Paper

Performance Comparison of Protection Strategies in WDM Mesh Networks

Hemant K. Singh, Shreya Aggarwal, Satendra Singh, Baibaswata Mohapatra, Rajendra K. Nagaria, and Sudarshan Tiwari

Abstract—Recent development in optical networking employing wavelength division multiplexing (WDM) fulfills the high bandwidth demand applications. Failure of such networks, leads to enormous data and revenue loss. Protection is one of the key techniques, which is used in designing survivable WDM networks. In this paper we compare dedicated and shared protection strategies employed in WDM mesh networks to protect optical networks failure, particularly fiber failure. Dijkstra's shortest path algorithm is considered for carrying out simulations. The paper compares the performance of protection schemes, such as, dedicated path protection (DPP), shared path protection (SPP) and shared link protection (SLP) schemes. Capacity utilization, switching time and blocking probability are the parameters considered to measure the performance of the protection schemes. Simulation results show that, SPP is more efficient in terms of capacity utilization over DPP and SLP schemes, whereas, SLP offered better switching time than both DPP and SPP schemes. The average call drop rate is minimum for shared path protection scheme and maximum for shared link protection scheme.

Keywords*—*blocking probability, protection, survivability, switching time, WDM networks.

1. Introduction

Wavelength division multiplexing (WDM) technology allows transmitting number of non-overlapping wavelength bands in optical networks hence, provides enormous capacities in the networks. It also provides a common infrastructure over which a range of services can be delivered. In a WDM network a lightpath is established between the source and destination for a point-to-point connection. Extremely high bandwidth (nearly 50 (Tbit/s)) offered by WDM optical network, where failure of fiber link would lead to a failure of several lightpaths traversing the link. Such failure leads to large data and revenue loss. Survivability is defined as, the ability of the network to continue to provide service in the event of failure. The lightpath traverse on different links maintains same wavelength throughout the entire path for an end-to-end communication in the absence of wavelength converter. This is known as wavelength continuity constraint. Two lightpaths sharing the same fiber link can not have same wavelength. In a network with set of demands between the node pair, determine a route and assign a wavelength for the demand is said to be routing and wavelength assignment (RWA) problem [1]–[3].

A lightpath is routed through many nodes in the network between the source and destination. There are many elements (node, link, and active components) along the path, upon failure leading to data loss. To ensure network survivability, protection schemes are being widely adopted. Protection schemes are implemented by providing some redundant capacity within the network. Upon link failure traffic is rerouted around the failed link by using this redundant capacity. On the other hand, restorations schemes involve dynamically discover the backup route and available wavelength channels to restore the traffic. Protection schemes usually implemented in a distributed fashion without using centralized control in the network, to ensure fast restoration. Most cases, protection schemes are studied under single link failure event, which means, the failed link will be repaired before another failure occurred. The maximum restoration time is 60 ms, for synchronous optical network/synchronous digital hierarchy (SONET/SDH) networks [1]. Protection schemes may be categorized as dedicated or shared based. In dedicated based protection $(1:1)$ scheme, a path disjoint wavelength channel is reserved for each lightpath which is not shared by any other backup lightpaths. On the other hand, in shared based protection $(1:n)$ scheme, a path disjoint wavelength channel is also reserved for each lightpath. However, the backup paths may be shared among different wavelength channels. As a result, backup channels are multiplexed among themselves; thereby offer better capacity efficiency over dedicated protection schemes. The details of protection strategies are explained in Section 2 by taking a simple example network.

Wavelength division multiplexing mesh networks with scheduled lightpath demand [4] is reported, where the connection setup and teardown times are known in advance also the demands between a node pair are known. The author proposed conventional integer linear programming (ILP) formulations for dedicated and shared scheduled protection without wavelength converter in the network. The study report minimum capacity utilization for fixed demand and maximize the number of demands for a fixed available capacity, while providing 100% protection for accepted connections. In [5], a RWA scheme is proposed for lightpath restoration in WDM networks, where an active multi-backup paths method is used. The author derives successive backup lightpaths up to the last node along the primary path until an available backup lightpath is found. The work has been carried out without wavelength converter in the network. The algorithm is based on the iterative Dijkstra's algorithm to find a backup path for the failed primary path. Source and destination pair (s,d) as well as the cost matrix of the network were considered as inputs to the routing algorithm. Dedicated and shared resource allocation strategies [6] for survivability have been presented which reserve the resources for the primary and backup lightpaths. The author compare simulation results for different networks to evaluate the performance, which shows, shared resources strategy performs better than dedicated resources strategy in terms of blocking probability, because it utilizes the resources more efficiently.

A mixed-integer linear program (MILP) formulation for dynamic lightpath allocation for survivable WDM networks [7], is proposed by taking dedicated and shared path protection schemes. Multiple levels of services have been investigated and optimal solution is reported. Another approach called multi-commodity flow problem is widely accepted to tackle issues in WDM networks. A multi-commodity flow problem is presented [8] to address the issues of survivable network in terms of capacity allocation. The author considered different versions of node-arc and arc-path model to allocate working and spare capacity. Taking unequal arc-capacity in both the direction of the fiber links, ILP formulations is presented for capacity allocation. Our work resemble with [9], where, ILP based survivable algorithms are investigated for WDM mesh networks. This study focus on protection and restoration schemes to calculate capacity utilization and switching time for survivable schemes such as, dedicated path, shared path, and shared link protection. Restorable network design with static traffic demand is reported in [10]–[12], while, the performance of survivable algorithms with dynamic traffic is mentioned in [2], [3], [13], [14]. A review on WDM optical mesh networks is presented in [15].

Pre-configured cycle (p-cycle) is a recently proposed transport networks survivability scheme [16]–[19] combining the speed of ring networks with the capacity efficiency of mesh networks. Pre-configured cycles are ring-like pre-configured structures used to protect WDM networks against fiber failure. This protects on-cycle spans (spans that are part of the p-cycle, e.g., link B-E in Fig. 1) as well as straddling spans (spans whose end-nodes are both on the p-cycle, but that are not part of the primary paths, e.g., link B-F). Pre-configured cycle, a technique for span protection are preplanned and fully pre-connected closed loop structures of spare capacity, hence, real-time switching actions are required only at the two end nodes of the failed span to protect both on-cycle and straddling failures. Therefore switching time is quite less compared to path based and link based protection techniques. Since p-cycles are pre-planed structures consequently this scheme consumes more capacity/wavelengths compared to shared path protection [8]. Because p-cycles are formed only in the spare capacity, routing of primary paths is not affected. Also, it have been proposed to provide dual or multiple failure networks survivability [20] with re-configurable or shared p-cycles.

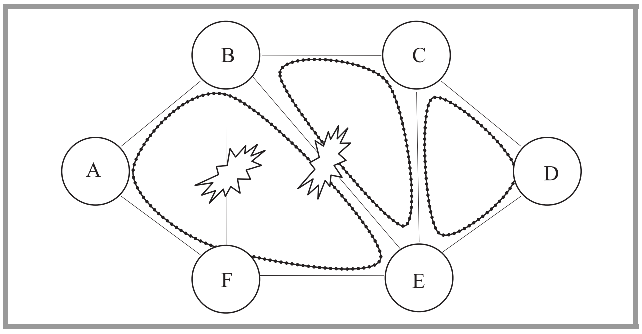

Fig. 1. Different p-cycles formed in the network.

The rest of the paper is organized as follows. Section 2 presents the simulation approach. Section 3 includes results and discussion. Conclusions of the work are presented in Section 4.

2. Simulation Approach

In this section, we will discuss the details of our proposed simulation environment developed in C language. We have taken three different protection strategies mainly, dedicated path protection, shared path protection and shared link protection schemes. Three different parameters such as, capacity utilization, switching time and blocking probability/connection drops are calculated to compare the performance of the protection strategies. We assume that, wavelength converters are not present in the networks; hence the connection between the source and the destination is established with a single wavelength link. Above protection schemes are explained by taking a simple 6-node and 8-links network arbitrarily. Taking simulation time into account, we have considered four wavelengths in each fiber to calculate capacity and seven numbers of demands/connections are considered between the node pairs randomly. Static demands are being considered and connections are exists for infinite duration of time.

2.1. Capacity Utilization

In dedicated path protection we first derive the shortest path between all node pairs using Dijkstra's shortest path algorithm. We consider these paths as the primary/working paths. In a similar fashion backup/spare paths are being derived. The wavelength assignment is done by checking the free wavelengths available on all the links in the entire path. We try to find out the minimum value of sum of working and spare capacity for all the links. For example, suppose there are two connections A→E and F→C exist. Then, the primary path would be A→B→E for connection A→E with wavelength λ_1 and the backup path is A→F→E with wavelength λ_1. For connection F→C the primary path is F→B→C with wavelength λ_1 and the backup path is F→E→C with wavelength λ_2 is reserved in this scheme.

Hence, in this scheme a total of 8 wavelength links is utilized both for primary and the backup lightpath. We derive all the possible combinations of link disjoint backup lightpaths during the simulations.

Where as, in shared path protection scheme the backup resource is not reserved. Backup resources such as, paths as well as wavelengths are shared for different connections. For example, suppose for the above two connections A→E as A→B→E with wavelength λ_1 and F→C as F→B→C with wavelength λ_2 as the primary paths may be considered. Both the backup paths A→F→E for A→E and F→E→C for B→D may use the wavelength λ_1. Even if both the backup path utilize wavelength λ_1 for the link F→E, under single fiber failure assumption, both the primary paths can not fails simultaneously. So a total of 7 wavelength links are utilized both for primary and the backup lightpaths for guaranteed service.

Link protection can be categorized as dedicated and shared. It is observed that, dedicated link protection consumes more capacity. In shared link protection we derive backup path for every links used for primary paths. From the example network (Fig. 2) for the connection A→E, the primary path would be A→B→E with wavelength λ_1. The backup path A→F→B→E for the failure of link A→B with wavelength λ_1 and A→B→F→E for the failure of the link B→E with wavelength λ_2 may be considered. Where as, for the connection F→C, the primary path would be F→B→C with wavelength λ_2. The backup path F→E→B→C for the failure of link F→B with wavelength λ_2 and F→B→E→C for the failure of the link B→C with wavelength λ_1 may be utilized for definite protection. Hence, a total of 13 wavelength links are utilized both for primary and the backup lightpaths. Though, the shared link protection scheme consumes more wavelength links compared to shared path and dedicated path protection, but it's switching time is less than path protection schemes.

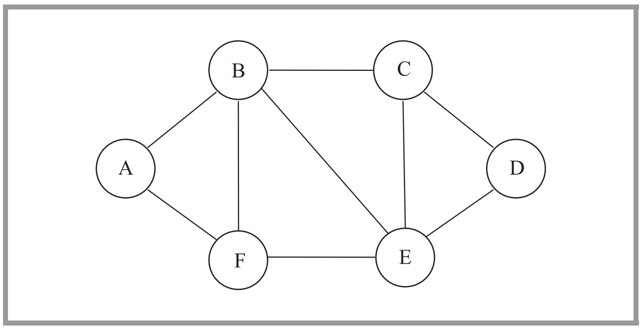

Fig. 2. Example network.

Some of the notations we have adopted in our algorithm while performing simulations and these are given below.

- Minimize $(w_j + s_j)$, where w_j and s_j denotes working and spare capacity on link j.
  $w_j + s_j \geq W$, where W represents the total number of wavelengths available on link j.
- $\gamma^{s,d}_{p,w_p} = 1$ if the connection between the source s and the destination d used by the primary path p utilizes wavelength w_p; else zero.
- $\alpha^{s,d}_{p,b,w_b} = 1$ if the backup path b is used to protect the primary path p with wavelength w_b for the connection between the source s and the destination d; else zero.
- $\delta^{s,d}_{p,b,w_b} = 1$ if the shared backup path b is used to protect the primary path p with wavelength w_b for the connection between the source s and the destination d; else zero.
- $m^{l_s,l_d}_{w_b} = 1$ if the backup route passes through link(l_s, l_d) utilizes wavelength w_b; else zero.
- w_p, w_b are used for wavelength for primary path and backup paths, respectively.
- l_s, l_d are the link source and link destination, respectively.

Algorithm 1 describes the basic steps involves for simulating different protection schemes to calculate minimum capacity utilization.

Algorithm 1: Protection schemes

```
Step 1:  run Dijkstra algorithm for all node pair
Step 2:  get connection demand matrix
Step 3:  assign $p$, $b$, $w_p$, $w_b$ for all connection
Step 4:  is $w_j + s_j \leq W$ for all links NO go to Step 8
Step 5:  for all $W$, for all links
         check for $\lambda$ continuity NO go to Step 8
Step 6:  better than the previous record NO go to Step 8
Step 7:  over write the previous record
Step 8:  is more iteration available YES go to Step 3
Step 9:  print results
```

Algorithm 2 and 3 describes the wavelength assignment after routing process is completed. The fundamental assumption for the wavelength assignment is that, two lightpaths must not have same wavelengths.

Algorithm 2: λ continuity for dedicated path protection scheme

```
for all Links do
  for all W do
    for all node pair do
{
for all route in routeSet and Link in route
  Sum $\gamma^{s,d}_{p,w_p} = X$
}
{
for all backup route in routeSet and Link in route
  Sum $\alpha^{s,d}_{p,b,w_b} = Y$
}
$X + Y \leq 1$
end
```

Algorithm 3: λ continuity for shared path and shared link protection scheme

```
for all Links do
   for all W do
{
for all node pair, demand $> 0$ do
   for all route in routeSet and Link in route
      Sum $\gamma_{p,w_p}^{s,d} = X$
}
$X + m_{w_b}^{l_s,l_d} \leq 1$
end
```

2.2. Protection Switching Time

Switching time [1], [9] is the time taken from the instant a link fails to the instant the backup path of the connection is activated. In this section, we will describe the protection switching time for the different protection techniques. Assuming a link failure may be detected by the network nodes adjacent to the failed link. All network nodes participate in a distributed protocol outlined below to perform protection switching. Standard data has been taken from the literatures for calculation of switching time. We run the simulation and failed the link randomly, the average switching time calculated given below.
Let:

- t_p – the message-processing time at any node is considered as 10 μs.
- t_d – the propagation delay on each link is 400 μs.
- t_{OXC} – optical cross connect (OXC) configuration time is 10 μs.
- t_f – the time to detect a link failure is 10 μs.
- n – number of hops from the failed link source to the source node of the connection is 2.
- m – in path (link) protection, is equal to the number of hops in the backup route from the source (link-source) node to the destination (link-destination) node is 10.

2.2.1. Dedicated Path Protection

The end nodes (link-source, link-destination) of the failed link detect a failure. End nodes then send a link-fail message to the source and the destination nodes. Source node sends a connection setup message to the destination node along the backup path (which is predefined at the time of connection setup).The destination node, upon receiving the message, sends an acknowledgment (ACK) message back to the source node. This completes the protection-switching procedure and backup path is restored for the dedicated path protection. Communication continue through the backup path and the total switching time may be written as

$$t_{total} = t_f + n\,t_d + (n+1)t_p + 2mt_d + 2(m+1)t_p \,. \qquad (1)$$

2.2.2. Shared Path Protection

In shared path protection backup paths are multiplexed with the available wavelengths. The end nodes of the failed link detect a failure. End nodes then send a link-fail message to the source and the destination nodes. Source node sends a connection setup message to the destination node along the backup path (which is predefined at the time of connection setup). OXCs are being configured at each intermediate node along the backup path. The destination node, upon receiving the message, sends an ACK message back to the source node. Which completes the protection-switching procedure for shared path protection and path is being restored for the shared path protection. The total switching time may be written as

$$\begin{aligned} t_{total} &= t_f + nt_d + (n+1)t_p + (m+1)\,t_{OXC} \\ &\quad + 2mt_d + 2(m+1)t_p \,. \end{aligned} \qquad (2)$$

2.2.3. Shared Link Protection

The end nodes of the failed link detect a failure. The link-source of the failed link sends a connection setup message to the link destination along the shortest backup route (which is determined in advance at the time of connection setup). OXCs are being configured at each intermediate node along the backup path around the failed link. The link destination, upon receiving the setup message, sends an ACK message back to the link source. This completes the protection-switching steps for the shared link protection and communication continue through the backup path and the total switching time may be written as

$$t_{total} = t_f + (m+1)t_{OXC} + 2(m+1)t_p + 2mt_d \,. \qquad (3)$$

2.3. Blocking Probability

Blocking probability (BP)/connection dropped, is one parameter out of the many parameters which provides the performance of the survivable WDM networks. Request acceptance rate is the ratio of the number of connection requests accepted out of the total number of connection requests made. Where as, blocking probability is the ratio of the number of connections rejected to the total number of connection requests made. If M is the total number of connections, then blocking probability may be written as

$$BP = \frac{no.\ of\ rej.\ connection}{M} = \frac{M - no.\ of\ acc.\ connection}{M} \,.$$

We adopt a simple method to calculate the blocking probability in our model. Keeping the demand fixed, we calculate the number of possible connection by taking a fixed number of wavelengths on a given link. The number of call dropped can be calculated. We increase the link capacities up to 7 number of wavelength on each fiber and present the result for the networks shown.

3. Results and Discussion

The simulation is performed with randomly taking seven numbers of connections, between the node pair. Protection schemes are implemented in random fiber failure. The simulation is carried out in Windows P-IV PC with 512 Mbit RAM. We have taken 4 wavelengths in each fiber for capacity utilization.

Table 1
Spare/protection wavelength required for the networks for different protection schemes for a demand of 7

Network	Dedicated path protection	Shared path protection	Shared link protection
NSF Net	41	36	76
India Net	42	37	57
US Net	32	29	36

From Table 1 it is observed that shared path protection consumes minimum number of wavelengths, where as, shared link protection requires maximum number of wavelengths for assured protection.

Tables 2–4 present blocking probability/call drops for different networks by taking fixed number of wavelengths and connections. Taking simulation time into account we could increase number of connections (10) and higher number of wavelengths (7) in each fiber. From the below given tables we observe that, number of connection drop is maximum for shared link protection and minimum for shared path protection techniques. As we increase the number of wavelengths the call drop should decrease in a continuous fashion, which doesn't reflect from the tables. This happened as we are taking less number of connections during our simulations.

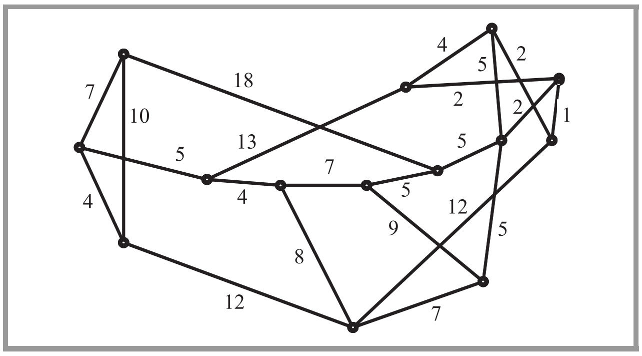

Fig. 3. NSF Net (14 nodes, 22 links).

Table 2
Number of connection blocked taking different protection strategies for demand of 10 for NSF Net (Fig. 3)

Wavelengths	Dedicated path protection	Shared path protection	Shared link protection
1	9	8	9
2	7	5	8
3	5	3	5
4	3	0	4
5	0	0	2
6	0	0	0
7	0	0	0

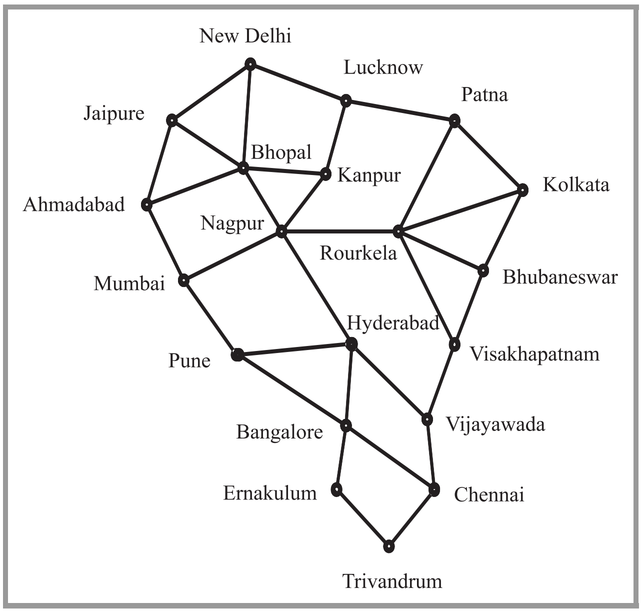

Fig. 4. India Net (20 nodes, 33 links).

Table 3
Number of connection blocked taking different protection strategies for demand of 10 for India Net (Fig. 4)

Wavelengths	Dedicated path protection	Shared path protection	Shared link protection
1	9	8	8
2	6	3	8
3	5	0	7
4	1	0	5
5	0	0	4
6	0	0	1
7	0	0	0

The average switching time is calculated and shown in Table 5. From the above results, as a network designer, we may provide different protection techniques as per the customer's requirement. For example, to generate maximum revenue we may employ shared path protection scheme by utilizing minimum number of wavelengths for a fixed demands. Where as, from quality of service point of view, where protection switching time is the parameter as a priority, we may consider shared link protection scheme, while providing a definite protection.

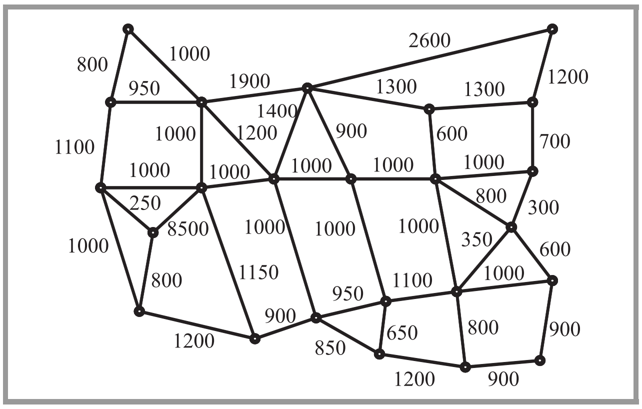

Fig. 5. US Net (24 nodes, 43 links).

Table 4
Number of connection blocked taking different protection strategies for demand of 10 for US Net (Fig. 5)

Wavelengths	Dedicated path protection	Shared path protection	Shared link protection
1	9	9	9
2	8	8	8
3	7	0	3
4	0	0	2
5	0	0	2
6	0	0	0
7	0	0	0

Table 5
Average protection switching time for different protection strategies in milliseconds for the networks

Network	Dedicated path protection	Shared path protection	Shared link protection
NSF Net	4.96	5.02	3.36
India Net	9.06	9.17	3.36
US Net	3.73	3.78	1.7

4. Conclusions

Survivability is an essential and challenging issue in high speed networks. In this paper we examined different protection schemes such as dedicated path, shared path and shared link protection to manage WDM optical network failure. In particular, we examine capacity utilization, blocking probability and protection switching time for dedicated path, shared path and shared link protection strategies for WDM mesh networks. The chosen performance parameters such as wavelength consumption, blocking probability and switching are the measures of the quality of service. This shows the network performances under failure scenario without modifying the existing architecture.

The results show out of these three protection schemes, spare capacity utilization is minimum for shared path protection, where as it is maximum for shared link protection compared to dedicated path protection scheme. On the other hand, protection switching time is minimum for shared link protection scheme and it is maximum for shared path protection scheme. The average blocking probability or the call drop rate is minimum for shared path protection scheme and it is maximum for shared link protection scheme. Though p-cycle offers better protection switching time compared to shared path protection scheme but its wavelength consumption is worse. Moreover, further investigations are in progress to develop efficient algorithms to minimize network capacity utilization as well as switching time and blocking probability, for survivable WDM mesh networks.

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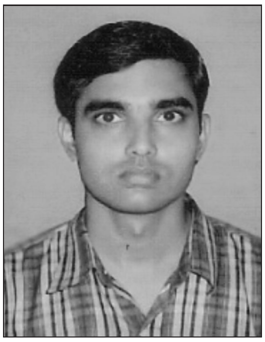


Hemant Kumar Singh received the B.Tech. degree in electronics and communication engineering from the Motilal Nehru National Institute of Technology, Allahabad, India, in 2009.

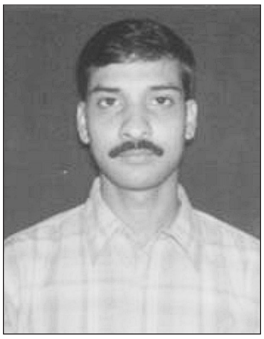
e-mail: hksingh1987@gmail.com
Department of Electronics
and Communication Engineering
Motilal Nehru National Institute of Technology
Telierganj, Allahabad-211004, India

Shreya Aggarwal received the B.Tech. degree in electronics and communication engineering from the Motilal Nehru National Institute of Technology, Allahabad, India, in 2009.

e-mail: shreya5055@gmail.com
Department of Electronics
and Communication Engineering
Motilal Nehru National Institute of Technology
Telierganj, Allahabad-211004, India

Satendra Singh received the B.Tech. degree in electronics and communication engineering from the Motilal Nehru National Institute of Technology, Allahabad, India, in 2009.

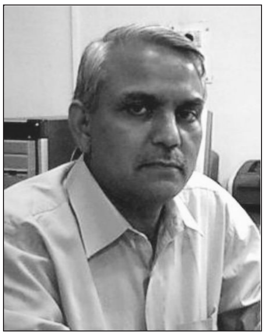
e-mail: silversurfer.mnnit@gmail.com
Department of Electronics
and Communication Engineering
Motilal Nehru National Institute of Technology
Telierganj, Allahabad-211004, India



Baibaswata Mohapatra received the B.Eng. degree in electronics and telecommunication engineering from the Utkal University, Bhubaneswar, India, in 1999, the M.Tech. degree in electronics and communication engineering from the U.P. Technical University, Lucknow, India, in 2006. He is currently working towards the Ph.D. degree with the M.N. National Institute of Technology, Allahabad, India, since 2007. He is a life member of Indian Society of Technical Education (India) and has more than 7 years of teaching and research experience. His research interest include, routing and resource optimization in WDM optical networks.
e-mail: rel0707@mnnit.ac.in
Department of Electronics
and Communication Engineering
Motilal Nehru National Institute of Technology
Telierganj, Allahabad-211004, India

Rajendra Kumar Nagaria is an Associate Professor of electronics and communication engineering at the Motilal Nehru National Institute of Technology (MNNIT), Allahabad, India. He received a B.Tech. and M.Tech. in electronics engineering from the Kamla Nehru Institute of Technology (KNIT) Sultanpur, India, and Ph.D.(Eng.) from the Jadavpur University, Kolkata, India. He has been over 22 years of teaching and research experience. He has published more than forty research papers of national and international reputes. His name is enlisted in an exclusive directory Marquis Who's Who in the world. He is also nominated for the award as International Educator of the year 2005, by International Biographical Centre, Cambridge England. He is fellow of professional bodies like Institute of Engineers (India) and Indian Society of Technical Education. He has guided the thesis of many PG students and presently four research scholars are working under his supervision. His area of interest is mixed-mode signal processing, high speed networks/VLSI design.

e-mail: rkn@mnnit.ac.in
Department of Electronics
and Communication Engineering
Motilal Nehru National Institute of Technology
Telierganj, Allahabad-211004, India



Sudarshan Tiwari received the B.Tech. degree in electronics engineering from the I.T.BHU, Varanasi, India, in 1976, the M.Tech. degree in communication engineering from the same institution in 1978 and Ph.D. degree in electronics and computer engineering from the IIT Roorkee, India, in 1993. Presently, he is a Professor and Head of Department of Electronics and Communication Engineering, Motilal Nehru National Institute of Technology (MNNIT), Allahabad, India. He has also worked as Dean Research and Consultancy of the institute from June 2006 till June 2008. He has more than 28 years of teaching and research experience in the area of communication engineering and networking. He has supervised a number of M.Tech. and Ph.D. thesis. He has served on the program committee of several seminars, workshops and conferences. He has worked as a reviewer for several conferences and journals both nationally and internationally. He has published over 78 research papers in different journals and conferences. He has served as a visiting Professor at Liverpool John Moore's University, Liverpool, UK. He has completed several research projects sponsored by government of India. He is a life member of Institution of Engineers (India) and Indian Society of Technical Education (India), he is a member of Institution of Electrical and Electronics Engineers (USA). His current research interest include, in the area of WDM optical networks, wireless ad hoc and sensor networks and next generation networks.

e-mail: stiwari@mnnit.ac.in
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and Communication Engineering
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Telierganj, Allahabad-211004, India