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# Performance of resource delayed release strategy in software-defined OTN over WDM networks for uniform and non-uniform traffic

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ABSTRACT

In today's wide area networks, especially in Optical Transport Networks (OTN) with Software Defined Networking (SDN) features enabled over Wavelength Division Multiplexing (WDM), Bandwidth on Demand (BoD) is an important service that can be satisfied by dynamic end-to-end service provisioning. Service provisioning time (SPT) and Blocking Probability (BP) are critical performance metrics for the users and carriers. This paper extends the concept of the Resource Delayed Release (RDR) strategy for WDM networks. The basic idea of this strategy is to introduce a delay in releasing the optical channel, when the channel is no longer carrying any services. This delay can help speed up the provisioning time for carrying the next service request, avoiding the time usually taken to establish a new optical channel. The main goals of the RDR method are to reduce SPT and BP while simultaneously satisfying the quality of service (QoS) constraints. In this paper, we investigate the effects of uniform and non-uniform traffic on the performance of RDR strategy. For non-uniform traffic simulation, we use a mesh topology with the 14 most populous cities in USA as of 2018 and model the non-uniform traffic based on population density. Further, we introduce a new metric called the Bandwidth Blocking Probability (BBP) to measure the quality of the service offered by the network. Simulation results show advantages of using the RDR method under a wide variety of traffic scenarios for both uniform and non-uniform traffic distributions compared to the traditional method. RDR reduces SPT by 45–90% for uniform traffic and 41–75% for non-uniform traffic. RDR reduces BP by 35–85% for uniform traffic and 30–75% for non-uniform traffic. Additionally, RDR lowers BBP by 31–73% for uniform traffic and 29–68% for non-uniform traffic.

## 1. Introduction

In today's wide area networks, burstiness and time-variation are two critical factors [1] for traffic carried for data centers and bulk data transmissions in eScience networks [2]. A common example of multi-layer telecommunication networks is the Optical Transport Network (OTN) over Wavelength Division Multiplexing (WDM) [3]. Wavelength-division multiplexing (WDM) is used in optical networks in which many wavelength channels are simultaneously transmitted along the optical fiber cable. In these multi-layer networks, the static mode is the common mode which, however, is not an efficient provisioning mode, since it results in low rates of capacity utilization. On the other hand, dynamic service provisioning makes any network more efficient in terms of resource allocation. With the emergence of Software Defined Networking (SDN), dynamic service provisioning becomes more achievable [4]. Applications with SDN features enabled, such as multi-layer bandwidth-on-demand (BoD) and dynamic bandwidth allocation (DBA), have been explored before [5,6]. These applications have the capability to dynamically reconfigure the network based on the user demands.

Recently, some methods with SDN features enabled were proposed to decrease the SPT. In those strategies, the configurations can be sent to the network elements (data-plane) in parallel. No doubt, using parallel configuration mode can help to reduce SPT but it still takes about a few seconds to establish the new channel (approximately 10 s and mostly for power equalization) [7–9].

Erbium-doped fiber amplifier (EDFA) has been introduced as the underlying technology to make these systems possible. Since gain in EDFA does not uniformly change with wavelength, then there is a significant differential signal-to-noise ratio (SNR) and power among many

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channels. Power equalization is needed within DWDM optical network channels to provide reasonable optical signal-to-noise ratios (OSNR). In optical channels, the dependency of wavelength to some optical elements in fiber-optic transmission system, gain or loss of EDFAs, transmission fiber, and dispersion compensators are why the power of the optical channels is not equalized. We need dynamic gain equalization (DGE) in some networks, such as ultra-long-haul (ULH) networks when signals pass through to 50 EDFAs, especially when there is no electrical regeneration, as the problem then becomes more significant. The gain non-uniformity causes lower signal strength and increases above the maximum recommended power in some channels [10].

Our proposed method, Resource Delayed Release (RDR strategy) [1], is an efficient method to reduce Service provisioning time (SPT), Blocking Probability (BP), Bandwidth Blocking Probability (BBP), as the measures of performance. The metric BBP is a ratio of the bandwidth of rejected requests to the total requested bandwidth, and to eliminate power equalization time by adding the concept of the idle state. The idle state starts when the channel is no longer carrying any services. This delay can help speed up the provisioning time for carrying the next service request, avoiding the time usually taken to establish a new optical channel (approximately 10 s and mostly for power equalization). During the idle state, the optical channel and its resources are in standby mode for the certain amount of time called "delay time" ($t_{delay}$) Any new request is carried out by the idle channel immediately without spending time for channel establishment.

The core idea of the Resource Delayed Release (RDR) strategy is to improve the Service Provisioning Time (SPT) performance and reducing the blocking probability by delaying the release of an optical channel when the channel no longer carries any services. Blocking probability represents the chance of a call being blocked due to the channel not being available to serve that call on its arrival. In the traditional model, there is no queue to keep all arrival calls and due to this reason, all new call arrivals are dropped due to no channel being available. However, when RDR is employed the channels are kept in an IDLE state for a certain amount of time after a call ends. If there are any new call arrival during this time period, they are readily picked up by one of the IDLE channels. This procedure intends to save the channel establishment time for that call directly by reducing the time taken for the power equalization phase. It is important to note that, the overall blocking probability of the calls also go down because, when a channel finishes carrying its service, it goes to the IDLE state. Therefore, when there are a limited number of channels and a larger number of calls arriving, RDR strategy reduces the total amount of time all the channels spend in the channel establishment phase. Consequently, the likelihood of a call dropping is lower as the channels are less likely to be busy with establishment time for existing calls. We illustrate this logic with a simple example as follows. This means that there are overall more channels available to accept the incoming calls at a given time compared to the traditional method. Consider 3 calls and a single channel. All 3 calls arrive at three different times and have call durations of 5 s, 1 s and 3 s respectively. The first call arrives at time t1. The channel is established to serve the first call. The first call ends at time t1 + 15 s. Now, the second call arrives at time t1 + 17 s i.e. 2 sec after the first call ended. Therefore, the channel goes through power equalization again for 10 s before serving the second call. The third call arrives at time t1 + 21 s. So when the third call arrives, the channel is being established to serve the second call, and hence the third call is blocked. Now, consider the RDR strategy with the same 3 calls, their arrival times and durations. The first and second calls finish at times t1 + 15 s and t1 + 18 s since there is no power equalization phase for the second call. The channel goes to the IDLE state once the second call finishes. Now, when the third call arrives at time t1 + 21 s, it is not blocked because the channel is IDLE and ready to serve a new call. When we extend this scenario to multiple calls with a range of call durations or service times as well as multiple channels, we could surmise how the blocking probability of the calls is reduced overall owing to the fact that the channel spends less time staying busy for calls. Our strategy also works for reducing the Bandwidth Blocking Probability (BBP) because the number of channels (and hence the number of calls that can be served) is directly proportional to the total available bandwidth.

We study both static RDR and dynamic RDR. In Static RDR X: the released delay "$t_{delay}$" will be set as a static and uniform value for every Idle optical channel. X is the set value for tdelay, which can be a positive number or infinity. D RDR: For different Idle optical channels, "$t_{delay}$" may be set as different values. "$t_{delay}$" should dynamically change due to different traffic loads and service requests, and to increase the service provisioning time. If there are fewer optical channels than our statistics suggest we need, then the value of "$t_{delay}$" for the current idle channel is set to infinity. This is done to prevent the idle channel from being removed, as our statistics suggest that we should be receiving a new request in the near future. Once the number of occupied optical channels is greater than the number we need, "$t_{delay}$" is set as the average duration time of all services. "$t_{delay}$" can not be fixed, It should dynamically change while the real traffic changes. The method will be explained in detail in sections III.

The basic ideas of our approach are as follows:

### 1.1. RDR function in idle state

In our model when an optical channel is idle, i.e., in the idle state, the channel does not carry any services but the channel will not be released immediately. Based on network conditions or formerly set conditions, an amount of time (called $t_{delay}$) will be considered. After the delay time has elapsed, then the channel will be released. In the RDR strategy when the optical channel does not carry any OTN services, it still holds the optical layer resources. Therefore, there will be a reduction of available resources. Consequently, service provisioning for a new request may fail. To handle this situation we come up with an enhancement of resource allocation.

### 1.2. Enhancement of the regular optical resource allocation method

Due to fewer available resources, the service provisioning of any new service request may fail. The following steps complete our method: When a new optical channel is requested, the controller uses the regular resource allocation method (to allocate from all the free optical resources) to create a new optical channel; If the request is not satisfied by the available resources, then all the resources which are occupied by idle channels will be considered for resource allocation. All affected idle optical channels are identified by the controller and they will be removed before creating a new optical channel [1].

The capabilities of our model are namely to avoid or eliminate frequent optical channel establishment in WDM networks. Our strategy helps to reduce the average SPT, BP, and the average BBP. The RDR strategy's effectiveness was evaluated under uniform traffic and non-uniform traffic distributions. The comparison metrics include SPT, BBP, and the number of occupied optical channels. The analysis was performed under three variations of service duration (60, 300, and 1500 s) and over 3 different traffic loads. We used distinct ratios of disparate fixed bandwidth OTN services. Analysis of the results prove the better network performance in terms of service provisioning, BBP, and the number of occupied channels for different types of RDR under both uniform and non-uniform traffic distributions. In non-uniform traffic, BBP is increased. This is due to the fact that requests may get blocked when too many channels are congested or when the bandwidth is not enough. Based on simulations, we observe that SPT and BBP were slightly increased for non-uniform traffic compared to uniform traffic. But in comparison to not using the RDR method, they still give better results.

In a brief earlier work presented at ANTS [1] we investigated RDR strategy in a limited setting under uniform traffic. SPT and BP were the metrics that we used in our earlier work. In this work, we will investigate the adoption of the Resource Delayed Release (RDR) strategy under both uniform and non-uniform traffic scenarios for further reducing SPT and Bandwidth Blocking Probability (BBP).

The remainder of this paper is structured as follows. The background and related work are described in Section II. The RDR strategy is presented in detail in Section III. We present a uniform and non-uniform traffic models in Section IV. Section V shows the simulation results and comparisons between uniform and non-uniform traffic. Finally, Section VI concludes the paper and discusses our future work.

## 2. Background and related work

Significant progress in next-generation optical transport networks was achieved by migrating to 100G wavelengths from 10G and beyond. It is important to evaluate if that evolution can keep the transponder with ROADM (Reconfigurable Optical Add-Drop Multiplexer) architectures efficient. OTN switching functionality is based on using far fewer unique wavelengths and virtualization bandwidth between nodes. In addition, the combination of OTN switching with SDN gives the ability to virtualize optical network bandwidth. Hence, in this paper, we investigate dynamic service provisioning carried out end-to-end (E2E). Therefore, we use the OTN devices over WDM network as access points for the end-to-end client services. Three types of OTN services are used in this work, namely 10G, 40G and 100G. Our work maps E2E OTN services to an Optical Data Unit (ODU) port at the ingress and egress ports. Afterward, they are optically routed through intermediate ROADM nodes.

The authors in Ref. [5] proposed a new design for self-bootstrapping and self-configuring optical transport networks. The main focus of the work was on infrastructure elements comprising the network and the applications that could be built on top of these elements.

The authors of the book [11] provide a theoretical description as well as well-known techniques for traffic grooming. The authors emphasize the importance of traffic grooming for the policy design of the network, especially for dynamic traffic. The book discusses a few heuristic algorithms for traffic grooming that network control plane can employ to make decisions in response to traffic change events.

In [12], the authors proposed a novel method for network-wide BP evaluation for end-to-end optical burst switching (OBS) networks. This method was evaluated under non-uniform On-Off traffic with heterogeneous link capacities. The simulation results show that the method is about four times faster than the earlier approaches. The performance analysis of the proposed method shows that the proposed strategy is reliable and more efficient for large-sized networks. However, a drawback of the proposed method is the simulation time, which seems to be relatively high.

[13] presents an emulation of Software Defined Optical Networked (SDON) under Mininet in several aspects such as end-to-end, interactive emulation of an SDON, Discrete emulated optical components such as transceivers, amplifiers, optical fiber spans, and ROADMs, and SDON control and monitoring interfaces. The study show the capability of Mininet to simulate both small and large networks relatively easier compared to other existing testbeds such as COSMOS [14].

Finally, the authors in Ref. [10] proposed an algorithm called "dynamic scheduling and distance adaptive transmission" under a software defined networking architecture for energy-efficient QoS provisioning. Their scheme exploits the over-provisioning capacity in OTNs under dynamic traffic. In this work, the QoS measurement was defined as the probability of congestion at the core router ports. To provide a solution for energy-efficient assignment of optical transponders and electronic switching capacity, while ensuring a certain level of quality of service to core routers, a stochastic linear programming approach was used. They proposed a traffic forecasting model with considerations for both long-term and short-term forecasts. By applying the Auto-Regressive Integrated Moving Average (ARIMA) method, future traffic was estimated. The study shows that the number of optical light paths had a reduction of 45%. As a result, there was a 48% improvement in the energy efficiency of optical networks.

Our contribution to reducing SPT and BBP for uniform and non-uniform traffic is many-fold. We achieve this by adding an idle state, which is not present in the above works. Additionally, unlike other works, we measure SPT. This is due to the fact that unlike in other works, a channel may not need to be created, allowing for the effective SPT to be significantly reduced. We have proposed this strategy expecting increased BBP and SPT when used with non-uniform traffic. This non-uniform distribution more accurately reflects real-world traffic situations. We expected increased BBP and SPT due to asymmetric probability of traffic sent between source and destination pairs, in comparison to the uniform model. This was confirmed with a marginal increase in BBP and SPT; however, our tests showed that our method was still more effective than standard methods. We conclude that the strategy both works and is more effective than standard methods for non-uniform traffic.

## 3. Description of RDR strategy

In this section, we discuss the RDR strategy in greater detail. Briefly, the different states for optical channels are as follows:

- Establishing State: This phase consists of the time for configuring ROADMs (processing time) and also time for power equalization (waiting time).
- Working State: When channels are carrying any OTN services.
- Idle State: When channels are momentarily not being used by any OTN services. No changes to any devices are required in the idle state. This state is managed entirely by the software control mechanisms.
- Removing State: In this last phase, the optical channel connection is being deleted.

### 3.1. Problem illustration

In this section, we show how RDR strategy affects SPT. A comparison of the RDR strategy to standard methodology is shown in Fig. 1(a) and (b). As it can be seen the optical channel in both (a) and (b) were carrying a service till time $t_0$. Fig. 1 (a) shows the regular optical channel management algorithm without using RDR. In this case, when the optical channel stops carrying any services at time $t_0$, it will be removed. $\triangle t_1$ is the amount of time that takes to release the transport resource. Fig. 1 (b), shows the optical channel management algorithm in case of using the RDR strategy. Based on this strategy, the optical channel is not removed when it does not carry any service request; rather, it goes to the idle state. To illustrate how the RDR strategy affects SPT, let us have a new service request at time $t_1$. This service request comes with the same source and destination as the prior request. In case of not using RDR (Fig. 1 (a)), a new optical channel to carry the new service will be allocated by the controller. $\triangle t_2$ is the amount of time that takes to establish the transport channel. In contrast, Fig. 1 (b), shows that the idle optical channel A is used to carry the new service immediately. In this case, there will not be any wait time to set up a new optical channel. As shown in Fig. 1 (b), which is using RDR strategy, there is a reduction

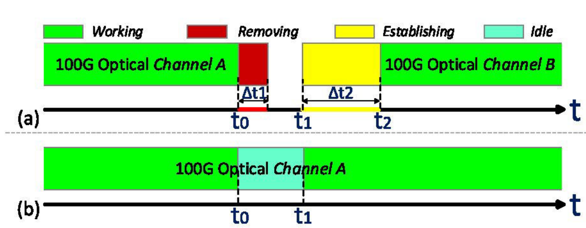



**Fig. 1.** Idle optical channel, (a) without RDR and (b) with RDR cases.

in the SPT of the new service.

### 3.2. RDR technique

In this work, we investigate the novel RDR technique which results in reduced SPT and BBP. As an additional benefit, using RDR helps to avoid persistent channel establishment and frequent optical end-to-end circuits removal.

The rules of RDR method are as follows:

1. We define "$t_{delay}$", $0 \leq t_{delay} \leq \infty$, for the time that optical channels are in the idle state. The idle state is entered when the optical channel does not carry any service requests.
2. A working optical channel is the highest preference for the controller.
3. An idle optical channel can be converted to a working channel and is the next preference for the controller.
4. In the event no existing (working or idle) channel can be used, free optical resources are chosen by the controller to establish a new optical channel.
5. If a new channel cannot be constructed with free resources the controller uses resources that are free and idle.
6. If resources from an idle channel are used in a new channel then the controller releases the affected idle optical channel(s).

Fig. 2(a) is the RDR workflow for setting up an E2E OTN service, and Fig. 2(b) is the illustration of releasing an E2E OTN service. To show how our proposed method can affect the network performance metrics such as SPT and BBP, we considered RDR strategies under two circumstances: *Static_RDR strategy* and *Dynamic_RDR* strategy.

#### 3.2.1. Static_RDR_X

All idle optical channels have a single static value corresponding to the release delay ($t_{delay}$). In our simulations $t_{delay}$ is simulated on a variety of values for *X*. *TS* is the unit of the variable *X*.

#### 3.2.2. Dynamic_RDR

$t_{delay}$ may vary for each idle optical channel. Equation (1) is used by the controller to calculate the number of optical channels which are required for each pair of sites.

$$n_{oc,need(s,d)} = \sum_{ty_{otn} \in TY_{OTN}} \left\lceil \frac{tl_{(s,d)} \times prop_{ty_{otn},(s,d)}}{N_{ty_{otn}}} \times comp \right\rceil. \quad (1)$$

This is done on the basis of the network statistics that are recomputed when the state of any optical channel changes to idle. Note that we include a compensation value when we are calculating the number of required optical channels for services between source *s* and destination *d*. This value is included to allow for a margin of error with respect to our calculated distribution. This value can also be fine tuned to adjust for the behavior of different network topologies. If there are less optical channels than our statistics suggest we need, then the value of $t_{delay}$ for the current idle channel is set to infinity. This is done to prevent the idle channel from being removed, as our statistics suggest that we should be receiving a new request in the near future. Once the number of occupied optical channels is greater than the number we need, $t_{delay}$ is set as the average duration time of all services ($dura_{AVE,(s,d)}$).

Table 1 illustrates all the notations and variables which were used for the RDR method.

### 3.3. RDR generalization

A crucial issue in WDM network is dropping calls due to fluctuation in traffic. In our previous work, we studied how uniform traffic load influences the SPT and BP. Even though, we believed that our model under non-uniform traffic will give us the same impact on SPT, BP, and BBP with some fluctuation but it was necessary to show the amount of

**Table 1**
Notations and variables.

| Symbol | Definition |
|---|---|
| TS | time slice, unit base of time |
| $t_{oc,remove}$ | cost of the time to remove each optical channel |
| $t_{oc,estab}$ | cost of the time to establish each optical channel |
| $t_{otn,\ remove}$ | cost of the time to remove a pair of OTN circuits |
| $t_{otn,\ estab}$ | cost of the time to establish a pair of OTN circuits |
| $t_{delay}$ | holdup time till an Idle optical channel can be released. |
| $dura_{AVE,(s,d)}$ | the average of total traffic duration between source *s* and destination *d*. |
| $n_{oc,need(s,d)}$ | the number of required optical channel between source *s* and destination *d*, according to Dynamic RDR method. |
| $n_{oc,exist(s,d)}$ | a quantity of existing optical channels between each source and destination. |
| $TY_{OTN}$ | different types of OTN, $ty_{otn} \in TY_{OTN}$ = {OTN_10G, OTN_40G, OTN_100G} |
| $tl_{(s,d)}$ | amount of traffic between each source and destination. |
| $N_{ty_{otn}}$ | a quantity of OTN services that can be carried by a channel. $ty_{otn}$: means (OTN_10G; value = 10), (OTN_40G; value = 2), and (OTN_100G; value = 1). |
| $prop_{ty_{otn},(s,d)}$ | the proportion of specific type OTN services between source *s* and destination *d*. |
| *comp* | the compensation value of calculating $n_{oc)}$, which is bigger than 1 (real request distribution may not exactly fit the math model). |

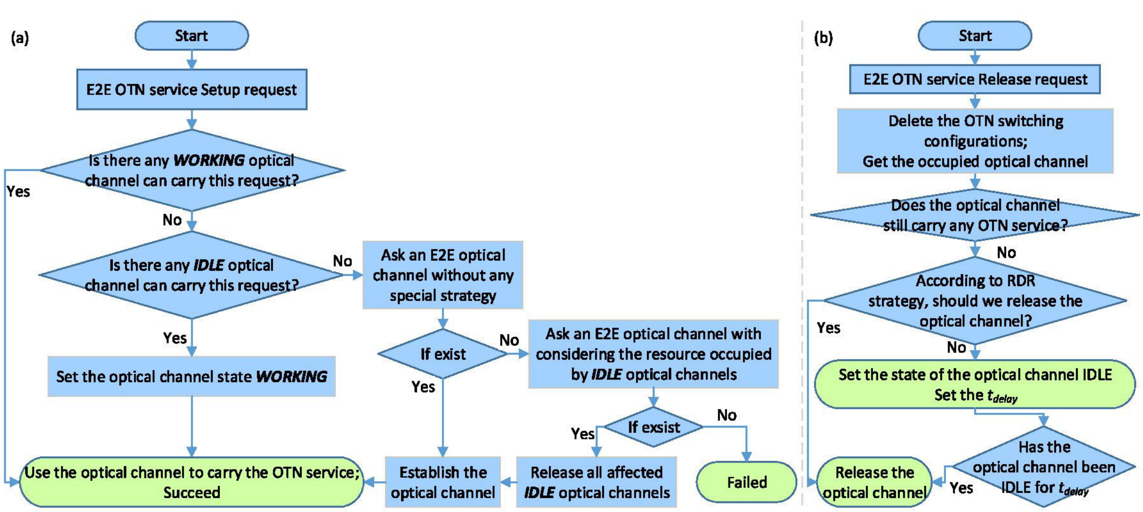



**Fig. 2.** RDR work flow in OTN over WDM networks for both (a) the setup and (b) release of any request.

this fluctuation. Less fluctuation will prove that our strategy would generalize well to non-uniform traffic distributions even under heavy traffic.

In the RDR strategy, there is a decrease in SPT because there is a greater probability that any new service request is carried immediately on an idle optical channel. Thus, we will have less BBP. This effect is greatest when we have a good estimate for new arrival service requests, such as in uniform traffic distributions. In this case, we can set the $t_{delay}$ based on an estimate of arrival time for new service requests, allowing us to optimize for carrier cost, while still meaningfully reducing SPT and BBP. However, in non-uniform traffic, there exists no good metric for predicting new traffic requests. Therefore selecting a value for $t_{delay}$ is difficult. If $t_{delay}$ is too short we drop calls unnecessarily and if it is excessively large we have more idle channels which are not cost-efficient. Thus in a real-world situation, we need to optimize $t_{delay}$ to achieve a minimal cost to the carrier. We knew that having infinite $t_{delay}$ would result in better performance, however we were unsure that we would have significant efficiency gains at lower values. While there is obviously a value for $t_{delay}$ that is effectively as good as infinite, we were concerned that this value would be too high for practical application. In non-uniform traffic, we notice that for the heavy traffic intensity, while increasing the arrival rate ratio, the bandwidth blocking dramatically increases.

## 4. Uniform and non-uniform traffic model

In this paper, we considered both uniform and non-uniform traffic patterns. To evaluate how RDR strategy effects the network performance in both traffic distributions, the two important metrics in highly dynamic traffic scenarios such as SPT and BBP are considered in this work. SPT, is the time taken for responding to a service request and BBP, measures the quality of the service offered to the arrival calls. In this work, we assume that there are no queues and hence all the service requests which arrive while all transmission channels are occupied or when the bandwidth is not enough, will be dropped. BBP is calculated based on the fraction of the bandwidth requests which are blocked. For both the traffic models considered here, the average BBP, B, is calculated by Equation 2.

$$B = \frac{\text{Total Bandwidth Blocked}}{\text{Total Bandwidth Requested}} x100 \tag{2}$$

### 4.1. Uniform model

The uniform model we use in this work is obtained by setting all pairs with the same randomly selected probability.

The topologies which were used in the simulations were based on the NSFNet Fig. 3(a) and Pan-European (COST 239) Fig. 3(b). Each fiber was modeled with 80 wavelengths. Each wavelength has a capacity of 100G. K-shortest path routing was used to construct the route between each source and destination. In this work, we randomly create a set of connections where k = 4. For wavelength assignment, we use the First Fit algorithm. Therefore we select the first path, selected from our k shortest paths, that has a free wavelength from source to destination.

### 4.2. Non-uniform traffic model

In regards to non-uniform traffic, we used Equation (3) to generate the non-uniform traffic. To make it clear why the particular traffic formulation was chosen, we argue that traffic, for both Circuit-Switched (CS) and Packet-Switched (PS), is directly related to population density. Population distribution estimation has been the source of attention during the past few decades. The Distribution of the human population affects things such as available technologies, which in turn affects network traffic being generated at a particular location. Population centers also tend to affect infrastructure, for example, the construction of railways. This specifically affects the ease of laying fibers, again affecting the likelihood of traffic generated at a location. This leads to our approach to generating the non-uniform traffic being based on population density. The resultant distribution is not uniform. Further one could consider the fluctuation of population, resulting in a distribution that is not static. For non-uniform traffic simulation, we used a mesh topology with the 14 most populous cities in USA as of 2018 [15] as 14 nodes in our topology with 19 links (see Table 2).

The data shows the probability of carrying traffic between arbitrary source and destination. In this matrix, the probability of moving traffic from one location to another location is given by the intersection cells. BBP is one of the important metrics to measure the performance of network services. A lower BBP implies a more efficient network. The average BBP is calculated using Equation 2 as before.

Consider a network with a mesh topology of $N$ nodes such that all the nodes are on a connected graph and every (i,j) is an arc with weight $w_{i,j}$. We chose $w_{i,j}$ equal to $p_i.p_j$ where for each $k = 1, \ldots 14$, $p_k$ denotes the population at node $k$. Similar to Example 4.36 of Ross (2010) [16], With $J_i$ {1, 2, …, N} - {i}, we define the probability of going directly from node $i$ to node $j$ as follows:

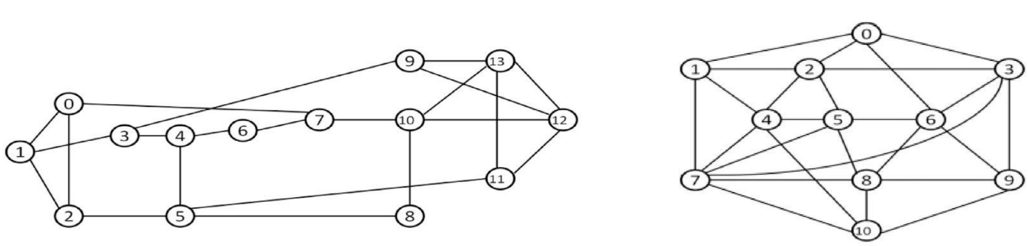
$$P_{i,j} = \begin{cases} \frac{p_i.p_j}{\sum_{j \in J_i} p_i.p_j} & \text{i} \neq \text{j} \\ 0, & \text{i} = \text{j} \end{cases} \tag{3}$$

For the case where all populations are the same, the $w_{i,j}$'s are the same, and hence all the $P_{i,j}$'s are equal, which is the uniform case.

## 5. Simulations and results

The RDR strategy was simulated for network performance purposes on the topologies outlined in Section 4 We worked with traditional metrics such as SPT and BBP. We also studied the number of occupied optical channels under different types of the RDR method (Without_RDR, Static_RDR_X, and D_RDR). The *Without_RDR* strategy is the standard strategy, in which channels not carrying data are removed immediately.

Table 3 shows the values of TS, $t_{oc,remove}$, $t_{oc,estab}$, $t_{otn,\ remove}$, and $t_{otn,}$




(a) The NSFNET mesh topology (b) The Cost 239 optical mesh topology

**Fig. 3.** (a) The NSFNET mesh topology (b) The Cost 239 optical mesh topology.

**Table 2**
Non-Uniform transition matrix based on population density.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0.187 738 272 | 0.127 308 417 | 0.109 407 478 | 0.078 110 521 | 0.074 528 658 | 0.072 086 693 | 0.067 087 638 | 0.063 280 186 | 0.048 463 825 | 0.045 365 086 | 0.042 525 105 | 0.042 107 282 | 0.041 990 841 |
| 2 | 0.327 261 609 | 0 | 0.105 440 472 | 0.090 614 402 | 0.064 693 367 | 0.061 726 766 | 0.059 704 26 | 0.055 563 901 | 0.052 410 46 | 0.040 139 126 | 0.037 572 661 | 0.035 220 508 | 0.034 874 455 | 0.034 778 015 |
| 3 | 0.311 662 96 | 0.148 078 896 | 0 | 0.086 295 343 | 0.061 609 812 | 0.058 784 612 | 0.056 858 507 | 0.052 915 494 | 0.049 912 36 | 0.038 225 928 | 0.035 781 792 | 0.033 541 752 | 0.033 212 193 | 0.033 120 35 |
| 4 | 0.307 323 734 | 0.146 017 221 | 0.099 016 685 | 0 | 0.060 752 03 | 0.057 966 164 | 0.056 066 877 | 0.052 178 762 | 0.049 217 439 | 0.037 693 716 | 0.035 283 609 | 0.033 074 756 | 0.032 749 786 | 0.032 659 222 |
| 5 | 0.300 020 68 | 0.142 547 356 | 0.096 663 712 | 0.083 071 75 | 0 | 0.056 588 691 | 0.054 734 537 | 0.050 938 817 | 0.048 047 866 | 0.036 797 985 | 0.034 445 151 | 0.032 288 788 | 0.031 971 54 | 0.031 883 128 |
| 6 | 0.299 206 937 | 0.142 160 727 | 0.096 401 532 | 0.082 846 435 | 0.059 147 494 | 0 | 0.054 586 082 | 0.050 800 656 | 0.047 917 546 | 0.036 698 178 | 0.034 351 726 | 0.032 201 211 | 0.031 884 824 | 0.031 796 652 |
| 7 | 0.298 654 687 | 0.141 898 339 | 0.096 223 603 | 0.082 693 524 | 0.059 038 325 | 0.056 331 043 | 0 | 0.050 706 893 | 0.047 829 104 | 0.036 630 444 | 0.034 288 322 | 0.032 141 777 | 0.031 825 974 | 0.031 737 964 |
| 8 | 0.297 530 487 | 0.141 364 203 | 0.095 861 396 | 0.082 382 248 | 0.058 816 092 | 0.056 119 001 | 0.054 280 237 | 0 | 0.047 649 065 | 0.036 492 559 | 0.034 159 253 | 0.032 020 789 | 0.031 706 174 | 0.031 618 496 |
| 9 | 0.296 679 918 | 0.140 960 076 | 0.095 587 352 | 0.082 146 737 | 0.058 647 951 | 0.055 958 571 | 0.054 125 063 | 0.050 371 608 | 0 | 0.036 388 236 | 0.034 061 6 | 0.031 929 249 | 0.031 615 534 | 0.031 528 106 |
| 10 | 0.293 415 781 | 0.139 409 203 | 0.094 535 679 | 0.081 242 941 | 0.058 002 694 | 0.055 342 902 | 0.053 529 567 | 0.049 817 409 | 0.046 990 101 | 0 | 0.033 686 847 | 0.031 577 956 | 0.031 267 693 | 0.031 181 227 |
| 11 | 0.292 742 171 | 0.139 089 154 | 0.094 318 648 | 0.081 056 427 | 0.057 869 534 | 0.055 215 848 | 0.053 406 676 | 0.049 703 04 | 0.046 882 223 | 0.035 905 265 | 0 | 0.031 505 461 | 0.031 195 91 | 0.031 109 643 |
| 12 | 0.292 127 52 | 0.138 797 118 | 0.094 120 614 | 0.080 886 238 | 0.057 748 029 | 0.055 099 916 | 0.053 294 542 | 0.049 598 682 | 0.046 783 788 | 0.035 829 877 | 0.033 538 943 | 0 | 0.031 130 41 | 0.031 044 324 |
| 13 | 0.292 037 309 | 0.138 754 256 | 0.094 091 549 | 0.080 861 26 | 0.057 730 196 | 0.055 082 9 | 0.053 278 084 | 0.049 583 366 | 0.046 769 341 | 0.035 818 813 | 0.033 528 586 | 0.031 429 603 | 0 | 0.031 034 737 |
| 14 | 0.292 012 179 | 0.138 742 316 | 0.094 083 452 | 0.080 854 302 | 0.057 725 228 | 0.055 078 16 | 0.053 273 499 | 0.049 579 099 | 0.046 765 316 | 0.035 815 73 | 0.033 525 701 | 0.031 426 898 | 0.031 118 119 | 0 |

**Table 3**
Factors and values.

| Factors | Values | Factors | Values |
|---|---|---|---|
| TS | 1 s | *comp* | 1.25 |
| $t_{oc,remove}$ | 2 TS | $t_{oc,estab}$ | 10 TS |
| $t_{otn,\ remove}$ | 1 TS | $t_{otn,\ estab}$ | 1 TS |

$_{estab}$ that were considered for the simulation results. Each topology was tested by simulating about 200 000 service requests per round of simulation. We then aggregated multiple simulations to guarantee a 95% confidence level. Our simulation results demonstrate the behavior of SPT and BBP under both uniform and non-uniform conditions. Also, the results show that both dynamic RDR and static infinite RDR perform significantly better than when we do not use RDR under both uniform and non-uniform traffic conditions. In our simulation, we compare the performance of using the RDR strategy for static RDR and dynamic RDR. It should be noted that even though SPT and BBP went up under non-uniform conditions, in comparison to uniform traffic, they are still less than when we do not use the RDR strategy.

### 5.1. *Traffic Duration's impact for uniform and non-uniform traffic*

Figs. 4 and 5 present the effect of different RDR scenarios, such as different types of Static_RDR, D_RDR, and Without_RDR on SPT, BBP, and the number of occupied optical channels for uniform and non-uniform traffic respectively. The performance of the network was evaluated in terms of SPT, BBP, and the number of occupied optical channels. For the simulation results on Figs. 4 and 5, the traffic request ratio (OTN_10G: OTN_40G: OTN_100G) is 1:1:1. The same ratio will be used for the non-uniform traffic as well.

The first row of Figs. 4 and 5 using sub-figures a, b and c show the SPT comparison between all the different RDR scenarios (Static_RDR_X, D_RDR, and Without_RDR) for different traffic loads under three different service duration parameters (where TS is 60, 300, and 1500) for both uniform and non-uniform traffic respectively. As we can see, in all 3 different service durations, the highest value of SPT belongs to the scenario of Without_RDR method. The other types of RDR have lower SPT, this is a direct result of the delay we set for an idle optical channel's removal. Comparing different Static_RDR strategy_X, with different released-delay ($t_{delay}$), shows that as the $t_{delay}$ increases, the SPT drops. The existence of more idle optical channels gives a chance for the new service request to be carried immediately instead of waiting to establish a new optical channel. Our results show that service duration impacts SPT and BBP, especially for longer durations. The impact is seen more so on BBP and the number of occupied optical channels. Currently, we have not considered the impact of release time "R" of the channel in our study. Once a call finishes, the channel goes to the IDLE state for a time equal to the average call duration. This means that the impact of R on our scheme is tied to the duration of the IDLE state. If the IDLE state duration is not accurate then the channel would release for "R" duration since it expects no calls. If a new call arrives during this release time and there is a queue of waiting calls, then the call's waiting time will be R + E or less than R + E depending on the release strategy that is chosen. The effect of waiting queues and release strategies are currently in our plans for future work. Other results we get from the comparison of those sub-figures are as follows:

- Decreasing the SPT means any service will finish faster than before. Therefore, there will be more chances for the new request to be carried by an existing optical channel. In this work, we assume if the request can not be served, the request is blocked.
- Comparing the SPT in the case of using the Static_RDR strategy, under different service durations shows the lowest value of SPT under heavy traffic loads is in the case of Static_RDR_Infinite.

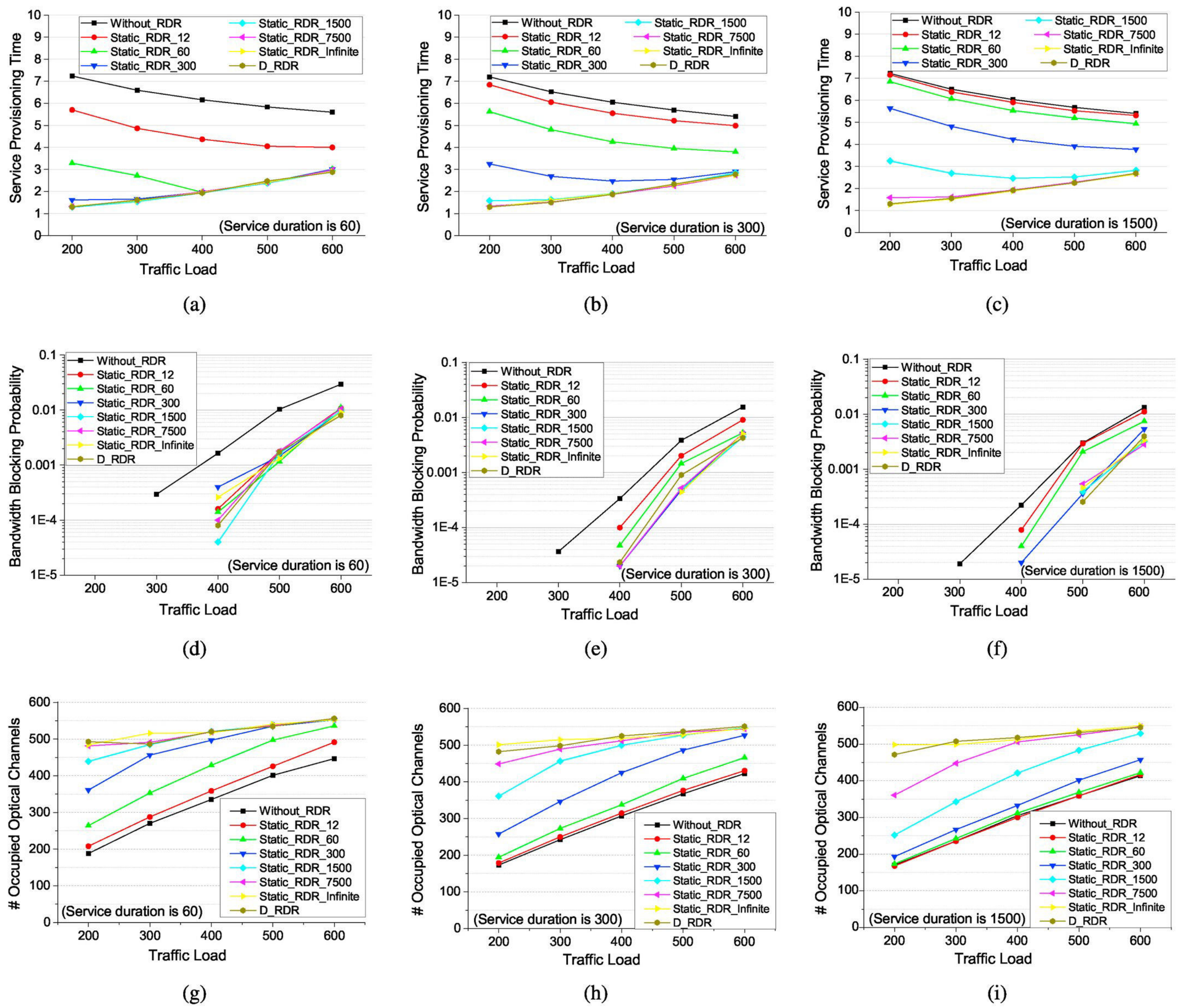



**Fig. 4.** Uniform traffic- For the relative service weight of 1:1:1; Sub-figures a, b, c: Comparing SPT under service duration of 60, 300 and 1500; Sub-figures d, e, f: Comparing BBP under different traffic durations; Sub-figures g, h, i: Comparing occupied optical channels under different service durations.

- Since, under high traffic loads, there will be more new OTN service requests, any increase in $t_{delay}$ helps to use all existing idle channels. This directly reduces the SPT for incoming service requests.
- We can optimize the SPT performance by using the dynamic RDR strategy under both uniform and non-uniform traffic. In the case of the Static RDR Infinite strategy, we can obtain better SPT performance compared to the dynamic RDR.
- We will show later, one of the main factors which will affect the SPT performance is the number of occupied optical channels. This agreed with our expectation that we would see the lowest SPT when using the RDR_Infinite strategy.
- Based on sub-figures a, b, and c of Figs. 4 and 5 , we reach the conclusion that in order to maintain better SPT performance under the Static RDR strategy it is necessary to increase the value of $t_{delay}$. This result is due to the need to avoid destroying idle optical channels inefficiently.
- The second row of Figs. 4 and 5 using sub-figures d, e, and f shows BBP comparisons between all different RDR scenarios (Static_RDR_X, D_RDR, and Without_RDR) for different traffic loads under three different service duration parameters (where TS is 60, 300, and 1500) under uniform and non-uniform traffic respectively. As we can see in the sub-figures, the BBP, when compared to Without_RDR, decreased using the Static_RDR method or the Dynamic_RDR method.
- In sub-figure a, we see that the SPT will decrease as traffic load increases for any type of RDR.
- In sub-figure g, we see that the BBP will increase as traffic load increases for any type of RDR.
- The best result in both Figs. 4 and 5 is when the $t_{delay}$ is infinite.
- In general, as traffic load increases all of these strategies tend toward the same asymptotic performance in all three measured metrics.
- Our proposed strategy is efficient and reliable in all different scenarios tested. Static_RDR_Infinite has shown that it is more applicable when reducing SPT is more important.
- Dynamic_RDR may be more efficient than Static_RDR_Infinite when attempting to balance network utilization and SPT, as the SPT is comparable but the network utilization is lower.

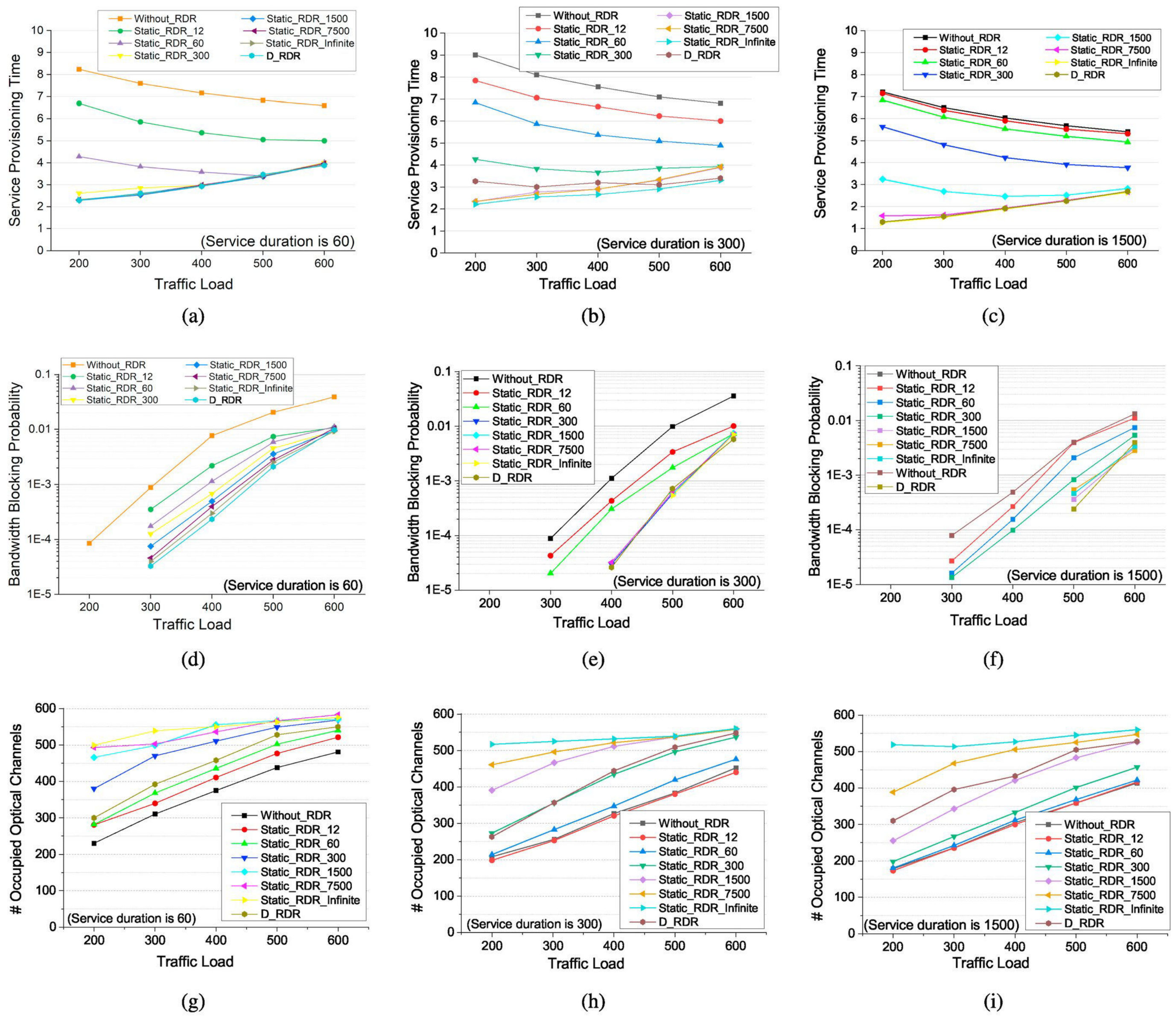



**Fig. 5.** Non-Uniform traffic- For the relative service weight of 1:1:1; Sub-figures a, b, c: Comparing SPT under service duration of 60, 300 and 1500; Sub-figures d, e, f: Comparing BBP under different traffic durations; Sub-figures g, h, i: Comparing occupied optical channels under different service durations.

### *5.2. Service type Combination's effects on uniform and non-uniform traffic*

Figs. 6 and 7 show the effects of service type on SPT, BBP, and the number of occupied optical channels under uniform and non-uniform traffic respectively. To simplify the results of the simulation, we just consider the service duration of 60 for all different RDR scenarios (Static_RDR_X, Dynamic_RDR, and Without_RDR) with different traffic loads. In this simulation, we used OTN_10G for all service requests. By comparing the first row of Figs. 6 and 7 we can see the effects of different RDR scenarios (Static_RDR_X, Dynamic_RDR, and Without_RDR) for different traffic loads. Sub-figures a, b, and c respectively use a ratio of 10:1:1, 1:10:1, and 1:1:10. Both figures use the same parameters but under a different network traffic model. Fig. 6 shows the simulation result of uniform traffic and Fig. 7 is the simulation result under non-uniform traffic. Since we used OTN_10G service requests under both uniform and non-uniform traffic, there is a lower chance of changing a Working optical channel to an idle optical channel. The below results were given by the simulation:

- SPT is reduced in both uniform and non-uniform traffic. Although, the average SPT in case of non-uniform is a little bit higher than the average value under uniform traffic pattern.
- Comparing sub figures (a) from Figs. 7 and 5 under non-uniform traffic, shows that the average of SPT in Fig. 7 is reduced. We got the same result for the uniform traffic.
- Comparing sub figures (b) from Figs. 7 and 5 under non-uniform traffic, we obtained that the average of SPT in Fig. 7 is reduced because of having ratio 1:10:1. The same result is obtained for the uniform traffic.
- Comparing sub figures (c) from Figs. 7 and 5 under non-uniform traffic, we found out that the average of SPT in Fig. 7 is reduced because of having ratio 1:1:10. The same result is obtained for uniform traffic.
- Sub-figure (c) of Fig. 7 has greater numbers of OTN_100G service requests; therefore the SPT will increase directly with an increasing traffic load.
- Sub-figures (e, f) of Figs. 7 and 6 are the simulation results of BBP between all the different RDR scenarios (Static_RDR_X, D_RDR, and

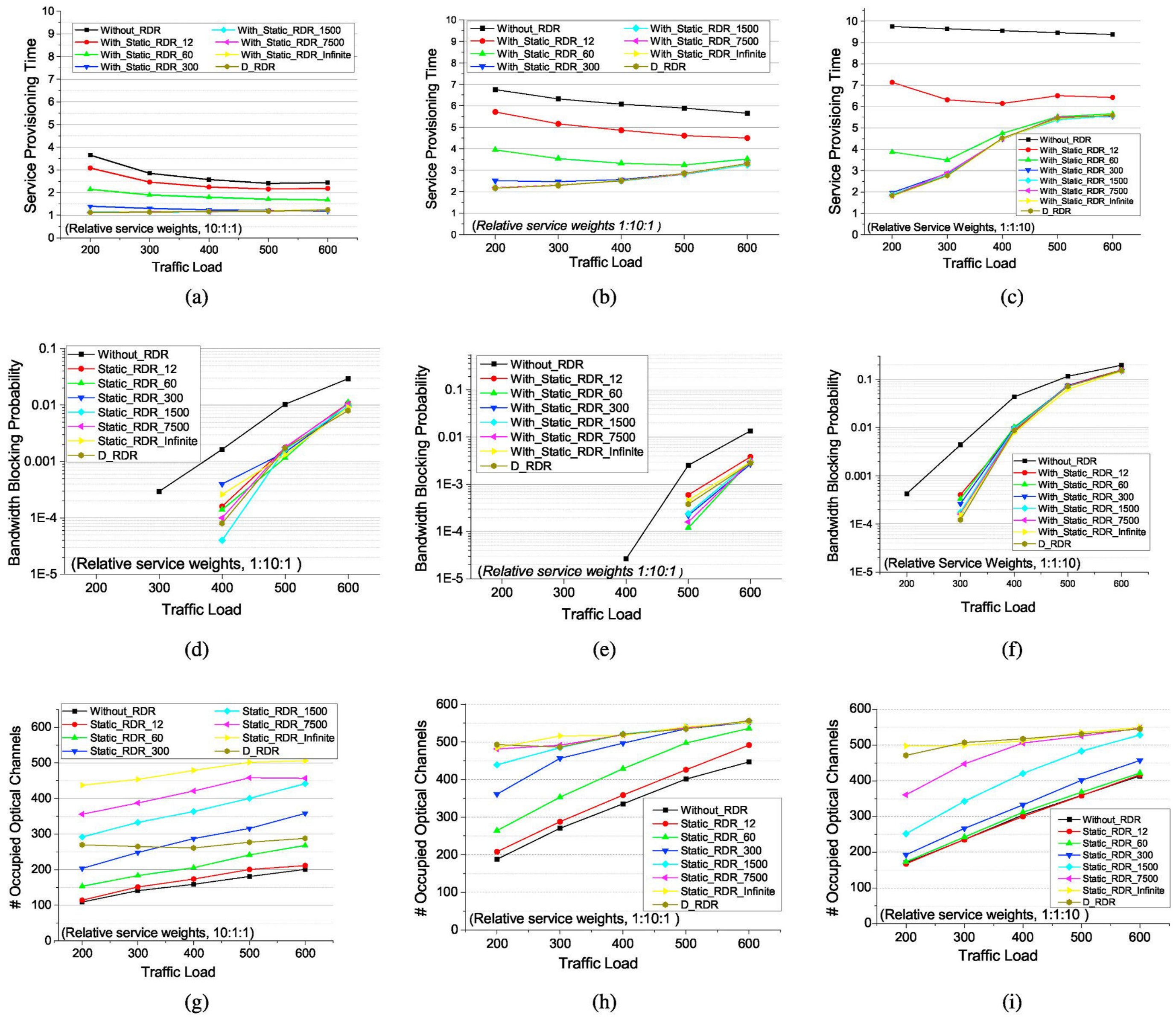



**Fig. 6.** Uniform traffic; Sub-figures a, b, c: SPT with different relative service weights of (OTN_10G, _40G, _100G); Sub-figures d, e, f: BBP with different relative service weights of (OTN_10G, _40G, _100G); Sub-figures g, h, i: The number of occupied optical channels with different relative service weights for (OTN_10G, _40G, _100G).

Without_RDR) for different traffic loads and using OTN ratios of 1:10:1 and 1:1:10. Clearly, we see the BBP reduction under two types of RDR (Static_RDR_X, Dynamic_RDR).

- Sub-figures (d,e,f) of Figs. 7 and 6 with (OTN_10G,_40G,_100G), show that the traffic load increasing doesn't directly increase the number of occupied optical channels.
- We reached the same conclusions for uniform traffic and non-uniform traffic. Even though under a uniform traffic model we had a better network performance (measured by SPT, BBP, and the number of occupied optical channels) we show that our strategy is efficient to reduce SPT under non-uniform traffic as well.

## 6. Conclusions and future work

SDN was recently proposed to improve the flexibility of network service provisioning. More recently, there is an increasing effort to utilize SDN support in the operation of the transport layers of the network. In this work, we showed the importance of service provisioning in SDN networks especially in the case of dynamic traffic. We evaluated the adoption of the RDR strategy under different traffic loads and different service durations for uniform and non-uniform traffic patterns. Our simulations were done under two different topologies, namely, NSFNet and COST239. Our results show that very similar improvements when RDR was adopted into both topologies. For the sake of brevity, we chose to only include the results for NSFNET topology. We proved that when we have an infinite delay then our method results in the lowest SPT. Also, we observed that with increased traffic load, SPT decreases. The reason for this is that when the traffic load is heavy then we have fewer idle optical channels. In this situation, all possible optical channels will be used to carry the OTN services. The main objectives of our proposed method are to improve network performance metrics such as SPT and network bandwidth utilization. Since the bandwidth and hop-count had been the sources of much attention to improve the network performance, our future work will investigate the routing performance under RDR strategy and QoS of routing algorithms under both uniform and non-uniform traffic. And for future improvement on SPT and BBP, we

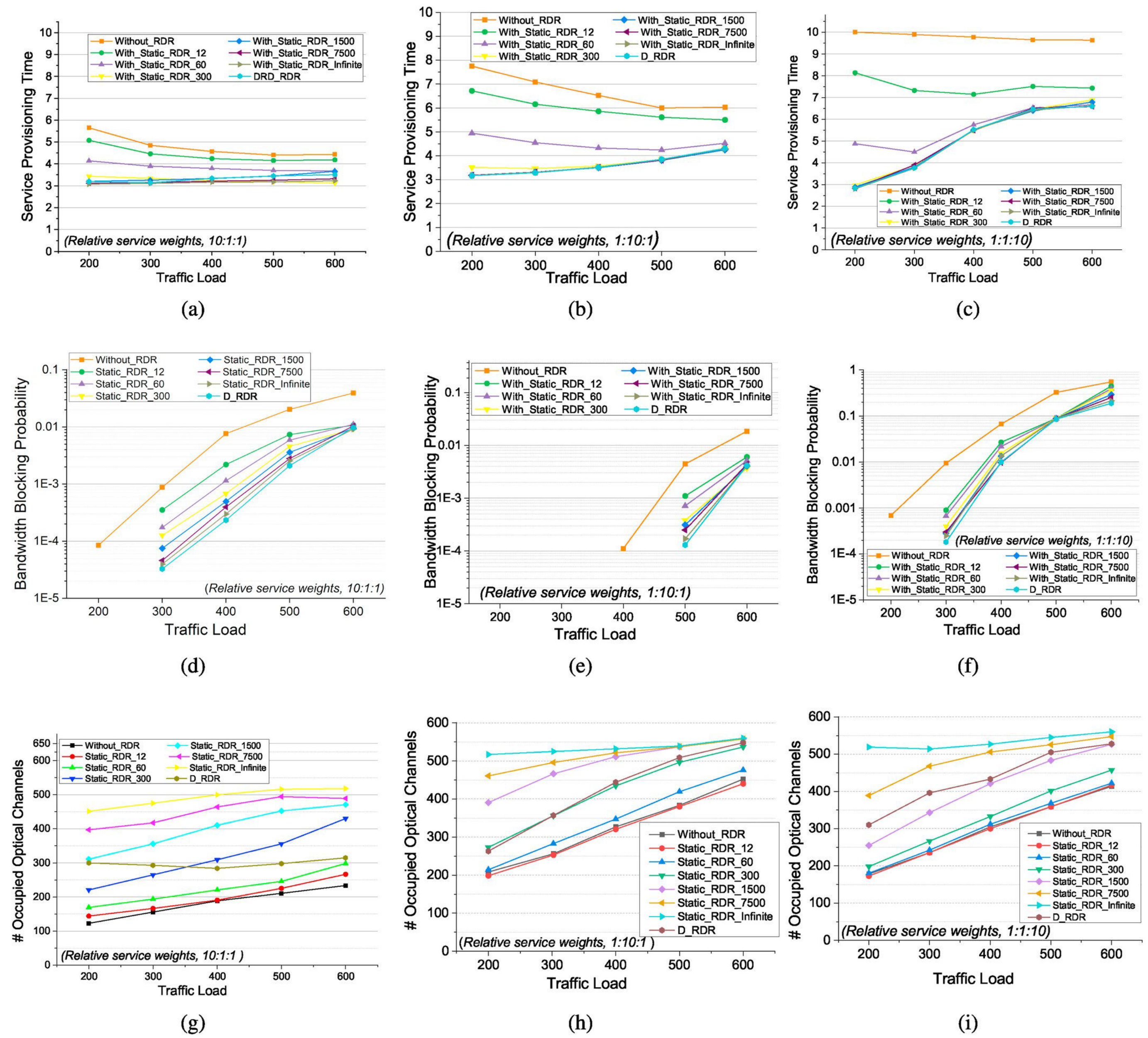



**Fig. 7.** Non-Uniform traffic; Sub-figures a, b, c: SPT with different relative service weights of (OTN_10G, _40G, _100G); Sub-figures d, e, f: BBP with different relative service weights of (OTN_10G, _40G, _100G); Sub-figures g, h, i: The number of occupied optical channels with different relative service weights for (OTN_10G, _40G, _100G).

will work on queuing all the service requests when they can not be carried by any optical channel instead of being blocked. Since in this work we used the FirstFit algorithm for channel assignment, in the future we will investigate other resource allocation methods for channel assignment. We will also prioritize the requests and incorporate priority levels in our solutions. We would potentially investigate the impact of our scheme on the power consumption of the optical channels. Currently, our focus is directed towards the quality-of-service (QoS) parameters only such as Service Provisioning Time (SPT) and Bandwidth Blocking Probability (BBP).

### Author statment

Shideh Yavary Mehr: Data curation, Formal analysis, Coding, Conceptualization, Writing the first draft- Review and editing, Investigation, Methodology, Implementing the purpose method, Changing the paper based on reviewers, feedback. Byrav Ramamurthy: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Yu Zhou: Conceptualization, investigation, proposed method. Bingli Guo: Conceptualization, investigation, proposed method. Shanguo Huang: Conceptualization, investigation, proposed method.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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