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The Role of Network Topologies in the Optical Core of IP-over-WDM Networks with Static Wavelength Routing *

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Abstract. In this paper, we present a performance analysis of network topologies for the optical core of IP-over-WDM networks with static wavelength routing. The performance analysis is focused on regular degree four topologies, and, for comparison purposes, degree three topologies are also considered. It is shown that the increase of the nodal degree from three (degree three topology with smallest diameter) to four (degree four topology with smallest diameter) improves the network performance if a larger number of wavelengths per link is available. However, the influence of wavelength interchange on the nodal degree gain is small. The performance of regular degree four topologies with smallest diameter is also compared with the performance of mesh–torus topologies (which are also degree four topologies), and it is shown that the blocking probability of degree four topologies with smallest diameter is about two orders of magnitude lower than the blocking probability of mesh–torus topologies. It is also presented a performance comparison of WDM-based networks with nodal degrees ranging from two to five and it is shown that the increase of the nodal degree from two to three leads to high nodal degree gains, while de increase of the nodal degree from four to five leads to low nodal degree gains. These results show that degree three and degree four topologies are very attractive for use in the optical core of IP-over-WDM networks.

Keywords: optical networks, optical Internet, routing, network topologies

1. Introduction

IP-over-WDM (IP: Internet Protocol; WDM: Wavelength Division Multiplexing) networks are expected to be an infrastructure for next generation Internet, by directly carrying IP packets on WDM-based networks [Qiao et al., 9; Dixit and Lin, 4]. Optical networks are already in use to provide WDM point-to-point connections for a multi-layer architecture to transport IP traffic. Although this approach increases the link bandwidth by using WDM, it does not solve the problem of network bottleneck due to the expo-

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nential traffic growth driven by Internet-based services, since this solution only shifts the bottleneck problem from the link to the electronic router. A solution to this problem that also leads to lower management costs and lower complexity consists in the use of a two-layer architecture, in which IP traffic is transported directly over optical networks. In this new approach, some of the switching and routing functions, which have been performed by electronics, are incorporated into the optical domain. Therefore, next generation backbone networks should include both IP routers with IP-packet switching capabilities and optical cross-connects with wavelength-path switching capabilities to reduce the burden of heavy IP-packet switching loads.

Recent technology developments, such as the advent of optical add/drop multiplexers and optical cross-connects, enabled the evolution from point-to-point WDM links to wavelength routing networks. Optical networks with wavelength routing in a mesh topology are under intense research. In [Hjelme, 8], a study of the influence of nodal degree on the fibre length, capacity utilisation, and average and maximum path lengths of wavelength routed mesh networks is presented. It is shown that average nodal degrees varying between 3 and 4.5 are of particular interest. In this paper, our attention is focused on regular topologies with nodal degrees of 3 and 4.

Different topologies in the optical core of IP-over-WDM networks can lead to different network performances. Therefore, it is desirable to design a network which is as fast as possible (performance optimization) and requires the least amount of optical hardware (cost optimization). In the context of the performance of optical wide area networks, the primary concern is congestion.

Two main approaches have been used to identify the best topology [Haque, 7]: mathematical optimisation techniques and regular topologies. The first approach is generally based on a static traffic model and attempts to design an optimal logical topology and to determine a routing scheme over the given physical topology. The topology desing and routing problem can be formulated as a mixed integer linear program (MILP) which minimizes the congestion, subject to an upper bound of the maximum propagation delay. The main drawback of this approach is that the number of constrains of the MILP grow rapidly with the size of the network and it may become infeasible for networks with a moderate size. This problem may be simplified by decoupling the logical topology design from the problem of determining the optimum routing scheme and heuristics have been proposed for the design of the logical topology and for the problem of finding an optimal routing. However, if wavelength conversion is considered, performances obtained with static traffic models are worst than the performances obtained with dynamic traffic models. The second approach that has been used for the design of network topologies is to ignore traffic demands and to design regular topologies that have some desirable properties such as a low diameter and a low average path length.

In this paper, we consider both regular topologies and a dynamic traffic model (probabilistic model). Topologies with smallest diameter are identified and their traffic performance is assessed. This approach has already been used in [Freire and da Silva, 5, 6; Coelho and Freire, 1; Coelho et al., 2, 3] to analyze the performance of WDM networks with degree three topologies.

In [Freire and da Silva, 6], the authors have investigated wavelength routed optical networks with chordal ring topology. Chordal rings are a well-known family of regular degree three topologies used for interconnection of parallel and distributed systems. In [Freire and da Silva, 6], the authors have shown that the best network performance is obtained for the chord length that leads to the smallest network diameter. In [Freire and da Silva, 5], the same authors have shown that the performance of a chordal ring network (which has a nodal degree of 3), with a chord length that leads to the smallest diameter, is similar to the performance of a mesh–torus network (which has a nodal degree of 4). Since a (bi-directional) chordal ring network with N nodes has $3N$ (unidirectional) links and a (bi-directional) mesh–torus network with N nodes has $4N$(unidirectional) links, the choice of a chordal ring with minimum diameter, instead of a mesh–torus, reduces network links by 25%. Moreover, since chordal rings have lower nodal degree, they require in each switch, a smaller number of node-to-node interfacing (NNI) ports.

In [Coelho and Freire, 1], we presented an assessment of the traffic performance in wavelength routing networks with random topologies of average nodal degrees of 2 and 3. It was shown that the performance of a network, with a random topology and an average nodal degree of 2, is better than the performance of rings and some chordal rings. It was also shown that the performance of a network, with a random topology and an average nodal degree of 3, is better than the performance of a network with a chordal ring topology with smallest diameter. This fact led us to the question of the existence of degree three topologies that outperform chordal rings.

In order to try to find degree three topologies that may outperform chordal rings with smallest diameter, in [Coelho et al., 2], we introduced a general regular degree three topology family, of which the chordal ring family is a particular case. We analysed all topologies of that general regular degree three topology family and we showed that there are several regular degree three topologies with the same smallest diameter of the chordal ring with smallest diameter and with exactly the same path blocking performance, but we have not found any degree three topology outperforming chordal rings with smallest diameter.

Since we have not found any regular degree three topology outperforming chordal rings with smallest diameter, we looked for irregular degree three topologies. In [Coelho et al., 3], we have obtained a lower bound of the traffic performance in networks with irregular degree three topologies and we have shown that this lower bound is very close to the performance of a network with a random topology and an average nodal degree of three, while the performance of a network with a chordal ring topology (regular topology) with smallest diameter is worse than the lower bound of the traffic performance in networks with irregular degree three topologies.

In this paper, a general regular topology family for any nodal degree is introduced and the performance of WDM networks with nodal degrees ranging from 2 to 5 is analysed. Particular attention is paid to WDM networks with nodal degrees of 3 and 4.

The remainder of this paper is organised as follows. Section 2 introduces regular topology families for any nodal degree. Section 3 briefly describes the model used to evaluate the path blocking performance in WDM networks with shortest path routing.

A performance analysis of WDM networks with regular degree 3 and degree 4 topologies is presented in section 4. A performance comparison of WDM networks with nodal degrees ranging from 2 to 5 is presented in section 5. Main conclusions are presented in section 6.

2. General topology family for a given nodal degree

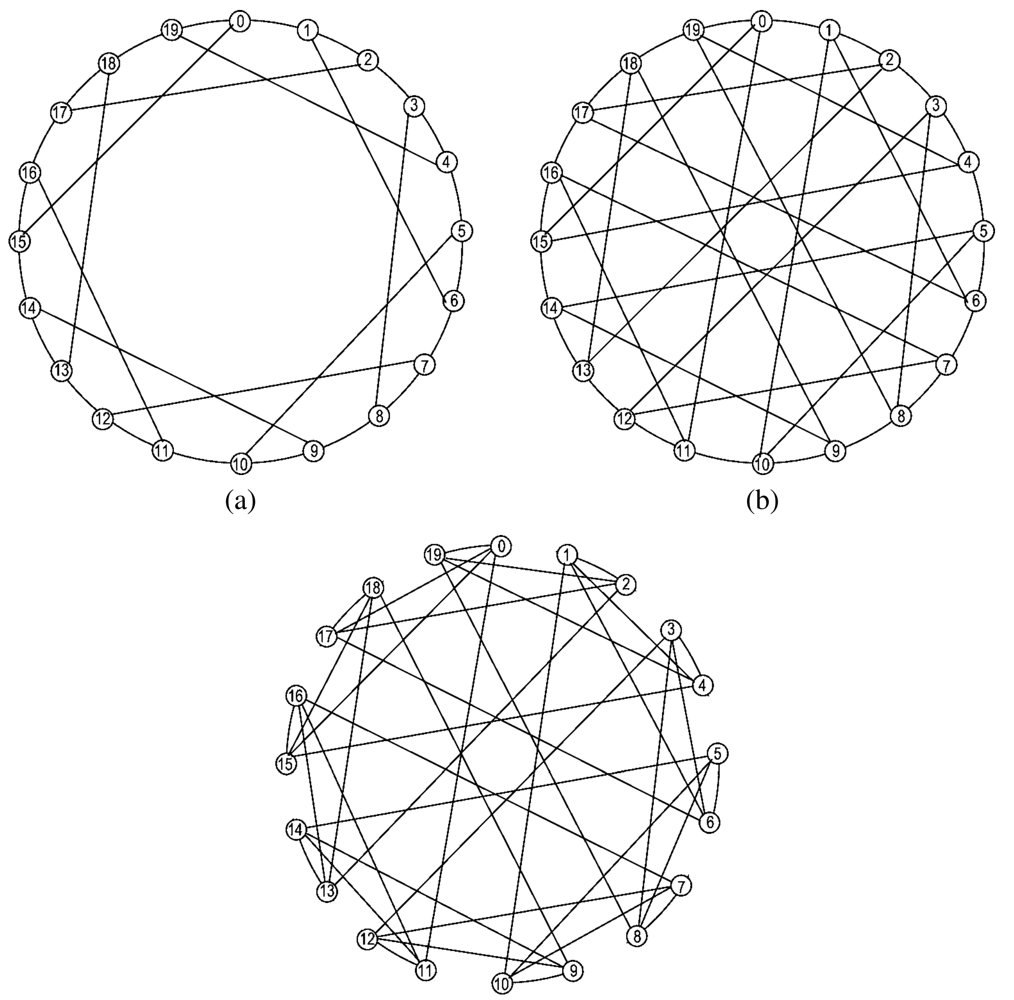
A chordal ring is basically a bi-directional ring network, in which each node has an additional link, called a chord. The number of nodes in a chordal ring is assumed to be even, and nodes are indexed as $0, 1, 2, \ldots, N-1$ around the N-node ring. It is also assumed that each odd-numbered node i ($i = 1, 3, \ldots, N-1$) is connected to a node $(i + w) \bmod N$, where w is the chord length, which is assumed to be positive odd. For a given number of nodes there is an optimal chord length that leads to the smallest network diameter. The network diameter is the largest among all of the shortest path lengths between all pairs of nodes, being the length of a path determined by the number of hopes.

In [Coelho et al., 2], we introduced a general family of degree three topologies, of which the chordal ring family is a particular case. In each node of a chordal ring, we have a link to the previous node, a link to the next node and a chord. In [Coelho et al., 2], we assumed that the links to the previous and to the next nodes are replaced by chords. Thus, each node has three chords, instead of one. Let w_1, w_2 and w_3 be the corresponding chord lengths, and N the number of nodes. We represented a general degree three topology by DTT(w_1, w_2, w_3). We assumed that each odd-numbered node i ($i = 1, 3, \ldots, N-1$) is connected to the nodes $(i + w_1) \bmod N$, $(i + w_2) \bmod N$, and $(i + w_3) \bmod N$, where the chord lengths, w_1, w_2, and w_3 are assumed to be positive odd, with $w_i \leqslant N-1$ ($i = 1, 2, 3$), and $w_i \neq w_j$, $\forall i \neq j \wedge 1 \leqslant i, j \leqslant 3$. In this notation, a chordal ring with chord length w is simply represented by DTT$(1, N-1, w)$.

Here, we introduce a general topology for a given nodal degree. We assume that instead of a topology with nodal degree of 3, we have a topology with a nodal degree of n, where n is a positive integer, and instead of having 3 chords we have n chords. We also assume that each odd-numbered node i ($i = 1, 3, \ldots, N-1$) is connected to the nodes $(i + w_1) \bmod N$, $(i + w_2) \bmod N, \ldots, (i + w_n) \bmod N$, where the chord lengths, $w_1, w_2, \ldots, w_n$ are assumed to be odd positive integers, with $w_i \leqslant N-1$ ($i = 1, \ldots, n$), and $w_i \neq w_j$, $\forall i \neq j \wedge 1 \leqslant i, j \leqslant n$. Now, we introduce a new notation: a general degree n topology is represented by DnT$(w_1, w_2, \ldots, w_n)$. In this new notation, a chordal ring with chord length w is represented by D3T$(1, N-1, w)$. As an example, figure 1 shows three topologies for networks with $N = 20$ nodes: D3T(1, 19, 5) (degree three chordal ring with a chord length of 5), D4T(1, 19, 9, 5) (degree four chordal ring with chord lengths of 5 and 9), and D4T(1, 3, 5, 9).

3. Computation of the path blocking probability

One of the key performance metrics used in optical networks with wavelength routing is the path blocking probability, i.e., the probability of a connection request being denied



(a) (b) (c)

Figure 1. Schematic representation of DnT topologies for $N = 20$: (a) D3T(1, 19, 5); (b) D4T(1, 19, 9, 5); (c) D4T(1, 3, 5, 9).

due to unavailable optical paths. To compute the path blocking probability in optical networks with wavelength conversion, we have used the model presented in [Subramaniam et al., 10], since it applies to topologies with low connectivity, has a moderate computational complexity, and takes into account dynamic traffic and the correlation between the wavelengths used on successive links of a multi-link path.

The following assumptions are used in the model [Subramaniam et al., 10]:

(1) Call requests arrive at each node according to a Poisson process with rate λ, with each call equally likely to be destined to any of the remaining nodes.

(2) Call holding time is exponentially distributed with mean $1/\mu$, and the offered load per node is $\rho = \lambda/\mu$.

(3) The path used by a call is chosen according to a pre-specified criterion (e.g., random selection of a shortest path), and does not depend on the state of the links that make up a path; the call is blocked if the chosen path can not accommodate it; alternate path routing is not allowed.

(4) The number of wavelengths per link, F, is the same on all links; each node is capable of transmitting and receiving on any of the F wavelengths; each call requires a full wavelength on each link it traverses.

(5) Wavelengths are assigned to a session randomly from the set of free wavelengths on the associated path.

In [Subramaniam et al., 10], it is assumed that, given the loads on links $1, 2, \ldots, i-1$, the load on link i of a path depends only on the load on link $i-1$ (Markovian correlation model). It is also assumed that the hop-length distribution is known, as well as the arrival rates of sessions at a link. The arrival rates at links have been estimated from the arrival rates of sessions to nodes, as in [Subramaniam et al., 10].

The hop-length distribution is a function of the network topology and the routing algorithm, and is easily determined for most regular topologies with the shortest-path algorithm. In this work, instead of defining the hop-length distribution through an analytical equation used by the analytical framework to compute the path blocking probability, we developed an algorithm that provides the hop-length distribution for a given DnT$(w_1, w_2, \ldots, w_n)$ topology.

4. Performance analysis of WDM networks with regular degree four topologies

In this section, we present an assessment of the traffic performance in WDM networks with D4T(w_1, w_2, w_3, w_4) of smallest diameter. A performance comparison with D3T(w_1, w_2, w_3) and with mesh–torus topologies is also provided. The performance analysis is focused on networks with $N = 100$ nodes.

Figure 2 shows the network diameter for mesh–torus topology, for two degree three topologies, D3T$(1, 99, w_3)$ and D3T$(1, 3, w_3)$, with $3 \leqslant w_3 \leqslant 99$, and for two degree four topologies, D4T$(1, 99, 3, w_4)$ and D4T$(1, 99, 5, w_4)$, with $3 \leqslant w_4 \leqslant 99$. As may be seen, for $N = 100$ nodes, the maximum and minimum diameters of both degree three topologies are 26 and 9, respectively, while, the maximum and minimum diameters for D4T$(1, 99, 3, w_4)$ are 18 and 7, respectively, and, for D4T$(1, 99, 5, w_4)$, 18 and 6, respectively. The diameter of the mesh–torus topology, for $N = 100$, is 10, which is slightly higher than the smallest diameter of a degree three topology with smallest diameter (9, for $N = 100$). As shown in [Coelho et al., 2], in any regular degree three topology family there are no diameters lower than the smallest diameter of the chordal ring family (but there are several other topologies with the same smallest diameter of the chordal ring with smallest diameter). However, the families D4T$(1, 99, 3, w_4)$ and

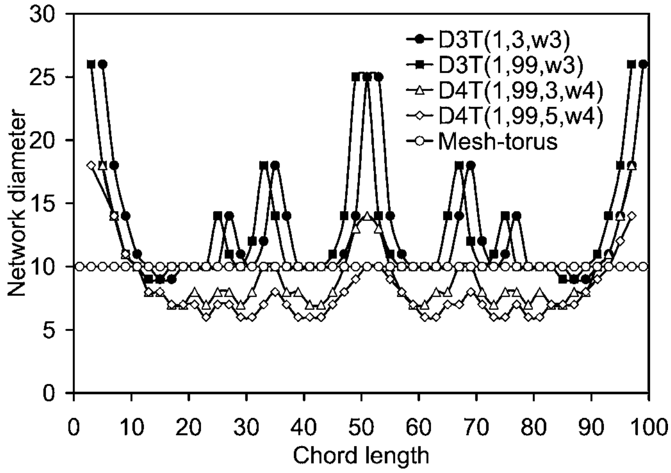


Figure 2. Network diameters for mesh–torus topology ($N = 100$), D3T$(1, 99, w_3)$ and D3T$(1, 3, w_3)$, with $3 \leqslant w_3 \leqslant 99$, and for D4T$(1, 99, 3, w_4)$, D4T$(1, 99, 5, w_4)$, with $3 \leqslant w_4 \leqslant 97$.

D4T$(1, 99, 5, w_4)$, which are degree four chordal ring families, have different minimum diameters. Minimum and maximum diameters for the family D4T$(1, 99, w_3, w_4)$, as a function of w_3, are shown in figure 3. We also investigated minimum and maximum diameters for all D4T topologies with w_3 and w_4 free (both ranging from 1 to 99, with $w_1 \neq w_2 \neq w_3 \neq w_4$), for each fixed value of w_1 and w_2. The smallest diameter we found for the D4T(w_1, w_2, w_3, w_4) family was 6, for $N = 100$ nodes (see figure 3, for the case of the family D4T$(1, 99, w_3, w_4)$). Therefore, we will concentrate, on the path blocking performance for this smallest diameter of degree four topologies, which, for D4T$(1, 99, 5, w_4)$, occur at $w_4 = 23$, $w_4 = 29$, $w_4 = 31$, $w_4 = 39$, $w_4 = 41$, $w_4 = 43$, $w_4 = 61$, $w_4 = 63$, $w_4 = 73$, $w_4 = 75$, $w_4 = 79$, and $w_4 = 81$.

In figure 4, we compare the path blocking probability for networks with D3T$(1, 99, 13)$, which is a degree three chordal ring topology with smallest diameter, and D4T$(1, 99, 5, 23)$, which is a degree four chordal ring topology with smallest diameter, and for networks with a mesh–torus topology (which is a degree four topology with a diameter of 10, for $N = 100$ nodes). Although mesh–torus topologies are widely considered for performance analysis of wide area optical networks, this figure shows that, for $F = 12$ and blocking probabilities below 10^{-3}, the blocking probability of D4T topologies with smallest diameters is about two orders of magnitude lower than the blocking probability of mesh–torus networks.

The nodal degree gain is the gain in blocking probability due to the increase of nodal degree from $(n - 1)$ to n, and is defined as [Freire and da Silva, 6]

$$G_{\text{nd}} = \frac{P_{(n-1)}}{P_n}, \tag{1}$$

where $P_{(n-1)}$ is the blocking probability in a network with a nodal degree of $n - 1$, and P_n is the blocking probability in a network with a nodal degree of n (both obtained for

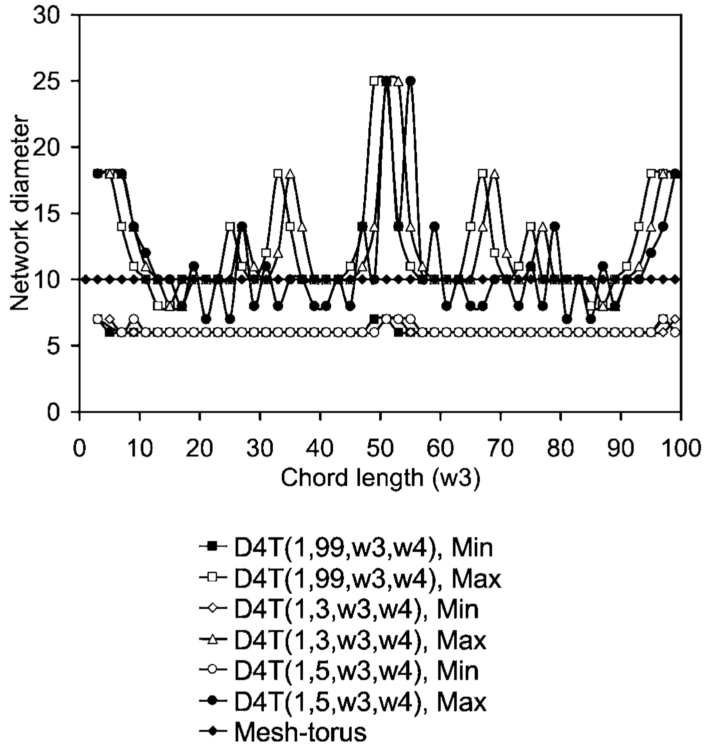


Figure 3. Minimum (Min) and maximum (Max) network diameters for mesh–torus topology ($N = 100$) and D4T(1, 99, w_3, w_4), D4T(1, 3, w_3, w_4), D4T(1, 5, w_3, w_4), with $3 \leqslant w_3 \leqslant 99$, and $3 \leqslant w_4 \leqslant 99$.

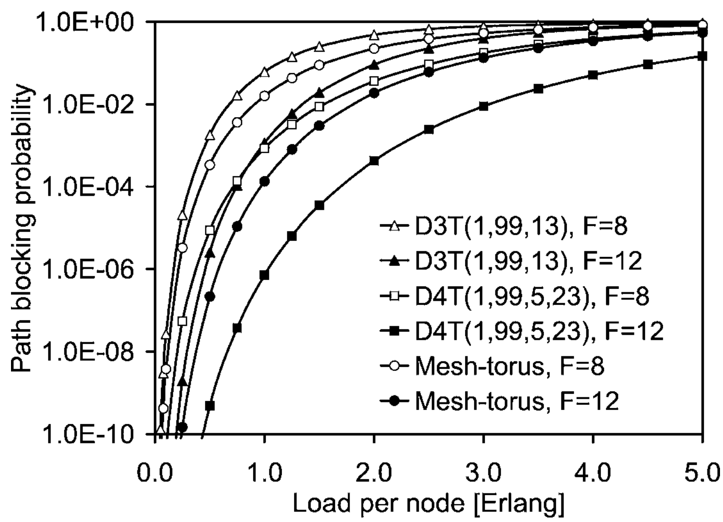


Figure 4. Path blocking probability for D3T(1, 99, 13), and for D4T(1, 99, 5, 23), and mesh–torus topology without wavelength interchange. $N = 100$; F: number of wavelengths per link.

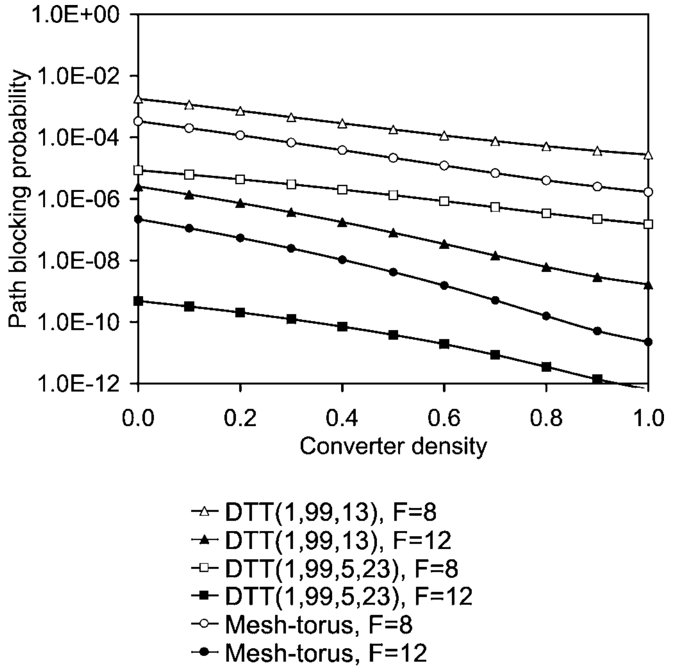


Figure 5. Path blocking probability versus converter density for networks with mesh–torus topology, D3T(1, 99, 13) and D4T(1, 99, 5, 23). $N = 100$; load per node: 0.5 erlang; F: number of wavelengths per link.

the same number of nodes, the same wavelengths per link, the same load per node, and the same converter density).

In this case, $n = 4$, and the nodal degree gain increases as the number of wavelengths per link increases. This observation suggests that the increase of the nodal degree (and, as a consequence, the number of links) may improve the network performance if a larger number of wavelengths per link is available, and if the network diameter is smaller.

In figure 4, no wavelength conversion (or wavelength interchange) is considered. However, performance improvements due to wavelength conversion need to be investigated. Figure 5 shows the blocking probability as a function of the wavelength converter density for the mesh–torus network, for the degree three chordal ring network with $w_3 = 13$ and for the degree four network with $w_3 = 5$ and $w_4 = 23$. As may be seen in figure 5, for the degree four network with 12 wavelengths per link, the path blocking probability decreases about 3 orders of magnitude as the converter density increases from 0% (network without wavelength conversion) to 100% (all nodes have full wavelength conversion capability). However, for a given number of wavelengths per link, the curves of blocking probability for degree three and degree four chordal ring networks have a similar behaviour, which suggest that the converter density has a small influence on the nodal degree gain. It may also be observed that, for a given converter density, the nodal degree gain increases as the number of wavelengths per link increases, which confirms our previous comments about this observation. It may also be observed that the performance improvement due to the replacement of a chordal ring with smallest diameter by the mesh–torus is very small.

5. Performance comparison of WDM networks with nodal degrees ranging from two to five

In the following, we present an assessment of the blocking performance in WDM-based networks for topologies with nodal degrees between 2 and 5. For each nodal degree, the performance analysis is concentrated on networks with 100 nodes. The performance analysis is focused on chord lengths that lead to the smallest diameter. Figure 6 shows the influence of the increase of nodal degree on the nodal degree gain.

As may be seen in figure 6, when the load per node is low, there is a higher nodal degree gain due to the increase of nodal degree from 2 to 3. This high nodal degree gain clearly decreases if the nodal degree is increased from 3 to 4. If we increase the nodal degree from 4 to 5, this nodal degree gain becomes small, which means that the increase of nodal degree to values larger or equal than 5 leads to small improvements of the network traffic performance. Therefore, the increase of the nodal degree, i.e. the inclusion of more links between nodes, is a less attractive (and not cost effective as well) option to increase the performance of WDM-based networks with nodal degrees larger than 4. These results are confirmed in figure 7, which shows the path blocking performance as a function of the wavelength converter density. The decrease of the nodal degree gain with the increasing of the nodal degree is due to the small differences among smallest diameters as the nodal degree increases: for $N = 100$, the smallest diameter of

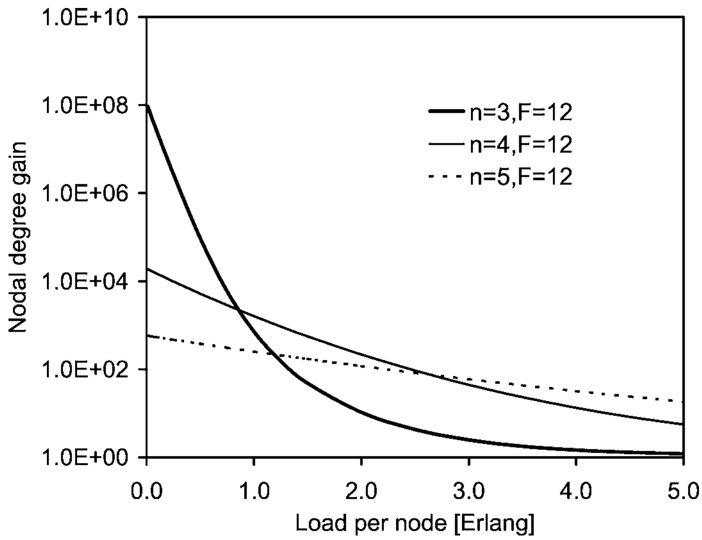


Figure 6. Nodal degree gain, as a function of the load per node, when the nodal degree increases from 2 to 3 ($n = 3$), when the nodal degree increases from 3 to 4 ($n = 4$) and when the nodal degree increases from 4 to 5 ($n = 5$). $N = 100$; F: number of wavelengths per link.

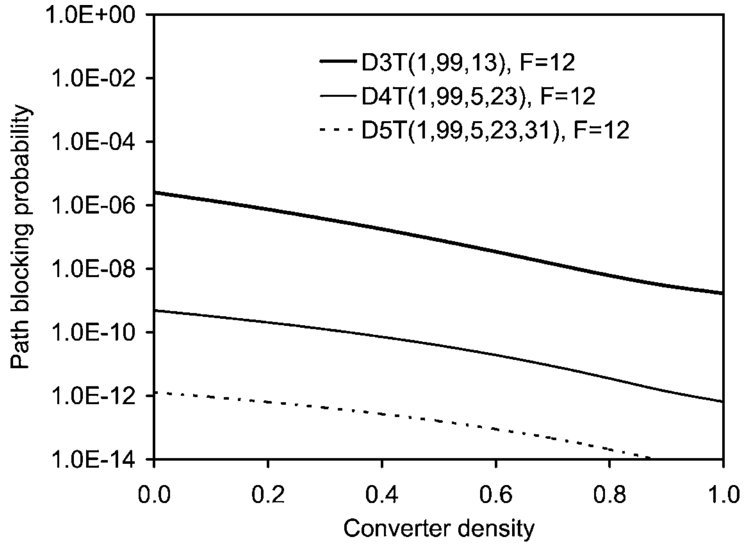


Figure 7. Path blocking probability versus load per node for networks with D3T(1, 99, 13), with D4T(1, 99, 5, 23) and D5T(1, 99, 5, 23, 31); $N = 100$; F: number of wavelengths per link. Load per node: 0.5 erlang.

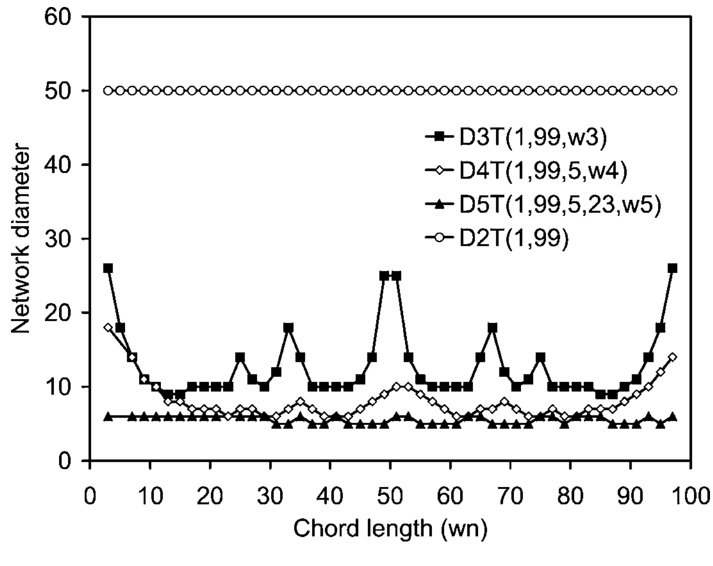


Figure 8. Network diameters for D2T(1, 99), D3T(1, 99, w_3), D4T(1, 99, 5, w_4) and D5T(1, 99, 5, 23, w_5) with $3 \leqslant w_3 \leqslant 99$, $3 \leqslant w_4 \leqslant 99$ and $3 \leqslant w_5 \leqslant 99$ and $w_1 \neq w_2 \neq w_3 \neq w_4$.

a D4T is 6 and the smallest diameter of a D5T is 5, while the smallest diameter of the D3T is 9 and the diameter of the D2T (bidirectional ring with even number of nodes) is 50 ($N/2$), as we may see in figure 8, for $N = 100$.

6. Conclusions

We presented an assessment of the traffic performance in WDM-based wide area networks, used in the optical core of IP-over-WDM networks. The performance assessment was focused on networks with degree four topologies with smallest diameter. It was shown that the increase of the nodal degree from 3 to 4 improves the network performance if a larger number of wavelengths per link is available. It was also shown that the influence of wavelength interchange on the nodal degree gain is small, which means that performance improvements due to wavelength interchange in degree three topologies and degree four topologies, both with smallest diameter, are very similar. The performance of regular degree four topologies with smallest diameter is also compared with the performance of mesh–torus topologies, and it is shown that the blocking probability of degree four topologies with smallest diameter is about two orders of magnitude lower than the blocking probability of mesh–torus topologies.

It was also presented a performance comparison of WDM networks with nodal degrees ranging from 2 to 5. The performance analysis was focused on networks with smallest diameters and it was shown that the increase of the nodal degree from 2 to 3 leads to high nodal degree gains, while the increase of the nodal degree from 4 to 5 leads to low nodal degree gains. These results show that degree 3 and degree 4 topologies are very attractive for use in the optical core of IP-over-WDM networks.

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