Deferred Protection of Deadline-Driven Requests in Inter-Datacenter Elastic Optical Networks

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***Abstract*—Inter-Datacenter Elastic Optical Networks (IDC-EONs) can serve increasing traffic demands among distributed datacenters (DC). Inter-DC traffic demands are typically characterized by flexibility in terms of start time, end time, and assigned transmission rates. In addition, such traffic demand can have a backup data transfer path that can be flexibly scheduled (as long as it is completed before a certain deadline). Such demands are called Deadline-Driven Requests (DDRs). For high DDR transmission rates, even a few milliseconds of traffic interruption (e.g., due to some equipment failure) can result in huge amount of data loss. Existing protection mechanisms against failures, such as Dedicated Path Protection (DPP), originally designed for transport networks, have limitations in case of IDC-EONs due to high spectrum utilization. This work proposes a novel DPP approach applicable to DDRs in IDC-EONs, called Deferred Protection (DP), which schedules the backup path at a later time than the working path, and its reservation can be gradually removed while the working data is successfully delivered. Illustrative numerical results demonstrate that DP decreases blocking probability and provides more efficient use of spectral resources compared to traditional DPP for realistic case studies.**

***Index Terms*—Inter-datacenter elastic optical networks; deadline-driven requests; dedicated path protection; deferred protection.**

I. INTRODUCTION

Inter-Datacenter Elastic Optical Networks (IDC-EONs) are a promising candidate for next-generation inter-DC networks thanks to their ability to flexibly support diverse rates of modern cloud services. Most cloud services require to transmit large amount of data (e.g., tens to hundreds of GBs) before a pre-established deadline [1]. In these types of services, e.g., data backups/synchronization, the maximum allowable time to complete a data transfer is defined by the service requirements. Hence, there is flexibility in its transmission rate, starting time, and end time, as long as deadline is met. These kind of requests are called as Deadline-Driven Requests (DDRs).

Survivability is an important research problem in IDC-EONs, as, given the high data rates in IDC-EONs [2], interruptions of a few milliseconds can lead to significant data loss [3]. Dedicated Path Protection (DPP) is a well-known protection technique traditionally deployed in optical networks to prevent such losses. DPP assigns a dedicated backup route to each established primary route, such that, in case of a failure in the primary path, the dedicated protection path can take over the data transfer.

The traditional DPP schemes (e.g., 1+1 and 1:1, in this study we will focus on the later) have inefficiencies in IDC-EONs, particularly in case of deadline-driven services, e.g., in terms of excessive spectrum utilization [4]. As transmission rates across DCs increase, need for more efficient protection schemes becomes more compelling. A deadline-aware protection scheme, which can leverage DDRs' flexibility, is needed to overcome the inefficiencies of traditional DPP schemes.

In this study, we present a novel protection mechanism for DDRs in IDC-EONs. Our proposal is based on the concept of *deferred protection*, i.e., we consider reserving capacity for the dedicated backup path of DDRs in later time intervals with respect to the working paths, as long as deadline is not violated. Besides, instead of deallocating backup resources only after the transfer of primary resources is completed, we implement a new deallocation policy, which allows dynamic removal of backup capacity (namely, frequency slots in the IDC-EONs) just after some subsets of working data has been transferred. These two features are jointly considered in our proposed heuristic Routing, Modulation Level, and Spectrum Assignment (RMLSA) algorithm (named DP+DD), that allows to periodically schedule and assign proper bandwidth for primary and backup routes of DDRs within a pre-determined deadline. To the best of our knowledge, this is the first study to address the problem of deferred protection of DDRs in IDC-EONs.

The rest of the study is organized as follows: Section II discusses related works. In Section III, we introduce the proposed protection mechanism and related heuristic algorithm. Numerical examples are presented in Section IV. Section V concludes the paper with possible future directions.

II. RELATED WORK

The problem of providing DPP to DDRs in IDC-EONs has not been addressed in the literature yet but several studies have approached survivability and DDRs in EONs separately, or applied them in other research areas.

Ref. [5] addressed an offline version of the Routing and Spectrum Assignment (RSA) problem with DPP in Elastic Optical Networks (EONs), where an optimal solution based on integer linear program (ILP) and meta-heuristic algorithms for large-scale optimization instances were developed. Also, in [6], the RSA problem with DPP was formulated as an ILP

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and a heuristic solution was proposed, but for mixed unicast and anycast demands. In [6], the problem is solved while accounting for physical-layer impairments.

Ref. [7] presented a solution to the RMLSA problem, that takes into account survivability and traffic behavior in time domain in EONs. Different survivability policies were presented by considering immediate reservation (IR) and advanced reservation (AR) requests. By taking into account survivability, for protection of IR and AR requests but not DDRs, the work in [7] is the closest to our proposal. IR and AR differ from DDRs as requests whose start time of data transmission is specified (AR) or assumed to be immediate (IR) yet not necessarily must be delivered before a pre-established deadline (DDRs). Ref. [4] evaluated energy and cost-efficiency of EONs and compares them with conventional wavelength-division-multiplexing (WDM) networks. Due to importance of resilience in optical networks, they also evaluated different protection schemes. Again, DDRs were not addressed in this study.

DDRs have been subject of study in several areas of networking, such as silicon-photonics interconnection networks [8], cloud computing [9], flow scheduling systems [10], inter-datacenter transfers [11], multicasting in overlay networks [12], and bulk-data transfers [13].We will concentrate below on the most relevant contributions with respect to our problem in EONs.

Ref. [12] considered a multilayer optimization problem that combined two approaches: (1) optimization of overlay multicast DDRs and (2) provisioning of created overlay multicast DDR trees as a sets of unicast demands in the underlying EONs. Although this study addressed the use of DDRs in EONs, survivability was not considered.

Authors in [13] proposed joint frequency and time-domain optimization algorithms of static RSA for DDRs in EONs. They formulated the problem as an ILP and then proposed six scheduling schemes, which combine three request ordering strategies with two RSA algorithms. However, Ref. [13] studied an offline version of the RSA problem, and survivability was not considered. As previously stated, none of these works address the problem of DPP for DDRs in IDC-EONs.

III. AN ALGORITHM FOR DPP OF DDRS BASED ON DEFERRED PROTECTION

Here, we present a novel approach to provide DPP to DDRs based on deferred protection, and we described a heuristic RMLSA algorithm (DP+DD) to allocate resources to connections using our proposed scheme. The approach consists of two steps: (i) a new scheme to reserve protection capacity, called Deferred Dedicated Path Protection (DDPP) and (ii) a novel backup deallocation policy, called Dynamic Deallocation of Backup Slots (DDBS).

A. *Deferred Dedicated Path Protection (DDPP)*

The DDR request model offers high flexibility in the search for feasible primary and backup paths. That is because, as long as the requested amount of data is transmitted before the deadline, different transmission rates and holding times can be used to transmit the data on the primary path and to protect it on the backup path. Deferred Dedicated Path Protection (DDPP) is a novel protection scheme that benefits from such a flexibility by decoupling both the bandwidth provision and reservation time of the primary path from the backup path. Hence, when the reservation mechanism is called, it chooses the primary path as the one with the maximum number of available slots, taking as a reference the current time. The idea behind using the maximum transmission time is to shorten its holding time, which in turn may allow accommodating new requests while giving more degree of freedom to the search for backup resources. After that, it searches for the backup path taking into consideration for the bandwidth assignment, the remaining time and the amount of data to be transmitted. The main idea behind reserving resources in a late period is to have more available spectrum at current time (so that blocking probability is minimized) while still keeping the data transmissions protected.

It is worth noticing, since deferred protection is designed to operate with DDRs and might not occur in parallel with the primary/working data, in case of a failure, protection switching time becomes irrelevant as long as the requested deadline is met. In fact, reservation of backup resources will be scheduled at a future instant of time after transmission through primary path is over, and will only be activated in case of a failure in the primary path.

Fig. 1 illustrates the differences between the proposed protection scheme and existing dedicated path protection scheme DPP 1:1. In Fig. 1(a), the operation of a DPP 1:1 scheme is shown. Although the data is transmitted only on the primary path, while the backup path is reserved for use in case of failure, primary and backup resources are assigned simultaneously (same start and end times). In this configuration, during normal network operation, backup path can also be used for transmission of low-priority traffic. In the event of a failure on primary path, transmission of low-priority traffic in backup path is interrupted, and the backup

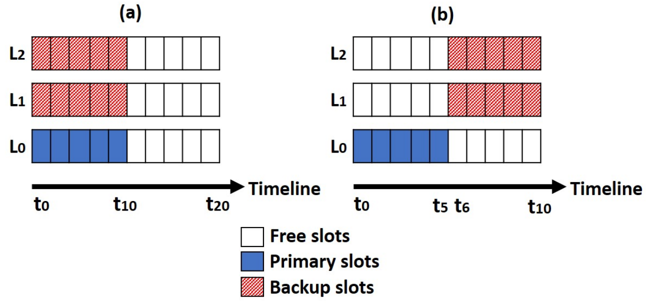

Fig. 1. Differences between (a) DPP 1:1 and (b) DDPP protection schemes. Consider in this example that deadline for finishing the transmission is 10 s. Thus, start and end time of primary/backup paths in DPP 1:1 are the same (from t_0 to t_{10}). In DDPP, however, start and end time of primary/backup paths are different (the first is provisioned from t_0 to t_5 and the latter from t_6 to t_{10}).

path is used to restore the primary transmission affected by the failure. Fig. 1(b) shows the operation of the proposed DDPP scheme. Main difference between DDPP and the other protection scheme is that DDPP is a deadline-aware protection scheme, i.e., it takes advantage of the flexibility offered by DDRs to perform data protection. This way, DDPP starts transmitting data only through the primary path and schedules the transmission through the backup path at a later time (different start and end times), without violating the deadline.

B. Dynamic Deallocation of Backup Slots

Dynamic Deallocation of Backup Slots (DDBS) is a policy that gradually and dynamically removes backup frequency slot reservations while the working data is successfully delivered. A frequency slot is a portion of optical spectrum (usually with spectral width of 12.5 GHz) that is used to represent the amount of data being transmitted. The idea behind this policy is that, as each request needs to be transferred in a certain time, each allocated primary slot of this request will take a certain period of time to be transferred. We call "transmission time per slot" (TT_{slot}) the amount of time to transmit each slot of a given connection. Note that, as different connections may have different transmission times, TT_{slot} may also may be different from one connection to another. TT_{slot} can be calculated as follows:

$$TT_{slot} = \frac{TT_{req}}{NSlots_{req}}, \tag{1}$$

where TT_{req} is transmission time of the request and $NSlots_{req}$ is total number of slots of the request, i.e., sum of frequency slots allocated in each link of the chosen primary path. So, after the duration time of a slot is passed, we can assume that the amount of data in this transmitted slot no longer needs to be protected, allowing the backup slots protecting it to be removed. This process is illustrated in Fig. 2. During transmission time, as primary slots are being successfully transferred, they no longer need to be protected, allowing the corresponding amount of backup slots to be removed from the backup path, thus increasing the availability of spectral resources.

The number of frequency slots to be removed (NS_{rm}) from the backup path can be calculated as follows:

$$NS_{rm} = \frac{TT_{slotP}}{TT_{slotB}}, \tag{2}$$

where TT_{slotP} and TT_{slotB} are the "transmission time per slot" of the primary and backup paths, respectively. For example, let us consider the transmission time of the request ($\mathrm{TT}_{request}$) in Fig. 2 to be 5 seconds. In this example, primary and backup paths have different lengths (hence different modulation formats). So, by calculating TT_{slot} of the primary path using Eqn. (1), we find that TT_{slot} of primary path is 1 s. Then, we calculate TT_{slot} of the backup path using the same equation, finding that TT_{slot} of backup path is 0.5 s. So, using Eqn. (2), we find that each transmitted primary slot is equivalent to, in this example, two backup slots. Therefore, as depicted in Fig. 2, for each transmitted slot in the primary path, two slots with the closest time are removed from the backup path by DDBS policy. Note that we start removing from the closest time and not from the furthest because we want closer available spectrum to serve incoming requests that may require using these links. However, since removal of the furthest slots can be beneficial at light loads, a comparative analysis between both cases will be addressed in future work.

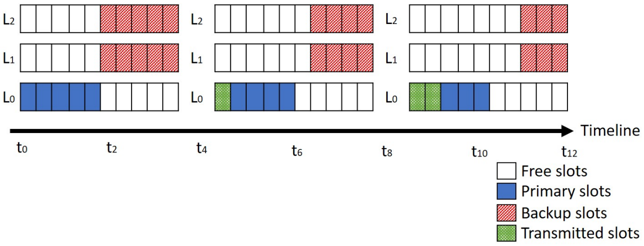

Fig. 2. Operation of DDBS policy.

C. Heuristic RMLSA Algorithm for DDRs

Our RMLSA algorithm is called Deferred Dedicated Path Protection with Dynamic Deallocation of Backup Slots (DP+DD). As arriving requests are deadline-driven, they are defined as tuples $r_i = (s, d, b, t_i, D_M)$, where *s* is source node, *d* destination node, *b* is amount of data to be transferred, t_i is request arrival time, and D_M is maximum allowed time to finish the data transfer. We assume that a lightpath can only be established if it can be protected by a dedicated backup path.

To guarantee protected transmission of the requested data within the deadline, DP+DD calculates minimum transmission rate (and hence, transmission time) of the incoming request based on $TR_{min} = {}^{b}\!/_{t}$, where *b* is amount of data to be transferred and *t* is transmission time to be considered.

DP+DD is formally described in Algorithm 1. Whenever a new request r_i arrives (line 1), DP+DD must calculate the transmission time and associated transmission rate for r_i (line 2). Hence, initially, DP+DD calculates the minimum transmission rate required to ensure that transmission time (or "holding time") is ${}^{1}\!/_{n}$ of the required deadline. After that, search for primary path starts by seeking for all shortest paths with source node *s* and destination node *d* and storing it in $Sp_{s,d}$ (line 3). Then, for a given *path* in $Sp_{s,d}$ (line 4), we compute its length and appropriate modulation format (line 5). Line 6 verifies if this *path* has enough available slots to accommodate r_i. If so, *path* is defined as *primary path* of r_i (line 7). If not, remaining paths in $Sp_{s,d}$ are tested (Line 6). If no path with available spectrum is found (line 8), then r_i is blocked (Line 20). If there is a *primary path* defined for r_i, DP+DD starts searching for another *path* in $Sp_{s,d}$ (line 9) that must be disjoint of the *primary path* (line 10). If such *path* is found, its availability is then verified to protect the *primary path* of r_i (line 12). If this *path* is able to do so, it is defined as *backup path* of r_i (line 13). If no other path is found (line 14), r_i is blocked (Line 20). If two disjoint paths

Algorithm 1: DP+DD Algorithm

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1  Arrival of request $r_i$;
2  Calculates transmission rate and transmission time for $r_i$;
3  Search for all shortest paths with s-d pair of $r_i$ and stores in $Sp_{s,d}$;
4  for $path\ in\ Sp_{s,d}$ do
5      Compute path length and modulation format;
6      if $path$ is able to accommodate $r_i$ then
7          $path$ is defined as primary path;
8  if ∃ primary path then
9      for $path\ in\ Sp_{s,d}$ do
10         if $path \neq$ primary path then
11             Compute path length and modulation format;
12             if $path$ is able to accommodate $r_i$ then
13                 $path$ is defined as backup path;
14     if ∃ backup path then
15         $r_i$ is accepted;
16         Allocate $r_i$ in primary path and reserve in backup path;
17         While wait for $r_i$ holding time, deallocate from backup path using DDBS policy;
18         After $r_i$ transmission time, deallocate and close $r_i$ from primary path;
19     else
20         Blocks $r_i$
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with available spectrum are found, then r_i is accepted (line 15). Line 16 executes the spectrum allocation (*primary path*) and reservation (*backup path*) ensuring spectrum continuity and contiguity constraints. Then, while the holding time of r_i is not over, DDBS policy dynamically removes backup slots that are no longer protecting primary slots (line 17). After r_i transmission time, primary slots are deallocated and both connections are closed (line 18). Runtime complexity of DP+DD algorithm is on the order of $\mathcal{O}((W + P) \times E \times T)$, where *W* and *P* represents the search for primary and backup paths, respectively, *E* represents the spectrum assignment and *T* the assignment in the time domain.

IV. NUMERICAL EXAMPLES

We developed a discrete-event simulator in Python to evaluate the performance of DP+DD. In an IDC-EON scenario, we compared DP+DD with DPP 1:1 protection scheme[1] applied to a RMLSA algorithm, in line to the one proposed in [4]. The comparison between DP+DD and DPP 1:1 was divided in two parts: first, we evaluated overall performance of DP+DD compared to DPP 1:1 protection scheme. For this, transmission-rate assignment in DPP 1:1 was performed in traditional way, i.e., using minimum transmission rate required to meet the requested deadline. For DP+DD, however, we used proportion $1/n$ of the required deadline (with n = 4, 3 or 2, depending on spectrum availability). DP+DD starts with $1/4$ of the deadline in an attempt to finish the data transfer as quickly as possible, since we have discovered through simulations that, in our settings, with higher bandwidth assignments (hence transmission times shorter than $1/4$ of the deadline), there are no performance gains in terms of blocking probability (more sensitivity analisys of this parameter is left as future work). For this first scenario, we use the acronyms 'DP+DD' and 'DPP 1:1'. In the second part, we decided to evaluate in isolation the performance of deadline-aware scheduling of backup path in our proposed scheme, fixing the transmission-rate assignment. For this, we performed transmission assignment in both DP+DD and DPP 1:1 using the same transmission rate and same deadline proportion ($1/2$ of required deadline). For this scenario, we use the acronyms 'Fixed DPP 1:1' and 'Fixed DP+DD'.

Independent simulation runs with 10,000 requests randomly generated among all node pairs were repeated, and blocking results were averaged to generate plotted results with confidence intervals of +-5% for a confidence level of 95%. Since we are studying an IDC-EON scenario, we considered each network node as a different DC to quantify overall blocking probability (BP), spectrum utilization (SU), and fragmentation ratio (FR) in the network. Amount of data to be transferred among DCs was uniformly extracted between 12.5 GB and 62.5 GB, and request arrivals follow a Poisson process. Deadline to terminate the transmission ranged from 5, 10, 25, and 50 seconds. Network topology used in the simulations was NSFNET, with 14 nodes and 21 edges (Fig. 3).

Each link had 300 slots, with spectral width of 12.5 GHz. Modulation formats used, their respective transparent reaches (km) and capacity per slot (GHz) are: BPSK (4000 and 12.5), QPSK (2000 and 25), 8-QAM (1000 and 37.5), and 16-QAM (500 and 50) [14]. For spectrum allocation and reservation, First-Fit policy was used. Other metrics considered to evaluate the proposed approach were: average number of primary slots (NPS) and average number of backup slots (NBS) allocated per accepted request, and the average duration time (ADT) of accepted requests.

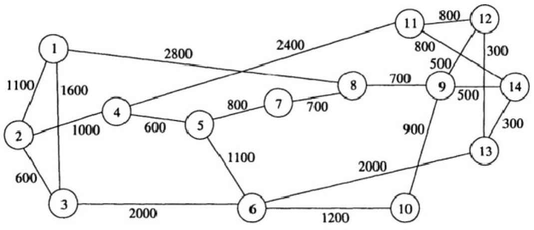

Fig. 3. NSFNET network topology (distances in km).

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[1] As DPP 1+1 is used to minimize protection switching time, and in DDRs real target is deadline, this protection scheme was not considered in simulations.

A. DP+DD versus DPP 1:1

Fig. 4 shows the results for BP (top), SU (center), and FR (bottom) as a function of network load. Results for BP show that DP+DD had best performance, as blocking becomes non-negligible, i.e., in our settings, larger than 10^{-5}, for loads higher than 35Erl (25Erl for DPP 1:1). As the network load increases, the gap remains high (almost 37% less blocking for DP+DD) which demonstrates the utility of using deferred protection and flexible transmission rates. Observing SU, DP+DD and DPP 1:1 present very similar results. We see that DP+DD performs better up to the start of higher loads (65 Erl), where it is surpassed by DPP 1:1. Even though DP+DD performed worse for higher loads, this small difference in terms of SU apart from the great performance for BP further shows the potential of offering deferred protection. Regarding FR, DP+DD also achieved best results, reaching about 15% less fragmentation even under high load. In summary, DP+DD presents significant improvements in terms of blocking probability while providing efficient use of spectral resources without over-fragmenting the network.

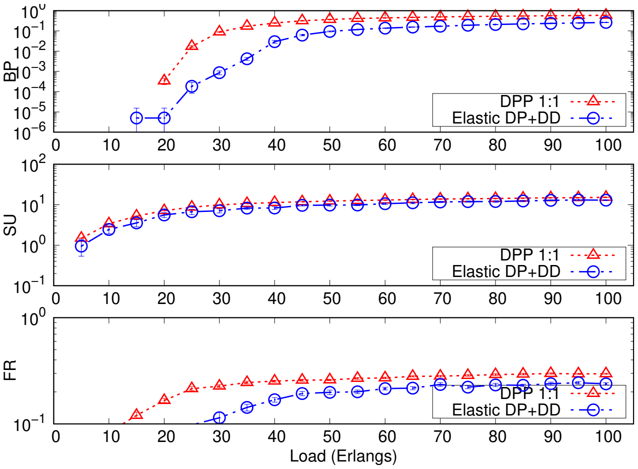

Fig. 4. BP, SU, and FR as a function of network load (Erlangs).

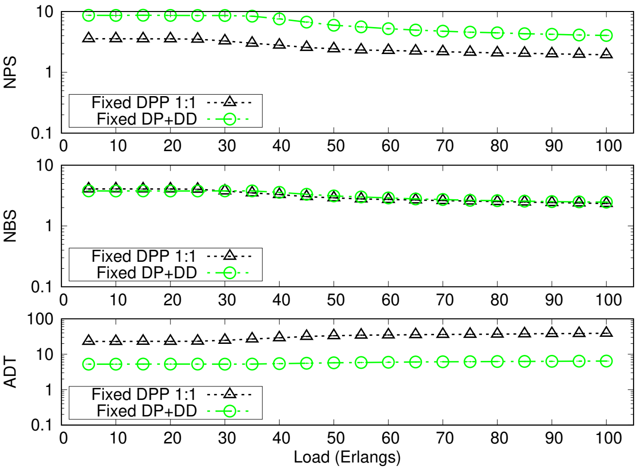

Fig. 5. NPS, NBS, and ADT as a function of network load (Erlangs).

NPS, NBS, and ADT as a function of network load are presented in Fig. 5. As we can see, DP+DD assigns a greater amount of slots for primary paths (top of Fig. 5). Hence, transmission is performed in a considerably shorter time than the deadline. On the other hand, although NBS (center of Fig. 5) of DP+DD is lower than NPS due to more available time to perform data protection, it is still greater compared to NBS and NPS of DPP 1:1. Lastly, as DP+DD allocates more frequency slots in primary paths so that the transmission can be performed more quickly, ADT (bottom of Fig. 5) is much smaller than DPP 1:1. In other words, DP+DD offers more bandwidth so that the requests are allocated for less time, thus avoiding the prolonged negative impacts on normal DC operation by minimizing time interval between backup start and end times.

B. Fixed DP+DD vs. Fixed DPP 1:1

Fig. 6 shows the results for BP, SU, and FR as a function of network load. Top figure shows results for BP. As we can see, blocking for 'Fixed DP+DD' becomes non-negligible considerably later (from 35Erl) than for 'Fixed DPP 1:1' (from 15Erl). As load increases, BP of DP+DD continues to be 28% less than DPP up to the maximum load. This performance of 'Fixed DP+DD' demonstrates the advantage of deferring backup reservation instead of using traditional protection schemes such as DPP 1:1. For SU (center), 'Fixed DP+DD' presented very similar results compared to 'Fixed DPP 1:1', although the latter performed better (especially under higher network loads). In relation to FR (bottom), 'Fixed DP+DD' also had best results, especially under lower network loads. As load increases, the difference becomes smaller (around 2%), although 'Fixed DPP 1:1' never surpasses 'Fixed DP+DD'. This good performance of 'Fixed DP+DD' regarding BP, SU, and FR reinforces the potential and efficiency of using deferred protection.

NPS (top), NBS (center), and ADT (bottom) as a function of network load are presented in Fig. 7. As we can see, 'Fixed DP+DD' and 'Fixed DPP 1:1' had very similar results

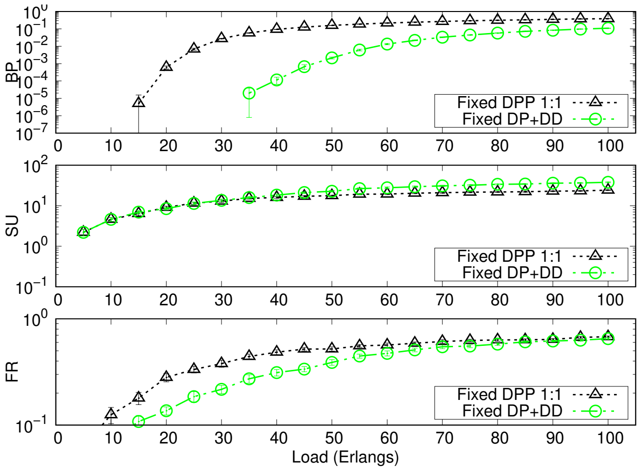

Fig. 6. BP, SU, and FR as a function of network load (Erlangs).

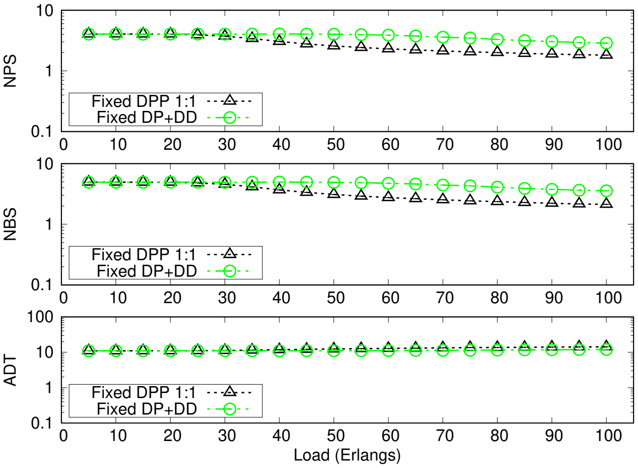

Fig. 7. NPS, NBS, and ADT as a function of network load (Erlangs).

regarding NPS, NBS, and ADT. This similarity was already expected, since we used the same parameters for both rate and transmission time.

V. CONCLUSION

Survivability is very important aspect of IDC-EONs. We proposed a novel approach that offers deferred dedicated path protection of deadline-driven requests, along with dynamic deallocation of backup slots. The proposed DP+DD algorithm shows significant improvement in terms of spectrum utilization and network congestion compared to prior protection approaches. Blocking probability and network fragmentation ratio are reduced by around 37% and 15% in the first scenario and 28% and 2% in the second scenario, respectively. Future studies can improve DP+DD by applying shared backup techniques, elastic protection (i.e., transmission rate associated to backup path can vary in time), and by exploring the space-division-multiplexing techniques.

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