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Performance Implications of Meshing Degree for Optical Burst Switched Networks Using One-Way Resource Reservation Protocols*

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Abstract. This paper discusses performance implications of meshing degree (or nodal degree) for optical burst switching (OBS) mesh networks using one-way resource reservation protocols. The analysis is focused on the following topologies: rings, chordal rings with nodal degrees ranging from three to six, mesh-torus, NSFNET, ARPANET and the European Optical Network (EON). It is shown that the largest nodal degree gain, due to the increase of the nodal degree from two to around three, is observed for degree-three chordal ring topology, where as the smallest gain is observed for the ARPANET. For these cases, the magnitude of the nodal degree gain is slightly less than three orders for the degree-three chordal ring and less than one order of magnitude for the ARPANET. On the other hand, when the nodal degree increases from two to a value ranging from about four up to six, the nodal degree gain ranges between four and six orders of magnitude for chordal rings. However, EON, which has a nodal degree slightly less than four has the smallest nodal degree gain. The observed gain for this case is less than one order of magnitude. Since burst loss is a key issue in OBS networks, these results clearly show the importance of meshing degree for this kind of networks.

Keywords: optical burst switching, optical internet, resource reservation protocols, performance

1. Introduction

Optical burst switching (OBS) [2,3,8,14,16,17] has been proposed as an alternative paradigm to overcome the technical limitations of optical packet switching (OPS), namely the lack of optical random access memory and the problems with synchronization. OBS combines the best of OPS and circuit switching, and it is a technical

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compromise between wavelength routing (i.e., circuit switching) and optical packet switching, since it does not require optical buffering or packet-level processing and is more efficient than circuit switching if the traffic volume does not require a full wavelength channel. In OBS networks, IP (Internet Protocol) packets are assembled into very large size packets called data bursts. These bursts are transmitted after a burst header packet, with a delay of some offset time. Each burst header packet contains routing and scheduling information and is processed at the electronic level, before the arrival of the corresponding data burst. The burst offset is the interval of time, at the source node, between the transmission of the first bit of the setup message and the transmission of the first bit of the data burst.

According to the way of reservation, resource reservation protocols may be classified into two classes: one-way reservation and two-way reservation. In the first class, a burst is sent shortly after the setup message, and the source node does not wait for the acknowledgement sent by the destination node. Therefore, the size of the offset is between transmission time of the setup message and the round-trip delay of the setup message. Different optical burst switching mechanisms may choose different offset values in this range. Tell And Go (TAG) [15], just-in-time (JIT) [16], JumpStart [2,3,17], JIT^{+} [13], just-enough-time (JET) [8] and Horizon [14] are examples of one-way resource reservation protocols.

In the TAG protocol, a source node sends a control packet and immediately after sends a burst. At each intermediate node, the data burst has to go through with an input delay equal to the setup message processing time. If a channel cannot be reserved on a link, along the ingress-egress path, the node preceding the blocked channel discards the burst. To release the connection, a "tear-down" control signal or packet is sent [4,15] and [4]. In this protocol a burst may need to be delayed (buffered) at each node, while waits for the processing of setup message and the configuration of the optical cross-connect (OXC) switch fabric. TAG is practical only if the switch processing time of the setup message and the optical switch configuration time are very short (Xu(2003)).

The offset in two-way reservation class is the time required to receive an acknowledgement from the destination. The major drawback of this class is the long offset time, which causes the long data delay. Examples of resource reservation protocols using this class include the Tell And Wait (TAW) protocol [15] and the Wavelength Routed OBS network (WR-OBS) proposed by Duser and Bayvel [5]. Due to the impairments of two-way reservation class and the critical limitation of TAG, the study is focused on one-way reservation schemes, being considered the following resource reservation protocols: JIT, JumpStart, JIT^{+}, JET, and Horizon.

A major concern in OBS networks is the contention and burst loss. The two main sources of burst loss are related with the contention on the outgoing data burst channels and on the outgoing control channel. In this paper, we consider bufferless networks and we concentrate on the loss of data bursts in OBS networks.

The reminder of this paper is organized as follows. In Section 2, we present an overview of one-way resource reservation protocols considered along this study. In Section 3, we describe the model of the OBS network under study, and in Section 4 we discuss performance implications of the nodal degree for OBS networks with mesh topologies. Main conclusions are presented in Section 5.

2. One-way resource reservation protocols

This section provides an overview of one-way resource reservation protocols for OBS networks. This kind of protocols may be classified, regarding the way in which output channels (wavelengths) are reserved for bursts, as immediate and delayed reservation. JIT and JIT^+ are examples of immediate channel reservation, while JET and Horizon are examples of delayed reservation schemes. The JumpStart signaling protocol may be implemented using either immediate or delayed reservation.

Just-in-Time (JIT) resource reservation protocol was proposed by Wei and McFarland [16]. Under JIT, an output channel is reserved for a burst immediately after the arrival of the corresponding setup message. If a channel cannot be reserved immediately, then the setup message is rejected and the corresponding burst is lost. JIT protocol is an example of one-way resource reservation protocols with immediate resources reservation. JIT protocol uses explicit releases to set free the switch fabric resources. This message is sent either by the source node or the destination node, to tear down all OXCs along the path on an existing connection trail. Whenever any network element detects a setup failure, it sends a release message to all network elements along the path to the source node.

JumpStart [2,3,17] is a joint project supported by Advanced Research and Development Agency (ARDA) developed by the North Carolina State University (NCSU) and MCNC Research and Development Institute. The goal of JumpStart project is the definition of a signaling protocol and associated architecture for a WDM burst-switching network. Under JumpStart [2], a source edge OBS node first sends a setup message to its ingress OBS core node with information related to the burst transmission, including the source and destination addresses. If the ingress core node can switch the burst, it returns a setup Ack message to the edge node. Moreover, it forwards the setup message to the next node. Otherwise, the ingress core node refuses the setup message and returns a reject message to the edge node and the corresponding burst is dropped. In this case, the edge node enters in an idle period waiting for another burst. When a new burst arrives, the edge node repeats the process.

Horizon protocol was proposed by Turner in Terabit Burst Switching [14]. Horizon is considered a resource reservation protocol in the sense that it performs a delayed reservation, as mentioned in [2,13,17]. This resource reservation protocol introduces the concept of Time Horizon for a given channel and it is called Horizon because every data channel has a time horizon during which it is reserved. Time horizon is defined as the earliest time to which there is no prevision to use the channel (wavelength). This concept is used in other protocols with one-way resource reservation schemes such as JET and JIT^+ that are considered in this section. In Horizon, an output channel is reserved for a burst only if the arrival of the burst happens after the time horizon for that channel; if upon the arrival of the setup message, the time horizon for that channel is later than the predicted arrival time of the first bit of the burst, then, the setup message is rejected and the corresponding burst is lost.

Just-Enough-Time (JET) resource reservation protocol was proposed in [8]. Under JET, an output channel is reserved for a burst only if the arrival of the burst (1) happens after the time horizon defined for that channel, or (2) coincides with an idle state (Void) for that channel, and the end of the burst (plus the TOXC) is sooner than the end of the idle interval; if, when the Setup message arrives, it is determined that none of these conditions are met for any channel, then the setup message is rejected and the corresponding burst is lost. JET is the best-known resource reservation protocol having a delayed reservation scheme with void filling (idle state), which uses information (from the setup message) to predict the start and the end of the burst. The authors of JET made analytical and simulation studies which confirmed the good effects of delayed reservation on burst loss probability in an OBS network.

The most recently proposed resource reservation protocol is JIT^+ [13]. It was defined as an improvement of JIT and it combines JIT simplicity with the utilization of the time horizon used by delayed resource reservation protocols, such as Horizon or JET. JIT^+ is a modified version of JIT protocol, which adds limited burst scheduling (for a maximum of two bursts per channel). Under JIT^+, an output channel is reserved for a burst only if (i) the arrival time of the burst is later than the time horizon of that data channel and (ii) the data channel has at most one other reservation.

3. Network model

In this study, we consider OBS networks with the following mesh topologies: chordal rings with nodal degrees between 3 and 6, mesh-torus with 16 and 20 nodes, the NSFNET with 14-node and 21 links [11], the NSFNET with 16 nodes and 25 links [9], the ARPANET with 20 nodes and 32 links [6,11], and the European Optical Network (EON) with 19 nodes and 37 links [7]. For comparison purposes bi-directional ring topologies are also considered. These topologies have the following nodal degree: ring: 2.0; degree-three chordal ring: 3.0; degree-four chordal ring: 4.0; degree-five chordal ring: 5.0; degree-six chordal ring: 6.0; mesh-torus: 4.0; NSFNET with 14-node and 21 links: 3.0; the NSFNET with 16 nodes and 25 links: 3.125; the ARPANET with 20 nodes and 32 links: 3.2; and the EON: 3.89.

Chordal rings are a well-known family of regular degree three topologies proposed by Arden and Lee [1] in early eighties for interconnection of multi-computer systems. A chordal ring is basically a bi-directional ring network, in which each node has an additional bi-directional 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 $(i + w) mod\ N$, 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 hops.

In each node of a chordal ring, we have a link to the previous node, a link to the next node and a chord. Here, 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 D3T(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 $(i + w_1) mod\ N$, $(i + w_2) mod\ N$, and $(i + w_3) mod\ N$, where the chord lengths, w_1, w_2, and w_3 are assumed to be positive odd, with $w_1 \leq N-1$, $w_2 \leq N-1$, and $w_3 \leq N-1$, and $w_i \neq w_j$, $\forall_{i \neq j \wedge 1 \leq i,j \leq n}$. In this notation, a chordal ring with chord length w_3 is simply represented by D3T(1,$N-1$, w_3).

Now, 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, …, $N-1$) is connected to the nodes $(i + w_1) mod\ N$, $(i + w_2) mod\ N$, …, $(i + w_n) mod\ N$, where the chord lengths, $w_1, w_2, \ldots w_n$ are assumed to be positive odd, with $w_1 \leq N-1$, $w_2 \leq N-1$, …, $w_n \leq N-1$, and $w_i \neq w_j$, $\forall_{i \neq j \wedge 1 \leq i,j \leq n}$. Now, we introduce a new notation: a general degree n topology is represented by DnT(w_1, w_2,…,w_n). In this new notation, a chordal ring family with a chord length of w_3 is represented by D3T(1, $N-1$, w_3) and a bi-directional ring is represented by D2T(1, $N-1$). Figure 1 shows chordal ring networks with 20 nodes, i.e. D3T(1,19,w_3), for $w_3 = 3$, $w_3 = 5$, and $w_3 = 7$.

We assume that each node of the bi-directional OBS network supports $F + 1$ wavelength channels per unidirectional link with full channel permutability (wavelength

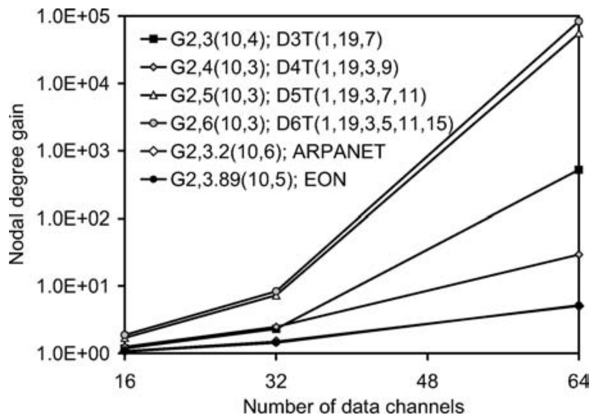

Figure 1. Nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,19)) to: 3 (D3T(1,19,7)), 3.2 (ARPANET), 3.89 (EON), 4 (D4T(1,19,3,9)), 5 (D5T(1,19,3,7,11)), and 6 (D6T(1,19,3,5,11,15)) as function of the number of data channels, in the last hop of each topology, for JIT protocol; $N = 20$.

conversion) between channels. One wavelength is used for signaling (carries setup messages) and the other F wavelengths carry data bursts. Each OBS node, according to Teng and Rouskas [12], consists of two main components: (i) a signaling engine, which implements the OBS signaling protocol and related forwarding and control functions; and (ii) an optical cross-connect (OXC), which performs the switching of bursts from input to output. It is assumed that each OXC consists of non-blocking space-division switch fabric, with full conversion capability, but without optical buffers.

It is assumed that each OBS node requires [12]: (i) an amount of time, T_{OXC}, to configure the switch fabric of the OXC in order to set up a connection from an input port to an output port, and requires (ii) an amount of time, $T_{\text{setup}}(X)$ to process the setup message for the signaling protocol X, where X can be JIT, JET, and horizon. It is also considered the offset value of a burst under reservation scheme X,$T_{\text{offset}}(X)$, which depends, among other factors, on the signaling protocol, the number of nodes the burst has already traversed, and if the offset value is used for service differentiation. As in Teng and Rouskas [12], it is assumed that: $T_{\text{OXC}} = 10$ ms, $T_{\text{setup}}(JIT) = 12.5\ \mu$s, $T_{\text{setup}}(JET) = 50\ \mu$s, $T_{\text{setup}}(Horizon) = 25\ \mu$s, the mean burst size, $1/\mu$, was set to 50 ms, and the burst arrival rate λ, is such that $\lambda/\mu = 32$ (except for figure 3).

4. Performance assessment

In this section, we make a careful study of the influence of nodal degree on the performance of OBS mesh networks for JIT, JIT$^+$, JumpStart, JET, and Horizon signaling protocols. Details about the simulator used to produce simulation results can be found in Rodrigues et al. [10]. In chordal ring topologies, different chord lengths can lead to different network diameters, and, therefore, to a different number of hops. One interesting result that we found is concerned with the diameters of the D3T(w_1,w_2,w_3) families, for which $w_2 = (w_1 + 2) mod\, N$ or $w_2 = (w_1 - 2) mod\, N$. Each family of this kind, i.e. D3T(w_1, $(w_1 + 2) mod\, N$, w_3) or D3T(w_1, $(w_1 - 2) mod\, N$, w_3), with $1 \leq w_1 \leq 19$ and $w_1 \neq w_2 \neq w_3$, has a diameter which is a shifted version (with respect to w_3) of the diameter of the chordal ring family (D3T(1, $N-1$, w_3)). For this reason, we concentrate the analysis on chordal ring networks, i.e., DnT(1, 19, $w_3, \ldots, w_n$).

In order to quantify the benefits due to the increase of nodal degree, we introduce the nodal degree gain, $G_{n,k}(i,j)$, defined as:

$$G_{n,k}(i, j) = \frac{P_i(n)}{P_j(k)} \tag{1}$$

where $P_i(n)$ is the burst loss probability in the i-th hop of a degree n topology and $P_j(k)$ is the burst loss probability in the j-th hop of a degree k topology, for the same network conditions (same number of data wavelengths per link, same number of nodes, etc.), and for the same resource reservation protocol.

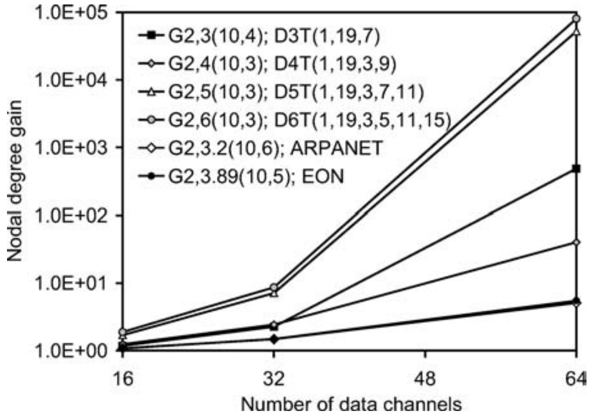

Figure 2. Nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,19)) to: 3 (D3T(1,19,7)), 3.2 (ARPANET), 3.89 (EON), 4 (D4T(1,19,3,9)), 5 (D5T(1,19,3,7,11)), and 6 (D6T(1,19,3,5,11,15)) as function of the number of data channels, in the last hop of each topology, for JumpStart protocol; $N = 20$.

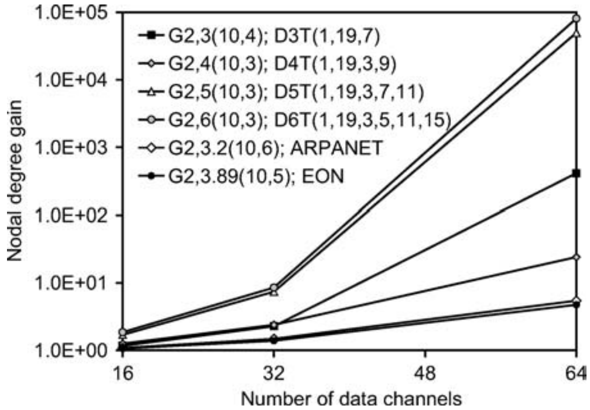

Figure 3. Nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,19)) to: 3 (D3T(1,19,7)), 3.2 (ARPANET), 3.89 (EON), 4 (D4T(1,19,3,9)), 5 (D5T(1,19,3,7,11)), and 6 (D6T(1,19,3,5,11,15)) as function of the number of data channels, in the last hop of each topology, for JIT^+ protocol; $N = 20$.

Figures 1–5 show, respectively for JIT, JumpStart, JIT^+, JET, and Horizon, the nodal degree gain, in the last hop of each topology, due to the increase of the nodal degree from 2 (D2T(1,19)) to: 3 (D3T(1,19,7)), 3.2 (ARPANET), 3.89 (EON – European Optical Network), 4 (D4T(1,19,3,9)), 5 (D5T(1,19,3,7,11)), and 6 (D6T(1,19,3,5,11,15)). Concerning chordal rings, we have chosen among several topologies with smallest diameter the ones that led to the best network performance. As may be seen in those figures, the considered topologies may be sorted from the best performance for the worst performance as: D6T(1,19,3,5,11,15), D5T(1,19,3,7,11), D4T(1,19,3,9), D3T(1, 19, 7), ARPANET, and EON – European Optical Network. For networks with 20 nodes,

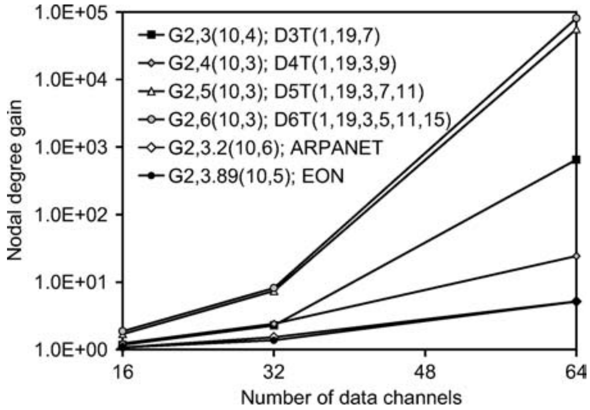

Figure 4. Nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,19)) to: 3 (D3T(1,19,7)), 3.2 (ARPANET), 3.89 (EON), 4 (D4T(1,19,3,9)), 5 (D5T(1,19,3,7,11)), and 6 (D6T(1,19,3,5,11,15)) as function of the number of data channels, in the last hop of each topology, for JET protocol; $N = 20$.

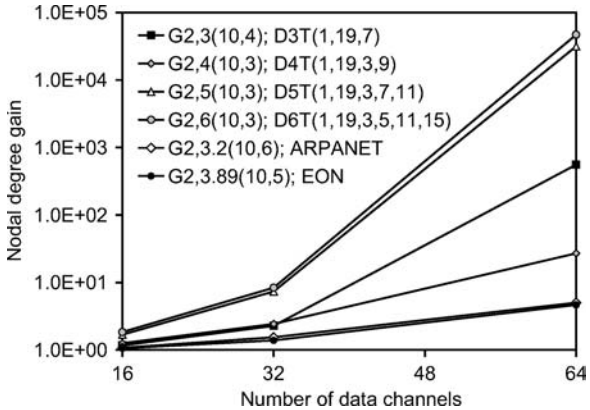

Figure 5. Nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,19)) to: 3 (D3T(1,19,7)), 3.2 (ARPANET), 3.89 (EON), 4 (D4T(1,19,3,9)), 5 (D5T(1,19,3,7,11)), and 6 (D6T(1,19,3,5,11,15)) as function of the number of data channels, in the last hop of each topology, for Horizon protocol; $N = 20$.

when the nodal degree increases from 2 to 4 (chordal-rind), 5 and 6, the gain is between four and five orders of magnitude.

We observed that the performance of the ARPANET is very close to the performance of EON. ARPANET has a nodal degree (3.2) near to the degree-three topology (D3T(1,19,7)) and EON has a nodal degree (3.89) near to the degree-four topology (D4T(1,19,3,9)). However, the performance of both ARPANET and EON is worst than the nearest chordal ring degree topology. This results reveals the importance of the way links are connected in the network, since chordal rings and ARPANET and EON have similar nodal degrees and therefore a similar number of network links. Results

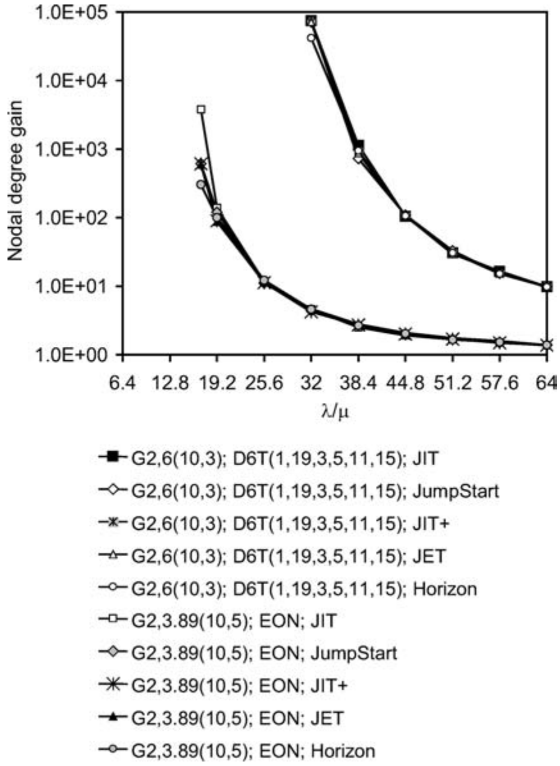

Figure 6. Nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,19)) to: 3.89 (EON), and 6 (D6T(1,19,3,5,11,15)), as a function of λ/μ, in the last hop of each topology, for JIT, JumpStart, JIT$^+$, JET, and Horizon protocols; $N = 20$, $F = 64$.

presented in these figures (from 1 to 5) were obtained for the JIT, JumpStart, JIT$^+$, JET, and Horizon resouce reservation protocols, and, as may be seen, their performance is very close. This result is confirmed in fig. 6, that presents the performance comparison of the nodal degree gain for the best (D5T(1,19,3,7,11)) and the worst (EON) of the topologies showed in figures 1 to 5. Figure 6 shows the nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,19)) to: 3.89 (EON), and 6 (D6T(1,19,3,5,11,15)), as a function of λ/μ, in the last hop of each topology, for JIT, JET, Horizon, JIT$^+$, and JumpStart signaling protocols ($F = 64$).

Figures 7–11 plot, respectively for JIT, JumpStart, JIT$^+$, JET, and Horizon, the nodal degree gain in the last hop of each topology, as a function of the nodal degree, due to the increase of the nodal degree from 2 (D2T(1,14)) to 3 (NSFNET ($N = 14$)), from 2 (D2T(1,15)) to: 3 (D3T(1,15,5)), 3.125 (NSFNET ($N = 16$)), 4 (D4T(1,15,5,13) and Mesh-Torus ($N = 16$)), and 5 (D5T(1,15,7,3,9)), from 2 (D2T(1,18)) to 3.89 (EON ($N = 19$)), from 2 (D2T(1,19)) to: 3 (D3T(1,19,7)), 3.2 (ARPANET ($N = 20$)), 4 (D4T(1,19,3,9)), 5 (D5T(1,19,3,7,11)), 6 (D6T(1,19,3,5,11, 15)), from 2 (D2T(1,24))

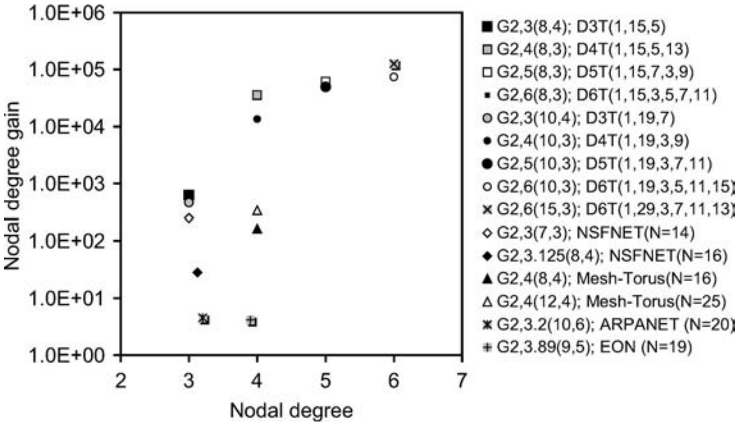

Figure 7. Nodal degree gain in the last hop of each topology, as a function of the nodal degree for JIT resource reservation protocol; $\lambda/\mu = 32$; $F = 64$.

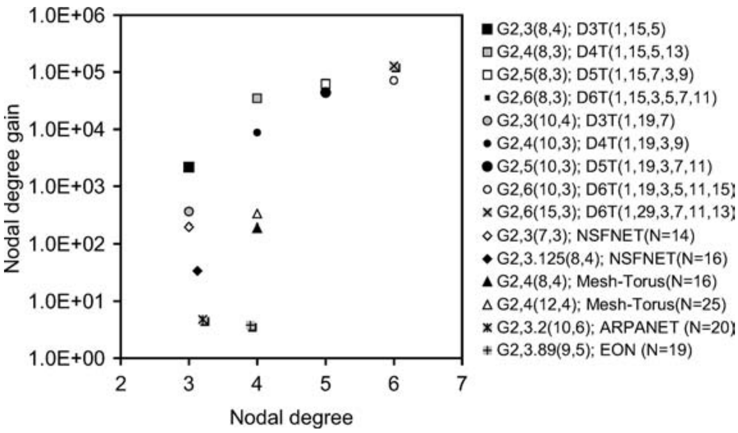

Figure 8. Nodal degree gain in the last hop of each topology, as a function of the nodal degree for JumpStart resource reservation protocol; $\lambda/\mu = 32$; $F = 64$.

to 4 (Mesh-Torus ($N = 25$)), and from 2 (D2T(1,29)) to 6 (D6T(1,29,3,7,11,13)). As may be seen, when the nodal degree increases from 2 to around 3, the largest gain is observed for degree-three chordal rings (slightly less than three orders of magnitude) and the smallest gain is observed for the ARPANET (less than one order of magnitude). When the nodal degree increases from 2 to around 4, the largest gain is observed for degree-four chordal rings (with a gain between four and five orders of magnitude) and the smallest gain is observed for the European Optical Network (with a gain less than one order of magnitude). When the nodal degree increases from 2 to around 5 or 6, the gain is between four or six orders of magnitude. These results clearly show the importance

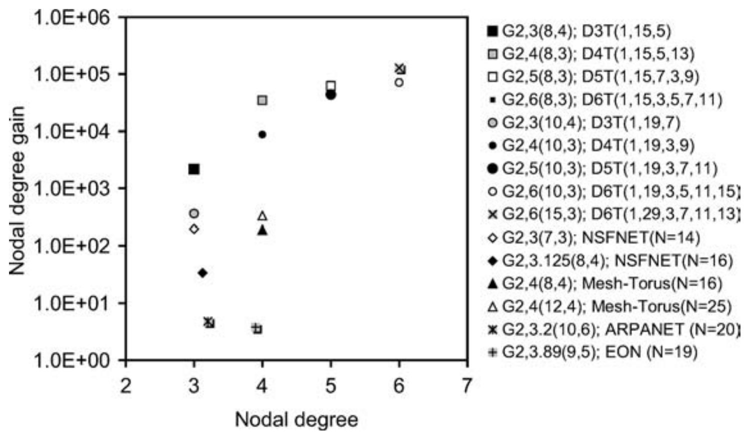

Figure 9. Nodal degree gain in the last hop of each topology, as a function of the nodal degree for JIT$^+$ resource reservation protocol; $\lambda/\mu = 32$; $F = 64$.

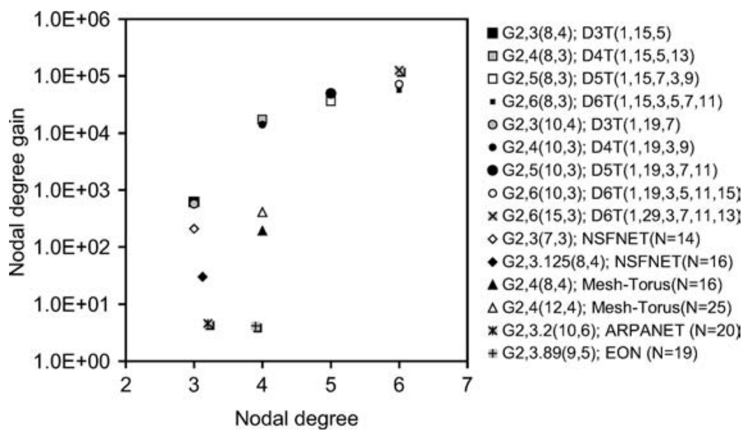

Figure 10. Nodal degree gain in the last hop of each topology, as a function of the nodal degree for JET resource reservation protocol; $\lambda/\mu = 32$; $F = 64$.

of the way links are connected in OBS networks, since, in this kind of networks, burst loss probability is a key issue.

In figure 12, it is compared the nodal degree gain in the last hop of each topology, as a function of the nodal degree, due to the increase of the nodal degree from 2 (D2T(1,15)) to 3 (D3T(1,15,5)) and 4 (D4T(1,15,5,13)), and from 2 (D2T(1,19)) to 5 (D5T(1,19,3,7,11)), for JIT, JumpStart, JIT$^+$, JET, and Horizon resource reservation protocols ($F = 64$). Topologies leading to the best performances for nodal degree of 3, 4, and 5 have been considered for this figure. This confirms previous results where the performance of the resource reservation protocols considered is very close.

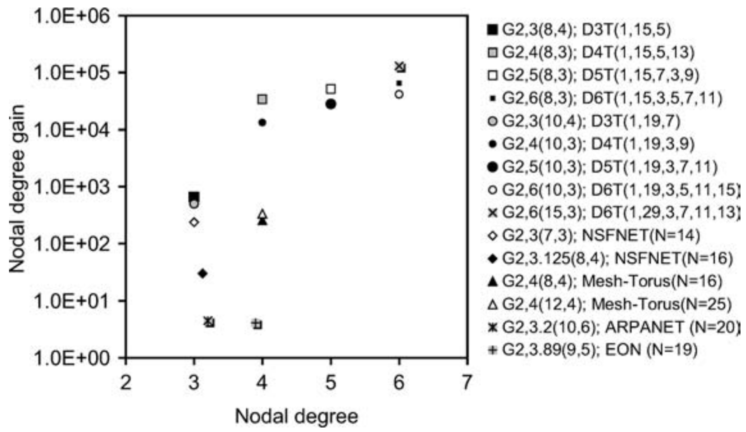

Figure 11. Nodal degree gain in the last hop of each topology, as a function of the nodal degree for Horizon resource reservation protocol; $\lambda/\mu = 32$; $F = 64$.

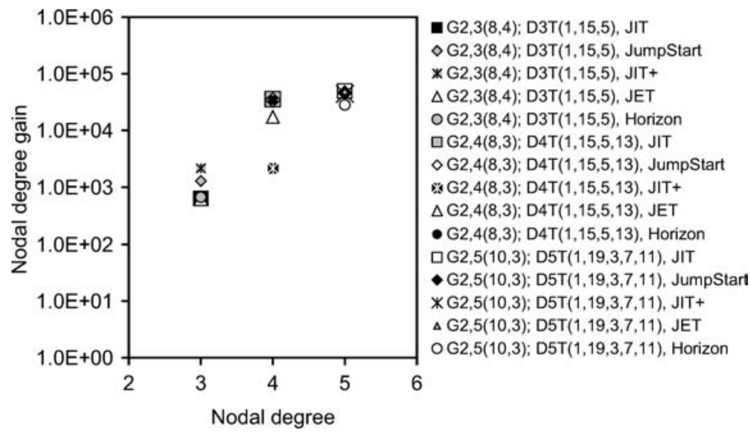

Figure 12. Nodal degree gain in the last hop of each topology, as a function of the nodal degree for JIT, JumpStart, JIT$^+$, JET, Horizon resource reservation protocols; $\lambda/\mu = 32$; $F = 64$.

5. Conclusions

In this paper, we analyzed the influence of nodal degree on the performance of OBS mesh networks with the following topologies: rings, chordal rings, mesh-torus, NSFNET, ARPANET and the EON. It was shown that when the nodal degree increases from 2 to around 3, the largest gain occurs for degree-three chordal rings, being slightly less than three orders of magnitude and the smallest gain occurs for the ARPANET, being the gain less than one order of magnitude. When the nodal degree increases from 2 to around 4, the largest gain is observed for degree-four chordal rings, being between four and five orders of magnitude and the smallest gain is observed for the European Optical Network, being less than one order of magnitude.

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