Comparison of bandwidth to the network size by varying the load

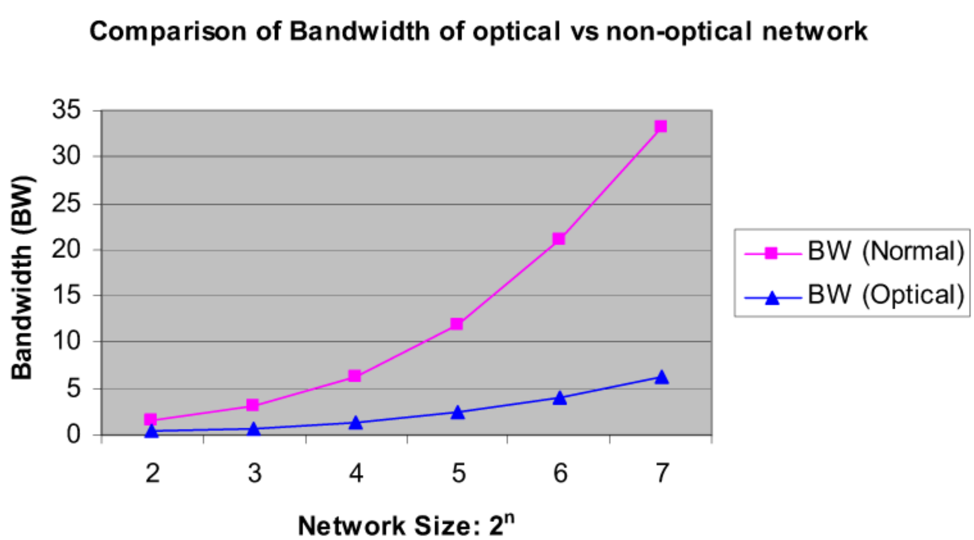


Fig. 7 Comparison of bandwidth of optical vs. non-optical network for different sizes of networks

Fig. 8 Comparison of bandwidth to the network size by varying the load for an optical Banyan network

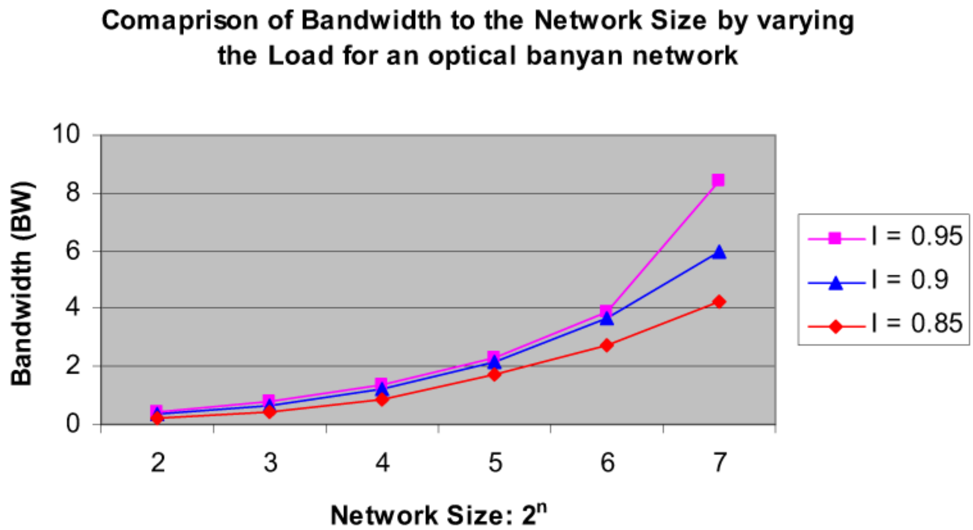
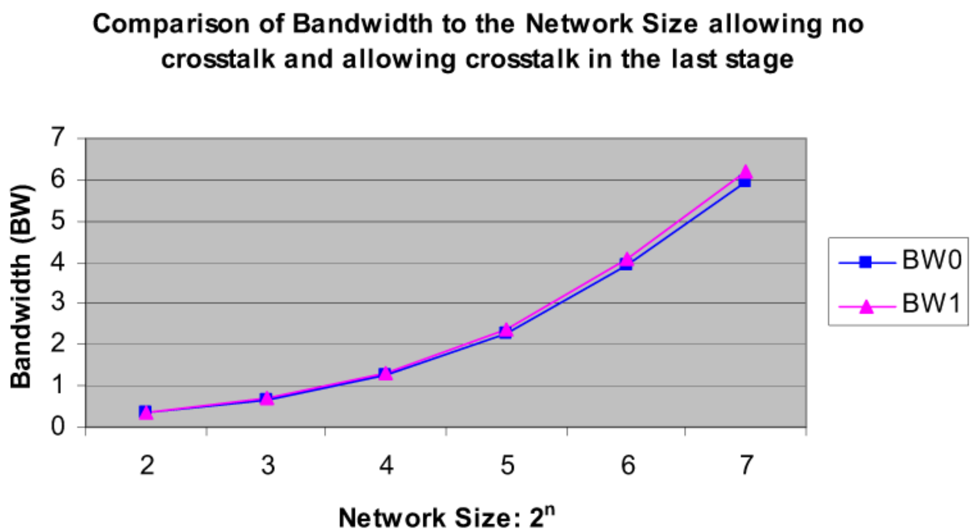


Fig. 9 Comparison of bandwidth to the network size allowing no crosstalk and allowing crosstalk in the last stage



that of an optical network. This is because in an optical network we do not allow any 2-active switches and hence few messages can be routed at a time, which causes a decrease in the bandwidth.

Figure 8 shows the BW of an optical banyan network operating under different loads of $l = 0.95$, $l = 0.9$, $l = 0.85$ respectively for different sizes of networks.

From Fig. 8 it is clear that for small optical banyan network sizes, the bandwidth is nearly equal for different loads, but as the size of the network becomes large, the graph clearly illustrates that load plays a dominant factor on the bandwidth. This behavior of the load playing a dominant role on the bandwidth is similar for both optical and non-optical banyan networks as shown in Fig. 8 and Fig. 6. At higher loads for a given load as the network size increases the bandwidth increases.

In our research we allow C ($C < \log_2 n$) limited crosstalk's. So for a network of size 8 we can allow crosstalk in 6 stages of the network.

Figure 9 shows the performance curve of an optical banyan network in which limited crosstalk is allowed at the last stage of the network to that in which no crosstalk is allowed. For this purpose we calculate the BW of such an optical banyan network operating at a load of $l = 0.9$ for different network sizes.

In Fig. 9 BW0 represents the bandwidth of an optical banyan network allowing no crosstalk and BW1 represents the bandwidth of an optical banyan network allowing crosstalk in the last stage. From Fig. 9 we can see that the performance improves if we allow some amount of crosstalk in the network.

Figure 10 shows the performance curve of an optical banyan network in which limited crosstalk is allowed at the last stage of the network to that in which no crosstalk is

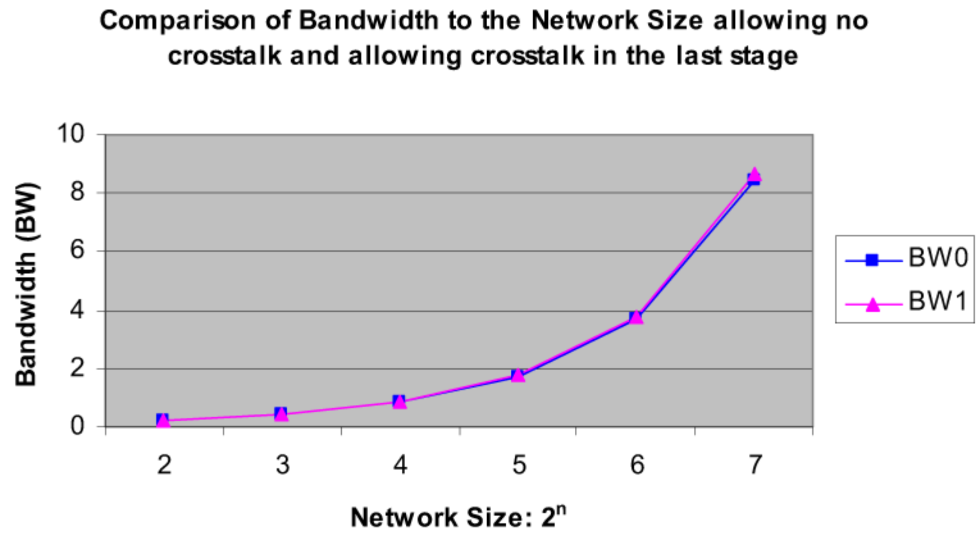


Fig. 10 comparison of bandwidth to the network size allowing no crosstalk and allowing crosstalk in the last stage

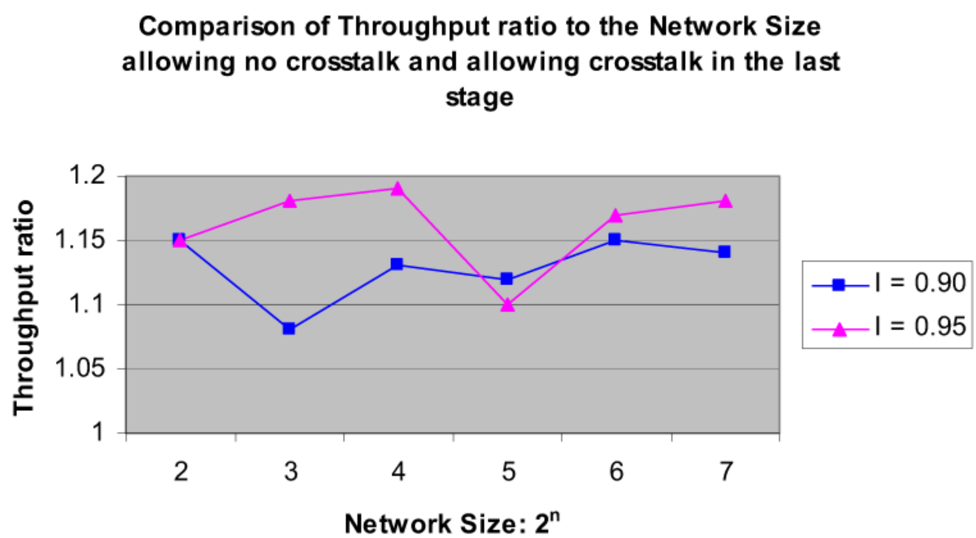


Fig. 11 Comparison of throughput ratio to the network size allowing no crosstalk and allowing crosstalk in the last stage

allowed. For this purpose we calculate the BW of such an optical banyan network operating at a load of $l = 0.95$ for different network sizes.

In Fig. 10 BW0 represents the bandwidth of an optical banyan network allowing no crosstalk and BW1 represents the bandwidth of an optical banyan network allowing crosstalk in the last stage. Again from Fig. 10 we can see that the performance improves if we allow some amount of crosstalk in the network. From Fig. 9 and Fig. 10 we can conclude that the performance improves if we allow some amount of crosstalk in the network.

Figure 11 shows the performance curve of an optical banyan network in which limited crosstalk is allowed at the last stage of the network to that in which no crosstalk is allowed. For this purpose we calculate the throughput ratio of such an optical banyan network operating at a load of $l = 0.9$ and $l = 0.95$ for different network sizes. The throughput ratio is obtained by dividing the bandwidth when limited crosstalk is allowed by the bandwidth when no crosstalk is allowed. A value of more than 1 for the throughput ratio indicates that the network with limited crosstalk performs better than the network without any crosstalk.

From Fig. 11 we can see that the throughput ratio is always greater than 1, which indicates that the performance improves if we allow some amount of crosstalk in the network.

5 Conclusion

In this research, we analyzed the performance of an OMIN with limited crosstalk by calculating the bandwidth and throughput of the network operating under a load l and allowing random traffic and using a greedy routing strategy. Equations are derived using the theory of probability and the performance curves are plotted. The results obtained show that the performance of the network improves by allowing limited crosstalk in the network.

In the future, research can be performed to analyze the performance of an OMIN with limited crosstalk under bursty traffic, uneven traffic and self-similar traffic conditions. More rigorous analysis can be performed by incorporating WDM or a combination of WDM and TDM into the banyan or benes networks and then analyzing the performance of the network with limited crosstalk.

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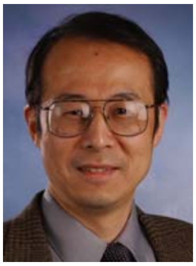

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