OPTIMIZATION ANALYSIS OF OPTICAL TIME SLOT INTERCHANGERS IN ALL-OPTICAL NETWORK

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ABSTRACT
A passive optical time slot interchanger (POTSI) is a simplified form of the Optical Time Slot Interchanger (OTSI). OTSIs are well known devices used in designing optical TDM switches to switch traffic in the time domain (i.e. inter-changing timeslot positions). Employing timeslot interchangers in optical TDM is similar to employing wavelength converters in WDM. The former converts between wavelengths, and the latter between timeslots. In this paper, we conduct a comparison between POTSI and the various OTSIs noted in the literature in terms of fiber length, crossbar size, and number of switching operations. Furthermore, we propose an optimized form of POTSI, Limited Range POTSI (POTSI-LR), which can switch a timeslot within a subset of nearby slots in a frame. We investigate the sharing of POTSI-LR as opposed to the dedication of one device per link. Finally, we analyze the network performance in terms of blocking probability and system complexity.

KEY WORDS
Optimization, time-slot interchanger, wavelength converter, performance model

1. Introduction

With the advent in WDM, many research initiatives focus on bandwidth sharing in all-optical networking (AON). In an all-optical network, traffic stays in the light domain after leaving the source node till it reaches the destination. Optical Packet Switching (OPS), Optical Burst Switching (OBS), and Optical Time Division Multiplexing (OTDM) are three major bandwidth sharing techniques that have received increased attention over the last few years.

Optical Packet Switching is the best candidate among the other techniques in terms of bandwidth utilization; however, the immaturity of all-optical devices and buffers renders this technique infeasible for the time being. In addition, the problem of packet header extraction and replacement increases the switch complexity beyond the current technology. Thus, OPS remains a research concept waiting for the emergence of efficient optical buffering and logical processing.

In the wait for a breakthrough in OPS, Optical Burst Switching seems to offer an interim solution. With OBS, a burst of traffic is aggregated electronically at the source node before being sent optically in the network. It is an attempt to benefit from electronic buffering at the source before sending traffic through the optical network. In addition, the packet header is replaced with a control header that travels ahead in time on a separate control channel. The control header is used to reserve resources on intermediate switches for a limited period, enough to forward the corresponding traffic burst. If a network resource happens to be busy or faulty, the burst is dropped. Clearly, a major disadvantage of OBS is the steep increase in packet loss as the traffic load gets higher. Several enhancements were introduced to reduce contention and improve loss ratio. Deflection routing, wavelength conversion, and fiber delay lines are the main contention resolution techniques.

Another candidate for filling the time gap between now and the emergence of OPS is Optical Time Division Multiplexing (OTDM). It reduces the granularity of traffic segments traveling in the network, maximizes bandwidth utilization, and reduces contention by proper scheduling. OTDM allows several connections to coexist on the same wavelength in a repeating frame of N timeslots. The same continuity constraint problem existing in Wavelength Routing also exists in OTDM. A traffic segment arriving on a given timeslot is blocked if the corresponding outgoing slot is busy.

1.1 Optical Time Slot Interchanger (OTSI)

The Optical Time Slot Interchanger (OTSI) was investigated in the literature as a possible solution for contention. An OTSI serves as an optical component that switches between timeslots. The OTSI is made of an optical crossbar and a number of variable size fiber delay lines (FDL) needed to induce factors of timeslot delay. Each FDL starts from and ends at the optical crossbar. When a traffic segment in a timeslot enters an OTSI, it gets circulated through an appropriate selection of delay lines, before exiting the interchanger in another timeslot.

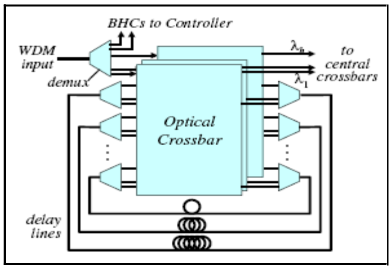

Figure 1: 1, 2, …, N-1 OTSI Architecture

The three basic characteristics that would affect the cost and performance of an OTSI are the size of its internal crossbar, the total length of delay lines, and the number of switching operations to achieve one slot interchanging task. In [1], Turner et al. compare the characteristics of several types of OTSIs based on the crossbar size, fiber length, and number of switching operations. Table 1 features the result of this comparison. OTSIs are classified under two categories: blocking and non-blocking. A non-blocking OTSI, having a crossbar size of $N+1 \times N+1$, is made of N delay lines, where each corresponds to 1 timeslot in length. To delay a timeslot j by d timeslot positions, the traffic at slot j gets re-circulated/switched d times in the j^{th} delay lines before being switched out. To reduce the number of required switching operations to just 2, an OTSI made of N-1 delay lines of size 1, 2, …, N-1 respectively can be adopted. See figure (1). A more practical approach, which cuts on fiber length, is to use a set of delay lines of size 1, 2, …, A, with another set of lines of size 2A, 3A, …, (B-1)A, where A and B are integer values. In the last two approaches, the number of switching operations was reduced to a maximum of 3 at the expense of a longer fiber length. A re-arrangeably non-blocking OTSI, made of 2 sets of fiber lines of size 1, 2, 4, …, N/4, and a single fiber line of size N/2, minimizes the crossbar size and total fiber length in the non-blocking category. As a further improvement, a blocking OTSI, made of N/2 fiber lines of size 1, 2, …, N/2, reduces the fiber length and crossbar size to N/2 and $log2N \times log2N$ respectively.

1.2 Passive optical time slot interchanger (POTSI)

In [2], we proposed a similar slot delaying technique, but with different characteristics. We called the employed device Sequencer, to which we will refer in this paper as passive optical time slot interchanger (POTSI). The proposed POTSI is made of a multi-input queue of N sequentially connected fiber delay lines, and an optical crossbar connected to the N inputs of the queue; see figure (2). The delay imposed by every FDL is exactly equal to one timeslot period. To delay a timeslot by d slot positions, the crossbar directs the slot to the d^{th} FDL in the multi-input queue; from that point, traffic flows passively through d FDLs before reaching the output point of the queue. In this case, a traffic segment experiences a delay in the POTSI equal to $d \times T$, where T is the timeslot period. The total length of the delay lines employed in the passive interchanger is a factor of N, and the number of needed switching per time slot is 1. Furthermore, the size of the optical crossbar is 1 × N. The device is non-blocking based on the following definition: a non-blocking interchanger is always capable of delaying two different timeslots i and j by d_i and d_j as far as $i + d_i \neq j + d_j$. A major concern with this architecture is the insertion loss caused by the coupling of optical signal at each delay unit. To work around such limitation we need to interleave a few amplifiers among the FDLs depending on the loss ratio of optical couplers and fiber lines.

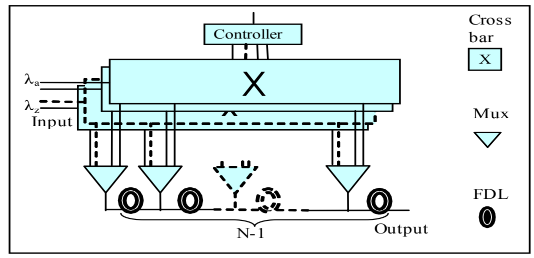

Figure 2: Exported Topologies of Agile All-Photonic Network

It is evident that the POTSI provides the best number of switching operations, crossbar size and total fiber length in the non-blocking family of interchangers. In this paper, we investigate a new optimized form of POTSI, where the number of FDLs is reduced to a fraction of N, and hence the crossbar size and number of amplifiers. In addition, we investigate the sharing of POTSIs as opposed to using dedicated POTSI per link in the optical switch. Due to the apparent functional similarity between OTSI and optical wavelength converter, we dedicate a section summarizing the similarity and differences between the two devices. We then present an analytical model in Section 4. Before concluding, we discuss numerical and simulation results in Section 5.

2. Limited Range POTSI in Shared Switch Architecture

2.1 Limited-Range POTSI (POTSI-LR)

We propose the limited-range POTSI (POTSI-LR) as an attempt to reduce the switch complexity and fiber length. It was proven in the literature that a limited range wavelength converter, having a 30 percent conversion range, achieves the same network performance of a full range converter [7]. Similarly, we believe that the same conclusion, if not better, can be applied in the case of POTSI-LR. In this work, we consider a POTSI-LR of size M ($M < N$). A POTSI of interchanging-range M is capable of delaying timeslot i to timeslot j if $i < j < i + M < N$, or $0 < j < (i + M \bmod N)$. We denote the interchanging rage as M/N.

TABLE 1: OTSI ARCHITECTURE COMPARISON

Delay Lines per OTSI	Crossbar Size	Fiber Length	Switching operations	Blocking Type
N	N+1 × N+1	N	N	Non Blocking
1, 2, . . .,N - 1	N × N	$N^2/2$	2	
1, . . . , A, 2A, . . . , (B - 1)A	$2\sqrt{N}-1 \times 2\sqrt{N}-1$	$N\sqrt{N}/2$	3	
2 × (1, 2, 4, ..., N/4),N/2	2 $\log_2$ N × 2 $\log_2$ N	(3N/2) - 2	2($\log_2$ N) - 1	
1, 2, . . . , N/2	$\log_2$ N × $\log_2$ N	N – 1	Variable (3 for N = 256)	Blocking
POTSI size N-1	1 × N-1	N	1	Non Blocking
POTSI size M (1 < M < N)	1 × M	M	1	

2.2 Shared Switch Architecture

In [2], we proposed a switch architecture having one POTSI of size N per output line. In this paper, we employ a shared POTSI-LR architecture as show in figure (3). Each node has a pool of POTSIs to share. We define the sharing-percentage, as

$$\frac{\#\ of\ LR\text{-}POTSI\ shared\ per\ node}{Node\ degree}.$$

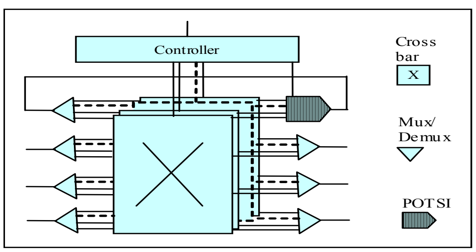

Figure 3: Shared OTSI Architecture

3. OTSI Vs Wavelength Converter

By definition, an all-optical wavelength converter (OWC) converts wavelength λx to λy by pure optical means without opto-electronic processing. Similarly, OTSI converts between timeslots instead of wavelengths. At this point, many researchers concluded that both devices would yield similar results in terms of network performance. In fact, this conclusion is not very precise. An OWC can serve only one call, riding on a wavelength, during a given period; on the other hand, an OTSI can serve multiple concurrent calls, riding on different timeslots during the same period. Thus, it is closer to the truth to say that an OTSI, in an OTDM node, achieves similar performance improvement to a bank of N OWCs in a Wavelength Routed Optical Network (WRON) node, where N is the number of timeslots per frame in the network.

We say that the above conclusion is very close to the truth, and not completely true, because of a little discrepancy when considering limited-range conversion. A full range converter covers the whole spectrum of wavelengths in a WDM system. A limited range converter covers a subset of the WDM spectrum; the covered spectrum is relative to the input wavelength, and is between $-k$ and $+k$ from that wavelength. A wavelength within a distance j from the boundaries of the WDM spectrum, where $j < k$, cannot take full conversion advantage of the limited range converter. In contrast, thinking of a limited range OTSI, we see that this limitation does not exist. An interchanger has the capability of delaying one timeslot beyond its frame boundaries to another timeslot in the next frame.

One final discrepancy is the size. Wavelength converters are tiny in size as compared to the bulky nature of the OTSI. As defined, an OTSI is made of a number of FDLs each having a delay capacity equal to one timeslot. By a quick calculation, we derive that 2 km of fiber is needed to form one FDL that delays a timeslot equal to 10 µs. Given that the diameter of a single mode fiber is around 150 µm, the volume of one FDL cable is close to 45 cm^3.

4. Analytical Modeling

In this section, we develop a performance model (in terms of blocking probabilities) to study the effect of POTSI optimization. The basic idea of our analytical model is to divide a path into several segments spanning between intermediate nodes that have no POTSI available (see Fig. 4.). Accordingly, our analytical model consists of four parts: a path-level model, a segment-level model, a link-level model, and an interchanger-state model.

4.1 Assumptions and System Parameters

1) Each link in the network has one wavelength; each wavelength consists of N time-slots per frame.
2) Calls for a node pair R arrive according to an independent stationary Poisson process with rate λ_R. Each call requires a full time-slot on each link of its path.
3) The duration of each call is exponentially distributed with a mean of one unit ($1/\mu = 1$).
4) We assume fixed routing, where each node-pair has one single pre-determined route.
5) A POTSI (with interchanging-range M) is used only when there is no common free time-slot along the path.
6) The number of POTSIs in the POTSI pool is is $f \times D(n) \times N$, where $D(n)$ is the degree of node n and f is the sharing-percentage.
7) We assume that the state of a time-slot on link j is independent of the state of timeslots on link $j-1$.This is also called link-load independence assumption.

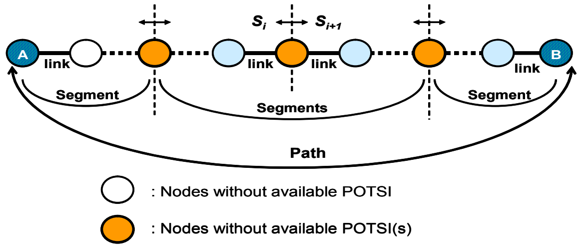

Fig. 4: A path can be segmented into segments spanning between nodes without available POTSI. Each segment comprises of link(s).

4.2 Link-level Model

The number of idle time-slots on link j can be viewed as a birth-death process. The arriving and serving behavior on link j forms an M/M/N/N system. Since all the states in the associated Markov chain are ergodic, the equilibrium state distribution of the chain can be derived as follows:

$$q_j(m) = \frac{N(N-1)...(N-m+1)}{\alpha_j(1)\alpha_j(2)...\alpha_j(m)} q_j(0) \tag{1}$$

where,

$$q_j(0) = \left[1 + \sum_{m=1}^{N} \frac{N(N-1)...(N-m+1)}{\alpha_j(1)\alpha_j(2)...\alpha_j(m)}\right]^{-1} \tag{2}$$

$q_j(m)$ is the probability that exactly m time-slots are idle on link j. $\alpha_j(m)$ is the state-dependent traffic arrival rate on link j and can be obtained approximately, [6], as follows:

$$\alpha_j(m) = \sum_{R: j \in R} \lambda_R \tag{3}$$

4.3 Segment-level Model

A segment consists of several connected links. Note that the time-slot continuity constraint must be followed within the segment.

Suppose a segment is two-hop (link *j* and *j+1*). We denote Y_S and X_j as the random variables represent the number of idle time-slots on the segment *S* and link *j*, respectively. Then using the link-load independence assumption and total probability, we have

$$\Pr\left\{Y_S^{(2)} = k\right\} = \sum_{i=0}^{N}\sum_{l=0}^{N} \Pr\left\{X_S = k \mid X_j = i, X_{j+1} = l\right\} \times q_j(i) \times q_j(l) \tag{4}$$

where

$$\Pr\left\{Y_S = k \mid X_j = i, X_{j+1} = l\right\} = \binom{l}{k} \times \binom{N-l}{i-k} \Big/ \binom{N}{i} \tag{5}$$

Regarding an h-hop (h>2) segment, it can be derived recursively:

$$\Pr\left\{Y_R^{(h)} = k\right\} = \sum_{i=0}^{N}\sum_{l=0}^{N} \Pr\left\{X_R^{(h)} = k \mid X_R^{(h-1)} = i, X_h = l\right\} \times \Pr\left\{X_R^{(h-1)} = i\right\} \times q_h(l) \tag{6}$$

4.3 Path-level Model

Now suppose a path *R* consists of two segment, S_1 and S_2. Then, the blocking probability of the path *R*, $P_{R:S_1,S_2}$, can be computed as follows.

$$P_{R:S_1,S_2} = \sum_{x \ge 0}\sum_{y \ge 0} \Pr^{(r)}(Y_R = 0 \mid Y_{S_1} = x, Y_{S_2} = y) \times \Pr\left\{Y_{S_1} = x\right\} \times \Pr\left\{Y_{S_1} = y\right\} \tag{7}$$

If segment S_1 has *x* time-slots free, and S_2 has y time-slots free, then the probability of S_1 and S_2 having common *m* time-slots free, given the absolute range of time-slot interchanger as *M*, and $\Pr^{(M)}(Y_R = m \mid Y_{S_1} = x, Y_{S_2} = y)$, can be obtained by extending Tripathi's work [3]:

$$\Pr^{(M)}(m \mid x, y) = \sum_{k=\min(N, x+M)}^{\min(N, x \cdot M)} \binom{k}{m} \times \binom{N-k}{y-m} \Big/ \binom{N}{y} \times \left[\binom{N}{1}\binom{k-M}{x} \Big/ \binom{N}{x} - \binom{N}{1}\binom{k-M-1}{x} \Big/ \binom{N}{x}\right] \tag{8}$$

Let *m*=0 in (8), plus (4-6), we can compute (7). Meanwhile, if the path *R* consists of more than two segments, the blocking probability of path *R* can be computed recursively, just like what we did in Equation (6).

However, the segmentation of route *R* is decided by whether the nodes along *R* have free POTSI or not, which we named as interchanger-state, denoted by *Z*. Then the blocking probability of path *R*, B_R, is

$$B_R = \sum_Z \left[P_{R:S_1,S_2,...,S_s} \times P_R(Z)\right] \tag{9}$$

where, $P_{R:S_1,S_2,...,S_s}$ is the blocking probability of path *R* when *R* is segmented into segments S_1, S_1, ... S_s ; $P_R(Z)$ is the probability of path *R* in associated interchanger-state *Z*.

4.4 Interchanger-state Model

According to its definition, we have $P_R(Z) = \prod_{n=1}^{T_R} E_R^{(n)}$,

where T_R is the number of transit nodes along R, $E_R^{(n)}$ is the interchanger-state probability of node n along path R, and

$$E_R^{(n)} = \begin{cases} P_{R,n}(0), & \text{without available POTSI at node } n; \\ 1 - P_{R,n}(0), & \text{with available POTSI at node } n. \end{cases} \tag{10}$$

To compute $P_{R,n}(0)$, we involve the concept of virtual "unit-POTSI". This is inspired by the discussion in Section III. A POTSI in an OTDM node (with *N* as the frame size) achieves the same performance improvement of a bank of *N* OWCs in a WRON node (with no TDM). We, thus, assume one POTSI equals a bank of *N* identical unit-POTSIs. Each unit-POTSI has the same interchanging-range as the original POTSI. In addition, a shared bank of unit-POTSIs is assumed in the shared POTSI architecture. Hence $P_{R,n}(0)$ can be derived from M/M/V/V model as follows by assuming Poisson traffic arrival:

$$P_{R,n}(0) = \left[1 + \sum_{m=1}^{M} \frac{V(V-1)\ldots(V-m+1)}{\beta_j^{\,m}} \right]^{-1} \qquad (11)$$

where $\beta_j = \sum_{R:j\in R} \lambda_R (1-B_R)\Pr(X_R = 0)$, (see assumption 5); and $V = f \times D(n) \times N$ (12)

4.5 Analysis of a Network

From the above analysis, a set of non-linearly coupled equations (Equ. 1-3, 5, 6, 8-12) serves for the computation of network-wide blocking probabilities, which is the ratio of the total blocked load versus the total offered load. A simple iterative method is used accordingly to find the solution by repeated substitution [8]. In practice, the solutions converge in a few iterations for a variety of topologies

5. Numerical Results and Discussion

In this section, we study the optimization of two key POTSI configuration parameters, i.e., the sharing-percentage and interchanging-range, through analytical and simulation results.

The accuracy of our analytical model is demonstrated by comparing the analytical results to the simulation. Simulation results are plotted along with 95% confidence intervals estimated by the method of replications. The number of replications is 30; with each simulation run lasting until at least 100,000 arrivals. For the analytical results, we have terminated the iterative algorithm when all blocking probability values have converged within 10^{-5}.

Both the analytical model and simulation experiments are conducted on the 14-node 21-link NSFNET network topology [8]. In the simulations, the call requests arrive at the network following a Poisson process, and the call holding time is exponentially distributed. We assume that all the source-destination node pairs have the same traffic load in Erlang. Each fiber link has a fixed capacity (20 timeslot channels). Fixed shortest path routing is used to calculate the shortest path (in hop-counts) for each node pair. The granularity of a connection is an optical-trail, which occupies one time-slot on each link along the route. To find out the optimal values of the sharing-percentage and the interchanging-range with finer granularity and exactness, we start our discussions with unit-POTSI as minimum unit.

5.1 Optimal sharing-percentage and interchanging-range of unit-POTSI bank

Figure (5) and (6) demonstrate the numerical results obtained from our analytical model for the NSFNET network. It can be observed in figure (5) that the network-wide blocking probabilities increase as the network load becomes heavier. In addition, the big difference between the blocking performance curves indicates that deploying POTSIs can substantially improve the performance. However, it is not necessary to deploy dedicated full interchanging-range POTIs, i.e., one full range POTSI per output port in each node, to achieve such a big performance improvement. As seen in figure (5), reducing the number of POTSIs (represented by sharing-percentage) and decreasing the interchanging-range of POTSIs at the same time can yield almost the same improvement. Especially, we find that both parameters can decrease to 20%-30% without affecting the performance improvement.

Based on our previous comparison between OWC and OTSI, the conclusions we obtained in this paper can be applied directly to wavelength conversion in wavelength routed networks.

Furthermore, we present the blocking performance curves of various combinations of these two parameters in figure (6). We have the following observations:

1) When the POTSI interchanging-range is not less than 50%, the sharing-percentage of POTSIs bank can be as small as 10%.
2) When the sharing-percentage range of a POTSIs bank is not less 50%, the interchanging-range of POTSIs can be as small as 20%-30%. Both of the above observations match the conclusions of using OWCs in wavelength-routed WDM networks [3, 4, 5, and 6].
3) It seams that the effect of the sharing-percentage on network-wide blocking probability is stronger than that of the interchanging-range. The most efficient combination of these two parameters in a POTSI bank is 20% (sharing-percentage) and 30% (interchanging-range) to achieve comparable performance to that of dedicated full-range POTSI. Increasing any of these parameters will improve blocking performance for sure, but not too much; while decreasing any of these two will substantially degrade the blocking performance.

5.2 Optimally Deploying POTSI

We now can use the above observations to deploy POTSI physically and optimally. In the NSFNET network, most nodes have a nodal degree equal to 3. Hence, we claim that only one shared POTSI, having an interchanging-range of 30%, is enough to achieve very close performance to that of dedicated-full-range POTSI. In practice, this conclusion shows that the cost and crossbar complexity of deploying timeslot interchangers can be substantially reduced and still maintain close to optimal performance gain. Both the analytical (figure 7a) and simulation results (figure 7b) proved the above claim. Meanwhile, figure (7b) compares the numerical results obtained from the analytical models to those from simulation experiments. The numerical results of NSFNET conform closely to the simulation results. It confirms the correctness of our analytical model developed in Section IV in general. As a further step, our future work will focus on sparse deployment of POTSI.

6. Conclusion

Compared to the non-blocking family of optical timeslot interchangers noted in the literature, the passive optical time slot interchanger (POTSI), proposed in an earlier work [2], has the best number of switching operations, crossbar size and total fiber length. This paper addresses the optimization issue of POTSI: we propose an optimized form of POTSI, Limited-Range POTSI (POTSI-LR), whose capability is limited to switching a timeslot to a subset of nearby timeslots in the frame instead of all possible timeslots. Meanwhile, we investigate the sharing of POTSI-LR as opposed to dedicating one device to each ongoing link. Through analytical and simulation results, we show that deploying shared limited-range POTSIs can achieve blocking probabilities very close to those of dedicated full-interchanging-range POTSIs. Precisely, the POTSI sharing-percentage can be as small as 20% of the nodal degree together with an interchanging-range as small as 30%. Thus, the overall cost and crossbar complexity can be substantially reduced while still maintaining close to optimal performance gain. The results in this paper can be used to guide the design of OTSIs for optical networks.

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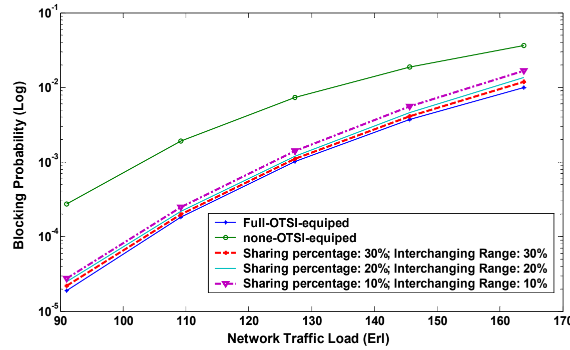


Figure 5: The effects of varying sharing-percentage and interchanging

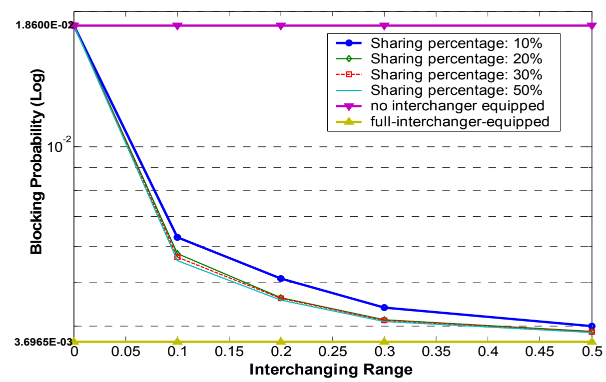
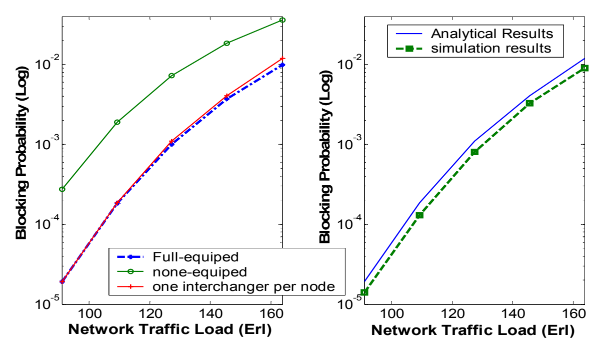


Figure 6: The effects of sharing-percentage and interchanging-range on network blocking probabilities in NSFNET, with network load 145.6 Erl.



(a) Numerical Results (b) Numerical vs. Simulation Results

Figure 7: Blocking probability in NSFNET, when using one POTSI per node (30% interchanging range).