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EDF-based Connection Setup Management in WDM Optical Networks

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To my family
- Marwa, Ahmad and Rawad -

Abstract

The worldwide network domain tendency to evolve towards dynamic Quality of Service (QoS) enabled wavelength division multiplexing (WDM) optical networks is imminent. WDM has drastically increased the transmission capacity of today's optical networks. An increase in the available bandwidth is promoting the introduction of new services, each having different quality of service (QoS) requirements. Improving connection setup conditions is considered to be one of the major requirements in this regard. This work addresses the interesting topic of quality of service (QoS) aware connection setup provisioning in WDM optical networks. The impact that the connection setup time of an optical connection may have on the setup of a connection has not been adequately addressed in the open literature. As such, this work presents a novel connection setup mechanism that uses the optical connection setup time as a service differentiator during connection provisioning. The proposed connection setup mechanism utilizes the well known Earliest Deadline First (EDF) queuing discipline to achieve deadline-based connection setup management with the deadline being the setup time requirement of an optical connection. The proposed EDF-based setup scheme has been proved to be optimal and it is expected to allow the network operator to improve the QoS perceived by their end customers. Performance of this novel scheme is analyzed by precisely calculating various measures, such as the fraction of connections provisioned prior to deadline expiration, and the average time it takes to successfully setup a connection. Our numerical results whose correctness was asserted through extensive simulations highlighted the service differentiation feature achieved by the EDF-based connection setup management approach.

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List of Abbreviations

WDM: Wavelength Division Multiplexing

QoS: Quality of Service

QoT: Quality of Transport

EDF: Earliest Deadline First

OXC: Optical Cross Connect

RWA: Routing and Wavelength Assignment

SLA: Service Level Agreement

WL: Wavelength

WR: Wavelength Router

MTTS: Mean Time to Service

POA: Probability of Absorption

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Chapter 1

Background Information

1.1 Introduction

In an environment of fast changing technologies and uncertain business tendencies, network operators, constructors and organizations face new challenges to keep up with the increasingly bandwidth needs of our world. This is a major driver for the technological development of Wavelength Division Multiplexing (WDM) enabled optical networks. Wavelength Division Multiplexing (WDM) is presenting itself as the de facto technology for driving up the transmission capacity of optical networks by multiplexing many non-overlapping wavelength channels (WDM channels) onto the same optical fiber. Each of the WDM channels can be operated at the peak electronic speed of several gigabits per second. Therefore, the capacity of a single fiber link increased to several orders of gigabits/second (Gb/s). Hence, fibers and WDM are providing carriers with a significantly increased transmission capacity for today's optical transport networks. At the same time, they are playing important roles in supporting the explosive growth in terms of data traffic.

In fact, the continuous advent of new applications, each having different Quality of Service (QoS) requirements, coupled with the need to carry these applications over optical networks is proving to be the next big challenge for future WDM optical networks. In other words, preparing the huge amount of bandwidth provided by WDM-based fibers to meet the rapidly growing Internet traffic will require that WDM optical networks be optimized for QoS

enforcement. A key feature is the capability to offer differentiated services in a single network in order to accommodate for the different requirements of the various clients. This is especially true since existing optical networks still need to evolve from single service networks to multi-service ones [2], in which different types of services with different QoS requirements can be supported.

In summary, the main trend is leaning towards transitioning from a “dumb” optical network with static point-to-point connections to a new era of dynamic wavelength-routed WDM optical networks [3].

1.2 WDM networks

In a WDM optical network, transmission of data is achieved by sending the data into optical circuits referred to as lightpaths. Specifically, a device called optical cross-connect (OXC) switches a WDM channel from an input port to an output port; thus a connection (lightpath) can be established from a source node to a destination node [4]. The established lightpath may span multiple fiber links. Figure 1 shows a sample wavelength routed network with a lightpath on wavelength λ_1 connecting nodes A and B [1].

Figure 1 A lightpath between routers A and B

Prior to lightpath establishment, a Routing and Wavelength Assignment (RWA) algorithm is used to select a path of physical links between the source and destination nodes and to reserve a particular wavelength on every link for the lightpath [5]. It is important to note in this respect that different lightpaths traversing the same fiber are assigned different wavelengths.

1.3 Quality of Service in optical networks

As already mentioned, the perpetual growth in terms of data traffic has been the main motive for the gradual improvement of carrier's optical networks. However, parallel to this increase in traffic capacity, there is increasingly a strong need for quality of service differentiation due to the introduction of new services, each presenting different QoS requirements. Hence, a great deal of effort has been made to provide predictable quality of transport (QoT) services in the context of optical networks. In this regard, numerous research studies (cf [6, 7, and 8]) have envisaged equipping these wavelength-routed optical networks with a multi-service capability by enabling them to provide predictable quality of transport services. Quality of transport is measured by the set of the parameters that affect the data flow after the lightpath is established [7, 10].

However, most of these previous studies left out of their analysis a crucial parameter relating to the setup of a connection, namely the *connection setup time*. In view of this, we turn our attention in this work to the connection setup time parameter that is likely to become a common feature of a customer's service profile. The author's in [9, 10] presented the connection setup time as a potential service differentiator in Service Level Agreements (SLA) between optical operators and their customers. The agreed upon connection setup time is the amount of time separating the instant a lightpath setup request is received by the operator and the moment the requested lightpath is established. This work aims at studying the impact that the connection setup time as a service differentiator may have on the setup of an optical connection.

1.4 Motivation

This work is motivated by the need to consider the optical connection setup time as a timely increasing priority indicator (a kind of competition-oriented parameter which may be linked to pricing) during the setup process. As such, the connection setup time can be viewed as a *deadline*. Building on this observation, 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 lack of optical resources, we propose to store the

blocked connection request at A in an Earliest Deadline First (EDF) queue. In other words, instead of dropping those connection requests that cannot be satisfied by the optical network, we envisage having those requests queued at the entry point of the network in an order consistent with their respective priorities (deadlines).

1.5 Contributions

Our proposal is therefore an adaptation of the well-known EDF scheduling discipline to the special case of optical connection setup management. This proposal consists mainly with inserting the blocked connection setup requests into a queue and then serving them according to an EDF discipline, whereby the connection request with the smallest connection setup time (i.e., deadline) requirement is served first. The proposed approach has the advantage of enforcing quality of service differentiation among customers having different connection setup requirements. This service differentiation feature is made possible by giving a higher priority to customers with short setup time requirement.

The contributions of this work are twofold. First, we propose the application of an EDF-based connection setup mechanism to wavelength routed networks. Second, we present a novel mathematical study to evaluate numerically the benefits of the service differentiation feature introduced by the proposed setup mechanism. We propose in this respect a computational method for the estimation of some major performance metrics of EDF queues, such as the probability of being served prior to deadline expiration and the average delay before being served. The next section underlines the novelty of these contributions.

1.6 Related work

The authors in [11, 12] investigated the problem of dynamic bandwidth allocation for Deadline-Driven Requests (DDRs). They proposed in this regard algorithms for choosing the best transmission rate to serve DDRs. The difference between our work and theirs stems from the fact that they define the deadline to be the maximum connection holding time.

Our proposal may be applied to schedule the provisioning of the blocked DDRs, and thus improve the fraction of un-provisioned requests achieved by their proposed algorithms. As for the performance evaluation of the proposed setup schemes, it is important to note the following. The deadline-based connection setup mechanism revolves around the EDF queuing discipline so it benefits from and it inherits the properties of EDF. The Earliest Deadline First (EDF) queuing discipline was first proposed by Jackson in 1955 [13]. The application of EDF to computer networking has been extensively studied (cf [14, 15, 16] for some of the early papers, and [17, 18, 19] for more recent papers).

As a distinguishing feature from other queuing disciplines, EDF minimizes the deadline missing probability. Many papers have been published, such as [20, 21, 22], for characterizing the EDF queue and assessing its main performance metrics. Yet, the general characterization of the EDF (queue length distribution, and stability condition) is still an open research problem. In particular, to the best of our knowledge, 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. In this work, we develop a computational method to address the previously mentioned issue and evaluate among other things the fraction of provisioned connections, and the deadline mismatch ratio under the proposed setup approach.

1.7 Thesis Outline

The rest of this manuscript is organized as follows.

In chapter 2, we analyze the deployment of the EDF-based connection setup approach in the special context of point to point connection establishment between two isolated optical nodes. We first handle the simplified case where one wavelength exists between the two stand-alone optical nodes. Then, we consider the case of multiple wavelengths between the two isolated optical nodes.

The studies presented in chapter 2 lack generality since they don't deal with wavelength-routed optical networks. Therefore, we take in chapter 3 one step further by considering the case where the optical nodes are not isolated but instead belong to a wavelength routed WDM optical network. Finally, we draw our conclusions and envisage future work in chapter 4.

Chapter 2

Point-to-point Connection Setup Management

2.1. Introduction

As we already pointed out in the previous chapter, the connection setup time represents a great opportunity for optical operators to reduce *connection blocking probability*. This is especially true since the connection setup time provides optical operators with a predefined period of time during which the blocked lightpath request tolerates being queued. This tolerance may be *firm* (i.e., the mismatch leads to connection drop) or *soft* (i.e., the request is maintained even if the tolerated period expires). This chapter thus defines a new connection setup management approach that takes advantage of the connection setup time when dealing with blocked connection requests. But, it is worth mentioning that the study conducted in this chapter is limited to the case of point-to-point connection establishment between two optical nodes A and B.

To gain insight into the merit of the proposed scheme, we will step through a series of increasingly complex models of the underlying point-to-point optical network. We first analyze the performance of the EDF-based connection setup scheme in the simplified context of a point-to-point optical network consisting of a single wavelength fiber interconnecting two isolated

optical nodes. Subsequently, we extend this performance analysis to the case of two wavelength routers interconnected by a multi-wavelength fiber link.

2.2. Single wavelength point-to-point optical network

2.2.1. Scenario description

In this section, we study the performance of the propose setup scheme in the context of the specific scenario presented in Figure 2.

Figure 2 A sample senario

In Figure 2, the wavelength router (WR) A is connected to the (WR) B through a fiber link which we assume holding one wavelength. So, when a connection t is established between A and B, future connection requests between A and B will be blocked as long as t occupies the sole wavelength on link A-B. Note that connections with stringent setup times are queued in front of those with longer setup times. A queuing representation of this scenario is depicted in Figure 3.

Figure 3 A queuing representation of the scenario implemented

The service here is the offer of an optical connection or simply the occupation of a λ during the connection. For sake of simplicity, we first suppose that the connection service process is of constant duration where connection occupies a predefined time slot. In addition, the setup process is considered to be non-preemptive. Once t is in service, the queued connections cannot disrupt its service.

Finally, we consider the case where a connection setup is provisioned even if the setup time is exceeded. In other words, the setup time is considered as a loose priority indicator rather than a hard constraint.

We will use the vocabulary of *customer* instead of connection setup request, *server* instead of optical connection providing, and *laxity* instead of setup time.

As asserted before, the evaluation of deadline mismatch ratio is an open problem. It is probably due to the fact that the deadline-based scheduling uses implicitly the sojourn history. Indeed, the position of a customer is determined by its urgency compared to the urgency of every other customer in the queue. Some of them may arrive after our target customer. The urgency of (and so the place taken by) a customer is not fixed upon its arrival, but it is timely increasing. We present our approach which takes the initial position of the customer as a parameter of the problem.

This additional initial condition allowed us to develop a Markovian model, and calculate some interesting performance metrics. The underlying principle behind this proposal can be explained by moving the view point from the queue to the arrival process. Consider a target customer queued at time t , with an initial laxity (margin before deadline expiration) L .

Note that those customers who come after our target customer will be served before our target customer. The EDF policy insures that those customers must have their initial laxity smaller than the remaining deadline margin of our target customer at the time of their arrival.

As time progresses, the laxity of the target customer is getting smaller and smaller and these customers are getting rarer and rarer. Thus, we get the following observation for our target customer: *the EDF scheduler acts as a filter with the residual laxity as the filtering parameter, only the accepted customers are inserted before our target customer. This observation is the basis of the presented approach.*

For technical reasons, we have also to deal with slotted time axis and queues with limited buffers. As a customer eventually gets served or rejected, we obtain a transient Markov chain with absorbing states. We would like to point out that the additional condition we made, namely the knowledge of initial position and laxity, is readily available for our connection setup process (for free).

2.2.2. Scenario model

2.2.2.1. Definitions and Assumptions

- The time axis is slotted. Time is divided into equal length unit-slots. Customers arriving during one slot are considered at the beginning of the next slot.
- The service time is constant. It is assumed to be one time slot.
- Each customer comes with an initial laxity (denoted by L), which is the relative margin to its deadline expiration. The latter is defined related to the beginning of service.
 - We assume that the initial laxities of customers are independent and identically distributed (i.i.d) integer random variables (r.v). The CDF (Cumulative Distribution Function) of the initial laxity will be denoted by $F_L(.)$. For the purpose of numerical computability, we assume further that L is

upper bounded by Λ . Thus, we have in particular $F(0) = 0$, and $F(l) = 1$, for $l \geq \Lambda$.

- Of course, the residual laxity of a customer decreases as time advances. For the sake of simplicity of formulation and without loss of generality, we consider a customer alive at a slot if in the beginning of this slot its residual laxity is strictly positive. We do not consider the tardiness (i.e. negative laxity). So, when a customer's laxity goes down to 0, it remains at 0.
- Services are non-preemptive and work conserving. This means that dead customers (those having 0 residual laxities) are served as well.
- The queue has a capacity of $(K - 1)$ places. It can accommodate $K - 1$ waiting customers in addition to the one being served. By convention, waiting places are numbered from 1 to $K - 1$, the (virtual) position 0 will be later used to refer to a service completion situation, and the (virtual) position K refers to a rejection situation.
- The initial position of each customer is known. Customers move in the queue until being served (position 0) or being pushed out of the queue (position K) by a customer having tighter laxity.
- The overall arrival process is Poisson, denoted P , with arrival rate λ_0 . As the initial laxities are i.i.d integer variables, customers coming with initial laxity strictly smaller than a particular laxity value l form also a Poisson process $P(l)$ with arrival rate $\lambda(l)$ given by $\lambda(l) = F_L(l - 1)\lambda_0$ where $F_L(\cdot)$ is the CDF of the initial laxity law. For a target customer C with residual laxity equal to l at the beginning of a slot, only those coming within the slot and having their initial laxities strictly smaller than l are to be inserted prior to C . Note that $F_L(0) = 0$, this means that $\lambda(l) = 0$. Actually, customers with residual laxities of 1 cannot be further delayed. For $l \geq 2$, let $A(l)$ denoted the number of customers arriving in a slot with initial laxity $d < l$. As such, $a(l, i)$, the probability of having i customers inserted before a target customer with residual laxity l , is given by

$$a(l, i) = \Pr \{A(l) = i\} = e^{-\lambda(l)} \frac{[\lambda(l)]^i}{i!} \quad (1)$$

2.2.2.2. A Markov Chain Model

Let us consider a target customer C arriving in a slot taken as time origin ($t = 0$) with an initial laxity L and initial queuing position N . The state of C at the i -th slot (S_i) can be described by a pair of random variables (r.v) $S_i = (n_i, m_i)$ where

- The meaning of n_i depends on its value
 - For $1 \leq n_i \leq K - 1$, n_i gives the queuing position occupied by C equivalent to the number of customers which have to be served before C , assuming that C is still in the queue at that slot.
 - By convention, $n_i = 0$ means that C gets eventually served. Once C enters a state with $n_i = 0$, it stays there forever.
 - By convention, $n_i = K$ means that C is rejected without service. Once C enters a state $n_i = K$, it stays there forever.
- m_i gives the residual laxity. By convention, $m_i = 0$ means that there is no more residual laxity, thus $m_i = 0 \dots \Lambda$.

The $\{S_i\}_{i \geq 0}$ form a markov chain. Indeed, the evolution of the (n_i, m_i) is determined by the following relation:

$$\bullet \quad m_{i+1} = \max (0, m_i - 1) \quad (2)$$

$$\bullet \quad n_{i+1} = \minmax \{ 0, n_i - 1 + A (m_i), K \} \quad (3)$$

where the function $\minmax (m, x, M)$ is a double limitation function given below

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

and $A(m_i)$ is the number of customers arriving during the i -th slot with initial laxity strictly smaller than m_i . The law of $A(m_i)$ is given by Equation 1.

The evolution of S_i is thus totally predicted from its current position. In addition, $P(A(m_i) = I)$ depends only on the values of the residual laxity m_i , and does not depend on the particular time position i . Thus, we obtain a transient homogeneous Markov chain with absorbing states.

Actually, the states $(0, m)$ and (K, m) for $m = 0 \dots \Lambda$ are absorbing states by our convention.

- The states $(0, m)$ are those representing a customer eventually being served with laxity m .
- The states (K, m) are those representing a customer eventually being pushed out of the queue with laxity m .

These absorbing states are of particular interest. With adequate interpretation (semantics), they provide estimation of useful performance metrics. Eventually, we present a framework for computing the probability of entering these states from a given initial position. We then define and compute some performance metrics of interest.

2.2.2.3. Computation

For a Markov chain, assessing the probability of entering one absorbing subset prior to the other one is a classical problem. We recall the basic model here, and then adapt it to our EDF queuing system for the estimation of performance metrics. We consider a homogenous Markov chain $X = \{X_n\}_{n \in \mathbb{N}}$ with a finite state space Ω , and transition probabilities $p_{ij} = \Pr\{X_{n+1} = j | X_n = i, (i, j) \in \Omega^2\}$. Ω contains a subset of absorbing states A , which is further divided into two subsets, respectively G and B . $\forall i \in G, \forall j \in \Omega - G, p_{ij} = 0$ (same statement for B). Let $M = \Omega - (G \cup B)$, M is the non-absorbing substates. The triplet (G, M, B) forms a partition of Ω .

We attribute the semantic of good (living) places to G and bad (killing) places to B . For our problem, G may be the event that a customer is served prior to its deadline, and B the event the customer is rejected (pushed out of the queue) or it is served too late. We are interested by the probability of entering these absorbing states, i.e. the probability of the event $G(i)$ that a chain which started at $X_0 = i$ enters eventually in G (and stay there forever).

$$G(i) = \{\exists n \geq 0, \exists j \in G, X_n = j | X_0 = i\}$$

Let $g(i) = Pr\{G(i)\}$. Before drawing down the computation of $g(i)$, notice that:

$$\text{a) for } i \in G, g(i) = 1$$

$$\text{b) for } i \in B, g(i) = 0$$

Thus, we only have to find formula for the cases $X_0 = i, i \in M$.

Due to the memoryless property and by assuming that $\{X_1 = j, X_0 = i\}, j \in \Omega$, does take place, we have

$$Pr\{G(i)|X_1 = j\} = Pr\{G(j)\} \times p_{ij} = g(j) \times p_{ij}$$

We also have

$$\begin{aligned} g(i) &= \sum_{j \in \Omega} Pr\{G(i)|X_1 = j\} \\ &= \sum_{j \in M} g(j)p_{ij} + \sum_{j \in G} 1 \times p_{ij} + \sum_{j \in B} 0 \times p_{ij} \end{aligned}$$

Thus, we get the solution of all the $g(i), i \in M$ by solving a system of $\text{Card } \{M\}$ linear equations with $\text{Card } \{M\}$ unknowns, in the form of

$$\sum_{j \in M, j \neq i} p_{ij} \times g(j) + (p_{ii} - 1)g(i) = -[\sum_{l \in G} 1 \times p_{il}], \quad i \in M \quad (4)$$

Now, we apply the basic model to our specific EDF-queueing system. The latter has been previously modeled as a transient homogenous Markov chain with state descriptor (n, m) where $n = 0 \dots K$ and $m = 0 \dots \Lambda$. For the sake of commodity, we denote the states by a scalar i , instead of the pair (n, m) , with the relation $i(n, m) = n + m(K + 1)$. (5)

Note that this indexing is useful only for computation.

2.2.3. Performance Metric Evaluation

2.2.3.1. Metric Definitions

Deadline mismatching and rejection due to buffer overflow are two phenomena to be taken into consideration. This leads to the following metrics, all of them are conditioned on the initial position (inserted at position N with laxity L) of the target customer.

- Conformed setup completion ($m > 0$) probability, denoted by $P_{CS}(N, L)$
- Setup completion in late ($m = 0$) probability, denoted by $P_{LS}(N, L)$
- Setup rejection ($m > 0$) probability, denoted by $P_{SR}(N, L)$
- Reasonable rejection ($m = 0$), denoted by $P_{RR}(N, L)$

These metrics are obtained by computing $g(i(N, L))$ (cf. Equations 4 and 5) with corresponding definition of G given below:

- For $P_{CS}(N, L)$, $G = \{j(0, m) / j = m(K+1), m = 0 \dots \Lambda\}$
- For $P_{LS}(N, L)$, $G = \{j(0, 0) / j = 0\}$
- For $P_{SR}(N, L)$, $G = \{j(K, m) / j = K + m(K+1), m = 0 \dots \Lambda\}$
- For $P_{RR}(N, L)$, $G = \{j(K, 0) / j = K\}$

We would like to point out that among the four metrics of the second group, P_{RR} is actually identically zero. In fact, due to our work-conserving hypothesis and the ML (minimum laxity) insertion rule, a customer with laxity $m = 0$ (or even $m = 1$) cannot be pushed toward the queue tail by new customers coming with laxity at least equal to 1. Once the laxity becomes 1, an already queued customer is surely to be served. Our computational results (cf. Table 1); formally calculated according to our framework, confirm this theoretical deduction.

We can further define:

- The setup completion probability $P_S(N, L) = P_{CS}(N, L) + P_{LS}(N, L)$
- The setup rejection probability $P_R(N, L) = P_{SR}(N, L) + P_{RR}(N, L)$

2.2.3.2. Sample Results

The computation of metrics we proposed require mainly the solution of linear equations, according to previously established Proposition.

Following the guidelines presented in [10], this scenario is defined as follows.

- The duration of each connection is 5 minutes. According to our model, it is normalized to 1 time slot.
- Buffer size $K = 20$, we accept to keep waiting up to 20 connection setup requests.
- There are two classes of customers:
 - Class C_2 , with initial laxity set to 2 and arrival rate set to 0.25 customers/slot. This corresponds to a setup time of 10 minutes, with 1 request every 20 minutes.
 - Class C_{12} , with initial laxity set to $\Lambda = 12$ (a setup time of 60 minutes). We don't need to precise the arrival rate of C_{12} customers since it has no impact on the metrics we want to compute.

We computed the various metrics for customers of class C_{12} as function of their initial position. Only some sample results are given in Table 1. We notice that the setup rejection probability (P_{SR}) remains very low, whereas if the initial position is 11-th position or higher, then the probability of matching the setup time requirement vanishes.

N	P_{CS}	P_{LS}	P_S	P_{SR}	P_{RR}	P_R
5	0.987	0.013	1.000	0.000	0	0.000
8	0.758	0.242	1.000	0.000	0	0.000
9	0.544	0.456	1.000	0.000	0	0.000
10	0.287	0.713	1.000	0.000	0	0.000
11	0.082	0.918	1.000	0.000	0	0.000
18	0.000	0.996	0.996	0.004	0	0.004
19	0.000	0.963	0.963	0.037	0	0.037

Table 1 SCENARIO: METRICS FOR CUSTOMERS COMING WITH INITIAL LAXITY SET TO 12, N GIVES THE INITIAL POSITION

2.2.4. Concluding Remarks

The rationale behind this approach lies in the application of the EDF scheduling policy on the optical blocked connections to increase the probability of connection success rate as well as to handle efficiently the time constraints of these requests.

For this model, we presented a numerical method for assessing some of the performance metrics, such as the setup completion ratio. The latter is computed in function of the intensity of various requests with different specific time constraints (laxity), the buffer size, and finally the knowledge of initial conditions (laxity and position). The last condition is the basic assumption of this framework. We made our choice here not to reject the connection whose setup time is not met. This means that the setup time is used as a *soft* priority indicator, and not as a *hard* time constraint.

Our framework cannot be directly used to deal with the latter case where dead customers have to quit the queue. Thus, there is a double impact of the sojourn history on both the queuing position and the death-and-departure event. Our framework is intended to deal with the first issue by the knowledge of the initial position.

One direction of our future work is to extend the approach presented to the case of multiple wavelengths forming the fiber link connecting two wavelength routers.

2.3. Multi-wavelengths point-to-point optical network

2.3.1. Scenario description

We take a step further and study the case of multiple wavelengths (W) between the two isolated optical nodes A and B. Consider the scenario presented in Figure 4 where two wavelength routers A and B are connected through a fiber link that holds W wavelengths (WLs). Note that we handled the case of a single wavelength between the two WRs previously. As a key distinguishing feature from this previous work, we take in this part one step further by considering the general case of multiple (W) WLs per fiber link. When W connections are

established between A and B (occupying all W WLs), future connection requests will be blocked.

Figure 4 A sample scenario

However, if the proposed setup management approach is deployed, the blocked connections are guaranteed to be queued at A's level in an EDF queue according to an increasing order of their required setup times. A queuing representation of this scenario is depicted in Figure 5.

Figure 5 A queuing representation of the implemented scenario above

The service here is the offer of an optical connection. The W WLs are thus represented in Figure 5 by W servers.

We presented our second model that tackles the previously aforementioned open problem by taking the initial position of the customer as a parameter of the problem. This additional initial condition allowed us to develop a Markovian model, from which we were able to derive some key performance metrics. In the following subsections, we will use the vocabulary of *customer* instead of connection setup request, *server* instead of wavelength, and *laxity* instead of setup time.

2.3.2. Scenario Model

2.3.2.1. Assumptions and Definitions

- The time axis is slotted. Time is divided into equal length unit-slots. Customers arriving during one slot are considered at the beginning of the next slot.
- The service time is constant. It is assumed to be one time slot. As such, any customer in service at the beginning of a given slot will have left the system at the beginning of the next slot.
- Each customer comes with an initial laxity (denoted by L), which is the relative margin to its deadline expiration. The latter is defined related to the beginning of service.
 - We assume that the initial laxities of customers are independent and identically distributed (i.i.d) integer random variables (r.v). The CDF (Cumulative Distribution Function) of the initial laxity will be denoted by $F_L(.)$. For the purpose of numerical computability, we assume further that L is upper bounded by Λ . Thus, we have in particular $F(0) = 0$, and $F(L) = 1$, for $L \geq \Lambda$.
 - Of course, the residual laxity of a customer decreases as time advances. For the sake of simplicity of formulation and without loss of generality, we consider a customer alive at a slot if in the beginning of this slot its residual laxity is strictly positive. We do not consider the tardiness (i.e. negative laxity). So, when a customer's laxity goes down to 0, it remains at 0.
- Services are non-preemptive and work conserving. This means that dead customers (those having 0 residual laxities) are served as well.

- The queue has a capacity of $(K - 1)$ places. It can accommodate $K - 1$ waiting customers in addition to the one being served. By convention, waiting places are numbered from 1 to $K - 1$, the (virtual) position 0 will be later used to refer to a service completion situation, and the (virtual) position K refers to a rejection situation.
- The initial position of each customer is known. Customers move in the queue until being served (position 0) or being pushed out of the queue (position K) by a customer having tighter laxity.
- The overall arrival process is Poisson, denoted P , with arrival rate λ_0 . As the initial laxities are i.i.d integer variables, customers coming with initial laxity strictly smaller than a particular laxity value l form also a Poisson process $P(l)$ with arrival rate $\lambda(l)$ given by $\lambda(l) = F_L(l - 1)\lambda_0$ where $F_L(\cdot)$ is the CDF of the initial laxity law. For a target customer C with residual laxity equal to l at the beginning of a slot, only those coming within the slot and having their initial laxities strictly smaller than l are to be inserted prior to C . Note that $F_L(0) = 0$, this means that $\lambda(l) = 0$. Actually, customers with residual laxities of 1 cannot be further delayed. For $l \geq 2$, let $A(l)$ denoted the number of customers arriving in a slot with initial laxity $d < l$. As such, $a(l, i)$, the probability of having i customers inserted before a target customer with residual laxity l , is given by

$$a(l, i) = \Pr \{A(l) = i\} = e^{-\lambda(l)} \frac{[\lambda(l)]^i}{i!} \quad (6)$$

2.3.2.2. A Markov Chain Model

Let us consider a target customer C arriving in a slot taken as time origin ($t = 0$) with an initial laxity L and initial queuing position N . The state of C at the i -th slot (S_i) can be described by a pair of random variables (r.v) $S_i = (n_i, m_i)$ where

- The meaning of n_i depends on its value
 - For $1 \leq n_i \leq K - 1$, n_i gives the queuing position occupied by C equivalent to the number of customers which have to be served before C , assuming that C is still in the queue at that slot.
 - By convention, $n_i = 0$ means that C gets eventually served. Once C enters a state with $n_i = 0$, it stays there forever.

- By convention, $n_i = K$ means that C is rejected without service. Once C enters a state $n_i = K$, it stays there forever.
- m_i gives the residual laxity. By convention, $m_i = 0$ means that there is no more residual laxity, thus $m_i = 0 \dots \Lambda$.

The $\{S_i\}_{i \geq 0}$ form a markov chain. Indeed, the evolution of the (n_i, m_i) is determined by the following relation:

$$\bullet \quad m_{i+1} = \max(0, m_i - 1) \quad (7)$$

$$\bullet \quad n_{i+1} = \minmax\{0, n_i - W + A(m_i), K\} \quad (8)$$

where the function $\minmax(m, x, M)$ is a double limitation function given below

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

and $A(m_i)$ is the number of customers arriving during the i -th slot with initial laxity strictly smaller than m_i . The law of $A(m_i)$ is given by Equation 6.

The evolution of S_i is thus totally predicted from its current position. In addition, $P(A(m_i) = l)$ depends only on the values of the residual laxity m_i , and does not depend on the particular time position i . Thus, we obtain a transient homogeneous Markov chain with absorbing states.

Actually, the states $(0, m)$ and (K, m) for $m = 0 \dots \Lambda$ are absorbing states by our convention.

- The states $(0, m)$ are those representing a customer eventually being served with laxity m .
- The states (K, m) are those representing a customer eventually being pushed out of the queue with laxity m .

These absorbing states are of particular interest. With adequate interpretation (semantics), they provide estimation of useful performance metrics.

Consequently, we present a framework for computing the probability of entering these states from a given initial position. We then define and compute some performance metrics of interest.

2.3.2.3. Computation

For a Markov chain, assessing the probability of entering one absorbing subset prior to the other one is a classical problem. We recall the basic model here, and then adapt it to our EDF queuing system for the estimation of performance metrics. We consider a homogenous Markov chain $X = \{X_n\}_{n \in \mathbb{N}}$ with a finite state space Ω , and transition probabilities $p_{ij} = \Pr\{X_{n+1} = j | X_n = i, (i, j) \in \Omega^2\}$. Ω contains a subset of absorbing states A , which is further divided into two subsets, respectively G and B . $\forall i \in G, \forall j \in \Omega - G, p_{ij} = 0$.

Let $M = \Omega - (G \cup B)$, M is the non-absorbing substates. The triplet $(G, M, \text{and } B)$ forms a partition of Ω .

We attribute the semantic of good (living) places to G and bad (killing) places to B . For our problem, G may be the event that a customer is served prior to its deadline, and B the event the customer is rejected (pushed out of the queue) or it is served too late. We are interested by the probability of entering these absorbing states, i.e. the probability of the event $G(i)$ that a chain which started at $X_0 = i$ enters eventually in G (and stay there forever).

$$G(i) = \{\exists n \geq 0, \exists j \in G, X_n = j | X_0 = i\}$$

Let $g(i) = \Pr\{G(i)\}$. Before drawing down the computation of $g(i)$, let us notice that **for** $i \in G, g(i) = 1$. Thus, we only have to find formula for the cases $X_0 = i, i \in M$.

Due to the memoryless property and by assuming that $\{X_1 = j, X_0 = i\}, j \in \Omega$, does take place, we have

$$\Pr\{G(i) | X_1 = j\} = \Pr\{G(j)\} \times p_{ij} = g(j) \times p_{ij}$$

We have

$$\begin{aligned} g(i) &= \sum_{j \in \Omega} \Pr\{G(i) | X_1 = j\} \\ &= \sum_{j \in M} g(j) p_{ij} + \sum_{j \in G} 1 \times p_{ij} + \sum_{j \in B} 0 \times p_{ij} \end{aligned}$$

Thus, we get the solution of all the $g(i), i \in M$ by solving a system of Card $\{M\}$ linear equations with Card $\{M\}$ unknowns, in the form of

$$\sum_{j \in M, j \neq i} p_{ij} \times g(j) + (p_{ii} - 1)g(i) = -[\sum_{l \in G} 1 \times p_{il}], \quad i \in M \quad (9)$$

2.3.3. Performance Metric Evaluation

2.3.3.1. Metrics Definitions

We apply now the second proposed model to our specific EDF queuing system. We take into account the following metrics, which are conditioned by both the initial position N and the initial laxity L of the target customer.

- Conformed setup completion ($m > 0$) probability, denoted by $P_{CS}(N, L)$
- Setup completion in late ($m = 0$) probability, denoted by $P_{LS}(N, L)$
- Setup rejection ($m > 0$) probability, denoted by $P_{SR}(N, L)$
- Reasonable rejection ($m = 0$), denoted by $P_{RR}(N, L)$

These metrics are obtained by computing $g(i(N, L))$ (cf. Equation 9) under an appropriate definition of G :

- For $P_{CS}(N, L)$ $G = \{j(0, m) / j = m(K+1), m = 0, \dots, \Lambda\}$.
- For $P_{LS}(N, L)$, $G = \{j(0, 0) / j = 0\}$.
- For $P_{SR}(N, L)$, $G = \{j(K, m) / j = K + m(K+1), m = 0, \dots, \Lambda\}$.
- For $P_{RR}(N, L)$, $G = \{j(K, 0) / j = K\}$.

2.3.3.2. Sample Results

Following the guidelines presented in [10] and in the case of a single wavelength, this scenario is defined as follows.

- The duration of each connection is 5 minutes. According to our model, it is normalized to 1 time slot.
- The number of servers is set to 4.
- The waiting space size $K - 1$ is set to 29. That is when all W servers are busy, up to 29 connection requests can be queued.

- There are two classes of customers:
 - Class C_2 , with initial laxity set to 2 and arrival rate set to 0.75 customers/slot.
 - The second class, C_{12} , is assigned an initial laxity set to $\Lambda = 12$. The arrival rate of C_{12} has no impact on the metrics we want to compute.

We computed the various metrics for customers of class C_{12} as function of their initial position. Only some sample results are given in Table 2. We notice that the setup rejection probability (P_{SR}) remains very low, whereas if the initial position is 25-th position or higher, then the probability of matching the setup time requirement (P_{CS}) drops slightly below 1.

N	P_{CS}	P_{TS}	P_{SR}	P_{err}
24	1.0000	0.0000	0.0000	0
25	0.9999	0.0001	0.0000	0
26	0.9997	0.0003	0.0000	0
27	0.9992	0.0008	0.0000	0
28	0.9980	0.0019	0.0001	0
29	0.9940	0.0050	0.0010	0

Table 2 CUSTOMERS WITH INITIAL LAXITY 12 AND INITIAL POSITION N

2.3.4. Concluding Remarks

In this section, we presented a detailed mathematical model for multi-wavelengths optical connection setup management approach that relies on the EDF scheduling algorithm. We used this model to find some of the major performance metrics pertaining to QoS-aware connection setup. Finally, we motivated the use of the proposed management scheme since it allows optical operators to reduce the connection blocking probability. This is achieved by exploiting the connection setup time requirement of a connection to queue the blocked connection requests.

Chapter 3

Connection Setup Management in Wavelength- routed Optical Networks

3.1. Introduction

In chapter 2, we limited the study conducted to the case of point-to-point connection establishment between two optical nodes. This previous chapter also depicts that W connection setup requests are being established towards the end of any given time slot in the case of W-wavelengths point-to-point optical network (respectively a single connection setup request is established in the case of single point-to-point optical network).

Thus, chapter 3 defines a new connection setup management approach that takes advantage of the optical network state at the time of lighpath setup. Here, we envisage the case of connection setup management in wavelength-routed WDM optical networks. That is, we take the whole network state (i.e. not isolated parts of the network) as an additional parameter to well provision a connection.

3.2. Description of the connection setup management approach

Different applications and services have different connection setup time (deadline) requirements. As new applications continue to emerge, this difference is expected to become more pronounced. For example, 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. We propose in our work to achieve this objective via the introduction of an EDF queue at the OXC level enabling the optical operator to exploit the connection setup time requirement when dealing with blocked connection requests. Our approach views the connection setup time requirement as a period of time during which the blocked connection requests tolerate being delayed (i.e. queued) and furthermore as a service differentiator 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, let us consider the following sample scenario. Figure 6 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. We assume here that each connection setup request requires a full wavelength of bandwidth. The service in this context is the offer of a lightpath (i.e. the occupation of a series of wavelengths along the physical path allocated to the connection request).

Figure 6 An example of a real optical network

For instance, OXC A will attempt to establish a lightpath to carry each connection request it receives. The number of lightpaths that may originate from A is however limited by the number of outgoing wavelengths (W wavelengths). As a result, the maximum number of lightpaths that A may provide to the incoming connection requests is bounded by W . In addition, some of the connection requests received by OXC A will be affected to a great extent by the state of the optical network. Such connection requests will not be able to always take full advantage of the W lightpaths that A may establish.

For example, the number of lightpaths that may be set up between A and C will be greatly influenced by the number of lightpaths already established between B and C. this observation asserts that the number of lightpaths made available by A will depend not only on the number of requests (load) that OXC A gets but also on the load between of OXC B. That is, the availability of the W lightpaths that may be offered by A strongly depends on the blocking probability (denoted by p) imposed by node B. In light of this fact, one can draw the following conclusion. Connection blocking occurs if either of the following situations arises:

- OXC A is not able to make the most of the W lightpaths due to resource depletion caused by the connections generated from OXC B to C. Connection blocking under this condition happens with a probability p .
- OXC A is able to deliver up to W lightpaths but all these lightpaths are busy serving W other connection requests originated at A.

The W lightpaths that may be provided by A can be consequently modeled as W servers. But in order to cover all the possible blocking situations presented above, the following assumptions should be 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 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 immediately be 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. The planned scheme 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 queuing representation of the proposed scheme is depicted in Figure 7 that shows the EDF queue placed in front of the W servers. The EDF discipline 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 in which dead customers are served and the non work-conserving variant in which dead customers are dropped. We deal with the work-conserving EDF variant in our planned approach.

Figure 7 A queuing representation of the proposed approach

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) discussed earlier becomes idle. But even then, it is not guaranteed to join a freed-up server. To gain insight into the model, let us make the following assumptions. Every server is assumed to have the same constant service time which is normalized to one unit of time. 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 a probability $(1-p)$ or will remain at the front of the queue blocking the customers queuing behind it with a 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 connection requests happen to be waiting in the EDF queue and W lightpaths are available at the start of a time slot S , then the probability that k (where $k \leq W$) connection requests get served during S is given by the following expression:

$$Pr\{D_p = k\} = (1 - p)^k \times p \quad (10)$$

In fact, the queuing model under study has a generic fundamental significance that goes beyond the specific scenario presented in Figure 6. Due to this generality, the proposed queuing model can be applied to any wavelength routed optical network irrespective of the number nodes and wavelengths that make up the optical network.

3.2.1. A Markovian model

In what follows, we will make use of the word customer to denote a connection setup request, the term server to refer to a lightpath, and the term laxity to represent connection setup time.

3.2.1.1. Rationale behind the model

As indicated in the previous section, the evaluation of the deadline mismatch probability in an EDF-based queuing 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 our 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.

So, we tackle this problem by presenting an approach that takes both the initial position and the initial laxity of a customer as given 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, we assumed a slotted time axis and a finite capacity EDF queue.

The rationale behind the proposed modeling approach is as follows. Let us consider a target customer 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 C in the EDF queue. As time advances, L will keep on decreasing and the number of customers placed in front of C consequently gets smaller and smaller. As a conclusion, our modeling approach is based on the following observation:

“From a queued customer’s viewpoint, 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.”

3.2.1.2. System definitions and assumptions

We consider a discrete-time queuing system model as described below:

- The time axis is slotted, i.e. time is divided into equal lengths 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 comes with an initial laxity (denoted by L), which is the relative margin to its deadline expiration. We assume that the initial laxities of customers are independent and identically distributed (i.i.d) integer random variables (r.v.). The CDF (Cumulative Distribution Function) of the initial laxity will be denoted by $F_L(\cdot)$. To simplify numerical computation, we assume that L is upper bounded by Λ . Thus, we have

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

The residual laxity of a customer decreases as time progresses. For the sake of simplicity of formulation and without loss of generality, we consider a customer to be alive if at the beginning of a time slot its residual laxity is strictly positive. Since we are mainly interested in getting the deadline mismatch probability, we do not consider the tardiness, i.e. negative laxity. In other words, a customer's laxity is maintained at zero whenever it hits this value 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 a customer having more stringent laxity requirements.

- The overall arrival process is Poisson, denoted by P , with arrival rate λ_0 . For a target customer 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 C . As the initial laxities are i.i.d integer variables, customers arriving with an initial laxity strictly smaller than l form a Poisson process $P(l)$ with an arrival rate $\lambda(l)$ given by $\lambda(l) = F_L(l-1)\lambda_0$, where $F_L(\cdot)$ 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 smaller than l . As such, $a(l, i)$, the probability of having i customers inserted before the target customer C is given by

$$a(l, i) = \Pr \{A(l) = i\} = e^{-\lambda(l)} \frac{[\lambda(l)]^i}{i!} \quad (11)$$

Note that we assume $F_L(0) = 0$, 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 before, the number of customers going into service in one time slot $\mathbf{D}_p$ follows a geometric distribution with parameter p and whose probability mass function is given by Equation (10). 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 6). This means that p will be directly proportional to the total load to which all the other nodes are subject.
- The calculation of the blocking probability p is beyond the scope our work (refer to [23, 24, 25]) for more information about how to calculate p .

3.2.1.3. A Markov chain model

Let us consider a target customer C arriving in a slot taken as the time origin ($t = 0$) with an initial laxity L and an initial queuing position N . The state of C at the s -th time 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 $1 \leq n_s \leq K-1$, n_s gives the queuing position occupied by C , equivalent to the number of customers which have to be served before C .
 - By convention, $n_s = 0$ means that C starts its service. Thus, once C enters a state with $n_s = 0$, it stays there forever.
 - By convention, $n_s = K$ means that C is dropped out of the queue without being able to receive its service. Thus, once C enters a state with $n_s = K$, it stays there forever.
- m_s gives the residual laxity, $m_s = 0, \dots, \Lambda$. By convention, $m_s = 0$ means that there is no more residual laxity.

The $\{X_s\}_{s \geq 0}$ form a Markov chain with a finite space shown in Figure 8. The dashed box presented in Figure 8 defines the set of non-absorbing states of the target customer C (i.e. $1 \leq n_s \leq K-1$). The absorbing states of C (i.e. $(0, m_s)$ and (K, m_s) , $m_s = 0 \dots \Lambda$) are organized into two absorbing subsets represented by the two solid boxes shown in Figure 8:

Figure 8 state space of the EDF queuing system. The empty point (n, m) is a transient state. The black points are potential one-step evolutions in the queue, and r is a rejection absorbing position

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

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

$$\bullet \quad m_{s+1} = \max(0, m_s - 1) \quad (12)$$

- $n_{s+1} = \text{minmax}(0, n_s - D_p + A(m_s), K)$ (13)

where the function $\text{minmax}(m, x, M)$ 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 time slot with an initial laxity strictly smaller than m_s ($A(m_s)$ is described by Equation (11)). 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 D_p is given by Equation (10). Given that at most W customers attempt to access the optical network at the 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, $D_p = 0 \dots \min(n_s, W)$.

The next state of the target customer 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); (b) the probability distributions of $A(m_s)$ 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 . this implies that $X = \{X_i\}_{i \in \mathbb{N}}$ is an absorbing homogeneous Markov chain.

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

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

and M (the subset of transient states) is defined as follows:

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

Multiple definitions may be envisaged for G and B according to the semantic attributed to each of these absorbing states. We choose to define G to be the “good” set of absorbing states in the sense that G represents the event that the target customer C is eventually served. In contrast,

B represents the event that C is dropped out of the queue. These definitions translate into the following expressions:

- $B = \{i(K, m), m = 0 \dots \Lambda\}$
- $G = \{i(0, m), m = 0 \dots \Lambda\}$

The absorbing states are of particular interest as they can be used to estimate different useful performance metrics. Next, we present a method for computing among other things the probability that a given customer ends up in one of the above-presented absorbing subsets.

3.2.1.4. Computation of performance metrics

The Markov chain X described previously has two subsets of absorbing states. In this context, one can find among other things the probability of absorption (POA), which is the probability that a customer C ends up in one of the absorbing subsets [26]. Moreover, it is possible to determine the mean time of absorption that represents the expected number of steps (i.e. time slots) before C reaches one of the absorbing subsets. In this respect, we will specifically focus our attention on finding the mean number of steps taken by X until absorption into G . In other words, we will be concerned with the mean time to service ($MTTS$), which indicates the average amount of time spent by 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 computation of POA and $MTTS$ makes use of the one step transition probabilities p_{ij} where $(i, j) \in \Omega^2$. So let us examine these one step transition probabilities. p_{ij} indicates the probability that the chain shifts in one time slot from state $i(n, m)$ to state $j(n', m')$. The one step transition probabilities are obtained as follows:

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

$\forall i(n, m) \in M, \forall j(n', m') \in \Omega$, it follows from Equations (12) and (13) that

- $m' = \max(0; m - 1)$ and
- $n' = \min(\max(0; n - D_p + A(m); K)$

D_p and $A(m)$ are two random variables whose probability distributions are given by Equations (10) and (11) respectively. As indicated before, for $D_p = 0 \dots \min(n, W)$, p_{ij} can therefore be expressed as below

$$p_{ij} = \sum_{d=0}^{\min(n,W)} Pr\{D_p = d\} \cdot Pr\{A(m) = n' - n + d\} \quad (14)$$

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. $\text{Card}\{\Omega\}$. This means that P is a $\text{Card}\{\Omega\} \times \text{Card}\{\Omega\}$ matrix. Let t and r denote the total number of transient and absorbing states respectively. That is, $t = \text{Card}\{M\}$, $r = \text{Card}\{A\} = \text{Card}\{B\} + \text{Card}\{G\}$, and $(t + r) = \text{Card}\{\Omega\}$. We organize the one step probabilities in P according to the guidelines presented in [27, 28], 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. $p_{ij}, \forall i(n, m) \in M, \forall j(n', m') \in \Omega$). The last r rows of P include the one step transition probabilities relating to the absorbing states of X (i.e. $p_{ij}, \forall i \in A, \forall j \in M$). The resulting matrix P has the following canonical form.

$$P = \begin{pmatrix} Q & R \\ 0 & I \end{pmatrix} \quad (15)$$

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 indicated 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 Equation (14). Since X is an absorbing Markov chain, it

follows that the matrix $(I_{\text{txt}} - Q_{\text{txt}})$ is invertible [27, 28]. Let $N_{\text{txt}} = (I_{\text{txt}} - Q_{\text{txt}})^{-1}$. The matrix N_{txt} is called the fundamental matrix of X . N_{txt} 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. $i \in G$) precede the bad absorbing states (i.e. $i \in B$) in P , we are going to use the following numeric representation for each state $i \in \Omega$:

- $i = 0, \dots, t$ $i \in M$
- $i = (t + 1), \dots, (t + \text{card}\{G\})$ $i \in G$
- $i = (t + \text{card}(G) + 1), \dots, (t + r)$ $i \in B$

Let us now examine the structure of the fundamental matrix N_{txt} .

3.2.1.4.1. The fundamental matrix

The (i, j) th entry of Q_{txt} given in Equation (15) gives the probability of being in transient state j one time slot after leaving the transient state i . In a similar manner, the (i, j) th entry of Q_{txt}^s , denoted by p_{ij}^s , indicates the probability that X moves from the transient state i to the 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 $Q_{\text{txt}}^{s+1} \rightarrow 0_{\text{txt}}$ as $s \rightarrow \infty$.

Note that

$$(I_{\text{txt}} - Q_{\text{txt}})(I_{\text{txt}} + Q_{\text{txt}} + Q_{\text{txt}}^2 + \dots + Q_{\text{txt}}^s) = I_{\text{txt}} - Q_{\text{txt}}^{s+1}$$

Multiplying both sides by the fundamental matrix N_{txt} gives

$$(I_{\text{txt}} + Q_{\text{txt}} + Q_{\text{txt}}^2 + \dots + Q_{\text{txt}}^s) = N_{\text{txt}}(I_{\text{txt}} - Q_{\text{txt}}^{s+1})$$

Letting s tend to infinity, we get

$$N_{\text{txt}} = I_{\text{txt}} + Q_{\text{txt}} + Q_{\text{txt}}^2 + \dots \dots \dots \quad (16)$$

Let n_{ij} be the $(i, j)^{\text{th}}$ entry of matrix N_{tot} . Given that $Q_{t \times t}^0 = I_{t \times t}$, Equation (16) implies that n_{ij} can be written as

$$n_{ij} = p_{ij}^{(0)} + p_{ij}^{(1)} + p_{ij}^{(2)} + p_{ij}^{(3)} + \dots \dots \dots \quad (17)$$

3.2.1.4.2. The probability of absorption

In this case, we are interested in finding the probability of the event $G(i)$, respectively $B(i)$, that the Markov chain, starting at state $X_0 = i$, reaches G , respectively B . $G(i)$ and $B(i)$ are given by:

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

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

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

First let us examine $g(i)$, $i \in M$. The probability of going from $i \in M$ to $j \in G$ in s steps ($s \geq 1$), p_{ij}^s can be computed using the Chapman-Kolmogorov equation as follows:

$$p_{ij}^s = \sum_{i \in M} p_{il}^{(s-1)} \times p_{lj} \quad (18)$$

From the definition of $G(i)$, we have:

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

Using Equations (17) and (18), we obtain

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

Thus, $g(i)$ for $i \in M$ is given by

$$g(i) = \sum_{j=t+1}^{t+card\{G\}} \sum_{l=1}^t n_{il} \times p_{lj} \quad i \in M \quad (19)$$

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

$$b(i) = \sum_{j \in B} \sum_{l \in M} n_{il} \times p_{lj} \quad i \in M \quad (20)$$

3.2.1.4.3. The mean time to service

As we 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. G or B). However, in the case of the proposed setup mechanism, the performance measure of interest to us is the mean time that the target customer C spends in the EDF queue before receiving its service. In other words, we are interested 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 G . $MTTS(i)$, $i \in M$ can be obtained as follows.

Let $V_{s,i,j} = 1$ if prior to absorption into G , X visits transient state $X_s = j$ at time slot s starting from transient state $X_0 = i$ and let $V_{s,i,j} = 0$ otherwise. 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 G . Let us define

G to be the event that X gets absorbed into the absorbing subset 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 G is

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

By assuming over all possible states $j \in M$, we get $MTTS(i)$ the expected number of steps until X is absorbed into G starting from the transient state i . Hence, $MTTS(i)$ for $i \in M$ can be written as

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

Using Bayes' theorem, we get

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

It follows from Equation (17) that $MTTS(i)$ for $i \in M$ becomes

$$MTTS(i) = \sum_{j \in M} n_{ij} \times g(j) = \sum_{j=1}^t n_{ij} \times g(j) \quad i \in M \quad (21)$$

Based on this analysis presented thus far, we put forward the following proposition.

Consider a homogeneous transient Markov chain with state space partitioned into an absorbing subset A and its complement the non absorbing (transient) subset M . The subset A is further divided into G and B . Designate by $X_0 = \mathbf{i} \in \mathbf{M}$ the initial state of X . We can obtain $g(\mathbf{i})$ (respectively $b(\mathbf{i})$), the probability of absorption into G (respectively B) starting from $X_0 = \mathbf{i} \in \mathbf{M}$, by means of Equation (19) (respectively Equation (20)). Moreover, we can get MTTs ($\mathbf{i}$), the mean time to service starting from $X_0 = \mathbf{i} \in \mathbf{M}$, by using Equation (21).

3.2.2. Performance metric evaluation

3.2.2.1. Definition

We apply now the developed proposition in section 3.1.2.1 to the proposed EDF-based connection setup mechanism.

In what follows, we will distinguish 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 C . We consider the following POA-related metrics:

- Conformed setup completion probability, denoted by $P_{CS}(N, L)$. This is the probability that C goes into service with a laxity $m > 0$.
- Late setup completion probability, denoted by $P_{LS}(N, L)$. This is the probability that 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 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 C is dropped out of the queue with a laxity $m = 0$.

In order to obtain the POA-related metrics, we compute $g(\mathbf{i}(N, L))$, and $b(\mathbf{i}(N, L))$ using Equations (19), and (20) under the following definitions for G and B .

- For $P_{CS}(N, L)$, $G = \{j(0, m); m = 1 \dots \Lambda\}$
- For $P_{LS}(N, L)$, $G = \{j(0, 0)\}$
- For $P_{SR}(N, L)$, $B = \{j(K, m); m = 1 \dots \Lambda\}$

- For $P_{RR}(N, L)$, $B = \{j(K, 0)\}$

In addition, we designate the setup probability 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, we consider a single *MTTS*-related performance metric that we denote by $T_s(N, L)$. This is the average time that the target customer 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 Equation (21) for the case where $G = \{j(0, m), m = 0 \dots \Lambda\}$.

3.2.2.2. Sample results

To study the performance of the proposed setup scheme, we tested various scenarios involving different values of the blocking probability p and of the number of servers W . For each scenario, we calculated the above-presented metrics based on both the initial position N and the initial laxity L (i.e. deadline) of the target customer C . Following the guidelines presented in [9, 10], L is supposed to be dependent on the class of service chosen by C . In this context, a more stringent deadline requirement (i.e. a smaller L) will lead to a higher class of service for C . Even though our computational framework can be applied to any number of quality of service (QoS) classes, we consider in our study 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 we drew 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, we first study its performance under the following assumptions:

- The blocking probability and the number of servers 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.

We computed the various probability of absorption related metrics for a Bronze customer as a function of its position N . A sample set of results is given in Table 3. These results show the rejection probability P_R achieved by the proposed setup scheme. Although we considered a scenario where the blocking probability p is quite high, the Bronze client experiences 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 3 POA related metrics for bronze customers, N gives the initial position

As indicated before, a customer whose deadline reaches 0 is guaranteed to receive its service because we are dealing with a work-conserving EDF queue. The numerical results given in Table 3 confirm this theoretical deduction as P_{RR} was found to be always equal to zero. The initial laxity of 14 that we chose to assign 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.

Figure 9 Setup Probability (P_s) per class of service for $p = 0.3$ and $W = 8$

Figure 10 Time to service (T_s) per class of service for $p = 0.3$ and $W = 8$

Respectively, Figures 9 and 10 show 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. Please note that in Figure 9 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 Figure 9 as the setup probability P_s for Gold customers is found to be equal to 1. The Bronze customers on the 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 Figures 9 and 10. We have considered so far the case where $p = 0.3$ and $W = 8$. In what follows, we will study the impact of the variation of these values on the QoS perceived by the various classes of customers. An emphasis will be put in this respect on the performance gains that are

made possible by the proposed setup scheme. Figures 11 and 12 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 we 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.

Figure 11 Gold late setup (P_b) for $W = 8$ and $N = 1, 2, 3$

Figure 12 Silver late setup probability (P_{LS}) for $W = 8$ and $N = 7, 8, 9$

Since the Gold customers are most likely to be found towards the front of the EDF queue, Figure 11 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 Figure 12. We turn now to the impact that the number of servers W may have on the performance of the proposed setup scheme. In this regard, Figures 13 and 14 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 Figure 13 demonstrate that the probability P_{CS} of provisioning a Bronze customer on time increases drastically as the number of available servers goes up.

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

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 N th position and hence they will have a minor effect on this Bronze customer. The results shown in Figure 14 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 .

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

Chapter 4

Conclusion and future work

We introduced a novel approach for connection setup in wavelength routed optical WDM networks. The proposed setup mechanism is based on the idea of treating the setup time of an incoming connection request as a priority indicator during connection provisioning. The planned EDF-based setup scheme has been proved to be optimal and it is expected to allow the network operator to improve the QoS perceived by their end customers. Performance of this novel scheme is analyzed by precisely calculating various measures, such as the fraction of connections provisioned prior to deadline expiration, and the average time it takes to successfully setup a connection. Our numerical results whose correctness was asserted through extensive simulations highlighted the service differentiation feature achieved by the EDF-based connection setup management approach.

Possible directions for our future work may include investigating the role that non-work conserving EDF queues with exponential service time may play in optical connection setup management. We may also address the effect of different preemption strategies on the service differentiation feature and solve the problem of penalizing lower class clients.

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