Fuzzy Controlled Dynamic QoT Routing and Wavelength Assignment in Transparent Optical Networks

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ABSTRACT

In a transparent optical network, a transmitted signal remains in the optical domain over the entire route (lightpath) assigned to it between its source and destination nodes. In this paper, a novel Fuzzy dynamic routing and wavelength assignment technique is proposed for a wavelength division multiplexing (WDM) optical network, to achieve the best quality of network transmission and network service. This paper presents a novel Fuzzy logic controlled quality of transmission aware dynamic routing and wavelength assignment (FCD-QoT-RWA) algorithm, where the optimum path is chosen by a Fuzzy Rule Based System (FRBS) with hop constrained paths and at a specified traffic load. The optical signal traverses a number of cross connect switches (XCS’s), fiber segments, and optical amplifiers such as erbium doped fiber amplifier (EDFA). Thus, the signal quality degrades as it encounters crosstalk at the XCS’s and also picks up amplified spontaneous emission (ASE) noise at the EDFA’s. These impairments continue to degrade the signal quality as it progresses towards its destination, and the received optical signal to noise ratio (OSNR) at the destination node becomes unacceptably low. The proposed algorithm incorporates quality of transmission aware linear impairments such as polarized mode dispersion (PMD), amplified spontaneous emissions noise (ASE), switch crosstalk (SC), demultiplexer crosstalk (DC) for computation of OSNR for each of the path generated for the call request. The proposed FRBS takes OSNR and two quality of service aware parameters such as hop count (HC) and free channel availability (FCA) of each path as input parameters. The defuzzified value determines the optimal path for establishment of lightpath. In this study, the performance metrics of the hop-constrained lightpaths evaluated at different number of system wavelengths at a specified load. This paper attempts to improve the mean blocking probability, the mean execution time and mean FCA using fuzzy system.

Keywords: Routing, all optical networks, QoS constraints, QoT constraints, Wavelength division multiplexing (WDM), polarized mode dispersion (PMD), amplified spontaneous emissionnoise (ASE), Switch crosstalk, Hop constrain, Fuzzy rule base system, Blocking probability, Defuzzification, lightpath. Optical signal to noise ratio (OSNR).

1. INTRODUCTION

Transparent optical networks are considered as the most reliable and economic solution to achieve high transmission capacities with quality of transmission (QoT) and also provide support to huge traffic in the future communication networks. To transfer data in wavelength routed optical network, a lightpath must be established between source-destination pair by a Routing and Wavelength Assignment (RWA) technique.

A lightpath is an all optical communication channel between two nodes, which may consist of one or more fiber links. The complexity arises for selection of lightpath with appropriate wavelength between pair of nodes in the network. Wavelength continuity is a common problem in wavelength routed networks, where every link in the lightpath must share a free common wavelength. A proper RWA scheme must be implemented in order to avoid blocking in future connection requests. As the optical signal from the source node propagates along a lightpath in an all optical transparent wavelength routed network towards the destination node, the quality of signal degrades as there is no OEO (Optical-Electronic-Optical) conversion and therefore, the Bit Error Rate (BER) of the signal increases or the optical signal to noise ratio (OSNR) decreases at the destination node. OSNR below the threshold level is unacceptable by the user.

Again, the lightpath is not acceptable if establishment of a lightpath decreases the OSNR of other existing lightpaths. RWA technique added with physical layer impairment constraints is much more practical for lightpath establishment and is called quality of transmission aware routing and wavelength assignment techniques (QoT-aware-RWA) [1-7, 9-10].

The RWA problem is known to be NP-complete [1], [19]. Out of the two existing types of RWA problems, the dynamic RWA (DRWA) problem, is more challenging, and is widely investigated in the literature.

Currently, high-speed networks are expected to support a wide range of multimedia applications. In case of DRWA, the connection requests are dynamic and holding time is exponentially distributed [1-7].QoT-aware-DRWA in transparent optical network is a complex problem, where both the impairments in the lightpath and RWA are integrated to find the optimal lightpath. In a lightpath different type of linear and non-linear impairments are accumulated at different nodes along the lightpath and at the destination node, when signal propagates through different non-ideal optical devices such as optical amplifier, OXCs, multiplexers, demultiplexer and fiber segments, and the signal is worst affected and contaminated with noise, which is unacceptable by the user due to the high bit error rate (BER) [1-7], [9-11]. Out of various linear impairments,
node crosstalk and amplified spontaneous emission noise (ASE) noise degrade the signal quality even at low transmission power and low data rate. Due to these impairments, the received signal quality may become so poor that the BER reaches an unacceptably high value, rendering the light-path unusable [3-5]. Noise is also generated due to the signal leakage at the OXCs known as switch crosstalk (SC) or imperfect filtering in demultiplexer known as demultiplexer crosstalk (DC). PMD arises due to the geometry and composition of fiber containing impurities.

These types of non-uniformity or irregularities render obstacle to an optical pulse along its path. These obstacles cause different polarization of the optical signal to travel with different group velocities resulting in the pulse spread in frequency domain known as PMD [7], [10]. As the channel bit rate increases beyond 10 Gbps, PMD becomes one of the limiting factor in high-speed data transmission network. PMD strongly affects the transparent transmission length [7], [10]. Therefore, it is necessary to consider these four physical layer constraints, like ASE, SC, DC and PMD while solving the dynamic routing and wavelength assignment (DRWA) problem in transparent optical networks. In this work, the above four linear impairments are taken into consideration for lightpath establishment in transparent wavelength routed network using a fuzzy logic controller (FLC) referred in this work as Fuzzy Controlled Dynamic-QoT-aware-RWA (FCD-QoT-RWA). In conjunction to the QoT parameters, this work also attempts to incorporate the Quality of Service (QoS) parameters such as Available Free Channel (AFC) and number of hops (NH) that affect the quality of signal indirectly at the destination node. The inclusion of both QoT and QoS parameters in the DRWA problem in the proposed algorithm makes the DRWA problem more complex [3-5].

In this proposed work, a novel fuzzy based algorithm is developed at the bit rate of 40 Gbps, which incorporates QoT parameters like ASE, PMD, SC and DC and QoS parameters like AFC, Hop Count (HC). ASE is developed due to the amplification by Erbium Doped Fiber Amplifier (EDFA), PMD is developed as the optical signal travels with different group velocity due to different polarization. SC is generated due to power leakage at OXCs and DC is generated due to imperfect channel isolation in the filters at the demultiplexer.

The research works carried out in this paper include the following salient feathers:

- Generation of multiple paths for a connection request with hop count constraint.
- Design of Fuzzy Rule Base System (FRBS) with three input variable (OSNR, AFC and NH) extracted from the path and one output variable.
- Three parameters (OSNR, AFC and NH) of each path are exported to FRBS as input variables.
- The defuzzified value determines the optimal lightpath for the connection request.

The rest of the paper is organized as follows:

Section 2 describes the previous works on QoT-aware-DRWA. Section 3 introduces the problem definition and system model. Section 4 describes the proposed algorithm (FCD-QoT-RWA). Section 5 describes the simulation results. Finally, section 6 concludes the paper.

2. RELATED WORK

Prior research works on the QoT aware-RWA algorithms in optical networks are found in the literature [1], [6-7]. It is found from the survey that the classical approaches are addressed by adding the physical layer impairment related constraints to the RWA problem. However, the QoT aware-RWA problem is an NP-complete problem and mostly it is solved using other alternative approaches like heuristics or metaheuristic based approaches [1]. These approaches yield optimal or sub-optimal solutions with a low computational overhead.

The heuristic approaches yield near optimal solutions if the search space is convex and problem is simple. But, these may incur a heavy computational burden when the search space is non-convex [24]. Hence, a fuzzy logic approach is created, which obtain an approximate solution to practically any kind of problem. The approaches using fuzzy logic are appealing as they do not involve any complex mathematical formulations. To reduce the computational complexity, the QoT aware-RWA problem is usually decomposed into two sub problems: the routing sub problem and the wavelength assignment sub problem, which are solved mostly using heuristics [2], [8-10]. However, there are very few papers available that propose to utilize metaheuristic to solve the QoT aware-RWA [3-5], [11], [14-15] problem. In [11], the authors consider two linear impairments like PMD and ASE noise and solve the problem using the genetic algorithm (GA) based approach. The authors have attempted to minimize the number of wavelength converters, amplifiers, and PMD compensating devices.

In this paper, the authors consider the effect of PMD, which is observed only for data rates beyond 40 Gbps, and fail to incorporate the effect of important linear impairments such as node crosstalk, which can occur at low or moderate data rates. In [15], the authors incorporate ant colony optimization (ACO) to solve a specific type of impairment aware RWA problem, known as RWA with power constraints (RWA-P) that maintains an acceptable level of optical power and adequate signal to noise ratio (SNR) all over the network. In this paper, an attempt is made to minimize the aggregate power in each link so as to minimize the effect of non-linearity on the network. While calculating the power, only the ASE noise is taken into consideration. The authors also propose an extension of their approach to find a lightpath in a distributed generalized multiprotocol label switching (GMPLS) network [15]. In both [14] and [15], the authors have neglected the effect of node crosstalk while setting up a lightpath. Few of the papers available in the...
literature, consider the effect of node crosstalk [2-3], [8-10], [16-17], [23]. Out of these papers, in [3], [16] the authors try to alleviate the effect of node crosstalk by using a specific wavelength ordering technique and in [17-18] the authors propose a crosstalk aware wavelength assignment scheme to reduce the effect of switch crosstalk. The authors in [2], [9-10] consider the effect of switch crosstalk and ASE noise while establishing suitable lightpath. The authors in these papers neglect the effect of polarize mode dispersion (PMD) that effect the signal at a higher data rate of 40 Gbps. In [3], the authors purpose a QoT aware evolutionary programming algorithm (QoT aware EP) to solve the QoT aware DRWA problem. The authors in this paper try to minimize the average blocking probability and average execution time of the algorithm incorporating the effect of ASE noise, switch crosstalk, and demultiplexer crosstalk in the algorithm at a data rate of 2.5 Gbps. However, the authors have not considered the effect of PMD on the signal quality that affects the signal at a data rate of 10 Gbps or beyond 10 Gbps.

Very few research works has been carried out, considering fuzzy approach for the lightpath establishment in QoS aware-DRWA technique. The authors try to improve the blocking probability and minimizing the average number of hops in the work, where the inputs to fuzzy systems are traffic load and number of hops [12]. In a recent research paper, the authors designed a Fuzzy Rule Based System (FRBS) to establish a RWA scheme using Generalized Multiprotocol Label Switching (GMPLS) over WDM network, where the inputs to fuzzy systems are request bandwidth, average utilization of each wavelength and co-efficient of data traffic and output determines the probability of successful connection [13]. The authors propose a novel algorithm, which allows the network to adapt to the real time traffic change and ensure the network survival using FLC [13]. In all the above mentioned papers, the algorithm implement fuzzy logic on the network parameters, but ignore the physical layer impairments.

Ample of works are available in the literature [1-2], [6-7], [9-10], [16-18] on QoT aware DRWA problem using classical approach, which incorporates specific types of physical layer impairments into the account. However, very few papers are available, which implement metaheuristic algorithms like GA (Genetic Algorithm), Evolutionary Programming (EP), Fuzzy Inference System (FIS), Ant Colony Optimization (ACO) to find a solution to the QoT aware DRWA problem [3-5], [11-15].

3. PROBLEM DEFINITION AND SYSTEM MODEL

3.1 Problem Definition

A fuzzy controlled dynamic QoT aware routing and wavelength assignment (FCD-QoT-RWA) problem is a call admission problem where, lightpath requests are initiated dynamically. A lightpath is a path in the network that satisfies the wavelength continuity constraint that is the same wavelength must be assigned on each link of the path that a lightpath traverses. Each lightpath is assumed to be defined by three network specific parameters S, D, T which represent the source node, destination node and the holding time respectively. The holding time defines the time period during which a lightpath and the associated resources remain engaged. Once the holding time expires, the resources become free to serve other lightpath requests. During lightpath establishment, care has been taken to ensure that the QoT parameters such as number of available free channels (AFC), number of hops (NH) and OSNR are fuzzified and are incorporated in the algorithm.

3.2 Network Model

The network under study is a transparent optical network of N nodes that can be modeled as a graph G (V, E), where V and E respectively represent the set of nodes and the set of bidirectional network links. A total of W equally spaced wavelengths are assumed to be available per fiber. Each wavelength routing node (WRN) consists of a cross connect switch (XCS), transmitter and receiver arrays, optical taps and EDFAs as shown in Figure. 1 [2].

![Figure 1: Architecture of a wavelength routing node (WRN) [2]](image)

A transmission lightpath follows the model illustrated in Figure. 2. No inline amplifiers are assumed to be there throughout the lightpath. The span length in the proposed model varies from 30 km to 100 km. A tap is present at the input and output of each XCS to monitor the signal condition. The EDFA at the input side compensates for the fiber loss and the tap loss and the EDFA at the output side compensates for the switch loss. In Figure.2, WRN (1) represents the source node, WRN (m) represents the destination node, and WRN (k) represents the kth intermediate node. Arrays of transmitters and receivers are present in each node for locally adding or dropping the traffic.
3.3 Routing Model

In the proposed routing model a variable $l_{ij}^{lp}$ is used, which describes a link (i, j) used by the lightpath lp. When the link (i, j) is used by the lightpath lp, $l_{ij}^{lp}=1$; otherwise, $l_{ij}^{lp}=0$. This is considered to be a positive variable when the lightpath link leaves the node, and negative in the opposite case. A lightpath from the source S to the destination D is represented as path (lp) and is a collection of all the links belonging to the lightpath from S to D. The number of available wavelength or channel for a path (FLC), hop count for a path, and OSNR(dB) for a path are fuzzified by the FRBS to yield the cost of a lightpath (lp) referred in this work as cost. LP is the set of all the lightpaths. In the proposed algorithm, dijikstra’s shortest path routing and different wavelength assignment approaches are integrated [19-21].

Objective function:

In this work, the objective is to dynamically find a cost optimal or sub optimal lightpath.

Lightpath conservation constraint [3-5], [19-21]:

$$\sum_{i \in \text{in}} l_{ij}^{lp} - \sum_{j \in \text{out}} l_{ij}^{lp} = 1, \; \text{if} \; i = S, \; l_p \in \text{LP}$$

$$\sum_{i \in \text{in}} l_{ij}^{lp} - \sum_{j \in \text{out}} l_{ij}^{lp} = -1, \; \text{if} \; i = D, \; l_p \in \text{LP}$$

$$\sum_{i \in \text{in}} l_{ij}^{lp} - \sum_{j \in \text{out}} l_{ij}^{lp} = 0, \; \text{if} \; i \neq S, \; i \neq D, \; l_p \in \text{LP}$$

Constraint to ensure that the lightpath is without loops [3-5], [19-21]:

$$\sum_{(i,j) \in E} f_{ij}^{lp} \leq 1, \; \text{if} \; i = D, \; l_p \in \text{LP}$$

$$\sum_{(i,j) \in E} f_{ij}^{lp} = 0, \; \text{if} \; i = D, \; l_p \in \text{LP}$$

The constraint (1a) guarantees that the solutions obtained are valid paths from S to D. The first part of the constraint (1a) ensures that for each pair of source and destination node only one lightpath exists from source node S. The second part of the constraint (1a) ensures that for each pair of source and destination nodes only one lightpath reaches the destination node D. Third part of the constraint (1a) ensures that a path that reaches an intermediate node also exits that node through another link. The constraint (1b) ensures that the lightpath is without any loops [3-5], [19-21].

3.4 OSNR and PMD Constraint Evaluation Model

The linear impairment that affects the channel mostly at higher data rate of 40 Gbps or beyond is the polarized mode dispersion. In this work, the effect of PMD is taken into consideration. PMD arises due to the geometry and composition of fiber i.e. containing impurities, non-circularity or subjected to external stress like heating. These types of non-uniformity or irregularities render obstacle to an optical pulse along its path. These obstacles cause different polarization of the optical signal to travel with different group velocities resulting in pulse spreading in frequency domain known as PMD [7]. The differential group delay (DGD) is proportional to the square root of fiber length $L$ i.e. $\Delta \tau = D_{PMD} \sqrt{L}$, Where $D_{PMD}$ is the PMD parameter of the fiber.

The PMD value varies from 0.01 to 10 ps$/\sqrt{\text{km}}$ [7]. As the channel bit rate increases beyond 10 Gbps, PMD becomes one of the limiting factor for high-speed data transmission network. PMD strongly affects the transparent transmission length [10].

The PMD for a lightpath is described as below:

$$B \times \sqrt{\sum_{k=1}^{H} D_{PMD}^{2}(k) \times L(k)} \leq \delta \quad 2(a)$$

Where, B is the data rate; $D_{PMD}$ is the fiber PMD parameter in the kth hop of the transparent lightpath consisting of H hops; and L is the fiber length of the kth hop [10]. The parameter “$\delta$”, represents the fractional pulse broadening, should typically be less than 10% of a bit’s time slot for which the PMD is tolerated [10]. The fibers having different $D_{PMD}$ induces different PMD limit.

In the work, it is assumed that all the fibers that are used in the network have the same $D_{PMD}$.

OSNR at the destination is calculated as described below [3-5]

$$P_{\text{signal}_{lp}}(k, \lambda_j) = P_{\text{signal}_{lp}}(k - 1, \lambda_j) L_{fp} L_{dm}(k) L_{sw}(k) L_{mx}(k) G_{out}(k) L_{tap}^2 \quad 2(b)$$

$$P_{\text{stp}}(k, \lambda_j) = P_{\text{stp}}(k - 1, \lambda_j) L_{fp} G_{in}(k) L_{dm}(k) L_{sw}(k) L_{mx}(k) G_{out}(k) L_{tap}^2 + \sum_{i=1}^{12} \lambda_{sw} P_{\text{tap}}(i, k, \lambda_j) L_{sw}(k) G_{out}(k) L_{tap} \quad 2(c)$$

$$P_{\text{asep}}(k, \lambda_j) = P_{\text{asep}}(k - 1, \lambda_j) L_{fp} G_{in}(k) L_{dm}(k) L_{sw}(k) L_{mx}(k) G_{out}(k) L_{tap}^2 + 2 \eta_{sp} G_{in}(k) \eta_{sp} B_{\alpha} L_{dm}(k) L_{sw}(k) L_{mx}(k) G_{out}(k) L_{tap}^2 + 2 \eta_{sp} G_{out}(k - 1) B_{\alpha} L_{tap} \quad 2(d)$$
In the above equations 2(a) to 2(d), $P_{\text{signal}}(k, \lambda_j)$ represents the signal power of $k$th node at wavelength $\lambda_j$ for path P. $P_{\text{signal}}(k-1, \lambda_j)$ represents the signal power of $(k-1)$th node at wavelength $\lambda_j$ for path P. $L_{fp}(k-1, k)$ represents the fiber loss between the $(k-1)th$ and the $k$th node for the path P. $G_{in}(k)$ represents the gain of the EDFA at the input of the $k$th node at a wavelength $\lambda_j$. $L_{dm}(k)$ represents the demultiplexer loss. $L_{sw}(k)$ represents the switch loss. $G_{out}(k)$ represents the gain of the EDFA at and wavelength $\lambda_j$. $L_{tap}(k)$ represents the tap loss. $P_{\text{txP}}(k, \lambda_j)$ represents the switch crosstalk power at wavelength $\lambda_j$. $P_{\text{txP}}(k-1, \lambda_j)$ represents the switch crosstalk power of $(k-1)$th node at wavelength $\lambda_j$. $P_{\text{aseP}}(k, \lambda_j)$ represents the ASE noise power of $k$th node at wavelength $\lambda_j$. $P_{\text{aseP}}(k-1, \lambda_j)$ represents the ASE noise power of $(k-1)$th node at wavelength $\lambda_j$. $P_{\text{mtP}}(k, \lambda_j)$ represents the multiplexer crosstalk power of $k$th node at wavelength $\lambda_j$ and $P_{\text{mtP}}(k-1, \lambda_j)$ represents the multiplexer crosstalk power of $(k-1)$th node at wavelength $\lambda_j$ for the path P respectively. The term $F_{\text{mpP}}(i, k, \lambda_j)$ represents the power of the $t$th co-propagating signal at the $k$th node for the path P. $\eta_{sp}$ represents the spontaneous emission factor for the EDFA. $X_{sw}$ is the switch crosstalk ratio that represents the fraction of unwanted power introduced by a signal into another signal as they co-propagate through the switch i.e. the ratio of the power at the unselected output port over the total input power in a switch element. $X_{adj}$ represents adjacent wavelength or channel rejection ratio, is the fraction of power leakage from a wavelength to the adjacent wavelength due to the non-ideal channel isolation of the optical filters in the demultiplexer. In this work, only the first order switch induced in-band crosstalk is considered because the higher order crosstalk is insignificant and hence neglected. The term $P_p(t, k, \lambda_j)$ is the power of the $t$th signal for the path $P$ at $\lambda_j$ that contributes to the in-band crosstalk at the input of the demultiplexer at the $kth$ node. $T_{k}$ is the number of such demultiplexer crosstalk sources at the $kth$ node and $B_o$ is the optical bandwidth.

$$P_{\text{noiseP}}(k, \lambda_j) = P_{\text{txP}}(k, \lambda_j) + P_{\text{aseP}}(k, \lambda_j) + P_{\text{mtP}}(k, \lambda_j)$$

(3)

In the above equation (3), $P_{\text{noiseP}}(k, \lambda_j)$ denotes the total noise accumulated at $k$th node at wavelength $\lambda_j$ for path $P$, which is the summation of $P_{\text{txP}}(k, \lambda_j)$, $P_{\text{aseP}}(k, \lambda_j)$ and $P_{\text{mtP}}(k, \lambda_j)$. When the node $k$ is the egress or the destination node, the equation is rewritten as below.

$$P_{\text{noiseP}}(\lambda_j) = P_{\text{txP}}(\lambda_j) + P_{\text{aseP}}(\lambda_j) + P_{\text{mtP}}(\lambda_j)$$

(4)

In the equation (4), $P_{\text{noiseP}}(\lambda_j), P_{\text{txP}}(\lambda_j)$, $P_{\text{aseP}}(\lambda_j)$ and $P_{\text{mtP}}(\lambda_j)$ represent the total noise power, switch crosstalk power, ASE noise power and demultiplexer crosstalk power at the destination node at wavelength $\lambda_j$ for the path $P$ respectively.

Optical signal to noise ratio at the destination node is described as below.

$$\text{OSNR}_{\text{dp}}(\lambda_j) = \frac{P_{\text{signalP}}(\lambda_j)}{P_{\text{noiseP}}(\lambda_j)}$$

(5)

**Table 1: (System parameters used in the Model)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>1550.92-1556.55(8-Channel)</td>
</tr>
<tr>
<td></td>
<td>1544.53 to 1556.55(16-Channel)</td>
</tr>
<tr>
<td></td>
<td>1544.53 to 1569.59(32-Channel)</td>
</tr>
<tr>
<td>Number of Wavelength</td>
<td>Eight, Sixteen, Thirty-two</td>
</tr>
<tr>
<td>Channel spacing (nm)</td>
<td>0.8</td>
</tr>
<tr>
<td>Channel bit rate (B)</td>
<td>40 Gbps</td>
</tr>
<tr>
<td>Signal power per channel (mW)</td>
<td>1</td>
</tr>
<tr>
<td>Electronic bandwidth (B_e)</td>
<td>30 GHz</td>
</tr>
<tr>
<td>Optical bandwidth (B_o)</td>
<td>90 GHz</td>
</tr>
<tr>
<td>ASE factor ($\eta_{sp}$)</td>
<td>1.5</td>
</tr>
<tr>
<td>Multiplexer loss (L_{mx})</td>
<td>-4 dB</td>
</tr>
<tr>
<td>Demultiplexer loss (L_{dm})</td>
<td>-4 dB</td>
</tr>
<tr>
<td>Switch loss (L_{sw})</td>
<td>-8 dB</td>
</tr>
<tr>
<td>Fiber loss (L_f)</td>
<td>-0.2 dB/km</td>
</tr>
<tr>
<td>Input EDFA gain (G_{in})</td>
<td>18 dB</td>
</tr>
<tr>
<td>Output EDFA gain (G_{out})</td>
<td>14 dB</td>
</tr>
<tr>
<td>Loss of tap (L_{tap})</td>
<td>-1 dB</td>
</tr>
<tr>
<td>Switch crosstalk ratio (X_{sw})</td>
<td>-30 dB</td>
</tr>
<tr>
<td>Adjacent wavelength rejection ratio (X_{adj})</td>
<td>-30 dB</td>
</tr>
<tr>
<td>Fiber PMD Parameter (D_{PMD}(k))</td>
<td>0.13 ps/(km)${}^{1/2}$</td>
</tr>
<tr>
<td>Fiber Pulse broadening (\delta)</td>
<td>0.1</td>
</tr>
<tr>
<td>OSNR threshold</td>
<td>13.09 dB (for BER=10^{-12})</td>
</tr>
</tbody>
</table>
In the above equation (5), $\text{OSNR}_{dp}(\lambda_j)$ represents the optical signal to noise ratio at the destination node at the wavelength $\lambda_j$. Similarly, $P_{\text{signaldp}}(\lambda_j)$ denotes the signal power at the destination node at the wavelength $\lambda_j$ for the path $P$. Table-1, above furnishes details of system parameters used in the proposed network model.

4. PROPOSED ALGORITHM

The M-Code is developed for the proposed algorithm FCD-QoT-RWA on the basis of the following steps as written below.

a. Connection Matrix is created for the topology, which has twenty-four (24) nodes and forty (40) bi-directional links and each link has a length in between 30 km to 100km, which are generated randomly.

b. Traffic Load is initialized to hundred-sixty (160) Erlangs on the basis of mean holding time and mean inter arrival time.

c. Source node and Destination node are generated randomly.

d. Exponential holding time is generated for the source and destination pair.

e. Five (5) paths are selected on the basis of number of hops in ascending order i.e. path with minimum number of hops to the path with maximum number of hops and maximum number of hops not exceeding seven (7).

f. M number of paths out of 5 paths is selected that satisfy the hop constraints, where the number of hops is varied from two (2) to seven (7) per path. If M is equal to zero (0) then the request is blocked and if connection request is less than $10^5$, then back to step-3, else the program is terminated.

g. N number of paths is selected out of M number of paths satisfying wavelength continuity constraint (WCC), where number of wavelengths used vary from 8 to 32 depending on the algorithm. If N is equal to zero (0) then the request is blocked and if connection request is less than $10^5$, then back to step-3, else the program is terminated.

h. The optical signal to noise ratio (OSNR), number of hops (NH) and available free channels (AFC) of each of the N path is stored.

i. P numbers of paths are selected out of N paths satisfying OSNR and PMD constraint. If P is equal to zero (0) then the request is blocked and if connection request is less than $10^5$, then back to step-3, else the program is terminated.

j. The parameter like OSNR, NH and AFC of each of the P paths are passed through fuzzy rule base system (FRBS) as the input parameters. The defuzzified value (crisp) of each of the path is stored. As per the fuzzy rule, the optimal lightpath is established between source node and destination node, on the path having minimum defuzzified value. If connection request is less than $10^5$, then back to step-3, else the program is terminated.

k. In the proposed algorithm FCD-QoT-RWA, the traffic load is kept constant and different performance metrics like mean blocking probability, mean execution time, mean OSNR and mean AFC are evaluated by fixing the number of channels for different hop count constraints which varies from two (2) to seven (7).

The proposed algorithm can be explained from the Pseudo code developed below.

Algorithm FCD-QoT-RWA (Pseudo code)

1. Connection matrix is created for the topology
2. Traffic load is set up // set up for 160 erlangs
3. hc=m; // number of Hops constraint
4. itr= $10^5$; // number of connection request
5. block = 0; // for the calculation of blocking
6. for j = 1:itr // most outer loop
7. connection request CR arrive;
8. Five paths are selected in ascending order of hops starting from minimum hops, path (i) , where I varies from 1 to 5;
9. N = 0;
10. for I = 1:5
11. if (number of hops in path (i) < m && path (i) satisfy first-fit assignment && path (i) satisfy OSNR & PMD constraint)
12. N = N + 1;
13. path (N) is stored along with the parameters OSNR, NH and AFC;
14. end
15. end
16. if (N ≥ 1)
17. for k = 1:N
18. the parameters OSNR, NH and AFC of path (k) are passed to FRBS as the input parameters;
19. path_dfuz (k) = defuzzified value of path (k);
20. end
21. path corresponding to min (path_dfuz) is selected for establishment of lightpath for the CR;
22. else
23. block=block+1; //CR is blocked
24. End
25. end

Table-2 below describes the membership function and range of the variables used in FRBS and Table-3 below, describes twenty-seven rules (27) developed for FRBS of the proposed FCD-QoT-RWA algorithm. In the above table-3, ‘E’ denotes Excellent, ‘VG’ denotes Very Good, ‘G’ denotes Good and ‘P’ denotes Poor.

For example the rule number-19 can be interpreted as “If OSNR is good and AFC is excellent and Number of Hops is very good then cost is excellent”. 

http://www.cisjournal.org
The above figure 3 shows the membership function of input variable “Number of Hops” which uses trapezoidal membership function for three linguistic variables Very Good, Good and Poor.

Table 2: (Rules developed for the proposed FRBS)

<table>
<thead>
<tr>
<th>RULES</th>
<th>OSNR (dB)</th>
<th>AFC</th>
<th>NUMBER OF HOPS</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>E</td>
<td>E</td>
<td>VG</td>
<td>E</td>
</tr>
<tr>
<td>2</td>
<td>E</td>
<td>E</td>
<td>G</td>
<td>E</td>
</tr>
<tr>
<td>3</td>
<td>E</td>
<td>E</td>
<td>G</td>
<td>E</td>
</tr>
<tr>
<td>4</td>
<td>E</td>
<td>VG</td>
<td>VG</td>
<td>E</td>
</tr>
<tr>
<td>5</td>
<td>E</td>
<td>VG</td>
<td>G</td>
<td>VG</td>
</tr>
<tr>
<td>6</td>
<td>E</td>
<td>VG</td>
<td>P</td>
<td>VG</td>
</tr>
<tr>
<td>7</td>
<td>E</td>
<td>G</td>
<td>VG</td>
<td>VG</td>
</tr>
<tr>
<td>8</td>
<td>E</td>
<td>G</td>
<td>G</td>
<td>VG</td>
</tr>
<tr>
<td>9</td>
<td>E</td>
<td>G</td>
<td>P</td>
<td>G</td>
</tr>
<tr>
<td>10</td>
<td>VG</td>
<td>E</td>
<td>VG</td>
<td>E</td>
</tr>
<tr>
<td>11</td>
<td>VG</td>
<td>E</td>
<td>G</td>
<td>VG</td>
</tr>
<tr>
<td>12</td>
<td>VG</td>
<td>E</td>
<td>P</td>
<td>VG</td>
</tr>
<tr>
<td>13</td>
<td>VG</td>
<td>VG</td>
<td>VG</td>
<td>VG</td>
</tr>
<tr>
<td>14</td>
<td>VG</td>
<td>VG</td>
<td>G</td>
<td>VG</td>
</tr>
<tr>
<td>15</td>
<td>VG</td>
<td>VG</td>
<td>P</td>
<td>G</td>
</tr>
<tr>
<td>16</td>
<td>VG</td>
<td>G</td>
<td>VG</td>
<td>VG</td>
</tr>
<tr>
<td>17</td>
<td>VG</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>18</td>
<td>VG</td>
<td>G</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>19</td>
<td>G</td>
<td>E</td>
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<td>20</td>
<td>G</td>
<td>E</td>
<td>G</td>
<td>VG</td>
</tr>
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<td>21</td>
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<td>P</td>
<td>VG</td>
</tr>
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<td>G</td>
<td>VG</td>
<td>VG</td>
<td>VG</td>
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<tr>
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<td>G</td>
<td>VG</td>
<td>G</td>
<td>VG</td>
</tr>
<tr>
<td>24</td>
<td>G</td>
<td>VG</td>
<td>P</td>
<td>G</td>
</tr>
<tr>
<td>25</td>
<td>G</td>
<td>G</td>
<td>VG</td>
<td>VG</td>
</tr>
<tr>
<td>26</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>P</td>
</tr>
<tr>
<td>27</td>
<td>G</td>
<td>G</td>
<td>P</td>
<td>P</td>
</tr>
</tbody>
</table>

5. SIMULATION RESULT AND ANALYSIS

In this work, a MATLAB Version of 7.5 with Intel (R) Core-Duo CPU (3.3 GHz) is used for simulation.

Figure 4: Topology used in the proposed network model [22]

In this paper, a 23 node topology is used as shown in figure 4, which has 40 bi-directional links [22]. Network or traffic load in the proposed model indicates the duration of time a network remains busy and is defined as mean arrival rate $\lambda$ mean holding time of connection requests. It is measured in erlangs. Mean blocking probability is defined as the number of requests blocked divided by total number of requests processed. A connection request is said to be blocked when a wavelength continuous route is not found. Mean execution time is estimated as the total simulation time divided by total number of requests processed. The experiment is carried out with fuzzy controlled mechanisms (with FLC). Exponential holding time and First-fit (FF) wavelength assignment technique is used to estimate different network related QoT parameters. Following steps are carried out for the proposed FCD-QoT-aware-RWA. The algorithm is simulated at a single network load i.e. 160 erlangs and for 100000 call requests. The mean holding time is fixed at 2 and means arrival rate is fixed at 80 to meet the desired network load condition. Different network related QoT performance metrics are evaluated for different number of hops. Each of these network parameters is plotted versus number of hops with exponential holding times and FF wavelength assignment technique. Figures below show the details of the simulation results.

Table 3: (Details of variables for the proposed FRBS)

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Range (per path)</th>
<th>Membership function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 OSNR (dB)</td>
<td>Input</td>
<td>13-30</td>
<td>Trapezoidal</td>
</tr>
<tr>
<td>2 Available Free Channel</td>
<td>Input</td>
<td>1-8(8-Channel) 1-16(16-)</td>
<td>Trapezoidal</td>
</tr>
</tbody>
</table>

The figure 5 below exhibits the graph of mean blocking probability vs. Number of hops at fixed traffic load of 160 erlangs with exponential holding time and first-fit wavelength assignment technique for different number of channels (8, 16 and 32). The mean blocking probability is high for all the channels, at lower hop count, but when the hop count exceeds four the mean blocking probability gradually decreases and it is lowest when the...
number of channels is fixed at 32 (32-wavelengths) and highest when the number of channels is fixed at 8 (8-wavelengths). It is difficult to achieve wavelength continuity for establishment of lightpath when the number of wavelengths is assumed to be eight. Therefore, the mean blocking probability is highest when the number of wavelengths is fixed at eight.

**Figure 5:** Mean blocking probability (BP) vs. Number of hops at traffic load of 160 erlangs with exponential holding time and first-fit wavelength assignment policy for different number of channels

The figure 6 shows the graph of mean execution time vs. Number of hops at fixed traffic load of 160 erlangs with exponential holding time and first-fit wavelength assignment technique for different number of channels (8, 16 and 32). Establishment of lightpath takes more execution time when the number of wavelength equals to 32 because the number of paths established are more when the number of wavelengths are equal to 32. Therefore, the mean execution time is more at higher wavelengths.

**Figure 6:** Mean execution time (ET) vs. Number of hops at traffic load of 160 erlangs with exponential holding time and first-fit wavelength assignment policy for different number of channels

The number of channels (8, 16 and 32). As is obvious, the AFC is more at higher number of channels in comparison to the lower number of channels. AFC is dominant input variable to the FRBS. The AFC plays an active role in the reduction of mean blocking probability.

**Figure 7:** Available free channels (AFC) vs. Number of hops at traffic load of 160 erlangs with exponential holding time and first-fit wavelength assignment policy for different number of channels

The figure 8 displays the graph of mean optical signal to noise ratio (OSNR) vs. Number of hops at fixed traffic load of 160 erlangs with exponential holding time and first-fit wavelength assignment technique for different number of channels (8, 16 and 32). OSNR depends on the number of hops present in the lightpath. At lower hop number i.e. when the hop count constraint is high the mean OSNR is high in contrast to higher hop number. The OSNR is higher when the numbers of channels are fixed at 8 in comparison to 16 or 32 as the average hop count is lower for both the channels. When the number of hops exceed 3.5, network with 32 wavelengths possess higher OSNR than 16 wavelengths.

**Figure 8:** Mean optical signal to noise ratio (OSNR) vs. Number of hops at traffic load of 160 erlangs with exponential holding time and first-fit wavelength assignment policy for different number of channels

The figure 9 shows the surface of the output COST (in Z-Axis) vs. input OSNR (in X-Axis) and FCA (in Y-Axis), fixing the third input, Hop-Count at six (6) for channel-32. It is observed that when FCA increases
the COST decreases although OSNR at low value, which is in accordance with the fuzzy rules as the rules, emphasizes maximum to FCA then to Hop-Count and least to OSNR. Minimum value of output is obtained at highest value of FCA (32) and highest value of OSNR (30), which is compatible with the fuzzy rules.

Figure 9: 3D- plot of input variables (OSNR & AFC) vs. output variable (COST) fixing third input variable Number of Hops at six (6)

6. CONCLUSION
The proposed FCD-QoT-RWA with hop constraint is a powerful and efficient algorithm. The algorithm verifies the parameters associated with the paths like OSNR, AFC and average hop count through fuzzy rule base system (FRBS) and then establishes the optimal lightpath. The OSNR of the lightpath is improved by sacrificing certain blocking probability when the hop count constraint is included in the algorithm. Not imposing hard hop count constraint, improvement in OSNR is possible by not hampering much to the blocking probability. The performance metrics of the proposed algorithm are found better as compared to the DRWA problem based on evolutionary programming or signaling-based optical control plane(S-OCP) Daisy network [3], [23].

ACKNOWLEDGEMENT
The authors would like to extend their sincere appreciation to the All India Council of Technical Education (AICTE) for the funding of this research through the research project number. 20/AICTE/RIFD/RPS (POLICY-II) 2/2012-13.

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