Deadline-based Connection Setup in Wavelength-routed WDM Networks

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February 8, 2010

Abstract

This article addresses the ubiquitous topic of Quality of Service (QoS) aware connection provisioning in wavelength routed WDM optical networks. The impact of the connection setup time of an optical connection has not been adequately addressed in the open literature. As such, this paper presents a novel approach that uses the optical connection setup time as a service differentiator during connection provisioning. The proposed approach utilizes the Earliest Deadline First (EDF) queueing algorithm to achieve deadline-based connection setup management with the deadline being the setup time requirement of an optical connection. The proposed EDF-based approach would allow the network operator to improve the QoS perceived by the end clients. Performance of this novel scheme is analyzed by accurately calculating various parameters, such as the fraction of connections provisioned on-time (i.e. prior to deadline expiration) and the average time it takes to successfully setup a connection. In addition, the presented approach is validated by a simulation that analyzes the performance of the proposed connection setup scheme in the specific context of the National Science Foundation Network (NSFNET). The obtained results show that a deadline-based setup strategy can minimize blocking probability while achieving QoS differentiation.

Index Terms: Optical networks, connection setup management, Earliest Deadline First scheduling, performance analysis.

1 Introduction

Wavelength Division Multiplexing (WDM) is becoming the de facto technology for driving up the transmission capacity of optical networks and thus enabling optical operators to keep up with the continuous growth of data traffic. WDM multiplexes many non-overlapping WDM channels onto the same optical fiber, where each of these channels can be operated at the peak rate of several gigabits per second. Optical fiber communication is therefore being firmly established as the preferred means of communications for the ever-emerging bandwidth consuming applications and services. However, the perpetual advent of new applications, each having different QoS requirements, aggravated by the need to carry these applications over optical networks, is proving to be the next big challenge for future WDM optical networks. This is especially true since existing optical networks still need to evolve

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from single service networks to multi-service ones [1], in which different types of services with different QoS requirements can be supported. Hence, the main trend is leaning towards migrating from a plain optical network with static point-to-point connections to a new era of dynamic, wavelength-routed, all-optical WDM optical networks [2].

In a wavelength-routed WDM network, an Optical Cross-Connect (OXC) switches the optical signal on a WDM channel from an input fiber to an output fiber; thus a connection (lightpath) may be established from a source to a destination. In this regard, numerous research efforts ([3, 4, 5]) have contemplated equipping these networks with a multi-service capability making them provide predictable quality of transport services. Quality of transport is measured by the set of parameters that affect the data flow after the lightpath is established.

However, most of the previous efforts did not consider in their formulations the crucial parameter of *connection setup time*. Inspired by these observations, this work focuses on the connection setup time parameter that is likely to become a common feature of a customer's service profile. The authors in [6, 7] presented the connection setup time as a potential service differentiator in Service Level Agreements (SLAs) between optical operators and their customers.

The connection setup time is widely defined as the amount of time separating the instant a lightpath (i.e. a service) setup request is received by the operator and the moment the requested lightpath is established. This paper investigates the impact of the connection setup time on the setup of a connection as a service differentiator. The work is motivated by the need to consider the optical connection setup time as a timely increasing priority indicator (a type of competition-oriented parameter which may be linked to pricing) during the setup process.

Therefore, connection setup time can be viewed as a *deadline*. A connection setup request arriving at an optical source node A at instant t with a setup time requirement equal to S will be assigned a deadline of $t+S$. If such a setup request can not be met due to a lack of optical resources, the blocked connection request at A is stored in an Earliest Deadline First queue. In other words, instead of dropping connection requests that cannot be satisfied by the optical network, they will be queued at the entry point of the network in an order consistent with their respective priorities (deadlines).

The proposed approach utilizes an adaptation of the well-known *Earliest Deadline First* scheduling algorithm aimed at optical connection setup management. More specifically, blocked connection setup requests are inserted into a queue and are then served according to an EDF scheduling discipline, whereby the connection request with the earliest setup time deadline, is served first. The main advantage of this technique is to enforce quality of service differentiation among customers having different connection setup time requirements.

The rest of this paper is structured as follows: in Section 2, the deadline-based connection setup approach is described and its relation to the literature is discussed. Section 3 introduces a mathematical model to compute the success probability of a deadline-driven connection setup request. Numerical results to evaluate the benefits of the proposed approach are presented in Section 4. Section 5 highlights further the merits of the deadline-based setup scheme through a simulation in the context of the National Science Foundation Network (NSFNET). Finally, Section 6 concludes the paper and presents future perspectives for research.

2 The Proposed Scheme and Related Work

2.1 Description of the Deadline-Based Connection Setup Approach

Different applications and services have different connection setup time requirements. As new applications continue to emerge, this gap in the deadline requirements is expected to become more pronounced. For instance, online trading and stock market applications are expected to have stringent connection setup requirements compared to IP best effort and database backup applications. Taking this diversity into consideration would offer the network operators the opportunity to maximize throughput while meeting the deadline requirements of their end users. This paper achieves this objective by introducing an EDF queue at the OXC level, enabling the optical operator to exploit the connection setup time requirement when dealing with blocked connection requests. Thus, connection setup time requirements are seen as period of times during which the blocked connection requests can be delayed (i.e. queued) as well as service differentiators once those blocked connections join the EDF queue.

In order to show how the proposed scheme can be usefully implemented in the context of a wavelength routed WDM network, the following sample scenario is considered. Figure 1 depicts a wavelength-routed network comprising three OXCs (namely, A, B and C) that are interconnected through two fiber links, each of which has W wavelengths. It is assumed that each connection setup request requires a full wavelength of bandwidth. The service in this context is to offer a lightpath (i.e. the occupation of a series of wavelengths along the physical path allocated to the connection request). For instance, OXC A will attempt to establish a lightpath to carry each connection request that it receives. However, connection blocking can occur if either of the following situations arise:

- OXC A is able to deliver up to W lightpaths but all these lightpaths are busy serving W other connection requests originating at A.
- OXC A is not able to benefit from all W lightpaths due to resource depletion caused by the connections generated from OXC B to C. Stated differently, the availability of the W lightpaths that may be provided to A strongly depends on the *blocking probability* (denoted by p) imposed by node B.

The W lightpaths that may be provided by A can be consequently modeled as W servers. But in order to cover the possible blocking situations presented above, the following assumption is made. A connection request arriving at OXC A while at least one of the W servers is idle is not necessarily guaranteed to start a service on one of the available servers. Specifically, the incoming connection request will

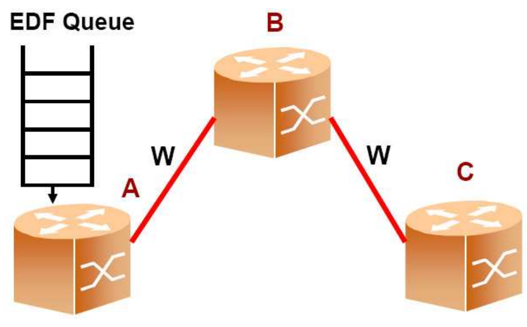

Figure 1: An example of an optical network.

either join one of the idle servers with a probability $(1-p)$ or will be blocked with a probability p. In the classical approach, a blocked connection will be immediately dropped. However, in our proposed scheme, the blocked connection requests at A are stored in an EDF queue in an increasing order of their requested setup times. As stated previously, the proposed approach considers the connection setup time as a period of time during which the blocked lightpath request tolerates being queued. This tolerance may be soft (i.e. the request is kept in the queue even if the tolerated time has expired) or firm (i.e. the request is dropped when its tolerated time has expired). A queueing representation of the proposed scheme is depicted in Figure 2 where the EDF queue placed in front of the W servers. The EDF algorithm implicitly assumes that the priority of a blocked connection request increases as the request gets closer to its deadline. A pending request that reaches its deadline is referred to as a dead customer. The EDF policy has two main variants, namely the work-conserving variant where dead customers are served and the non work-conserving variant in which dead customers are dropped. In this paper, the work-conserving EDF variant is adopted.

A blocked connection request will keep on advancing until it reaches the top of the EDF queue. Once it gets to the front of the queue, it waits there until one of the W servers (lightpaths) becomes idle. But even then, it is not guaranteed to join a freed-up server. To gain insight into the model, the following assumptions are made. Every server is assumed to have the same constant service time which is normalized to *one unit of time*. The time axis is divided into discrete time slots having the same length of *one time unit*. The connection will either gain access to the optical network with probability $(1-p)$ or will remain at the front of the queue blocking the customers queueing up behind it with probability p. In the latter case, it is assumed that the job waits until the start of the next time slot before retrying to access one of the W servers. It follows from these assumptions that the number of connection requests going into service at the start of a time slot (denoted by D_p) is a geometric random variable with parameter p. In other words, if W customers happen to be waiting in the EDF queue and W servers are available at the start of a time slot S, then the probability that k (where, $k \leq W$) customers get served during S is given by the following expression:

$$Pr\{D_p = k\} = (1-p)^k \times p \quad (1)$$

A performance evaluation study of the proposed setup scheme is presented in Section 3 and it is based on the queueing model presented in Figure 2. This queueing model is based on some restricted assumptions, but it permits us to study the EDF queue and obtain insights into its performance. In order to further study the EDF queue, we have also developed a simulation model of an optical network based on the NSFNET topology, without the restricting assumptions of the analyt-

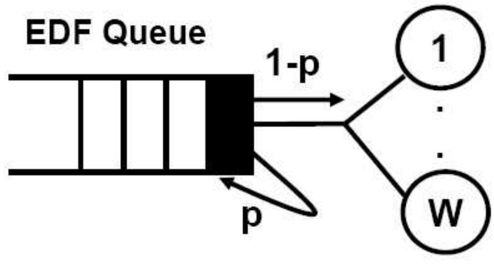

Figure 2: The queueing system under study.

ical model, such as prior knowledge of the call blocking probablity and constatnt service times. The results obtained are given in Section 5.

2.2 Related Work

The contributions of this paper are two fold. First, an EDF-based connection setup mechanism is applied to wavelength routed networks. Second, a novel mathematical study to numerically evaluate the benefits of the service differentiation feature is introduced. A computational method is proposed for the estimation of several major performance metrics of EDF queues, such as the probability of being served prior to deadline expiration and the average delay before being served. This subsection aims at underlining the novelty of each of these contributions.

In previous studies [8, 9], the deployment of the EDF-based connection setup approach was studied in the special context of point-to-point connection establishment between two isolated optical nodes. In [8], the simplified case where one wavelength (one server) exists between the two stand-alone optical nodes was targeted. Subsequently, [9] considered the case of multiple wavelengths (multiple servers) between the two isolated optical nodes. Yet, both studies lacked generality since they did not deal with wavelength-routed optical connections. In this paper, a further step is taken to consider the case where the optical nodes are not isolated but instead belong to a wavelength routed WDM network. Hence, this study takes into account the effect that other optical network nodes may have on establishing the connection. The authors in [10, 11] investigated the problem of dynamic bandwidth allocation for Deadline-Driven Requests (DDRs). The authors proposed in this regard, algorithms for choosing the best transmission rate to serve DDRs. However, the difference with the approach presented in this paper stems from the fact that they define the deadline to be the maximum connection holding time; whereas the approach in this work may be applied to schedule the provisioning of the blocked DDRs, and thus improve the fraction of un-provisioned requests achieved.

The second contribution of this work is the performance evaluation of the proposed technique. It is important to note that the deadline-based connection setup mechanism revolves around the EDF queueing algorithm so it benefits from and inherits the properties of EDF. The Earliest Deadline First algorithm was proposed by Jackson in 1955 [12]. The application of EDF to computer networking has been extensively studied (cf [13, 14, 15] for some of the early research, and [16, 17, 18] for more recent work). As a distinguishing feature from the other scheduling techniques, EDF minimizes the deadline missing probability. Many articles have been published, *e.g.* [19, 20, 21], for characterizing the EDF queue and assessing its main performance metrics. Yet, the general characterization of EDF, such as queue length distribution and stability condition, is still an open research problem. In particular, the calculation of the deadline mismatch ratio remains an open problem. The evaluation of this parameter is a crucial issue for the proposed connection setup approach since it yields the probability of setting up a connection on-time. This paper presents a computational method to address this issue and evaluate among other things the fraction of provisioned connections and the deadline mismatch ratio.

3 The Markovian Model

In what follows, the word *customer* denotes a connection setup request, the term *server* refers to a lightpath, and the term *laxity* represents connection setup time.

3.1 Rationale Behind the Model

As stated previously, the evaluation of the deadline mismatch probability in an EDF-based queueing system remains an open problem. This is probably due to the fact that deadline-based scheduling uses implicitly the *sojourn history*. In fact, the position of a customer is determined by its relative urgency with respect to every other customer waiting in the queue, including those that may arrive after the target customer. The urgency level of (and so the position in the queue occupied by) each customer is not fixed, but will change over time. This fact makes the modeling of the problem using a Markovian approach a real challenge. This paper tackles this problem by presenting an approach that takes both the initial position and the initial laxity of a customer as input parameters of the problem. Based on this assumption, the evolution of a customer in the queue can be modeled by a Markov chain with absorbing states. For technical reasons, a slotted time axis and a finite capacity EDF queue are assumed.

The rationale behind the proposed modeling approach is illustrated in the following example. Consider a target customer $\mathcal{C}$ that joins the EDF queue at time t with an initial laxity of L (margin before deadline expiration). Incoming customers whose deadlines are less than L are guaranteed to be inserted in front of $\mathcal{C}$ in the EDF queue. As time advances, L will keep on decreasing and the number of customers placed in front of $\mathcal{C}$ consequently gets smaller and smaller. In conclusion, the proposed modeling approach is based on the following observation:

> *From a queued customer's standpoint, the EDF scheduler behaves as a filter that utilizes the queued customer's laxity as a filtering parameter; and only the incoming customers that are accepted (not filtered out) are inserted in front of the target queued customer.*

3.2 System Definitions and Assumptions

A discrete-time queueing system model is considered and described below.

- The time axis is slotted, i.e. time is divided into equal-length unit-slots. Customers arriving during one slot are considered at the end of the slot and thus will attempt to access one of the W servers at the beginning of the next time slot.

- The service times provided by each one of the W servers is constant, and is assumed to be equal to one time slot. This assumption implies that a customer that starts receiving its service at the beginning of a given time slot will have its service completed by the start of the following time slot. In light of this assumption, W servers would be available at the beginning of each time slot.

- Each customer arrives with an initial *laxity* (denoted by L), which is the relative margin to its deadline expiration. Initial laxities of customers are assumed to be independent and identically distributed integer random variables. The Cumulative Distribution Function (CDF) of the initial laxity will be denoted by $F_L(.)$. To simplify numerical computation, it is assumed that L is upper bounded by Λ. Thus,

$$F(0) = 0, \quad \text{and} \quad F(l) = 1, \ \forall l \geq \Lambda.$$

  The residual laxity of a customer decreases as time progresses. For the sake of simplicity of formulation and without loss of generality, a customer is considered to be *alive* if at the *beginning* of a time slot its residual laxity is *strictly* positive. Since the main interest lies in getting the deadline mismatch probability, the *tardiness*, i.e. negative laxity, is not considered. In other words, when a customer's laxity reaches zero, the laxity is maintained at 0 so that it serves as an indicator of deadline mismatch.

- Services are non-preemptive and work conserving. This means in particular that *dead* customers (those having residual laxity of 0) are served as well.
- The EDF queue has $K-1$ waiting places. By convention, these waiting places are numbered from 1 to $K-1$.
- The initial position of each customer is known. Customers move in the queue until being served or being pushed out of the queue by customer having more stringent laxity requirements.
- The overall arrival process is Poisson, denoted as $\mathcal{P}$, with arrival rate λ_o. For a target customer $\mathcal{C}$ in the queue with residual laxity equal to l at the beginning of a slot, only those arriving within the slot with an initial laxity strictly smaller than l will be inserted ahead of $\mathcal{C}$. As the initial laxities are independent and identically distributed integer variables, customers arriving with an initial laxity strictly smaller than l, form a Poisson process $\mathcal{P}(l)$ with arrival rate $\lambda(l)$ given by $\lambda(l) = F_L(l-1)\lambda_o$, where $F_L(.)$ is the CDF of the initial laxity law). Let $A(l)$ denote the number of customers arriving within one time slot with an initial laxity strictly less than l. As such, $a(l,i)$, the probability of having i customers inserted before the target customer $\mathcal{C}$is given by
$$a(l,i) = Pr\{A(l)=i\} = e^{-\lambda(l)}\frac{[\lambda(l)]^i}{i!}. \quad (2)$$
Note it is assumed that $F_L(0)=0$, which means that $\lambda(1)=0$ and thus the customers waiting in the queue with a residual laxity of 1 will have 0 incoming customers inserted in front of them.
- As discussed in section 2, the number of customers going into service in one time slot D_p follows a geometric distribution with parameter p and their probability mass function is given by Eqn. (1). Note that p represents the percentage of incoming connection requests (customers) that are blocked due to resource shortage caused by the provisioning of the connection requests received by the other nodes (i.e. nodes B and C in Figure 1). This means that p will be directly proportional to the total load to which all other nodes are subject.
- The calculation of the blocking probability p is beyond the scope of this paper (refer to [22, 23, 24] for more information about how to calculate p).

3.3 A Markov Chain Model

Let us consider a target customer $\mathcal{C}$ arriving in a slot taken as the time origin ($t=0$) with an initial laxity L and an initial queueing position N. The state of $\mathcal{C}$ at the s-th slot (X_s) can be described by a pair of random variables $X_s=(n_s,m_s)$ where

- the meaning of n_s depends on its value as follows:
  - For $1 \le n_s \le K-1$, n_s gives the queueing position occupied by $\mathcal{C}$, which is, in an equivalent manner, the number of customers which have to be served before $\mathcal{C}$.

- By convention, $n_s = 0$ means that $\mathcal{C}$ starts its service. Thus, once $\mathcal{C}$ enters a state with $n_s = 0$, it stays there forever.
- By convention, $n_s = K$ means $\mathcal{C}$ is dropped out of the queue without being able to receive its service. Thus, once $\mathcal{C}$ enters a state with $n_s = K$, it stays there forever.

- m_s gives the residual laxity, $m_s = 0, \ldots, \Lambda$. By convention, $m_s = 0$ means that there is no more residual laxity.

The $\{X_s\}_{s \geq 0}$ slots form a Markov chain with a finite state space shown in Figure 3. The dashed box presented in Figure 3 defines the set of *non-absorbing* states of the target customer $\mathcal{C}$ (i.e. $1 \leq n_s \leq K-1$). The *absorbing* states of $\mathcal{C}$ (i.e. $(0, m_s)$ and (K, m_s), $m_s = 0, \ldots, \Lambda$) are organized into two absorbing subsets represented by the two solid boxes shown in Figure 3:

- The first subset (leftmost solid box) is made up of the states $(0, m_s)$ ($m_s = 0, \ldots, \Lambda$);
- The second subset (rightmost box) contains the states (K, m_s) ($m_s = 0, \ldots, \Lambda$).

The evolution of (n_s, m_s) is governed by the following equations:

$$m_{s+1} = \max(0, m_s - 1) \quad (3)$$

$$n_{s+1} = \text{minmax}\,(0, n_s - D_p + A(m_s), K) \quad (4)$$

where the function minmax (m, x, M) is given as follows:

$$\text{minmax}\,(m, x, M) = \begin{cases} m, & x \leq m \\ x, & m < x < M \\ M, & x \geq M \end{cases}$$

$A(m_s)$ is the number of customers arriving during the s-th slot with an initial laxity strictly smaller than m_s ($A(m_s)$ is described by Eqn. (2)). D_p is the number of customers whose position is less than or equal to n_s, and that go into service during the s-th time slot. The probability mass function of D_p is given by Eqn. (1). Given that at most W customers attempt to access the optical network at the

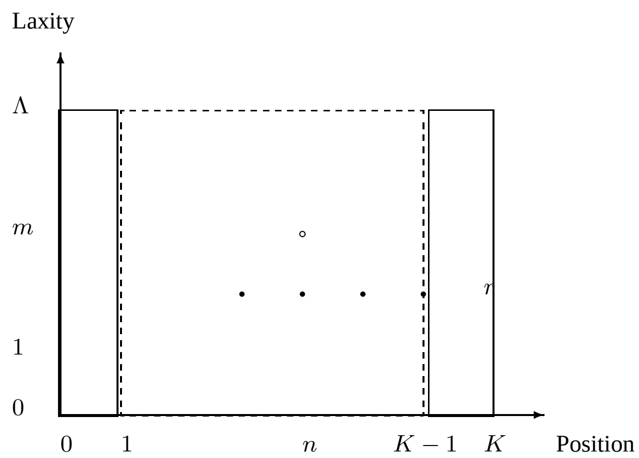

Figure 3: State space of the EDF queueing system. The empty point (n, m) is a transient state. Black points are potential one-step evolutions in the queue, and r is a rejection absorbing position.

start of each time slot, it follows that D_p takes on values in the range from 0 to $\min(n_s, W)$ (inclusive), That is, $D_p = 0, \ldots, \min(n_s, W)$.
The next state of the target customer $\mathcal{C}$ (denoted by $j(n_{s+1}, m_{s+1})$) can thus be probabilistically determined based on: (a) its current state $i(n_s, m_s)$; and (b) the probability distributions of the $A(m_s)$ and D_p random variables. Hence, the transition probabilities of the Markov chain X_s (i.e. $p_{ij} = Pr\{X_{s+1} = j/X_s = i\}$, $(i, j) \in \Omega^2$) do not depend on the particular time slot s, since the probability distributions of $A(m_s)$ and D_p are independent of s. This implies that $X = \{X_s\}_{s \in \mathbb{N}}$ is an *absorbing homogeneous* Markov chain.

As stated before, X is defined on a finite state space, Ω that contains a subset of absorbing states $\mathcal{A}$. These states encompass two absorbing subsets, namely $\mathcal{G}$ and $\mathcal{B}$. Let $\mathcal{M} = \Omega - (\mathcal{G} \cup \mathcal{B})$; $\mathcal{M}$ is the subset of non-absorbing states (also referred to as *transient* states). The triplet $(\mathcal{G}, \mathcal{M}, \mathcal{B})$ forms a partition of Ω. It follows by temporal homogeneity that the states of X may be described by the pair (n, m) where $n = 0, \ldots, K$, and $m = 0, \ldots, \Lambda$. Thus, the state space Ω is given by:

$$\Omega = \{i(n, m), n = 0, \ldots, K, \text{and } m = 0, \ldots, \Lambda\}$$

and $\mathcal{M}$, the subset of *transient* states, is defined as follows:

$$\mathcal{M} = \{i(n, m), n = 1, \ldots, (K - 1), \text{and } m = 0, \ldots, \Lambda\}$$

Multiple definitions may be envisaged for $\mathcal{G}$ and $\mathcal{B}$ according to the semantic attributed to each of these absorbing subsets. $\mathcal{G}$ is defined in this work to be the "good" set of absorbing states in the sense that $\mathcal{G}$ represents the case that the target customer $\mathcal{C}$ is eventually served. In contrast, $\mathcal{B}$ represents the case that $\mathcal{C}$ is dropped out of the queue. These definitions translate into the following expressions:

- $\mathcal{G} = \{i(0, m), m = 0, \ldots, \Lambda\}$;
- $\mathcal{B} = \{i(K, m), m = 0, \ldots, \Lambda\}$.

The absorbing states are of particular interest as they can be used to estimate several useful performance metrics. In the following subsection, a method is presented for computing among other things, the probability that a given customer ends up in one of the absorbing subsets.

3.4 Computation of Performance Metrics

The Markov Chain X described previously has two subsets of absorbing states. One important performance metric that can be calculated is the *Probability Of Absorption* (POA), which is the probability that the target customer $\mathcal{C}$ ends up in one of the absorbing subsets [25]. Furthermore, it is possible to determine the *mean time to absorption* that represents the expected number of steps (i.e. time slots) before $\mathcal{C}$ reaches one of the absorbing subsets. In this respect, the focus is on finding the mean number of steps (i.e. time slots) taken by X until absorption into $\mathcal{G}$; in other words, the *Mean Time To Service* (MTTS), which indicates the average amount of time spent by $\mathcal{C}$ in the EDF queue before starting its service. Computing POA and MTTS is essential in obtaining several major performance metrics pertaining to the EDF-based setup scheme under study.

The computations of POA and MTTS make use of the one step transition probabilities p_{ij} where $(i, j) \in \Omega^2$. p_{ij} indicates the probability that the chain shifts in one time slot (i.e. one step) from state $i(n, m)$ to state $j(n', m')$. The one step transition probabilities are obtained as follows.

- $\forall i \in \mathcal{A}, \forall j \in \mathcal{M}, p_{ij} = 0$ as once the Markov chain gets to an absorbing state, it stays there forever.

- $\forall i(n,m) \in \mathcal{M}, \forall j(n',m') \in \Omega$, it follows from Eqns. (3) and (4) that $m' = \max(0, m-1)$ and $n' =$ minmax $(0, n - D_p + A(m), K)$. D_p and $A(m)$ are two random variables whose probability distributions are given by Eqns. (1) and (2) respectively. As indicated before $D_p = 0, \ldots, \min(n, W)$, p_{ij} can therefore be expressed as:

$$p_{ij} = \sum_{d=0}^{\min(n,W)} Pr\{D_p = d)\} \cdot Pr\{A(m) = n' - n + d\} \tag{5}$$

The p_{ij}'s can be used to construct X's transition matrix P that plays a major role in obtaining POA and MTTS. P is a square matrix that has as many columns (respectively rows) as the total number of states, i.e. Card$\{\Omega\}$. This means that P is a Card$\{\Omega\} \times$ Card$\{\Omega\}$ matrix. Let t and r denote the total number of transient, and absorbing states respectively. That is, $t =$ Card$\{\mathcal{M}\}$, $r =$ Card$\{\mathcal{A}\} =$ Card$\{\mathcal{B}\} +$ Card$\{\mathcal{G}\}$, and $(t + r) =$ Card$\{\Omega\}$. The one step probabilities in P are organized according to the guidelines presented in [25, 26], whereby the rows and columns are labeled so that all the transient states precede all the absorbing states. The first t rows of P hold the one step transition probabilities related to the transient states of X (i.e. p_{ij}, $\forall i(n,m) \in \mathcal{M}$, and $\forall j(n',m') \in \Omega$). The last r rows of P hold the one step transition probabilities relating to the absorbing states of X (i.e. p_{ij}, $\forall i(n,m) \in \mathcal{A}$, and $\forall j(n',m') \in \Omega$). The resulting matrix P has the following canonical form.

$$P = \left(\begin{array}{c|c} Q_{t\times t} & R_{t\times r} \\ \hline 0_{r\times t} & I_{r\times r} \end{array} \right) \tag{6}$$

Here $I_{r\times r}$ is an $r \times r$ identity matrix, $0_{r\times t}$ stands for an $r \times t$ matrix whose components are all equal to zero, $R_{t\times r}$ is a non-zero t-by-r matrix, and $Q_{t\times t}$ is a $t \times t$ matrix. As stated before, the last r rows in P correspond to the absorbing states. This justifies the existence of the $0_{r\times t}$ and $I_{r\times r}$ matrices in the lower part of P for once the Markov chain enters an absorbing state it stays there forever. The first t rows in P are associated with the transient states. Therefore, the elements of $Q_{t\times t}$ are the one step transition probabilities among the transient states, while the elements of $R_{t\times r}$ are the one step transition probabilities from the transient to the absorbing states. The entries of $Q_{t\times t}$ and $R_{t\times r}$ can be calculated using Eqn. (5).

Since X is an absorbing Markov chain, it follows that the matrix $(I_{t\times t} - Q_{t\times t})$ is invertible [25, 26]. Let $N_{t\times t} = (I_{t\times t} - Q_{t\times t})^{-1}$; the matrix $N_{t\times t}$ is called the *fundamental matrix* of X. $N_{t\times t}$ allows us to compute some performance metrics of particular importance, namely the probability of absorption and the mean time to service.

For convenience and assuming that the *good* absorbing states (i.e. $i \in \mathcal{G}$) precede the *bad* absorbing states (i.e. $i \in \mathcal{B}$) in P, the following numeric representation will be used for each state $i \in \Omega$:

- $i = 1, \ldots, t$ for $i \in \mathcal{M}$;

- $i = (t+1), \ldots, (t +$ Card$\{\mathcal{G}\})$ for $i \in \mathcal{G}$;

- $i = (t +$ Card$\{\mathcal{G}\} + 1), \ldots, (t + r)$ for $i \in \mathcal{B}$.

The structure of the fundamental matrix $N_{t\times t}$ is examined next.

3.4.1 The Fundamental Matrix

The $(i,j)^{th}$ entry of $Q_{t\times t}$ given in Eqn. (6) provides the probability of being in transient state j one time slot after leaving the transient state i. Similarly, the $(i,j)^{th}$ entry of $Q^s_{t\times t}$, denoted by $p^{(s)}_{ij}$, indicates the probability that X moves from transient state i to transient state j in s time slots. In an absorbing Markov chain, the probability of being absorbed is eventually equal to 1. Thus, it can be easily shown that $Q^s_{t\times t} \rightarrow 0_{t\times t}$ as $s \rightarrow \infty$.
Note that

$$(I_{t\times t} - Q_{t\times t})(I_{t\times t} + Q_{t\times t} + Q^2_{t\times t} + \cdots + Q^s_{t\times t}) = I_{t\times t} - Q^{s+1}_{t\times t}$$

Multiplying both sides by the fundamental matrix $N_{t\times t}$ results in:

$$(I_{t\times t} + Q_{t\times t} + Q^2_{t\times t} + \cdots + Q^s_{t\times t}) = N_{t\times t}(I_{t\times t} - Q^{s+1}_{t\times t})$$

Letting s tend to infinity:

$$N_{t\times t} = I_{t\times t} + Q_{t\times t} + Q^2_{t\times t} + \ldots \tag{7}$$

Let n_{ij} be the $(i,j)^{th}$ entry of the matrix $N_{t\times t}$. Given that $Q^0_{t\times t} = I_{t\times t}$, Eqn. (7) implies that n_{ij} can be written as

$$n_{ij} = p^{(0)}_{ij} + p^{(1)}_{ij} + p^{(2)}_{ij} + \ldots \tag{8}$$

3.4.2 The Probability of Absorption

In this case, the probability of the event $G(i)$ (respectively $B(i)$), that the Markov chain, starting at state $X_0 = i$, reaches $\mathcal{G}$(respectively $\mathcal{B}$) is calculated. $G(i)$ and $B(i)$ are given by:

$$G(i) = \{\exists s \geq 0, \exists j \in \mathcal{G}, X_s = j | X_0 = i\}$$

$$B(i) = \{\exists s \geq 0, \exists j \in \mathcal{B}, X_s = j | X_0 = i\}$$

Let $g(i) = Pr\{G(i)\}$ and $b(i) = Pr\{B(i)\}$. It is important to point out that: (a) for $i \in \mathcal{G}$, $g(i) = 1$ and $b(i) = 0$; (b) for $i \in \mathcal{B}$, $g(i) = 0$ and $b(i) = 1$. Hence, only $g(i)$ and $b(i)$ for $i \in \mathcal{M}$ need to be calculated.

First, $g(i), i \in \mathcal{M}$ is examined. The probability of going from $i \in \mathcal{M}$ to $j \in \mathcal{G}$ in s steps ($s \geq 1$) p^s_{ij} can be computed using the Chapman-Kolmogorov equation as follows.

$$p^{(s)}_{ij} = \sum_{l\in\mathcal{M}} p^{(s-1)}_{il} \times p_{lj} \tag{9}$$

From the definition of $G(i)$,

$$Pr\{G(i)\} = \sum_{j\in\mathcal{G}} \sum_{s=1}^{\infty} p^{(s)}_{ij}$$

Using Eqns. (8) and (9),

$$\begin{aligned} Pr\{G(i)\} &= \sum_{j\in\mathcal{G}} \sum_{l\in\mathcal{M}} \sum_{s=1}^{\infty} p^{(s-1)}_{il} \times p_{lj} \\ &= \sum_{j\in\mathcal{G}} \sum_{l\in\mathcal{M}} n_{il} \times p_{lj} \end{aligned}$$

Thus, $g(i), i \in \mathcal{M}$, is given by

$$g(i) = Pr\{G(i)\} = \sum_{j=t+1}^{t+\text{Card}\{\mathcal{G}\}} \sum_{l=1}^{t} n_{il} \times p_{lj}, \quad i \in \mathcal{M} \tag{10}$$

Similarly, it can be easily shown that $b(i), i \in \mathcal{M}$, may be expressed as follows.

$$b(i) = Pr\{B(i)\} = \sum_{j \in \mathcal{B}} \sum_{l \in \mathcal{M}} n_{il} \times p_{lj}, \quad i \in \mathcal{M} \tag{11}$$

3.4.3 The Mean Time to Service

As indicated previously, the mean time to absorption is the average amount of time until X is absorbed into one of the absorbing subsets (i.e. $\mathcal{G}$ or $\mathcal{B}$). However, in the case of the proposed setup mechanism, the performance measure of interest is the mean time that the target customer $\mathcal{C}$ spends in the EDF queue before receiving its service. In other words, the interest lies in determining the mean time to service $MTTS(i)$ which is the expected number of steps (i.e. time slots) that X, starting from transient state i, makes before being absorbed into the specific absorbing subset $\mathcal{G}$. $MTTS(i), i \in \mathcal{M}$ can be obtained as follows.

Let $V_{s,i,j} = 1$ if prior to absorption into $\mathcal{G}$, X visits transient state $X_s = j$ at time slot s starting from transient state $X_0 = i$; otherwise, let $V_{s,i,j} = 0$. Then, $\sum_{s=0}^{\infty} V_{s,i,j}$ is the expected number of times X, starting in transient state i, is in transient state j prior to absorption at $\mathcal{G}$. Let G be defined as the event that X gets absorbed into the absorbing subset $\mathcal{G}$. Given that X begins in the transient state i (i.e. $X_0 = i$), the expected number of times X is in the transient state j before getting absorbed into $\mathcal{G}$ is

$$\begin{aligned} E\left[\sum_{s=0}^{\infty} V_{s,i,j}\right] &= \sum_{s=0}^{\infty} E\left[V_{s,i,j}\right] \\ &= \sum_{s=0}^{\infty} Pr\{X_s = j, G | X_0 = i\} \end{aligned}$$

By summing over all possible states $j \in \mathcal{M}$, $MTTS(i)$ is obtained - the expected number of steps until X is absorbed into $\mathcal{G}$ starting from the transient state i. Hence, $MTTS(i), i \in \mathcal{M}$, can be written as

$$\begin{aligned} MTTS(i) &= \sum_{j \in \mathcal{M}} E\left[\sum_{s=0}^{\infty} V_{s,i,j}\right] \\ &= \sum_{j \in \mathcal{M}} \sum_{s=0}^{\infty} Pr\{X_s = j, G | X_0 = i\} \end{aligned}$$

Using Bayes' theorem:

$$\begin{aligned} MTTS(i) &= \sum_{j\in\mathcal{M}}\sum_{s=0}^{\infty} Pr\{X_s = j|X_0 = i\} \times Pr\{G|X_s = j, X_0 = i\} \\ &= \sum_{j\in\mathcal{M}}\sum_{s=0}^{\infty} Pr\{X_s = j|X_0 = i\} \times Pr\{G(j)\} \\ &= \sum_{j\in\mathcal{M}}\sum_{s=0}^{\infty} p_{ij}^s \times g(j) \end{aligned}$$

It follows from Eqn. (8) that $MTTS(i), i \in \mathcal{M}$, becomes

$$MTTS(i) = \sum_{j\in\mathcal{M}} n_{ij} \times g(j) = \sum_{j=1}^{t} n_{ij} \times g(j), \quad i \in \mathcal{M} \tag{12}$$

Based on the analysis presented thus far, the following proposition is proposed.

Proposition 1. *Consider a homogeneous transient Markov chain with state space Ω partitioned into an absorbing subset $\mathcal{A}$ and its complement the non-absorbing (transient) subset $\mathcal{M}$. The subset $\mathcal{A}$ is further divided into $\mathcal{G}$ and $\mathcal{B}$. Designate by $X_0 = i \in \mathcal{M}$ the initial state of X. Probabilities $g(i)$ (respectively $b(i)$), the probability of absorption into $\mathcal{G}$ (respectively $\mathcal{B}$) starting from $X_0 = i \in \mathcal{M}$, can be obtained by means of Eqn. (10) (respectively Eqn. (11)). In addition, $MTTS(i)$, the mean time to service starting from $X_0 = i \in \mathcal{M}$, can be obtained from Eqn. (12).*

4 Performance Metric Evaluation

4.1 Definition

Proposition 1 is now applied to the proposed EDF-based connection setup mechanism. In what follows, there is a distinction between metrics related to the probability of absorption (POA) and metrics related to the mean time to service (MTTS). It is important to note that each one of these metrics is a function of the initial position N and the initial laxity L of the target customer $\mathcal{C}$.
Consider the following POA-related metrics:

- Conformed setup completion probability, denoted by $P_{cs}(N, L)$. This is the probability that $\mathcal{C}$ goes into service with a laxity $m > 0$;
- Late setup completion probability, denoted by $P_{ls}(N, L)$. This is the probability that $\mathcal{C}$ goes into service with a laxity $m = 0$, that is, the deadline mismatch probability;
- Setup rejection probability, denoted by $P_{sr}(N, L)$. This represents the probability that $\mathcal{C}$ is dropped out of the queue with a laxity $m > 0$;
- Reasonable rejection probability, denoted by $P_{rr}(N, L)$. This represents the probability that $\mathcal{C}$ is dropped out of the queue with a laxity $m = 0$;

In order to obtain the POA-related metrics, $g(i(N, L))$ and $b(i(N, L))$ are calculated using Eqns. (10) and (11) under the following definitions for $\mathcal{G}$ and $\mathcal{B}$.

- For $P_{cs}(N, L)$, $\mathcal{G} = \{j(0, m), m = 1, \ldots, \Lambda\}$.

- For $P_{ls}(N, L)$, $\mathcal{G} = \{j(0, 0)\}$.
- For $P_{sr}(N, L)$, $\mathcal{B} = \{j(K, m), m = 1, \ldots, \Lambda\}$.
- For $P_{rr}(N, L)$, $\mathcal{B} = \{j(K, 0)\}$.

In addition, the setup probability is designated by $P_s(N, L) = P_{cs}(N, L) + P_{ls}(N, L)$, and the rejection probability by $P_r(N, L) = P_{sr}(N, L) + P_{rr}(N, L)$.

On the other hand, a single MTTS-related performance metric is considered that is denoted by $T_s(N, L)$. This is the average time that the target customer $\mathcal{C}$, starting from an initial position N with an initial laxity L, spends in the EDF queue before it ends up receiving its service with a laxity $m \geq 0$. $T_s(N, L)$ can be obtained by computing $MTTS(i(N, L))$ using Eqn. (12) for the case where $\mathcal{G} = \{j(0, m), m = 0, \ldots, \Lambda\}$.

4.2 Sample Results

To study the performance of the proposed setup scheme, various scenarios involving different values of the blocking probability p and of the number of servers W were tested. For each scenario, the above-presented metrics were calculated based on both the initial position N and the initial laxity L (i.e. deadline) of the target customer $\mathcal{C}$. Following the guidelines presented in [6, 7], L is supposed to be dependent on the class of service chosen by $\mathcal{C}$. In this context, a more stringent deadline requirement (i.e. a smaller L) will lead to a higher class of service for $\mathcal{C}$.

Even though the proposed computational framework can be applied to any number of quality of service (QoS) classes, this paper considers three QoS classes, namely, Gold, Silver, and Bronze. The optical network operator should be able to determine the value of the deadline associated with each QoS class according to the specific business model that it implements. Nonetheless, there is a set of guidelines that is drawn from the different examined scenarios which the operator needs to follow when choosing the deadlines. The operator should not assign relatively small deadlines to its clients as this may result in a very high deadline mismatch probability. In addition, the operator cannot go with very large deadlines as this would degrade the quality of service perceived by its clients. In light of this, the operator should try to find the right balance between acceptable deadline values and reasonable deadline mismatch probabilities.

To gain insight into the proposed scheme, its performance is analyzed under the following assumptions.

- The blocking probability and the number of severs are $p = 0.3$ and $W = 8$ respectively;
- The EDF queue has $K - 1 = 20$ waiting places and is therefore able to hold up to 20 blocked connection requests;
- The parameters for the three classes of customers are as follows:
  - Gold customers are associated with an initial laxity of 6 time slots and an arrival rate of 0.3 customers/slot;
  - Silver customers arrive at the rate of 0.7 customers/slot with an initial laxity of 10 time slots;
  - Bronze customers arrive with an initial laxity of 14. The arrival rate of the Bronze customers has no impact on the metrics we want to compute and thus is not specified.

The various probability of absorption related metrics are computed for a Bronze customer as a function of its position N. A sample set of results is given in Table 1. These results show the rejection probability P_r achieved by the proposed setup scheme. Although the considered scenario has relatively high blocking probability p, the Bronze clients experience a fairly low rejection probability P_r.

N	P_{cs}	P_{ls}	P_s	P_{sr}	P_{rr}	P_r
2	0.965	0.035	1.000	0.000	0	0.000
5	0.930	0.070	1.000	0.000	0	0.000
8	0.872	0.128	1.000	0.000	0	0.000
10	0.814	0.186	1.000	0.000	0	0.000
12	0.742	0.257	0.999	0.001	0	0.001
14	0.660	0.334	0.994	0.006	0	0.006
16	0.560	0.410	0.970	0.030	0	0.030

Table 1: POA-related metrics for Bronze customers ($p = 0.3$, $W = 8$); N gives the initial position

As indicated in section 3.2 a customer whose deadline reaches 0 is guaranteed to receive its service due to a work-conserving EDF queue. The numerical results given in Table 1 confirm this theoretical deduction as P_{rr} was found to be always equal to zero.

The initial laxity of 14 that was assigned to Bronze customers explains the gradual increase of P_{ls}, the late setup probability (i.e. deadline mismatch probability), as the value of the initial position N increases to 14.

Figs. 4 and 5 show respectively the setup probability P_s and the mean time to service T_s (measured in units of time slots) experienced by the 3 classes of customers for different values of the initial position N. The results highlight the service differentiation feature introduced by the setup scheme under study. Note that in Fig. 4 the curves corresponding to Gold and Silver customers overlap.

The Gold customers that are waiting in the EDF queue are guaranteed to receive their respective services since they cannot be pushed out of the queue by the lower class customers (i.e. Silver and Bronze customers). This fact is asserted by the results presented in Fig. 4 as the setup probability P_s for Gold customers is found to be equal to 1. The Bronze customers, on the other hand, will have Gold and Silver customers inserted in front of them and hence they experience the lowest setup probability and the longest mean time to service as shown in Figs. 4 and 5.

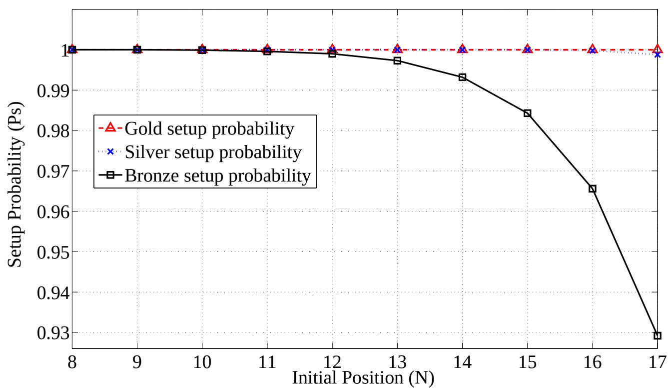

Figure 4: Setup probability (P_s) per class of service for $p = 0.3$ and $W = 8$.

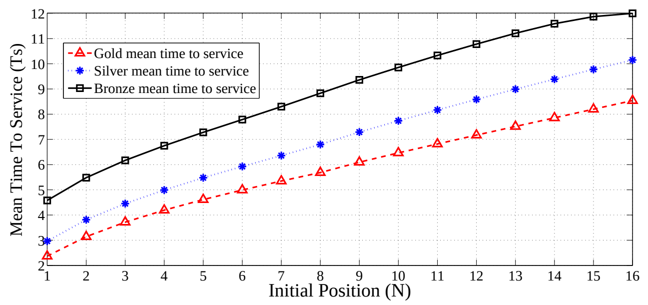

Figure 5: Time to service (T_s) per class of service for $p = 0.3$ and $W = 8$.

Thus far, the case where $p = 0.3$ and $W = 8$ was considered. In what follows, the impact of the variation of these values on the QoS perceived by the various classes of customers will be studied. An emphasis will be placed in this respect on the performance gains that are made possible by the proposed setup scheme.

Figs. 6 and 7 show the deadline mismatch probability associated with the Gold and the Silver customers, respectively, for different values of the blocking probability p. The results demonstrate that the EDF-based setup scheme has the advantage of increasing the probability of provisioning the connection requests on-time even under severe blocking conditions. In other words, the deadline mismatch probabilities p_{ls} that were obtained for different initial positions N of the Gold and the Silver customers are relatively low compared to the blocking probability p imposed by the optical network. Since the Gold customers are most likely to be found towards the front of the EDF queue, Fig. 6 presents the results associated with these customers for small values of N. Silver customers, on the other hand, are expected to occupy the middle of the queue, hence the choice of N in Fig. 7.

Next, the impact that the number of servers W may have on the performance of the proposed setup scheme, is considered. In this regard, Figs. 8 and 9 show the conformed setup probability P_{cs} and the mean time to service T_s corresponding to the Bronze customers for different values of W. Different set of results are presented in order to account for different initial position of the Bronze customers. The choice of N is justified by the fact that the Bronze customers are very likely to be found towards the end of the queue.

The results presented in Fig. 8 demonstrate that the probability P_{cs} of provi-

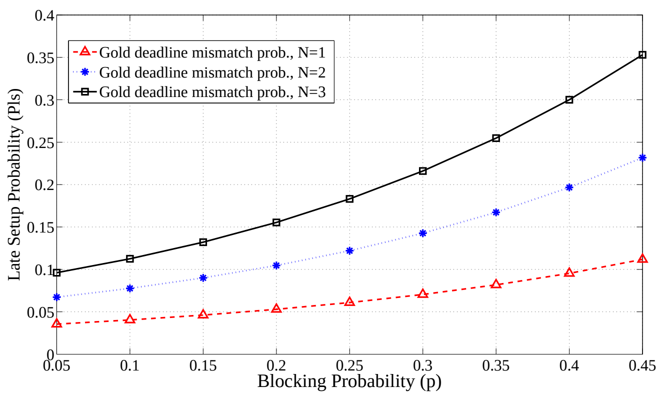

Figure 6: Gold late setup probability (P_{ls}) for $W = 8$ and $N = 1, 2, 3$.

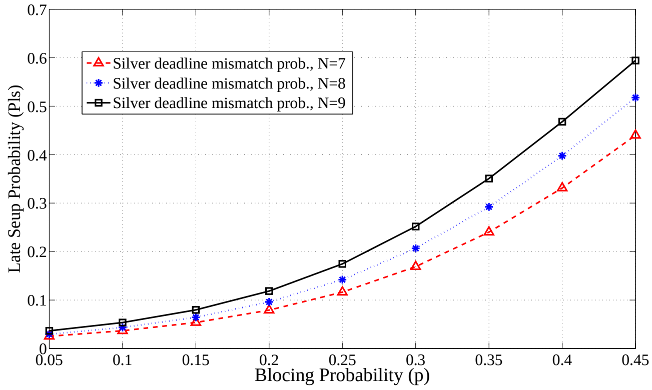

Figure 7: Silver late setup probability (P_{ls}) for $W = 8$ and $N = 7, 8, 9$.

sioning a Bronze customer on-time increases drastically as the number of available servers increases. However, when the number of servers W exceeds the value of the initial position of the Bronze customer N, only a slight increase in terms of P_{cs} is observed. This follows from the fact that the extra $W - N$ servers are used to serve the customers queued behind the Bronze customer occupying the Nth position, and hence will have a minor effect on this Bronze customer.

The results shown in Fig. 9 show that the mean time to service T_s experienced by a Bronze customer decreases as the number of servers W increases before it levels off when W goes past the initial position of the customer N.

5 Simulation Study and Numerical Results

To gain further insight into the proposed EDF-based setup approach, an in-house Java-based discrete event simulator was implemented to analyze the technique's performance in the context of the NSFNET topology shown in Fig. 10. The topology contains 24 nodes and 43 bidirectional fiber links. The aim of the simulation is twofold: first, to quantify the performance of the EDF-based setup strategy in the context of a real life optical network topology; and second, to get away from some of the rigid assumptions made in the analytical study. In particular, the connection holding time is assumed to be exponentially distributed, and the arrival process to

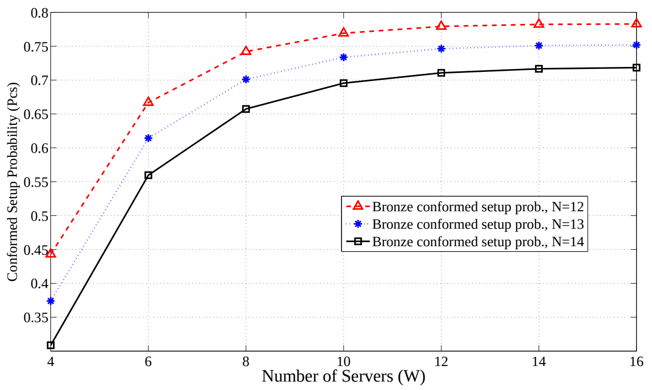

Figure 8: Bronze conformed setup probability (P_{cs}) for $p = 0.3$ and $N = 12, 13, 14$.

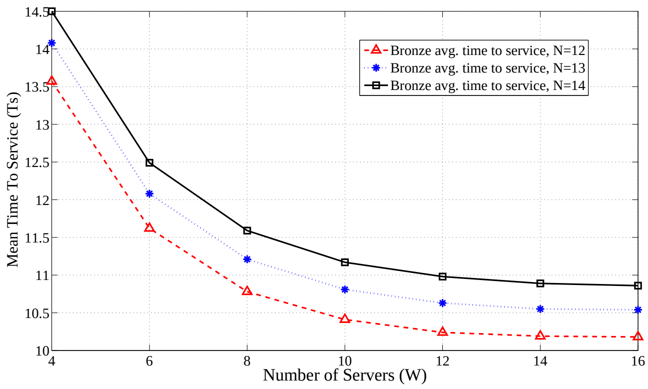

Figure 9: Bronze mean time to service (T_s) for $p = 0.3$ and $N = 12, 13, 14$.

each EDF queue is Poisson. In addition, unlike the mathematical study, the simulation assumes that a non work-conserving EDF queue is associated with each of the 24 nodes and, consequently, dead customers (i.e. whose deadlines reach 0) are dropped. Furthermore, the simulation framework is designed around the following assumptions:

- Each node has a full wavelength conversion capability;
- Each fiber link can support up to 16 wavelengths in each direction;
- Connection requests are uniformly arranged into 3 priority levels, namely gold, silver, and bronze, which collectively arrive at the network according to a Poisson arrival process with a fixed arrival rate of 24 customers per unit of time;
- 6, 10, and 14 units of time are the deadline requirements of the gold, silver, and bronze customers respectively;
- Incoming connection requests are uniformly distributed among the 24 nodes of the NSFNET network topology and require a full wavelength of bandwidth;
- Dijkstra's shortest path algorithm is used to route the arriving connections, while wavelengths are assigned to the routed connections according to a first-fit strategy;
- One EDF queue is used per node to store blocked connection requests. The capacity of each EDF queue is set to 150.
- Connections admitted to the network have an exponentially distributed holding time with a mean $\frac{1}{\mu}$.

The performance measures used to evaluate the benefit of the proposed scheme are different from those used in the mathematical study. Specifically, the two performance measures that are calculated by simulation are the blocking probability denoted by P_b and the deadline mismatch probability denoted by P_m. P_b is the fraction of customers that are blocked due to buffer overflow, while P_m is the fraction of customers that are denied access to the network due to a deadline mismatch. 10^6 connection requests are simulated per run of the simulator. Each obtained value

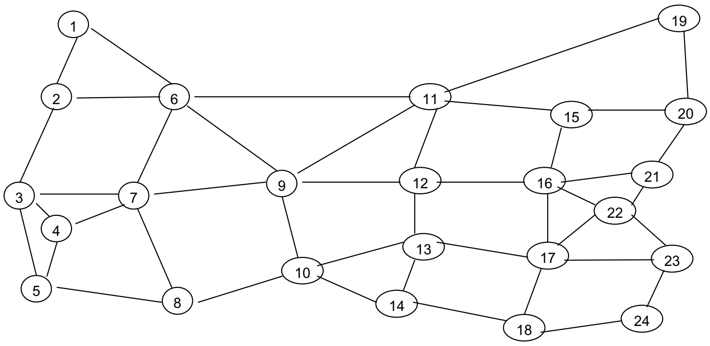

Figure 10: Network topology used in simulation.

of P_b as well as of P_m is the result of multiple simulation runs to make sure that a very narrow 95% confidence interval is achieved.

Fig. 11 contrasts the blocking probabilities obtained in the case of an NSFNET topology using EDF-based connection setup with those resulting from a topology where no queues are deployed as a function of μ. It is important to note that P_b in the latter case represents the ratio between the number of blocked connection requests and the total number of received requests. It is clear from the results reported in Fig 11 that as μ increases, the blocking probability experienced by arriving connection requests decreases. However, P_b depends strongly on whether or not EDF queues are used in the network. This is especially true since an EDF-based connection setup strategy results in lower blocking probabilities as compared to a traditional setup strategy that does not implement queues. It follows from this observation that the deployment of a deadline-based connection setup scheme allows optical operators to accomodate more customers in the network relative to a classical approach.

The mismatch probabilities resulting from the deployment of the EDF-based strategy are given in Fig. 12 for different values of the service rate μ. Based on the reported results, small mismatch probabilities are observed for values of μ

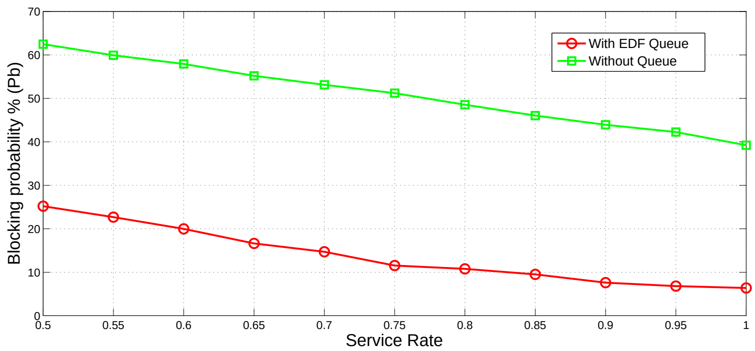

Figure 11: Percentage of blocking probability (P_b) vs. service rate (μ).

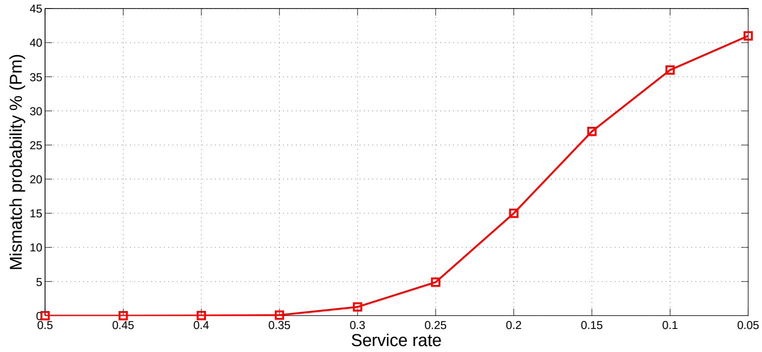

Figure 12: Percentage of deadline mismatch probability (P_m) vs. service rate (μ).

greater than 0.35 . However, when μ drops below 0.35, the number of customers that suffer from a violation of their deadline requirements starts to increase. One interpretation for such a finding is that as the holding time of connection requests gets larger, the time that a pending connection request spends in an EDF queue increases, and thus a larger number of pending connection requests are dropped due to deadline mismatch. This confirms that the proposed strategy is well-suited for a network environment where connections are dynamic and have short holding times.

Fig. 13 compares the performance of the EDF-based setup scheme to that of a strategy that uses FIFO (First In First Out) queues to schedule the setup of blocked connection requests as a function of μ. The performance measure used in the comparison is the deadline mismatch probability of gold connections, which represents the fraction of gold connections with violated deadline requirements. The following observation can be made based on the results presented in Fig. 13. An EDF-based strategy enables operators to serve a larger number of gold clients prior to deadline expiration than a FIFO-based connection setup scheme. This holds even for small values of the service rate μ.

Although the simulation results and the analytic ones stem from two different frameworks, an attempt is made in what follows to capture the correlation existing

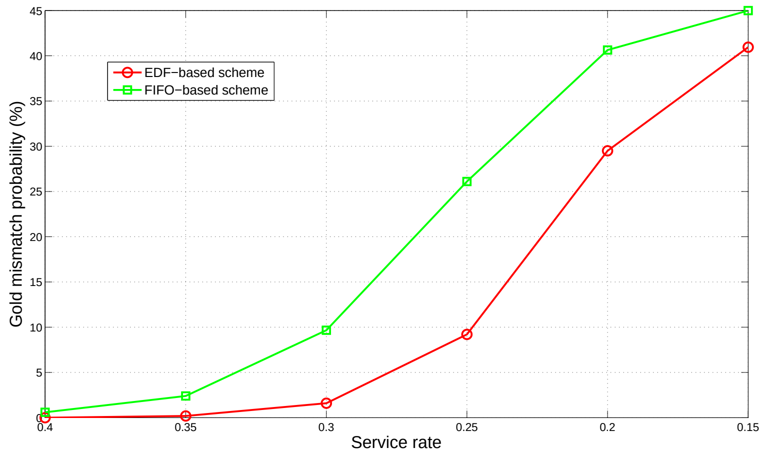

Figure 13: Gold deadline mismatch probability for EDF-based and FIFO-based setup schemes.

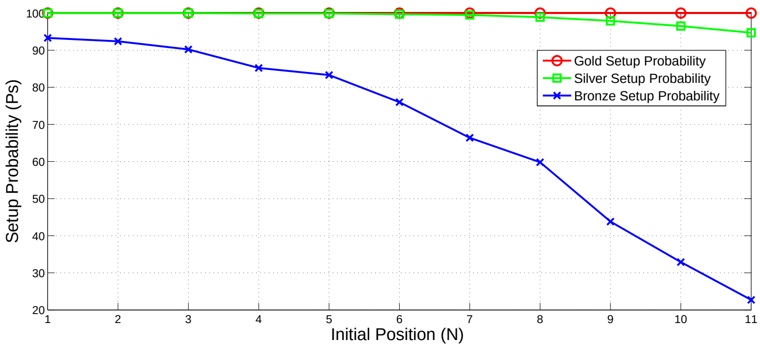

Figure 14: Setup probability (P_s) per class of service.

between them. This is accomplished by modifying the parameters of the simulator to make sure that the simulation study is somewhat conducted under the same conditions as in the mathematical one. In particular, EDF queues with 20 waiting places and constant holding times are considered. In addition, The arrival rates of the gold and silver connections are set to 0.3 and 0.7 respectively.

Under these conditions, the simulator is used to compute the setup probability (P_s) of a pending connection request, which is one of the metrics investigated in the mathematical study. The results produced by the simulator in this context are given in Fig. 14 as a function of the initial position of the pending client in the EDF queue (N). The following facts can be established based on these results:

- The customers occupying the front of the queue are more likely to access the network than those found at the rear end of the queue;
- Pending gold clients are guaranteed to gain access into the network;
- The probability that a silver client gets setup is slightly influenced by the gold clients that might be inserted in front of it;
- The setup probability of a bronze client is greatly dependent on the position at which it is initially inserted in the EDF queue. Specifically, bronze customers occupying lower order initial positions have higher chances of being accepted than those occupying higher order initial positions;

These observations demonstrate the following. Even though the simulation study and the mathematical framework were designed around different sets of assumptions, the conclusions drawn from both are perfectly aligned with each other.

6 Concluding Remarks and Future Work

This paper introduced a novel approach for connection setup in wavelength routed optical WDM networks. The proposed setup mechanism is based on the concept of treating the setup time of an incoming connection request as a priority indicator during connection provisioning. In view of this, the EDF queueing policy was adapted to the particular case of connection setup scheduling, by giving the highest priority to those connections with the shortest setup time requirement.

Furthermore, a computational method was presented for the estimation of several performance metrics, such as the probability of setting up a connection, the deadline mismatch probability, and the mean time to service. Since the initial position of the customer was assumed to be known, the evolution of a customer in the EDF queue was modeled using a Markov Chain with absorbing states, and the desired performance metrics were derived.

Finally, the performance of the proposed setup strategy was further analyzed using a simulation model with a view to obtaining an estimate of its impact on the blocking and mismatch probabilities of the incoming connection setup requests. The numerical results obtained from this simulation study highlighted some of the important features achieved by the proposed connection setup approach.

Possible directions for future work may include investigating Head of Line (HoL) blocking that may arise in EDF-based connection setup management when the optical connections have long holding times.

References

[1] A. Szymanski and al. Grade-of-Service-based routing in optical networks. In *IEEE Communications Magazine*, pages 82–87, Feb. 2007.

[2] R. Ramaswami. Optical fiber communication: from transmission to networking. In *IEEE Communications Magazine*, pages 138–147 vol.40, May 2002.

[3] A. Szymanski and al. Performance evaluation of the Grade-of-Service routing strategies for optical networks. In *Proc. of IEEE ICC'08*, pages 5252–5257, May 2008.

[4] C. Pinart and al. Challenges and requirements for introducing impairement awareness into the management and control planes of ASON/GMPLS WDM networks. In *IEEE Communications Magazine*, pages 76–85 vol.44, Dec. 2006.

[5] A. Jukan and G. Franzl. Path selection methods with multiple constraints in service-guaranteed WDM networks. In *IEEE/ACM Transactions on Networking*, pages 59–72 vol.12, Feb. 2004.

[6] C. Pinart and G.J. Giralt. On managing optical services in future control-plane-enabled IP/WDM networks. In *IEEE Journal of Lightwave Technology*, pages 2868–2876, Oct. 2005.

[7] W. Fawaz and al. Service Level Agreement and provisioning in optical networks. In *IEEE Communications Magazine*, pages 36–43, January 2004.

[8] W. Fawaz and K. Chen. A Shortest Setup Time First optical connection setup management approach with quantifiable success rate. In *Proc. of IEEE Globecom'06*, pages 1–5, Nov. 2006.

[9] W. Fawaz, K. Chen, and C. Abou-Rjeily. A novel connection setup management approach for optical WDM networks. In *IEEE Communications Letters*, pages 998–1000 vol.11, Dec. 2007.

[10] D. Andrei, M. Batayneh, C.U. Martel, and B. Mukherjee. Provisioning of Deadline-Driven Requests with flexible transmission rates in different WDM network architectures. In *Proc. of OFC/NFOEC'08*, pages 1–3, Feb. 2008.

[11] D. Andrei, M. Batayneh, C.U. Martel, and B. Mukherjee. Deadline-Driven bandwidth allocation with flexible transmission rates in WDM networks. In *Proc. of IEEE ICC'08*, pages 5354–5358, May 2008.

[12] R.W. Conway, W.L. Maxwell, and L.W. Miller. *Theory of scheduling*. Addison-Welsey, 1967.

[13] J. Peha and F. Tobagi. Evaluation scheduling algorithms for traffic with heterogenous performance objectifs. In *Proceedings of GlobeCom'90*, pages 21–27 vol.1, December 1990.

[14] S. Pingali and J. Kurose. Scheduling Two Classes of Real Time Traffic With Identical Deadlines. In *Proceedings of IEEE GlobeCom'91*, pages 460–465, December 1990.

[15] K. Ramamrithan and J. Stankovic. Scheduling Algorithms and Operating Systems Support for Real-Time Systems. In *Proceedings of IEEE*, pages 55–67, Jan. 1994.

[16] M. Andrews. Probabilistic end-to-end delay bounds for earliest deadline first scheduling. In *Proceedings of IEEE INFOCOM'00*, pages 603–612, Mar. 2000.

[17] V. Sivaraman, F. M. Chiussi, and M. Gerla. End-to-end statistical delay service under GPS and EDF scheduling: A comparison study. In *Proceedings of IEEE INFOCOM'01*, pages 1113–1122, Apr. 2001.

[18] A. Grilo, M. Macedo, and M. Nunes. A scheduling algorithm for QoS support in IEEE802.11e networks. In *IEEE Wireless Communications*, pages 36–43 vol.10, June 2003.

[19] S. Panwar, D. Towsley, and J. Wolf. Optimal Scheduling Policies for a Class of Queues wth Customer Deadlines to the Beginning of Service. In *Journal of the ACM*, pages 832–844 vol.35, Oct. 1988.

[20] J.W. Hong, X.N. Tan, and D. Towsley. A Performance Analysis of Minimum Laxity and Earliest Deadline Scheduling in a Real-Time System. In *IEEE Transanctions on Computers*, pages 1736–1744 vol.38, Dec. 1989.

[21] Ph. Nain and D. Towsley. Comparison of Hybrid Minimum Laxity/First-In-First-Out Scheduling Policies for Real-Time Multiprocessors. In *IEEE Transactions on Computers*, pages 1271–1278 vol.41, October 1992.

[22] A. Birman. Computing approximate blocking probabilities for a class of all-optical networks. In *IEEE JSAC*, pages 852–857 vol.14, June 1996.

[23] R.A. Barry and P.A. Humblet. Models of blocking probability in all-optical networks with and without wavelength changers. In *IEEE JSAC*, pages 858–867 vol.14, June 1996.

[24] A.N. Washington and H. Perros. Call blocking probabilities in a traffic-groomed tandem optical network. In *Journal of Computer Networks, Elsevier*, pages 281–294 vol.45, June 2004.

[25] M. Kijima. *Markov processes for stochastic modeling*. CRC Press, 1997.

[26] C. Grinstead and J. Snell. *Introduction to Probability*. American Mathematical Society, 1997.