Wavelength Allocation in Regional Access Network with Optical Add-Drop Multiplexers

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Abstract— Optical add-drop multiplexers (OADMs) may cost-effectively provide regional nodes with large bandwidths. But, each dropped or added wavelength requires a costly TDM terminal. We discuss ways to decrease the number of TDM terminals in regional-access networks (RANs) with OADMs, while ensuring high network utilization and sufficiently low probability of blocking new connection requests. We propose two wavelength assignment schemes that provide full-connectivity in RANs with fixed-tuned OADMs: (1) wavelengths are assigned to nodes according to Hadamard code, and (2) bands of contiguous wavelengths are assigned to nodes. Simulation results show that on the average, the Hadamard wavelength assignment schemes approach the performance of RANs with OADMs that add-drop all wavelengths, while saving 50% of the TDM terminals. The saving of TDM terminals by using wavelength tunable OADMs vary in different cases. Tunable OADMs are advantageous for lower traffic granularity and more interactions of a RAN with the outside network.
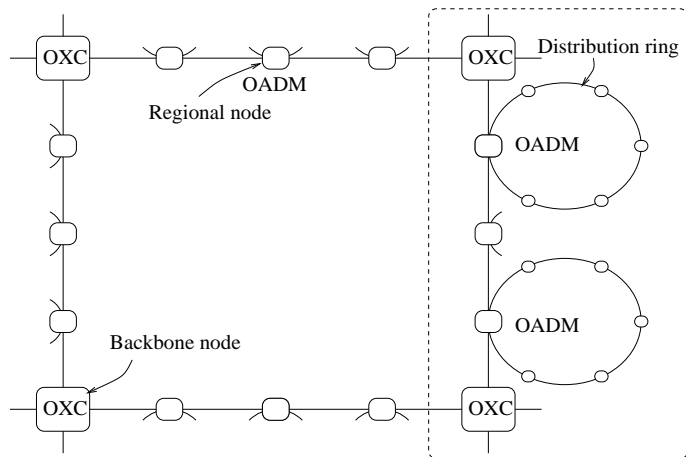
Fig. 1. RAN as a part of the two-tier WAN

I. INTRODUCTION

The regional access network (RAN) under consideration is a part of the two-tier wide area network (WAN) as shown in Figure 1. Nodes are divided into backbone and regional. Backbone nodes are equipped with optical cross connects (OXCs), and regional nodes are equipped with less expensive optical add-drop multiplexers (OADMs). The RAN is a bus network between two backbone nodes as encircled in Figure 1. Wavelengths are divided into backbone and local. Backbone wavelengths pass through the regional nodes, without being add/dropped. Regional nodes communicate through local wavelengths. If a connection is requested from the outside network for some node in the RAN, it is carried on a backbone wavelength to the backbone node, and then on a local wavelength from the backbone to the regional node. Also, if a connection is requested by some regional node to the outside network, it is carried on a local wavelength from the regional to a backbone node, and then on a backbone wavelength to the destination node, being converted at the backbone node. Traffic is carried on bidirectional pairs of fibers.

Adding and dropping all wavelengths at each regional node is appropriate if it exchanges the information only with the adjacent node. Actually, a connection may traverse multiple nodes without being dropped at intermediate nodes, so the required number of ports per node should be less than the total number of wavelengths to save cost. A few papers discussed minimizing the number of OADM ports in RANs assuming static traffic [4], [7], [11]. They assume apriori node-to-node demand for bandwidth, and assign wavelengths to be add/dropped at nodes to meet the demand while minimizing the number of OADM ports. Simmons et al. [11] calculated the saving of OADM ports in a RAN for uniform and distance dependent static traffic patterns. If nodes may request a fraction of the bit-rate transported by a single wavelength, the saving is calculated through 'super-node' modeling. Nodes are grouped into 'super-nodes' which request only full wavelength bit-rates. Gerstel et al. [4] proposed two heuristics to minimize the number of OADM ports in a ring network. Li and Simha [7] further improved the heuristics in [4] by combining them with routing decisions. While in [4], [7], [11] WDM optical network serves the SONET layer, in [5] it serves the ATM layer. At each node, packets on dropped wavelength are either received by that node or routed to the added wavelengths together with the packets generated by that node.

Virtual connections are requested and released according to the specified statistics. Blocking probability of connection requests is calculated for the proposed system with reduced number of OADM ports.

With exponentially increasing demand for bandwidth, dynamically reconfigurable optical networks will soon become a reality [13]. In such networks, wavelengths are assigned and released on demand. We analyze the performance of a RAN based on different OADM technologies and with dynamic traffic. Routing is done on-line, so that connections are not rearranged when a new connection is requested. Connections can carry a full bit-rate of wavelengths, or only the portion of it. A connection is carried on a single wavelength, and it is not converted at intermediate nodes. As pointed out in [11], such a choice simplifies network management. Given this assumption, each pair of nodes in a RAN with fixed-tuned OADMs should have at least one wavelength in common. We propose two wavelength assignment schemes which ensure full connectivity while reducing the number of required ports by 50%. The Hadamard assignment scheme evenly distributes the number of wavelengths in common for any pair of nodes, while the banding assignment scheme provides pairs of nodes with different numbers of wavelengths in common [12]. We assess their performance for dynamic traffic. We also obtain through simulations the number of tunable transceivers required to achieve a desired performance in a RAN with tunable OADMs. Section 2 gives an overview of the OADM technology. Wavelength assignment schemes appropriate for different OADM technologies are discussed in Section 3. Their performance is analyzed in Section 4. Section 5 concludes the paper.

II. Optical Add-Drop Multiplexer Technology

The system architecture and wavelength add/drop schemes may be constrained by the actual implementation of the OADMs. These implementation considerations also form the basis of the system architectures that we chose to study. An OADM is defined as a network element that has a common input port, a common output port, one or more add and drop ports. Each drop port drops one individual wavelength from the multi-wavelength network traffic connected to the common input port. The remaining wavelengths are combined with the wavelengths of traffic added at the add ports, and emerge from the common output port.

In the simplest form, an OADM can be made with one pair of wavelength demultiplexer/ multiplexer, e.g. an arrayed waveguide router (AWG) [2], and a number of 2 × 2 optical switches in specified add/drop wavelength paths as shown in Figure 2 (a). Each wavelength will be add/dropped at the specified port if the associated switch is set to the cross state. If 2 × 2 optical switches are included in all the arms between the demul-

tiplexer/multiplexer pair, we obtain a full OADM that can add and drop all the wavelengths. Alternatively, the array of 2 × 2 optical switches can be replaced by $(W + T) \times (W + T)$ optical cross-connect such as a micro-electro-mechanical (MEM) optical cross-bar switch [9], where T is the number of add/dropped wavelengths, as shown in Figure 2 (b). Such design will allow each port to arbitrarily add/drop any of the W wavelengths. These solutions have several disadvantages. First, its insertion loss is usually very high which degrades the power budget. Second, if multiple such OADMs are connected, the express wavelengths will pass a cascade of the optical filters. Filter misalignments and narrowing effects could degrade the express wavelength signals significantly. Thirdly, no filter is perfect and there will be multi-path signal leakage problems, resulting in unwanted cross-talk effects in the wavelength channels.

Another commonly used OADM technology is a combination of fiber Bragg grating (FBG) and optical circulators [1] as shown in Figure 2 (c) and (d). An FBG reflects the particular wavelengths it is designed for. It is made as a piece of optical fiber with periodic refractive index variation. Being a very good narrow band wavelength filter, an FBG is physically transparent to the expressed wavelengths. So, there is no signal degradation imposed on those wavelengths. The three-port optical circulators separate the reflected light from the incident light, according to the directions of the photons striking at individual ports. Since FBGs can be made with essentially negligible loss, most of the insertion loss comes from the circulators. To add/drop multiple wavelengths, FBG-circulator structures with different reflection wavelengths can be cascaded. The insertion loss increases linearly with the number of add/dropped wavelengths. In order to reduce the cascading loss seen by the express traffic and to preserve the overall power budget in the network, one may want to "sandwich" multiple gratings between a pair of circulators, and add/drop wavelengths in a hierarchical fashion. This reduces the worst channel loss to a logarithmic dependence on dropped channels. FBGs can be made tunable by changing the grating periodicity either thermally or through mechanical strains (Figure 2 (d)). The tuning range is usually only in the neighborhood of only 1 or 2 adjacent wavelengths. However, researchers are actively working on FBG OADMs with broad tuning ranges. It should be noticed that in this OADM implementation, pairs of transmitters and receivers are tuned to the same wavelengths.

The third type of commonly used OADM technology is a multi-layer thin film filter [10] as shown in Figure 2 (e) and (f). Light is incident at an angle to the filter. The demultiplexed wavelength is passed through while the remaining wavelengths are all reflected. It is also true that the express wavelengths are not filtered and suffer min-
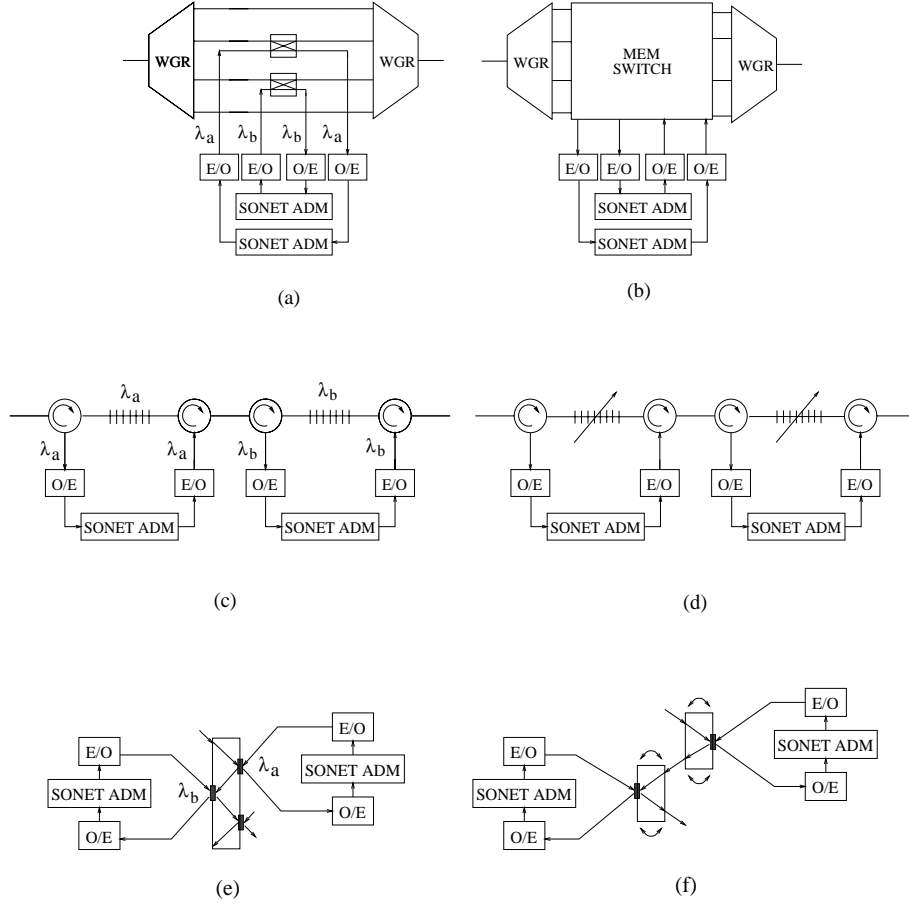
Fig. 2. OADM based on (a) Fixed-tuned WGR, (b) tunable WGR, (c) fixed-tuned fiber-grating, (d) tunable fiber-grating, (e) fixed-tuned thin-film filter, (f) tunable thin-film filter.

imal degradation except the insertion loss. Similar to FBGs, one can demultiplex multiple wavelengths by cascading these filters at a cost of increased insertion loss. However, thin film filters can be made with broad bandwidths covering several consecutive wavelengths. In order to reduce cascading loss to the express traffic, the optical spectrum is usually grouped into bands of consecutive wavelengths. Demultiplexing usually starts with a coarse band-pass filter followed by stages of finer filters. Thin film filters are tuned by changing the incident angle of the light.

Although there are numerous other technologies that can be used for wavelength add/drop purposes, the above three implementations are the major contenders that are commercially viable at the current time.

III. Wavelength Assignments

A. RAN with fixed-tuned OADMs

Assuming that a connection is carried on only one wavelength, each pair of nodes should have at least one wavelength in common. A wavelength assignment that balances the number of wavelengths in common for any pair of nodes relates well to the construction of error-correction codes, as will be explained shortly. In another scheme, each node adds and drops a different band of wavelengths. These bands are long enough so that they overlap for any pair of nodes. Such banding wavelength assignment has a practical implementation which improves the power budget, as explained in the previous section. Wavelength assignment is defined by vectors $\mathbf{C}_i = \{c_{ij}\}_{1 \times W}$, $1 \leq i \leq N$, where $c_{ij} = 1$ if node i add/drops wavelength j, and $c_{ij} = 0$ otherwise. N is the number of nodes in RAN. The weight of vector $\mathbf{C}_i$ is defined as follows:

$$w(\mathbf{C}_i) = \sum_{j=1}^{W} c_{ij}. \qquad (1)$$

If the pointwise multiplication of vectors $\mathbf{C}_i$ and $\mathbf{C}_j$ is defined like:

$$\mathbf{C}_i \cdot \mathbf{C}_j = \{c_{ik} \cdot c_{jk}\}_{1 \times W}. \qquad (2)$$

then nodes i and j have $w(\mathbf{C}_i \cdot \mathbf{C}_j)$ wavelengths in common.

Wavelength assignment may equalize the number of wavelengths in common for any pair of nodes. It holds that:

$$w(\mathbf{C}_i \cdot \mathbf{C}_j) = (w(\mathbf{C}_i) + w(\mathbf{C}_j) - w(\mathbf{C}_i \oplus \mathbf{C}_j))/2, \quad (3)$$

where $1 \oplus 0 = 0 \oplus 1 = 1$, $1 \oplus 1 = 0 \oplus 0 = 0$. A block error correction code is defined in the same way as the wavelength assignment: it is a set of binary vectors of the specified length. It tends to maintain $w(\mathbf{C}_i \oplus \mathbf{C}_j)$ approximately equal for all pairs of i, j. Also, ones are evenly spread over all vector coordinates, implying that the same number of nodes tune to any wavelength. If codewords in an error correction code have the same weight, then equation (3) implies that $w(\mathbf{C}_i \cdot \mathbf{C}_j)$ is approximately equal for all pairs i, j. The Hadamard code features this property [12]. It can be shown that in a Hadamard code, $w(\mathbf{C}_i) = W/2$, $1 < i \leq W$, and $w(\mathbf{C}_i \cdot \mathbf{C}_j) = W/4$, $1 < i \neq j \leq W$, where complements of codewords are excluded (see Appendix). An example of Hadamard wavelength assignment for $W = 16$ and $N = 8$ is given in Table 3 (a). The all-one codewords are assigned to backbone nodes. The first $N - 2 = 6$ codewords other than the all-one codeword in Hadamard code are assigned to regional nodes. Any regional node is tuned to $W/2 = 8$ wavelengths, and any two regional nodes have $W/4 = 4$ wavelengths in common. For example, node 2 add/drops odd wavelengths.

Alternatively, contiguous sets of wavelengths may be assigned to nodes in a RAN. Different bands of wavelengths should be assigned to nodes so that the same number of nodes are tuned to any wavelength. In order to achieve this property, bands of wavelengths assigned to nodes are shifted by W/N, assuming that W/N is an integer. It is easy to conclude that $W/2 + 1$ contiguous wavelengths should be assigned to each node in order to ensure full connectivity among nodes. The band that starts at wavelength i and the one that starts at wavelength $(W/2 + i) \bmod W$ have two wavelengths in common. Bands that start at wavelengths i and $(W/2 + i + kW/N) \bmod W$, $k > 0$, have $1 + kW/N$ wavelengths in common. An example of banding wavelength assignment for $W = 16$ and $N = 8$ is given in Table 3 (b). As in the Hadamard wavelength assignment the all-one codeword are assigned to backbone nodes. For example, node 3 add/drops wavlengths 3-11.

B. RAN with tunable OADMs

In the case of tunable OADMs, any pair of nodes can communicate as long as there is a wavelength available along the route between them, and an idle transceiver at each site. We will assess the performance of two kinds of tunable OADMs shown in Figure 2 (b), (d) and (f). In the first case in Figure 2 (b), transmitting and receiving wavelengths are independent at each node. In the second

WAVELENGTHS

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	2	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
N	3	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0
O																	
D	4	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
E	5	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0
S	6	1	0	1	0	0	1	0	1	1	0	1	0	0	1	0	1
	7	1	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1
	8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

(a)

WAVELENGTHS

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	2	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
N	3	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0
O																	
D	4	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
E	5	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0
S	6	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
	7	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1
	8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

(b)

Fig. 3. (a) Hadamard and (b) banding wavelength assignments for $W = 16$, $N = 8$

case in Figures 2, (d) and (f), a node that transmits at some wavelengths will have to receive traffic at the same wavelengths, and vice versa. In the simulations, we will assess the network performance for different numbers of tunable transmitters and receivers per node.

IV. PERFORMANCE ANALYSIS

Connections are dynamically established in the RAN under consideration. Connection requests arrive according to a Poisson point process. An arriving connection is established if there are available resources; in other words, if idle wavelengths and transceivers can be assigned to the new connection. A connection lasts a finite amount of time described by an exponential distribution, before it is released. Such dynamic wavelength assignment is emerging as a result of exponentially increasing demand for bandwidth [13]. We adopt on-line first-fit routing algorithm, i.e. the wavelength with the lowest ordinal number is assigned to the newly requested connection while existing connections remain unchanged. Connections requested by nodes outside the RAN and destined for nodes in the RAN are modeled by requests generated by backbone nodes. We assume that a given connection is requested from the outside network with probability P_1. Also, connections requested in the RAN

for nodes outside the RAN are considered only up to the backbone nodes. A connection generated by a node in RAN is destined to the outside network with probability P_2. All nodes are identical in terms of traffic that they generate and receive. Nodes might request only a portion of the bit-rate carried by a wavelength. In that case multiple connections with different sources and destinations can use one wavelength on a link. The granularity G denotes the maximum number of connections carried by one wavelength on a link. For example, if wavelengths carry OC-192, and nodes request OC-48, the granularity is $G = 4$.

In Figure 4 we compare the blocking probability of connection requests for different network parameters in the RAN with fixed-tuned and tunable OADMs. It is assumed that there are $W = 32$ local wavelengths and $N = 8$ nodes in the RAN. The interaction of the RAN with the outside network is represented by parameter $P = P_1 = P_2 \in \{0, 0.5\}$. Traffic granularity can take values $G \in \{1, 4\}$. Tunable OADMs are assumed to contain $T \in \{4, 8, 16\}$ tunable transmitters and receivers. Tunable-1 denotes the case for which transmitters and receivers are independently tunable, while tunable-2 denotes the case for which transmitters and receivers are tuned to the same wavelengths, as explained in Section 3.2. In our simulations a 95% confidence interval is within 1% of the calculated mean value.

Figure 4 shows the blocking probability as a function of network utilization. A connection length is the number of its constituent node-to-node links. Network utilization is the averaged total length of established connections divided by the network capacity $(N - 1) \cdot W$. For $P = 0$, $G = 1$, a RAN with fixed-tuned OADMs employing Hadamard wavelength assignment performs significantly poorer than a RAN with full OADMs that terminate all wavelengths, as can be seen from Figure 4 (a). However, the performance of Hadamard assignment approach the performance of full OADMs as the portion of express traffic (P) and granularity (G) increase, as indicated by Figure 4 (b), (c), and (d). Namely, for some fixed blocking probability the RAN based on Hadamard assignment accommodates slightly lower network efficiency than the RAN based on full OADMs. In these realistic cases 50% of TDM terminals can be saved by using the Hadamard wavelength assignment scheme. A RAN based on banding assignment cannot provide low blocking probabilities and high network efficiency. For $G = 1$ a tunable OADM with $W/2 = 16$ transmitters and receivers achieve the same blocking probability as having a full OADM per node, but for $G = 4$ it provides the lower blocking probability. For lower granularity and higher portion of expressed traffic, a RAN with $T = W/4 = 8$ tunable transceivers per node performs as well as RAN based on the Hadamard assignment scheme

as can be seen in Figure 4 (b), and saves 75% of the terminals. In other cases, RANs with fixed-tuned OADMs are advantageous. The blocking probability in a RAN with tunable OADMs degrades as the granularity increases. A tunable transceiver tunes to a particular wavelength even though only a fraction of its bit-rate is requested; so, this wavelength may remain underutilized while the new requested connections are blocked, as seen in Figure 4 (c) and (d). Two types of tunable OADMs perform similarly. Tunable-2 type OADMs improve the network performance by requiring a node to transmit and receive at the same wavelength. Such requirement avoids unused "gaps" on wavelengths.

Tables I,II show the rough estimates of network utilization for different parameters W, N, P, G and RAN architectures providing blocking probability of 0.01. For granularity $G = 1$, a RAN with tunable OADMs with $T = W/4$ transceivers approach performance of a RAN based on the Hadamard assignment. So, a RAN with tunable OADMs saves a larger number of TDM terminals (75%). For granularity $G = 4$, a RAN with fixed-tuned OADMs based on the Hadamard assignment outperforms a RAN with tunable OADMs, saving the same number of TDM terminals while achieving higher network utilization. As a conclusion, finer granularity not only provides more flexible management, but also improves the network utilization.

V. SUMMARY

We have discussed RAN as a part of the two-tier WAN. Regional nodes access only local wavelengths by using OADMs. We propose two wavelength assignments that provide full connectivity among nodes in RAN with fixed-tuned OADMs. Proposed Hadamard wavelength assignment scheme saves 50% of the TDM terminals while approaching the performance of having full OADMs in many cases. The banding wavelength assignment scheme performs poorer. Simulation results indicate that a RAN with tunable OADMs can save up to 75% TDM terminals in certain cases. However, since tunable OADMs involve more sophisticated optical technology, a RAN based on the Hadamard wavelength assignment might be more attractive even in those cases. The saving of TDM terminals by using tunable OADMs increases with the expressed portion of the traffic to and from the WAN, and decreases as the traffic granularity increases. On the other hand, the performance of RANs with fixed-tuned OADMs improves as the traffic granularity increases.
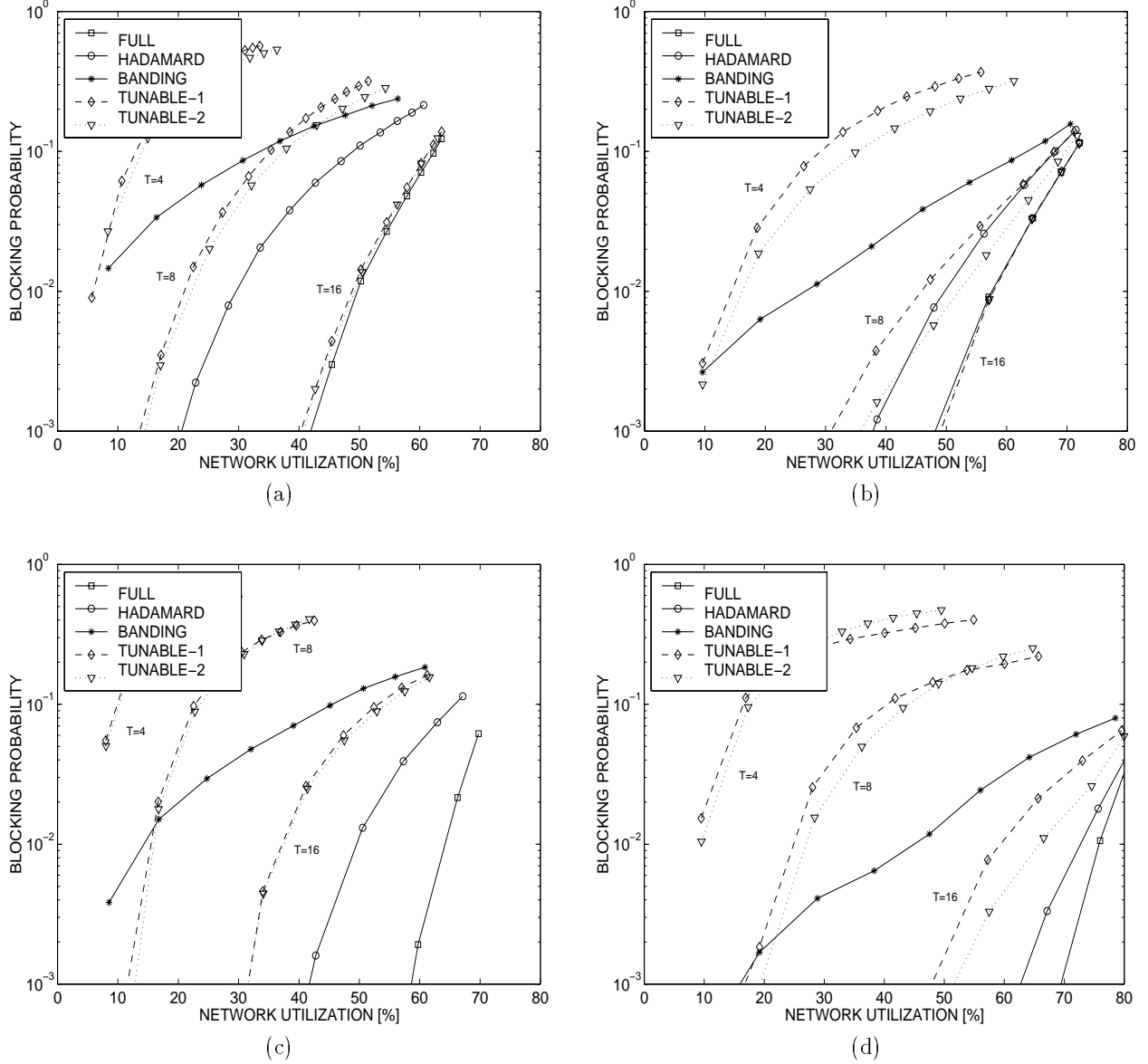
Fig. 4. Blocking probability versus network utilization, $W = 32$, $N = 8$, $T \in \{4, 8, 16\}$ (a) $P = 0$, $G = 1$, (b) $P = 0.5$, $G = 1$, (c) $P = 0$, $G = 4$ and (d) $P = 0.5$, $G = 4$.

Appendix

Codewords in Hadamard code can be obtained from the following matrix recursion:

$$\mathbf{H}_1 = [1], \tag{4}$$

$$\mathbf{H}_{2^k} = \begin{bmatrix} \mathbf{H}_{2^{k-1}} & \mathbf{H}_{2^{k-1}} \\ \mathbf{H}_{2^{k-1}} & \mathbf{E} - \mathbf{H}_{2^{k-1}}, \end{bmatrix} \tag{5}$$

where $\mathbf{E}$ is a matrix with all entries equal to one. Rows of the matrix $\mathbf{H}_{2^k}$ and their complements are Hadamard codewords of length 2^k. We exclude complements from wavelength assignment because they do not have wavelengths in common with their complementary rows of $\mathbf{H}_{2^k}$. It is straightforward to prove by mathematical induction the well known features of Hadamard code: $w(\mathbf{C}_i) = W/2$, $1 < i \le W$, and $w(\mathbf{C}_i \oplus \mathbf{C}_j) = W/2$, $1 < i \ne j \le W$. From equation (3), it follows that $w(\mathbf{C}_i \cdot \mathbf{C}_j) = W/4$, $1 < i \ne j \le W$.

TABLE I

NETWORK UTILIZATION [%] FOR 1% BLOCKING PROBABILITY, $G = 1$

W	32				64				128			
N	8		16		8		16		8		16	
P	0	0.5	0	0.5	0	0.5	0	0.5	0	0.5	0	0.5
Full	50	60	45	55	60	70	50	65	60	80	55	70
Hadamard	30	50	30	45	45	65	40	60	50	80	55	70
Banding	5	30	10	30	0	30	10	30	0	20	0	35
$T = W/2$	50	60	45	55	60	70	50	65	60	80	55	70
$T = W/4$	20	50	35	55	35	65	45	65	40	80	55	70
$T = W/8$	5	20	10	30	15	30	20	50	15	40	25	35

TABLE II

NETWORK UTILIZATION [%] FOR 1% BLOCKING PROBABILITY, $G = 4$

W	32				64				128			
N	8		16		8		16		8		16	
P	0	0.5	0	0.5	0	0.5	0	0.5	0	0.5	0	0.5
Full	65	75	60	70	70	80	60	80	70	90	60	80
Hadamard	50	70	50	70	60	80	55	80	60	90	60	80
Banding	15	45	30	45	10	30	25	45	5	30	10	45
$T = W/2$	35	65	50	70	40	75	50	80	50	90	55	80
$T = W/4$	15	25	20	40	20	25	25	50	25	40	25	60
$T = W/8$	0	10	10	15	10	10	10	20	10	20	10	15

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