Chapter 3

Performance Analysis of Major Conventional RWA Schemes

3.1 Introduction

Routing and wavelength assignment (RWA) \cite{8,10} is considered to be one of the key functionality for WDM based optical networks, due to its information transparency and wavelength reuse characteristics. RWA selects the best end-to-end route and assigns the suitable wavelength to establish a lightpath for serving a connection request. If a lightpath for a connection request cannot be established within holding time\(^1\), it is treated as a blocked connection. In a WDM based wavelength-routed optical network, RWA approaches can play the crucial role to improve the network performance. The performance of the network depends on the selection of RWA approach. In this context, this chapter provides the performance analysis of the major conventional RWA approaches in terms of call blocking. The rest of this chapter is organized as follows. Section 3.2 formally defines the problem and describes the constraints used for RWA approaches throughout this dissertation. In this section we also address the model assumptions, and define the basic terms, symbols and notations which are used throughout this chapter as well as this dissertation. The performance of major conventional RWA approaches is evaluated through simulation study in section 3.3. Further, in this section we also analyze about the pros and cons of major routing algorithms and wavelength assignment schemes based on the simulation results. Finally, section 3.4 concludes this chapter.

\(^1\)which is supplied by the network designer according to user requirement and the connection request should be established within this time.
3.2 Problem Statement

We model the physical topology of an optical network as a connected graph $G' (V', E')$, where $V'$ and $E'$ are the set of nodes and set of bi-directional optical fiber links in the network, respectively. Here, each link $e \in E'$ has a finite number of wavelengths denoted by $W$. A non-negative link cost $C(e)$ is assigned to every link $e$ in the network, which represents the distance between the adjacent node pair connected by $e$. The following assumptions are considered in our model.

3.2.1 Assumptions

- Each fiber link can carry an equal number of wavelengths and the network is without wavelength conversion capabilities.
- All the lightpaths sharing at least one fiber link are allocated distinct wavelengths.
- Each node can work as both an access node and a routing node.
- Each node is equipped with a fixed number of tunable transceivers.
- All channels have the same bandwidth.

3.2.2 Definitions and Notations

The following definitions and notations [8] that have been used for RWA approaches throughout this chapter as well as this dissertation are explained below.

- **Distance matrix**: Distance matrix, denoted as $D_{\text{matrix}}$, specifies the distances between adjacent node pairs. It is a two-dimensional matrix with $N$ rows and $N$ columns. An entity in $D_{\text{matrix}}$ corresponds to the distance from node $x$ to node $y$ and it is represented by $d^{x,y}$.

- **Traffic matrix**: Traffic matrix, denoted as $T_{\text{matrix}}$, specifies the average traffic flow between node pairs. It is a two-dimensional matrix with $N$ rows and $N$ columns. An entity in $T_{\text{matrix}}$ corresponds to the average traffic flow from node $x$ to node $y$ which is denoted by $t^{x,y}$.

- **Hop matrix**: Hop matrix, denoted as $H_{\text{matrix}}$, specifies the allowable maximum number of physical hops in a lightpath between a node pair. It is
a two-dimensional matrix with $N$ rows and $N$ columns. An entity in $T_{\text{matrix}}$ corresponds to the allowable number of physical hops in a lightpath from node $i$ to node $j$ and it is represented by $h_{i,j}^P$.

- **Link indicator**: It indicates the existence of physical links between node pairs. The value of this indicator variable, denoted as $l_{x,y}$, is 1, if there exists a physical link from node $x$ to node $y$. Otherwise its value is 0.

- **Lightpath indicator**: It indicates the existence of a lightpaths between node pairs. The value of this indicator variable, say $P_{i,j}$, is 1, if there exists a lightpath from node $i$ to node $j$. Otherwise its value is 0.

- **Lightpath-wavelength indicator**: It indicates the existence of lightpaths with particular wavelengths between node pairs. The value of this indicator variable, denoted by $P_{i,j,\lambda}$, is 1, if there exists a lightpath from node $i$ to node $j$ and it is assigned to wavelength $\lambda$. Otherwise its value is 0.

- **Lightpath-wavelength-link indicator**: This indicator is used to indicate the existence of lightpaths on specific wavelengths between node pairs and it uses particular physical links. The value of this indicator variable, say $P_{i,j,\lambda,x,y}$, is 1, if there exists a lightpath from node $i$ to node $j$ and it uses wavelength $\lambda$ on a physical link from node $x$ to node $y$. Otherwise its value is 0.

- **Virtual hop distance**: Virtual hop distance, denoted as $h_{i,j}$, from node $i$ to node $j$ is the number of virtual hop from node $i$ to node $j$ on the virtual topology.

- **Traffic flow and bandwidth**: The component of traffic due to a source-destination node pair offered onto a lightpath from node $i$ to node $j$ which is denoted by $\alpha_{i,j}^{s,d}$. $C_B$ and $B^{s,d}$ are the maximum bandwidth of a channel and a connection between source-destination node pair, respectively.

### 3.2.3 Constraints

The following constraints [8] which have been used for RWA approaches throughout this chapter as well as this dissertation are explained below.

- **Virtual degree constraints**: Virtual degree constraints that relate the number of transmitters and receivers for each node in the network are given below.

  \[
  \sum P_{j,i} \leq D^w_{in} \quad \forall i
  \]  
  \[ (3.1) \]
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\[ \sum P_{i,j} \leq D_{\text{out}}^{v} \quad \forall j \]  

Equations (3.1) and (3.2) state that the virtual out-degree \( D_{\text{out}}^{v} \) and in-degree \( D_{\text{in}}^{v} \) of each node is same in the network.

- **Wavelength constraints**: Wavelength constraints that pertain to the assignment of wavelengths to lightpaths for serving connection requests in the network are given below.

\[ P_{i,j} = \sum_{\lambda=0}^{W-1} P_{i,j,\lambda} \quad \forall (i,j) \]  

Equations (3.3), (3.4) and (3.5) state the wavelength used by a lightpath is unique, wavelength continuity constraint and distinct channel constraint, respectively.

- **Bandwidth constraint**: Bandwidth constraint relates the bandwidth of a connection and the maximum capacity of a channel in the network which is given below.

\[ B_{s,d} \leq C_B \]  

Equation (3.6) states that the bandwidth of a connection between a source-destination node pair does not exceed the channel capacity.

- **Hop constraint**: Hop constraint that pertains to the number of physical links traversed by a lightpath in the network is given below.

\[ \sum P_{i,j,\lambda}^{x,y} \leq h_{i,j}^p \quad \forall (i,j), \lambda \]  

Equation (3.7) states that the number of physical links traversed by a lightpath is at most a value specified by the physical hop matrix, \( H_{\text{matrix}} \).

- **Variable value constraints**: The constraint given by Equation (3.8) ensures that the traffic flow on a lightpath due to a node pair is a positive quantity.

\[ \alpha_{i,j}^{s,d} \geq 0 \quad \forall (i,j), (s,d) \]  

Lightpath indicator, link indicator, lightpath-wavelength indicator, lightpath-wavelength-link indicator are binary variables and they are cap-
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tured by the following constraints.

\[
P_{i,j} \in 0, 1 \quad \forall(i,j) \quad (3.9)
\]

\[
l_{x,y} \in 0, 1 \quad \forall(x,y) \quad (3.10)
\]

\[
P_{i,j,\lambda} \in 0, 1 \quad \forall(i,j), \lambda \quad (3.11)
\]

\[
P_{i,j,\lambda}^{x,y} \in 0, 1 \quad \forall(i,j), (x,y), \lambda \quad (3.12)
\]

3.3 Performance Analysis

In this section we will present simulation results in two experimental setups to evaluate the performance of some major conventional RWA approaches in terms of call blocking. Our experimental setup consists of 14 nodes with 24 bi-directional physical links of the Indian network and 14 nodes with 21 bi-directional physical links of NSFNET [10] as shown in Figure 3-1 and Figure 3-2, respectively. The following assumptions have been made for the purpose of simulations.

- The distances between adjacent cities are taken as given in Figure 3-1 and Figure 3-2 for configuring the example networks - the Indian network and NSFNET, respectively.

- The connection requests are generated randomly based on a Poisson process, and the arrival time between two successive requests follows an exponential distribution. We choose the Poisson model because the burstiness of traffic on the backbone is usually suppressed by the huge amount of aggregation of services and the actual traffic distribution remains unknown.

- The holding times of the connection requests are exponentially distributed. For the sake of simplicity, the holding time of all the connection requests having same source-destination pair are assumed to be same. However, differences in holding times for connection requests having same source-destination pair can be handled by taking the maximum of their holding times (similar to [52]) as the holding time for all of them.

- For least-used wavelength assignment, we have blocked (considered as used wavelengths) few wavelengths (1%) randomly in the different links of the networks.
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Figure 3-1: The Indian network and distances between its adjacent cities in kilometers.

- The maximum bandwidth requirement of a connection request is 622.08 Mbps according to SONET OC-12/STS-12 [9].

- The maximum capacity of each wavelength channel is 9953.28 Mbps according to SONET OC-192/STS-192 [9].

We have performed the simulation study of the routing algorithms and conventional wavelength assignment approaches. For this purpose, we generated a number of connection requests, distributed randomly among all the possible source-destination pairs.

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3.3. Performance Analysis

![National Science Foundation Network (NSFNET) and distances between its adjacent cities in kilometers.](image)

<table>
<thead>
<tr>
<th>WA</th>
<th>Seattle</th>
<th>PA</th>
<th>Pittsburgh</th>
</tr>
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<tbody>
<tr>
<td>CA1</td>
<td>Palo Alto</td>
<td>GA</td>
<td>Atlanta</td>
</tr>
<tr>
<td>CA2</td>
<td>San Diego</td>
<td>MI</td>
<td>Ann Arbor</td>
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<tr>
<td>UT</td>
<td>Salt Lake City</td>
<td>NY</td>
<td>Ithaca</td>
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<td>MD</td>
<td>College Park</td>
</tr>
<tr>
<td>NE</td>
<td>Lincoln</td>
<td>IL</td>
<td>Champaign</td>
</tr>
</tbody>
</table>

Figure 3-2: National Science Foundation Network (NSFNET) and distances between its adjacent cities in kilometers.

### 3.3.1 Routing

Here, we will show the performance of routing algorithms in terms of blocking probability and average setup time which are defined in Equation (3.13) and Equation (3.14), respectively. For wavelength assignment purpose, we take First-fit (FF) method, due to its lower call blocking and computational complexity compared to other wavelength assignment schemes.

\[
Blocking\ \text{Probability} = \frac{Total\ \text{Number\ of\ Blocked\ Calls}}{Total\ \text{Number\ of\ Connection\ Requests\ in\ the\ Network}} \quad (3.13)
\]

Figure 3-3 and Figure 3-4 show the blocking probability versus number of wavelengths in the Indian network and NSFNET, respectively, with 5000 connection requests. In both the figures, \( K = 1 \) corresponds to a primary path and other values of \( K (i.e. K > 1) \) represent using \( K-1 \) number of alternate paths. It
has been revealed that in both the networks, blocking probability decreases with increase in number of wavelengths. On the other hand, blocking probability also decreases with the increase in number of paths. The variation of blocking probability with number of wavelengths, using up to three (i.e. \( K=4 \)) alternate paths is close to that of using up to two (i.e. \( K=3 \)) alternate paths in the Indian network. Similarly, in NSFNET, the variation of blocking probability using up to two (i.e.
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Alternate paths is close to that of using up to one (i.e. $K=2$) alternate path.

Figure 3-5 and Figure 3-6 show the average setup time versus number of wavelengths for the different paths in the Indian network and NSFNET, respectively, with 5000 connection requests. It has been observed from Figure 3-5 and Figure 3-6 that the average setup time [23] increases with increase in number of alternate paths. This is mainly due to extra time required to find the next alternate path. However, the average setup time of different paths remains almost constant after a particular number of wavelengths. This is because, all the connections in the network are established after a particular number of wavelengths.

$$Average\ Setup\ Time = \frac{Total\ Execution\ Time\ in\ the\ Network}{Total\ Number\ of\ Successful\ Connections}$$

(3.14)

**Figure 3-5:** Average setup time versus $W$ for the different paths in the Indian network

By analyses of Figure 3-3 to Figure 3-5, we can summarize that as the number of alternate paths increases, the blocking probability decreases and the average setup time increases. Therefore, it is required to trade off between blocking probability and average setup time. Thus, the number of alternate paths for RWA purpose is considered up to one and two for NSFNET and the Indian network, respectively. The same observation is being used for further analysis of routing and wavelength assignment approaches.

Figure 3-7 and Figure 3-8 show the blocking probability versus number of wavelengths for routing algorithms, namely, Fixed Routing (FR), Fixed Alternate Routing (FAR) and Adaptive Routing (AR) using FF method in the Indian network.
network and NSFNET, respectively, with 5000 connection requests. From the literature study, it had been found that the performance of Least Congested Routing (LCR) in terms of call blocking is almost same as that of using FAR. Therefore, we do not consider LCR in our simulation study. It has been revealed from Figure 3-7 and Figure 3-8 that the blocking probability decreases with increase in number
of wavelengths irrespective of the routing algorithm used. However, the rate of decrease in blocking probability for AR is more than that of other routing algorithms. This is because, AR considers all the possible end-to-end routes between source-destination pair on the basis of link-state information. Furthermore, it can be observed that the blocking probability using FAR is less than that of using FR due to FAR’s consideration of alternate paths for establishing connection requests. We also found that the blocking probability in the Indian network is less compared to NSFNET.

3.3.2 Wavelength Assignment

Here, we will show the performance of wavelength assignment schemes, namely, FF, Random (R) and Least-used (LU) in terms of blocking probability. From the literature, it had been revealed that the computational complexity of remaining conventional wavelength assignment schemes, such as Max-sum (MS), Relative Capacity Loss (RCL), Min-product (MP) and Least-loaded (LL) are much higher compared to FF, R and LU schemes. Therefore in our simulation study, we have only considered FF, Random and LU wavelength assignment schemes.

Figure 3-9 and Figure 3-10 show the blocking probability versus number of wavelengths using different wavelength assignment schemes in the Indian network and NSFNET, respectively, with 5000 connection requests. It has been revealed
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Figure 3-9: BP versus $W$ for the different wavelength assignment schemes in the Indian network

Figure 3-10: BP versus $W$ for the different wavelength assignment schemes in NSFNET

from Figure 3-9 and Figure 3-10 that the blocking probability decreases with increase in number of wavelengths irrespective of the wavelength assignment scheme used. However, the rate of decrease in blocking probability using FF scheme is more than that of using other schemes. This is because FF always chooses the low-
3.4 Conclusion

In this chapter, we have analyzed the performance of some major routing algorithms and conventional wavelength assignment approaches in the wavelength-routed optical networks. The effectiveness of the routing algorithms and wavelength assignment approaches have been examined through the performance evaluation in two example optical networks, namely, (i) the Indian network and (ii) NSFNET. From the simulation results we draw the following conclusions:

- It has been found that the performance of first-fit wavelength assignment approach in terms of blocking probability is the best among all the wavelength assignment schemes considered.

- Although adaptive routing with first-fit wavelength assignment scheme provides the best performance in terms of blocking probability, its average setup time is higher compared to others.

- Fixed alternate routing trades-off between blocking probability and average setup time.

Furthermore, it has been observed from the simulation study that for serving 5000 connection requests, a large number (∼350) of wavelengths is required which is practically impossible (using C+L spectrum band) in a wavelength-routed optical network. To overcome this problem, traffic grooming mechanism can be incorporated with RWA approach, in which a number of low-speed connection requests are multiplexed onto a high-capacity wavelength channel to enhance overall channel utilization and minimize the call blocking in the network. In the next three chapters, we have incorporated traffic grooming mechanism with RWA approaches for better utilization of network's resources.