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Capacity-bounded lightpath routing in WDM optical networks

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ABSTRACT

To meet the increasing user bandwidth demands, the ICT networks are constantly expanding. The optical fiber technology has completely revolutionized the bandwidth capacity of both the core networks and the access networks. In core networks, the optical links provide very high bandwidth connectivity over long distance. Thus, any link failure due to disastrous events like earthquake, flood, landslide etc. can lead to massive service outages and huge fiscal losses. Normally, optical fibers are laid in 1 + 1 configuration to route the traffic to the alternate path in such scenario. However, a natural disaster event may lead to simultaneous failure of multiple lightpaths. Therefore, routing algorithm, running on network nodes (routers or switches), are required in such case to establish new routes. Nevertheless, generally the routing schemes follow the least hop count and shortest distance approach to route the traffic to another backup path. Nonetheless, this approach may result in congestion on some links while other links may have unutilized capacity. This also makes it progressively tougher to fit more connection requests from the access network. Hence, implementation of more advanced path computation capabilities is required at the network nodes of the core network to ensure efficient routing of network traffic in disastrous scenario. This problem is referred to as capacity-bounded lightpath (CBL) problem. We proposed an exact algorithm which addresses this problem by considering the channel capacity of each link in addition to distances. The performance of the proposed algorithm is evaluated through simulation for three parameters: link capacity, connection requests and un-used links. It is revealed that existing shortest path algorithm improves the performance in terms of blocking probability of links and lightpaths at the cost of underutilization of the network capacity. Whereas, proposed algorithm regulates the capacity utilization by prioritizing link capacity over link length to establish more optimal shortest lightpath against connection requests.

1. Introduction

The services and resources delivered by information and communication technology (ICT) networks have revolutionized the world into a global village. For most of the world population, the Internet access has become a necessity rather than a comfort. In ICT network, the role of optical fiber has significantly increased and it has been estimated that about 99% of the global internet traffic is carried by undersea fiber optic cables [1,2]. The dramatic increase in the demand for ICT services has up surged the bandwidth requirements. It is investigated that bandwidth requirement of the users is rising faster than the network capacity to deliver it [3]. According to Cisco forecast 2017, internet traffic will grow threefold over the next five years, whereas more than 63% of internet traffic will be caused by wireless and mobile devices data in 2021 [4]. According to ITU 2016 report, 95% of the world population lives in the area that is covered by cellular networks whereas mobile broadband networks (3G or above) covered area encompasses 85% of the global population [5]. This ever-increasing bandwidth requirement ultimately contributes towards overloading of network resources or network congestion. It also means available network capacity cannot fulfill the total connection requests in the network. This may happen for several reasons like low bandwidth, multicasting, bad configuration, too many hosts in the broadcast domain, broadcast storm (can be a busy day for e-commerce or Black Friday sales) or the re-routing of disrupted or blocked traffic due to disaster-based failures. Such situations lead to network congestion which might also cause service outages, data losses, service downtimes as well as financial losses to network operators. It has been estimated that the losses due to service downtime may range from 25 to 150 thousand USD per hour [6].

Congestion can be avoided by network segmentation, backpressure routing and prioritizing the network traffic. Generally, optical networks

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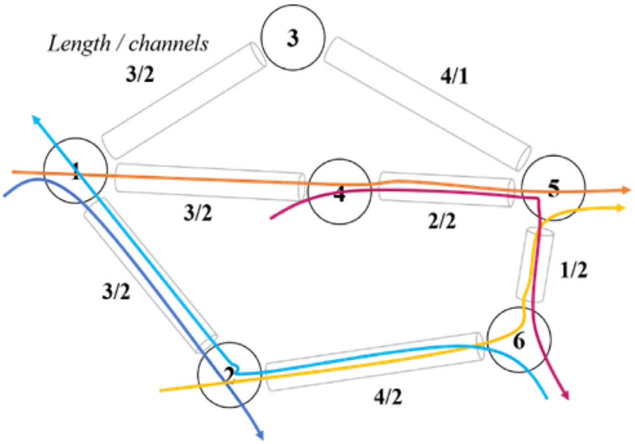


(a) Network with Lightpath Establishment

Links	Length	Offered Channels	Channels Used
1↔2	3	2	2
1↔3	3	2	0
1↔4	3	2	1
2↔6	4	2	2
3↔5	4	1	0
4↔5	2	2	2
6↔5	1	2	2

(b) Network Traffic Table

Fig. 1. Example of RWA Problem.

might have some spare capacity to avoid or alleviate traffic congestion. Such capacity can be utilized to give better assurance against network failures as well. If the network capacity is appropriately utilized and the network load is symmetrically distributed over the links, the congestion can be controlled in terms of connection acceptance rate and lower blocking probability [7]. In wavelength-routed optical networks, routers are interconnected by fiber links which have the massive bandwidth. This accessible capacity over a fiber link is divided into multiple all-optical WDM channels of non-overlapping wavelengths. Each channel may have a capacity of 100 Gigabits per second or higher. In a wavelength-routed optical network, end users communicate with one another via these channels, which are referred to as lightpaths [8,9]. The basic optimization problems that arise in optical networks are routing and wavelength assignment (RWA) which are handled either as separate problems or a joint problem. The objective of the joint RWA problem is to provision a lightpath for each connection request consisting of a routing path and all-optical WDM channel over each constituent link of the routing path [10].

A simple illustration of RWA problem is given in Fig. 1. Five lightpaths have been established upon connection requests on the first-fit rule. Taking the current statistics in view, Fig. 1(a) clearly indicates that connection requests between nodes (1 ↔ 4), (1 ↔ 3) and (3 ↔ 5) can be established immediately because of channel availability. If a connection request arrives other than these requests, then it has to wait for a channel to be free which will delay the connection request or may also cause it to drop off. In case of the connection request (4 ↔ 5), a lightpath can be established immediately, however, it incorporates a delay at the cost of path length (i.e. 4 → 1 → 3 → 5 as there is no channel available at 4 → 5). Hence, it can be concluded that there is a tradeoff between path length and capacity while establishing a connection between two nodes of a network.

Disrupted lightpaths require re-routing if network component ceases to function in the event of a disaster. This may lead to traffic congestion as network capacity is a finite resource and should be used in an efficient manner. Therefore, congestion-aware techniques are required to ensure the provisioning of most survivable lightpaths against connection requests between any two network nodes whereas network congestion is controlled or balanced. In this paper, optimization of network capacity utilization has been focused and shortest lightpath problem contingent to link capacity is analyzed. The organization of the rest of the paper is based on four sections. Related work is reviewed in Section 2. Section 3 will provide an insight of the problem and proposed algorithm. Section 4 illustrates the numerical results and compares the performance of the proposed algorithm with that of existing one and this paper will be concluded in Section 5.

2. Related work

One of most used state of the art algorithm to compute the shortest lightpath from source node to destination node is Dijkstra algorithm [11]. However, Fuhao et al. [12] exhibited the inefficiency of this algorithm for large-scale optical networks. Several modifications have been proposed to Dijkstra algorithm with and without data processing [13–17] and used in finding spatial disjoint lightpaths [18,19]. All services in optical network finally converge at IP layer and move into the cloud. It is essential for service providers to employ optimized path computation techniques for efficient routing. Routing protocols like open shortest path first (OSPF) and Intermediate System to Intermediate System (ISIS) use Dijkstra algorithm to find the shortest path for every source-destination pair. As a result, short weighted links easily get congested while capacity of other links remained underutilize. Hao et al. in [20] introduced a novel centralized Path Computation Element (PCE) that employs refined path computation algorithm with dynamic link cost metrics to enable network-embedded routing protocols in discovering paths that use available link capacity more efficiently. Further, PCE applies software-defined networking (SDN) paradigms to separate path computing and path signaling functions, which gives operators more control over their network. Hao et al. proposed that centralized PCE with STAR (Self-Tuned Adaptive Routing) algorithm subsidizes to the efficient consumption of link capacity for load balancing as well as avoids links overloading. Overall, single PEC or multiple PECs in a network results in more revenue-bearing traffic.

In [21], Wu et al. proposed a model for per link congestion control by balancing network resource allocation considering current and future demands of lightpath requests. Realistic networks have irregular network topology and random connection requests. Whenever traffic load increases, the number of idle channels per link decreases in establishing the connection requests. Ultimately, connection requests start blocking when there is zero channel available on the link and can be measured as blocking probability. Rani et al. [22] proposed a congestion-aware dynamic strategy that seeks to minimize the blocking probability by symmetrically distributing the network traffic over the links to enhance resource utilization. It also helps to control network congestion. Wason et al. developed a low complexity mathematical model to calculate and reduce the blocking probability of WDM network in [23,24], and analyzed blocking probability against a number of links, number of free wavelengths and length of routes. In [25], Wason et al. proposed another mathematical model for wavelength-routed WDM networks to optimize the blocking probability. They compared all models proposed in [23–25] and showed that recent model gives improved results than earlier models.

RWA is an important issue in all-optical networks. It can be treated either as a single problem (i.e. routing problem and wavelength assignment problem) or as individual problems (i.e. routing problem or wavelength assignment problem) on the basis of scale, size and other preferences of the network. Sohal et al. [26] addressed the routing problem in wavelength-routed optical networks. They studied the performance of Dijkstra algorithm and least congested path routing algorithm in terms of path lengths and blocking probability. RWA can also be utilized either in centralized or distributed manner. For small-scale networks, there is a small number of requests; hence, centralized RWA approach can be used to tackle the problem. However, for large-scale networks where traffic is high, the distributed method should be utilized. Zanjani et al. [27] proposed a congestion-aware distributed lightpath allocation (DLA) routing algorithm which considered the congestion as a decision point to allocate resources. The end-to-end connectivity assurance and congestion avoidance have raised the need for robust and low latency routing protocols. Stewart et al. presented congestion avoidance shortest path routing (CASPaR) algorithm in [28] which pursues to enhance the packet delivery probability (PDP) and reduces the latency.

In most of the works on RWA problem, fixed shortest path routing (FSPR) has been considered as one of the major provisioning strategies being employed. FSPR can cause unbalanced load distribution and hence lead to network congestion. In [29], Li et al. proposed a Load-Balanced Fixed Routing (LBFR) algorithm to avoid network congestion whilst retaining the operational theme of FSPR. A forecasted traffic load matrix is used to train FSPR and find the lightpath routes under wavelength continuity constraint. According to Jungang et al. [30] load misbalancing in the network is the cause of network congestion. In this regard, they proposed an RWA algorithm based on load balancing using a weight factor β. Jungang et al. showed that the speed at which a network achieves a balance state is inversely proportional to β but resource utilization is directly proportional to the values of β.

3. Problem Formulation and proposed algorithm

Suppose an undirected network as $\mathscr{G} = (N, L)$ describing a physical network with $|N|$ total nodes and $|L|$ connecting links which may have two weight characteristics; (*i*) length ω that remains constant and (*ii*) capacity channels λ which can be engaged or utilized to serve connection requests. Formal notations and their brief descriptions are given in Table 1.

Maximal utilization of individual link capacities λ_k helps in computing path capacities σ_k and network capacity. Path capacity is assumed to have minimum channel number over its constituent links and is obtained as Eq. (1).

Table 1
Notations and Descriptions.

Notation	Description
n_k	The kth node where $N = \{n_1, n_2, n_3, \cdots, n_{\vert N\vert}\}$
l_k	The kth link where $L = \{l_1, l_2, l_3, \cdots, l_{\vert L\vert}\}$
ω_k	The kth link weight where $\omega = \{\omega_1, \omega_2, \omega_3, \cdots, \omega_{\vert L\vert}\}$
λ_k	No. of capacity channels on kth link
λ_T	The sum of all link capacities when network is idle
$\lambda_T^{'}$	The sum of capacities of only those links which have been engaged to server connection requests when network was idle
Z	Set of zero-capacity links i.e. $Z = \{l \; \forall \; \lambda = 0\}$
$\mathscr{L}$	Set of Link Channels where $\mathscr{L} = \{\lambda_1, \lambda_2, \lambda_3, \cdots, \lambda_{\vert L\vert}\}$
P_k	The kth path for a connection request (s_i, d_j) where $P = \{P_1, P_2, P_3, \cdots, P_k\}$
σ_k	The kth path capacity where $\sigma = \{\sigma_1, \sigma_2, \sigma_3, \cdots, \sigma_k\}$
W_k	The kth path weight where $W = \{W_1, W_2, W_3, \cdots, W_k\}$
β_{link}	Link blocking probability
β_{path}	Path blocking probability
ρ_{link}	Link capacity utilization ratio
$\rho_{network}$	Network capacity utilization ratio
X	Set of unestablished connection requests as $X = \{(s_i, d_j) \vert i \neq j\}$

$$\sigma_k = \underset{\forall\, l \in p_k}{\text{Minimize}} \lambda_k \tag{1}$$

The link with $\lambda = 0$ is known as zero-capacity link which indicates that either whole capacity over the link is utilized (congested link) or damaged. The path weight is computed by adding lengths of its constituent links as:

$$W_k = \sum \omega_{k_l} \;\; \forall \; l \in P_k \tag{2}$$

Network congestion is responsible for blocking probability which may be defined as chances of denial of service due to lack of resources or capacity. Blocking probability relies on its constituent links with minimum number of λ and can be observed as link blocking probability or path blocking probability computed by Eqs. (3) and (4) respectively.

$$\beta_{link} = \frac{|Z|}{|L|} \tag{3}$$

$$\beta_{path} = \frac{|P \; \forall \; \sigma = 0|}{|P|} \tag{4}$$

Network capacity utilization ratio (ρ) has been focused at link level and network level represented in Eqs. (5) and (6) respectively. For idle network, we get ρ = 1 if no connection request is served, and ρ gradually declines to zero with progressive establishment of connection requests. Suppose $\boldsymbol{m}$ is a set which represents the indices of those links whose capacity is utilized after establishing some connection requests.

$$\rho_{link} = \frac{\sum_{k=1}^{m} \lambda_k}{\lambda_T^{'}} \tag{5}$$

$$\rho_{network} = \frac{\sum_{k=1}^{m} \lambda_k}{\lambda_T} \tag{6}$$

Shortest path problem can be perceived as $\underset{(s_i, d_j) | i \neq j}{\text{Minimize}} W_k$ i.e. provisioning a lightpath from $\boldsymbol{i}$ node to $\boldsymbol{j}$ node such that the sum of the lengths of its constituent links is minimized.

Fig. 2 depicts a sample network in the idle state. Links are labeled with an ordered pair of length and unit channel. After establishing the connection request (4, 6), shortest lightpath $\text{P}_{4\rightarrow6}$ will engage the only channel available on the link 4 → 6 and has been congested (i.e. zero capacity link). If we need to establish another connection request (1, 6), SP algorithm will compute the shortest lightpath $\text{P}_{1\rightarrow4\rightarrow6}$ based on link lengths which may not be possible at the current state of the network as link 4 → 6 is inaccessible. Keeping accessible capacity of links in view, three more lightpaths can be computed as:

$\{\text{P}_{1\rightarrow2\rightarrow7\rightarrow6}, \text{P}_{1\rightarrow4\rightarrow3\rightarrow5\rightarrow6}, \text{P}_{1\rightarrow3\rightarrow5\rightarrow6}\}$ with corresponding lengths $\{7, 10, 10\}$.

Among these three lightpaths, $\text{P}_{1\rightarrow2\rightarrow7\rightarrow6}$ will be considered as the

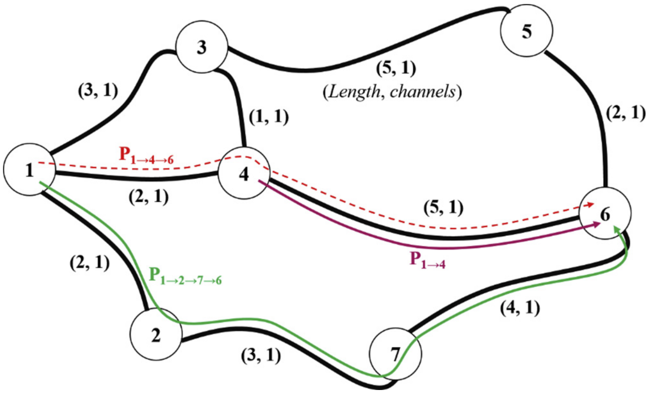


Fig. 2. Problem Formulation.

most optimal path because of capacity availability and minimum computed length.

A. Capacity Bounded Lightpath (CBL) Problem:

Capacity bounded lightpath problem can be defined as finding a lightpath between two network nodes with minimum length but restraint to the available capacity channels over links which constitute the lightpath.

The domain of the shortest lightpath problem encloses the following problems:

i. Single source – Single destination shortest lightpath problem
ii. Single source shortest lightpath problem
iii. All pair shortest lightpath problem

The proposed Capacity Bounded Lightpath (CBL) algorithm is designed to work best with first two problems. It can handle single as well as multiple connection requests. However, connection requests belong to a single source. The objective is to find out capacity-aware end-to-end shortest routes while maximizing network resource utilization.

Algorithm 1: CBL
Input: Sets of nodes ***N*** and links ***L*** of the network. Set of link lengths ω, set of link channels information $\mathscr{L}$, source node ***s*** and set of destination nodes ***T*****.Output:** Set of lightpaths P, set of lightpath lengths W, set of lightpath capacity σ, updated set of link channels $\mathscr{L}$ and set of unestablished connection requests ***X***.

```
1   P := ϕ, W := ϕ, σ := ϕ, Q[1:|N|] := false, dist[1:|N|] := ∞, pred[1:|N|] := 0
2   dist(s) := 0 // distance from source node is zero
3   for i from 1 to |N|-1
4     temp[1:|N|] := 0
5     for h from 1 to |N|
6       if Q(h) is false then temp(h) := dist(h) else temp(h) := ∞ end if
7     end for
8     u := find the index of the minimum value in temp
9     Q(u) := true
10    for v from 1 to |N|
11      k := find index of matching link u ↔ v in L. This enables to track link
    length $\omega_k$ and corresponding link capacity$\lambda_k \in \mathscr{L}$
12      if $\lambda_k > 0$ then // Capacity constraint
13        if dist(v) > $\omega_k$ + dist(u) then // Minimizing lightpath length
14          dist(v) := $\omega_k$ + dist(u)
15          pred(v) := u
16        end if
17      end if
18    end for
19  end for
20  for each t in T
21    d := t
22    if pred(d) not 0 then
23      sp := d
24      while d not s
25        sp := {pred(d)} U {sp}
26        d := pred(d)
27      end while
28      P := P U {sp} and W := W U {dist(t)}
29    else
30      X := X U {(s, t)}
31    end if
32    for each l as edge in sp
33      k := find index of matching link l in L. This enables to track link length $\sigma_k$
    and corresponding link capacity$\lambda_k \in \mathscr{L}$
34      $\lambda_k := \lambda_k - 1$
35      $\mathscr{L}$(k): =$\lambda_k$
36      $\sigma$(k): =$\underset{\forall l \in P_k}{\text{Minimize}} \lambda_k$
37    end for
38  end for
```

The procedural flow of CBL is based on the principle of relaxation. Lines 1–2 describe the necessary initializations e.g. distance to source node will be zero whereas to other nodes set to ∞. Also, node set Q is initialized to *false* to represent node status as un-visited. It reduces the number of iterations by restricting to visit a node again, as the shortest lightpath to all other nodes could be calculated without the need for a second visit to any nodes. The outer loop at lines 3–19 iterates $|N| - 1$ times. Inner loops at lines 5–7 and 10–18 decide on visiting of nodes and calculating distances with predecessor sets respectively. Line 12 sets the link capacity bottleneck and lines 13–16 updated the minimum lightpath length with corresponding predecessor node. Single or multiple connection requests from a single source are handled by another for a loop at lines 20–38. Condition check as predecessor not being zero at line 22 lets it be decided whether a connection request had set up or blocked due to the capacity constraint. Blocked connection requests are inserted in the set X (refer to line 30) so that they may be handled separately with delay constraint. Lines 24–27 construct the shortest lightpath from source to destination nodes using predecessor set. Lastly, capacities of constituent links of shortest lightpath and capacity computed shortest lightpath are updated using for-loop at lines 32–37.

B. Complexity and Hardness Analysis

Shortest lightpath problem seeks minimum distance or length from node A to node B and it is in P [31] because it can be solved through deterministic polynomial time algorithms (e.g. Dijkstra, Bellman-Ford and BFS for non-weighted graphs). Hardness of CBL problem depends on the establishment of lightpath according to the static or dynamic nature of connection requests which is proven to be NP-Hard [32–34]. However, the computational complexity to establish static lightpath is found to be lower than that of dynamic lightpath establishment. If a network consists of $|N|$ nodes and $|L|$ connecting links, then worst-case time complexity of CBL can be computed as $O(|N|^2 |L|)$.

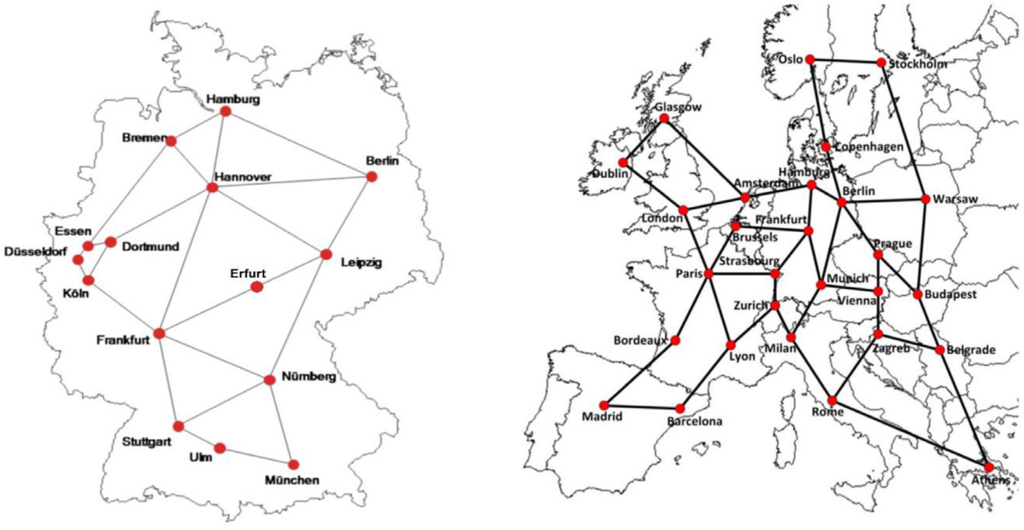
4. Simulation Results and Discussion

We now quantitatively evaluate our CBL through simulated results and benchmark with proposed SP algorithm in [26]. We have simulated two networks with the assumptions that the processes of connection requests and channel assignment to links are Poisson, whereas connection request-holding time follows a negative exponential distribution. Both algorithms are coded in MATLAB R2017a and simulations are performed on 3rd Generation Intel® Core i5-3210 M 2.5 GHz machine of 6 GB RAM. All numerical results are averaged over 1000 runs. We have used two real-life networks (i) German-15 and (ii) Europe-28 as shown in Fig. 3.

German network consists of 15 nodes and 24 fiber links. European network consists of 28 nodes and 41 fiber links. Link lengths are computed geographically in kilometers. Simulations are performed by varying number of channels per link and connection requests and observing the blocking probability, capacity utilization, number of unused links and connection acceptance rate.

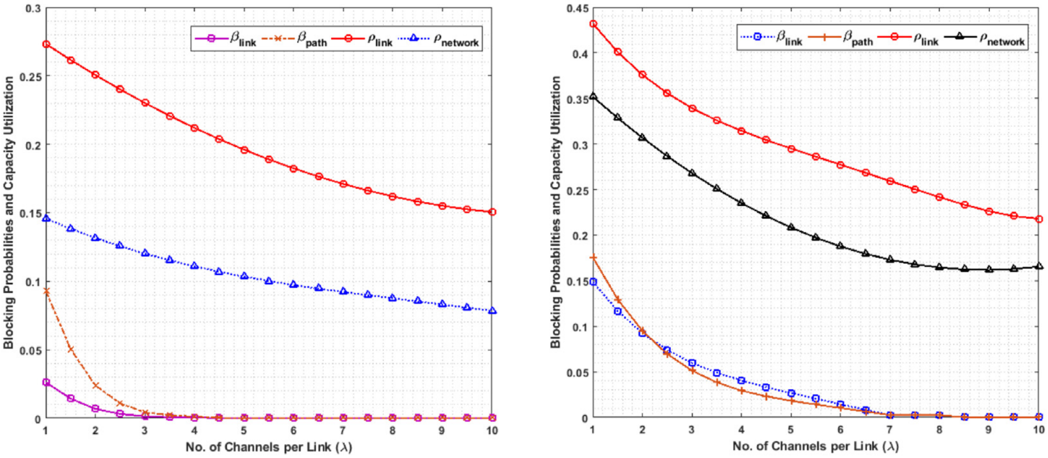
Figs. 4 and 5 describe how blocking probabilities for establishing lightpaths and their links vary when capacity channels per link are increased. It can be observed that CBL provides enhanced capacity utilization as compared to benchmark. Link blocking probability and path blocking probability are almost similar for CBL and gradually decreases which show that path blocking probability intrinsically rely on link blocking probabilities.

Fig. 6 depicts the usage of link for a fixed number of connection requests in both networks. A number of un-used links for SP algorithm remains constant and higher than that of CBL which indicates that benchmark technique tries to engage specific links repeatedly and completely ignores the valuable capacity of other links. This leads to the congestion of specific links and results in terms of connection blocking. CBL tries to engage the capacity over the links of network whichever available and number of un-used links steadily increases with increase in the number of channels per link. This demonstrates that CBL utilizes the network resources more efficiently as compared to benchmark technique.



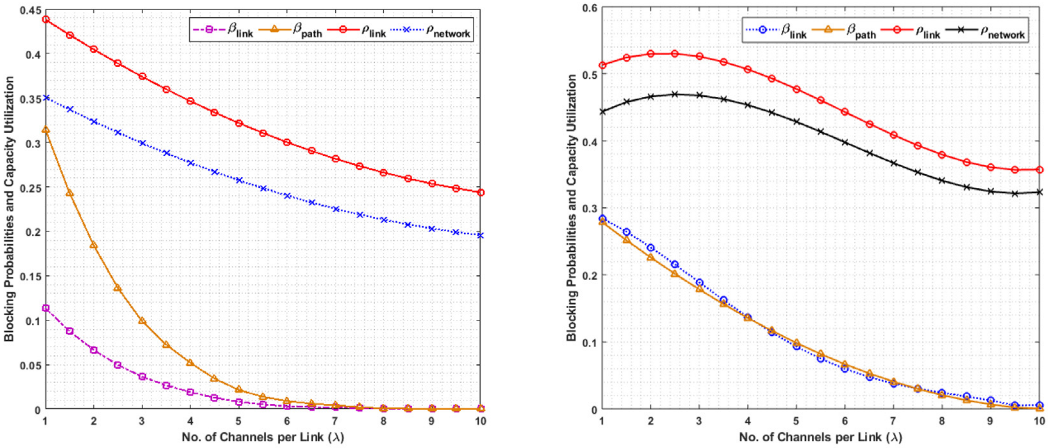
(a) German-15 (b) Europe-28

Fig. 3. Simulating Networks.



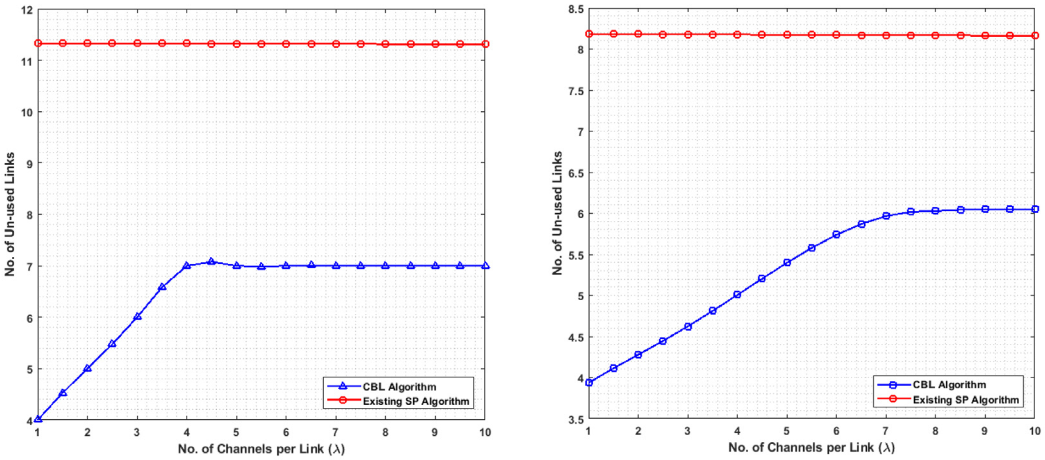
(a) Existing SP Algorithm (b) CBL Algorithm

Fig. 4. Channels per Link Vs. Blocking Probability and Capacity Utilization in German-15.



(a) Existing SP Algorithm (b) CBL Algorithm

Fig. 5. Channels per Link Vs. Blocking Probability and Capacity Utilization in Europe-28.



(a) German-15

(b) Europe-28

Fig. 6. Channels per Link Vs. Un-used Links.

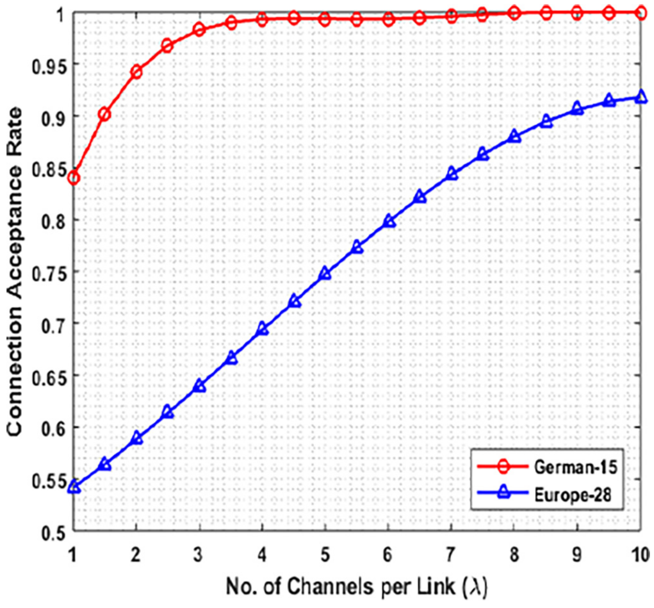


Fig. 7. Channel per Link Vs. Connection Acceptance Rate.

Connection acceptance rate for existing technique will be 100% for all number of link channels (as it only focuses to minimize the lightpath weights) which is practically difficult to achieve. Fig. 7 depicts the simulated statistics for connection acceptance rate while number of channels increases over the links. For small-scale optical networks, connection acceptance rate will be higher and soon converge to maximum acceptance rate i.e. 100%.

Blocking probability and capacity utilization are also observed under the assumption of dynamic connection requests arriving randomly. In the dynamic establishment of connection requests, routes are not predetermined but established in real-time without having the knowledge of future lightpath provisioning events. Here, an attempt is made to select routes for arriving connections to minimize the network congestion and maximizing the network resource utilization. After a certain amount of time, the established connections are no longer required and then these lightpaths are taken down dynamically [35]. Subsequently, set $\mathscr{L}$ is updated accordingly. In the meantime, blocked connection requests are tried to re-establish by re-running CBL. Using this criterion, CBL tries to fit more and more lightpaths within the existing resources of the network in order to enable network operators to fulfill connection requests quickly and economically.

Figs. 8 and 9 describe the performance comparison of CBL and benchmark technique for blocking probability and network utilization ratio when then number of connection requests increases. Number of channels per link are assigned randomly. It is observed that proposed

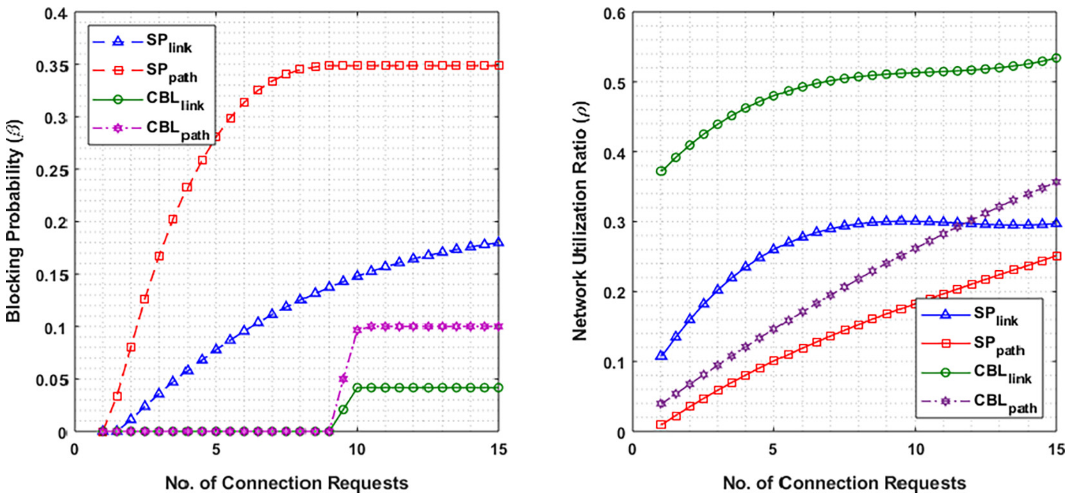


Fig. 8. No. of Requested Connections Vs. Blocking Probability and Network Utilization in German-15.

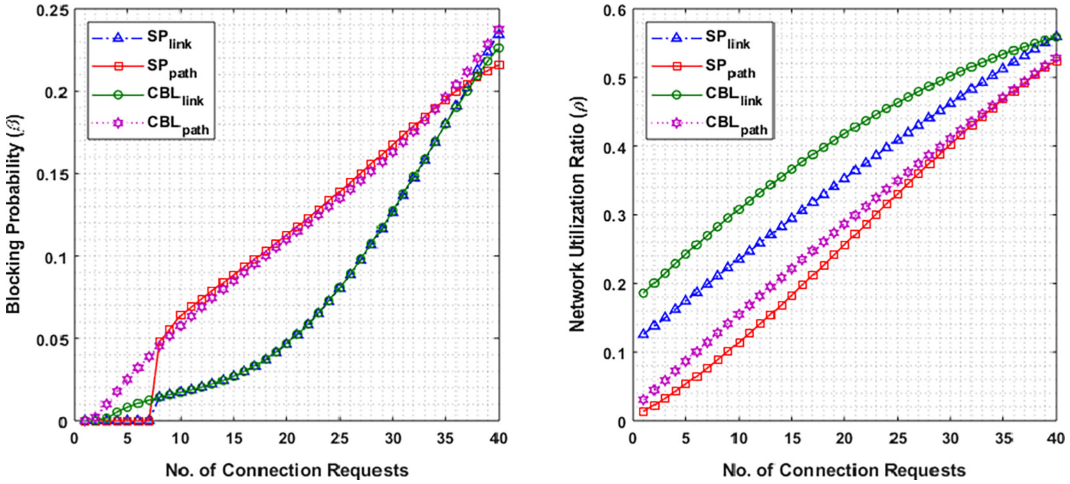
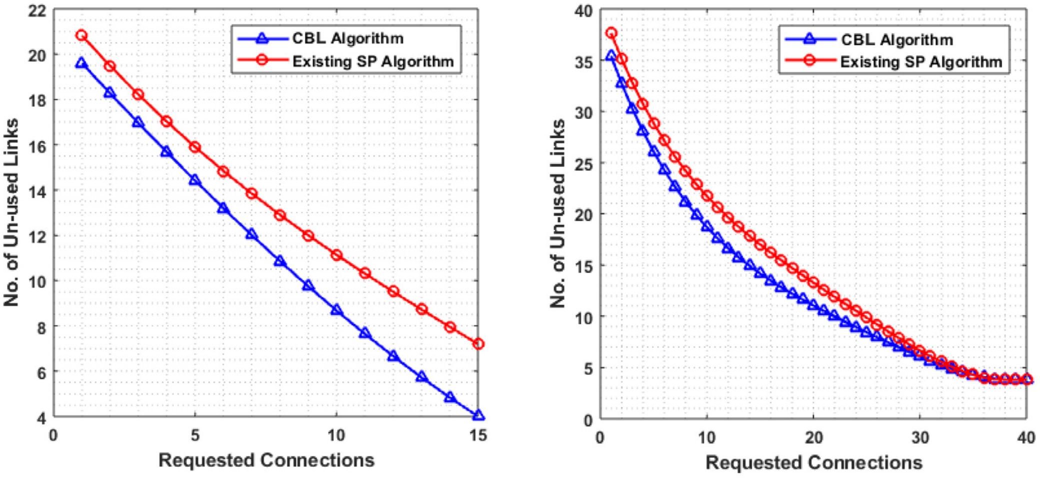


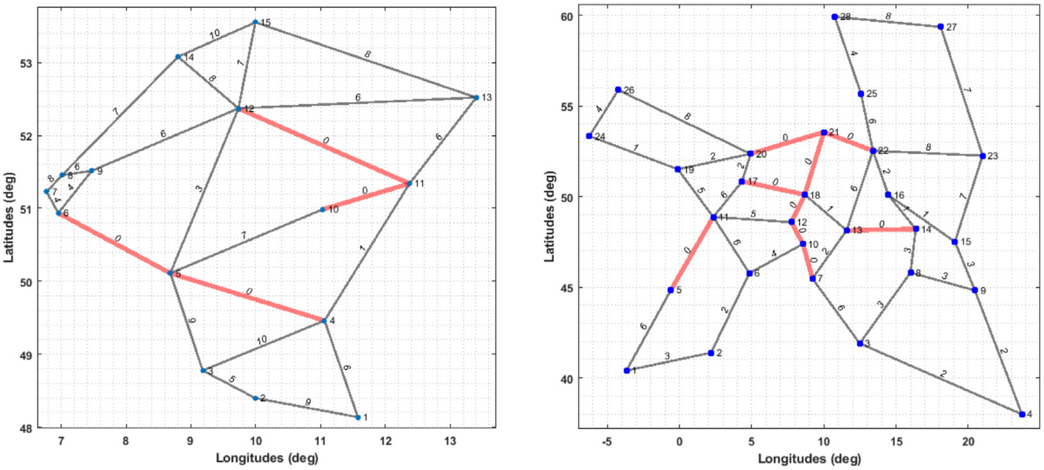
Fig. 9. No. of Requested Connections Vs. Blocking Probability and Capacity Utilization in Europe-28.



(a) German-15

(b) Europe-28

Fig. 10. No. of Requested Connections Vs. Un-used Links.



(a) German-15

(b) Europe-28

Fig. 11. Plot of Zero Capacity Links after Fitting all Connection Requests.

technique improves performance in terms of the blocking probability and network capacity utilization. Furthermore, capacity utilization ratio for links will be greater than for network conforming of Eqs. (5) and (6).

Fig. 10 shows the declining fashion of a number of un-used links for both techniques against a number of requested connections. Allocation of capacity channels over links is random. CBL used more number of links to establish lightpaths; the SP which leads to the symmetric fitting of traffic over the network. This will significantly reduce the network congestion.

Zero capacity links criterion may be assumed for large-scale disasters when multiple nodes and links are disrupted and cannot take part in the establishment of connection requests. Fig. 11 depicts the situation when some suitable end-to-end routes between source-destination pairs cannot be established under current network state. The figure also shows that, sometimes, it would be crucial to split up some of the existing lightpaths and establish some new lightpaths in response to network component failures.

5. Conclusions

The core network in the ICT is based on the optical lightpaths. The optical links are very high capacity links and carry huge amount of traffic. Any failure of an optical link may lead to huge financial losses and thus, the traffic of the damaged lightpath should be immediately re-routed. To achieve fast and shorter lightpaths convergence, routing techniques used by network nodes overload the particular links on common routes and do not account for the capacity of other links. Moreover, re-routing of blocked traffic in response to disaster-based failures yet again contributes towards network congestion. Therefore, the congestion aware routing is the utmost requirement of network operators which congregates the shortest route while maximizing the network resource utilization.

Appropriate utilization of network capacity (particular stranded capacity) enables to lower the blocking probability and improve connection acceptance rate leading towards controlled network congestion. In this paper, we have proposed a polynomial-time algorithm to mitigate the congestion problem. The proposed exact algorithm employs the sophisticated path computation limited to dynamic capacity available over the links to fit more progressive connection requests. Simulated evaluation of proposed exact algorithm results in lower blocking probabilities of links and their corresponding lightpaths as compared to existing routing techniques. The capacity utilization improves in terms of capacity utilization ratios and un-used links which ultimately increase connection acceptance rate.

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Appendix A. Supplementary data

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References

[1] A. Agrawal, P. Sharma, V. Bhatia, S. Prakash, Survivability improvement against earthquakes in backbone optical networks using actual seismic Zone Information, *arXiv:* 1703.02358 (2017) 2017.

[2] M. Ashraf, S. Idrus, F. Iqbal, R. Butt, M. Faheem, Disaster-resilient optical network survivability: a comprehensive survey, Photonics 5 (2018) 35.

[3] How much bandwidth do we need? Availabe online: https://arstechnica.com/business/2012/ 05/bandwidth-explosion-as-internet-use-soars-can-bottlenecks-be-averted/ (accessed on 13 April 2017).

[4] Cisco. Cisco Visual Networking Index: Forecast and Methodology, 2016–2021; June 06, 2017.

[5] F.J. Effenberger, Industrial trends and roadmap of access, J. Lightwave Technol. 35 (2017) 1142–1146.

[6] P.P. Tallon, Corporate governance of big data: perspectives on value, risk, and cost, Computer 46 (2013) 32–38.

[7] B. Mukherjee, M. Habib, F. Dikbiyik, Network adaptability from disaster disruptions and cascading failures, IEEE Commun. Magz. 52 (2014) 230–238.

[8] Siva, R.M.C.; Mohan, G. WDM optical networks: concepts, design and algorithms. In Proceedings of PHI.

[9] B. Mukherjee, Optical WDM networks, Springer Science & Business Media, 2006.

[10] P. Singh, A.K. Sharma, S. Rani, Routing and wavelength assignment strategies in optical networks, Opt. Fiber Technol. 13 (2007) 191–197.

[11] E.W. Dijkstra, A note on two problems in connexion with graphs, Numerische mathematik 1 (1959) 269–271.

[12] Z. Fuhao, L. Jiping, An Algorithm of Shortest Path based on Dijkstra for Huge Data, Proceedings of FSKD'09. Sixth International Conference on Fuzzy Systems and Knowledge Discovery, 2005, pp. 244–247.

[13] A.V. Goldberg, C. Harrelson, Computing the Shortest Path: A Search Meets Graph Theory, Proceedings of Proceedings of the sixteenth annual ACM-SIAM symposium on Discrete algorithms, 2005, pp. 156–165.

[14] S. Nazari, M.R. Meybodi, M.A. Salehigh, S. Taghipour, An advanced Algorithm for Finding Shortest Path in Car Navigation System, Proceedings of First International Conference on Intelligent Networks and Intelligent Systems (ICINIS'08), 2008, pp. 671–674.

[15] R. Geisberger, P. Sanders, D. Schultes, D. Delling, Contraction Hierarchies: Faster and Simpler Hierarchical Routing in Road Networks, Proceedings of International Workshop on Experimental and Efficient Algorithms, 2005, pp. 319–333.

[16] G. Jagadeesh, T. Srikanthan, Route computation in large road networks: a hierarchical approach, IET Intelligent Transp. Syst. 2 (2008) 219–227.

[17] Q. Song, X. Wang, Efficient routing on large road networks using hierarchical communities, IEEE Trans. Intell. Transp. Syst. 12 (2011) 132–140.

[18] M.W. Ashraf, S.M. Idrus, F. Iqbal, Maximally spatial-disjoint lightpaths in optical networks, Indonesian J. Electr. Eng. Comput. Sci. 10 (2018).

[19] M.W. Ashraf, S.M. Idrus, F. Iqbal, R.A. Butt, On spatially disjoint lightpaths in optical networks, Photonic Network Commun. (2018) 1–15.

[20] Hao, F.; Jansen, A.; Kodialam, M.; Lakshman, T.V. Path computation for IP network optimization. Availabe online: https://insight.nokia.com/path-computation-ip-network-optimization (accessed on 25 November 2017).

[21] J. Wu, J. Zhang, G. von Bochmann, M. Savoie, Forward-Looking WDM network reconfiguration with per-link congestion control, J. Network Syst. Manage. 20 (2012) 6–33.

[22] S. Rani, A.K. Sharma, P. Singh, Survivability Strategy with Congestion Control in WDM Optical Networks, Proceedings of International Symposium on High Capacity Optical Networks and Enabling Technologies (HONET), 2016, pp. 1–4.

[23] A. Wason, R. Kaler, Blocking in wavelength-routed all-optical WDM networks, Optik-Int. J. Light Electron. Opt. 121 (2010) 903–907.

[24] Shaveta Rani, Ajay K. Sharma, Paramjeet Singh, Resource allocation strategies for survivability in WDM optical networks, Opt. Fiber Technol. 13 (3) (2007) 202–208.

[25] A. Wason, R. Kaler, Blocking probability optimization in wavelength routed optical WDM networks, Optik-Int. J. Light Electron Opt. 124 (2013) 3131–3133.

[26] E.S.K. Sohal, E.S. Kaur, Blocking probability of dijkstra shortest and least congestion routing algorithm in wavelength-routed WDM, Network (2014).

[27] S.B. Zanjani, A.G. Rahbar, Least-Congested Distributed Lightpath Allocation, Proceedings of 5th International Symposium on Telecommunications (IST), 2010, pp. 151–156.

[28] M.F. Stewart, R. Kannan, A. Dvir, B. Krishnamachari, CASPaR: Congestion avoidance shortest path routing for delay tolerant networks, Proceedings of International Conference on Computing, Networking and Communications (ICNC), 2017, pp. 1–5.

[29] Y. Li, L. Peng, G. Shen, Load-balanced fixed routing for wavelength routed optical networks, IEEE Commun. Lett. 17 (2013) 1256–1259.

[30] Y. Jungang, N. Junyong, T. Xiangyuan, A Load Balance based Routing and Wavelength Assignment Algorithm, Proceedings of 2014 7th International Conference on Intelligent Computation Technology and Automation (ICICTA), 2014, pp. 23–27.

[31] P. Festa, On Some Special Network Flow Problems: The Shortest Path Tour Problems, Dynamics of Information Systems: Mathematical Foundations, Springer:, 2012, pp. 245–263.

[32] R. Ramaswami, Optical fiber communication: from transmission to networking, IEEE Commun. Mag. 40 (2002) 138–147.

[33] S. Mandal, S. Jana, D. Saha, A Heuristic Search for Dynamic Lightpath Establishment in WDM Optical Networks with Limited Wavelength Conversion Capability, Proceedings of International Conference on Communication Technology Proceedings (ICCT 2003), 2003, pp. 702–705.

[34] R. Datta, I. Sengupta, Static and dynamic connection establishment in WDM optical networks: A review, IETE J. Res. 51 (2005) 209–222.

[35] K. Kuppuswamy, D.C. Lee, Some analysis of call blocking probabilities in hierarchical WDM networks offering multiclass service, Int. J. Commun. Syst. 24 (2011) 709–731.