On QoS-Assured Degraded Provisioning in Service Differentiated Multi-Layer Elastic Optical Networks

Zhizhen Zhong\textsuperscript{1}, Jipu Li\textsuperscript{1}, Nan Hua\textsuperscript{1}, Gustavo B. Figueiredo\textsuperscript{3}, Yanhe Li\textsuperscript{1}, Xiaoping Zheng\textsuperscript{1}, Biswanath Mukherjee\textsuperscript{2}
\textsuperscript{1}Tsinghua National Laboratory for Information Science and Technology (TNList), Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
\textsuperscript{2}University of California, Davis, California 95616, USA, \textsuperscript{3}Federal University of Bahia, Salvador, Brazil
zhongzz14@mails.tsinghua.edu.cn, xpzheng@mail.tsinghua.edu.cn

Abstract—The emergence of new network applications is driving network operators to not only fulfill dynamic bandwidth requirements, but offer various grades of service. Degraded provisioning provides an effective solution to flexibly allocate resources in various dimensions to reduce blocking for differentiated demands when network congestion occurs. In this work, we investigate the novel problem of online degraded provisioning in service-differentiated multi-layer networks with optical elasticity. Quality of Service (QoS) is assured by service-holding-time prolongation and immediate access as soon as the service arrives without set-up delay. We decompose the problem into degraded routing and degraded resource allocation stages, and design polynomial-time algorithms with the enhanced multi-layer architecture to increase the network flexibility in temporal and spectral dimensions. Illustrative results verify that we can achieve significant reduction of network service failures, especially for requests with higher priorities. The results also indicate that degradation in optical layer can increase the network capacity, while the degradation in electric layer provides flexible time-bandwidth exchange.

I. INTRODUCTION

Network operators continuously upgrade their networks due to increasing demands for ubiquitous communications caused by two reasons. The increased burstiness of high-volume traffic is the first. As popularities of cloud computing, Internet of Things (IoT), and high-speed mobile communications increase, network traffic is becoming extremely dynamic and bursty. Thus, just enlarging the network capacity is not an economical choice for network operators, while neglecting it will strongly affect the QoS. Second, various emerging networking applications, such as online gaming, data backups and virtual machine migrations, which are aimed at ubiquitous communications, also result in heterogeneous demands in optical telecom networks. In addition, today’s network customers request more customized services, such as Virtual Private Network (VPN) and Video on Demand (VoD), as well as more differentiated requirements with different prices. For some of the traffic which is delay-insensitive and can accept some compromise in bandwidth or other aspects, it can be preempted by more “important” requests when the network becomes congested. Therefore, to maintain cost-effectiveness and customers’ loyalty, network operators can provide different grades of service besides sufficient bandwidth for these emerging demands, instead of managing to support all the traffic without distinction.

To address these problems, degraded provisioning is proposed for network operators to provide a degraded level of service when network congestion occurs instead of no service at all. Generally, degraded provisioning refers to two different approaches: 1) keeping the total amount of transferred traffic constant by time prolongation or modulation level adjustment with immediate service access (QoS-assured), and 2) directly degrade request bandwidth without time or modulation compensation, or no guarantee for immediate access (QoS-affected). We focus on QoS-assured degraded provisioning problems in this study. When performing degradation, two questions may come up: which request to degrade? and how much to degrade? A new Service Level Agreement (SLA) [3] with the customer may answer these questions when traffic requests are sorted in different priorities in service-differentiated networks.

In multi-layer networks, QoS-assured degradation has different implementation methods in different layers. The basic idea of degraded provisioning in electric layer is trading time for space. This means that, for a delay-insensitive and degradation-tolerant traffic request, when congestion occurs and the bandwidth is in shortage, we degrade its transmission rate to enlarge the current available bandwidth (space), and extend its service holding time accordingly on the premise that the full traffic amount is constant. Note that a traffic request cannot be degraded arbitrarily, and it may be constrained by a certain deadline, no matter strict or relaxed [4]. In the elastic optical layer, degradation refers to decreasing the number of occupied spectrum slots for a lightpath and raising the modulation level accordingly to guarantee the data rate of the lightpath. In OFDM-based elastic optical networks, modulation level can be reconfigured in the DSP and DAC/ADC via software [5], which enables the dynamic adjustment of lightpath modulation level. However, higher-level modulation tends to have shorter transmission reach [6], which is also a constraint on optical degradation. Therefore, we should...
A. Related Work

Due to the flexibility enabled by degraded provisioning, there have been many studies on this topic in different kinds of optical networks in recent years. In conventional WDM networks, Roy et al. [7] studied supporting degraded service using multipath routing in a QoS-affected way. Zhang et al. [8] studied reliable multipath provisioning, exploiting the flexibility in bandwidth and delay. Andrei et al. [9] proposed a deadline-driven method to flexibly provision services in optical networks, but this work provided equal accessibility to all requests without distinction and did not guarantee immediate service access. Savas et al. [10] introduced a dynamic scheme to reduce blocking by exploiting degraded-service tolerance in telecom networks in QoS-affected way, but this work tried to degraded the minimum number of connections without considering different priorities of requests. They also applied this QoS-affected degraded-service-provisioning method to increase network survivability [11] with certain SLA.

Mixed-Line-Rate (MLR) network was proposed to provide flexibility in optical layer to reduce transmission costs [12]. In MLR networks, Vadrevu et al. [13] proposed a QoS-affected degradation scheme using multipath routing to support degraded services considering minimum-cost MLR network design. But the ITU-T grid limit still put constraints on optical layer flexibility.

As a major development of optical-layer technology, elastic optical networking enables more flexibility in optical modulation and spectrum allocation [14]. Distance-adaptive spectrum resource allocation [15] is a similar approach as optical degradation, but its limitations are that the modulation format of a lightpath is configured at one time based on the transmission reach and cannot be adjusted according to the fluctuation of traffic. Gkamas et al. [16] proposed a dynamic algorithm for joint multi-layer planning in IP-over-flexible-optical networks, but this work did not consider dynamic adjustment of lightpath modulation format when network congestion occurs. Recent progress in modulation format conversion [17] enables all-optical OOK to 16QAM adjustment, and its advantages in elastic optical networking were demonstrated by Yin et al. [18] when modulation format can be converted at an intermediate node of a lightpath. Therefore, the concept of degraded provisioning can be extended to the elastic optical layer, and this important issue has not been fully understood, with no previous studies.

B. Our Contributions

In this work, we investigate the dynamic QoS-assured degraded provisioning problem in service differentiated multi-layer elastic optical networks. We summarize our contributions as follows: 1) to the best of our knowledge, this is the first investigation on QoS-assured degraded provisioning problem in multi-layer networks with optical elasticity; 2) we propose an enhanced multi-layer network architecture and solve the complex dynamic degraded routing problem; and 3) we further propose novel dynamic heuristic algorithms in both layers to achieve degraded resource allocation. Illustrative numerical results show that a significant reduction of network service failures can be achieved by multi-layer degradation, up to two orders of magnitude.

II. Dynamic Degraded Provisioning Scheme

In dynamic traffic scenario, traffic requests arrive one at a time and hold for certain durations. We design dynamic heuristic algorithms to cope with online degraded provisioning problems in realistic topology. We first decompose the problem into two subroutines: 1) degraded routing, and 2) degraded resource allocation.

A. Degraded Routing

Degraded routing solves the subproblem of degraded-route computation when conventional routing can not be performed due to resource shortage in some links of the network. Optical degraded routing acts similarly as electric degraded routing, and the term request here refers to the lightpath request in optical layer, and the service request in electric layer. There are two major considerations on degraded routing: route hops and potential degraded requests. The route hops represent the overall amount of resources occupied by the new request, while the potential degraded requests represent how much the new request will affect existing requests.

We define a link in any layer of the multi-layer network as a tuple: \( V_{ij,k} = (\Theta, C) \), which is the \( k \)th link from \( i \) to \( j \). \( \Theta \) is a set that contains existing requests routed on this link, and \( C \) is the available capacity of this link. \( r_n \) is a request, and \( \mathcal{P}_{r_n} \) is a degraded route for \( r_n \) in electric or optical layer.

\[
\mathcal{P}_{r_n} = \{V_{ij,k}|r_n \in V_{ij,k} \Theta\}
\]

We introduce two metrics to evaluate the route \( \mathcal{P}_{r_n} \). Route Hops (RH) represents the resource occupancy of a request, and Potential Degraded Requests (PDR) evaluates the impact of a request on existing requests. Note that the \(|·|\) operation returns the number of elements in a set, and numbers of them are calculated as:

\[
N_{RH} = |\mathcal{P}_{r_n}|
\]

\[
N_{PDR} = |\bigcup_{c=1}^{\mathcal{P}_{r_n}} \mathcal{P}_{r_n}[c] \Theta|
\]

To calculate a route for minimizing RH, the Dijkstra algorithm is applied. However, minimizing PDR is not that easy. Because the minimizing-PDR problem aims to obtain a route that has the smallest PDR among all possible routes between a given source-destination (s-d) pair, while existing requests on a link are time-varying and several links may support the same request together. A straight-forward idea is to list all possible routes between a given s-d pair and compare their PDR. But, the complexity of this process is \( O((N-2)!)(N\text{ denotes the number of nodes}) \), which is not suitable for dynamic traffic, and new methods are needed.
Here, we propose the enhanced multi-layer network architecture by introducing the auxiliary request layer, which lies directly above the electric layer (Fig. 1), and solve the minimizing-PDR problem in polynomial time.

In the enhanced multi-layer architecture, the request layer consists of all nodes in the other two layers and directional weighted links. Link weight equals to the number of existing requests between the node pairs. In fact, in our proposed architecture, it is existing requests, rather than available resources in conventional multi-layer networks, that are mapped to the upper layer. This is because the goal is to minimize the potential affected requests, not resource occupancy. With this enhanced architecture, the minimizing-PDR problem on one layer (optical or electric layer) is transformed into a weighed shortest-path problem on the upper layer (electric or request layer), and thus can be solved using a shortest-path algorithm.

Algorithm: Minimizing-PDR Algorithm
1. Initialize topology matrix of the upper-layer \( \{ t_{i,j} \} = \{ 0 \} \);
2. for all requests \( r \) in current layer do
3. \( t_{r, source}, r, destination \); ++;
4. end for
5. run Dijkstra algorithm on the upper-layer topology \( \{ t_{i,j} \} \), and a route \( \mathcal{P} \) is returned;
6. for all links \( V_{m,n} \) in \( \mathcal{P} \) do
7. find a request among all \( t_{m,n} \) with the shortest traffic hops in lower layer, and acquire its route;
8. end for
9. combine all the acquired routes together, and return it;

Now, we introduce two policies of degraded routing:

1) Minimize Route Hops (MinRH): We manage to minimize RH first, and then minimize PDR.
2) Minimize Potential Degraded Requests (MinPDR): We try to minimize PDR as a primary goal, then we minimize RH.

B. Degraded Resource Allocation

When a degraded route \( \mathcal{P}^e \) (electric) or \( \mathcal{P}^o \) (optical) is acquired, we need to decide which request or requests to degrade, and how much to degrade them. In the multi-layer network, degraded resource allocation refers to different operations in different layers, which should be further studied separately.

1) Electric Degraded Bandwidth Allocation (ED-BA): We propose the ED-BA algorithm based on a determined degraded route. Fig. 2(a) shows the basic principle of the ED-BA algorithm, that requests with higher priorities can "preempt" those requests with no higher priorities. Here, the term "preempt" means that some existing requests are degraded in transmission rate due to arrival of a new request with priority no smaller than them. Degradation in transmission rate will cause service-holding-time prolongation, which should not exceed the deadline of the request. Meanwhile, when performing degradation, we manage to degrade the minimal number of requests to provide just-enough bandwidth for the new arriving one.

For convenience, a traffic service request on electric layer is defined as a tuple: \( r_n = (s, d, bw, t, \tau, \eta, \rho) \), which mean source, destination, bandwidth, arrival time point, holding time, prolongation deadline and priority of a service request, respectively. We define a function \( AS(S, k) \), which sorts elements in set \( S \) in ascending order of \( k \).

Algorithm: ED-BA Algorithm
1. Current time \( t_c \), arriving request \( r_0 \), flag = 1;
2. for all links \( V_n \) in \( \mathcal{P}^e \) do
3. if \( V_n.C < r_0.bw \) then
4. \( PDL(V_n) \leftarrow \{ r_0 \} \); /*potential degraded links*/
5. for all requests \( r \) in \( V_n, \Theta \) do
6. if \( r.\rho \leq r_0.\rho \) then
7. \( PDL(V_n).pushback(r) \);
8. else
9. continue;
10. end if
11. end for
12. if \( \sum_{u \in PDR(V_n)} u.bw \times \frac{u.\eta}{u.\tau + u.\eta} \geq r_0.bw \) then
13. \( ac_bw \leftarrow 0 \); /*accumulate available bandwidth*/
14. for all requests \( x \) in \( AS(PDL(V_n), priority) \) do
15. degrade \( x.bw \) to its maximum extent \( x.bw' \), s.t.
16. \( \frac{x.bw' x.\tau - (t_c-x.t) x.bw}{x.bw'} + t_c-x.t \leq x.\eta + x.\tau \);
17. if \( ac_bw > r_0.bw \) then
18. request \( r_0 \) routed successfully on \( V_n \); break;
19. end if
20. end for
21. else
22. request \( r_0 \) blocked; flag = 0; break;
23. end if
24. else
25. continue;
26. end if
27. end for
28. if flag == 1 then
29. request \( r_0 \) is routed successfully;
30. end if

2) Optical Degraded Modulation and Spectrum Allocation (OD-MSA): In an elastic optical network, optical degradation
refers to the reduction of occupied-spectrum-slot numbers of a lightpath, and the basic idea of optical degradation is to raise some of the lightpaths’ modulation level to spare enough slots for a new lightpath’s establishment. Optical degradation should obey the modulation-distance constraint, and thus shorter lightpaths have more opportunities to be degraded.

The number of spectrum slots in a fiber is \( B \). \( S_f \) is a binary bitmask that contains \( B \) bits to record the availability of each spectrum slot in fiber \( f \), e.g., \( S_f[p] = 1 \) means the \( p^{th} \) spectrum slot is utilized. A lightpath is defined as a tuple: \( L = (f, \xi_L, \xi_r, \eta, \delta) \), where \( f \) denotes the fiber the lightpath is routed through, and \( \xi_L, \xi_r \) denote the left and right indices of occupied spectrum slot, while \( \eta \) and \( \delta \) denote the modulation level and lightpath distance, respectively. Note that \((\xi_r - \xi_L + 1) \cdot \log_2 \eta \) should be constant when performing optical degradation. A lightpath request is defined as a tuple: \( r = (i, j, \theta) \), where \( i, j, \theta \) denote source, destination, and requested spectrum slots. And we define a function \( Q(\alpha) \) that returns the transmission reach of modulation level \( \alpha \).

Algorithm: OD-MSA Algorithm

1. Arriving lightpath request \( l_0 \);
2. for all fibers \( f \in \mathcal{P}^o \) do
3.   scan the spectrum to acquire \( \text{ASSI} \);
4.   \textbf{if} \( |\text{ASSI}| > 0 \) \textbf{then}
5.     choose consecutive available slots \( [l, r] \) with the largest \( r - l \) value in \( \text{ASSI} \);
6.     scan the spectrum to acquire \( L_1 \) and \( L_2 \) \( (L_1, \xi_r = l - 1 \&\& L_2, \xi_l = r + 1) \);
7.     \textbf{if} \( Q(a + 1) < L_1, \delta \leq Q(a) \) and \( Q(b + 1) < L_2, \delta \leq Q(b) \) \textbf{then}
8.       \( L_1, \eta = a; \quad \text{degrade} \ L_1 \) to modulation level \( a^{th} \);
9.     \textbf{if} \( (L_1, \xi_r - L_1, \xi_l + 1) (1 - \log_2 (\eta_0 - a)) + (l - r + 1) \geq l_0, \theta \) \textbf{then}
10.    setup a new lightpath with \( l_0, \text{spt} \) slots, starting from \( L_1, \xi_l + (L_1, \xi_r - L_1, \xi_l + 1) \log_2 (\eta_0 - a) \);
11.   \textbf{else if} \( (L_1, \xi_r - L_1, \xi_l + 1) (1 - \log_2 (\eta_0 - a)) + (l - r + 1) + (L_2, \xi_r - L_2, \xi_l + 1) (1 - \log_2 (\eta_0 - b)) \geq l_0, \theta \) \textbf{then}
12.        \text{continue the previous degraded path.}

setup a new lightpath with \(l_0 \cdot spt\) slots, starting from \(L_1 \cdot f_l + (L_1 \cdot \xi_r - L_1 \cdot \xi_l + 1) \log_2(\eta) - a\);

```java
12. \(L_2 \cdot \eta = b; /^{d e g r a d e} L_2\) to modulation level \(b^{*/}
13. setup a new lightpath with \(l_0 \cdot spt\) slots, starting
14. from \(L_1 \cdot f_l + (L_1 \cdot \xi_r - L_1 \cdot \xi_l + 1) \log_2(\eta) - a\);
15. else
16. request \(L_0\) blocked; break;
17. end if
18. else if \(|SBTL| > 0\) then
19. choose smallest \(w\) in \(SBTL\), and perform sentence
20. \(7\) to \(17\) (here, let \(l = r + 1 = w\));
21. else
22. request \(L_0\) blocked; break;
23. end if
```

C. Complexity Analysis

In degraded routing stage, both minimizing-RH and minimizing-PDR problems can be solved with \(O(N^2)\) (Dijkstra algorithm, \(N\)-node topology) complexity with the enhanced multi-layer architecture.

In degraded resource allocation stage, we further evaluate the complexity of the two proposed algorithms in different layers. The worst case for the degraded route \(P\) is that it goes through almost every node of the topology, and the hops is \(O(N)\). In ED-BA algorithm, we suppose that the maximum number of existing requests on each link is \(R\), which is related to traffic load, and the time complexity is \(O(NR)\). In OD-MSA algorithm, the time complexity is \(O(NB^2)\), where \(B\) is a constant parameter in a certain fiber configuration.

Hence, the complexity of the proposed dynamic degraded provisioning scheme is \(O(N^2 + NR)\) and can be used in online decision making for dynamic traffic accommodation.

III. ILLUSTRATIVE NUMERICAL EVALUATIONS

A. Experimental Setup

Table I summarizes the relationships among modulation formats, lightpath data rate, and transmission reach based on the results reported in [6] [20]. We assume that the default modulation format is BPSK in the network.

| TABLE I | MODULATION FORMAT VS. DATA RATE VS. TRANSMISSION REACH |
|---------|-------------------------------------------------------|
| Modulation format | BPSK | QPSK | 8QAM | 16QAM |
| Modulation level | 2 | 4 | 8 | 16 |
| Bits per symbol | 1 | 2 | 3 | 4 |
| Slot bandwidth (GHz) | 12.5 | 12.5 | 12.5 | 12.5 |
| Data rate (Gbps) | 12.5 | 25 | 37.5 | 50 |
| Transmission reach (km) | 9600 | 4800 | 2400 | 1200 |

We consider the USNet topology (Fig. 3) for dynamic performance simulation. All fibers are unidirectional with 300 spectrum slots, and the spectrum width of each slot is 12.5 GHz. Traffic requests are generated between all node pairs, and characterized by Poisson arrivals with negative exponential holding times. The granularities of requests are distributed independently and uniformly from 5 Gbps to 150 Gbps. The maximum acceptable value of degraded transmission rate is uniformly distributed between 100 and 25 percent of their original bandwidth [11]. There are 5 priorities with equal amount each. The lightpath establishment threshold for grooming is chosen to be 150 Gbps, which is equals to the largest request bandwidth, because this threshold has been demonstrated to perform the best of blocking performance [19]. An event-driven dynamic simulator has been developed to verify the effectiveness of the heuristic algorithms. Six degradation policies (OE-MinPDR, O-MinPDR, E-MinPDR, OE-MinRH, O-MinRH, E-MinRH), which are combinations of two degraded routing policies (MinPDR, MinRH), and three degraded resource allocation policies (OE: both-layer degradation, O: optical degradation only, E: electric degradation only) are studied.

B. Dynamic Analysis

Fig. 4 depicts the bandwidth blocking probability (BBP) advantages of our proposed scheme over the conventional scheme (threshold-based grooming [19], no degradation) with different degradation policies. Fig. 4(a) shows the overall performance of all requests, and we can find there is a crossing point between optical degradation and both-layer degradation. In low-load area (26-34 Erlang), both-layer degradation (OE-MinPDR, OE-MinRH) performs the best, up to two orders of magnitude, while in high-load area (36-44 Erlang), optical-layer degradation (O-MInPDR, O-MinRH) performs the best. The reason is that, in high-load conditions, electric degradation (E-MinPDR, E-MinRH) achieves worse BBP than no degradation, which affects the blocking reduction by optical degradation in both-layer degradation. Figs. 4(b) and 4(c) show the BBP performance of requests in the highest and lowest priority. And we can conclude that all degradation policies can achieve significant blocking reduction in the highest priority, while, for the lowest-priority, the blocking performance acts similar as requests with all priorities do.

We also observe some common patterns in these three graphs. First, optical degradation performs almost the same regardless of priorities, because optical degradation does not involve service priorities as electric degradation does. Second, MinPDR performs better in optical-related degradations (both-layer degradation and optical degradation), while MinRH performs better only in electric degradation. This is because...
the route MinPDR returns tends to have a smaller number of existing requests, which increases the elements in ASSI or SBTL, thus increasing possibility of successful optical degradation. And the route MinRH returns tend to have more existing requests, which provides more requests (thus, more bandwidth and more opportunity) for the arriving request to preempt on electric layer, which increases the possibility of successful electric degradation. Actually, different mechanisms of optical degradation and electric degradation determine that MinPDR is more suitable for optical degradation, while MinRH suits electric degradation better. The result that both-layer degradation and optical degradation performs similarly reveals that optical degradation has stronger influence on blocking reduction because it can enlarge the network capacity by high-order modulation while electric degradation just deals with the bandwidth-time exchange to trade time for bandwidth under a given network capacity.

C. Transient Analysis

To study the instantaneous working mechanism and performance of the proposed degraded provisioning scheme, we conduct transient analysis on instantaneous network throughput and BBP, and the results are shown in Fig. 5. From Figs. 5(a) and 5(b), we obtain similar conclusions as the dynamic evaluations, that optical-related degradation achieves better compliance with the offered load in MinPDR, while electric degradation accomplishes better improvements in MinRH. Fig. 5(c) shows the instantaneous BBP variance over time, and we observe that different levels of blocking reduction can be achieved by different degradation policies, both-layer degradation policies have the largest blocking reduction, and OE-MinPDR performs even better (almost zero blocking).

IV. Conclusion

In this work, we investigated dynamic QoS-assured degraded provisioning problem in service-differentiated multi-layer networks with optical elasticity. We proposed and leveraged the enhanced multi-layer architecture to design effective algorithms for network performance improvements. Numerical evaluations showed that we can achieve significant blocking reduction, up to two orders of magnitude via the new degraded provisioning policies. We also conclude that optical-related degradation achieves better performance with MinPDR, while electric degradation has lower blocking with MinRH due to different mechanisms of multi-layer degradation.

REFERENCES

[1] L. He, et al., “Pricing differentiated internet services.” in INFOCOM, 2005.
[2] A. Muhammad, et al., “Service Differentiated Provisioning in Dynamic WDM Networks Based on Set-Up Delay Tolerance,” IEEE/OSA J. Opt. Commun. and Netw., vol. 5, no. 11, pp. 1250-1261, 2013.
[3] W. Fawaz, et al., “Service level agreement and provisioning in optical networks,” IEEE Commun. Mag., vol. 42, no. 1, pp. 36-43, 2004.
[4] W. Fawaz, et al., “Deadline-based connection setup in wavelength-routed WDM networks,” Computer Netw., vol. 54, no. 11, pp. 1792-1804, 2010.
[5] G. Zhang, et al., “A Survey on OFDM-Based Elastic Core Optical Networking,” IEEE Commun. Surveys & Tutorials, vol. 15, no. 1, 2013.
[6] A. Bocci, et al., “Reach-dependent capacity in optical networks enabled by OFDM.” in OFC, 2009.
[7] R. Roy, et al., “Degraded-Service-Aware Multipath Provisioning in Telecom Mesh Networks,” in OFC, 2008.
[8] W. Zhang, et al., “Reliable adaptive multipath provisioning with bandwidth and differential delay constraints,” in INFOCOM, 2010.
[9] D. Andrei, et al., “Provisioning of Deadline-Driven Requests with Flexible Transmission Rates in WDM Mesh Networks,” IEEE/ACM Trans. Netw., vol. 18, no. 2, pp. 353-366, 2010.
[10] S. S. Savas, et al., “Exploiting Degraded-Service Tolerance to Improve Performance of Telecom Networks,” in OFC, 2014.
[11] S. S. Savas, et al., “Network Adaptability to Disaster Disruptions by Exploiting Degraded-Service Tolerance,” IEEE Commun. Mag., vol. 52, no. 12, pp. 58-65, 2014.
[12] A. Nag, et al., “Optical Network Design With Mixed Line Rates and Multiple Modulation Formats,” IEEE/OSA J. Lightw. Technol., vol. 28, no. 4, pp. 466-475, 2010.
[13] C. S. K. Vadrevu, et al., “Degraded Service Provisioning in Mixed-Line-Rate WDM Backbone Networks Using Multipath Routing,” IEEE/ACM Trans. Netw., vol. 22, no. 3, pp. 840-849, 2014.
[14] O. Gerstel, et al., “Elastic optical networking: A new dawn for the optical layer?” IEEE Commun. Mag., vol. 50, no. 2, pp. s12-s20, 2012.
[15] M. Jinno, et. al., “Distance-Adaptive Spectrum Resource Allocation in Spectrum-Sliced Elastic Optical Path Network,” IEEE Commun. Mag., vol. 48, no. 8, pp. 138-145, 2010.
[16] V. Gkamas, et al., “A Joint Multi-Layer Planning Algorithm for IP Over Flexible Optical Networks.” IEEE/OSA J. Lightw. Technol., vol. 33, no. 14, pp. 2965-2977, 2015.
[17] G. Huang, et al., “All-Optical OOK to 16-QAM Modulation Format Conversion Employing Nonlinear Optical Loop Mirror,” IEEE/OSA J. Lightw. Technol., vol. 30, no. 9, pp. 1342-1350, 2012.
[18] S. Yin, et al., “Dynamic routing, modulation level and spectrum allocation (RMLSA) in FWDM with modulation format conversion.” Optik, vol. 125, no. 11, pp. 2597-2601, 2014.
[19] X. Wan, et al., “Dynamic Traffic Grooming in Flexible Multi-Layer IP/Optical Networks,” IEEE Commun. Lett., vol. 16, no. 12, 2012.
[20] Z. Zhu, et al. “Dynamic Service Provisioning in Elastic Optical Networks With Hybrid Single-/Multi-Path Routing,” IEEE/OSA J. Lightw. Technol., vol. 31, no. 1, pp. 15-22, 2013.