# Routing in a Linear Lightwave Network

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***Abstract*— In this work, dynamic routing of point-to-point connections in a waveband selective linear lightwave network is addressed. Linear lightwave networks are all optical networks in which only linear operations are performed on signals in a waveband selective manner. Special constraints arise because of the linearity in the linear lightwave network. The overall problem of finding a path satisfying all the routing constraints for point-to-point connections is shown to be very complex. Owing to the complexity, the overall routing problem is decomposed into several subproblems. In particular, given a request for a point-to-point connection a waveband is first chosen for the call. Two heuristics, MAXBAND which allocates the most used band to a call and another MINBAND (least used band) were studied. Then, the problem of routing in a given waveband was further divided into smaller subproblems of finding a path in the waveband, checking for feasibility of the path in the chosen waveband and channel allocation (within the waveband). For finding paths in a waveband, K-SP, BLOW-UP and MIN-INT algorithms were proposed. A recursive algorithm checks for feasibility of the path on the waveband. Two channel allocation schemes (within a single waveband) MIN and MAX were presented. Simulations showed that using MAXBAND (waveband), MIN-INT (path on waveband) and MIN (channel within waveband) policies resulted in the best performance (least blocking).**

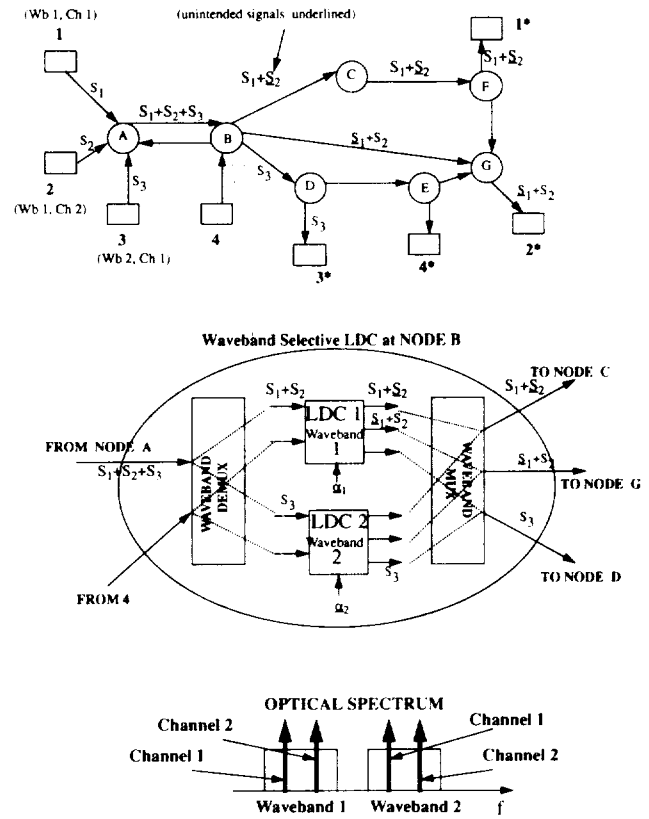


Fig. 1. Linear lightwave network.

## I. Lightwave Networks

Recently, architectures for multiwavelength optical networks, have been proposed [2], [3], [5], [6], [9]. The basic idea behind these architectures is to use a limited amount of optical switching so as to be able to reuse wavelengths in the network. All of the architectures use some form of wavelength selective routing. A comprehensive overview can be found in [7], [8].

## II. Linear Lightwave Networks

This work is based upon a "linear" lightwave network (LLN) [9] in which the network nodes perform waveband selective linear operations on the optical signals: including **controllable** power combining, dividing and possibly linear (nonregenerative) amplification. The objective of the architecture is to provide purely optical connections on demand, supporting a high degree of flexibility, including user-chosen modulation formats (digital or analog) and user-chosen bitrates (or bandwidths). In these networks the signals remain in the optical domain from transmitter(s) to receiver(s). The users in the LLN could be analog or digital sources that could be single workstations, video sources or displays, local area networks, PBX's or other communication devices. Each user is attached via an electronic interface to a network station which contains an optical transmitter and/or a receiver. The LLN's can have arbitrary topologies and can achieve a high degree of wavelength or channel reuse.

### A. Structure of the LLN

Fig. 1 shows an example of a linear lightwave network (LLN). The rectangular boxes represent both transmitters and receivers, with circles representing nodes in the network that perform the required wavelength selective switching, splitting and multiplexing of optical signals. Each transmitter takes an electronic signal as input and modulates it onto an optical

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carrier. Each receiver takes an optical signal as input and converts it back to electronic form. The links in the figure represent optical fibers carrying signals in the direction of the arrows.

The heart of the LLN is a linear divider-combiner (LDC) present at each node. Its function is to direct prescribed combinations of the inbound signals at the node to each outbound fiber in a controllable fashion. The LDC acts as a generalized optical switch, with the added functions of multicasting (signal dividing) and multiplexing (signal combining). As will be shown later it is highly desirable to do the combining and dividing in a waveband selective manner. With current technology it is possible to build devices that can selectively operate (linear operations) on portions of the optical spectrum with wavelength resolutions of 1 or 2 nm. Thus, in this work we assume that the optical spectrum used for signal transmission in the LLN is partitioned into "wavebands," each of the order of 1 or 2 nanometers and separated by appropriate "guard" bands. The optical power in each waveband can be independently processed by a waveband-selective LDC (WSLDC). One way of constructing a WSLDC is shown in Fig. 1. A three stage WSLDC is shown at node B having a Waveband Demultiplexing stage (e.g., using gratings), an LDC stage and a Waveband Multiplexing stage.

Wavebands of the size indicated (few nanometers) have enough bandwidth to carry many high-speed channels. One nanometer of bandwidth centered at 1500 nm contains about 125 GHz of bandwith. Thus, we subdivide each of the wavebands into many channels. Each fiber can carry many optical signals simultaneously by assigning each call sharing a fiber a unique waveband-channel pair. If the channels represent wavelengths in the optical spectrum then such a multiple access scheme is called wavelength division multiple access (WDMA). Each wavelength would typically carry a signal occupying a few GHz of bandwith compared with the waveband that is on the order of hundreds of GHz. In Fig. 1 two wavebands and two channels per waveband are shown. A laser transmitter and a corresponding receiver having a connection between them must be tuned to the same waveband-channel pair. Many other MA schemes are possible. The "coarse" subdivision of the optical spectrum into wavebands recognizable by the WSLDC's, and a "fine" subdivision of the wavebands into channels recognizable by the receivers is based on the capabilities of current technology. As shown later, the best performance (network throughtput) is achieved with maximum WSLDC selectivity, i.e., using many wavebands containing one channel each. This is a special case of the coarse/fine approach considered here.

Signals on the same waveband are sent to a single LDC. For the example of Fig. 1 signals on waveband 1 are sent to LDC 1 and signals on waveband 2 are sent to LDC 2. A single LDC performs linear operations on signals within the corresponding waveband. These operations include switching, multicasting and multiplexing. The node controller (or network manager) sets up the $\alpha$'s shown in Fig. 1 to carry out these operations. LDC's can be built [9], which are capable of directing a portion of the power from each input link to any output link. Thus, linear operations are performed on each waveband by a single LDC independent of other wavebands. Finally, as shown in Fig. 1, signals from each output port of LDC's are multiplexed by a waveband multiplexer onto their respective output ports.

This paper will assume that WSLDC's are located at each network node in the LLN. While some power attenuation occurs in traversing each node and each fiber, it is assumed that signal levels at all receivers are maintained sufficiently high (by optical amplification if necessary) for satisfactory reception.

### B. Properties and Constraints of the LLN

An LLN has the following properties:

1) Each signal is transported optically in essentially unmodified form from transmitter to receiver(s), i.e., there is no frequency conversion, regeneration, buffering or any other nonlinear operation within the network.
2) More than one signal, on the same waveband, may be combined (linearly) on each link (fiber). All signals sharing a fiber are termed "interfering" signals.

The structure of the LLN imposes some special constraints on the routing problem.

*a) Waveband-Channel Continuity:* A call must be allocated the same waveband-channel pair on all the links that it traverses within the LLN.

*b) Distinct Waveband-Channel Assignment:* All interfering calls are assigned distinct waveband-channel pairs. However, the same waveband-channel pair could be reused by calls using disjoint paths within the LLN.

*1) Constraints on Signals Using the Same Waveband c)-e):*

*c) Inseparability in a Waveband:* Signals using the same waveband, combined on a single fiber cannot be separated within the LLN. Inseparability occurs as a consequence of the fact that each LDC operates independently on the *aggregate* power carried within each waveband on an inbound link without distinguishing between signals on different channels within the waveband. It is therefore not possible for an LDC to separate signals sharing the same waveband using the same fiber.

Fig. 1 shows an example of inseparability. Signals $S_1$ and $S_2$ are in the same waveband $Wb1$. A call from source 1 to destination 1* is routed via the Minimum-Hop path 1A-AB-BC-CF-F1*, with a second call from 2 to 2* along Minimum-Hop path 2A-AB-BG-G2*. The label $S_i$ on a link denotes a signal from source $i$. Observe that power from both sources $S_1$ and $S_2$ is combined on link AB, and thereafter, the superimposed signals $S_1 + S_2$ are carried to both destinations, resulting in inseparability. Note that these two calls must be assigned to distinct channels within the waveband, so that the receivers can "tune in" the desired call and "tune out" the interferer. It can be seen that inseparability tends to create unintended multicast connections where point-to-point connections are intended. For the example shown in Fig. 1, receiver 1* receives signal $S_2$ unintentionally and receiver 2* receives signal $S_1$ unintentionally. This is an inevitable result of inseparability and tends to waste both power and bandwidth. For call 1-1* the path 1A-AB-BC-CF-F1* is called the intended path and BG-G2* is called the unintended path.

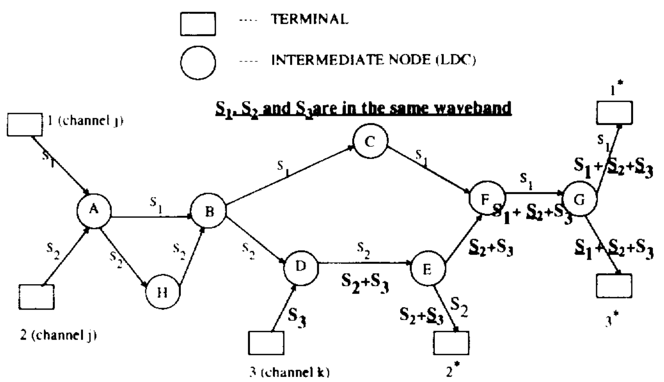


Fig. 2. Color clash.

Note that inseparability does not apply to signals on different wavebands which are routed independently of each other.

*d) Mutually Independent Sources Combining (MISC):* Only signals from mutually independent sources may be combined on the same fiber. Alternatively stated, a signal is not allowed to split, taking multiple paths in the network and then recombine on a link. Routing in violation of this condition results in a source interfering with itself, thereby "garbling" its information because of the differences in propogation delays along the multiple paths. See [1] for more details on this "multipath interference" constraint. The MISC constraint is a direct result of inseparability which tends to create unintended paths.

*e) Color Clash:* A color clash arises when a routing decision on a new call results in combining on the same fiber two or more calls, already in progress (on disjoint paths), which were previously assigned the same waveband-channel pair. This is illustrated in Fig. 2 where calls 1-1* and 2-2* are already in progress. Since these two calls have disjoint paths they were assigned the same waveband-channel, say waveband $w$ and channel $j$, without violating constraint (b), the Distinct Waveband-Channel Assignment constraint. Now a new call 3-3* requests a connection which is allocated to it on the path 3D-DE-EF-FG-G3*. Say, signals $S_1$, $S_2$ and $S_3$ are allocated in the same waveband. Since this call interferes with signal $S_2$ on link DE it is assigned a *different channel* $k \neq j$. Once again the effect of adding call 3-3* is shown in boldface. Due to inseparability, signal $S_3$ carries over signal $S_2$ onto link FG after combining with it on link DE. Now on link FG signals $S_1$ and $S_2$ share the same waveband-channel, i.e., $(w, j)$ in violation of constraint (b), the Distinct Waveband-Channel Assignment constraint, resulting in a Color Clash. Note that the Color Clash violation can be avoided by retuning source 2 to channel $i$ in waveband w, where $i \neq j \neq k$. The Color Clash violation can also be avoided by allocating call 3-3* on a different waveband from $S_1$ and $S_2$. If previously allocated calls are not allowed to retune to new channels and call 3-3* is on the same waveband as $S_1$ and $S_2$ then the call should not be routed on the path shown.

*2) Important Assumptions for Following Work:* Throughout this paper it is assumed that the LLN is constructed as a connected undirected multigraph $G(V, E)$ in which multiple edges between two nodes are allowed but no edge is allowed to have both ends at the same node. To construct the LLN from $G$ every vertex is converted into a node in the LLN and every edge is converted into two fiber links carrying optical signals in opposite directions. Furthermore, transmitters and receivers are attached to each node in the LLN via access fiber links.

Finally, it is assumed that there is a network manager and a signaling system that sets up calls on request from the transmitters, by establishing end-to-end (circuit switched) optical paths. The network manager determines the physical path to be allocated to the call, assigns an appropriate waveband-channel pair and sets the respective LDC parameters (e.g., $\alpha$'s in Fig. 1) along the route. The physical route allocated to the call is assumed to remain unchanged throughout its duration.

The objective of this paper is to propose dynamic routing algorithms for setting up point to point connections on demand, in a linear lightwave network. The proposed routing algorithms take into account the calls in progress, i.e., the "state" of the network. Thus, we consider the problem as one of dynamic routing, in contrast to static routing where paths for all connections are prescribed in advance independent of the network state. Furthermore, once a call is allocated, its path is not allowed to be changed. In [10] results of an initial study of a particular routing algorithm was presented without too many details. In this work we develop new routing algorithms (See Section III on new algorithms MIN-INT and BLOW-UP algorithms) and also provide detailed results.

Section III addresses the problem of routing point to point connections for the multiple waveband case. Section IV proposes algorithms for routing signals on a single waveband subject to constraints. Heuristic routing algorithms are presented for finding paths, checking for constraint violations and channel allocation. The algorithms for path selection basically involve finding paths of "least interference." Section V presents performance results obtained from a simulation study.

## III. Routing Point to Point Connections for Multiple Waveband LLN's

It will be shown later that the problem of routing point to point connections even for the case when a waveband is already chosen for a call is complicated. Hence, the problem of routing point to point connections with multiple wavebands is at least as complex as the single waveband case. Thus, we decompose the overall routing problem into smaller manageable subproblems. In this work, we choose one particular decomposition method that makes the problem simpler to handle. Finding and working out the details of other methods of decomposition along with comparative performance evaluations could be topics for future work. The problem of routing a point to point connection is decomposed into the following subproblems: choosing a waveband for a requested call, assigning a path on the chosen waveband, checking for violations of the LLN constraints, and assigning an appropriate channel to the call on the chosen waveband. As explained in Section II, an LLN can be thought of as consisting of many networks, one for each waveband. Signals on different wavebands are routed independently of each other. Two rules MAXBAND

and MINBAND are proposed to allocate a waveband to a call. The most difficult part of the routing problem is routing within a single waveband, which is discussed in Section IV.

Consider an LLN with $K$ wavebands $(Wb1, Wb2, \ldots WbK)$ and C channels per waveband. For the purpose of choosing a waveband for a given connection request, a sorted list $l$ of the wavebands is maintained. The wavebands can be sorted using different criteria. In this work two rules were used: MAXBAND in which the list is sorted in decreasing order of usage, and MINBAND where it is sorted in increasing order of usage. Two wavebands having the same usage are sorted in ascending numerical order. By "usage" we mean the active number of connections in the network using the waveband. Given a call request, the waveband at the top of list $l$ is chosen and an attempt is made to allocate the call on it. One of the routing and channel allocation algorithms presented below in Section IV for call allocation within a single waveband is used. If the call is blocked on the first waveband in list $l$ then the next one from the list is chosen and the above procedure is repeated. The call is blocked if it is blocked on each waveband in list $l$. Whenever a call is allocated or terminated the order of the wavebands in list $l$ is updated to reflect the change. The performance of these waveband selection rules is discussed in Section V.

## IV. Routing Point to Point Connections in A Single Waveband

Having proposed some simple rules for waveband selection, this section deals with routing within a *single* waveband. Inseparability between signals on a single waveband may convert an intended point to point connection to a point to multipoint connection (as in Fig. 1) involving unintended as well as intended paths. Ideally, we wish to find a path in the chosen waveband, such that the MISC and the Color Clash conditions are satisfied on it as well as on all of the associated unintended paths.

*Theorem A.1:* Finding a path, within a chosen waveband, from a source transmitter $s$ to destination receiver $t$ that satisfies the MISC constraint on it as well as all associated unintended paths due to inseparability is NP-Complete. For proof see [1].

*Theorem A.2:* A polynomial time algorithm exists which can find a path from a source $s$ to a destination $t$, within a chosen waveband, that satisfies the Color Clash constraint on it as well as all associated unintended paths. For proof see [1].

Given a call request from source $s$ to destination $t$, within a chosen waveband, the problem of finding a path $P$ from $s$ to $t$ that satisfies both the MISC and Color Clash constraints is difficult. Thus, instead of seeking a path that satisfies constraints we seek one that is likely to satisfy the constraints on the waveband. This is done by choosing a physical path for each call that results in a small amount of interference with other calls already in progress in the network on the chosen waveband. In some practical cases where the number of optical hops in the network is limited to a small number it might be possible to exhaustively search all paths for feasibility. However, for larger networks this might not be possible. The routing problem, within a waveband, is decomposed into the following subproblems, each one of which is discussed in detail as follows:

1) physical path allocation;
2) checking for MISC and Color Clash violations;
3) channel allocation.

Routing a call request in a waveband involves choosing a path, checking for violations of the LLN constraints and finally assigning an appropriate channel to the call. For the rest of Section IV it is assumed that everything pertains to routing within a *single waveband.* To avoid repetition, this fact will not be mentioned in the following subsections.

### A. Physical Path Allocation

Inseparability may convert an intended point-to-point connection to a point-to-multipoint connection. In the example shown in Fig. 1 the intended path for call 1-1* is 1A-AB-BC-CF-F1* and is referred to as the "physical path." Three algorithms, K-SP, BLOW-UP and MIN-INT, are considered as alternatives to allocate the physical path to the call. The basic idea behind all of these algorithms is to find paths that tend to minimize interference so as to reduce the chances of violations of the LLN constraints. The interference is defined as the number of independent signals the call encounters on its intended path (physical path) and on the chosen waveband. A path is feasible if it satisfies the MISC and Color Clash constraints on both the intended and unintended paths.

*1) K-SP:* The physical path allocation algorithm, K-SP, used here is based on finding $K$ shortest paths from source to destination [11]. Any meaningful link weight assignment (e.g., attenuation) can be used. If $K$ equals 1 then the physical path is the shortest path. Furthermore, if the link weights are all equal the shortest path is also the minimum hop path. There are three parts to the K-SP algorithm: 1) find $K$ shortest paths from source to destination, 2) check each of the $K$ paths for feasibility, and 3) from the subset of $K$ paths that are feasible, choose the one with the least interference for the call.

A path is feasible if it satisfies the MISC and Color Clash constraints for both the intended connection and all unintended connections. If none of the $K$ paths is feasible the connection request is blocked on the chosen waveband. An algorithm presented in Section IV-B checks for feasibility on a given path. Observe that Minimum Hop routing ignores the effects of inseparability. Both the MISC and the Color Clash violations occur as a result of inseparability. Furthermore, inseparability also tends to cause a waste of both power and bandwidth. The K-SP algorithm takes into consideration this fact by choosing the path of least interference from among $K$-paths $(K \geq 2)$ that do not violate the constraints. Less interference will possibly make it less likely that the constraints in the LLN will be violated for accomodating future connection requests. It also tends to allow for more channel reuse. Consider the example shown in Fig. 3 where call 1-1* is already in progress. Taking $K = 2$ and assuming link weights of 1 a new call from 2-2* is routed along an alternate nonshortest path (in this case the non-Minimum Hop path) to avoid interfering with signal

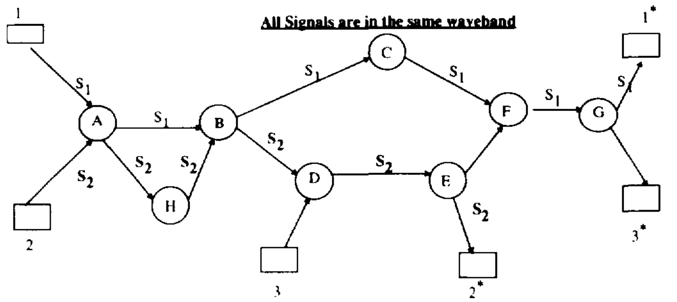


Fig. 3. Example of K-SP algorithm.

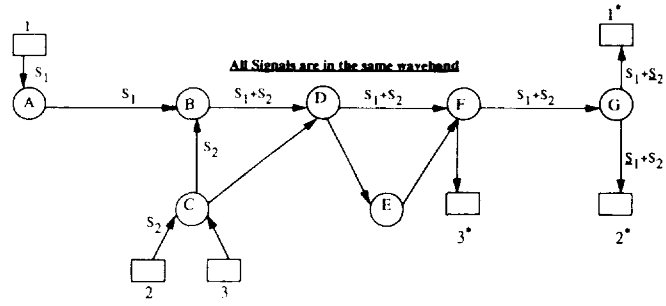


Fig. 4. LLN.

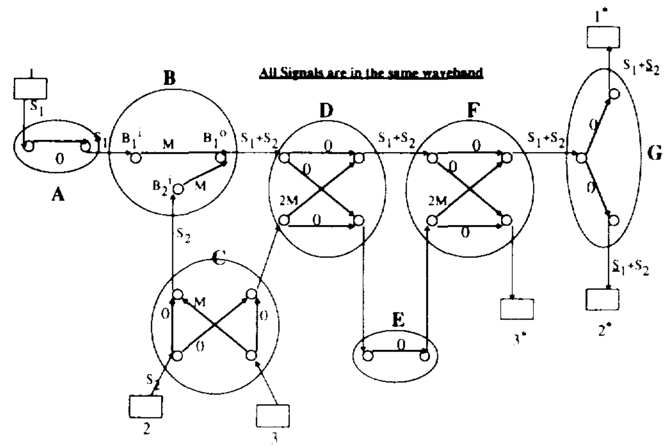


Fig. 5. IMAGE network for chosen waveband.

$S_1$. In Fig. 3 channel reuse can be achieved because signals $S_1$ and $S_2$ are on edge disjoint paths and can be allocated the same channel.

The time complexity of the K-Shortest Path algorithm can be shown to be $O(Kmlogn)$ [11] where $n$ is the number of nodes and m is the number of links in the LLN. The limitation of this approach is that the time complexity depends on the value of $K$ (Actually, the time complexity has been improved in recent work but the dependence on $K$ remains). Especially in cases where each pair of nodes has multiple fibers between them, a large value of $K$ is needed if the calls are to be distributed among the many fibers that go between two nodes.

*2) BLOW-UP:* While the K-SP algorithm tends to find a path of reduced interference it is not designed to find a path of minimum or least interference. We now attempt to find a path of "least" interference for a call on the chosen waveband. As suggested above, it is expected that a minimum interference policy will reduce the amount of blocking by reducing the number of potential violations of constraints. To achieve this objective an "Image" network is created as explained below. There is one Image Network for each waveband. Henceforth, all discussion in this section refers to the Image Network for a single waveband. In constructing the Image Network link weights are assigned which reflect the current state of ongoing calls. Using these weights "shortest paths" become paths of least interference.

*a) Image Network:* The network controller or manager maintains an "Image" of the network for each waveband. In the Image Network each node is "blown up" to create additional intranodal links between each input and output port pair (This is nothing more than the internal structure of the LDC for the chosen waveband). An example is shown in Fig. 4 and Fig. 5. Within each node of the LLN (e.g., node B in Fig. 4) an internal *node* is created for each inbound *link* (e.g., in Fig. 5 internal node $B_1^i$ represents the connection of inbound link A-B to node B, and internal node $B_2^i$ represents the connection of inbound link C-B to node B). Similar nodes are created for each outbound *link* (e.g., internal node $B_1^o$ represents the connection of outbound link B-D to node B). Now intranodal links are added between these internal nodes directed from the inbound links to the outbound links (e.g., in Fig. 5 intranodal links are added between $B_1^i$ and $B_1^o$ and between $B_2^i$ and $B_1^o$), such that every incoming link at the node has an intranodal link to every outgoing link.

Given that some calls are already in progress, weights are added to the links. Weight $w_{ij}$ is added to each intranodal link $i-j$ such that $w_{ij} = M \times |G_j - G_i|$ where $G_j$ represents the set of signals, on the chosen waveband, *outbound* from internal node $j$ (or carried on the corresponding output link) and $G_i$ represents the set of signals, on the chosen waveband, *inbound* to internal node $i$ (or carried on the corresponding input link). In Fig. 5 for example, $G_{B_1^o} = \{S_1, S_2\}$, $G_{B_1^i} = \{S_1\}$ and $G_{B_2^i} = \{S_2\}$. Also $G_{B_1^o} - G_{B_1^i} = \{S_2\}$ and $G_{B_1^o} - G_{B_2^i} = \{S_1\}$. Hence $|G_{B_1^o} - G_{B_1^i}| = |G_{B_1^o} - G_{B_2^i}| = 1$. For simplicity, let each internodal link (link in the original LLN) be assigned a weight of 1 (internodal links may also be assigned unequal weights) and $M$ be assigned a value greater than the sum of weights of all internodal links, i.e., $M$ is greater than the number of links in the original network when the internodal links have a weight of 1. These weights will be used in selecting paths through the network. The result of constructing such an Image network for a single waveband, can be seen by considering the following scenario. Say that calls 1-1* and 2-2* are already in progress as shown in Fig. 4. The network controller maintains the Image network of Fig. 5. Say an incoming call 3-3* is allocated on the same waveband as 1-1* and 2-2*. The network controller has a choice of any one of four paths on the waveband to allocate to 3-3* i.e., 3C-CB-BD-DF-F3*, 3C-CB-BD-DE-EF-F3*, 3C-CD-DE-EF-F3* and 3C-CD-DF-F3*. In the Image network (Fig. 5) the total weight $W$ accumulated along each of the paths 3C-CB-BD-DF-F3*, 3C-CB-BD-DE-EF-F3*, 3C-CD-DE-EF-F3* and 3C-CD-DF-F3* is 1+M+1+M+1+1+1, 1+M+1+M+1+1+1+1, 1+1+1+1+1 and 1+1+2M+1+1, respectively. Observe that along each path

$\lfloor W/M \rfloor$(where $\lfloor x \rfloor$ is the integer part of $x$) is equal to the number of signals that call 3-3* interferes with. Each of these signals is carried along by signal $S_3$ (due to inseparability) to its destination 3* . Since the value of $M$ is greater than the sum of the weights on all the edges of the network, the effect of weight $M$ on any path outweighs the effect of traversing all the edges of the network (provided the path traverses each edge at most once).

*b) Algorithm BLOW-UP:* The algorithm chooses the physical path for an incoming call, on a chosen waveband, that corresponds to the shortest path in the *Image network* for the chosen waveband. The physical path in the LLN is obtained from the shortest path in the Image Network by excluding the intranodal links. From Theorem B.1 it can be seen that the BLOW-UP algorithm can minimize the maximum incremental inteference under the conditions specified. The INCREMENTAL INTERFERENCE is defined as the additional interference caused at a receiver on the chosen waveband due to the introduction of the new call into the network. The maximization is over all receivers that get some additional interference due to the allocation of the new call.

*Theorem B.1:* If the MISC condition is satisfied on the shortest path for a given source-destination in the Image network then it is the path along which the MAXIMUM INCREMENTAL INTERFERENCE IS MINIMIZED from among all paths, between the source and destination, that satisfy the MISC constraint on the chosen waveband. For proof see [1].

The MIN-INT algorithm is discussed next. As explained below the two methods for physical path allocation, BLOW-UP and MIN-INT, are equivalent. However, from a time complexity point of view the MIN-INT is more efficient than BLOW-UP. In this manner BLOW-UP allocates each call a path of least interference within the chosen waveband.

The time complexity of the Blow-Up algorithm can be shown [1] to be at most $O(MlogN)$ where $M = m + nD^2$ and $N = n + nD$ (D is the maximum degree of the nodes). The problem with this approach is that for the case where each pair of nodes has multiple fibers between them, the value of $D$ can become quite large resulting in a large time complexity for the algorithm. However, one possible advantage of using BLOW-UP is that it provides the network manager with a detailed view of the operations at each node by using the Image network. Among other advantages, this could help in easy isolation of faults in the network nodes.

*3) MIN-INT:* The MIN-INT algorithm presented here provides a more efficient method of executing the minimum interference calculations implicit in the BLOW-UP algorithm. Recall that the intranodal links used in BLOW-UP are weighted to reflect the additional interference encountered when traversing a node in the LLN from a given inbound link to a given outbound link, taking into account all calls in progress on a given waveband. These weights are then used in shortest path calculations, which then yield minimum interference paths. In the MIN-INT algorithm presented in Fig. 6, the artifice of intranodal links is dropped. Instead, a modified version of Dijkstra's shortest path algorithm is used in which

**MIN-INT Algorithm:**

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Given a digraph G(V,E)
Let the nodes be 1, 2 ... n and d(i,k) be a non-negative weight on link (i,k)
Find "Shortest Path" on a chosen waveband from 1 to t
where the weights represent Incremental Interference on the chosen waveband.
Call this path the MIN-INT path

Let G_{i-k}= Set of signals on a chosen waveband, combining on link (i,k)
Let M = Large number greater than the sum of weights on all the links in the network
Each node i is assigned a label l(i), a weight w(i) and a predecessor p(i)

INITIALIZATION:
For every node i ≠ 1
        Set all labels l(i) = 0, i.e., label all nodes temporary
        Set all weights w(i) = ∞
        Set all weights p(i) = 0

For node 1
        Set w(1) = 0
        Set p(1) = 0
        Set l(1) = 0
BEGIN:

STEP1:  Find node i such that l(i)=0 and w(i) is minimum among all nodes j with
        temporary labels, i.e., l(j) = 0. Label it permanent, l(i) = 1

STEP2:  For every node k adjacent to node i on link i-k
        Compare (w(i) + f(p(i), i,k)) and w(k)
        where f(p(i), i,k) = M*|G_{i-k} - G_{p(i)-i}| + d(i,k)

        IF w(i)+f(p(k),i,k) < w(k)
        THEN
                set w(k) = w(i)+f(p(k),i,k)
                set p(k) = i

STEP 3: IF all nodes are labelled permanent then GOTO STOP
        ELSE GOTO STEP1

STOP:   The MIN-INT path from 1 to t can be obtained by tracing back the
        predecessors from t to 1

END
```

Fig. 6. MIN-INT algorithm.

additional weights (equivalent to the intranodal link weights in BLOW-UP) are added to represent interference. (See Step 2 in Fig. 6).

*Theorem B.2:* If the MISC condition is satisfied within the chosen waveband, on the path found using the MIN-INT algorithm, then it is the path along which the MAXIMUM INCREMENTAL INTERFERENCE IS MINIMIZED from among all paths, between the source and destination, that satisfy the MISC constraint on the chosen waveband. For proof see [1].

The time complexity of the MIN-INT algorithm is $O(m \log n)$. Compare this with the time complexity of the BLOW-UP algorithm. The paths found using the BLOW-UP or MIN-INT algorithm are likely to satisfy the constraints in the LLN as an indirect result of choosing paths of least interference. However, a path found by using either of the above algorithms still has to be checked for MISC and Color constraints. In the K-SP algorithm also we check each of the $K$ paths for feasibility.

## *B. Check for MISC and Color Clash Violations*

There is no guarantee that MISC and Color Clash conditions will be satisfied on the chosen waveband if the call is allocated on a path selected by one of the methods described above. Thus, it is necessary for the controller to check whether or not the MISC and Color Clash conditions are satisfied for the chosen waveband on the intended physical path as well as the associated unintended paths. The call is blocked if its allocation will result in a MISC or Color Clash condition violation. An efficient recursive algorithm [1] was developed which takes as input the chosen waveband and the intended path on the chosen waveband. It recursively finds all unintended paths associated with the intended physical path, and checks for violations of the MISC and Color Clash conditions along all of these paths. Given a path $P$, the complexity of the algorithm for MISC and Color Clash violations on $P$ can be shown to be $O(m)$ where $m$ is the number of links. A lot of effort was put into achieving a complexity of $O(m)$ for the the algorithm. (details in [1]).

### C. Channel Allocation

So far, a physical path has been chosen for the incoming call that satisfies the MISC and Color Clash constraints on it as well as on the associated unintended paths on the chosen waveband. It now remains to allocate a channel to the call assuming that a fixed number of channels are available in the waveband. Assume that calls are already in progress that satisfy both the MISC and the Color Clash constraints on the chosen waveband. A path that satisfies the MISC and Color Clash constraint on the intended and the unintended paths has been allocated for an incoming call. A channel remains to be allocated to the call. The allocation should be done without requiring the calls already in progress to change their paths or retune to new channels. Two simple heuristics are considered for channel allocation. In the first (MAX heuristic), the incoming call is allocated the most used channel (maximum reuse) in the waveband from among all the channels with which the call does not interfere (on either intended or unintended paths). A second, MIN heuristic allocates to the call the least used channel in the waveband, from among all the channels in the waveband with which the call does not interfere (on either intended or unintended paths). The MIN heuristic tries to distribute the calls evenly among the channels. By "usage" we mean the number of active connections that use a channel. When using the MISC and Color Clash checking algorithm a list of channels that can be allocated to the incoming call is generated. Note that finding the maximum used or minimum used channel from a given list of $C$ channels takes $O(C)$ time complexity.

Allocating a point to point call involves choosing a waveband, finding a physical path, checking for violations and then allocating a channel. $W$, $C$, $m$ and $n$ are the number of wavebands, the number of channels per waveband, the number of links in the LLN and the number of nodes (including transmitters and receivers) in the LLN, respectively. Thus the overall complexity of call allocation using the K-SP algorithm is $O(Km^2logn)$ where $K$, $W$ and $C$ are constants. A path is found using the BLOW-UP algorithm that has a complexity of at most $O(mMlogN)$ where $M = m+nD^2$ and $N = n+nD$. $D$ is the maximum degree of the nodes in the LLN. The complexity of call allocation using the MIN-INT algorithm on a single waveband is $O(m^2logn)$.

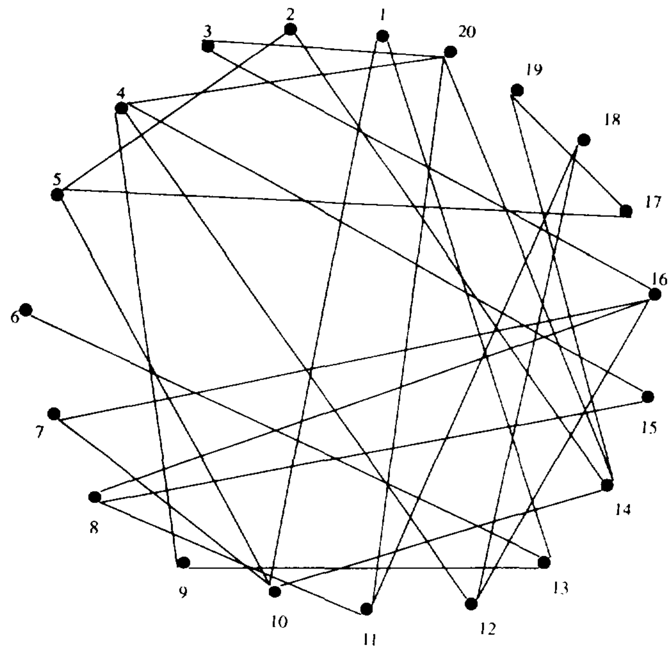

Fig. 7. 20 node average degree 3 random graph.

## V. Results

A simulator (see [1]) has been written in the C language which obtains the performance of each routing algorithm from the point of view of blocking probability. First we present results for the single waveband case and then show the improvement that can be obtained by using multiple wavebands. For the single waveband case examples of blocking up to 10 or 20% are shown. This range of blocking may at first glance seem impractically high. However the results of Section V-B show that the use of multiple wavebands reduces the blocking to small values. We tried many examples other than the ones presented below and obtained similar results. We present a sample here of some of those results.

For the single waveband case we compare the performance of K-SP for different values of $K$ and then compare K-SP to MIN-INT, especially for the case of multiple fibers. We also compare channel allocation heuristics MIN and MAX. For multiple wavebands, results are presented for MAXBAND and MINBAND policies.

### A. Single Waveband Case

*Example 1:* A simulation was run for the graph shown in Fig. 7 with 20 nodes and an average degree of 3. The graph was created using a random graph algorithm presented in [4], [1]. Each pair of adjacent nodes has one fiber in each direction between them. The number of wavebands was chosen to be 1, the number of channels 3 and the number of sources per node was 1 (total number 20). A large number of receivers were placed at each node and the receivers are chosen uniformly from among all available receivers. This reduces the possibility of blocking due to receiver contention. Also, it is not desirable to choose a receiver from among a small set of nonbusy receivers because this results in an artificial load distribution in the network. A two state Markov chain was used to model

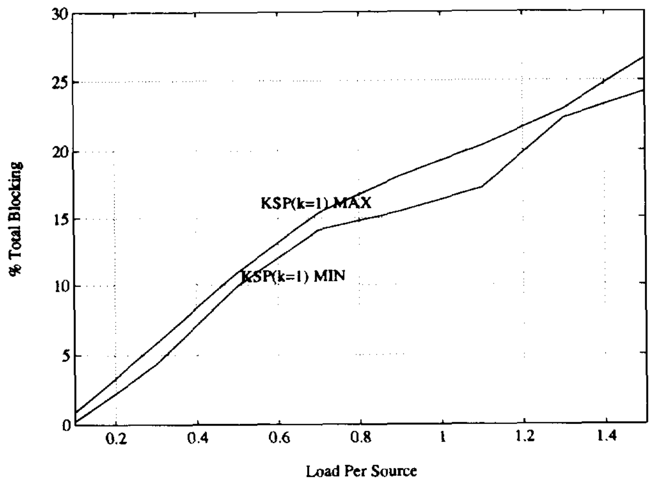


Fig. 8. Comparison between MAX and MIN (total blocking).

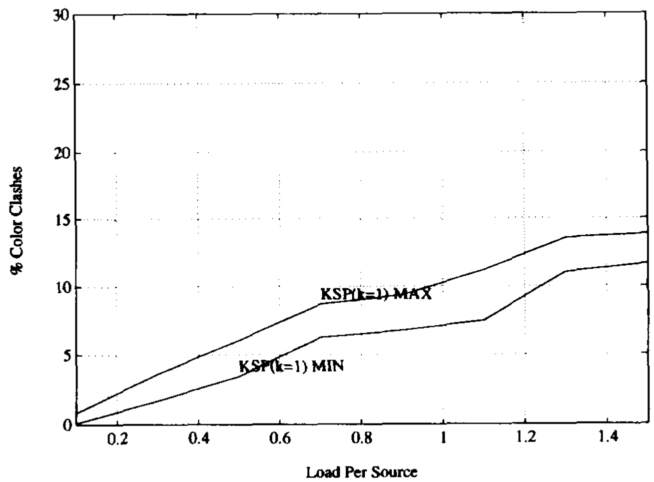


Fig. 9. Comparison between MAX and MIN (color clashes).

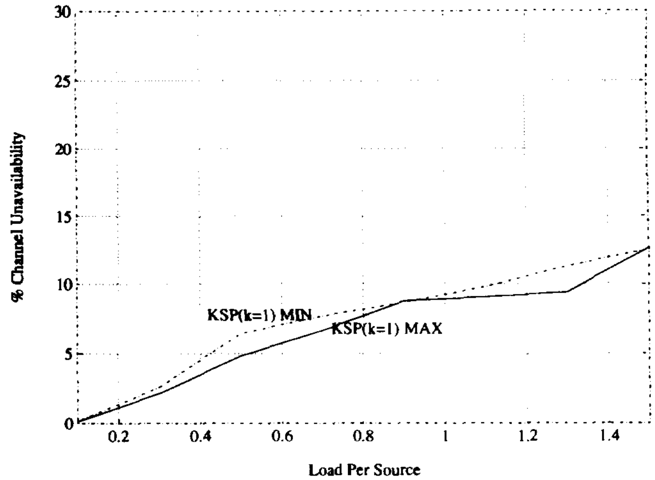


Fig. 10. Comparison between MAX and MIN (channel unavailability).

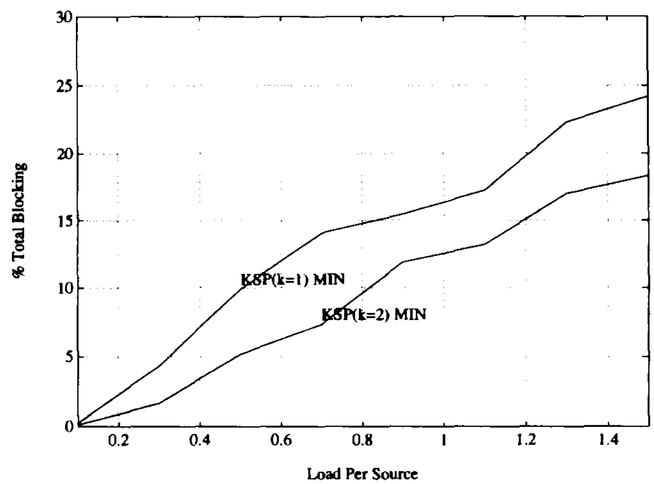


Fig. 11. Comparison between $K = 1$ and $K = 2$ (total blocking).

each source with average idle ("on hook") time $1/\lambda$ units and average call holding time $1/\mu$ units. The load for each source is defined as $\lambda/\mu$ and was varied from 0 to 1.5 units. The total offered load in the network is $S\lambda/(\lambda + \mu)$ Erlangs where $S$ is the total number of sources in the LLN. Results are presented for the K-SP algorithm for $K = 1$ and $K = 2$, and for MIN-INT. First, we look at the comparisons between the MAX and the MIN channel allocation heuristic using K-SP with $K = 1$. Fig. 8 shows that using the MIN heuristic results in less total blocking. As shown in Fig. 9, the MIN heuristic results in less blocking because of a reduction in the number of Color Clashes. This is to be expected because in the MAX heuristic a single channel is reused often on edge disjoint paths. This increases the chance that an incoming call will merge two such paths resulting in a Color Clash. However, Fig. 10 shows that the number of blockings due to unavailable channels was greater for the MIN heuristic. This suggests that the MAX heuristic acheives better channel usage than the MIN heuristic. In fact, in some examples it was found that the MAX heuristic performed slightly better than MIN because of this reason. However, in most cases the Color Clash violations dominated, making the MIN heuristic better than the MAX. For both cases, the number of MISC violations was found to be negligible.

Fig. 11 compares the blocking for $K = 1$ and $K = 2$ when using the K-SP algorithm. The overall blocking reduced as the value of $K$ was increased from 1 to 2. The MIN channel allocation heuristic was used for both cases. It was found that number of Color Clashes and the blocking due to channel unavailability both reduced as $K$ increased. This implies that routing the call on paths of less interference gives less blocking due to Color Clashes and channel unavailability. The number of MISC violations for both cases was negligible. Fig. 12 compares the performance of MIN-INT (or BLOW-UP) and the $K$-Shortest Path algorithm. For this case, the load per source was varied from 0.1 to 3.1. At loads below 1.7 units MIN-INT outperforms K-SP but at higher loads K-SP performs better. This could be explained by the fact that the MIN-INT algorithm sometimes finds unusually long intended paths in order to avoid interference. This tends to waste bandwidth on the links. The average path length for calls using MIN-INT was around 3.6 hops and for K-SP($k = 2$) was around 2.9 hops.

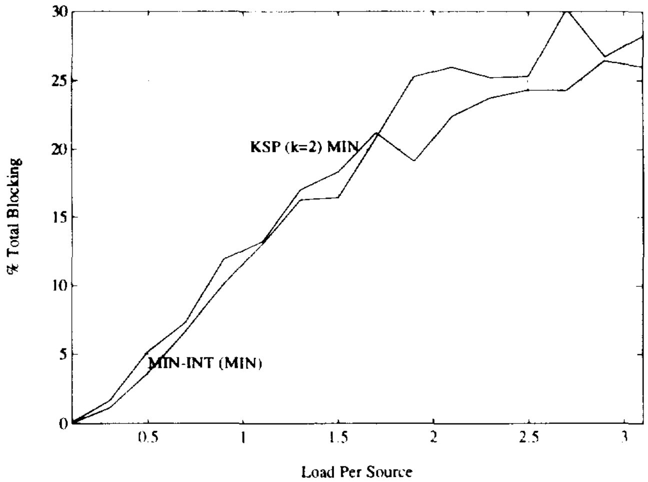


Fig. 12. Comparison between MIN-INT and $K = 2$.

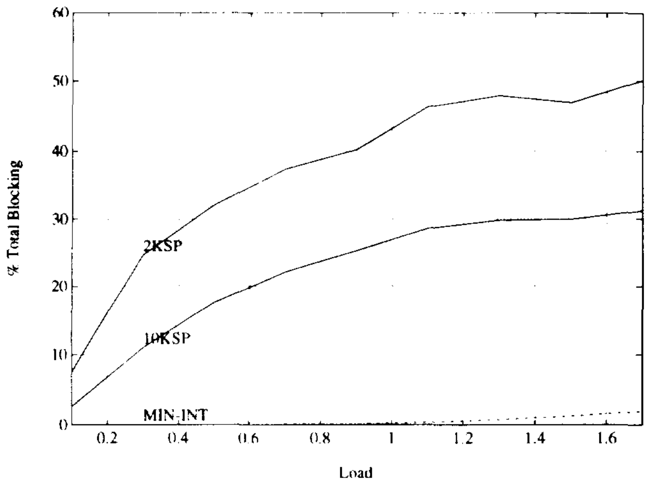


Fig. 13. MIN-INT, $K = 2$ and $K = 10$ for multiple fibers' case (total blocking).

*Example 2:* Here the same graph as in Example 1 was used, but 2 adjacent nodes have 5 fibers in each direction between them. The number of channels was chosen to be 3, the number of wavebands 1 and the number of sources per node 4 (total number 80). This case was specifically chosen to show the advantage of using the MIN-INT algorithm by comparing it with K-SP. Fig. 13 shows that the MIN-INT algorithm performs much better than the K-SP algorithm for both the cases $K = 10$ and $K = 2$. For the case of multiple fibers between nodes, the value of $K$ has to be large if the K-SP algorithm is to exploit the multiple fibers between nodes. This is a disadvantage because the complexity of the K-SP algorithm increases with the value of $K$. In fact, for cases where fiber cables have dozens of fibers, the K-SP algorithm will perform poorly from the point of view of both time complexity and blocking as compared to the MIN-INT algorithm. The MIN-INT algorithm exploits multiple fibers between nodes by distributing the load on them. For this example, it was found that the MIN-INT algorithm reduced Color Clashes and reduced blocking due to channel unavailability.

TABLE I
MIN-INT 1 Waveband, 3 Channels, 5 Fibers/Edge and 4 Sources/Node

| Load | AIA | AUA | G | H | L |
|---|---|---|---|---|---|
| 0.5 | 79.90 | 0.187 | 99.8 | 3.01 | 0.30 |
| 0.7 | 92.1 | 0.53 | 99.7 | 3.01 | 0.349 |
| 1.1 | 123.2 | 3.39 | 97.5 | 3.12 | 0.472 |
| 1.5 | 145.4 | 8.29 | 95.3 | 3.21 | 0.576 |
| 1.9 | 160.8 | 11.95 | 93.2 | 3.29 | 0.646 |

TABLE II
$K-SP$ ($K = 10$) 1 Wb, 3 Channels, 5 Fibers/Edge and 4 Sources/Node

| Load | AIA | AUA | G | H | L |
|---|---|---|---|---|---|
| 0.5 | 56.06 | 6.03 | 90.6 | 2.6 | 0.237 |
| 0.7 | 66.99 | 7.72 | 89.8 | 2.56 | 0.281 |
| 1.1 | 80.68 | 9.7 | 89.7 | 2.48 | 0.347 |
| 1.5 | 90.96 | 9.96 | 89.8 | 2.39 | 0.383 |
| 1.9 | 95.73 | 10.99 | 90.0 | 2.37 | 0.405 |

The curves of blocking probability alone do not give the whole story concerning performance of dynamic routing algorithms on a single waveband. Other important considerations are: the amount of network resources occupied by unintended connections as compared to that occupied by intended ones, the average call path length, and the average link load. We explore these quantities below using the following definitions.

Average Intended Area for a Single Waveband (AIA) =
Time Average of Total number of Channels occupied by intended signals

Average Unintended Area for a Single Waveband (AUA) =
Time Average of Total number of Channels occupied by unintended signals

Goodness (G) = (Intended Area)/(Intended Area + Unintended Area) Average Number of Hops (H) =
(Total Hops on intended path for allocated calls)/(Total Calls allocated)

Average Load (L) = Time Average of the total number of channels occupied per link.

For Example 2 we show Tables I and II for MIN-INT and K-SP ($K = 10$) case, respectively that show other parameters of interest like goodness(G), average intended area(AIA), average unintended area(AUA), average load(L)and average number of hops(H).

For a given load, the AIA found is greater when using MIN-INT as compared to K-SP. This is because MIN-INT finds paths of greater length in order to avoid interference. This is clear when comparing $H$ which is greater when using MIN-INT than K-SP. However, the AUA is much less when using MIN-INT than K-SP indicating that MIN-INT does a good job of avoiding the consequences of inseparability. It appears that the reduced interference results in less blocking due to less violation of constraints. $G$ is higher for MIN-INT than K-SP because of the reduced effect of the consequences of inseparability. Note that the average load $L$, is higher for MIN-INT than for K-SP because of the increase in intended path lengths. Recall that for the single fiber case (small $K$ needed) it was found for Example 1 that K-SP ($K = 2$) performs better than MIN-INT because of the longer intended paths that result from MIN-INT (See Fig. 12 from Example 1 in Section V-A). It must be pointed out that in cases where the performance of

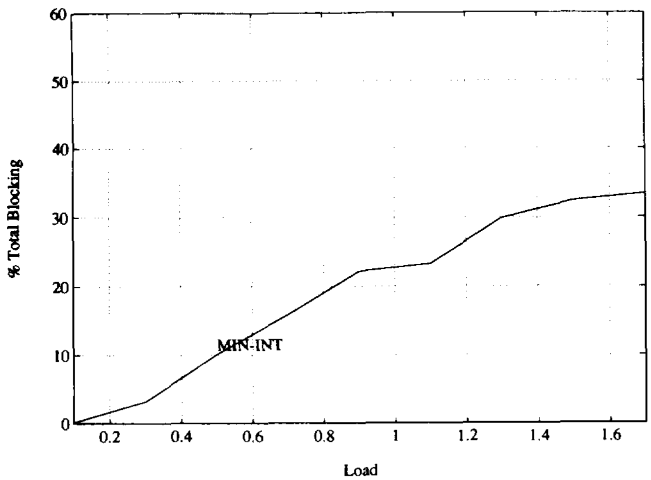


Fig. 14. Effect of 2 sources/node (double effective load) and double channels with one waveband (total blocking).

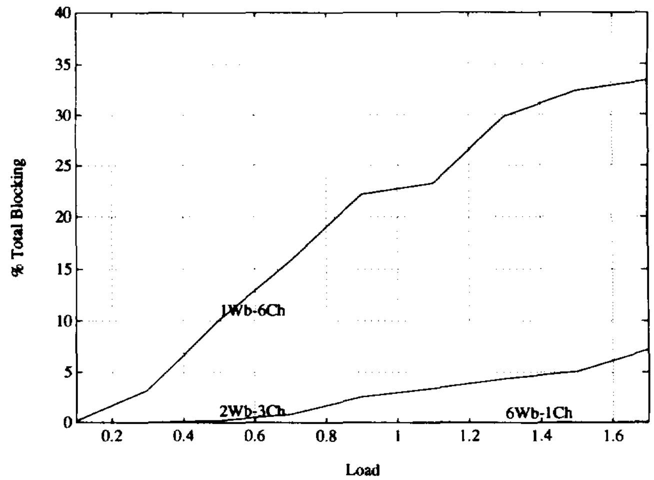


Fig. 15. Effect of 2 sources/node (double effective load) and varying (waveband, channel) pair (total blocking).

K-SP and MIN-INT were close, it was difficult to exactly explain the reason why one outperformed the other.

### B. Multiple Waveband Case

In the next four examples we compare LLN performace using different loads, different degrees of subdivision of the optical spectrum into wavebands, and using different methods of allocation of connections to wavebands. In each case the random graph of Example 1 is used, with 2 adjacent nodes having 1 fiber in each direction between them. Also, in each case, the path and channel allocation algorithms within a waveband were MIN-INT and MIN, respectively.

*Example 3:* Wavebands = 1, channels/waveband = 6, sources/node = 2. (Total of 40 sources.) The purpose of this example is to reexamine Example 1, with the offered load and the number of channels/fiber doubled. The simulation results are shown in Fig. 14. Comparing Fig. 14 to Fig. 12 shows that the blocking is higher for Example 3 than for Example 1. Thus simply doubling the number of channels is not enough to support double the load.

*Example 4:* Wavebands = 2, channels/waveband = 3, sources/node = 2. The MAXBAND rule is used for waveband selection.

*Example 5:* Wavebands = 6, channels/waveband = 1, sources/node = 2. The MAXBAND rule is used for waveband selection.

Fig. 15 compares the results from Examples 3, 4, and 5. In each case 6 channels in the optical spectrum are grouped into 1, 2, and 6 wavebands for Examples 3, 4, and 5, respectively. Example 5 is the case where the LLN is "fully" waveband selective and can distinguish between individual channels in the optical spectrum. Fig. 15 shows that higher waveband selectivity in the LLN, with the best case being 1 channel per waveband, results in much lower blocking.

*Example 6:* Example 6 is the same as Example 4 but MINBAND is used for waveband selection. Fig. 16 shows that MAXBAND outperforms MINBAND for waveband selection. Example 1 used 3 channels and 1 source per node. Example 4 used 2 wavebands with 3 channels per waveband and 2 sources per node, effectively doubling the wavebands and the load when compared to Example 1. Note that the blocking for Example 4 (See Fig. 15) is much smaller than Example 1 (See Fig. 12.) The blocking for Example 1 and 4 would be the same if each call arrival in Example 4 randomly selected a waveband. However, the MAXBAND heuristic loads up one waveband as much as possible and the "overflow" from waveband 1 is loaded onto the next waveband. This results in less blocking in Example 4.

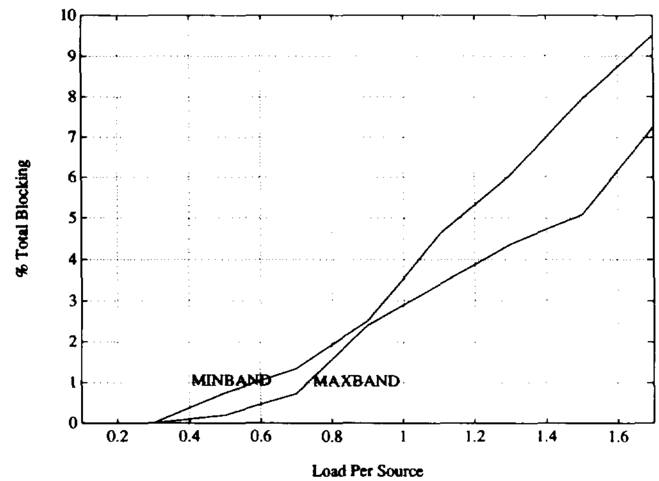


Fig. 16. MINBAND and MAXBAND rule comparison (total blocking).

## VI. Conclusions

Algorithms were proposed for the overall routing problem for point to point connections. Due to its complexity the routing problem was decomposed into the subproblems of choosing a waveband and routing the call within the chosen waveband. Performance of the proposed algorithms was measured on the basis of blocking obtained from a simulation.

Two rules MAXBAND and MINBAND were proposed for selecting a waveband for a call. It was shown that MAXBAND (maximum reuse of each waveband) outperformed MINBAND (minimum reuse of waveband). The problem of routing within a waveband was decomposed into the subproblems of finding a physical path for the call, checking for violations of constraints and allocating a feasible channel. Three algorithms, K-SP, BLOW-UP and MIN-INT were proposed for finding a physical path for the call. It was shown that under certain conditions MIN-INT and BLOW-UP outperformed K-SP. The basic principle behind all of these algorithms was that of finding paths with reduced interference. It was shown that routing along paths of reduced interference, in particular, minimum interference, tended to reduce blocking.

A recursive algorithm that checks for MISC and Color Clash violations on a chosen path was proposed. For the purpose of channel allocation the MIN heuristic (distributes the calls in progress evenly among the channels) outperformed the MAX heuristic (maximizes the reuse of each channel) owing to a reduction in the number of Color Clashes. Finally, large improvements in performance were shown when LLN's used multiple wavebands and multiple fibers.

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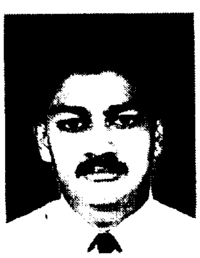

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