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Improved EDF-based Management of the Setup of Connections in Opaque and Transparent Optical Networks

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Abstract The need to support the diverse Quality of Service (QoS) requirements of the ever-emerging Internet applications is a major challenge for optical network operators. This paper tackles such a challenge through the definition of a QoS-aware optical connection setup management scheme. The proposed scheme utilizes the Earliest Deadline First (EDF) queueing discipline to schedule the setup of optical connections that cannot be established due to lack of optical resources. The EDF-based approach aims at minimizing blocking probability while realizing QoS differentiation. Blocking probability reduction is realized through the insertion of blocked connection requests into a queue giving them thus a second chance with respect to network access. QoS differentiation on the other hand is achieved as follows. The blocked connection requests are ranked in the EDF queue according to their connection setup requirements, which are viewed as deadlines during connection setup. In this way, pending connection requests having shorter setup time requirements are guaranteed to experience better QoS compared to the ones having longer setup time requirements. The performance of the EDF-based strategy is analyzed through extensive simulations in the context of both opaque and transparent nsfnet network topologies. The reported results show that the proposed strategy yields remarkable reduction in terms of blocking probability while effecting QoS differentiation.

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1 Introduction

The continuous emergence of new applications having diverse Quality of Service (QoS) requirements coupled with the need to match these requirements are driving the technological advance in Wavelength Division Multiplexing (WDM) optical networks. These networks are foreseen in the future to act as multi-service networks, in which various kinds of services will be supported. Given these aspirations, the creation of solutions that make optical networks to be QoS-enabled becomes necessary, leading thus to proposals like the one discussed in this paper. The main challenge in this regard lies in the pressing need to equip optical networks with the capability of offering QoS differentiation. In fact, numerous research efforts (*e.g.* [1–3]) envisaged addressing the aforementioned challenge by having WDM optical networks provide predictable quality of transport services. These studies contemplated measuring the quality of transport of an optical connection through the set of parameters that affect the flow of data once the connection has been established.

However, the role that the *connection setup time* (CST) can play in effectively managing the setup of optical connections has not been adequately studied in the open literature. Hence, this paper presents a novel connection setup management approach that uses the CST parameter as both a priority indicator for the connection request and as a measure of the delay tolerance associated with that request. According to the authors in [4,5], CST is expected to become an integral part of an optical connection's service profile and is thus foreseen as a potential service differentiator in the Service Level Agreements (SLAs) established between optical operators and their clients.

CST is defined as the maximum amount of time that elapses between the instant an optical connection is first requested and the instant the requested connection is setup. Therefore, CST can be interpreted as a *deadline* prior to which a received connection request must be established and thus provides an opportunity for network operators to carry out QoS differentiation during connection provisioning. This can be done by scheduling the setup of connection requests according to their CST requirements. Inspired by this observation, this paper proposes a setup management strategy that utilizes the *Earliest Deadline First* (EDF) discipline to schedule the establishment of the blocked connection requests in an order consistent with their respective deadlines. Whenever connection blocking occurs, the blocked connection setup requests are queued and then served according to the EDF discipline, whereby the connection request having the smallest CST requirement (i.e., deadline) is served first. This has the advantage of prioritizing the blocked setup requests consistently with the priority levels of the clients generating them. This is especially true since the proposed strategy ensures that high priority clients with stringent CST requirements are attributed a higher priority when it comes to network access compared to low priority clients. As a result, high priority clients are expected to experience smaller blocking probability relative to the low priority ones and the objective of effecting blocking probability differentiation in the network is achieved.

The rest of this paper is structured as follows. Section 2 describes the EDF-based connection setup strategy and discusses its main underlying concepts. In section 3, a selection of major related studies is summarized. Section 4 highlights the benefits of the proposed setup strategy through a discrete event simulation framework. Finally, section 5 concludes the paper.

2 Description of the Proposed Scheme

The sample network topology given in Fig. 1 is used to explain the main idea behind the EDF-based setup scheme under study. The figure shows three optical crossconnects (OXCs), namely: A, B, and C, that are interconnected through 2 fiber links. Each OXC serves an incoming connection request by attempting to establish an end-to-end lightpath connecting the source node of the request to its destination. When such an attempt fails, the connection request is said to be blocked.

Blocked connection requests were heretofore immediately dropped. Alternatively, this paper proposes to insert such connections into an EDF queue and to arrange them in an ascending order of their CST requirements. This solution is motivated by the studies made in [4,5], which stipulate that CST is a parameter that determines a connection request's class of service. More specifically, it was indicated in [4,5] that the smaller the CST requirement of a request is, the higher the request's class of service becomes. In the context of the considered EDF-based strategy, the priority of a connection request waiting in the EDF queue increases as time progresses. If a pending request reaches the deadline prior to which it must be provisioned without being admitted into the network, then this request is called a *dead request*. The way an EDF queue treats a dead request depends on whether a *work-conserving* or a *non work-conserving* EDF policy is implemented. In particular, the non work-conserving variant immediately drops a dead request, whereas the work-conserving one further holds dead requests in the queue until they get served. In this paper, the more realistic non-work conserving EDF variant is considered.

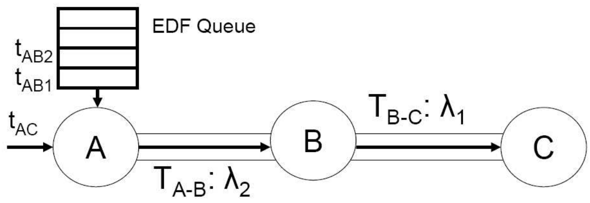


Fig. 1 A sample optical network topology.

As shown in Fig. 1, two connections are already established in the network on node pairs AB and BC. Let us denote by T_{A-B} and T_{B-C} these two one-hop connections. The paths and the wavelengths used by the said connections are indicated by both the arrows and the labels associated with them. For convenience, it is assumed that each connection request requires a single wavelength of bandwidth and that the capacity of each fiber link is limited to 2 wavelengths. These wavelengths are denoted by λ_1 and λ_2. Furthermore, let us assume that the EDF queue associated with node A contains 2 previously blocked requests, namely t_{AB1} and t_{AB2}, that are destined for B with t_{AB1} being the head-of-line pending request. The deadline requirements of t_{AB1} and t_{AB2} are assumed to be 1 and 2 units of time, respectively. Suppose now that a setup request t_{AC} addressed to node C arrives at node A with a deadline of 3. Eventually, the fate of this connection depends on whether the optical network shown in Fig. 1 is transparent or opaque. For this reason, both cases are considered independently in the following subsections.

2.1 Case of an opaque optical network

If the considered optical network is opaque, then wavelength conversion is supported by each OXC in the network. It follows that a connection is established in the network only if on all the links of its route, there is a least one wavelength available. Given that this condition is satisfied for t_{AC} in the context of the network topology given in Fig. 1, it follows that the network provisions t_{AC} along the $A - B - C$ route. Once t_{AC} has been served, the proposed event-driven EDF-based setup strategy comes into play. The event-driven aspect of the EDF-based setup scheme is highlighted by the fact that it is activated on the occurrence of an arrival event. As will be shown later, the proposed EDF-based setup scheme is driven not only by the occurrence of arrival events but also by the occurrence of departure events.

So, the arrival of t_{AC} causes the EDF-based setup strategy to be activated. Consequently, the proposed strategy examines the pending requests at node A one at a time and tries to service each request in turn. Obviously, either all of the pending requests will be provisioned or the proposed strategy will reach a pending request whose provisioning is impossible and put an end to the probing process. In the context of the considered example, t_{AB1} is examined and found to be non-admissible. Therefore, the proposed strategy concludes that none of the pending requests t_{AB1} and t_{AB2} can be admitted to the network.

Consider next the operation of the proposed strategy when a departure event occurs. Suppose that the already established T_{A-B} connection departs from the network before the deadline of t_{AB1} is violated. On the occurrence of the departure event, the EDF-based setup scheme is enabled requiring A to scan through the queue of pending requests and attempt to establish each pending request in turn. Following the departure of T_{A-B}, one of the wavelength on the $A-B$ fiber link is liberated allowing thus the accommodation of t_{AB1}. After the establishment of t_{AB1}, the EDF-based strategy discovers that t_{AB2} cannot be admitted and terminates its execution.

2.2 Case of a transparent optical network

Let us now look into the operation of the proposed EDF-based setup strategy in the context of a transparent optical network. In transparent optical networks, none of the OXCs is equipped with a wavelength converter. This means that a lightpath is established on a route only if there exists at least one wavelength which is simultaneously free on all the links of that route. Such a constraint is referred to as the *wavelength continuity constraint* (wcc). Given that wcc requires the optical network to allocate a connection the same wavelength on all the links along its route, t_{AC} will be blocked due to the inexistence of a wavelength continuous path between A and C. In fact as shown in Fig. 1, λ_1 is busy serving T_{A-B} while λ_2 is occupied by T_{B-C}.

Recall that the proposed scheme is driven by both arrivals and departures. So, the arrival of t_{AC} activates the EDF-based setup strategy. In the context of the scenario under study, t_{AB1} will hence be provisioned into the network. Then, the setup scheme turns to the next pending request attempting to serve it. This process continues until the setup strategy reaches a pending request that cannot be routed into the network. In this case, since the establishment of t_{AB2} turns out to be impossible, the setup scheme stops and inserts the blocked request t_{AC} into the EDF queue at the appropriate position relative to t_{AB2}. Given that t_{AB2}'s deadline is less than that of t_{AC}, t_{AC} ends up being enqueued behind t_{AB2}. As time evolves, the degree of urgency of both t_{AB2} and t_{AC} increases. Ultimately, if one of the pending requests reaches its deadline, that request is immediately dropped out of the queue, in which case a *deadline mismatch* is said to have taken place. Subsequently blocked connection requests whose deadlines are less than the deadline associated with t_{AC} are placed in front of t_{AC} in the EDF queue and as such are served prior to t_{AC}. Note that if the number of such connection requests is large enough, t_{AC} may end up being pushed out of the EDF queue. It is clear accordingly that the deadline mismatch, the process of pushing a connection out of the EDF queue and buffer overflow are the main causes for connection blocking in an optical network employing the proposed setup strategy.

Upon the occurrence of a connection departure event, say the departure of the previously provisioned t_{AB1} connection, the EDF-based setup scheme is enabled allowing the acceptance of t_{AB2} provided that its deadline is not violated. However, the setup scheme fails to serve t_{AC}. Hence, t_{AC} becomes the sole pending request in the EDF queue and would thus be obliged to wait until the next arrival or departure event occurs before retrying to access the network.

2.3 Generic description of proposed setup strategy

The EDF-based connection setup strategy proposed in this paper is activated upon the occurrence of two types of events, namely the departure and the arrival of connections. When a connection emanating from an arbitrary source node A departs from or arrives at the network, the setup strategy proceeds as follows. It scans through the EDF queue associated with A aiming at provisioning as many pending requests as possible. This process continues until either all pending requests are provisioned or the setup strategy comes across a pending request whose setup is impossible, in which case the setup strategy stops its probing for possible connection setups. This suggests that the proposed event-driven EDF-based setup strategy enjoys a wide setup probing scope.

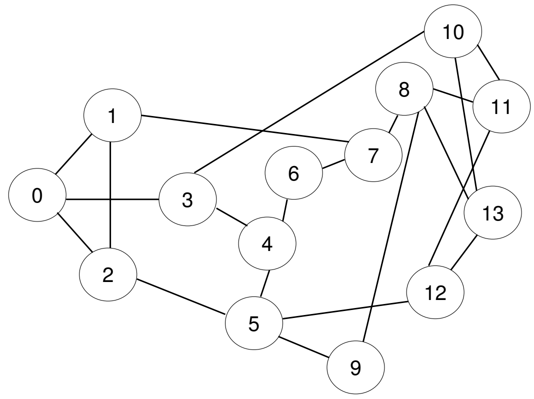


Fig. 2 NSFNET network topology with 14 nodes and 21 links.

3 Related Work

The authors in [6–8] tackled the problem of dynamic bandwidth allocation for Deadline-Driven Requests (DDRs). The algorithms that they proposed aimed mainly at allowing for flexible transmission rates during the provisioning of DDRs in WDM optical networks. Their approach differs from the one investigated in this paper in that they consider the deadline to be the maximum connection holding time. Nonetheless, the authors of [6–8] can supplement their algorithms with the connection setup strategy considered in this paper to increase the fraction of DDRs that are successfully provisioned into the network.

Similarly, the authors of [17] considered the problem of scheduling lightpaths and computing resources for sliding grid demands in WDM networks. Through perfect knowledge of the holding time of a lightpath, they were able to devise an optimal scheduling algorithm that determines the start time of the connection and the amount of resources to be allocated. Unlike [17], the present study does not make any such assumption. Instead, the proposed connection setup strategy relies only on the delay tolerance of the optical client to reduce the percentage of connection setup requests that are blocked due to resource shortage. As such, the devised solution is best viewed as a distributed one with imperfect information as opposed to the centralized solution with perfect information given in [17].

The authors of [9] studied the effectiveness of using an EDF-based queue for managing the setup of point-to-point connections in optical networks with single-wavelength fiber links. The work in [10] is an extension to [9] where the authors considered the multi-wavelengths fiber links' case. However, both of the aforementioned studies lacked generality as they did not assess the performance of their corresponding EDF-based connection setup management schemes when applied to a wavelength routed optical network. Indeed, it was proven in [11–13] that the EDF-based strategies proposed in [9, 10] may not be as efficient as expected when utilized in such networks. Instead, the authors presented improved strategies which they showed to be more suitable for wavelength routed optical networks. Nevertheless, those improved strategies also suffered from two major limitations: *a*) they were driven only by connection departures and *b*) they solely served the head-of-line pending request when a departure event occurred.

This paper alleviates the above observed deficiencies by introducing an improved event-driven EDF-based connection setup policy that, first, accounts for both a connection's arrival and departure, and second, ensures the setup of a wider spectrum of the pending requests upon the occurrence of a departure or an arrival event. This is achieved by having the proposed scheme target not only the head-of-line pending request but also a large portion of the other pending requests that may potentially be provisioned into the network. Finally, as a distinguishing feature from [14], this paper applies the EDF-based setup strategy to the case of all-optical WDM networks without wavelength conversion.

4 Simulation Study

A Java-based discrete event simulator was developed to analyze the performance of the proposed event-driven EDF-based connection setup strategy in the context of the *National Science Foundation Network* (NSFNET) optical network topology depicted in Fig.2. NSFNET consists of 14 nodes and 21 bidirectional fiber links. The data relating to the physical topologies of NSFNET was taken from [15]. Both an opaque and a transparent network architectures are considered for NSFNET in the simulation study, which is based on the following assumptions:

1. Incoming connection requests are uniformly arranged into 3 service classes referred to as gold, silver, and bronze.
2. Each incoming connection request has a bandwidth requirement of one wavelength unit.
3. The overall arrival process is Poisson and the connection holding time is exponentially distributed with a mean normalized to unity.
4. Following the guidelines presented in [4, 5], the parameters associated with the three service classes are as follows:
   – Gold connection requests arrive with an initial deadline of 6 units of time.
   – Silver requests have deadlines of 10 units of time associated with them.
   – The initial deadline of the bronze requests is set to 14 time units.
5. One EDF queue is deployed per optical node with a capacity to hold up to 20 pending connection requests.
6. The fixed routing algorithm [16] is used to route the arriving connections.
7. Wavelengths are assigned to the provisioned connections according to a first-fit strategy in the context of the transparent optical network architecture.
8. The capacity of each fiber link is set to 8 wavelengths in each direction.

It is important to stress that 10^6 connection requests are simulated per run of the simulator and that each obtained value of the results is the average of the outcomes of multiple simulation runs to ensure that a 95% confidence interval is realized. The 10^6 simulated connection requests are uniformly distributed among the nodes of the considered optical networks.

4.1 Performance Metrics and Benchmarks

The performance metrics used to gauge the benefits of the proposed event-driven EDF-based connection setup strategy are: (i) the overall blocking probability and (ii) the blocking probabilities for gold, silver, and bronze connection requests. Note that the blocking probability is nothing else but the fraction of connection requests whose access to the network is blocked. Blocking could occur either due to: (i) buffer overflow, (ii) deadline mismatch which, as mentioned earlier, happens when a request's CST expires prior to its provisioning, or (iii) the pushing of a pending connection out of the EDF queue.

Three connection setup management approaches will serve as benchmarks:

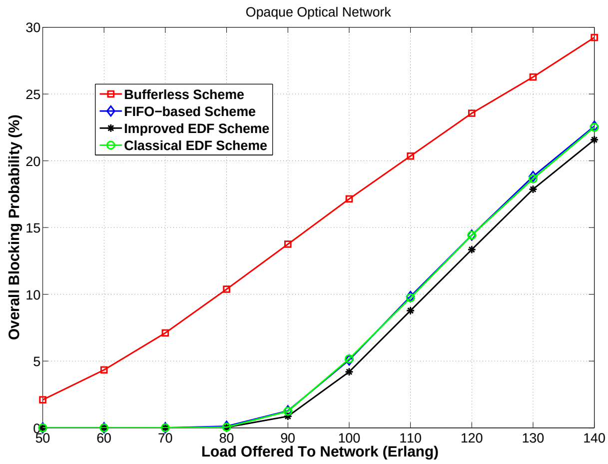


Fig. 3 Overall rejection probability for different setup strategies.

– A queue-free connection setup strategy, where no queues are used to store the blocked connection requests due to optical resource unavailability. This strategy will be referred to henceforth as the *Bufferless Scheme*.
– A First In First Out (FIFO) queue-based connection setup scheme, where blocked connections requests are queued and then served according to the FIFO principle.
– The EDF-based connection setup mechanism studied in [11–13].

In order to distinguish the newly proposed event-driven EDF-based strategy from the one defined in [11–13], this paper will refer, in what follows, to the proposed strategy as the *Improved EDF-based* (IEDF) connection setup strategy.

4.2 Numerical Results for Opaque Optical Network Architecture

Consider an opaque architecture for the NSFNET topology shown in Fig. 2. In this context, Fig. 3 compares the overall rejection probabilities achieved by all of the IEDF and the three benchmark schemes as a function of the load offered to the network. IEDF clearly outperforms the other three strategies as it presents the lowest blocking probabilities. In contrast, a bufferless scheme yields the worse performance in terms of the overall blocking probability since, simply, blocked connection requests are immediately dropped. Building on this observation, this scheme will not be considered in the subsequent set of results. It is worth mentioning that by limiting their setup probing scope to only the head-of-line pending request, the FIFO-based and the traditional EDF-based schemes achieved the same overall blocking probabilities and hence their blocking probability curves overlapped with each other.

The rejection probabilities for gold connection setup requests resulting from the deployment of the FIFO-based, EDF-based, and IEDF connection setup schemes are graphed in Fig. 4 in the context of the opaque NSFNET network. Based on the reported results, smaller gold rejection probabilities are observed for the classical EDF-based and IEDF schemes relatively to the FIFO-based strategy. This finding can be justified by the fact that, in terms of access to the network, the EDF-based and IEDF schemes privilege the connections with the smallest deadline requirements (*i.e.* gold connections). Furthermore, in contrast to the traditional EDF-based scheme, targeting more than one of the front pending gold connection setup requests upon the occurrence of a departure or arrival event, enabled IEDF to provision a larger number of those requests. This is due mainly to the fact that gold connection setup requests are most likely to be found towards the front of the EDF queue because of their small deadline requirements and thus have a higher chance of being provisioned on time under the proposed IEDF scheme. **To provide further insight into the improvement introduced by the deployment of the IEDF scheme, consider a load value of 140. Under this load value, it was found that the classical EDF-based scheme incurs a blocking probability of 5.5% for gold connections while the IEDF one yields a blocking probability of 3.4%, for an overall improvement of approximately 40%. Consequently, it is obvious that the proposed IEDF connection setup scheme causes a smaller number of gold connection setup requests to be blocked and as such results in a better quality of service from the perspective of gold clients.**

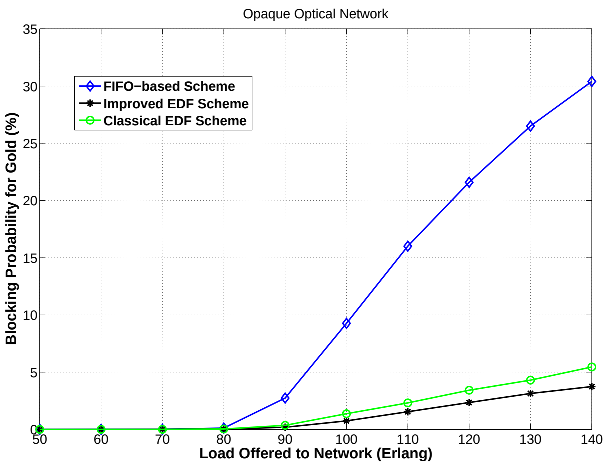
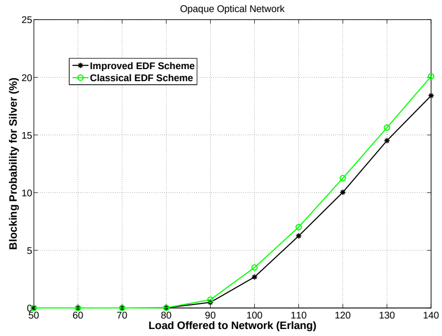
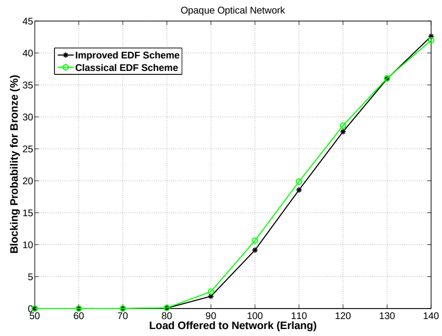


Fig. 4 Gold rejection probability for FIFO, classical EDF, IEDF based setup schemes.



(a) Silver Blocking Probability.



(b) Bronze Blocking Probability.

Fig. 5 Silver and Bronze blocking probabilities for classical EDF and IEDF based setup scheme.

Fig. 5(a) shows the rejection probability associated with silver connections for different values of the network's offered load. The results demonstrate that IEDF is also hard to beat when it comes to the provisioning of silver connection setup requests in comparison to the traditional EDF-based scheme. This is again due to the fact that silver connection setup requests occupy the middle of the EDF queue and thus can benefit from the wider setup probing scope characterizing IEDF. This feature causes more silver setup requests to be provisioned on time and accordingly reduces the silver rejection probability.

Fig. 5(b) compares the performance of IEDF to that of the EDF-based strategy in terms of the rejection probability corresponding to bronze requests as a function of the network offered load in the context of the opaque NSFNET network architecture. The fact that IEDF privileges gold and silver connection setup requests in terms of network access comes at the expense of bronze requests. This explains the slightly degraded performance that the bronze requests experience under IEDF compared to the EDF-based strategy.

4.3 Numerical Results for Transparent Network Architecture

This subsection discusses the results pertaining to the case when there is no wavelength conversion in the nsfnet topology. Under this condition, the overall blocking probability is expected to be higher due to the fact that a call is denied access due to both capacity exhaustion and wcc. Indeed, equipping the network with wavelength conversion capability is advantageous in that it decreases the blocking probability. This fact is asserted by the results reported in Fig. 3 and Fig. 6. A closer look at these figures reveals for example that an opaque architecture yields a blocking probability of 17% at 100 Erlang while its transparent counterpart incurs a blocking probability of 20.5% at that same load. Nonetheless, as shown in Fig. 6, the proposed IEDF setup strategy still presents the lowest blocking probabilities and hence the best performance compared to the benchmark strategies. In addition, the bufferless scheme remains the strategy with the worse blocking performance.

From Fig. 7, it is clear that the gold blocking probability curves follow a pattern that is analagous to the one observed in the case of the opaque nsfnet architecture. The FIFO-based scheme has a higher blocking probability relative to the IEDF and EDF-based schemes. However, it is important to highlight that the percentage of improvement is larger for the opaque architecture. For instance, in the case of the opaque nsfnet topology the percentage of blocking reduction achieved by IEDF with respect to the FIFO-based scheme is 88% at 140 Erlang while the one realized under the transparent architecture is approximately 80% at that same load. This is normal since the percentage of connection requests that can be rescued by IEDF drops in a transparent network architecture due to the wcc factor characterizing such a network architecture. **In addition, when contrasting the performance of IEDF with that of EDF under a load of 140 Erlang in the context of the transparent architecture, one can notice that while EDF causes a blocking probability of 10.6% for gold connections, the proposed IEDF scheme exhibits a blocking probability of 6%. This is equivalent again to a 40% percent blocking probability enhancement, which further reinforces the status of the IEDF scheme as the best choice when it comes to connection setup management.**

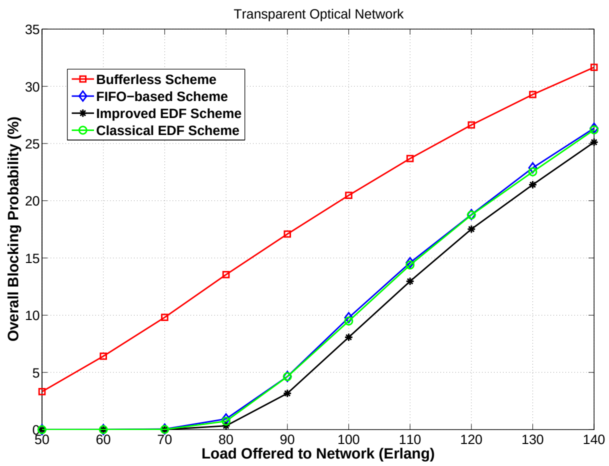


Fig. 6 Overall rejection probability for different setup strategies.

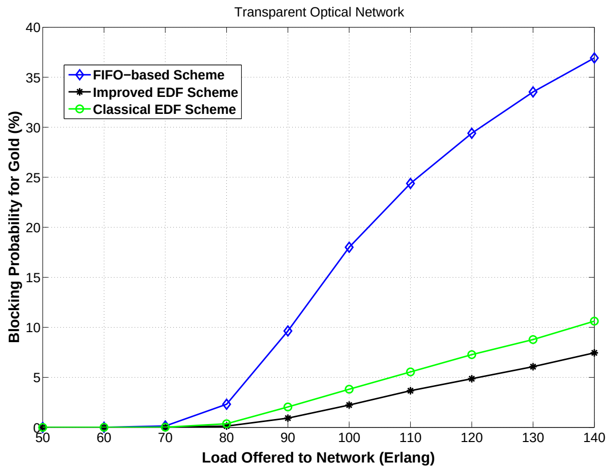
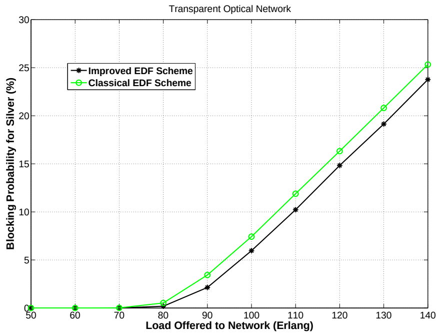


Fig. 7 Gold rejection probability for FIFO, classical EDF, IEDF based setup schemes.

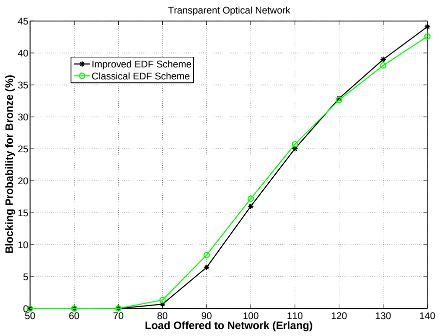
Finally, the conclusions that can be drawn based on Fig. 8(a) and Fig. 8(b) are similar to the ones highlighted in the case of the opaque network topology. Particularly, the IEDF scheme rescues more silver connections than the classical EDF-based scheme. The latter nevertheless is slightly better when it comes to the reduction of the blocking probability experienced by the bronze connection setup requests.

5 Conclusion

This paper proposes to improve the performance of the traditional EDF-based setup strategy studied in the open literature by making it event-driven and by having it serve a large number of pending setup requests. The main idea behind the improved strategy lies in triggering the setup of pending connection setup requests upon the arrival of new connection requests and the departure of existing connections. This increases the likelihood that a pending setup request gets established



(a) Silver Blocking Probability.



(b) Bronze Blocking Probability.

Fig. 8 Silver and Bronze blocking probabilities for classical EDF and IEDF based setup scheme.

before its associated deadline reaches 0, that is, before a deadline mismatch occurs. The other feature that characterizes the proposed event-driven scheme is its ability to provision larger numbers of pending setup requests per arrival/departure event relative to the traditional EDF-based setup scheme. Performance analysis of the event-driven connection setup strategy was carried out by simulation so as to measure its impact on the quality of service perceived by the end clients under an opaque and a transparent optical network architectures.

In the simulation study, the performance of the improved EDF-based (IEDF) setup approach was also compared to that of multiple other benchmark schemes, including the traditional EDF-based setup scheme. The obtained simulation results proved that IEDF has the upper hand when it comes to rejection probability improvement. Moreover, the simulation results showed that IEDF supports quality of service differentiation while reducing the blocking probability of the incoming connection requests. This was affirmed by the ability of IEDF to reduce the overall blocking probability while privileging high priority clients with respect to network access.

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