Assessment of Blocking Performance in Bidirectional WDM Ring Networks with Node-to-Node and Full-Mesh Connectivity

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Abstract. In this paper, we present an assessment of the blocking performance in bidirectional wavelength division multiplexing (WDM) ring networks with node-node and full-mesh connectivity, taking into account limitations on network scalability imposed by amplified spontaneous emission noise accumulation and crosstalk. WDM ring networks with 10 and 40 nodes and full-mesh WDM ring networks with 10 nodes are considered. The influence of wavelength interchange on the blocking performance is also investigated.

1. Introduction

Optical networks may be classified regarding their evolution as first-generation and second-generation networks. First-generation optical networks use optical fibre as a transmission medium, but all the switching, processing and routing functions are done at the electronic level. Today, these networks are widely deployed in all kinds of telecommunications networks, except perhaps in residential access networks. Examples of first-generation optical networks include SONET (Synchronous Optical Network) and SDH (Synchronous Digital Hierarchy) networks, which form the core of the telecommunications infrastructure in North America, in Europe and Japan, as well as a variety of enterprise networks such as ESCON (Enterprise Serial Connection), Fibre Channel, and HIPPI (High-Performance Parallel Interface) used for computer interconnection with other computers or peripheral systems, or FDDI (Fiber Distributed Data Interface) [1] and DQDB (Distributed Queue Dual Bus), widely deployed in LANs and MANs.

Recently, researchers have realised that optical networks are capable of providing more functions than just point-to-point transmission. Major advantages can be gained by incorporating into the optical domain some of the switching and routing functions, which have been performed by electronics. In first-generation networks, the electronics at a node must handle not only all the data intended for that node, but also the data that is being passed through that node to other nodes of the network. If the latter data could be routed through the optical domain, the load on the underlying electronics at that node would be
significantly reduced. This is one of the key driving issues for the second-generation optical networks [1].

The main distinction between the various types of second-generation networks is based on the multiplexing scheme: whether it is done in the wavelength domain (WDM), or in the time domain as in optical time division multiplexing (OTDM). WDM networks may be further split into [2]: point-to-point WDM links, access networks, broadcast and select networks, and wavelength routing optical networks (WRONs). Here, special attention is paid to WRONs, whose recently proposed layered architecture [3] is shown in Fig.1.

![Layered Architecture of Optical Transport Networks](Image)

WDM rings with wavelength routing are considered here with special reference to the case of bidirectional transmission over a single fibre or two separate fibres. The use of bidirectional transmission over a single fibre allows a reduction of the cost, but degrades the transmission performance and limits the network scalability. For a node-to-node ring with node spacing of about 40 km, the network can accommodate more than 40 nodes; however, the network can only accommodate about 14 nodes for an increase of the node spacing to 80 km [4]. For a full-mesh ring using optical add-drop multiplexers based on arrayed-waveguide gratings, it was shown that a network with 11 nodes is feasible [5].

In this paper, we assess the blocking performance of node-to-node WDM ring networks with 10 and 40 nodes and full-mesh WDM ring networks with 10 nodes.

The remainder of this paper is organised as follows. In section 2, an analytical model used to compute the blocking probability in WRONs is described. In section 3, the assessment of blocking performance in bidirectional WDM ring networks with node-to-node and full-mesh connectivity is presented. Main conclusions are presented in Section 4.

### 2. Model for Computing the Blocking Probability

Some models have been published for computing the call (session) blocking probability in circuit-switched WDM optical networks [6]-[10]. We have used the model given in [6], since it takes into account real-time input traffic and the correlation between the wavelengths used on successive links of a multi-link path. The following assumptions are used in the model [6]: 1) Call requests arrive at each node according to a Poisson process with rate \( \lambda \), with each call equally likely to be destined to any of the remaining
nodes; 2) Call holding time is exponentially distributed with mean $1/\mu$, the offered load per station being $\rho = \lambda / \mu$; 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.

For a network with $N$ nodes and a wavelength converter density $q$, the blocking probability is given by [6]:

$$P_b(q) = \sum_{l=1}^{N-1} \sum_{y_f=0}^{F} P_b^{(l)}(q, y_f) p_l,$$

(1)

where $p_l$ is the hop-length distribution and $P_b^{(l)}(q, y_f)$ is given by [6]:

$$P_b^{(1)}(q, y_f) = \begin{cases} Q(0), & \text{if } y_f = 0 \\ 0, & \text{otherwise} \end{cases},$$

(2)

and

$$P_b^{(l)}(q, y_f) = T^{(l)}(0, y_f)(1-q)^{(l-1)} + \sum_{i=1}^{l-1} Y^{(l)}(i, q, y_f) q(1-q)^{(l-i-1)}, \quad \text{for } l \geq 2,$$

(3)

where $Y^{(l)}(i, q, y_f)$ is given in terms of $P_b^{(l)}(q, y_f)$:

$$Y^{(l)}(i, q, y_f) = Q(y_f) - \left\{ \sum_{k_f=0}^{F} \left[ Q(k_f) - P_b^{(i)}(q, k_f) \right] \times \sum_{w_f=0}^{F} S(w_f | k_f) \times \left[ W^{(l-i)}(y_f | w_f) - V^{(l-i)}(0, y_f | w_f) \right] \right\}.$$  

(4)

The probabilities $Q(w_f), S(y_f | x_p), V(n_f, y_f | w_f), W(y_f | w_f)$, and $T^{(l)}(n_f, y_f)$, are given by [6]:

$$Q(w_f) = \sum_{x_c=0}^{F-w_f} \sum_{x_n=0}^{F-x_c} \Pi(F-w_f-x_c, x_c, x_n).$$

(5)
\[
S(y_f | x_{pf}) = \frac{\min(F - x_{pf}, F - y_f)}{\sum_{x_c = 0}^{F - x_{pf}} \Pi(F - x_{pf} - x_c, x_c, F - y_f - x_c)} \cdot \sum_{x_c = 0}^{F - x_{pf}} \sum_{x_n = 0}^{F - x_{pf} - x_c} \Pi(F - x_{pf} - x_c, x_c, x_n), \tag{6}
\]

\[
V^{(l)}(n_f, y_f | w_f) = \begin{cases} 1, & \text{if } n_f = y_f = w_f \\ 0, & \text{otherwise} \end{cases}, \tag{7}
\]

\[
V^{(l)}(n_f, y_f | w_f) = \sum_{x_{pf} = 0}^{F} \min(F - x_{pf}, F - y_f) \cdot \sum_{z_c = 0}^{F} \sum_{x_{ff} = 0}^{F} R(n_f | x_{ff}, y_f, z_c) \times \]

\[
U(z_c | y_f, x_{pf}) \times S(y_f | x_{pf}) \times V^{(l-1)}(x_{ff}, x_{pf} | w_f), \text{ for } l = 2, 3, ..., N - 1, \tag{8}
\]

\[
W^{(l)}(y_f | w_f) = \sum_{n_f = 0}^{y_f} V^{(l)}(n_f, y_f | w_f), \tag{9}
\]

\[
T^{(l)}(n_f, y_f) = \sum_{x_{pf} = 0}^{F} \sum_{x_{ff} = 0}^{F} \min(F - x_{pf}, F - y_f) \times \]

\[
U(z_c | y_f, x_{pf}) \times S(y_f | x_{pf}) \times T^{(l-1)}(x_{ff}, x_{pf}). \tag{10}
\]

The starting point of the recursion, \(T^{(1)}(n_f, y_f)\) is zero for \(n_f \neq y_f\) and is equal to \(Q(n_f)\) when \(n_f = y_f\). The probabilities \(U(z_c | y_f, x_{pf})\), and \(R(n_f | x_{ff}, y_f, z_c)\) are given by [6]:

\[
U(z_c | y_f, x_{pf}) = \frac{\Pi(F - x_{pf} - z_c, z_c, F - y_f - x_c)}{\sum_{x_c = 0}^{\min(F - x_{pf}, F - y_f)} \Pi(F - x_{pf} - x_c, x_c, F - y_f - x_c)}, \tag{11}
\]
In the above probabilities, \( \Pi(c_l,c_c,c_n) \) is the steady-state probability of the state \((c_l,c_c,c_n)\) and is given by [6]:

\[
\Pi(c_l,c_c,c_n) = \frac{\rho_e^{c_l} \rho_e^{c_c} \rho_e^{c_n}}{c_l! c_c! c_n!} \sum_{j=0}^{F} \sum_{i=0}^{F-j} \sum_{k=0}^{j} \rho_e^{i} \rho_e^{j} \rho_e^{k} \frac{i!}{j! k!},
\]

\[0 \leq c_l + c_c \leq F \quad .\]

\[0 \leq c_c + c_n \leq F \quad .\]

The analysis presented in [6] also assumes that the hop-length distribution, \(p_l\), is known, as well as the arrival rates of calls at a link that continue, and those that do not, to the next link of a path. The call arrival rates at links have been estimated from the arrival rates of calls to nodes as in [6]. 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. For a bidirectional \(N\)-node ring, we have found that the probability of an \(l\)-hop path be used for routing a session is given by:

\[
p_l = \begin{cases} 
\frac{2}{N-1}, & \text{for } N \text{ odd and } 1 \leq l \leq \frac{N-1}{2} \\
\frac{2}{N-1}, & \text{for } N \text{ even and } 1 \leq l < \frac{N}{2} \\
\frac{1}{N-1}, & \text{for } N \text{ even and } l = \frac{N}{2} 
\end{cases} .
\]

For a full-mesh bidirectional ring with \(N\) nodes, we have found that \(p_l\) is given by

\[
p_l = \begin{cases} 
1, & \text{for } l = 1 \\
0, & \text{for } 2 \leq l \leq N - 1 
\end{cases} .
\]
4. Assessment of Blocking Performance

In this section, we present an assessment of the blocking performance in WDM ring networks with node-to-node and full-mesh connectivity patterns. As referred in section 1, due to ASE (amplified spontaneous emission) noise accumulation in a bidirectional WDM ring, we consider node-to-node ring networks with 10 and 40 nodes. Due to crosstalk limitations in full-mesh rings, we consider full-mesh ring networks with 10 nodes.

Fig. 2 shows the blocking probability against the load per node for a 10-node bidirectional ring network with 4, 8, 12 or 16 wavelengths per link, and with (wi) or without wavelength interchange in all nodes. As can be seen, the increase of the number of wavelengths per link strongly reduces the blocking probability. For the same number of wavelengths per link, the difference between blocking probabilities, with and without wavelength interchange, also increases as the number of wavelengths increases. If we increase the number of nodes to 40 (see Fig. 3), the blocking probability decreases as the number of wavelengths per fibre increases but, in this case, the reduction of the blocking probability is less strong than the reduction when the number of nodes was 10. The difference between blocking probabilities, with and without wavelength interchange in all nodes, is also more reduced due to a lack of resources (wavelengths). From these figures, we can observe that wavelength converters are more useful when the number of wavelengths per link is larger. This may be explained as follows. Without wavelength interchange and when the number of wavelengths is large, blocking occurs primarily not due to a lack of resources (wavelengths per link), but due to the inability to use those resources. Thus, converters are more useful when the number of wavelengths is larger. When the number of wavelengths per fibre is small (e.g. 4) or when the load is very large, wavelength blocking occurs primarily due to a lack of resources and the use of wavelength converters does not improve significantly the blocking probability.

![Fig. 2. Blocking probability versus load per node for a 10-node bidirectional (Bi) WDM ring network with 4, 8, 12 or 16 wavelengths per link and with (wi) or without wavelength interchange in all nodes.](image)
Fig. 3. Blocking probability versus load per node for a 40-node bidirectional (Bi) WDM ring network with 4, 8, 12 or 16 wavelengths per link and with (wi) or without wavelength interchange in all nodes.

Fig. 4. Blocking probability versus load per node for a full-mesh 10-node bidirectional WDM ring network with 4, 8 or 12 wavelengths per link.

Fig. 4 shows the blocking probability versus load per node for a full-mesh bidirectional WDM network with 10 nodes and with 4, 8 or 12 wavelengths per link. Despite the reduced number of nodes, this network allows very high loads per node: a blocking probability of $10^{-3}$ corresponds to a maximum load per node of 38.0 Erlang for 12 wavelengths per link, 18.5 Erlang for 8 wavelengths per link, and 4.0 Erlang for 4 wavelengths per link. In a full-mesh network, the shortest path between each pair of nodes (source and destination) is of 1-hop. As a consequence, advantages from the point of view of blocking performance may arise only if alternate path routing is used. In [10], Ramamurthy and Mukherjee propose an approximate computational model that
incorporates fixed-alternate routing and sparse wavelength conversion. They have shown that i) the benefits of wavelength conversion increases with number of alternate routes and ii) a large proportion of the gain in blocking probability with full wavelength conversion is obtained with sparse wavelength conversion [10].

4. Conclusions

We have presented an assessment of the blocking performance in bidirectional WDM ring networks with node-to-node and full-mesh connectivity. Due to ASE noise accumulation in a bidirectional WDM ring, we considered node-to-node ring WDM networks with 10 and 40 nodes, and due to crosstalk limitations in full-mesh rings, we considered full-mesh ring networks with 10 nodes. We have shown that, in a node-to-node bidirectional WDM ring network, the blocking probability decreases as the number of wavelengths per link increases, but this reduction of the blocking probability becomes less strong as the number of nodes increases. In node-to-node ring networks, converters are more useful when the number of wavelengths is larger. For a full-mesh ring network, it is shown that high loads per node are allowed. In this case, benefits for blocking performance due to wavelength interchange may arise only if alternate path routing is used.

Acknowledgements

This work has been supported by the Institute of Telecommunications at Coimbra, Portugal.

References