Transmission Window Partition Mechanism in a Four-Wave Mixing Based WDM/DWDM Network

Saroj K. Mahapatra, Aditya Y. Sukhadeve, Vikram Kumar,
Kappala Vinod Kiran, and Santos K. Das*

Abstract—This research work proposes an efficient four-wave mixing (FWM) based routing and wavelength assignment (RWA) scheme for the improvement of connection blocking probability in WDM/DWDM networks. However, the traditional RWA schemes are less efficient for the better quality of transmission, and the proposed RWA scheme partitions the entire fiber transmission window into N number of bands and assigns wavelength randomly from one of the band based on connection length. Finally, the analytical result proves that the mechanism reduces the FWM effect significantly in terms of connection blocking probability with higher partition, lower FWM effect and better performance.

1. INTRODUCTION

In the present scenario of communication and network, the rapid increase in the number of users is a big challenge for all telecommunication service providers. To serve all the users in the network and deal with terahertz bandwidth, optical fiber communication is the ultimate solution using wavelength division multiplexing (WDM) and dense wavelength division multiplexing (DWDM) technology. This technology is being used in applications such as video imaging services, medical imaging services, CPU interconnects and many more [1]. The users in WDM/DWDM network communicate with each other through optical channels, called lightpaths. The lightpath consists of multiple fiber links and is set up only when it occupies the same wavelength over all the fiber links [2]. When many channels are present inside fiber transmission window, interaction will be more among themselves. This breeds four-wave mixing (FWM) effect, which causes degradation in transmission quality [3]. The degradation in service quality due to impairments is a big headache to all service providers.

FWM is a nonlinear impairment in fiber optics communication, whereas light waves interact to produce a new one. When two or more wavelengths interact inside fiber cable, they will generate some new wavelengths [3–5].

The process of setting up a lightpath starts after receiving a connection request in the network. In WDM/DWDM network, the traffic demand may be of two types: static and dynamic [6]. The dynamic traffic is the most efficient one because it processes the connection requests strictly in the order in which they arrive unlike the order decided by heuristics. Its objective is to set up lightpaths and assign wavelengths in a manner that minimizes the amount of connection blocking or that maximizes the number of connections established in the network at any time. There are three basic approaches for routing: fixed routing, fixed-alternate routing, and adaptive routing [2, 7]. Out of these, adaptive routing yields the best performance compared to other two methods [8]. There are few wavelength assignment heuristics have been proposed in literature [2, 7, 9–11]. Those heuristics are random wavelength assignment, first-fit, least-used, most used, min-product, least loaded, max-sum, relative capacity loss, wavelength reservation, and protecting threshold. Out of these, random wavelength

assignment is an efficient one. RWA algorithm assumes either centralized or distributed control for selecting routes and wavelengths [6]. In the case of centralized control, a central controller is assumed to be available. It keeps track of the state of the network and is responsible for selecting routes and wavelengths for the requests and sending control signals to appropriate nodes for establishing and releasing lightpaths.

Following introduction, Section 2 discusses the transmission window partitioning based proposed wavelength assignment (PWA) mechanism. Section 3 presents a procedure to serve a connection request using PWA scheme. Section 4 explains computation of bit error rate (BER). The analytical computation results of the PWA schemes are presented in Section 5, and finally Section 6 concludes the work.

2. TRANSMISSION WINDOW PARTITIONING MECHANISM

A lightpath is established means. Light has to travel through many concatenated links maintaining the same or different wavelengths. In every link, the same wavelength gets encountered by different wavelengths. So for the same lightpath the newly generated FWM components as well as power will vary from one link to another. FWM effect is zero at the start up region of lightpath and gets accumulated in each link throughout its route [4]. Let us consider WDM system where all channels are equally spaced. The FWM components are more crowded in the central part of the transmission window than the edges [3, 12].

The channels located in the central part of the transmission window will experience more FWM interference than in side edges. Using this observation, Adhya and Datta [3] have proposed a model, where short lightpaths are placed in the central segment of the window and the long lightpaths on the side edges (outer segments), to bring down the FWM effect at the central region. The long lightpaths have more FWM interference than short lightpaths, because of their duration of interaction. We considered it as the existing wavelength assignment (EWA) technique to reduce FWM interference.

We designed a new wavelength assignment scheme based on N number of partitions in transmission window as shown in Figure 1. These partitionings are named as equal number of odd and even partitionings. If there is N partitioning, the names of the bands will be 1, 2, 3, 4, ..., $N-2$, $N-1$ and N. The proposed partitioning mechanism divides the transmission window into N number of partitions. It has $N/2$ number of odd bands named as bands 1, 3, 5, ..., $(N-3)$, $(N-1)$. Similarly, it has also $N/2$ number of even bands named as 2, 4, 6, ..., $(N-4)$, $(N-2)$ and N.
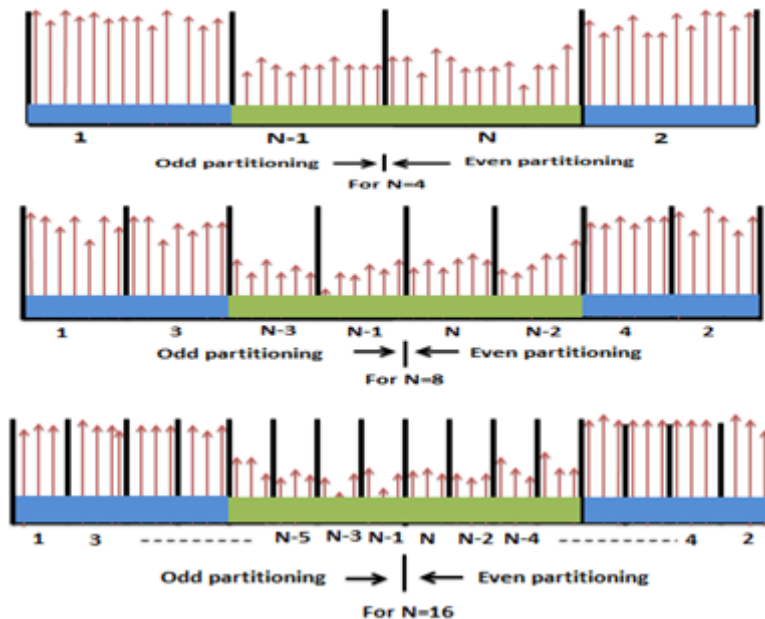
Figure 1. Transmission window partitions for $N = 4$, 8 and 16.

3. PROCEDURE TO SERVE A CONNECTION REQUEST USING PWA SCHEME

Algorithm 1 has been designed for FWM aware routing and wavelength assignment. It is also presented in the flowchart mentioned in Figure 2. Whenever a WDM network receives a connection request, it initializes the node pair containing the source node and destination node for the respective connection request. First, the network tries to compute all the possible paths between the source and destination

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Algorithm 1 FWM aware RWA algorithm

1: INPUTS: Simulation network topology, Parameters for simulation, s, d, Connection requests, BER_{thrs}, Partitions
    $N = 4, 8, 16$, All possible connections OUTPUTS: BER, Connection set up, Wavelength assignment
2: Initialize $(s, d) = (,)$ and take the first connection request
3: **for** cr=1 to CR **do**
4:    Get all possible connections and take the first connection
5:    **for** c=1 to C **do**
6:        Wavelength assignment using PWA schemes
7:        **for** $N = 4, 8, 16$ **do**
8:            Compute BER for each connection
9:            **if** $BER < BER_{thrs}$ **then**
10:               Accept and assign the connection to request, go for next request
11:            **else**
12:               Reject connection and go for next connection
13:            **end if**
14:        **end for**
15:    **end for**
16: **end for**

**Algorithm 2** Wavelength assignment using PWA scheme

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1: Compute all possible paths and d_{thrs}, Initialize K, L, M, N, d.
2: **if** $d > d_{thrs}$ **then**
3:    Assign wavelength to odd number connections from $(2n - 1)$th bands
4:    Assign wavelengths to even number connections from $(2n)$th bands
5:    Repeat assignment process in same band at a gap of $N_{\max}/2$
6:    **for** $n = 1$ to $N_{\max}/4$ **do**
7:        **if** $feasible\_in\_(2n - 1)$th$\_band$ **then**
8:            $k = K - 1$, $l = L + 1$
9:        **else**
10:            assign in $(2n)$th band, $k = K - 1$, $l = L + 1$
11:        **end if**
12:    **end for**
13: **else**
14:    **for** $n= (N_{\max}/4) + 1$ to $(N_{\max}/2)$ **do**
15:        Repeat assignment process in same band at a gap of $N_{\max}/2$
16:        **if** $feasible\_in\_(2n - 1)$th$\_band$ **then**
17:            $k = K - 1$, $l = L + 1$
18:        **else**
19:            assign in $(2n)$th band, $k = K - 1$, $l = L + 1$
20:            **if** $feasible\_in\_(2n)$th$\_band$ **then**
21:               $k = K - 1$, $l = L + 1$
22:            **else**
23:               Block the connection, $k = K - 1$, $m = M + 1$
24:            **end if**
25:        **end if**
26:    **end for**
27: **end if**
28: **if** $K = 0$ **then**
29:    Stop
30: **end if**
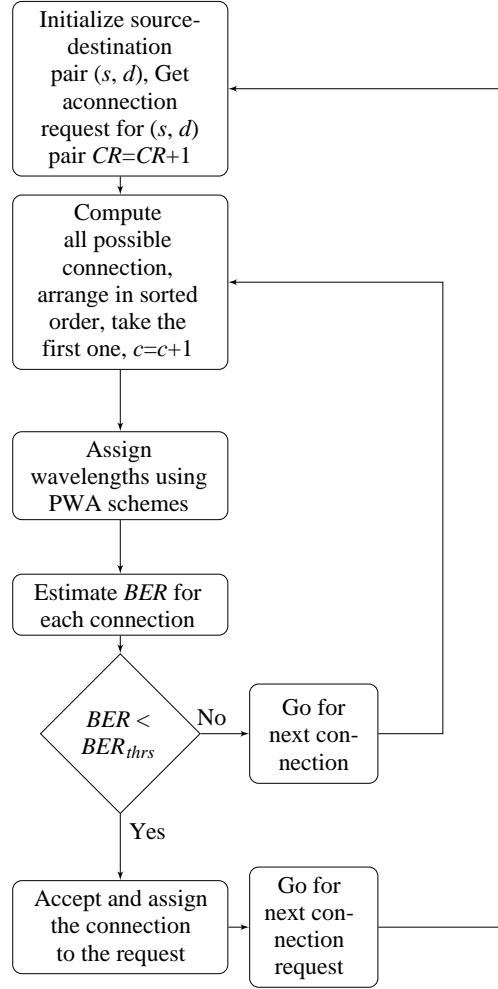
Figure 2. Flow chart for FWM aware RWA.

node pair. Those possible paths are arranged in a sorted order. Then it picks the first possible path and assign wavelength using PWA schemes. Assignment of wavelength using PWA scheme has been described in Algorithm 2. The *BER* is calculated each time for the same path under different schemes. If the calculated *BER* is less than the threshold level, BER_{thrs}, i.e., 10^{-9}, that connection will be accepted and network will switch to another connection request. But if it finds that calculated *BER* is greater than BER_{thrs}, it rejects that connection request and tries for another one, and this process continues. It stops when there is no more connection request.

Algorithm 2 has been designed to assign wavelengths using PWA schemes. Algorithm 1 will call Algorithm 2 during its wavelength assignment operation using PWA schemes. This algorithm is also presented in the flowchart mentioned in Figure 3. Initially, the threshold/average distance, d_{thrs}, for all existing K number of connections is calculated. Assume that the number of connections established is zero, i.e., $L = 0$ and that the number of connections blocked is zero, i.e., $M = 0$. Here N is the number of partitions to be applied inside fiber transmission window. Consider that the first connection is having distance, d. If it is greater than the threshold distance, it will try to assign from $(2n-1)$th and $(2n)$th bands for n values of 1, 2, ..., $N_{\max}/4$. The $(2n-1)$th bands for n values of $1, 2, \ldots, N_{\max}/2$ are odd partitioned bands. Similarly, the $(2n)$th bands for n values of 1, 2, ..., $N_{\max}/2$ are even partitioned bands. Here wavelength assignment task for connections is carried out in a sequential order. The connection coming first to the $d > d_{thrs}$ decision is treated as first and odd one. The next connection coming in is the second and even one, and the next is third and odd one. This sequence is followed in an equal manner for $d < d_{thrs}$ decision. When the first wavelength is assigned in any of band, K
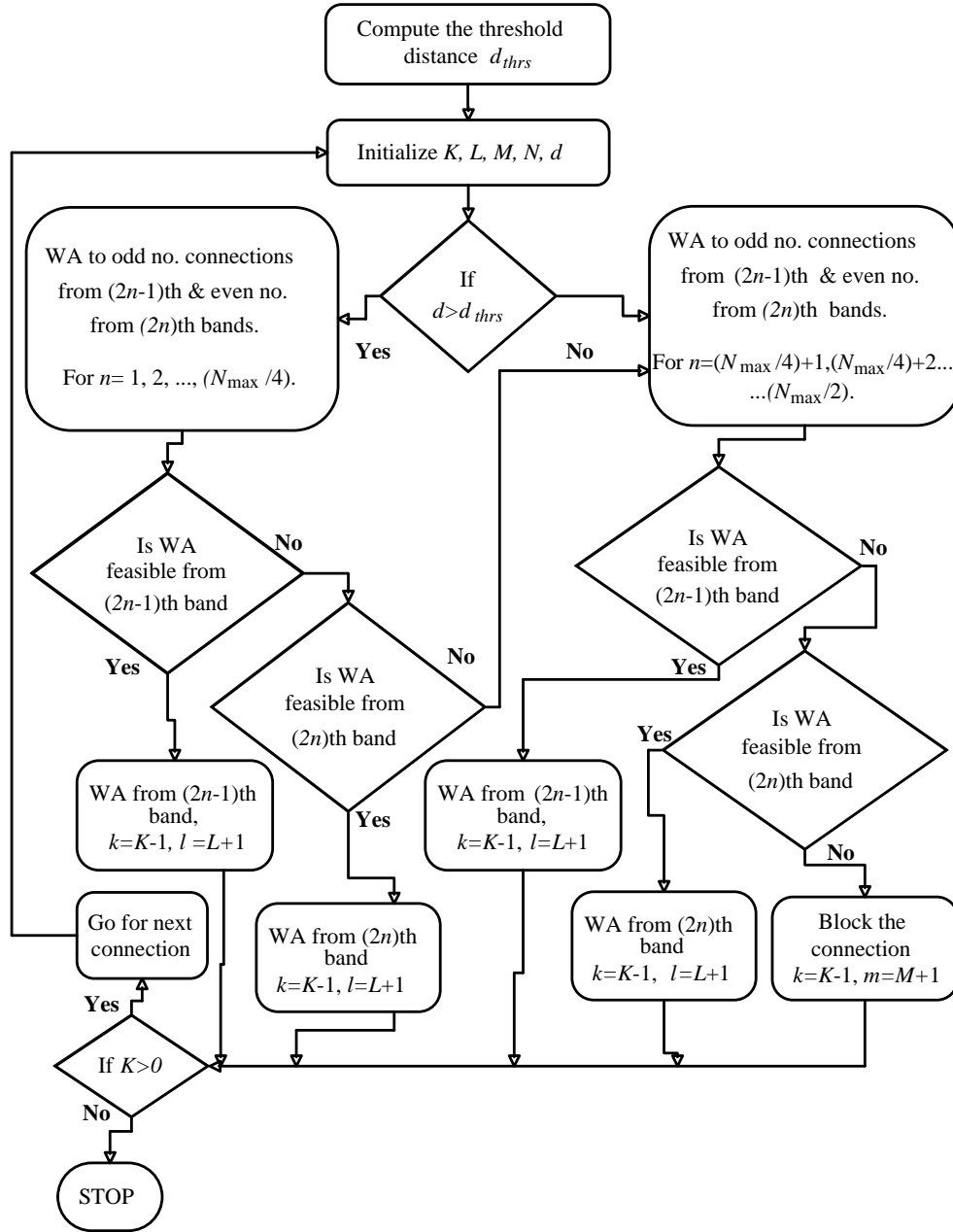
Figure 3. WA scheme flowchart.

and L values are updated to $k = K - 1$ and $l = L + 1$, respectively. The wavelength assignment may switch from $d > d_{thrs}$ to $d < d_{thrs}$ decision due to non-availability of wavelengths. After completion of each assignment process, it checks whether K is equal to zero or not. When it finds K is not equal to zero, it repeats the assignment task. When it finds a path having distance less than threshold distance, it assigns wavelength sequentially, odd number connection from $(2n - 1)$th and even number connection from $(2n)$th bands for values of $n = (N_{max}/4) + 1$, $(N_{max}/4) + 2$, ..., $N_{max}/2$. If the WA is not feasible in the $(2n)$th band for any values of $n = (N_{max}/4) + 1$, $(N_{max}/4) + 2$, ..., $N_{max}/2$, it blocks the connection, and the value of m gets updated to $M + 1$. The wavelength assignment task stops when it finds $K = 0$. When there are many connections, and bands are few such as 4, 8 or 16, repetition of wavelength assignment occurs from the same band, but it maintains a gap of $N_{max}/2$, where N_{max} is the maximum number of partitions.

4. COMPUTATION OF BIT ERROR RATE

As discussed earlier, when two or more wavelengths travel together in a fiber cable, they will generate some new wavelengths, which are called FWM components. Suppose that three equally spaced wavelengths λ_p, λ_q and λ_r move together, then a new FWM component $\lambda_{p,q,r}$ will be generated. It can be expressed as,

$$\lambda_{p,q,r} = \lambda_p \pm \lambda_q \pm \lambda_r \tag{1}$$

where, $p \neq r$ and $q \neq r$. In the above equation, λ_p, λ_q, λ_r are wavelengths of pth, qth and rth light waves. If three light waves interact, then there are 9 wavelengths generated [3], and this effect is dependent on the length of duration of interaction among channels inside fiber cable and the space between channels. The FWM power $P_{pqr}(i,j)$ generated in a link (i, j) can be represented as [8, 13–16]

$$P_{pqr}(i,j) = \frac{\eta}{9} d^2 \gamma^2 P_p P_q P_r e^{-\alpha L} L_{eff}^2 \tag{2}$$

where, p, q, r are index numbers; d is called degeneracy factor, d is 3, when $\lambda_p = \lambda_q$ and 6 when $\lambda_p \neq \lambda_q$; P_p, P_q, P_r are signal input power, L is the fiber length; α is the attenuation coefficient of fiber cable; γ is the non-linear coefficient; L_{eff} is the effective fiber length and can be represented as,

$$L_{eff} = \frac{\left(1 - e^{-\alpha L}\right)}{\alpha} \tag{3}$$

The efficiency, η, in the presence of FWM effect is represented as,

$$\eta = \frac{\alpha^2}{\alpha^2 + \beta_{pqr}^2} \left[1 + \frac{4e^{-\alpha L} \sin^2(\beta_{pqr} L/2)}{(1 - e^{-\alpha L})^2}\right] \tag{4}$$

The efficiency can be written as [15, 17]

$$\eta = \frac{\alpha^2}{\alpha^2 + \beta_{pqr}^2} \tag{5}$$

where, β_{pqr} is called propagation constant difference, which is dependent on spacing between channel as well as fiber chromatic dispersion. The propagation constant can also be represented as,

$$\beta_{pqr} = 2\pi c \lambda_k^2 \Delta\lambda_{pq} \Delta\lambda_{qr} \times \left[D_c + (\frac{\lambda_k^2}{2})(\Delta\lambda_{pq} + \Delta\lambda_{qr})\frac{dD_c(\lambda_k)}{d\lambda}\right] \tag{6}$$

where, λ_k = central wavelength, and C is the speed of light, D_c the fiber chromatic dispersion and $\frac{dD_c(\lambda_k)}{d\lambda}$ the dispersion slope. If the value of β_{pqr} is zero, efficiency, η, will be 1. If the propagation constant difference is far from the zero dispersion region, β_{pqr} is written as,

$$\beta_{pqr} = 2\pi c \lambda_k^2 D_c \Delta\lambda_{pq} \Delta\lambda_{qr} \tag{7}$$

When the channels inside transmission window are equally spaced, $\Delta\lambda_{pq} = \Delta\lambda_{qr} = \Delta\lambda$. So for the nth connection a source-destination node pair (s, d) comprises many links. Hence, the total FWM power can be written as,

$$P_{pqr}(s,d) = \sum_{(i,j)\in(s,d)} \sum_p \sum_q \sum_r P_{pqr}(i,j) \tag{8}$$

At the receiver end, the light of FWM and desired signal both are detected, so the noise power, σ_{FWM}, can be written as [15, 17]

$$\sigma_{FWM} = 2\rho^2 P_{ds} \frac{P_{pqr}(s,d)}{8} \tag{9}$$

where, P_{ds} is the optical signal power of the received signal at the receiver. It is represented as,

$$P_{ds} = P_i e^{-\alpha L} \tag{10}$$

where, P_i is the input power. In the case of FWM, the bit-error rate is computed as,

$$BER_{FWM} = 0.5 erfc\left(SNR_{FWM}\right) \tag{11}$$

where, SNR_{FWM} is represented as,

$$SNR_{FWM} = \frac{I_{ds}}{\sigma_{FWM}\sqrt{2}} \tag{12}$$

where, I_{ds} is the photo current and is written as $I_{ds} = \rho P_i$, and ρ is the receiver's responsivity.

5. ANALYTICAL COMPUTATION

We used a NSFNet topology for our analytical computation which contains 10 nodes and 16 links as shown in Figure 4. The distances between the nodes are expressed as numbers. Those numbers represent span, and one span is 70 km.

The values of parameters used in simulation are shown in Table 1.
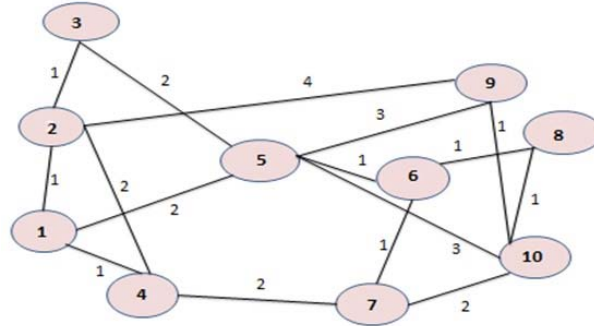

Figure 4. NSFNet topology.

Table 1. Parameters used in simulation.

Parameters	Values
Receiver's responsivity, ρ	1
Signal current, I_s	1 mA
Input powers, P_p, P_q, P_r	5 mW
Fiber attenuation, α	0.2 dB/km
Degeneracy factor, d	3 if $f_i = f_j$ and 6 if $f_i \neq f_j$
Efficiency, η	0 to 1
Chromatic dispersion, D_c	0.3 ps/nm-km
Dispersion slope, $dD_c/d\lambda$	0.07 ps/nm^2
Central wavelength, λ_k	1.55 μm
Nonlinear coefficient, γ	2.35 (w·km)$^{-1}$
Space between channels, $\Delta\lambda$	25 GHz

### 5.1. Wavelength Dependent Connection Blocking Performance

In this analysis, we tried to show how the connection blocking probability changes when we bring up any changes in number of wavelengths. Connection blocking performance is shown in Figure 5 for a source-destination (s, d) node pair by using EWA with 3 partitions, PWA with 4, 8 and 16 partitions. These are named as PWA(4), PWA(8) and PWA(16). The plots reflect that PWA schemes have better performance than EWA. Out of all these figures we can see that PWA scheme with 16 partitions, i.e., PWA(16), performs better than others. One more thing, we can bring to notice that if we go for more partitions of the fiber transmission window, the blocking probability will gradually go down.

5.2. Connection Request Based Blocking Performance

This analysis is carried out to show how blocking probability varies with variation of connection requests at different wavelength. The node pairs (1, 3) and (1, 8) have been taken for analysis. At fixed wavelength, when the number of connection requests varies from lower value to higher value, it is observed that the blocking probability also gradually decreases. Figure 6 represents the performance in
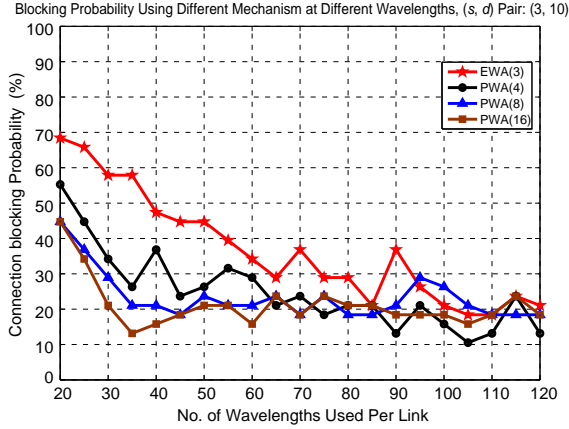
**Figure 5.** Connection blocking probability vs. no. of wavelengths used per link, (s, d) node pair $(3, 10)$.
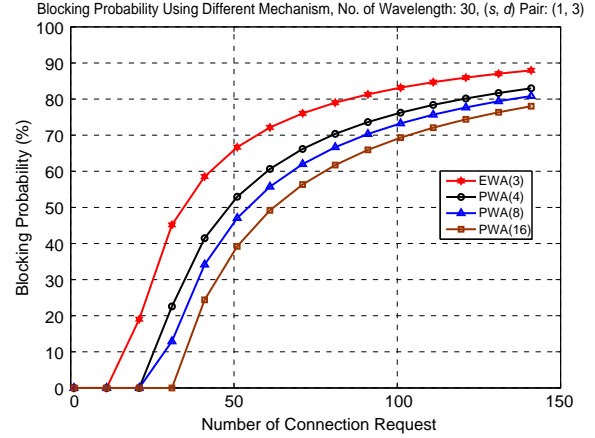
Figure 6. Blocking probability vs. no. of connection request of (s, d) pair: $(1, 3)$ at wavelength 30.

terms of blocking probability vs variation in number of connection requests for node pairs $(1, 3)$ and $(1, 8)$. The simulation plots are taken at different numbers of wavelengths. The result signifies that PWA scheme has less blocking probability. The figures reflect that the blocking probability moves downward with the increase in number of partitions.

5.3. Analysis of Connection Acceptance

This analysis shows how the number of connection acceptances vary at different wavelengths based on EWA and PWA mechanisms. The node pairs $(3, 5)$, $(2, 9)$ and $(6, 7)$ have been taken for analysis. Figure 7 represents the number of connections accepted for these (s, d) pairs at different wavelengths. The result shows that PWA scheme has a better connection acceptance rate than EWA. It can also be deduced that the acceptance rate can be improved for higher number of wavelengths.
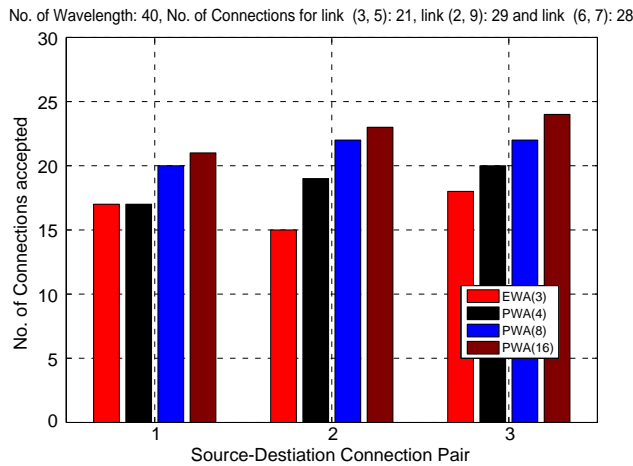
Figure 7. No of connections accepted for node pairs $(3, 5)$, $(2, 9)$ and $(6, 7)$ at wavelength 40.

6. CONCLUSION

The analytical results found earlier reflect the usefulness of transmission window partitioning over FWM crosstalk during routing and wavelength assignment in WDM/DWDM network. The PWA scheme has proved itself as a more effective and efficient one for WDM/DWDM networks, where there is always some FWM effect found inside fiber transmission window. The computation result demonstrates the

PWA schemes over EWA. It measures the performance of the network by calculating connection blocking probability related to variation in number of wavelengths and connection requests. The results show that these PWA schemes can reduce the FWM effect significantly, even the lightpaths which were rejected in EWA scheme, later got accepted in PWA schemes.

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