

Performance Analysis of Optical Packet-Switched Meshes: Metrics and Modeling

Ahmad Kianrad¹ Ahmad Khonsari^{1,2} Nasser Yazdani¹ Aresh Dadlani^{1,2}

¹Department of Electrical and Computer Engineering, University of Tehran, Tehran, Iran

²School of Computer Science, Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

Abstract

The surge of facilitating the ever-growing number of service classes in the contemporary Internet backbone has persuaded researchers worldwide to search for suitable underlying network topologies with desirable properties. Even in the presence of speedy optical technologies, the arrangement of nodes in a network can be highly influential in boosting network performance. Among all the topologies investigated so far, k -ary n -cubes have been reported to be widely adopted in the literature. However in a hybrid network, where the network comprises of a mixture of different types of topologies, the type and size of k -ary n -cubes can greatly influence the performance factor of the network. The objective of this paper is twofold. Firstly, we introduce a set of new metrics that can be used to analyze the performance behavior of simple regular meshes with their wrap-around variants (2-D and 3-D torus) for the Optical Packet Switching (OPS) paradigm. We then propose a simple and yet efficient switch-level analytical model for service differentiation in OPS in the presence of wavelength converters (WCs). The proposed model is further extended to include the impact of Fiber Delay Lines (FDLs) as well. Simulations are conducted for both cases to corroborate the accuracy of the models presented.

Keywords: Optical Packet Switching, Mesh Network, QoS Management, Wavelength Converter, Fiber Delay Line, Performance Evaluation.

1. Introduction

Within the past two decades, networking has been experiencing a migration towards optical based technologies [1]. The reason for such diversion is the high flexibility, increased scalability, service differentiation capability, and unlimited bandwidth provisioning introduced by such optical networks. Relevant to this context, a wide range of experimental switching paradigms have been proposed in the literature as viable candidates for the next-generation Internet backbone [2][3][4]. Among all these paradigms however, *optical packet switching* (OPS) has been the subject of several research projects [5][6]. Its potential to interface with the WDM transport layer and bridge the gap between the electrical (IP) layer and the optical (WDM) layer has added to its popularity [3][7].

Despite the implementation of OPS as the underlying technology [8][9], there are yet other prominent factors that influence the performance of networks such as network topology, switching method, routing algorithm, QoS management scheme, and traffic load [10]. The performance of OPS networks with regular and irregular mesh topologies has been partially studied in the literature [11]. However, due to the high adoption of k -ary n -cubes in OPS networks, in this work, we introduce a set of additional metrics upon which the performance of basic instances of such a topology can be compared with simple regular and irregular meshes for various sizes and under a specific traffic load.

With the increase in number of multimedia and time-critical applications, several efficient QoS management schemes have been anticipated in the research community to guarantee content delivery. A number of protocols have been proposed to support QoS in WDM networks by means of

offset-time exploitation [12] or resource reservation [13][14]. The resource reservation scheme uses the available resource (wavelength or FDL) to prioritize one class of traffic over the other. Based upon the type of resource adopted, this scheme is investigated under two alternatives namely, *threshold-based* and *wavelength-based* techniques [14]. To the best of our knowledge, no generalized closed-form solution has been reported for the wavelength-based QoS management approach in the literature.

In this paper, we take the first step in presenting a novel mathematical model for the wavelength-based technique to support any arbitrary number of service classes at a switch level. The generalized model is further extended to include optical buffers, known as *fiber delay lines* (FDLs), as well. These models are justified using numerical results obtained through extensive simulation experiments.

The rest of this paper is organized as follows. In Section 2, we provide a concise description on k -ary n -cubes and their variants and delineate the new set of network-level performance metrics proposed to study such networks. In Section 3, an overview of the different types of resource reservation-based QoS management schemes is provided. The derivation of a generalized wavelength-based QoS model is given in Section 4, along with the extended model in which both, wavelengths as well as FDLs are exploited together. The simulation environment and the obtained results are presented in Section 5. Finally in Section 6, we summarize our work and enlighten directions for possible future works.

2. Network Topologies and Metrics

In this section, we provide a brief description on the types of k -ary n -cubes and the various performance metrics upon which such networks can be evaluated.

2.1. The k -ary n -cube Topology

Network topology is the physical or logical arrangement of nodes interconnected through links. Generally, existing regular networks are broadly classified into *indirect* and *direct* networks. As opposed to indirect networks in which nodes are connected by means of stages of switches, in direct networks such as k -ary n -cube, mesh and tree, each node is connected directly to some other nodes [10]. Due to the high scalability of direct networks, and in particular k -ary n -cubes, they have been extensively employed in several networks [10][15].

The k -ary n -cube, where k denotes the radix and n symbolizes the dimension, is an n -dimensional grid structure with k nodes accommodated in each dimension. Each of the kn nodes can be identified by an n -digit radix k address [10][15].

Figure 1 illustrates a simple 3×3 regular mesh, followed by its 2-D and 3-D variants. If we denote the number of nodes in topology i as N_i and the number of edges as L_i , then the following equations hold for *simple regular meshes* (SRM) similar to that shown in Figure 1 (a):

$$\begin{aligned} N_{SRM} &= k^n, \\ L_{SRM} &= 2k(k-1). \end{aligned} \quad (1)$$

Likewise, for the 2-D and 3-D tori, as illustrated in Figures 1(b) and 1(c), the number of nodes is the same as that of N_{SRM} , while the number of links are given as:

$$\begin{aligned} L_{2-D} &= 2k^2, \\ L_{3-D} &= 3k^3. \end{aligned} \quad (2)$$

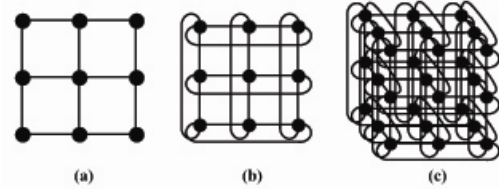


Figure 1. The k -ary n -cube variants under consideration (a) a simple 3×3 regular mesh (b) a 3-ary 2-cube (2-D torus), and (c) a 3-ary 3-cube (3-D torus).

2.2. Performance Metrics

The four metrics commonly used to evaluate the performance of a network in terms of network utilization, reliability and latency are *network throughput*, *packet-loss rate*, *average end-to-end delay* and *mean hop distance* [10][15][16]. Since our main interest is to study the topologies feasible for the optical domain, there exist other metrics that could be considered at an entire network level.

The primary key metric is the *cost of fibers* required to implement a network with higher performance. Due to the high cost of optical fibers, it has always been feasible to minimize the amount of fiber used in optical networks, unless the addition of a few links would efficiently enhance the performance. This metric is in trade-off with the average number of hops and depends on the structure of the topology under study. It is upon the routing algorithms to decide whether to utilize an extra fiber link or increase the hop distance of a packet traveling through the network. Based on the cost and mean hop distance, we introduce another valuable metric called the *routed capacity*. This measure determines the percentage of packets routed through the network by the routing algorithm in use. In order to study the performance behavior of different k -ary n -cubes with different sizes, it is mandatory to analyze such systems through pre-defined or meaningfully derived measures. A simulation-based comparison of various mesh topologies under these metrics can be found in [16].

3. The Resource Reservation-Based QoS Management Scheme

Apart from the metrics introduced in the preceding section, another influential factor is the selection of an apt QoS management scheme to be implemented in core switches so as to facilitate the phenomenal growth of multimedia and time-critical applications. In the resource reservation-based approach proposed by Callegati *et al* in [14] and [17], traffic classes are differentiated by adopting some form of reservation scheme based on the available resources (wavelength and/or FDLs) managed by some efficient *wavelength and delay selection* (WDS) algorithms. Considering the type of resources available, the resource

reservation-based QoS scheme is investigated under two alternatives namely, *threshold-based* and *wavelength-based* techniques.

As reported in [14] and [17], the main idea of this approach is to allocate more resources to higher prioritized classes than compared to lower prioritized classes. The scheme is applicable in either one or both of the following ways. For the sake of simplicity, it has been assumed that the incoming traffic is classified into two classes namely, *High (H)* and *Low (L)* [14]:

- *Threshold-based approach:* In this approach, a packet belonging to class *H* may be delayed in an FDL longer than a packet of class *L*. In other words, let T_h and T_l denote, respectively, the maximum amount of time that packets of classes *H* and *L* might be delayed in an FDL on encountering a contention in an intermediate core switch. Then, T_h is set to be greater than T_l , i.e. $T_h > T_l$. An example of this approach is illustrated in Figure 2 (a) where the number of wavelengths is 3 and the number of FDLs is taken to be 5. In this figure, T_l is equal to 3 and T_h is equal to 5 FDLs.

- *Wavelength-based approach:* In this approach, out of all the W wavelengths made available in a single optical fiber, S wavelengths are exclusively reserved for class *H* packets, while the remaining $W - S$ wavelengths are shared between packets belonging to both, *L* and *H* classes. As an example, Figure 2 (b) depicts this approach for a scenario with $W = 4$ and $S = 2$.

4. The Analytical Model

In this section, we present a mathematical model for the wavelength-based QoS management scheme with two classes of service ($k = 2$). The model is then extended to the case where the number of classes is taken to be any arbitrary number ($k \geq 2$). Finally, the generalized model is slightly altered to include the impact of FDLs as well. Hereafter, we concentrate merely on a single switch and focus on one of its output links.

4.1. Assumptions and Notations

In this subsection, we highlight the assumptions as well as notations considered throughout the step-by-step model derivation hereafter [17][18].

- There exist two service classes namely, *Low (L)* and *High (H)* with input rates λ_1 and λ_2 , respectively, which follow a Poisson distribution. Henceforward, unless stated, λ_i will be used to denote the input rate of service class i .
- Each optical fiber carries up to W wavelengths where

packets of class *L* are not allowed to use more than W_s wavelengths at any given time.

- No FDL is available. Although simplifying, this assumption is justifiable as the common trend in developing intermediate OPS switches is to use as few FDLs as possible and instead, try to increase the wavelength count in the optical fibers [19].

4.2. The 2-Class Model

The aforementioned assumptions lead to a two-dimensional birth-death process [18] as shown in Figure 3. The state of the system at each time instant can be characterized by the pair (n_1, n_2) where n_1 and n_2 are the number of packets of classes *L* and *H* being served by the network, respectively. The number of packets buffered for each class at the ingress node is limited and depends on the size of the buffer. Thus, $n_1 \leq W_s$ and $n_1 + n_2 \leq W$. Let π_{ij} be the steady state probability of having i packets of class *L* and j packets of class *H* in the system. Deriving the detailed balance equation [20] with respect to i and j in the steady state yields:

$$\pi_{ij} = \frac{\rho_1^i \rho_2^j}{i! j!} \pi_{00}, 0 \leq i \leq W_s, 0 \leq j \leq W - i, \quad (3)$$

In which $\rho_i = \lambda_i / \mu_i$ and μ_i is the service rate for $i = 1, 2$. Considering equation (3) and the normalization condition, we obtain:

$$\pi_{00}^{-1} = \sum_{i=0}^{W_s} \sum_{j=0}^{W-i} \frac{\rho_1^i \rho_2^j}{i! j!}. \quad (4)$$

Blocking probability can be derived from the system size distribution as follows. For class *H*, an incoming packet is lost when it finds all wavelengths busy serving other packets. Thus, the blocking probability, P_H , is given by:

$$P_H = \sum_{\substack{i+j=W \\ i \leq W_s}} \pi_{ij} = \frac{\pi_{00}}{W!} \sum_{j=W-W_s}^W \binom{W}{j} \rho_1^{W-j} \rho_2^j. \quad (5)$$

In the case where $W_s = W$, i.e. when both classes are equally prioritized, equation (5) reduces to:

$$P_H = \frac{\pi_{00}}{W!} (\rho_1 + \rho_2)^W, \quad (6)$$

which is obtained using Newton's binomial formula.

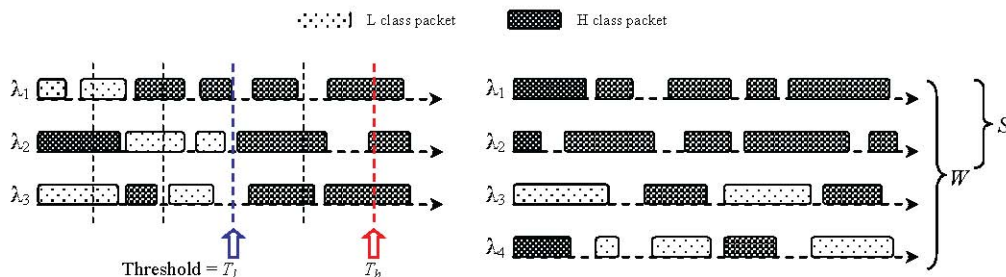


Figure 2. Examples of resource reservation-based QoS management schemes (a) The threshold-based QoS management approach with 3 wavelengths and 5 FDLs (b) The wavelength-based QoS management approach with 4 wavelengths (W), out of which λ_1 and λ_2 are reserved for class *H* packets (S).

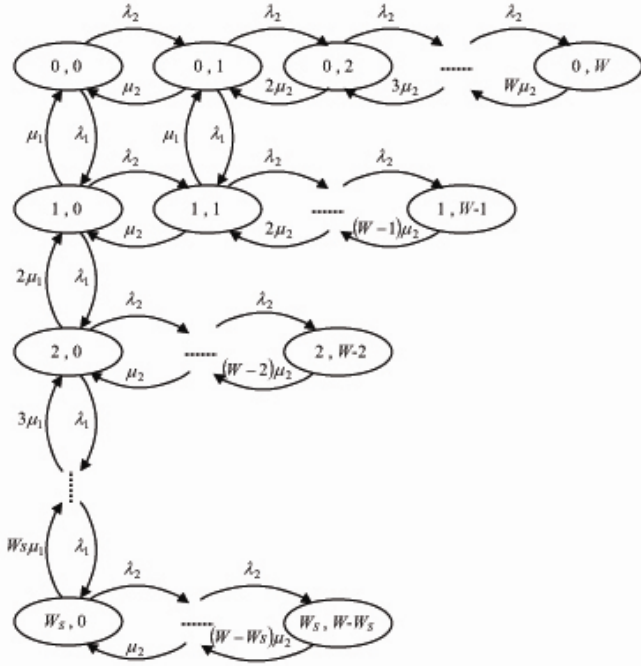


Figure 3. The markov model for the 2-class wavelength-based QoS management scheme.

On the other hand, a class L packet is lost not only when all the wavelengths are busy, but also when the number of other class L packets, already being served in the system, reaches the threshold W_S . Therefore, for $W_S < W$, P_L can be expressed as:

$$P_H = \sum_{\substack{i+j=W \\ i \leq W_S}} \pi_{ij} + \sum_{j=0}^{W-1} \pi_{W_S j} \quad (7)$$

$$= \pi_{00} \left[\frac{1}{W!} \sum_{j=W}^W \binom{W}{j} p_1^{W-j} p_2^j + \frac{p_1^{W_S} p_2^{W-1}}{W_S!} \sum_{j=0}^{W-1} \frac{p_2^j}{j!} \right],$$

where $W_0 = W - W_S$. For $W_S = W$, P_L is the same as P_H as obtained in equation (6). Finally, if we define P_T as the total fraction of packets that are lost, then we have:

$$P_T = \frac{\lambda_1}{\lambda_1 + \lambda_2} P_L + \frac{\lambda_2}{\lambda_1 + \lambda_2} P_H. \quad (8)$$

4.3. The Generalized K-Class Model

In this section, we generalize the 2-class model to support any arbitrary number of service classes ($k \geq 2$). Let λ_i and μ_i denote the arrival and service rates of packets of some class S_i ($0 \leq i \leq k-1$), respectively. Also, let L_i be the maximum number of wavelengths for class S_i .

Without loss of generality, it is assumed that $L_i \leq L_j$ when $i < j$ and the output fiber carries L_{k-1} wavelengths, which is equal to the number of wavelengths for class S_{k-1} . The state of the system at each time instant can be fully characterized by a k -tuple $(n_0, n_1, \dots, n_j, \dots, n_{k-1})$, where the j^{th} element denotes the number of packets of class S_j being served ($1 \leq j \leq k-1$). Writing the detailed balance equation with respect to $(n_0, n_1, \dots, n_{k-1})$, we get:

$$\pi(n_0, \dots, n_{k-1}) = \pi_0 \prod_{j=0}^{k-1} \frac{p_j^{n_j}}{n_j!}, \quad n_j \leq L_j, \sum_{j=0}^{k-1} n_j \leq L_{k-1}, \quad (9)$$

in which π_0 is the probability of the system being empty.

The normalization condition yields:

$$\pi_0^{-1} = \sum_{n_0=0}^{y_0} \sum_{n_1=0}^{y_1} \dots \sum_{n_{k-1}=0}^{y_{k-1}} \left(\prod_{j=0}^{k-1} \frac{p_j^{n_j}}{n_j!} \right), \quad (10)$$

where y_j ($0 \leq j \leq k-1$) is given as:

$$y_j = \begin{cases} \min \{L_j, L_{k-1} - \sum_{l=0}^{j-1} n_l\}, & (0 < j \leq k-1) \\ L_0, & j = 0 \end{cases} \quad (11)$$

A class S_j packet fails to get service if it either finds, at the instant of arrival, all wavelengths busy or the number of class S_j packets already in system reaching the threshold L_j . Hence, the blocking probability of such a class S_j is given by:

$$P_L^j = \sum_{\substack{\sigma=L_{k-1} \\ n_j=L_j}} \pi(n_0, \dots, n_{k-1}), \quad 0 \leq j \leq k-1, \sigma = \sum_{l=0}^{k-1} n_l. \quad (12)$$

4.4. The Extended Generalized K-Class Model

Additional to wavelengths, an optical link may be accommodated with a number of FDLs, which are optical buffers used to temporarily delay an incoming packet if all wavelengths of the output link are found busy transmitting other packets. In the context of queuing theory, such an FDL acts as a waiting space or buffer. Previous works show that even employing a limited number of FDLs would improve the performance of the optical network to a great extent [21].

Figure 4 demonstrates the structure of an FDL array comprising of a number of FDLs, each of which might be thought of as a fixed length tube with N exit points ($N > 1$). A packet entering an FDL may leave it at any exit point, but once passing an exit point, it travels inside the FDL until the next exit point is reached. Based upon the value of N , FDLs are classified into *fixed-delay* ($N = 1$) and *variable-delay* ($N > 1$) FDLs [21]. One important factor in designing variable-delay FDLs is the distance between two successive exit points. In Figure 4, the distance between exit points j and $j+1$ is 2^j time units. Following this design, if an FDL has N exit points (excluding the end point), its length can be calculated as follows:

$$L = \sum_{j=0}^{N-1} 2^j = 2^{N+1} - 1. \quad (13)$$

In this subsection, we take into account the impact of FDLs, thus ignoring the last assumption made in subsection 4.1. If we denote the maximum number of dedicated resources for classes L and H by R_L and R_H respectively, then $n_1 \leq R_L$ and $n_1 + n_2 \leq R_H$, where $R_L = W_S + T_L$ and $R_H = W + T_H$. By extending this notion for the generalized model, for any two classes S_i and S_j ($0 \leq i < j \leq k-1$), we have:

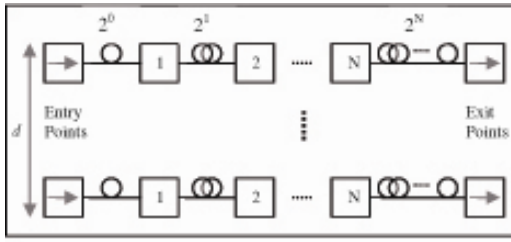


Figure 4. The structure of an FDL array. The array consists of d FDLs, each having N exit points (excluding its end point).

$$R_i \leq R_j; (0 \leq i < j \leq k-1). \quad (14)$$

Similar to the derivation provided in subsection 4.3, the balanced equation for such a system can be written as:

$$\pi(n_0, \dots, n_{k-1}) = \pi_0 \prod_{j=0}^{k-1} \frac{P_j^{n_j}}{n_j!}, n_j \leq R_j, \sum_{j=0}^{k-1} n_j \leq R_{k-1}. \quad (15)$$

Hence, the blocking probability of a packet of class S_j can be obtained similar to equation (12) as follows:

$$P_m^j = \sum_{\substack{\eta=R_{k-1} \\ n_j=R_j}} \pi(n_0, \dots, n_{k-1}), 0 \leq j \leq k-1, \eta = \sum_{m=0}^{k-1} n_m. \quad (16)$$

5. Numerical Results

In this section, we justify the correctness of our proposed model using results obtained through simulations conducted at switch-level. The simulations were conducted in the event-driven Ptolemy environment [22]. On average, 9 batches were generated in order to reach steady-state, each comprising of 10,000 packets. To exclude the impact of the warm-up period, the first batch was discarded. A single optical switch with just one output link and Poisson arrival process was considered for simulation under different

parametric values. In the following scenarios, the dotted lines denote the results obtained from the analytical model. We use the notations P_H , P_L , and $P_{classless}$ to denote the blocking probabilities of classes H , L , and the *classless* system, respectively.

The classless system is defined to be a single-class system with traffic intensity equal to the sum of the traffic intensities of classes L and H , and total number of wavelengths equal to those available to class H in the prioritized system.

Figure 5 (a) validates equation (3) for $W = 2$, $W_S = 1$ and $\rho_1 = 2.0$. For the sake of clarity, blocking probabilities of states (0, 2) and (1, 1) have not been illustrated. It can be observed that with increase in the traffic intensity of class H (ρ_2), the probability of being in state (1, 0) decreases, and for $\rho_2 > 2$, this probability falls below the curve for state (0, 1). Assuming $R_L = 1$, $R_H = 3$, and $\rho_1 = 2.0$ for the generalized model with accommodated FDL results in a similar plot given in Figure 5 (b). However, since the latter makes use of an additional FDL as well ($R_H = W + 1$), the blocking probabilities obtained are slightly lower compared to the results of Figure 5 (a).

Figure 6 (a) illustrates the blocking probabilities of both classes, and that of the classless system, in terms of W . In this figure, $\rho_1 = 3.0$, $\rho_1 = 2.0$, and $W_S = 3$. Not surprisingly, with increase in the wavelength count (W), P_H decreases and for $W > 8$, this value actually approaches 0. Although W_S is fixed to 3, P_L also decreases with increase in W since in this case, class L packets have better chance in utilizing their set of wavelengths (W_S) more effectively. For $W > 6$, increase in W does not influence P_L . As expected, $P_{classless}$ falls between P_H and P_L . The same can be inferred for the case where both, wavelengths and FDLs are considered together.

As depicted in Figure 6 (b), the blocking probability is plotted in terms of R_H for $\rho_1 = 3.0$, $\rho_2 = 2.0$, and $R_L = 3$. As mentioned earlier, this alleviated probability is due to the presence of FDLs as additional resources. Even in this scenario, the probability of the classless system falls between the class L and class H probabilities.

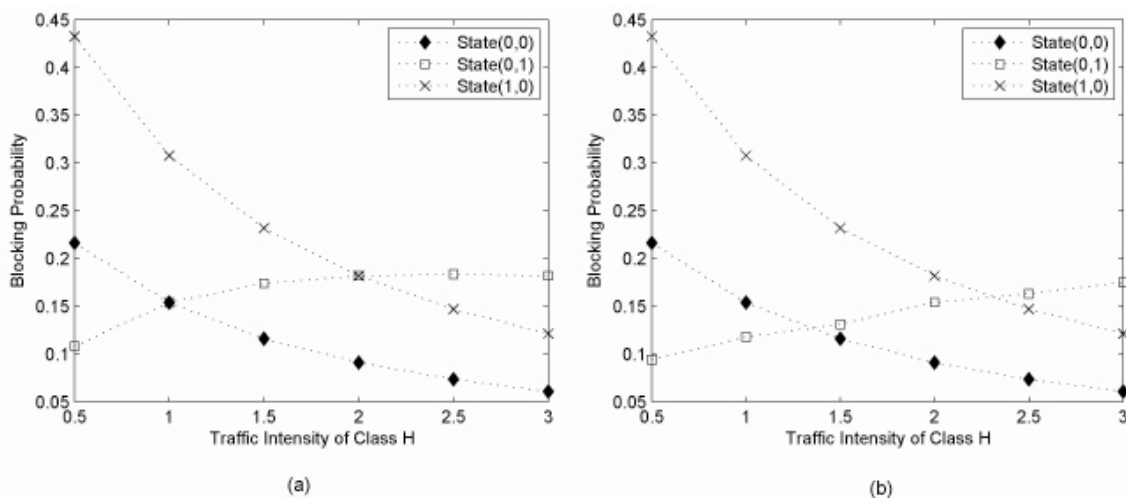


Figure 5. Validation of the steady-state probability, π_{ij} , for the 2-class model. (a) Only wavelength-based QoS with $W_S = 1$, $W = 2$, and $\rho_1 = 2.0$ (b) wavelength and threshold-based QoS with $R_L = 1$, $R_H = 3$, and $\rho_1 = 2.0$.

The blocking probability for the generalized system with any number of service classes is shown in Figures 7 (a) and 7(b). We conducted the following simulation for a 3-class system, i.e. $k = 3$. For the case where only wavelengths are available, $L_0 = 1, L_1 = 3, L_2 = 5, \rho_0 = 1.5$, and $\rho_2 = 2.5$. In this case, the blocking probabilities of all classes are depicted as functions of ρ_2 . As can be observed, the blocking probabilities of classes 0 and 2 lie above and below the classless system (denoted by Class 3 in the figures), respectively. For $\rho_2 < 1.5$, loss experienced by class 1 packets is higher than that of the classless system. But as ρ_2 increases, both the probabilities converge to each other. A similar observation can be made from Figure 7 (b) which illustrates the generalized model in which both, wavelengths and FDLs are taken into account. In this scenario, a 3-class system with $R_0 = 2, R_1 = 4, R_2 = 6, \rho_0 = 1.5$, and $\rho_2 = 2.5$ is taken into account. Unlike the parameters assumed in Figure 7 (a), for every $R_i (i = 0, 1, 2), R_i = L_i + 1$, i.e. we have dedicated a single FDL to each of the service classes. As expected, the presence of such FDLs further reduces the blocking probabilities of the different classes.

6. Conclusion

A myriad of factors have been proposed to study the performance of various underlying network topologies. In this paper, we introduced new performance metrics upon which the performance behavior of optical k -ary n -cubes could be evaluated and used for feasibility studies.

We also proposed an analytical model for the wavelength-based quality of service (QoS) provisioning scheme to suffice any arbitrary number of service classes at an optical switch level. The model was then extended to include the impact of another potential resource known as fiber delay lines (FDLs). Numerical results revealed that service classes privileged with more number of resources experience lesser loss compared to classless systems, while those with lesser resources suffer great losses. The next step of this research is to extend the model to a complete network of switches and study the relevant performance dynamics at a network-level under real-world traffic patterns.

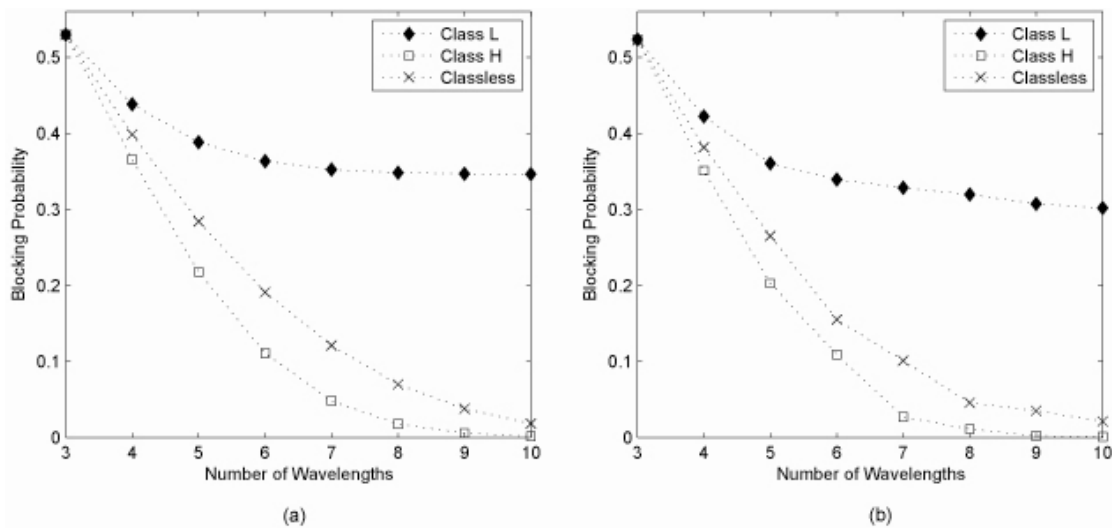


Figure 6. Comparison of class L, class H, and classless packets in terms of blocking probability. (a) $W = 3, \rho_1 = 3.0$, and $\rho_2 = 2.0$ (b) $R_L = 3, \rho_1 = 3.0$, and $\rho_2 = 2.0$.

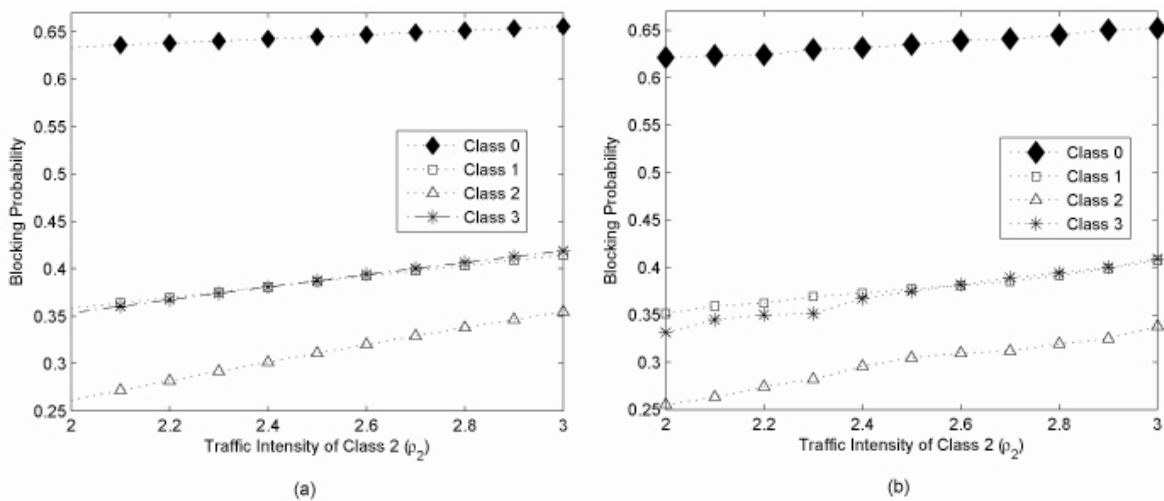


Figure 7. Comparison of classes 0, 1, 2, and classless packets in terms of blocking probability. (a) $L_0 = 1, L_1 = 3, L_2 = 5, \rho_0 = 1.5$, and $\rho_1 = 2.5$ (b) $R_0 = 2, R_1 = 4, R_2 = 6, \rho_0 = 1.5$, and $\rho_1 = 2.5$.

References

- [1] B. Arnaud, "Architectural and engineering issues for building an optical internet," *Proc, All Optical Communications Systems: Architecture, Control Network Issues*, Vol. 3531, pp. 358-377, 1998.
- [2] B. Meagher, "Design and implementation of ultra-low latency optical label switching for packet-switched WDM networks," *IEEE/OSA Journal of Lightwave Technology*, Vol. 18, No. 12, pp. 1978-1987, 2000.
- [3] M. J. O'Mahony, D. Simeonidou, D. K. Hunter, and A. Tzanakaki, "The application of optical packet switching in future communication networks," *IEEE Communications Magazine*, Vol. 39, pp. 128-135, 2001.
- [4] C. Qiao, and M. Yoo, "Optical burst switching (OBS) - a new paradigm for an optical internet," *Journal of High Speed Networks*, Vol. 8, No. 1, pp. 69-84, 1999.
- [5] P. Gambini, "Transparent optical packet switching: network architecture and demonstrators in the KEOPS project," *IEEE Journal on Selected Areas in Communications*, Vol. 16, No. 2, pp. 1245-1259, 1998.
- [6] L. Dittmann, "The European IST project DAVID: a viable approach towards optical packet switching," *IEEE Journal on Selected Areas in Communications*, Vol. 21, No. 7, pp. 1026-1040, 2003.
- [7] S. Yao, S. J. B. Yoo, B. Mukherjee, and S. Dixit, "All-optical packet switching for metropolitan area networks: opportunities and challenges," *IEEE Communications Magazine*, Vol. 39, pp. 142-148, 2001.
- [8] F. Callegati, A. C. Cankaya, Y. Xiong, and M. Vandenhoute, "Design issues of optical IP routers for Internet backbone applications," *IEEE Communications Magazine*, Vol. 37, pp. 124-128, 1999.
- [9] F. Callegati, and W. Cerroni, "Wavelength allocation algorithms in optical buffers," *Proc, IEEE Int. Conf. on Communications*, Vol. 2, pp. 499-503, 2001.
- [10] J. Duato, S. Yalamanchili, and L. M. Ni, *Interconnection networks: an engineering approach*, Los Alamitos, IEEE Computer Science Press, 1997.
- [11] B. Mukherjee, *Optical WDM Networks*, Springer Publications, 2006.
- [12] M. Yoo, and C. Qiao, "A new optical burst switching (OBS) protocol for supporting quality of service," *Proc, All Optical Communication Systems: Architecture, Control and Network Issues*, Vol. 3531, pp. 396-405, 1998.
- [13] F. Callegati, W. Cerroni, G. Muretto, C. Raffaelli, and P. Zaffoni, "QoS routing in DWDM optical packet networks," *Int. Workshop on Quality of Future Internet Service*, pp. 247-256, 2004.
- [14] F. Callegati, W. Cerroni, C. Raffaelli, and P. Zaffoni, "Wavelength and time domain exploitation for QoS management in optical packet switches," *Proc, The Int. Journal of Computer and Telecommunications Networking*, Vol. 44, pp. 569-582, 2004.
- [15] W. J. Dally, and B. P. Towles, *Principles and Practices of Interconnection Networks*, The Morgan Kaufmann Series in Computer Architecture and Design, 2004.
- [16] A. Kianrad, A. Dadlani, A. Rajabi, M. Aghajani, A. Khonsari, and S. H. Seyed Razi, "Performance comparison of simple regular meshes and their k -ary n -cube variants in optical networks," *Proc, 13th Int. CSI Computer Conference*, pp. 543-550, 2008.
- [17] F. Callegati, W. Cerroni, C. Raffaelli, and P. Zaffoni, "DWDM for QoS management in optical packet switches," *Proc, the Second Int. Workshop on Quality of Service in Multiservice IP Networks*, pp. 447-459, 2003.
- [18] L. Kleinrock, *Queuing Systems*, Wiley-Interscience, 1975.
- [19] L. Xu, H. Perros, and G. Rouskas, "A survey of optical packet switching and optical burst switching techniques," *IEEE Magazine on Communications*, pp. 136-142, 2001.
- [20] D. P. Bertsekas, and R. Gallager, *Data Networks*, 2nd Edition, Prentice Hall Publications, 1992.
- [21] M. Yoo, C. Qiao, and S. Dixit, "QoS performance of optical burst switching in IP-over-WDM networks," *IEEE Journal on Selected Areas in Communications*, Vol. 18, No. 10, pp. 2062-2071, 2000.
- [22] Ptolemy simulation tool,
<http://ptolemy.eecs.berkeley.edu/>.



Ahmad Kianrad received his BSc. degree in Software Engineering from Tarbiat Modarres University, Iran, in 2004 and MSc. degree in Information Technology from University of Tehran, Iran, in 2008. Since then, he has been working as research assistant in the School of Computer Science at the Institute for Studies in Physics and Theoretical Mathematics (I.P.M.), Iran. His current research interests focus on computer networks and in particular, WDM optical networks.
E-mail: a.kianrad@ece.ut.ac.ir



Ahmad Khonsari received his BSc. degree in Electrical and Computer Engineering from Shahid-Beheshti University, Iran, in 1991, and MSc. degree in Computer Engineering from the Iran University of Science and Technology, Iran, in 1996 and PhD. degree in Computer Science from the University of Glasgow, UK, in 2003. He is currently an assistant professor in the Department of Electrical and Computer Engineering, University of Tehran, Iran and a researcher in the School of Computer Science,

Institute for Studies in Theoretical Physics and Mathematics (I.P.M.), Iran. His research interests are performance modeling and evaluation, mobile and ubiquitous computing, communication networks and distributed systems, and high performance computer architecture.

E-mail: ak@ipm.ir



Nasser Yazdani received his BSc. Degree in Computer Engineering from Sharif University of Technology, Iran, in 1985. He worked in Iran Telecommunication Research Center (ITRC) as a researcher and developer for few years. To pursue his education, he entered and graduated with a PhD. degree in Computer Science and Engineering from Case Western Reserve University, Cleveland, Ohio, USA, in 1997. After working in various companies and research institutes in USA, he joined the ECE Department of the University of Tehran, Iran, as an assistant professor in 2000. His research interests include networking, packet switching, access methods, operating systems, and database systems.

E-mail: yazdani@ut.ac.ir



Aresh Dadlani earned his BSc. and MSc. degrees in Electrical and Computer Engineering, both from University of Tehran, Iran, in 2007 and 2009, respectively. He is also a research assistant in the School of Computer Science at the Institute for Studies in Theoretical Physics and Mathematics (I.P.M.), Iran. His research interests are in the areas of performance modeling and evaluation of WDM optical and wireless networks and Quality of Service (QoS) aspects in these networks.

E-mail: a.dadlani@ipm.ir

Paper Handling Data:

Submitted: 14.02.2009

Received in revised form: 23.08.2009

Accepted: 12.10.2009

Corresponding author: Ahmad Kianrad,
Department of Electrical and Computer Engineering,
University of Tehran, Tehran, Iran.