Performance Implications of Nodal Degree for Optical Burst Switching Mesh Networks Using Signaling Protocols with One-Way Reservation Schemes

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Abstract. This paper investigates the role of nodal degree (meshing degree) in optical burst switching (OBS) mesh networks using signaling protocols with one-way reservation schemes. The analysis is focused on the following topologies: rings, degree-three chordal rings, degree-four chordal rings, degree-five chordal rings, mesh-torus, NSFNET, ARPANET and the European Optical Network. It is shown that 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). On the other hand, 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). Since burst loss probability is a key issue in OBS networks, these results clearly show the importance of the way links are connected in this kind of networks.

1 Introduction

Optical burst switching (OBS) [1]-[4] has been proposed to overcome the technical limitations of optical packet switching, namely the lack of optical random access memory and to the problems with synchronization. OBS is a technical compromise between wavelength routing 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

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level, before the arrival of the corresponding data burst. Several signaling protocols have been proposed for optical burst switching networks. In this paper, we concentrate on just-in-time (JIT) [3], JumpStart [4]-[6], JIT$^+$ [7], just-enough-time (JET) [1], and Horizon [2] signaling protocols.

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 signaling protocols with one-way reservation schemes. 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 Signaling Protocols with One-Way Reservation Schemes

In OBS networks, 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 length of the burst offset, signaling protocols may be classified into three classes: no reservation, one-way reservation and two-way reservation. In the first class, the burst is sent immediately after the setup message and the offset is only the transmission time of the setup message. This first class is practical only when the switch configuration time and the switch processing time of a setup message are very short. The Tell And Go (TAG) protocol [8] belongs to this class. In signaling protocols with one-way reservation, 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. JIT, JIT+, JumpStart, JET and Horizon are examples of signaling protocols using one-way reservation schemes. 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 signaling protocols using this class include the Tell And Wait (TAW) protocol [8] and the scheme proposed in [9]. Due to the impairments of no reservation and two-way reservation classes, we concentrate the study in one-way reservation schemes. Therefore, the remaining of this session provides an overview of signaling protocols with one-way wavelength reservation schemes for optical burst switching networks. One-way reservation schemes may be classified, regarding the way in which output wavelengths are reserved for bursts, as immediate and delayed reservation. JIT and JIT$^+$ are examples of immediate wavelength reservation, while JET and Horizon are examples of delayed reservation schemes. The JumpStart signaling protocol may be implemented using either immediate or delayed reservation.

The JIT signaling protocol considers that an output wavelength is reserved for a burst immediately after the arrival of the corresponding setup message. If a wavelength cannot be reserved immediately, then the setup message is rejected and the corresponding burst is dropped. JIT$^+$ is a modified version of the immediate reservation scheme of JIT. Under JIT$^+$, an output wavelength is reserved for a burst if (1) the arrival time of the burst is later than the time horizon of the wavelength and (2) the wavelength has at most one other reservation. According to the authors, this signaling protocol does not perform any void filling. Comparing JIT+ with JET and Horizon, last ones permit an unlimited number of delayed reservations per wavelength, whereas JIT+ limits the number of such operations to at most one per wavelength. On the other hand, JIT+ maintains all the advantages of JIT in terms of simplicity of hardware implementation.

Delayed reservation, exemplified by JET and Horizon signaling protocols, considers that an output wavelength is reserved for a burst just before the arrival of the first bit of the burst. If, upon arrival of the setup message, it is determined that no wavelength can be reserved at the suitable time, then the setup message is rejected and the corresponding burst is dropped. In this kind of reservation scheme, when a burst is accepted in an OBS node, the output wavelength is reserved for an amount of time equal to the length of the burst plus T_{OXC}, being T_{OXC} the amount of time needed to configure the switch fabric of the OXC in order to set up a connection from an input port to an output port.

The Horizon considers that an output wavelength is reserved for a burst only if the arrival time of the burst is later than the *time horizon* of the wavelength. If, upon arrival of the *setup* message, it is determined that the arrival time of the burst is earlier than the smallest time horizon of any wavelength, then the *setup* message is rejected and the corresponding burst is dropped.

On the other hand, JET signaling protocol is the most known delayed wavelength reservation scheme *with void filling*, which uses information to predict the start and the end of the burst. In this protocol, an output wavelength is reserved for a burst if the arrival time of the burst (1) is later than the *time horizon* of the wavelength, or (2) coincides with a void on the wavelength, and the end of the burst (plus the OXC configuration time T_{OXC}) occurs before the end of the void. If, upon arrival of the setup message, it is determined that none of these conditions are satisfied for any wavelength, then the *setup message* is rejected and the corresponding burst dropped.

3 Network Model

We consider OBS networks with the following mesh topologies: chordal rings with nodal degrees between 3 and 5, mesh-torus with 16 and 20 nodes, the NSFNET with 14-node and 21 links [10], the NSFNET with 16 nodes and 25 links [11], the ARPANET with 20 nodes and 32 links [10], [12], and the European Optical Network (EON) with 19 nodes and 37 links [13]. 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; 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: 3.895.

Chordal rings are a well-known family of regular degree three topologies proposed by Arden and Lee in early eighties for interconnection of multi-computer systems [14]. 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,...,N-1 around the N-node ring. It is also assumed that each odd-numbered node i (i=1,3,...,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 $w1$, $w2$, and $w3$ be the corresponding chord lengths, and N the number of nodes. We represented a general degree three topology by D3T($w1$, $w2$, $w3$). We assumed that each odd-numbered node i (i=1, 3, ..., N-1) is connected to the nodes $(i+w1) mod\ N$, $(i+w2) mod\ N$, and $(i+w3) mod\ N$, where the chord lengths, $w1$, $w2$, and $w3$ are assumed to be positive odd, with $w1 \leq N-1, w2 \leq N-1$, and $w3 \leq N-1$, and $w_i \neq w_j, \forall i \neq j$ and $1 \leq i,j \leq 3$. In this notation, a chordal ring with chord length w is simply represented by D3T(1,N-1,$w3$).

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 $(i+w) mod\ N$, $(i+w2) mod\ N$, ..., $(i+wn) mod\ N$, where the chord lengths, $w1$, $w2$, ..., wn are assumed to be positive odd, with $w1 \leq N-1, w2 \leq N-1, ..., wn \leq N-1$, and $w_i \neq w_j, \forall i \neq j$ and $1 \leq i,j \leq n$. Now, we introduce a new notation: a general degree n topology is represented by DnT($w1$, $w2$,...,wn). In this new notation, a chordal ring family with chord length w is represented by D3T(1,N-1,w). In this new notation, a chordal ring family with a chord length of $w3$ is represented by D3T(1,N-1,$w3$) and a bi-directional ring is represented by D2T(1,N-1).

We assume that each node of the OBS network supports F+1 wavelength channels per unidirectional link. One wavelength is used for signaling (carries setup messages) and the other F wavelengths carry data bursts. Each OBS node consists of two main components [7]: 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, $T_{setup}(X)$ to process the setup message for the signaling protocol X, where X can be JIT, JET, horizon, and JumpStart. It is also considered the offset value of a burst under reservation scheme X, $T_{offset}(X)$, 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. In this study, it is assumed that [7]: $T_{OXC} = 10ms$, $T_{setup}(JIT) = 12.5\mu s$, $T_{setup}(JIT+) = 12.5\mu s$, $T_{setup}(JumpSart) = 12.5\mu s$, $T_{setup}(JET) = 50\mu s$, $T_{setup}(Horizon) = 25\mu s$, the mean burst size, $1/\mu$, was set to $50ms$, and the burst arrival rate λ, is such that $\lambda/\mu = 32$.

4 Performance Assessment

In this section, we investigate 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 [15].

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($w1$,$w2$,$w3$) families, for which $w2$=($w1$+2)$mod\ N$ or $w2$=($w1$-2)$mod\ N$. Each family of this kind, i.e. D3T($w1$,($w1$+2)$mod\ N$, $w3$) or D3T($w1$, ($w1$-2)$mod\ N$, $w3$), with $1 \leq w1 \leq 19$ and $w1 \neq w2 \neq w3$, has a diameter which is a shifted version (with respect to $w3$) of the diameter of the chordal ring family (D3T(1, N-1, $w3$)). For this reason, we concentrate the analysis on hordal ring networks, i. e., D3T(1, 19, $w3$).

In order to quantify the benefits due to the increase of nodal degree, we introduce the nodal degree gain, $G_{(n-1),n}(i,j)$, defined as:

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

where $P_i(n-1)$ is the burst blocking probability in the i-th hop of a degree (n-1) topology and $P_j(n)$ is the burst blocking probability in the j-th hop of a degree n topology, for the same network conditions (same number of data wavelengths per link, same number of nodes, etc), and for the same signaling protocol.

Figures 1, 2, 3, 4, and 5 show, respectively for JIT, JET, Horizon, JIT$^+$, and JumpStart, the nodal degree gain, in the last hop of each topology, due to the increase of the nodal degree from 2 (D2T(1,15)) to: 3 (D3T(1, 15, 5)), 3.125 (NSFNET), 4 (D4T(1,15,5,13) and mesh-torus), and 5 (D5T(1,15,7,3,9)). 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: D4T(1,15,5,13, D5T(1,15,7,3,9), D3T(1, 15, w3), mesh-torus, and NSFNET.

We observed that the performance of the NSFNET is very close to the performance of degree-three chordal rings with chord length of w3=3 or w3=7 (figure not shown due to space limitations). This results reveals the importance of the way links are connected in the network, since chordal rings and NSFNET have similar nodal degrees and therefore a similar number of network links. Also interesting is the fact that degree-three chordal rings with w3=5 have better performance than mesh-torus networks, which have a nodal degree of 4, i. e., more 25% of network links. Results presented in these figures (1 to 5) 2 were obtained for the JIT, JIT^{+}, JumpStart, JET, and Horizon protocols, and, as may be seen, their performance is very close, except for D5T in which a variation within one order of magnitude is observed.

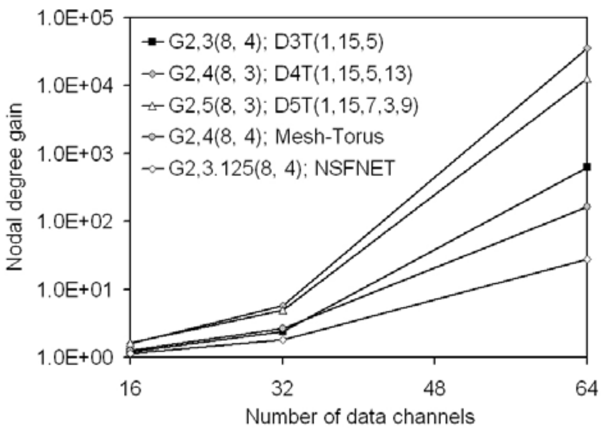

Fig. 1. Nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,15)) to: 3 (D3T(1, 15, w3)), 3.125 (NSFNET), 4 (D4T(1,15,5,13) and mesh-torus), and 5 (D5T(1,15,7,3,9)), as function of the number of data channels, in the last hop of each topology, for JIT signaling protocol; N=16.

Since the burst blocking probability is a major issue in OBS networks, clearly ring topologies are the worst choice for these network due to very high blocking probabilities and, surprisingly, degree-three chordal rings with smallest diameter have a very good performance with burst blocking probabilities ranging from 10^{-3}–10^{-5}, depending on the number of hops. For 16 nodes and 64 data channels per link, the nodal degree gain due to the increase of nodal degree from 2 (rings) to 3 (chordal ring with smallest diameter) is about three orders of magnitude in the last hop. This nodal degree gain increases to between 4 and 5 orders of

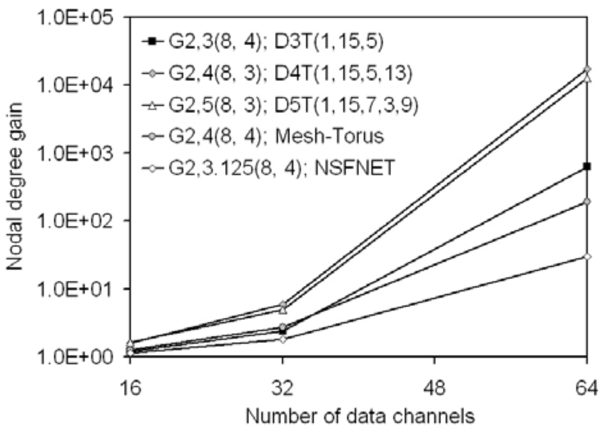

Fig. 2. Nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,15)) to: 3 (D3T(1, 15, w3)), 3.125 (NSFNET), 4 (D4T(1,15,5,13) and mesh-torus), and 5 (D5T(1,15,7,3,9)), as function of the number of data channels, in the last hop of each topology, for JET signaling protocol; N=16.

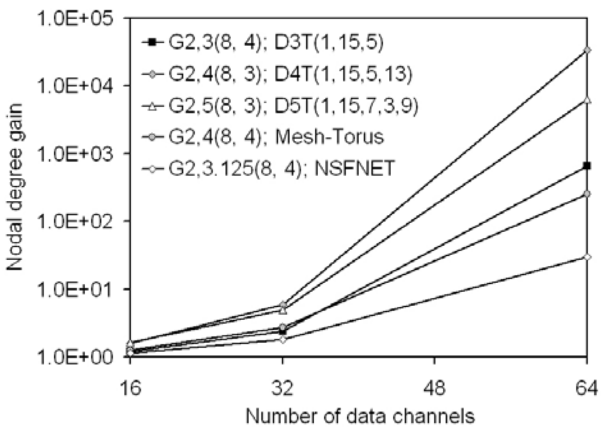

Fig. 3. Nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,15)) to: 3 (D3T(1, 15, w3)), 3.125 (NSFNET), 4 (D4T(1,15,5,13) and mesh-torus), and 5 (D5T(1,15,7,3,9)), as function of the number of data channels, in the last hop of each topology, for Horizon signaling protocol; N=16.

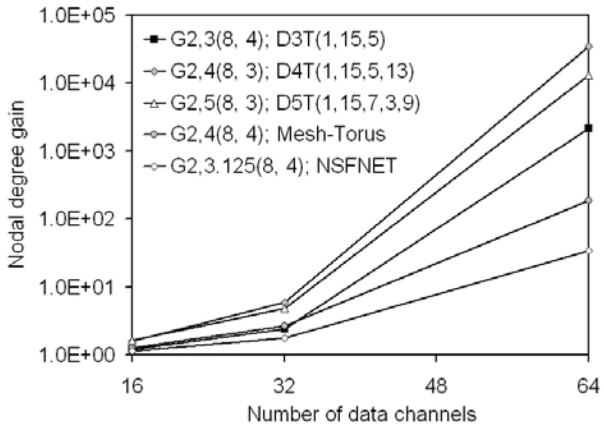

Fig. 4. Nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,15)) to: 3 (D3T(1, 15, w3)), 3.125 (NSFNET), 4 (D4T(1,15,5,13) and mesh-torus), and 5 (D5T(1,15,7,3,9)), as function of the number of data channels, in the last hop of each topology, for JIT$^+$ signaling protocol; N=16.

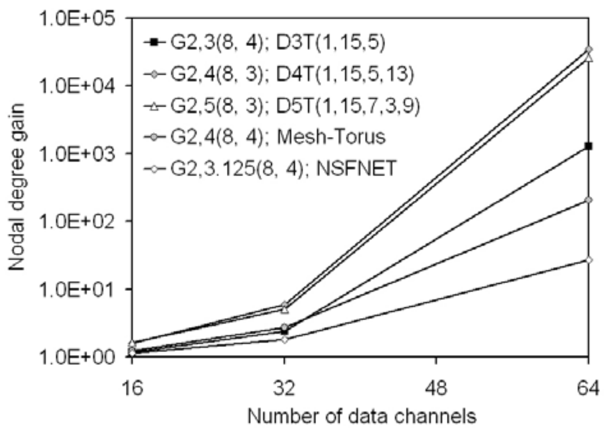

Fig. 5. Nodal degree gain due to the increase of the nodal degree from 2 (D2T(1,15)) to: 3 (D3T(1, 15, w3)), 3.125 (NSFNET), 4 (D4T(1,15,5,13) and mesh-torus), and 5 (D5T(1,15,7,3,9)), as function of the number of data channels, in the last hop of each topology, for JumpStart signaling protocol; N=16.

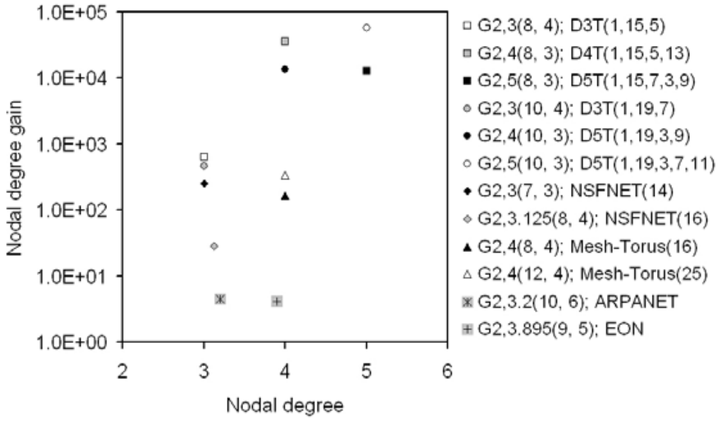

Fig. 6. Nodal degree gain in the last hop of each topology, as a function of the nodal degree, due to the increase of the nodal degree from 2 (D2T(1,15)) to: 3 (D3T(1, 15, 5) and D3T(1, 19, 7)), 3.125 (NSFNET), 4 (D4T(1,15,5,13) and mesh-torus with 16 and 25 nodes), and 5 (D5T(1,15,7,3,9)), for JIT signaling protocol; F=64.

magnitude if the nodal degree increases from 2 (rings) to 4 (D4T(1,15,5,13)), and increases to around 4 orders of magnitude if the nodal degree increases from 2 (rings) to 5 (D5T(1,15,7,3, 9)).

Fig. 6 shows the nodal degree gain, 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 D3T(1, 19, 7)), 3.125 (NSFNET), 4 (D4T(1,15,5,13) and mesh-torus with 16 and 25 nodes), and 5 (D5T(1,15,7,3,9)). As may be seen, when the nodal degree increases from 2 to around 3, the largest gain is observed for degree-three chordal rings (a bit 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). These results clearly show the importance of the way links are connected in OBS networks, since, in this kind of networks, burst loss probability is a key issue.

5 Conclusions

In this paper, we discussed performance implications of the nodal degree for 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, a larger gain of slightly less than three orders of magnitude is observed for degree-three chordal rings and a smaller gain less than one order of magnitude is observed for the ARPANET. When the nodal degree increases from 2 to around 4, a larger gain between four and five orders of magnitude is observed for degree-four chordal rings and a smaller gain less than one order of magnitude is observed for the European Optical Network.

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