ALGORITHM TO SOLVE THE RWA PROBLEM IN WDM ALL-OPTICAL NETWORKS

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ALGORITHM TO SOLVE THE RWA PROBLEM IN
WDM ALL-OPTICAL NETWORKS

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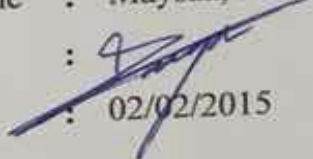|	
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ABSTRACT

ALGORITHM TO SOLVE THE RWA PROBLEM IN WDM ALL-OPTICAL NETWORKS

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In this thesis, Multi-Node Optimized Ant Colony Algorithm (M-NOACA) proposed and implemented to solve the routing and wavelength assignment problem in all-optical networks (with/without wavelength conversion) by simulating traffic with the routing and wavelength assignment (RWA) algorithms on all-optical WDM networks. A performance study will be apply to study the optimization problem of the routing and wavelength assignment under two cases of traffic; the *static* (offline) and *dynamic* (online) traffic by computing blocking probabilities, and the allowed load. With a comparison to show the performance and behavior of the network to approximate most of the possible traffic probabilities in the network by using a new methods and algorithms in addition with the classic algorithms. Determining an optimum set of parameters for an ant-based algorithm to achieve the best

performance remains an open problem, in this research, a deep study is done to introduce a new contribution to obtain the optimal setting of Ant Colony parameters.

ÖZ

TÜM WDM OPTİK AĞLARINDAKİ RWA PROBLEMLERİNİN BİR ALGORİTMA İLE ÇÖZÜMÜ

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Bu çalışmada, tüm optik ağlardaki (dalga boyu dönüşüm olsun ya da olmasın) dalga boyu atama problemine karşı, trafik similasyon modeli ve çok düğümlü karınca kolonisi optimizasyonu algoritması ile çözüm önerilmiş ve uygulanmıştır.

Bu performans çalışması; Trafik engelleme olasılıkları ile izin verilen yükü hesaplayarak trafiğin iki durum altında -Statik (çevrimdışı) ve dinamik (çevrimiçi)- yönlendirilmesi ve dalga boyu atama optimizasyon sorununu incelenmesi için uygulanacaktır. Bir karşılaştırma sonucunda klasik algoritmaların yanında yeni yöntemler ve algoritmalar kullanarak ağda bulunan muhtemel trafik olasılıkların en yaklaştığı ağ performansları ve davranışları gösterilecektir. Bu çalışmada karınca temelli algoritma ile açık problem karşısındaki en iyi performans ve en ideal

parametre setleri belirlenecektir. Daha derin bir çalışma ise Karınca Kolonisi Parametrelerinden en uygun ayarı elde etmek ve yeni bir katkı sağlamak için yapılacaktır.

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LIST OF ABBREVIATIONS

AON   All Optical Networks

ACO   Ant Colony Optimization

ADMs   Add-Drop Multiplexers

ATM   Asynchronous Transfer Mode

BBUs   Baseband Units

BRASs   Broadband Remote Access Servers

CDMA   Code-Domain Multiple Access

C-RANs   Cloud Radio Access Networks

CPRI   Common Public Radio Interface

CWDM   Coarse Wavelength Division Multiplexing

CD   Chromatic Dispersion

DLE   Dynamic Lightpath Establishment

DRCL   Distributed Relative Capacity Loss

DWDMs   Dense Wavelength-Division Multiplexers

DSF   Dispersion-Shifted Fiber

DSSM   Dispersion-Shifted Single-Mode

DFSM   Dispersion-Flattened Single Mode

DRCL   Distributed Relative Capacity Loss

ECC   Embedded Communications Channel

EDFAs   Erbium Doped Fiber Amplifiers

FWM   Four-Wave Mixing

FDMA   Frequency Domain Multiple Access

GRWA   Grooming Routing and Wavelength-Assignment

GA   Genetic Algorithm

HFC   Hybrid Fiber Coaxial

ILP   Integer Linear Programming

LED	Light-Emitting Diode
LTE-A	Long Term Evolution Advanced
MOACO	Multi Objective ACO
MMF	Multimode Fiber
NOC	Network Operations Center
OACA	Optimized Ant Colony Algorithm
OIF	Optical Internetworking Forum
OC	Optical Carrier
OLT	Optical Line Terminations
PMD	Polarization-Mode Dispersion
PDL	Polarization-Dependent Loss
POF	Plastic Optical Fiber
PONs	Passive Optical Networks
RWA	Routing and Wavelength-Assignment
SDH	Synchronous Digital Hierarchy
SMF	Single Mode Fiber
SCM	Subcarrier Multiplexing
SLE	Static Lightpath Establishment
SA	Simulated Annealing
SPF	Shortest Path First
SDH	Synchronous Digital Hierarchy
SONET	Synchronous Optical Network
TDM	Time Division Multiplexing
TDMA	Time Domain Multiple Access
WDM	Wavelength-Division Multiplexing

LIST OF SYMBOLS

Symbols

N	No of Nodes
n	Node İndex
s	Source Node İndex
d	Destination Node İndex
k	Next Hop İndex
W	No of Available Wavelength
w	Wavelength İndex Per Link With $w = 1,..,W$
r_{n,d_k}	Probability of Node n To Reach Destination d Using Next Hop k
S_w	The Wavelength Set Where W is the Total Number of Wavelengths Per Link
$\emptyset$	A Scalar Parameter to Reflect the Emphasis of Rout Length or Wavelength
A	Pheromone Parameter to Reflect the Emphasis of Rout Length or Wavelength on Pheromone Trail
B	Pheromone Parameter to Control Rout Length
Γ	Pheromone Parameter to Control Wavelength
Dr	Pheromone Amount in Routing Table
Dl	The Contribution of Rout Length in Pheromone Trail
dw	The Contribution of Wavelength in Pheromone Trail
μ	Service Rate
T	No of Sessions

CHAPTER 1

INTRODUCTION

1.1 Background

 "All Optical Networks (AON) have become an efficient mean to fulfill the tremendous demand of bandwidth due to huge increase of internet traffic. WDM (Wavelength-Division Multiplexing) is used in optical fiber networks to achieve the client's ever-increasing bandwidth loads" [1].

Wavelength Division Multiplexing (WDM) is "the most dominant methodology to achieve the dramatic increase in the massive loads in optical network which overshoots the congestion of electronic without deploying new links. The concept of a wavelength-routed WDM network depends on connecting end users with the WDM channels. These channels are often pointed to as light-paths. A wavelength-routed network is depicted in Fig. 1 We can see in this figure how to set up lightpaths between each access nodes pairs on distinct wave-lengths" [2].
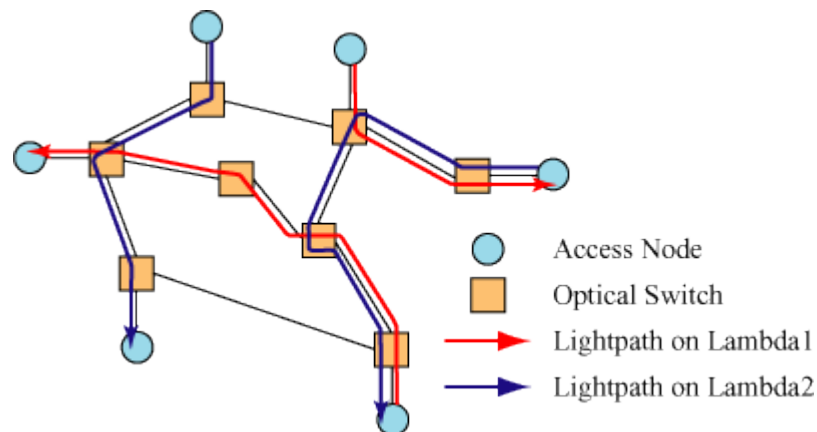
Figure 1 A wavelength-routed optical WDM network.

A lightpath can span multiple fiber links. In order to convert from wavelength to another through traverse the lightpath, the wavelength converter should be existed.

The absence of wavelength converters leads to inability to change the wavelength and the lightpath will use the concept of wavelength-continuity constraint which reserve the same wavelength on all the fiber connections.

One of challenge of All-optical network and wavelength-routed WDM network is how to set up the lightpaths and suitable choice of routing algorithms as well as the wavelength assignment for each connection.

"There are three types of connection requests: static, incremental, and dynamic" [3]. If the internal group of connections is definding before, the traffic is called static. The problem of static traffic is minimizing network resources in terms of wavelength and optical fibers when seting up lightpaths for these connections. The Static Lightpath Establishment (SLE) problem is the main problem in RWA for static traffic.

The second type of connection request is called of incremental-traffic. In this scenario, the connections are sequentially increased. For eah connection, a lightpath is setted up and maintained indefinitely. Finally, as the traffic arrives, a lightpath is established and released after session termination.

The target is the mechanism of knowing how to establish lightpaths and how to assign wavelengths with taking into account minimizing the blocking probability of connections request, or maximizing the number of established connections in the network which is kown as the DLE (Dynamic Lightpath Establishment) problem.

In the RWA, the establishing of light-path is performed by choosing the rout of a physical link between the transmitter and reciever edge nodes, then packing a certian wave-length on all links for the lightpath. So in WDM networks there are two sub problems to deal with. The first is the selection of the path (Routing) and the second is the allocating the available wavelengths for the connections (Wavelength Assignment).

The two sub problems provide one composite problem which is well known as RWA problem [4].

To decrease the processing complexity, RWA problem is solved in a two processes [5]:

- First, a lightpath orginated from the source to the destination node is choosed using a routing algorithm.
- Second, a free wavelength on the chosen path is determined using a wavelength-assignment algorithm.

constraints of RWA problem [5]:

- **Wavelength continuity-constraint**: the same wavelength is used on all connections along the full path from the source to the destination.
- **Distinct wavelength-constraint:** separate wavelengths are assigned for all light paths using the same fiber link.

These constraints provide additional complexity in analysis and model.

If there are not free wavelengths available on any link, the connection can not be established and as a result the arrived request will be rejected.

The blocking probability is calculated as in the following equation:

$$B.P = \frac{the\ number\ of\ call\ requests\ rejected}{the\ number\ of\ call\ connections\ requested} \tag{1.1}$$

"The performance of all-optical network is evaluated by metrics of blocking probability. The blocking probability is taken as a performance metrics in comparing different routing algorithms as well as various wavelength assignments. The blocking probability occurs when there are no available resources for the connections request. Therefore algorithm which have the minimum blocking is the best one regarding the performance" [6].

Three of the important wavelength assignment algorithms are the following:

- **Random wavelength assignment** [6]: Two steps are adopted here; the first one is to determine the wavelength set that is available on the designated route by scanning the wavelengths space. The second step is to pick randomly one available wavelength among the wavelengths set.

- **First fit wavelength assignment** [6]: all wavelengths are marked with predefined number. A wavelength that has lower number is selected before a higher-one while scanning for available wavelengths. The first lower order wavelength is then reserved. In this scheme, the idea is scroll the assigned wavelengths toward the lower end of the scanning domain. This make the selection probability from the scanning domain higher end large. This scheme has small computational overhead, so it is suited in practice. In addition it performs well in terms of fairness and blocking probability

- **Wavelength conversion assignment** [6]: each arriving light-path in the input side can package any wavelength on the output side. Wavelength continuity-constraint is eleminated.

İn the following we will introduce some routing algorithms that proposed in the literature.

- **Static routing algorithms:** If the entire set of connections is known in advance, the traffic is called static. The problem of static traffic is minimizing network resources in terms of wavelength and optical fibers when seting up lightpaths for these connections. The SLE (Static Lightpath Establishment) problem is the main problem in RWA for static traffic.

- **Adaptive routing algorithms:** connection requests arrive sequentially. Each connection is a stone for establishing a light apath; and this lightpath is maintained in the network indefinitely.

- **Dynamic routing algorithms:** here, for each arriving connection request a lightpath is established, and it is released after a determined epoch of time. The aim in the dynamic routing algorithms is solve the problem of establishing light paths and wavelengths assignment. Also the target is to generate a solution with foucing on minizing the blocking probability.

1.2 Related Work

In order to make the RWA Problem easier in analsis and solution, two subproblems "routing and wavelength assignment" are proposed to solve it suboptimally. For each one a separate solution is proposed. There are Heuristics methods which can be used to solve each one of them.

In the literature, there are several methods regarding the routing problem like: fixed routing mechnasim, fixed-alternate routing algorithm and adaptive routing algorithm [8-9]. Regarding the implementation simplicity, fixed routing technique is the best choice. On contrast, regarding the adaptability, the adaptive routing algorithm will be the best choice. Finally the alternate routing is a compromise choice regarding performance and complexity.

Also there are several heuristic methods regarding the wavelength-assignment problem have been proposed like: First-Fit, RWA, Least-Used, Most-Used, Least Loaded, MAX-SUM, Wavelength Reservation, Relative Capacity Loss and Protecting Threshold.
The objective of many researches which have been done on RWA problems is the minimization of the blocking probability.

Vishal Anand and Chunming Qiao [10] discuss the RWA in wavelength routed optical WDM networks with circuit switching using conversion of wavelength. Sun et al. [11] proposes a new mthodology for the analysis of performance of AON which use the first fit algorithm for wavelength assignment. To calculate the blocking probability of a source destination pair, the author analyzes the wave-length usage on the links, taking into account load correlation and wavelength correlation between links. This "model is accurate even in a system with large number of wavelengths" [11]

Vitthal J. Gond and Aditya Goel [12] addressed wavelength conversion technique to reduce blocking probability in wave-length routed networks. Because the wavelength conversion factor increases, "the blocking probability of traffic requests decreases.

The author in the previous work study the evaluation of RWA network with different wavelength converters, different traffic types which are carried out and results are shown that the blocking probability is minimum with 50% to 60% wavelength convertible nodes." [12]

Amrinder S.Arora and Suresh Subramaniam [13] addressed "the problem of optimally placing a limited number of wavelength converters in mesh topologies. Two objective functions, namely, minimizing the average blocking probability and minimizing the maximum blocking probability over all routes, are considered. In the first part of" [13] their paper, they "extend an earlier analytical model to compute the blocking probability on an arbitrary route in a mesh topology, given the traffic and locations of converters. Then propose heuristic algorithms to place wavelength converters, and evaluate the performance of the proposed" [13] heuristic using the analytical model.

Awwad et al. [14] "consider the RWA problem with traffic grooming (GRWA) for mesh networks under static and dynamic lightpath connection requests" [14]. "They propose an integer linear programming (ILP) model that accurately depicts the GRWA problem". [14]

Keyao Zhu and Biswanath Mukherjee [15] "investigate "the traffic-grooming problem in a WDM-based optical mesh topology network". [15] Their "objective is to improve the network throughput" [15] and "study the node architecture for a WDM mesh network with traffic-grooming capability. A mathematical formulation of the traffic-grooming problem is presented in this study and several fast heuristics are also proposed and evaluate". [15]

Mathematical models in WDM network is complex in nature. Some literatures have proposed mathematical models for the networks with wavelength conversion. In general, a network with the wavelength converters has a better performance in terms of call blocking performance than a network without wavelength converters.

"Saha and Sengupta proposed "a solution to the Virtual Static Topology Design using a simple *Genetic Algorithm* (GA), optimizing the weighted sum of the generated traffic and the hop count, among other objectives, considering wavelength continuity constrains" [16].

"Another work of Banerjee et al. presented a GA for the simultaneous optimization of the total wavelength count and the average delay, considering the wavelength continuity constraint and wavelength conflicts" [17]. On the other hand, Ant Colony Optimization (ACO) algorithms are "inspired by the behavior of ant colonies searching for food.ACO has been established as a valid alternative in the resolution of hard combinatorial optimization problems" [17].

Thus, Varelaand "Sinclair proposed a single-objective ACO approach for the routing problem, while the wavelength assignment was treated using a greedy method. This ACO approach minimizes the required number of different wavelengths (Network Wavelength Requirement or NWR) to allocate all unicast requests on a given optical network" [18].

Insfrán et al. recently treated "the RWA problem with two Multi Objective ACO (MOACO) algorithms, *MOACS and M3AS*, optimizing the hop count and the number of wavelength conversions" [18]. "However, a lot of work may be still needed in this area given the great variety of highly competitive MOACO algorithms that may be considered for this kind of hard Problems" [19-22]. "The MOACO algorithms were compared with classical routing and wavelength heuristics like Shortest Path (SP), K-Shortest Path (K-SP)" [22].

AntNet [23] "is an adaptive agent-based routing algorithm in which the paths are determined and computed with the help of forward and backward ant agents. The rationale behind using the two-way agents is to help the forward ants utilize the useful information gathered by the backward ants on their round trip between source and destination" [23].

In [24] "ACO-based algorithms are firstly used to solve RWA for optical networks and many additional works in" [25] and [26].

The basis of the ACO-based RWA algorithm depends on launching ants then it forwarded through the optical network to establish the connection request. Finally through their trips ants put trails ont the selected path to help the follower ants to optimally find paths of the network. Using these trails become less attractive over time due to pheromone evaporation property which make the trails disappear. Pheromone evaporation has a great role in avoiding the convergence and also helps to dynamic network exploration. In addition, evaporation helps to aviode stagonation which happens if all ants follow the same paths chosen by first ant.

Extensive research has focused in the area of RWA. In the current literature, there are problems when dealing with the complexity of the routing problem in optical WDM networks. For example, in fixed-routing protocol, there a problem in keeping it table updated with the contiuos changing in network state.

On the contrary, the adaptive RWA algorithms provide better performance in tracking the change in network; but they still centralized approach consequently they require gathering the whole topology information.

In [27], ACO based anycast algorithm to provide routing to the connection requests on optical WDM networks is presented and analysed.

We will illustrate some of the pervious algorithms later in this work and compare them from a performance and complexity point of view. Here, we introduce a ant colony algorithm called Optimized Ant Colony Algorithm (OACA), which is based on ACO and we will try to optimize their parameters and finally compare them with one the traditional routing approach.

1.3 Objectives

As mentioned in the previous sections, the routing and wavelength assignment problem is essential for achieving efficient performance in wavelength-routed WDM all optical networks.

We will use the co-operation between MATLAB and OPNET to allow MATLAB to use its strong mathematical functionality and OPNET to use its ability to manipulate simulations.

The research plan objectives are as follows:

- State-of-the-art on the proposed approaches to solve RWA in all-optical WDM networks.

- propose Multi-Node Optimized Ant Colony Algorithm (M-NOACA) to solve the RWA problem in all-optical WDM networks.

- Implement the proposed algorithm.

- Propose an optimum set of parameters for M-NOACA to solve RWA problem.

- a comprehensive evaluation by simulation using OPNET and MATLAB should be performed to validate the proposed solution.

1.4 Organization of the Thesis

This thesis contains six chapters. All the necessary information about how to solve the routing and wavelength assignment (RWA) problem in (AON) all optical networks with/without wavelength conversion can be found for different scenarios.

Chapter 1 is a background and objectives of this thesis.

Chapter 2 includes an introduction all optical networks and wavelength division multiplexing which will be used in this thesis. In addition, wavelength conversion process is introduced.

In Chapter 3, Routing and wavelength assignment strategies are studied. In addition, how to establish a virtual path is presented.

In Chapter 4, Ant colony optimization techniques and algorisms are investigated.

Chapter 5 includes the system model of optimized ant colony algorithm. Full analysis for results and finds are investigated.

Chapter 6 includes the conclusion part and future work.

CHAPTER 2

ALL-OPTICAL WDM NETWORKS

2.1 Overview

The different changes of communication " methods began to be different in the end of the twentieth century with rapid increasing of Internet usage. Because the user demands for distinct type of needs increases rapidly, therefore, it was expected that the need for network data rates and bandwidth would go after the same rule." [32]

The explosive and continuous growth in the number of servants is one of the essential causes of the huge demand for network capacity. However, " the data rates required by each individual user have been increasing dramatically too. Thus, it may be seems that servants have constant growth in number. In addition, the increasing in number of users become difficult to achieve satisfaction in terms of provided data rates, capacity or bandwidth (B.W.)." [32]

The reduction in the B.W. "cost encourages the progress of latest demanding services and applications that not only take benfet of the offered B.W. but usually ask for even more. As mentioned before, the need for more B.W. may be seem endless and usually high across all phases of networks evolution. Practically the demand for more BW capacity leads to be higher during some periods and lower in others." [32]

In addition, the data traffic growth rate is double times that of the traffic of voice per year. It may be the traffic of voice "grows at the rate of 13% annually" [32] whereas the growth of "data traffic at the rate of 7% to 20% monthly" [32]. Therfore, to support services and applications that may be require more bandwidth, less delay and less error rate we should employ networks that can fit the requirements.

Optical fibre was " basically used for transmission and simply may be used to provide high capacity. Then, the optical fiber became used to provide less bit error rates and more capacities than all copper cables. Although the optical fiber gives us with links that have the needed properties, network BW is limited by nodes processing speed. As the nodes processing must be done electronically. Therefore, the optical signal which carried on the fiber should be transformed to an electronic signal, then sginal processing occurs at low electronic speeds and finally the siganl converted back to the optical signals for re-transmission over the optical fiber." [1]

SONET (synchronous optical network) "consider the best examples of the 1st generation optical network. Synchronous Digital Hierarchy (SDH) networks form the core of the telecommunications infrastructure in North America, Europe and Asia. The second generations of optical networks have many features like routing, switching, and intelligence in optical layer" [1].

2.2 Optical Networks

"Optical networks are huge range routing networks that depend on optical Technologies and peripherils that supporting transmitting, grooming and recoverying at the wavelength level" [24]. In an AON, "data is conveyed in the optical form from the source to the destination with no optical-to-electrical transformations. Optical internetworking, as described and explained by the Optical Internetworking Forum (OIF), is an effective data network framwork in that switches and routers have combined optical interfaces and are strightly connected by fiber or optical interfaces [32]. In the last years, "optical signals might just transmit data for a defined space before the signal debased to the point which is to be changed to electrical form to be reestablished. The operation was so costly because it included complicated operations at the optical and electrical layers, latest technologies for instance, optical amplifiers and dense wavelength division multiplexers have decreased requesting for electrical regeneration, that saving money [2]." [32]

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The traffic for establishing a lightpath "between the transmitter node and the reciever node (t-r pair) can reach at random to the network, and need a random length of service time. The number of hops may change with the topology of the network"[28].

Establishing the traffic for "long lightpath sustain increasing in blocking probability than establishing the traffic for short lightpath. Because the no. of sessions interfered on apath leads to increase with the number of hopsin an AON. Data is transmitted in the optical compose (form) from source to destination with no optical to electrical conversions. Optical inter-networking, according to OIF (the Optical Internetworking Forum) definition, is a data optimized network infrastructure such that routers and switches have integrated optical interfaces. They are connected directly by fiber or the interfaces of optical such as DWDMs (dense wavelength-division multiplexers)." [28].

Optical signals "in the past could carry information just for a restricted distance. This process was costly because its complex processing involved either at the optical or at the electrical layers. Latest technologies such as DWDM (Dense Wavelength Division Multiplexers) and optical amplifiers have diminutive the requirment for electrical re-generation and saving long distance charges millions of dollars." [32]

By considering "the state of the art in all-optical processing technology and given analog engineering constraints, the notion of even national or global all optical networks is not practical operation.In detail, opto electronic tranformation may be need in optical network itmes to block the aggregation of transmission impairmentsthat result from such attributes as non linearities and fiber chromatic dispersion, cascading of non ideal flat gain amplifiers, optical signal cross talk, and transmission spectrum narrowing from cascaded non flat filters" [29-30].

2.2.1 Benefits of Optical Networks

Various causes are pushing the demand for the optical networks. There are some of important factors that driving the migration to optical networks:

Capacity of Fiber: "The 1st design of what has emanated as the optical network started on routes that have limitation on fiber. Requirments for more speed and data

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rates grew. All service providers are needed more bandwidth between their sites, but higher data rates was not available. The only and available options in these situations were to setup more fiber, or increase the rate of TDM (time division multiplexing) signals on the same fiber, which has a certain limit for speed. With Wave Division Multiplexing (WDM) we can create many virtual fibers on a single physical fiber. This achevied by submitting eachsignal at a different frequency (wavelength), network service providers may send more signals on singl fiber just as though they were each transmitting on its own fiber" [21]. Therefore, increasing the fiber capacity by the number of frequencies (wavelengths) sent without adding more fiber to the existing one.

Capability of restoration: "Any network depends on more than one layer. Usually each layer has its own built in protection mechanisms, independent of the other layers. Two reasons for the rule mentioned before. First one stated that each layer is supposed to work with a different of other layers above and below it [32]. "The second reason, every layer is sometimes sophisticated and standardized by a certain group of people" [31].

More network elements used by network planners to increase fiber capacity. a massive implications can be satisified by a fiber cut. Each network element performs its own restoration in current electrical architectures. "A fiber cut would initiate many failures for a WDM system with many channels on a single fiber, causing multiple failures of independent systems. Optical networks can do protection switching faster and more economically by using restoration in the optical layer rather than the electrical layer." [29]

"A simple switch system interconnecting two different routed fibers in a single WDM system can take care of the restoration, instead of each SONET link running over a WDM link taking care of the restoration by itself. In addition, the optical layer that currently does not have a protection scheme can provide restoration in networks." [31]

Cost Reduction: With the progress of EDFAs (Erbium Doped Fiber Amplifiers) the cost is very much indeed decreased as it remove the process of O E O conversion at uniform intervals. In ADMs (Add-Drop Multiplexers) Optical Network, the required channels are added and dropped despite of the other channels don't go through any conversion.

"The wavelengths which add or drop traffic at a certain site may be needed compatible electrical node transformation. The other channels may be simply passing through optically. This provides various cost savings in network management and equipment. Additionally, avoiding the high cost of electronic cross connects and simplifing network management, by performing space and wavelength routing of traffic." [32]

Services of Wavelength: the ability to resell bandwidth rather than fiber is considered one of the great revenue-producing aspects of optical networks. SPs (Service providers) "could improve revenue by maximizing capacity available on a fiber and sell wavelengths, regardless of the data rate needed." [32] "These SPs are the same bandwidth as a dedicated fiber to customers" [31].

2.2.2 Characterstics of Fiber

The characteristics of fiber optic cable compared with copper cable whcih make fiber cable much more fit for various speed of most communications [32]:

- **Bandwidth:** the capacity is too large.
- **Speed:** the speeds of Fiber optic networks may be reached Terabits.
- **Distance:** without needing to be strengthened, signals can be transmitted further.
- **Maintenance:** for maintainance, fiber optic cables may be cost much less.
- **Resistance:** the fiber cable electromagnetic noise such as radios, motors or other nearby cables is greater resistance than copper.

Functions of fiber optic cable as a (light guide), "routing the introduced light at one end of the cable through to the other end. The source of light can either be a LED (light-emitting diode) or a laser. The source of light is switched on and off, and a

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light sensitivereceiver on the other end of the cable transfers the pulses back into the digital ones (on) and zeros (off) of the original signals." [30]

If laser light shining through a cable of fiber optic, it is subject to loss of strength, primarily through dispersion and scattering of the light, within the cable itself. The more faster laser pulses, the greater the risk of dispersion. Strengtheners of Light, called repeaters, it is necessary to refresh the signal in certain services. "Some 10 billion digital bits can be transfered evry second along the link of optical fiber in a commercial network, enough to carry tens of thousands of telephone calls. Fibers of hair thin composed of two concentric layers of high purity silica glass, core and cladding, which are enclosed by a protective sheath. The rays of light modulated into digital pulses with a laser or light-emitting diodes move along the core without penetrating the cladding. To measure the cladding ability to bend light, the cladding has a lower refractive index as the light stays confined to the core [32].

The following are the three types of fiber optic cable:

1- Single mode.
2- Multimode.
3- Plastic optical fiber (POF).
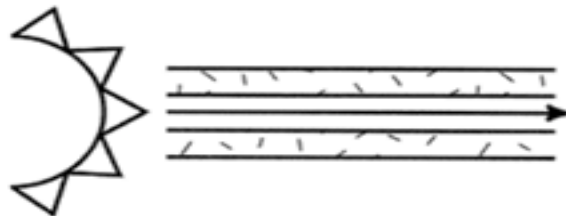
Figure 2.1 SMF

SMF (Single Mode Fiber): It is a single stand of glass fiber that "supports one mode of transmission with a core diameter of 8.3 to 10 microns.SMFs have a smalldiametercore such that only one mode is supported.SMF provides a higher and higher transmission rate and up to 50 times more distance than multimode fiber,but it may be costs more. Single mode fiber has a smaller core than multimode. Single lightwave and the small core virtually put aside any distortion that could result from overlapping light pulses and thehighest transmission speeds of any cable type.Single-mode optical fiber is an optical

fiber in which only the less order bound mode can propagate,at the wavelength of interest." [32]

MMF (Multimode Fiber): high bandwidth at high speeds over medium distances is provided by MMF.It has a larger core diameter than SMF, which allowsmultiple modes to spawn; i.e., a given wavelength (or frequency) of light hasdifferent modes along the fiber, where each mode can potentially be exploited as achannel. Some small "edge" networks already use MMF due to its lower cost compared to SMF.However, standardMMF fiber, which can support more than 100 modes, is more suitable when thereis just a single wavelength transmitted and the transmission distance is relativelyshort. Supporting a wave division multiplexing (WDM) signal with many modes per wavelength would be verydifficult to process. Ideally, the fiber capacity increases in proportion to the number of modes;this is dependent on the mode power.
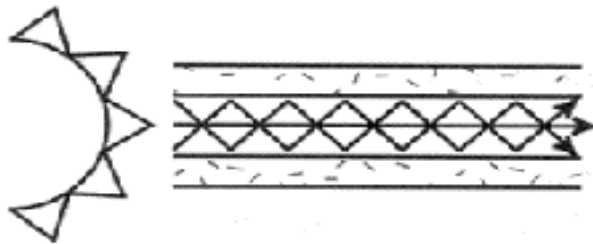
Figure 2.2 MMF.

Plastic optical fiber (POF): It is a newer plastic based cable that promises performance similar to cable glass on very short runs, but at a lower cost.

"Connectors and the equipment required to install fiber cables are very expensive than their copper counter-parts as fiber optic cable is cheaper than an equivalent length of the copper cable" [32].

2.3 WDM (Wavelength Division Multiplexing)

WDM (Wavelength Division Multiplexing) optical networks are considered the next generation networks that can meet the ever increasing demand for data rate of the end users.To support services that require high data rate (bandwidth), low delay and low error rate we must employ networks that can meet the requirements.While the

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optical fiber provides with links that have the required properties, network data-rate (bandwidth) is limited bythe processing speed of the nodes.

The cause is that the processing at the "nodes must be done electronically. I.e. the optical signal on the fiber must be transformed into an electronic signal, processed at low electronic speeds. A part from getting the network down, the electro optic conversion required to simplify electronic processing is also more expensive. The visible solution to this problem is to build networks in which the signals are processed in the domain of optical. Like AON (all-optical networks)" [1].

2.3.1 WDM History

A number of relevant milestones are enabled the development toward commercial WDM transport systems as the common basis of all metropolitan area,regional, national, and international telecommunications networks. [33]:

- 1960: Developing of laser.
- 1966: Kao and Hockham were described the dielectric waveguides as a potential means for data transmission.
- 1970: Low loss optical fiber produced (about 20 dB/km).
- 1976: InGaAsP diode laser for 1300 nm window.
- 1978: Low loss single mode fiber (0.2 dB/km).
- 1978: developing of experimental WDM systems.
- 1987: EDFA (Erbium-doped fiber amplifier).
- 1995: Availablility of commercial WDM systems

The previous milestones were escorted by "the developing of ever improved components like diode lasers for the 1550 nm window and various types of single mode fibers. Immense speed single-mode fiber transmission begun in 1981 with one route transmission; because there were sufficient availble semiconductor diode lasers. Chromatic dispersion was steady degradation impact for lately fiber transmission, limiting maximum reach." [33]

"Moreover, the field about 1300 nm had smallest fiber extenuation for wavelengths smaller than the waterpeak absorption field. The next step for single-route transmission was to adjust the fields of lowest CD and lowest fiber extenuation to further augment reach, especially for the oncoming 10 Gb/s transmission. Since fiber extenuation is essentially a material characteristic which cannot be affected extremely for silica fibers, the field of lowest CD had to be moved to ~1550 nm to adjust both parameters. CD can be altered since it based on both the material and geometry characteristics. Thus, it can be altered by designing a sufficient radial refractive index profile. This had done about 1990, and the outcome is the so-called DSF (dispersion-shifted fiber) frequently introduced to as DSSM (dispersion-shifted single-mode) fiber too. The distribution of DSF badly frustrated with the employment of first WDM systems. The error was happened by transmitting a few WDM channels about 1550 nm, at near to zero CD. The EDFA, that had meantime been created and that changed long reach fiber transmission, allowed long transparent link lengths more than 600 km. With increasing transparent link lengths and increasing total and per-channel fiber launch." [33]

"WDM transmission issue on fibers with near to zero CD then cause to the development of a group of adjusted single-mode fibers. These fiber designs, defined as NZ-DSF (nonzero dispersion-shifted fibers) or DFSM (dispersion-flattened single-mode) fibers put up with the thought to supplying nonzero yet smaller than that in SSMF to decrease the linear and nonlinear distortions. The second generation WDM systems could accomplished roughly the same largest reach that was still restricted in the 600 km range on SSMF and NZ-DSF.With transparent reach expanded into the ultra-long-haul domain and the techniques for optical CD restitution having been sophisticated during the 1990s, it appeared that nonlinear disfiguration were still the commanding reach limitation". [34]

This will cause the developing of some NZ-DSF with growing. At last, "with the product of translucent reach and total capacity on the one hand number of WDM channels, it became that in the existence of nonlinearity, SSMF with their high CD are the peak choice of silica fibers." [34].

Disorderly new fiber forms are probable desired by farther amedments of the bandwidth reach product.
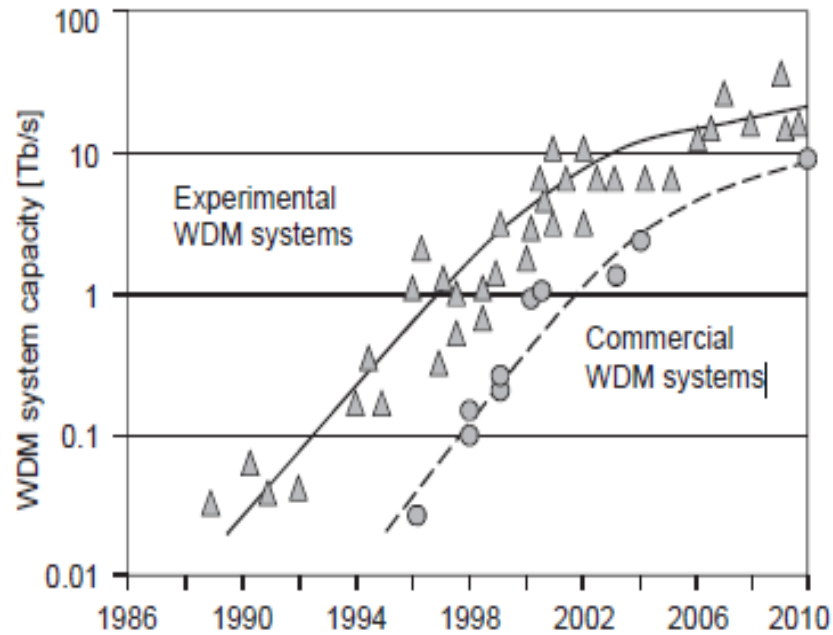
Figure 2.3 Development of WDM systems transport.

The whole transport capacity of WDM systems has hugely growed since the first trial with WDM and guided by amendments of components, adjustment and equation techniques.This is shown in figure 2.3 for both WDM systems the experimental and commercial.

"From Figure 2.3 two aspects can be derived the First one, commercial WDM systems are latter perfect experiments slightly more timely now and both are conveniant an area of retarded capacity improvement. In upcoming years, WDM on SSMF will at last reach what is known as the nonlinear Shannon limit. Moreover improving behind this limit will request new fiber forms." [34]

2.3.2 Theory of WDM

"WDM (Wavelength division multiplexing) points to a multiplexing and transmission in optical telecommunications fibers where various wavelengths, usually released by some lasers, are implied separately (i.e., they load separate data from the transmitters to the receivers). These wavelengths are then multiplexed in the

transmitter by aids of passive WDM filters, and as well they are separated or dermultiplexed in the receiver by aids of the same filters or consistent detection that commonly parts a disciplinary local waverer." [31]

"Wavelength division multiplexing is an effective methods for growing the transport capacity, or applicable bandwidth, especially of optical single-mode fibers. It lets the part of varous clients traffic in the wavelength range and can be used as a multiple-access mechanism." [33]

"Inclusion and multiplexed signals have be apart from each other or demultiplexed to be included. For partition, each couple of the respective signals have to supply perpendicularity. For any two signals to be perpendicularly, their scalar product has to be zero:

$$(f, g^*) = f^T . g^* = \sum_i f_i . g_i^* = 0, \text{ with } f_i . g_i^* = \int_a^b f_i(x) . g_i^*(x) dx, \ i = 1, ..., N. \ (2.1)$$

(f, g^*) is the scalar product of complex functions, where * indicates complex conjugation. Equation (2.1) is written for vector functions to be able to consider impacts of perpendicularly polarized signals. The disappearnce scalar product of the two signals is equal to a disappearnce cross liaison product or cross liaison function (CCF)." [33]

"For the CCF, significative integration bounds have to be counted, for instance, integration above one symbol period. For optical WDM, given that the various wavelength channels, inclusiving the Fourier transform-induced broadening owing to the modification, are fairly spaced in the wavelength field, any two various passbands of the WDM multiplexing (MUX) and demultiplexing (DMX) filters are perpendicular with regard to each other. Actually, Eq. (2.1) may not be established properly, but only nearly owing to linear or nonlinear cross talk. WDM is the generalization of frequency-field multiplexing that is long well-known from radio and coaxial transmissions. With a WDM channel, it can be jointed with any different of the known electrical multiplexing or multiple-access schemes. These contain electrical frequency-field multiplexing, that is then point to as subcarrier

multiplexing (SCM), time-field multiplexing (TDM), and code-field multiplexing." [33]

"One scheme of special concern for both the multiplexing and multiple access is perpendicular frequency-field multiplexing (OFDM), tha can be utilized inwards a wavelengthchannel or casing the optical frequencies of some wavelength channels. The respective multiple access schemes are time feild multiple access (TDMA), subcarrier multiple access (SCMA), frequency domain multiple access (FDMA), and code-domain multiple access (CDMA)." [33]

2.3.3 CWDM, DWDM and Passive WDM

"Networks in telecommunication systems are pyramidal orderly. Inhabitation and business advent is depend on wireless 2G/3G/4G and WiFi and wire line fiber P2P (point-to_point), PONs (point-to-multipoint passive optical networks), copper coiled pair, hybrid fiber coaxial (HFC) technologies.Access." [33]

The previous sites are pointed to as "LX (local exchanges) or COs (central offices). This retrograde can be depend on CWDM (coarse wavelength division multiplexing), DWDM (densewavelength division multiplexing), or pWDM (passive WDM) technology. Moreover, access and retrograde, there is a powerfull trend about mobile front haul or C-RANs (Cloud Radio Access Networks) in fourth generation LTE-A (LTEAdvanced) networks" [33].

Therefore, BBUs (some baseband units) "are intensified in BBUHs (BBU hotels) and linked to their antennas high fast speed links.Since these links have not to be statistically multiplexed ,and have narrow passivity and rage requirements,they have to run by point-to-point fiber or WDM (wavelength division multiplexing) channels. Some LX can be intensified, via DWDM or CWDM, in metropolitan-area core (PoPs)" [33].

Points of existence could conform switches used for collecting of a minor level. They are linked via protected rings or mesh of DWDM networks. Specially, local and international backbones are linked to the metro core network via two excessive PoPs

that may conform core routers, BRASs (broadband remote access servers), etc. The backbones exploit long-haul DWDM and high-capacity. Show figure 2.4.
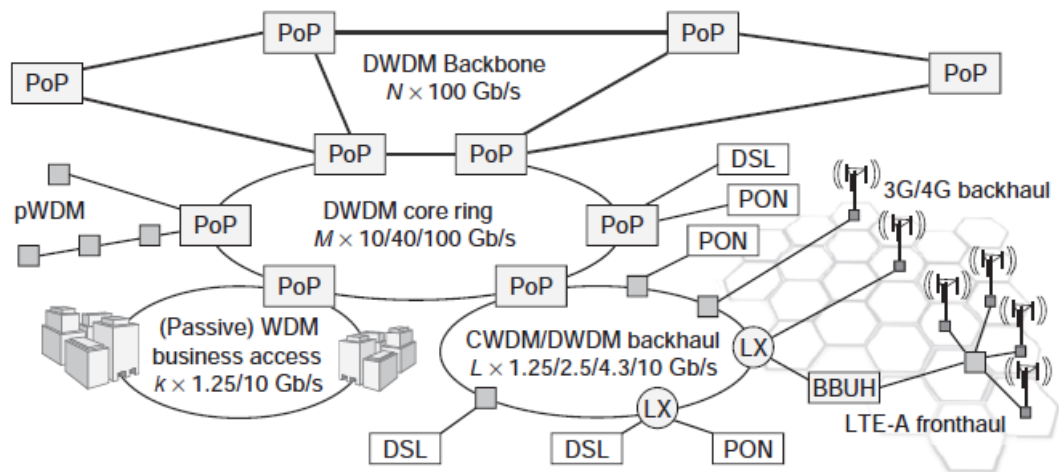
Figure 2.4 Hierarchical fiber-optic telecommunications network

CWDM: "Coarse WDM systems are used greatly for metropolitan feild backhaul and business outlet since the starting of the twenty-first century. They are depended on up to 18 CWDM channels spaced 20 nm in the wavelength feild 1270– 1610 nm, as explained and described in ITU-T tastament G.694.2. In the starting, CWDM had the feature of being cheaper than DWDM since CWDM components that do not request temperature control." [33]

"This feature is prospective to reducing since CWDM transceivers are not wideband tunable. DWDM transmitters, further, are full-band. This lets cost decreasing in industrialization, since only a single form of transmitter wants to be produced. It also lets operational cost reductions, since, for example, sparing and also network planning are greatly simplified." [33]

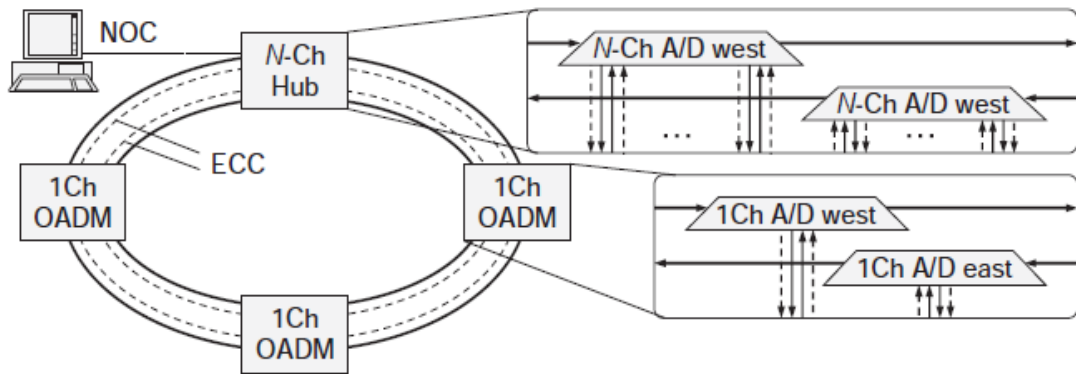**Figure 2.5** CWDM backhaul ring for hubbed traffic pattern.

"In many cases, CWDM was utilized for (DSLAM, GPON, wireless 2G/3G) backhaul, working one or multiple GbE services per wavelength. Up to 4GbE signals can be multiplexed at wire speed (after 10B/8B decoding) onto muxponders running at 4.3 Gb/s." [34]

"In CWDM backhaul, this bit rate is related because it has analogous cost than 2.5 Gb/s. This low cost was primarily forced by transmission of 4 Gb/s Fibre Channel (FC) signals. In common DWDM transmission, 4 Gb/s per channel is nearly unrealted owing to its shortage of spectral adequacy. Capacity boost up to 16X10 Gb/s has also been showed with CWDM. Backhaul topologies are often rings, which can be kept. For controlling aim, the OADMs can be linked to a network operations center (NOC) through an embedded communications channel (ECC). The ECC can convey narrowband management information. CWDM systems often use CWDM-colored small form-factor pluggables (SFPs) as distant interfaces. These can be conformed instantly in the client systems, or on transponders/muxponders. Per-channel bit rates of 1.25–4.3 Gb/s are insured (where 4.3 Gb/s share the transceiver technology with 4G Fibre Channel, which is one of the drivers behind the advantageous economics)." [32]

"As yet, devoted CWDM 40 or 100 Gb/s transceivers have not been established, and it is improbable this will ever happen. For 4 and 10 Gb/s, decreased chromatic dispersion (CD) allowance and also power budget must be counted. This may edge largest reach, without added aids like CD compensation (not commonly used in CWDM systems), or forward error correction (FEC) to <60 km. typically, in CWDM

systems, impacts of polarization-mode dispersion (PMD), polarization-dependent loss (PDL), and nonlinearity are concealed within thetransceiver specifications, owing to space restriction. If link lengths approach the respective specified CD limits, power budget penalties in the 1 dB range may have to be applied." [33]
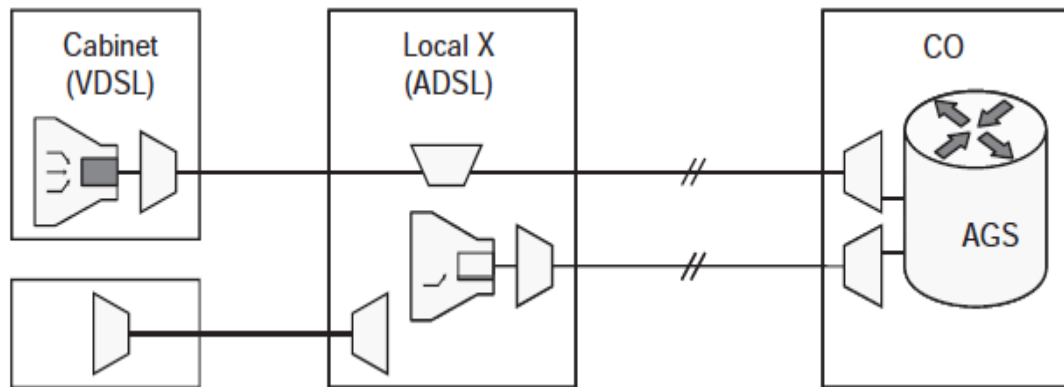

Figure 2.6 Concept of passive WDM.

DWDM: "Dense Wavelength Division Multiplexing (DWDM) is a technology that puts information from various sources altogether on an optical fiber. It sit in the operation of multiplexing many various wavelength signals onto a single fiber. So each fiber has a set of parallel optical channels each using somewhat various light wavelengths. Because arriving signals are never concluded in the optical layer, the interface can be bit-rate and format separate, letting the service supplier to merge DWDM technology easily with present outfits in the network while obtaining access to the untapped capacity in the embedded fiber." [33]

"A key feature of DWDM is that discrete wavelengths form an perpendicular set of carriers, which can be parted, routed, and switched without interfering with each other, as long as the total light thicknessis kept adequately low. It is the use of wavelength and its operation in unfavorable network elements, that differentiates optical networks, in common, from other network technologies [36]. It is also the newest technology to extend fiber's effort. It sets the basis for true optical networking and gives carriers a path to reach their terabit desires. Each signal carried can be at a various rate (OC-3/12/24, etc.) and in a various format (SONET, ATM, data, etc.)." [35]

"A system with DWDM can fullfiled all this elegantly during retaining the same degree of system efficiency, accuracy, and durability as running transport. Future DWDM terminals will hold up to 80 wavelengths of OC-48, a total of 200 Gbps, or up to 40 wavelengths of OC-192, a total of 400 Gbps – that is adequate capacity to conveys 90,000 volumes of an encyclopedia in a second. assume a highway analogy where one fiber can be imagined of as a multilane highway." [35]

Passive WDM: "Simple method of passive WDM-founded networking is called passive WDM; it is used in massive carriers' networks for (DSL) backhaul. Essentially, it is a method of the ITU-T G.695 black link approach. Passive CWDM filters are used to let CWDM pluggables (SFPs) to be connected immediately into client devices (DSLAMs and MSANs), and then to be multiplexed." [35]

"The use of multiple fibers are saved by using the previous approach. AGS1 (an accumulation switch of level 1) was conformed by pWDM connections between a central office. The use of standard CWDM SFPs permit by the pWDM concept, which is costefficient for definite applications like DSLAM backhaul.Altogether with the low enrollment loss of CWDM filters,these SFPs permit maximum reach in the range of 40–80 km." [35]

Aditionally, most CWDM filters outdoor hardened by the coarse channel spacing on the one hand the requested temperature range for full industrial, 40 to þ85 C. Actually, the 20 nm CWDM channel spacing was known following maximum temperature incited laser wave-length drift of roughly 6.5 nm over this temperature range.
"More novel pWDM various also cover DWDM with up to 80 channels. For DWDM filters and transceivers, attempt is needed for athermalization." [35]

2.4 Summary

This chapter discusses the topic of all optical network and illustrates its benefits and why it deserves a lot of research to be the next generation networks.Fiber cables

characteristics and types are presented. Finally, this chapter discusses an important aspect related to the optical networks which is wavelength division multiplexing.

CHAPTER 3

ROUTING AND WAVELENGTH ASSIGNMENT

3.1 Overview

RWA (Routing and Wavelength Assignment) considered one of the most crucial "problem in wavelength routing networks. İt may be explained by: In certain network topology, using the minimum possible number of wavelengths, how we could establish a set of light paths on best routes over the network and assigning their wavelength." [8]

In [8] two constraints were "described that should be considerd when we try to deal with the problem of RWA. The problem as described in the previous chapter was divided to subproblem, the sub-problem of routing and sub-problem of wavelength assignment. Actually this constrain the subproblem of wavelength assighnment. The routes of light paths are determined and settled. wavelength assignment (WA) remains to be done. The summarization of constraints as follow" [8]:

1. constraint of distinct wavelength assignment.
   İn order to avoid interference, All light paths with a similar fiber must be taken different wavelengths. This will be applied in AON (all optical network) as well as in access links.
2. Wavelength continuity constraint.
   İf we assigned a wavelength to certain light path. The light path will remain use this wavelength on every access links on its trip from transmiter node to reciever node.

Conserning the first constraint, it should be considerd when solving the WA problem in any wavelength routing network.

The second constraint is valid only on network without wavelength conversion capability inside their nodes. İn network with wavelength converter, this constraint is invalid.

The traffic can be divided into either static or dynamic in a wavelength routing network. Sometimes it is called offline or online light path request instead of static or dynamic traffic.

In a offline light path requests (in this case, The RWA problem is known as offline RWA), the setting of light path is all in-advance then remains inside network for a long period of time and may considerd permenantin sense.

In a online light path requests (The RWA problem here is known as online RWA), setting the light path for each connection as it arrives, also the light path is released after some certain amount of time.

A lot of literature in this context; in [4] there is a review of RWA algorithms. The general form of Most RWA algorithms can be concluded in this points:

- For a given pair of source destination, all light path demand is arranged in certain pre-scribed order in what is called a list of path.
- every wavelengths is arrange in pre-scribed order in what is called a list of wavelength.
- Given the list of path and wavelength. İf there are light path request,Attempt founding feasible route and wavelength for it starting from top of the specified lists.
- This can be repeated for all light path requests.

Control and Management Mechanism

One of the main issue in this part is the required signalling and reservation protocol to maintain the resources along the way as well as exchange control information between the node throughout the path. The integration of signalling and reservation protocols with the RWA protocols is called "Control and Management Mechanism".

Control and Management Mechanism after receiving a path request is as follow:

1.Select a suitable route

2. assigning the appropriate wavelength or more to the light path

3. Finally the network's switches should be configured accordingly.

The responsibility for observation of current used wavelength in each optical link lies on the control and management mechanism. This will help in correct routing decisions.

"The control and management Mechanism be divided into centralized or distributed control. The distributed control and management is preferable because it increase the robustness [4]".

The research in this area is taget to minimize the blocking rate of light path requests which leads to increasing the rate light path establishment. Some reaserchers concentrate in minimizing path set up delay, others intrest in minimizing the overhead traffic generated from signalling and control messages. These intrests in generally may conflicts and there are trade of between many topics of this research.

"Control and management mechnism which relates to to the online RWA is called dynamic light path establishment (DLE) while Control and management mechnism which relates to offline RWA is called light path establishment (SLE). Both protocols can be found in detais in" [5].

3.2 Wavelength Routing

The algorithms performance is affected by many factors such as the routing algorithms and wavelength assinment. İn this part, we will talk about the wavelength routing as one of critical factors that play an important role on the system performance and overall blocking probability, besides its impact in the design of all-optical networks. The router that assign wavelength to the rout is called wavelength router (WR). The wavelegth router will run a pre-allocated algorithm whenever a request arrives, it will then select the exit port and a

wavelength. So a WR has to function; the first is finding route for the light path request and the second is assigning a wavelength whcih minimizes the probability of blocking.

"Recalling the classification of RWA schemes into two fixed or adaptive(dynamic)" [4]. In a fixed RWA scheme, RWA scheme assigns the preallocated wavelength and route for this demand and all the routes and wavelengths for the light paths are fixed initially. Hence the routing procedure doesn't change with time.

Developing efficient algorithm and protocols with condition of minimizing the blocking rate in the network is the main goals in designing wavelength routed networks with dynamic traffic demands.

To solve the RWA problem, there are two objectives; the first is rout selection with shortest path length. The second is wavelength assignment with the aim of reducing the blocking probability.

3.3 Strategies of wavelength Assignment

Wavelength assignment is the basic parameter which affects the probability of blocking and there by the performance of network. Proper assignment of wavelengths can reduce number of wavelength converters which can decrease the overall network cost with great extent.

As stated before, In order to discuss this problem in details, we should consider the two cases of connection requests. Connection requests can be divided intotwo cases static and dynamic.The static case involves that the connections are given and the problem is to establish light paths for all demands in the condition that minimizing the No. of wavelengths required. On the other hand, in the dynamic case, requests of connection arriving randomly, therefore the dynamicRWA became more challenging.

At each node, each algorithm maintains a list of reserved and free wavelengths for each assignment scheme. This free wavelength is elected from the list of wavelength and then assigned to request. the folowing are some of the proposed wavelengthassignment algorithms:

(1) "Random, (2) First-Fit, (3) Least-Used and (4) Most-Used" [27].

In the following we will briefly explain the difference between the four methods.

- **<u>Random Assignment of Wavelength:</u>** This scheme is adopted in two steps; "the first is determineing the group of every wavelengths that are available on the selected route by searching on the space of wavelengths. The second is randomly choosing one wavelength λ_j (usually with uniform distribution) among the available wavelengths. This list of free wavelengths is updated by removing the elected wavelength λ_j from it. When the request is completed, then wavelength λ_j is released by removing from the list of reserved wavelengths and is added again to the list of free wavelengths to be packed randomly again." [27]

- **<u>First-Fit:</u>** In this scheme, "all wavelengths are labelled with number. A lower numbered wavelength is chosen before a higher-one when searching for available wavelengths. The first available wavelength is then selected.When complete the call the taken wavelength λ_f added back to the free wavelength set." [27]

  The main idea of this methodology is to pack all of the in use wavelengths toward the lower end of the wavelength space. This leads to thehigher end of the wavelength space will be chosen in ahigher probability by continuous longer paths. This scheme has small computational overhead, so it is suited in practice. In addition it performs well in terms of fairness and blocking probability [27].

- **<u>Least-Used:</u>** in this scheme the least wavelength used in the network is selected.Thereby attempting to balance the load among all the wavelengths. In this scheme,the connection requests which traverse a limited number of connections in the network will be serviced,so this scheme ends up breaking the long wavelength paths quickly.

  "The performance of Least-Used is worse than Random for several resons; first it introduces additional communication overhead due to the requirements for global information to compute the least-used wavelength. Second, this scheme also requires additional storage and computation cost to handle these overhead requirements; thus, Least-Used is not preferred in practice." [28]

- **Most Used scheme:** Most-Used scheme is the opposite of Least-Used in that it tries to select the most used wavelength in the network. So we can say that the communication overhead, computation cost and storage are similar to those in Least-Used. In performance, Least-Used outperforms Least-Used significantly [27].

In terms of packing connections into fewer wavelengths and conserving the spare capacity of less-used wavelengths, most-Used also is doing a better than least-Used one.

If we consider these "strategies from practical point of view, first-fit and random techniques are simple and easy to implement techniques. So they cconsider more practical than most and least-used techniques. This is because the random and first fit techniques do not require global knowledge of the entire network which is completely different from the most and least-used techniques. These two simple techniques rely on status of node at the istant of transmission. They simply bake up the wavelength from the free wavelength set" [28].

These random and first fit wavelength assignment will not provide optimum results because the status of the network are unknown for the used stratigies.

If we compare random strategy with first fit one, we can deduce that random technique behave better than first fit as it can select any wavelength from the available free wavelength. This leads to reduction in the contention of wavelength selection at any time istant by different nodes [32].

One ofthe very important requirement to apply both of "most used and least used techniques is the wide knowledge of the entire network. The more information you can gather about all network nodes, the more probable that these techniques behave better. Another important factor shouldbe consider as well, which is the accuracy of these information. This factor has a great impact in wavelength assignment in most-used and least-used techniques. These information shouldbe updated periodically becuase of changes of network at each instant. Providing these information to each nodes consumes nodes cpu and network bandwidth. So select the most used and least used

approach has a considerable effect in the avaiable bandwidth for the data traffic" [32,37]

The network states are "exchanged between nodes at fixed interval using predifined messages. These messages consume the bandwidth of the network to noticable extent and so reducing the availbale bandwidth for data traffic. İn addition these messages consumes node cpu and memory which affect in overall node performance in the network" [38].

"Wavelength assignment is often compared with the Graph-coloring problem. Given a graph, where colors are assigned to the paths with minimizing the number of colors used. The following method describes the graph-coloring approach." [39]

Build a Graph $G = (V, E)$, thus every node in the graph shows every light path. In graph (G), there is an un-directed edgebetween twin of nodes.If the corresponding light paths move through a common physical fiber link. The nodes of the graph (G) with taking into account that no two adjacent nodes have the same color.

"This problem is NP-complete Also the minimum number of colors needed to color a graph G, is difficult to determine. If we are given a fixed number of colors and we have efficient sequential graph-coloring algorithms, then optimal allocation of the given number of colors is reached." [39]

"For the technique that called sequential graph coloring, nodes usually are added sequentially to the the graph portion which already colored, and new colors are determined to have each adjoined vertex. At every step, the goal is to keep the total number of colors minimum" [39].

3.4 Establishment of Virtual Path

There are two steps shouldbe adopted "when a call is generated at any node. The first is finding the optimum route for this request and the second is wavelength assignment. To get the next link, the routing and wavelength asignment algorithm is used. After selecting the suitable wavelength according one of the four tecniques

specefied in the last section, the request is then routed to the next node. At the intermediate node, there are two cases; if the used wavelength to get to this intermediate node is still available for next hop, then it is picked to rout the request. Otherwise the request is blocked as long as there is no wavelength converter at this node. İf there is a wavewlength converter at this node, then the request can be routed to another wavelength" [40-44].

This approched is repeated at each node till the request reach to the distination."This will form what is called a 'virtual path' from the source to the distination. The path establishment is considered a circuit switching scheme that is fully established before any data is transmitted" [32].

The group of physical "links starting from the source and terminating at the distination is called 'physical path'. As the physical path can be performed from the same or different wavelengths, this physical path is called virtual path. So two requests from the same source and to the same distination have the same physical path but different virtual path which can be depicted at figure 3.1" [40].

İn figure 3.1, we can explain the difference between the physical and virtual path. Suppose that there are two requsets from node 1 and are distained to node 4. The two requests are following the same rout through node 2 & node 3. So the two requests have the same physical requests. For the first request, node 1 assign wavelength λ1 and route it to node 2. On the other hand, the the second request is assigned a wavelength λ2 and rout to node 2 as well. At node 2 which has a wavelength converter, due to un availability of wavelength λ1 for the first request and wavelength λ2 for the second request, a wavelength conversion is adopted for the two request. So the first request is assigned the wavelength λ2 and the second request is assigned a wavelength λ3 as shown. Node 3 has no wavelength converter, so the two requests are routed to node 4 with the same wavelength assignment. So the virtual path 1 and virtual path 2 are established using the wavelength assignment algorithms as shown in figure 8.
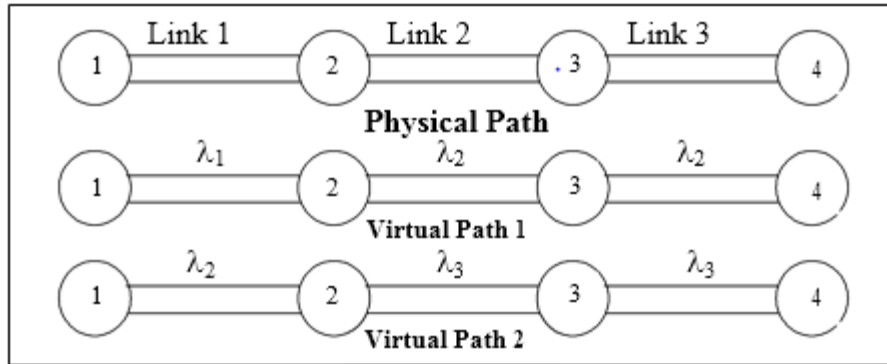
Figure 8 Virtual / Physical Paths.

In this example, "we can see that the two request has the same physical path as it established from the same source and to the same destination through the same intermediate nodes, but the two requests have two different wavelength. The maximum number of virtual paths which can be setup from certain source to certain destination is bounded by the total number of wavelength per this fiber. In nodes with wavelength converters, more virtual paths can be established and this leads toreducing the plocking rate for call requests." [40]

Wavelength converter

Choice of the placement of the converter is an important issue that should be considerd. İt can be treated as integer linear programming (ILP) problem. İn order to illustrate the problem in more details we can refer to maximum arrival rate between to random node 1 &2 by λ_{12}. " Beside let the number of sessions to be established between node 1&2 be M_{12}. The location of converter should be chosen so that the summition $\sum_{12} M_{12}$ is maximized subject to constraint of the wavelength continuity on segments between successive converters and traffic demand constraints, i.e., $M_{sd} \leq \lambda_{sd}$. This problem is shown to be NP-complete." [41-42].

The impact of presence of wavelength converter in blocking probability is modeled in the work of Barry and Humblet. The blocking probability is calculated with and without wavelength converter. They have shown that "the blocking probability with and without wavelength converters increase with the number of hops." [45]

They also "demonstrate that if there no wavelength converter, the network diameters should be minimized in order to reduce the blocking probability. In addition, the hop count has strike effect in blocking probability and the less the number of hop count, the smaller the blocking rate be." [42]

The impact of network topology is studied in [42] "by providing solution for the ring and bus topologies. By precise placement for wavelength converters, a noticeble improvment in blocking probability can be obtained when comparing with random placement. Even if we choose a uniform placement for wavelength converters, a modest gain is obtained." [42]

Optimal performance are produced by uniformly spaced converters when the link loads were un-correlated and uniform. For non- uniform traffic.

Heuristically, "the wavelength converter was positioned in nodes suffering of highest output link congestion. The performance is infeluenced with number of nodes. For example, NSFNET network, the systemprovide otimal results while it does not provide near optimal results for simple network such as ring topology with uniform traffic" [41].

" İf the path is divided into segements, and each segment has equal probability with other one, then the optimal placement for wavelength converter is between segments. İn fact it is difficult to acheive that as it is not easy to divide the path into equal probabilities segments." [42]

The analysis of "wavelength conversion was introduced in the litrature and an analytical models for network with converters are proposed. The connectivety of the network plays an important role in determining the usefulness of wavelength converters. For example in low connectivity tpology such as ring topology, converters are not very useful because of the high load correlation." [43]

In high connectivity case such as the hyper cube or a densely random topology, the importance of wavelength converters reduced to a great extent as a result of hop length.

İn network with a degree of connectivity between those of the ring and the hyper cube offers, such as A mesh-torus, network there are great advantages in the presence of wavelength converters.

"It was also shown that wavelength converters are more effective when the number of wavelengths is larger and when the load is lower. The improvement in the performance with respect to the converter density (number of converters to the total number of nodes) was also studied. It was shown that performance improves rapidly as the conversion density increases from zero, but the rate of improvement typically decreases with increasing conversion density." [44-48].

3.5 Summary

In this chapter, the problem of Routing and Wavelength Assignment is overviewed. Also the research goals and constraints are illustrated. Routing methodologies and some of the wavelength assignment schemes are discussed. Finally this chapter make a presentation for a group of converterplacementsolutions.

CHAPTER 4

ANT COLONY OPTIMIZATION

4.1 Introduction

Ant Colony Optimization (ACO) is a heuristic method energized by the contact of physical ants in form of trails of a natural material called pheromone. Simulated ants are mobile workers which use mathematical data (pheromone data) to share their knowledge in finding a solution for other ants' problem [49].

These fundmentals supply a typical scheme for usage of ant algorithms to conjunctional optimization problems [50]. Hence, algorithms which adopted from the ACO heuristic methods are named ACO algorithms.

In ACO algorithms, a particular ant builds up solutions to a conjunctional optimization problem with the beginning of an initial state and then adding incremental components in a repetitive fashion until a complete solution is achieved.

The ants employ data that gives back the knowledge gathered by the previous ants, named pheromone data to determine which solution element will be accumulated to its existing incomplete solution in form of a stochastic building process.

Each stage in an ACO algorithm where all ants form a reasonable solution will be named repetition. Each ant denotes a particular solution for the period of a certain repetition. Hence, when stating an ant, we indeed mean the solution of that ant.

After each repetition, feedback is given from each ant on the solutions they have built by dropping pheromone on solution elements that were used in their solution.

To keep pheromone up-to-date, the algorithm decides which ants are permitted to adapt its pheromone data and what is the way of adaptation. Usually, solution

elements which are used by other ants or are a fragment of superior solutions will get a greater pheromone amount and thus, it will be used more likely in the next repetitions of the algorithm.

Pheromone infinite accumulation can be avoided by the way of implementing an evaporation factor. Before updating the pheromone data, all deposited amounts are reduced by a factor that represents the evaporation process.

In this way, the amount of pheromone associated with a particular solution is reduced if there is no newer trails. Over time evaporation process is responsible for neglection of bad selections [50].

ACO algorithms can be implemented to solve any conjunctional optimization problem, it defines solution elements which used by the ants to bulid up their solutions.

At the beginning, initial parameters and pheromone data are assumed. After that, a main loop is lanucched and reiterated until a violation condition (break point) is happened, which it can be a threshold on the available computational interval or a predefined number of constructions.

During the main loop, solutions elements are added by ants to bulid up reasonable solutions. Furthermore, a local search may be used to enhance these solutions. Next, superior solution is derived. Then, the pheromone data is updated by a group of solutions which may include the best superior one. Befor the updating process, evaporation is occurred by reducing the pheromone deposits by a factor e.

Finally, the best solution is determined during the period from starting up the algorithm due to the main loop end.

4.2 Ant Colony Optimization

Intelligence performance obtained from the ant colony's foraging, the Ant Colony Optimization (ACO), has been applied to classical optimization problems, like quadratic assignment, salesman traveling and job-shop scheduling problems in a successful solving [49-55].

Other optimization methods based on the ant colony's foraging are driven from the novel method have been applied to the known problems: graph colouring [39], vehicle routing [2], and continuous spaces searching. In ACO algorithms, optimization problem is solved by a limited size colony of simulated ants that work to find a good solutions. Up on the problem, each ant builds up a solution, or an element of it, from the initial state depending on specific criteria.

Each ant gathers data include problem features and characteristics, these data enable them to build its particular solution and it is used to adapt the problem formulation for other ants.
Concurrently, Ants make an effort together and communication is being done among themselves. Reasonable solution is achieved in an incremental fashion. A solution is defined as the shortest path through all possibilities while considering constraints of the problem.

The cooperation of ant colony members achieves excellent results as the domainant behavior to synchronously bulid up the different solutions.

Each ant moves among a series of neighbor conditions to construct a solution. Stochastic process used to seach for the movement's vector directed by [43]:
- Ant individual information (the ant internal state, or memory).
- Publicly available pheromone trail.
- Problem-specific local information.

Moreover, the pheromone laid rest on the problem formulation. While constructing the required solution or after that construction or return to all the earlier states, ants can laid pheromone.

In ACO algorithms [49-55]: the chance of a hop selection increases as that hop used by other ants and this hop is become more attractive by the addition of trails.

Generally, the pheromone deposit is proportional to the goodness value of the solution which an ant constructs it. Along these lines, if a motion contributes in the solution generatation, its effectiveness will be proportionally upgraded to its involvement.

The stochastic process regarding the selection of ants' movement and the choice policy also the evaporation mechanism evade a quick shift near the selection space. Up on finishing its task, an ant builds a solution and deposits pheromone data, then the system kills and deletes the ant.

ACO algorithms are good choice to solve the distributed stochastic problems as a result of their simultaneous and adaptable nature [51].

4.3 ACO Algorithms for Network Routing

Research shows that traditional routing algorithms are not suitable to deal with the modern networks which has a large amount of computational complexity [2]. There are some problems in centralized algorithms like scalability; adaptation to network changes. In distributed algorithms, there are oscillations and instability problems.

Network routing uses movable ants as a promising technique to build distributed algorithms. In contrast, in traditional algorithms, small packets are moving from node to node as movable. In cooperation manner, they can accomplish complicated tasks in a distributed fashion [25].

These agents discover and work together in a network. They accumulate routing data and routing tables is updated in each node, for example a routing route can be estimated for data transfer. Number of routing algorithms which are based on ant-agents have been proposed [23-25].

AntNet [23] is the most clarified one, a routing algorithm that is an ant-based has group of superior routing algorithms on numerous packet-switched data networks. In the same context, it introduces a swarm dynamic routing technique based on Bellman's principle.

Furthermore, group of ant-based routing algorithms that is proposed for MANET networks e.g., in [51]. Ant-based routing approach is very elastic and can accomplish better behavior in comparison with traditional routing methods in data networks.

In [27] a session routing algorithm for communication networks has been proposed where ants were employed as movable agents and pheromones trails were represented as probabilities.

Each pair of source and destination is represented in a matrix, characterizes trails in the direction to the source of food.The matrix of probability is related to a movable agent in the direction to the source of food at time instant, which is used in packet forwarding as the routing table in the traditional routing algorithms.

In AntNet [23] asymmetric traffic is considered with its conditions. Two phases are lauched, the first one is the forwarding phase which serach for trails to find the best route according to the above mentioned process.

After arriving to the required destination, the route goodness is estimated and a strengthening value is calculated. When the second phase is launched, a movable gent return back to the source point along the selected path. Updating the probability matrix according to the movement from one point to another one in the same behavior as mentioned before.

Good quality routing table can be produced by using AntNet systems [23]. Load balancing is an important aspect also small delays are needed to be in a reasonable range to accept the new routing strategy in a packet switched network. Adaptive behavior to topology changes requires fast route selection which is implemented in [23].

In AntNet algorithm, investigation agents (ants) are used to make interactions by moving them forwarding and backwarding to form the routing. The idea of moving ants in the two opposite ways is the data which collected by the forward ants used by the backward ants along the path from the source to the destination.

Based on the concept of using two directional movable agents, routing tables update is accomplished by the backward ants not by the forward ones. The purpose of the forward ones is to demonstrate delay conditions and provide it to the backward ones. The backward ants uses the provided data from the forward ones to update the routing table of each node.

The sum of probabilities for each row in the pheromone matix which are recorded in the routing tables should be equal to one. Dual usage for these probabilities [23]:

- The bi-directional ants use these probabilities to select the next hop along its way to a particular destination, choosing a next hop is done in a random fashion among all possibilities according to the probabilities for a particular destination.
- Data packets pick the next hop based on determining the route which has the highest probability.

AntNet routing mechanism is working up on the following steps [23]:
- Every node generates ants in the forwarding direction in a regular periodic intervals to every possible destination.
- According to the probabilities found in the routing table, the ant randomly selects a route to the required destination.

- As the ant traverse the path nodes, it creates a stack for the current node.
- This stach which is created by the forwarding ants is used by the backwarding one.
- Using the stack information to determine the reverse path from the destination to the origin source.
- Updating the table of each traversed node in each time interval.

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Ant-based algorithm mentioned before discuss the routing problem no the problem of load. Routing table wich contains the probabilities is sustained in each node. Therefore, if we have more than one route and one of them is the best, user data will take that route with large priority.

In the same context optimization can be done using multiple number of ant colony as described in [52, 53]. These studies deliver new searching criteria for the optimal routes using multiple number of ant colonies with the same concept that each ant colony uses different color of pheromone trails. Revulsion strategy used to enforce ants associated to other colonies from not choosing the same best path.

Some ACO algorithms handle routing using virtual wavelength and how to allocate wavelengths. Differences here that the variants used in their ACO algorithms not varied according to the trails dropped by their own colony but with the trails of the other colonies.

The fact in virtual wavelength paths that we have limitations and we can only work with a number of wavelengths. The allocation where the target is to use per link the minimum no of wavelengths by making fair wavelength distribution with keeping the rout length short [52].

Pheromone attraction with the same concept is used in other applications of ACO, pheromone divergence helps in the distribution process and enhances the performance.

4.4 Multi Objectives ANT Colony Optimization

Multi objective ant colony algorithms (MOACO) are special type of ant colony implementation, these implementations stand up the idea of using number of colonies, pheromone data managing and the heuristic techniques [54].

These characteristics are combined together to establish different flavor of MOACO algorithms. First of all is to have numerous colonies, where we divide the colony size to separate smaller size colonies, while each one is handled as a dedicated colony. Using a supportive soul, results that are generated from each colony are exchanged to be taken into account in the pheromone updating process [54].

Two models exist. The first one, is to use single pheromone matrix regarding all information associated with all objectives. The second model is, to use dedicated pheromonvee matrix to each objective in our problem.

Transition criteria can be implemented according to a single objective. Also it may be implemented using combined formula of different pheromone matrices by using a weightening equation that assign a specific weight for each objective. Some of Multi objective antcolony techniques are summarized in the next section.

Multiple Objective Ant Q Algorithm (MOAQ): an algorithm which is suggested by Mariano and Morales. With the same concept of the multi objective algorithms, it allocates a separate ant colony for each objective. A problem with number of objectives Z, Z colonies will be used wher each colony is charged in optimizing a particular objective. The movement decision is based on the visibility values and of pheromones probabilities. The concept is to assign dedicated colonies to specific objectives and in the same time to share knowledge offered by each one of them.

Bicriterion Ant (BIANT): in this algorithm two different pheromone matrices are used where each matrix is assigned to each objective. Thus, it is supposed that ant colonies achieve their searches in many regions of the Pareto Front. Each matrix has

updated information of the pheromone and evaporation. The pheromone matrices are updated only by ant which found non-biased solutions.

Pareto Ant Colony Optimization (PACO) [19]: in his algorithm which was suggested by Doerner et al, several Z pheromone matrices are assigned, each one per

objective. Per iteration, an ant uses a series of calculated weights that in [19] were randomly selected, to be used with a movement decision.

Pheromone matrices are updated with its optimum two corresponding ants for each objective. Each instant which an ant developments to another solution, Z pheromone matrices are updated. A pseudo-random proportional rule used to select the next node.

Multi-Objective Ant Colony System (MOACS) [20]: in this algorithm which was suggested by Schaerer and Baran. Implementation considers two objectives; two visibilities and pheromone matrix are used, one matrix for each problem, with the same pseudo-random rule offered in [19] to favor exploitation.

When a non-biased solution is found, Pareto set is updated and the trail matrix is rested, taking into account that the data has been learned by sub-optimal solutions.

Multi-objective Max-Min Ant System (M3AS) [51]: in this algorithm which was suggested to extend the Max-Min Ant System [17] which solve multi objective problems. One main pheromone matrix is used, which sustains pheromone trails for all objectives. The non-biased solutions update the trail matrix where borders are executed on the pheromone levels.

COMPETants (COMP) [52]: it has been suggested for twice objectives problems, using two trail matrices and two visibilities. Each colony has variable number of ants, and they are dynamically generated during each cycle of the algorithm. While ants construct their solutions, more ants are assigned to the colony with the superior solutions in the next iteration.

Then, the ants are automatically adapted up on each colony performance. It also implement spy-ants per colony, where foreign information is utilized based on the superior solution per each colony.

Multi-objective Omicron ACO (MOA) [53]: in this algorithm which has been suggested by Gardel el al., it is based on the Omicron ACO (OA) suggested by Gómez and Barán [17]. Two objectives are implemented in this algorithm, it uses two visibilities and one pheromone matrix per objective.

The pheromone levels are updated by a Pareto set of non-biased solutions. A fixed level trails is added at all edges belonging to the solutions of the Pareto set. The parameter O that provides the name to this ACO algorithm is used to gives the movement decision. So, the pheromone level sustains between minor and major levels.

Multi objective Ant System (MAS) [54]: this algorithm has been suggested by Paciello et al., this algorithm is another extension shape of the Ant System to deal with multiple objectives. One pheromone matrix with a visibility is used per objective to be improved; search domain regions are targeted with the ants

Pseudorandom proportional rule in [44] is used. Updating for the pheromone table is performed by the non-dominated solutions ants before each iteration end. A tool of convergence controller is used by this algorithm has to improve exploration that reset the pheromone matrix to its initial values.

All discussed MOACO algorithms are optimization methods of independent general purpose. To specify them to the RWA, each ant construct the light paths set that generate a solution. Each Ant-RWA constructs a solution traveling called Wavelength Graph [51-53].

An Ant-RWA constructs if apossible, route for each request in Wavelength Graph.. Once we find a solutionthe to the problem, the light paths are found.Finally, mapping the solution to have the favorite solution in the original topology.

All of the previous MOACOs, the Ant-RWA algorithm can be implemented to build solutions. The main difference is how to select a light path using different visibilities and pheromone matrices.

4.5 Summary

In this chapter, an overview about ant colony optimization is presented. Also the idea and methodology of using ant colony in routing is surveyed, some of the recent researches in routing using the ant colony optimization are illustrated. Finally this chapter discusses the multi objective ant colony optimization; how it can deal with multi objective problems and lists some researches have been proposed in this area.

RWA PROBLEM IN WDM OPTICAL NETWORKS

5.1 Introduction

The high bandwidth " requirements of new emerging telecommunication applications can be provided by optical networks employing wavelength division multiplexing (WDM). The optical fiber has exteremly large bandwidth that be divided into several transmission channels with suitable bandwidth to the end user demands." [25].

Wavelength routing is a challenging " technique to provide larg bandwidth demands applications on the Internet. It gurantees of all optical data paths among entire network nodes. Data is transferred from entity in one side to another side entity using a light path. Each light path is uniquely identified by a physical path as well as a wavelength as shown in figure 9. A light is said to satisfy the wavelength-continuity constraint (WCC) when its path operates on the same wavelength over all the fiber links which passes through". [23].
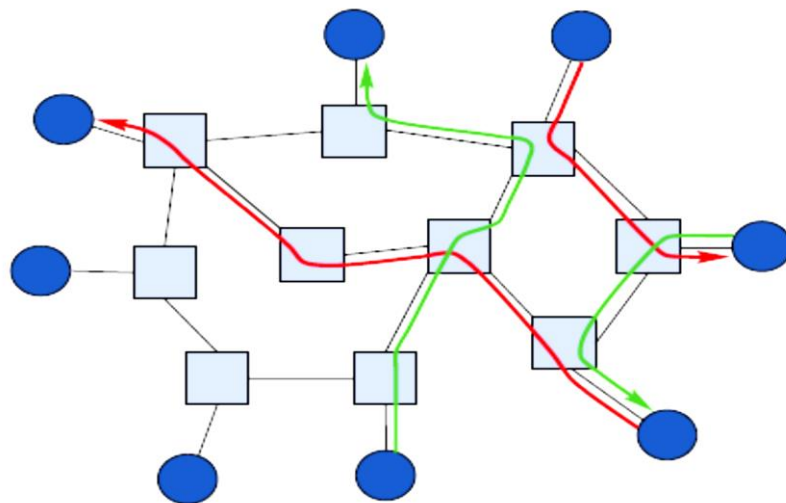
Figure 9 Wavelength-routed optical WDM Networks with light path connections

Routing and wavelength assignment (RWA)

Routing and wavelength assignment problem (RWA) is the greatest problems in optical wavelength division multiplexing (WDM) networks fro optimization point of view. This problem includes both the challenge of coice of a path as well as a wavelength for each connection request arriving to the network.

In order to discuss this problem in details, we should consider the two cases of connection requests. Connection requests can be divided into two cases as follow:

- Static case: in such case the connections are given in advance and the problem is to establish light paths for all these requests in the condition that minimizing the total number of required wavelengths.

- Dynamic case: in which the connection requests arriving randomly. this characteristic makes the dynamic RWA is more challenge.

Separation in analysis between routing problem and the wavelength assignment problem is more suitable. Given a certain number of wavelengths, the problem is how to maximize the number of connections which can be set up for a given set of connection requests.

Routing Classification

Routing is classified into three classifications:

- Static routing: In static routing, a connection always chooses the same route for a given source destination pair. The disadvantage of using static routing is high blocking probability. This is due to two reasons: the first is if there are no resources the request is blocked. The second is that it is difficult to deal with link break since static routing does not provide alternate paths to the destination.

- Static-alternate routing: One of the advantages of alternate routing is that the reduction of the connection blocking probability in comparison with static routing. This is due to the static-alternate routing supplies more than one route.

- Dynamic routing: in this strategy, the route is dynamically calculated depending on the network state. In general, when comparing dynamic routing with static and static-alternate routing, dynamics routing results in lower

blocking probability,but this is in price of longer set up delay and a higher control overhead.

For the case in which light paths arrive one at a time, it is suitable to use heuristic methods in assigning wavelengths to light paths.

Wavelength assignment

Four heuristics methods have been proposed: (1) Random, (2) First-Fit, (3) Least-Used and (4) Most-Used [27].

In the following we will briefly explain the difference between the four methods.

Random Wavelength Assignment: This scheme is adopted in two steps; "the first is determineing the set of all wavelengths that are available on the selected route by searching on the space of wavelengths. The second is randomly choosing one wavelength (usually with uniform distribution) among the available wavelengths." [27]

First-Fit: This scheme depends on "that all wavelengths are labelled with number. A lower numbered wavelength is chosen before a higher-one when searching for available wavelengths. The first available wavelength is then selected." [28]

In this scheme, "all of the busy wavelengths are packed toward the lower end of the wavelength set. This leads to that the higher end of the wavelength space will be chosen in a higher probability by continuous longer paths. This scheme has small computational overhead, so it is suited in practice. In addition it performs well in terms of fairness and blocking probability" [27].

Least-Used: in this scheme, the least wavelength used in the network is selected. " So this scheme is attempt to balance the load among all of the available wavelengths. In this scheme, the connection requests which traverse a limited number of connections in the network will be serviced, so this scheme ends up breaking the long wavelength paths quickly." [28]

The performance of " Least-Used is worse than Random for several resons; first it introduces additional communication overhead due to the requirements for global information to get the least-used wavelength. Second, this scheme requires additional storage and computation cost to handle these overhead requirements; thus, Least-Used is not preferred in practice." [27]

Most-Used scheme: Most-Used scheme is the opposite of Least-Used in that it tries to select the most used wavelength in the network. So we can say that the

communication overhead, computation cost and storage are similar to those in Least-Used. In performance, Least-Used outperforms Least-Used significantly [27].

In terms of assigining connections with less wavelengths as possible and saving the less-used wavelengths to optimize the capacity, most-Used also is doing a better than least-Used one.

As described in chapter 4, ACO is a probabilistic optimization technique that finds the optimal paths on the dynamic network by useing pheromone trails laid by ants along different routes.

5.2 System Model

The routing and wavelength assignment plays an important role in increasing the efficiency of all-optical networks. So providing an optimum path and suitable wavelength from all available choices for each connection in condition that no two paths sharing a link are provided the same wavelength is the more important challenge in this problem. This propolem is varying according to the provided topology and network connection.

As we mentioned before that RWA is a NP-complete problem, so it is divided to two sub-problems (routing and wavelength assignment).

In this thesis, ACO-based algorithm is proposed to solve the routing problem and in the same time it can handle the wavelength assignment problem with one of the traditional techniques which discussed above.
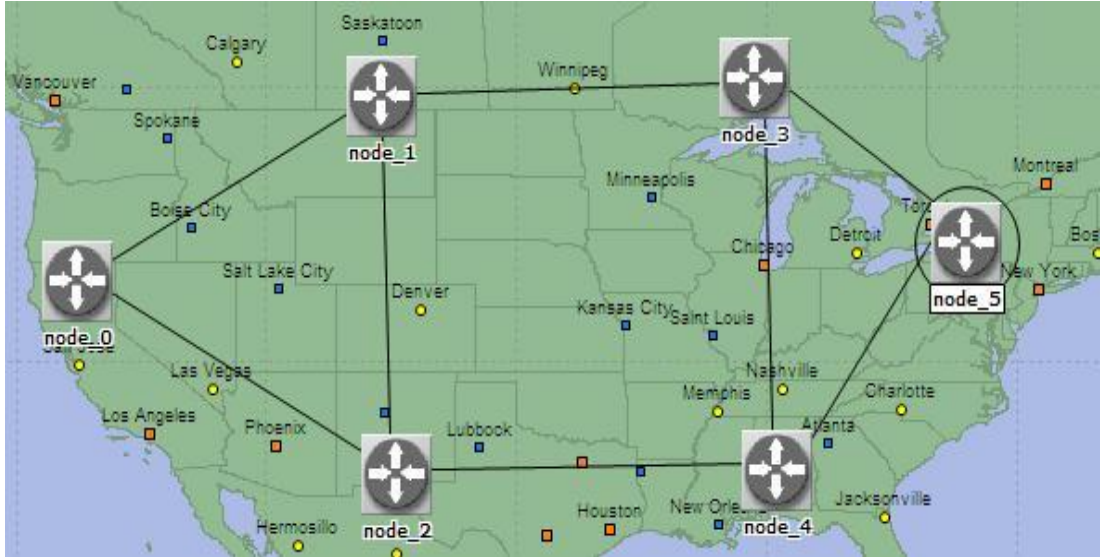
Figure 10 System (base model).

Let us consider our system has N nodes connected through group of fiber links as illustrated in figure 5.2 where each link has its C cost and W wavelengths and each node has two tables (P-route table, pheromone table). Traffic requests of users are modeled as static (offline) and dynamic (online). Table 1 lists all system parameters.

Table 1 System Model Parameters

n	node index, with $n = 1, ..., N$
s	source node index with $s = 1, .., N$
d	destination node index with $d = 1, .., N$
k	neighbor (next hop) index per node with $k = 1, .., K$
w	wavelength index per link with $w = 1, .., W$
m	wavelength index per link with $m = 1, .., M$
r_{n,d_k}	Probability of node n to reach destination d using next hop k
$S_w = \{1,2, ..., W\}$	The wavelength set where W is the total number of wavelengths per link

5.2.1 OPNET/MATLAB Co-simulations

In the proposed model, we use OPNET and Matlab. OPNET Modeler provides a comprehensive development environment supporting accurate model for telecommunication networks and distributed systems. The performance and behavior of modeled systems is analyzed by performing discrete event simulations. In addition, The Modeler environment incorporates tools for all phases of a study, starting from model design, simulation, data collection, and ending with data analysis.

Co-simulation enables users to leverage other specialized simulators with OPNET Modeler and get the "best of both worlds". Co-simulate OPNET with other simulators using: High-Level Architecture (HLA), Co-simulation API and Extensible Transceiver Pipeline (e.g., co-simulation with MATLAB). As we Know MATLAB is

a software simulator which is good for simulating the mathematical modeling and feedback control. We have created co-operation between MATLAB and OPNET to allow MATLAB to use its strong mathematical functionality and OPNET to use its ability to manipulate simulations.

5.3 ACO Routing Algorithm

In this section, the basic mechanisms in the ACO-based algorithm will be described. This includes the structure of routing table, the mechanisms of ants' generation and how they collect data, and how we update the routing tables by the collected so as to reflect more realistic figure for network status.

The structure of routing table

In Ant based algorithm, the douple routing table structre is adopted at each node. This structure comprises of a pheromone table [1] for ants' foraging and a P-route table [5.1] for connection establishment.

Suppose we have network of N nodes, which has k neighbors, has a probabilistic pheromone table:

$$r_s = \left[r_{n,d}^s \ \right]_{N-1,k} \qquad\qquad (5.1)$$

The row represents possible destinations which are equal to $N - 1$ and column represents the neighbors which is equal to K. The selection probability of neighbor

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node k, traveling from node n, and going to a destination node d is represented by the value $r_{n,d}^{s}$ in the pheromone table.

Similarly, the P-route table has structure of two columns and $N - 1$ rows, and describes all possible routes from the source node to every destination weighted by a corresponding preferable value. The value, dr, reflects the weight of that route and it depends on two parameters the first is the length of that rout toword the destination. The second is the number of free wavelength which available for this rout. There are several related works to compute these two parameters each other. One of these, is to use the following equations [27]

$$dr = \emptyset \, \frac{1}{(dl + 1)} + (1 - \emptyset)dw \,, \qquad (5.2)$$

Where

$$1 > \emptyset > \frac{[(W - 1)(N - 1)N]}{[W + (W - 1)(N - 1)N]} \,, \qquad (5.3)$$

$\emptyset$ is a scalar parameter used to tune the emphasis between two parameters; the first one is dl which represents the length of the path, and dw which represents the percentage of free wavelengths on that path. In the proposed model dl is equal to the difference between the length of the current path and the length of the overall shortest path to the destination.

To give more emphasis on shorter routs, a greater value of $\emptyset$ should be taken. On the other hand to give emphasis on free wavelength number, a smaller value of $\emptyset$ should be taken.

Data Collection by Ants

At data collection phase in ant colony algorithms, the ants are generated from random sources, s, and traversed to rondom destination. Through this trip it passes through each available neighbor and tries all probable routs till reach to destination. In this trip the ants collects data of all routes and the available wavelength as well. In addition the generated ants measure the length of each routs and availability of wavelength at each routs it guther. Through this collected data, the best neighbor node to carry the traffic to the destination d can be obtained. Selection of next hop depends on the selection probability. The neighbor with higher selection probability

is more probable to be the next hop. Another important parameter should be considerd which is the launching probability of ants ρ. This parameter controls the launch of the ants from certain node. Continuose process of routing table ubdates is performed in parallel with ants' data collection of data.

In order to collect data about wavelength availability information, the ant colony algorithm uses a binary mask M_{ant} while traversing nodes in a network [7]. This binary mask consists of W bits. These bits are corresponding to the number of wavelengths in the network. A value on bit $w = 1$ means the wavelength λ_i is free, and 0 otherwise. M_{ant} is updated according to the following equation.

$$M_{ant} = M_{ant} AND\ M_{link} \quad (5.4)$$

At the source node, the M_{ant} actual mask is initially set with all bits of 1, implying that all the wavelengths are free. M_{link} is the available wavelengths mask on the next selected link along the path. By anding between M_{ant} and M_{link} the remaning available wave length can be obtained.

Ant Movement in the Network

In order to calculate the pheromone trail amount whose should be added to routing table. Let an ant move from a random source s to a random destination node d. Let the ants use the following path$(s, \dots .., i-1, i, \dots .., d)$. By traversing from an intermediate node $(i-1)$ at time t, to intermediate node i, at time $t+1$ the selection probability for destination node d from source node s through certain intermediate node is ubdated using (5.5).

$$r^i_{i-1,s}(t+1) = r^i_{i-1,s}(t) \frac{\delta r}{(1+\delta r)} \quad\quad\quad (5.5)$$

While the selection probability of node i is increased by this value, the selection probability of all i neighbor node (which considerd non-chosen next hop for node $(i-1)$ in ant moving) are decreased with same value according to equation (5.6).

$$r^i_{n,s}(t+1) = r^i_{n,s}(t) \frac{1}{(1+\delta r)}, \quad\quad n \neq i-1 \quad\quad (5.6)$$

In (5.5) and (5.6) [7], δr is the pheromone trail amount of on a selected network path and it is calculated as,

$$dr = \alpha \delta l + (1-\alpha)dw , \quad\quad\quad\quad (5.7)$$

where, α is a scalar parameter which can be used for tuning the emphasis of two parameters δl and δw. The first one is δl which corresponds to the length of the path

traversed by the ant until now and the second is δw which corresponds to the percentage of free wavelengths on the corresponding path.

The values of δl and δw are caculated as illustrated in (5.8),

$$dl{=}e^{-\beta dl} \;\; dl = l - l_{min} \text{ and } \delta w = e^{\gamma w} - 1 \; , \qquad (5.8)$$

where w corresponds to the percentage of free wavelengths on the path. The design parameters of the pheromone trail,α, β, and γ which controls the conversion of length and the number free wavelength to probabilistic form, can be adjusted to improve the performance of the algorithm.

5.4 Routing and Wavelength Assignment in ACO

In this section, the routing algorithm for dynamic RWA in the proposed ACO WDM networks is discussed. The Ants generation and foraging from random

source and traverse through the network till reach to random destination according to algorithm illustrated in figure 5.3 during $AntGeneration(\;)$ and $AntForaging(\;)$ phase.

At this phse the P-route table is filled with enough candidate paths. After that, the traffic is dynamically generated according to connection requests. This is illustrated in figure 5.3 at phase of $RoutingAndWavelengthSelection(\;)$.

When traffic is generated from a random source s to a random destination, then the algorithm searchs in the P-route table of s into the list of all the routs. Given several possible destination d_i, the chosen path is based on the highest probability value for next hop for each destination.

```
1: Function: AntGeneration( )
2: repeat
3:      For each node in the network do
4:      select a random destination
5:      launch ants to this destination with probability p
6:      End for
7:      increase the time by a time − step for ants' generation
8: until end of simulation
9:
10: Function: AntForaging( )
11: For each ant from source s to d (in parallel) do
12:      while current node i ≠ d do
13:      update routing table elements
14:      push trip's state into the stack
15:          if (found a next − hop) then
16:          move to next − hop
17:          else
18:          kill ant
19:          End if
20:      End while
21: End For
22:
23: Function: RoutingAndWavelengthSelection( )
24: For each request do
25:    For each candidate node destination do
26:     select k paths from P − route table starting from s to d
27:     send needle ant packets over the k paths between s and d
28:    End for
29:    For at every destination node do
30:    choose path with highest goodness value having one free wavelength and
       track the path length
31:       if more than one free wavelength is available on a path then
32:       choose one free wavelength randomly
33:       acknowledge the source with the path and free wavelength chosen
34:       End if
35:       if no wavelengths are available then
36:       acknowledge to source that no path can be set
37:       End if
38:    End For
39:    source s chooses the destination with the shortest path length
40:    setup lightpath over the chosen path and wavelength
41: End For
```

Figure 11 Proposed ACO-based routing algorithm

The wave length is randomly assigned among the free wavelengths by di If the chosen rout Li has more than one wavelength free.

After that we follow this procedure by every node in the destination set in order for the request's source node to compute a set of lengths for every candidate destination $(L1, L2, \ldots, Lm)$.

After the best route is selected for each connection request in the first phase, the wavelength is selected in the second phase and finally the selected path is reserved for the new arriving request.

5.5 Results and Analysis

In order to study the proposed ant colony algorithm routing based and wavelength assignment, an extensive simulation enviirement has been built for system verification and analysis. The network environment is built using MATLAB/OPNET Co-operation. For comparison and verification our results, the performance metrics is compared with OSPF routing. The OSPF network is built using OPNET and its routing table is used in MATLAB to provide OSPF routs. Figure 5.4 illustrates the block diagram of the proposed ACO used in this work.
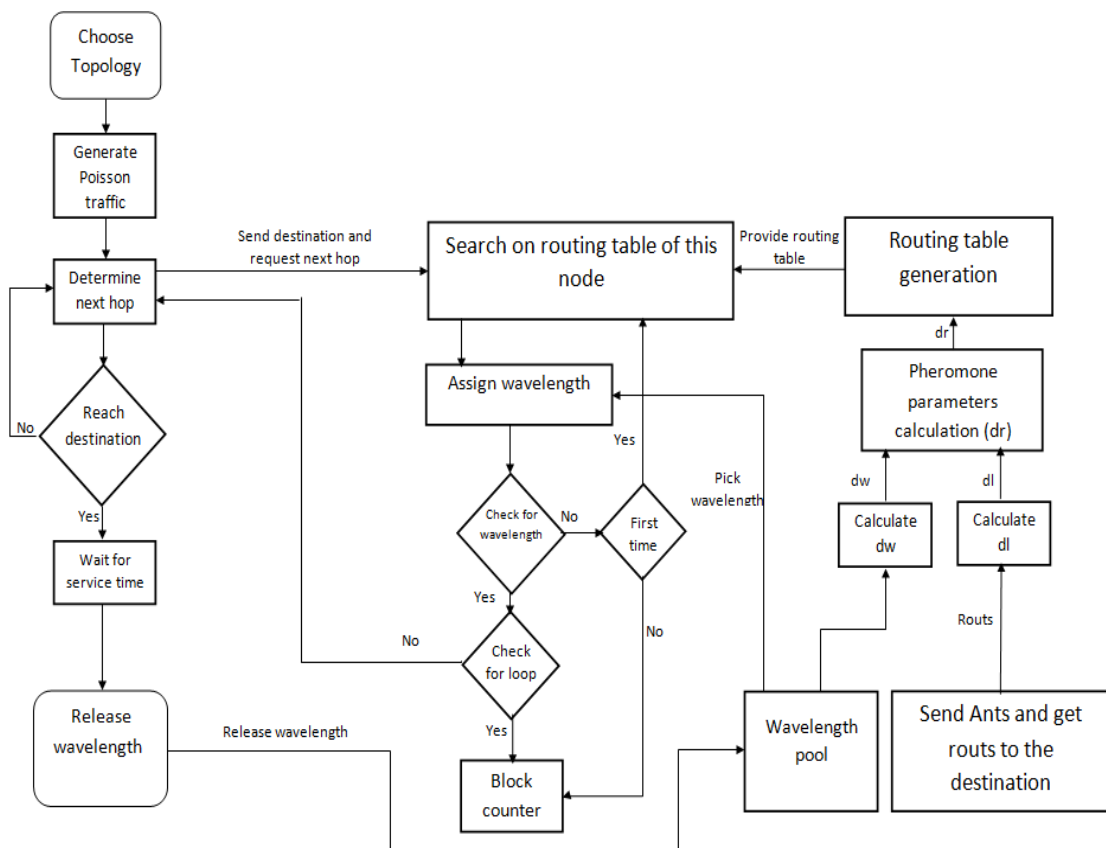
Figure 12 Block diagram of the proposed ACO algorithm

5.5.1 Simulation settings

In the following, we will present the network topologies that have been used in simulation and the main characteristic of generated traffic for system verification and analysis.

5.5.1.1 The selected network topology

Following [42], three typical network topologies are adopted in our simulation as shown in figure 5.4. The main properties of each network topology are characterized by three parameters:

- The average of shortest path (H),
- The variance of the average shortest path (D)
- The number of nodes (N).

Basically, these parametrs has a direct impact in the routing problem difficalty[23]. According to these three parameters (H, D, N,), we can diffrentiate between diffirent network topolgies. İn our simulation, The following network topologies are selected

1. Simple Net (1.5, 0.4, 6) which has 8 links
2. NSFNet backbone (2.2, 0.6, 14) which has 21 links
3. ARPA-2 backbone (3.5, 2.7, 21) which has 26 links.

5.5.1.2 Traffic generation scenario

To generate taffic in simulation scenario, the general dynamic traffic model widely accepted in the performance evalution of data communication networks is adopted. In order to adopt more realistic simulation, Suppose we have connection requests with arrival rate λ (call/s) and follows a Poisson process. These arriving connection requests are randomly distributed between nodes. The holding time of active sessions is exponentially distributed with mean μ (the mean holding time of active session is T seconds). The network load is computed by $T\lambda\mu$ (Erlangs) where T is the total number of sessions over the entire network, λ is the arrival rate and μ is the service rate. In our scenarios, we keep the parameters T and μ constants and varying the arrival rate to study the network performance under different traffic loads. These is repeated at $\mu = 10$ sec and $\mu = 20$ sec.

a.SimpleNet (1.5, 0.4, 6) with 8 links
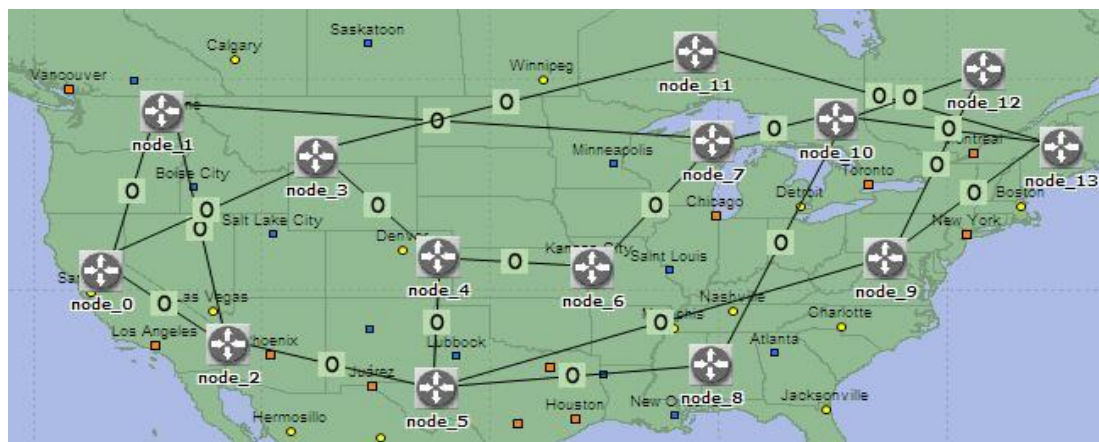
b.NSFNet backbone (2.2, 0.6, 14) with 21 links

c. ARPA-2 backbone (3.5, 2.7, 21) with 26 links.

Figure 13 Network topologies used in simulation

5.5.2 OSPF algorithms used for comparison

The routing algorithms used for comparison are the OSPF alglorithm. In OSPF routing algorithm, each node has a routing table that contains a list of fixed routes to each destination node with different cost for each routs and next hop for each of these routes according to Dijkstra algorithms.
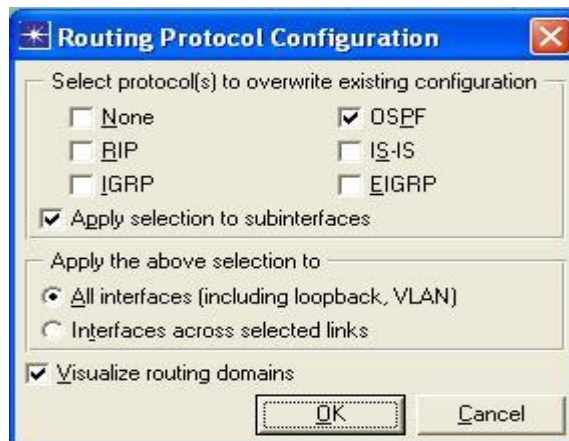
Figure 14 OSPF Routing Protocol Configuration

When a connection request arrives, the source node send call to the next hop according to the routing table which in turn forwards the call to the next hop specified in its routing table for destination node. In each node, when the next hop is determined the wavelength is picked in sequence for lightpath establishment. In case there is no available wavelength is available the request is blocked.

Figure 15 OSPF Routing Protocol Configuration

All the routing algorithms in this paper use the First-Fit heuristic for wavelength assignment. The routing table of the OSPF algorithms in our simulation is picked out from OPNET simulation (for the selected three topologies) and is used in the MATLAB environment.

	Destination	Source Protocol	Route Preference	Metric	Next Hop Address	Next Hop Node	Outgoing Interface	Outgoing LSP	Insertion Time (secs)
1	192.0.1.0/24	Direct	0	0	192.0.1.1	Enterprise Network.node_0	IF10	N/A	0.000
2	192.0.2.0/24	OSPF 1	110	44	192.0.3.2	Enterprise Network.node_2	IF11	N/A	22.191
3		OSPF 1	110	44	192.0.1.2	Enterprise Network.node_1	IF10	N/A	32.191
4	192.0.3.0/24	Direct	0	0	192.0.3.1	Enterprise Network.node_0	IF11	N/A	0.000
5	192.0.4.0/24	OSPF 1	110	44	192.0.1.2	Enterprise Network.node_1	IF10	N/A	32.191
6	192.0.5.0/24	OSPF 1	110	44	192.0.3.2	Enterprise Network.node_2	IF11	N/A	22.191
7	192.0.6.0/24	OSPF 1	110	66	192.0.3.2	Enterprise Network.node_2	IF11	N/A	32.191
8		OSPF 1	110	66	192.0.1.2	Enterprise Network.node_1	IF10	N/A	32.191
9	192.0.7.0/24	OSPF 1	110	66	192.0.1.2	Enterprise Network.node_1	IF10	N/A	32.191
10	192.0.8.0/24	OSPF 1	110	66	192.0.3.2	Enterprise Network.node_2	IF11	N/A	32.191
11									
12	Gateway of last resort is not set								
13									

a.SimpleNet routes
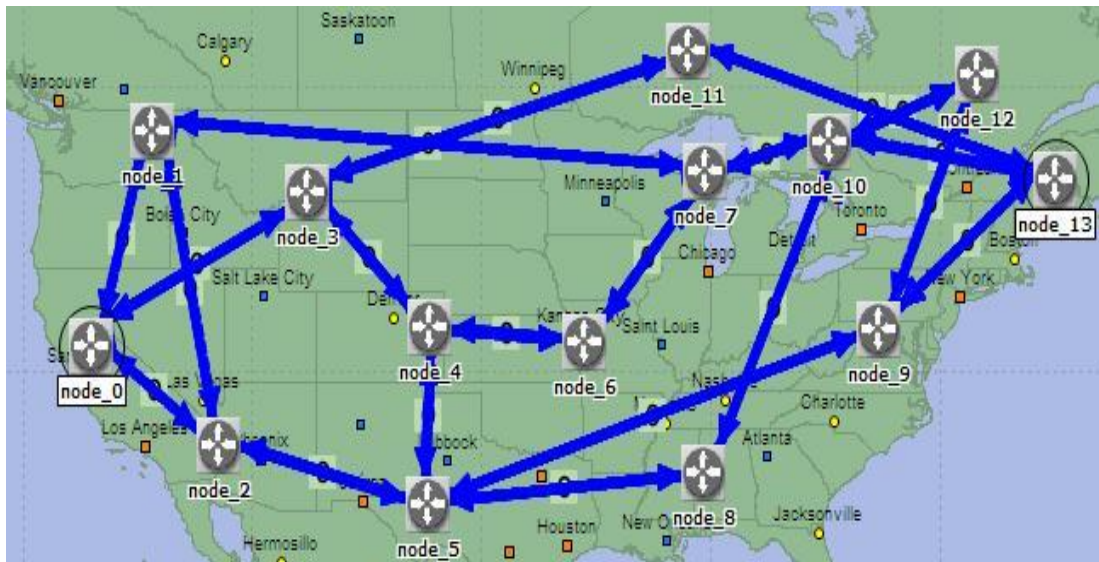
Performance.IP Forwarding Table at End of Simulation for Enterprise Network.node_0

File   Edit   View   Help

	Destination	Source Protocol	Route Preference	Metric	Next Hop Address	Next Hop Node	Outgoing Interface	Outgoing LSP	Insertion Time (secs)
1	192.0.1.0/24	Direct	0	0	192.0.1.1	Enterprise Network.node_0	IF10	N/A	0.000
2	192.0.2.0/24	Direct	0	0	192.0.2.1	Enterprise Network.node_0	IF11	N/A	0.000
3	192.0.3.0/24	OSPF 1	110	44	192.0.1.2	Enterprise Network.node_1	IF10	N/A	24.399
4		OSPF 1	110	44	192.0.2.2	Enterprise Network.node_2	IF11	N/A	34.399
5	192.0.4.0/24	Direct	0	0	192.0.4.1	Enterprise Network.node_0	IF4	N/A	0.000
6	192.0.5.0/24	OSPF 1	110	44	192.0.4.2	Enterprise Network.node_3	IF4	N/A	34.399
7	192.0.6.0/24	OSPF 1	110	44	192.0.2.2	Enterprise Network.node_2	IF11	N/A	34.399
8	192.0.7.0/24	OSPF 1	110	66	192.0.2.2	Enterprise Network.node_2	IF11	N/A	34.399
9		OSPF 1	110	66	192.0.4.2	Enterprise Network.node_3	IF4	N/A	34.399
10	192.0.8.0/24	OSPF 1	110	66	192.0.4.2	Enterprise Network.node_3	IF4	N/A	34.399
11	192.0.9.0/24	OSPF 1	110	44	192.0.1.2	Enterprise Network.node_1	IF10	N/A	24.399
12	192.0.10.0/24	OSPF 1	110	66	192.0.1.2	Enterprise Network.node_1	IF10	N/A	24.399
13	192.0.11.0/24	OSPF 1	110	66	192.0.2.2	Enterprise Network.node_2	IF11	N/A	34.399
14	192.0.12.0/24	OSPF 1	110	66	192.0.2.2	Enterprise Network.node_2	IF11	N/A	34.399
15	192.0.13.0/24	OSPF 1	110	66	192.0.1.2	Enterprise Network.node_1	IF10	N/A	24.399
16	192.0.14.0/24	OSPF 1	110	88	192.0.1.2	Enterprise Network.node_1	IF10	N/A	24.399
17		OSPF 1	110	88	192.0.2.2	Enterprise Network.node_2	IF11	N/A	34.399
18	192.0.15.0/24	OSPF 1	110	44	192.0.4.2	Enterprise Network.node_3	IF4	N/A	34.399
19	192.0.16.0/24	OSPF 1	110	88	192.0.2.2	Enterprise Network.node_2	IF11	N/A	34.399
20	192.0.17.0/24	OSPF 1	110	88	192.0.1.2	Enterprise Network.node_1	IF10	N/A	24.399
21	192.0.18.0/24	OSPF 1	110	88	192.0.1.2	Enterprise Network.node_1	IF10	N/A	24.399
22		OSPF 1	110	88	192.0.4.2	Enterprise Network.node_3	IF4	N/A	34.399
23	192.0.19.0/24	OSPF 1	110	66	192.0.4.2	Enterprise Network.node_3	IF4	N/A	34.399
24	192.0.20.0/24	OSPF 1	110	88	192.0.2.2	Enterprise Network.node_2	IF11	N/A	34.399
25		OSPF 1	110	88	192.0.4.2	Enterprise Network.node_3	IF4	N/A	34.399
26									
27	Gateway of last resort is not set								

b. NSFNet routes

c. ARPA-2 routes

Figure 16 All possible routes in all scenarios

5.5.3 Parameters setting and tuning

In this section we provide the main parameters used in our simulations. The time step for ant generation is set as t=1s. In comparing with OSPF, the numbers of wavelengths *W* per link, 8 and 16, are used in the simulation. For each case, the proposed number of sessions is 10 *T* sessions with the session holding time being set to 5s. By varying the arrival rate λ we can get different load values. The range of arrival rate is chosen in accordance that OSPF algorithm can achieve a practical blocking probability (about 5%). To obtain stable results, each experiment is executed in 150s and it is repeated twenty times. This twenty times is then averaged to obtain the blocking probability.

5.5.4 Optimization of pherormone parameters

One of very important object is the design of pherormone parameters which rarlely considred in most previous research despite of its great impact in the path selection at each node and consequently the obtained blocking rate. Obtaing the optimum seting of parameters ($α$, $β$, $γ$) for ACO algorithm which provide best system performance remains an open issue, which deserves further research efforts [42]. In this part will try to get the most suitable pherormone parameters that optimized system performace.

In the following, we will study the system behavior with respect to each each pherormone parameters. In order to trace the effect of each parameters individually, two of the three parameters should be constant while varying the third one. According two equations 5.7 & 5.8, there are three parameters: $β$ which rfers to the link length, $γ$ which refers the free wavelength at each link and finally α which used for adjusting the emphasis in link length or free wavelength available.

In order to more accurate parameters, the system performance will be extended at different load rates.

Figure 5.9 dipicts the blocking rate when varying $β$ while $α$ & $γ$ are constant. The regions of lowest blocking probability at each load are indicated. The optimized value of $β$ depends on the selection probability for each $β$ which illustrated in Figure 5.10. From figure 5.10, we can notice that region with low $β$ value has smaller selection probability that one in region wih high $β$ values. According to equation 5.7 the selected value of α will depend on the region at which β will work. In short, if we

take β in low region value (for example β=0.5), small values of α should be taken as well (this is because the linear relation of equation 5.7) and vice versa.
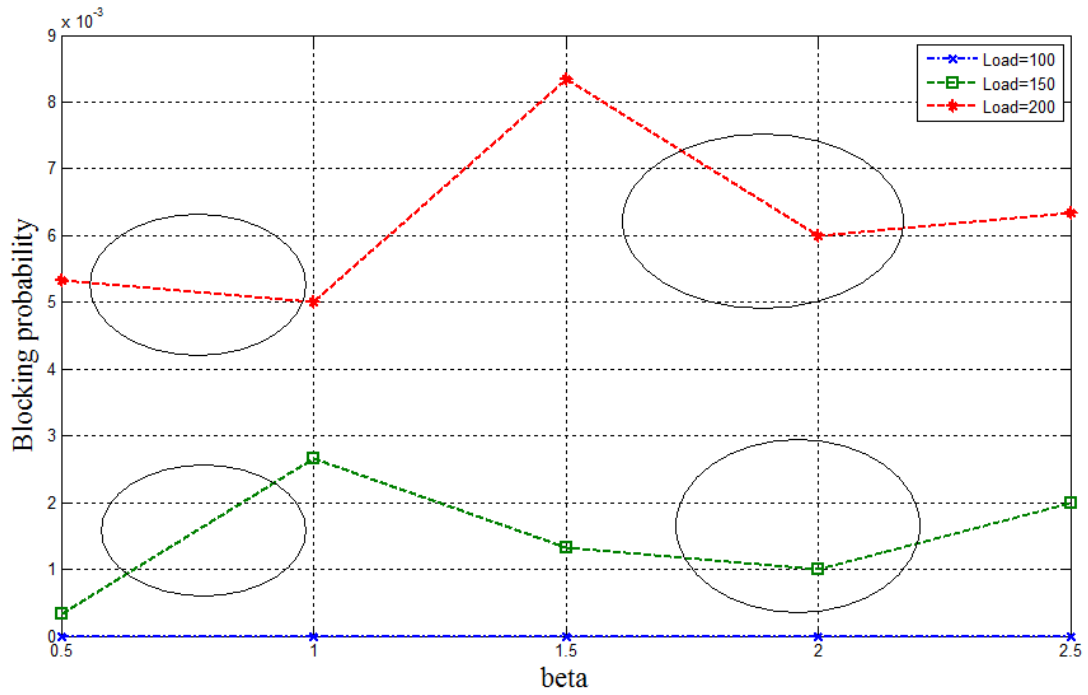

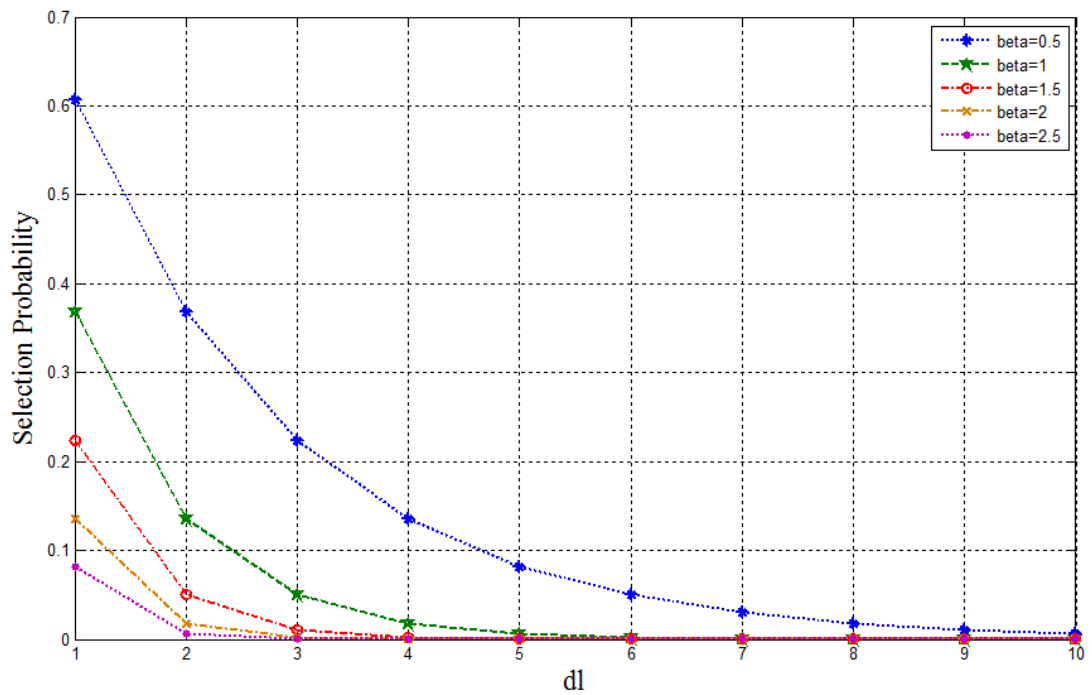**Figure 17** The blocking probability at different values β with 14 node network

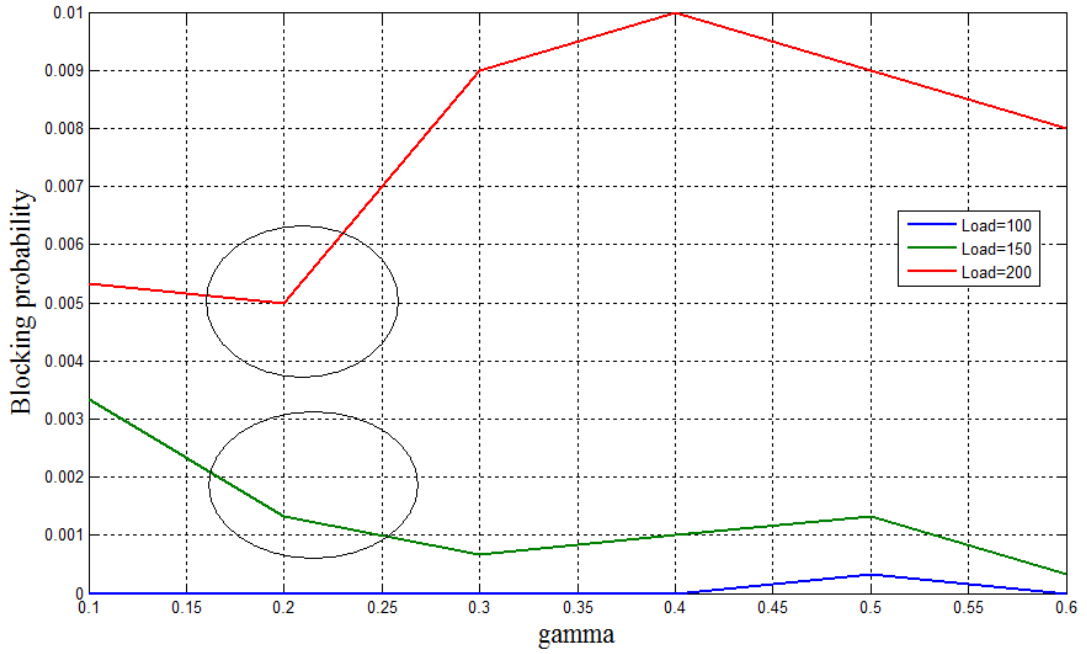**Figure 18** The Selection probability at different values dl.

Figure 19 The blocking probability at different values γ with 14 node network

Figure 5.11 depicts the relation between γ and blocking probability at different load values. It can be shown that region with γ less than 0.2 provides less blocking rate at different load.

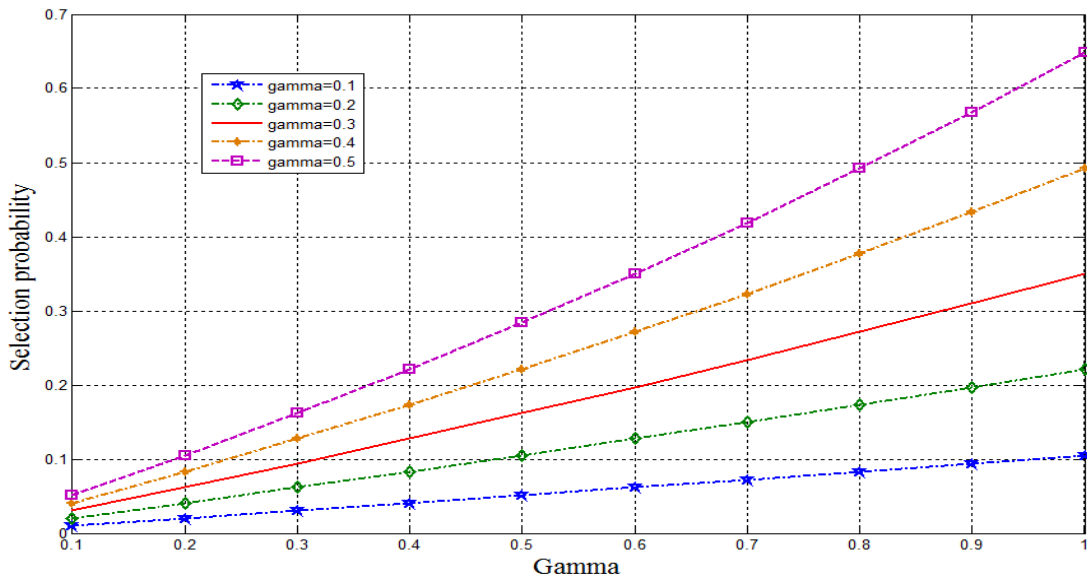In order to select α which suited to choosen γ, the selection probability of γ is provided at figure 5.12.

Figure 20 The Selection probability at different valuesof percent of free wavelength.

It can be noticed from figure 5.12, that the selection probability of $\gamma=0.2$ (in the selected region) varies from 0.02 to 0.21. This requires choosing low values of α for adjusting the emphasis in available free wavelength. In addition it suited for the ranges of γ values.

Figures 5.13 to 5.15 explain the blocking probability of the system in the three network topologies and compared with the blocking at OSPF algorithm. The number of wavelength in the obtained results is W =8 and the service rate μ = 10 sec while the number of sessions is set to T =10 sessions. The pheromone control parameters (α, β, γ) are equal to 0.2, 1.75 and 0.2 respectively. For convince and reasonability, the values of arrival rate were chosen such that the obtained blocking probability to be not to exceed its practical values.
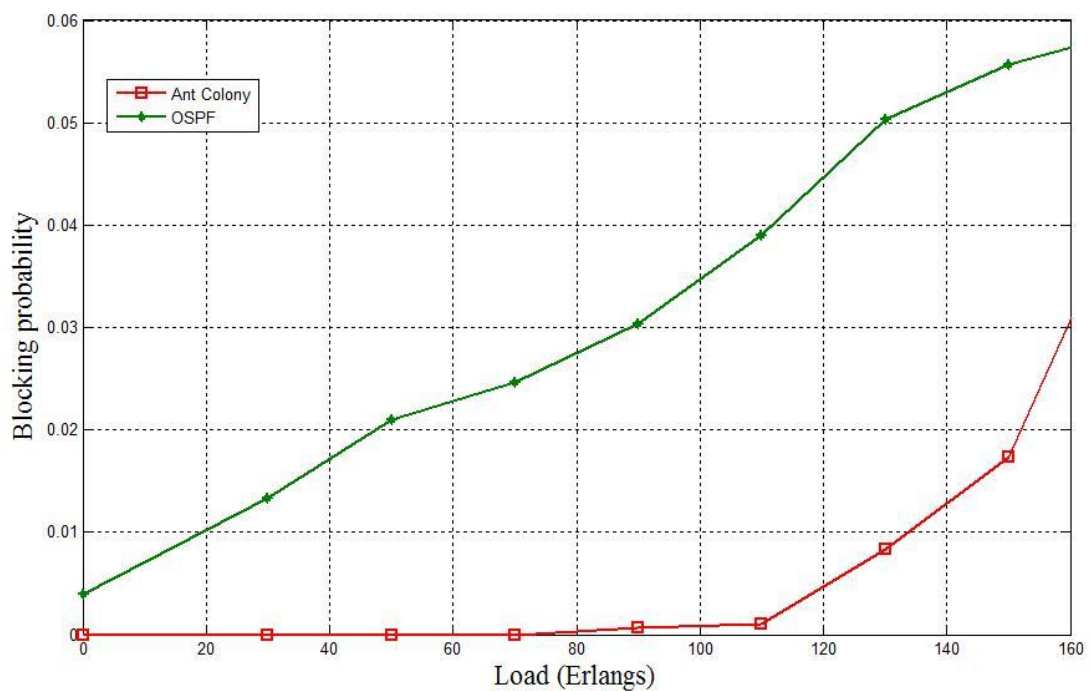

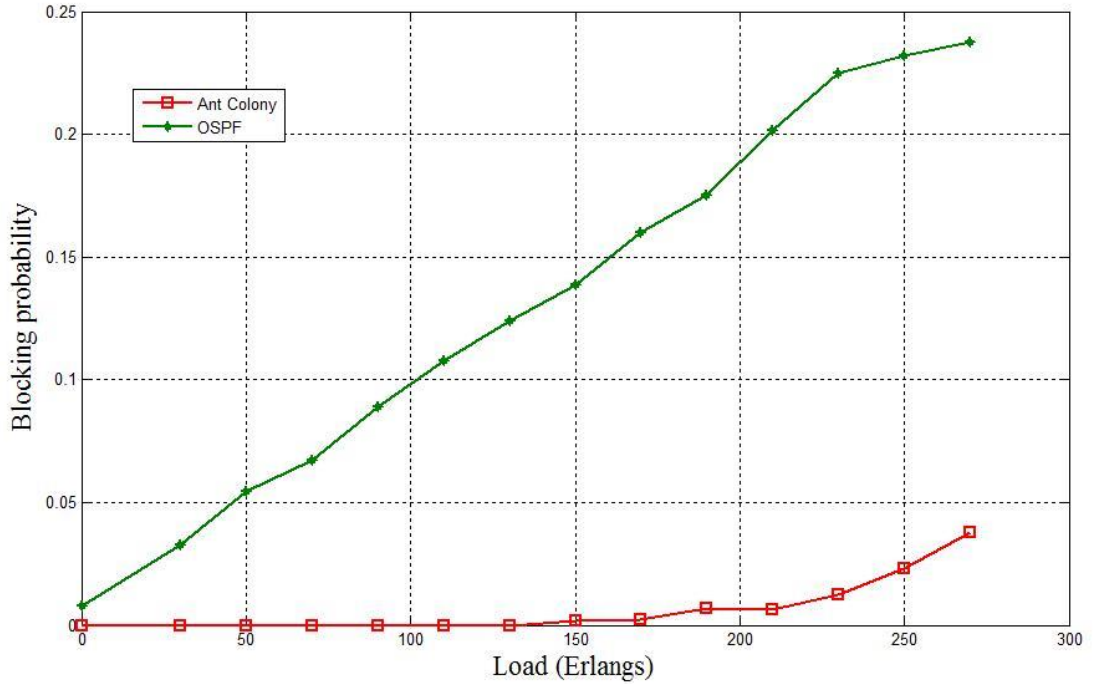**Figure 21** Comparison between blocking probability for ACO and OSPF at SimpleNet

Figure 22 Comparison between blocking probability for ACO and OSPF at NSFNet

It can be noticed from the three Figures that ACO algorithms provides better performance than OSPF at different load values. This can be interpreted as follow: In ACO, the routing policy is modified at every node by deposing a pheromone trail on its routing table; so the routing tables are adapted to the load changes at run time. So any change in both of wavelength and links are tracked and reported at each node routing table, so it is considered in each call next hop. These wavelength and links updates are not considered in OSPF case. So ACO behaves better than OSPF.

Another important aspect can be displayed when comparing the blocking probability at the three network topology is that blocking increases when the number of nodes increases and the network to be more complicated.
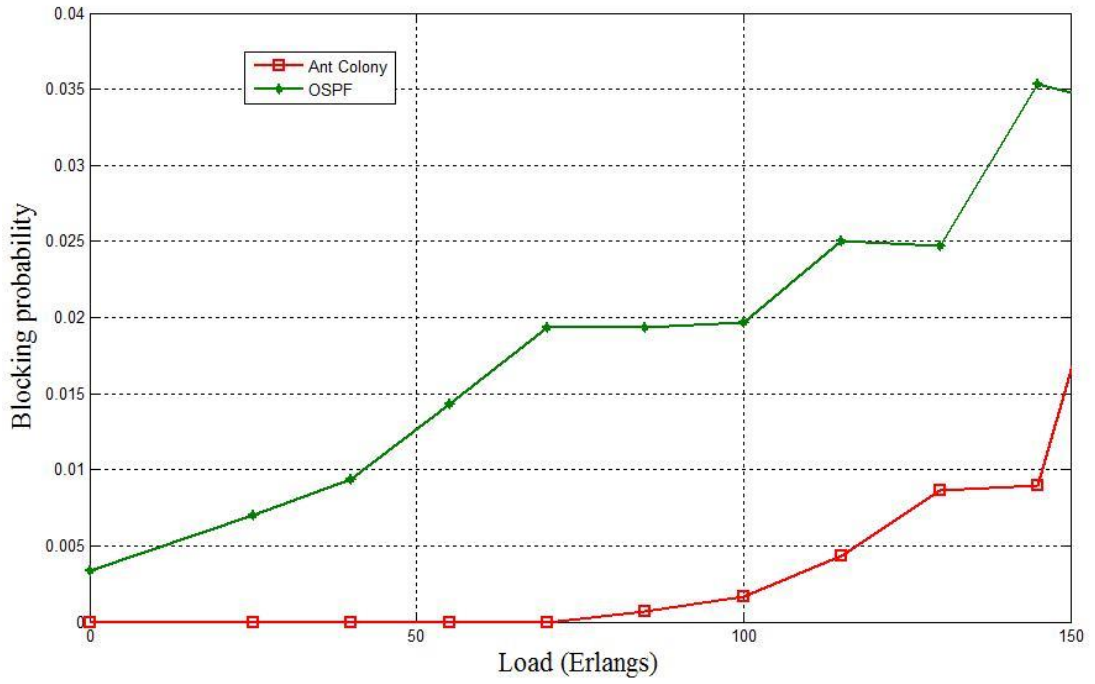
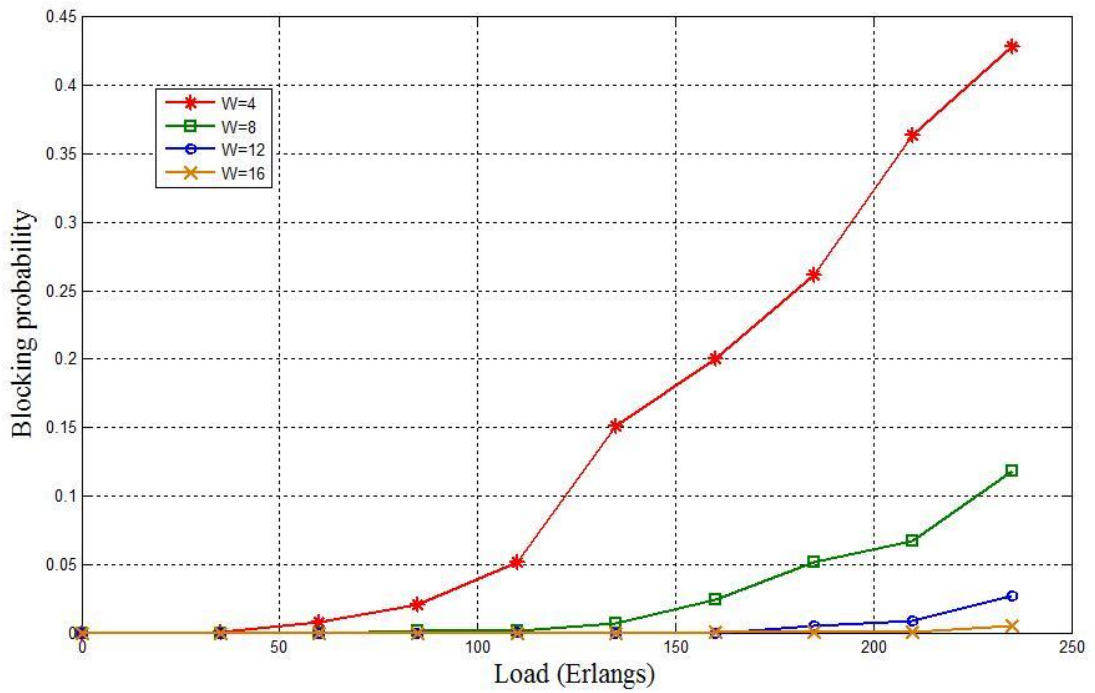**Figure 23** Comparison between blocking probability for ACO and OSPF at ARPA-2

Figure 24 The blocking probability at different values wavelength W at SimpleNet
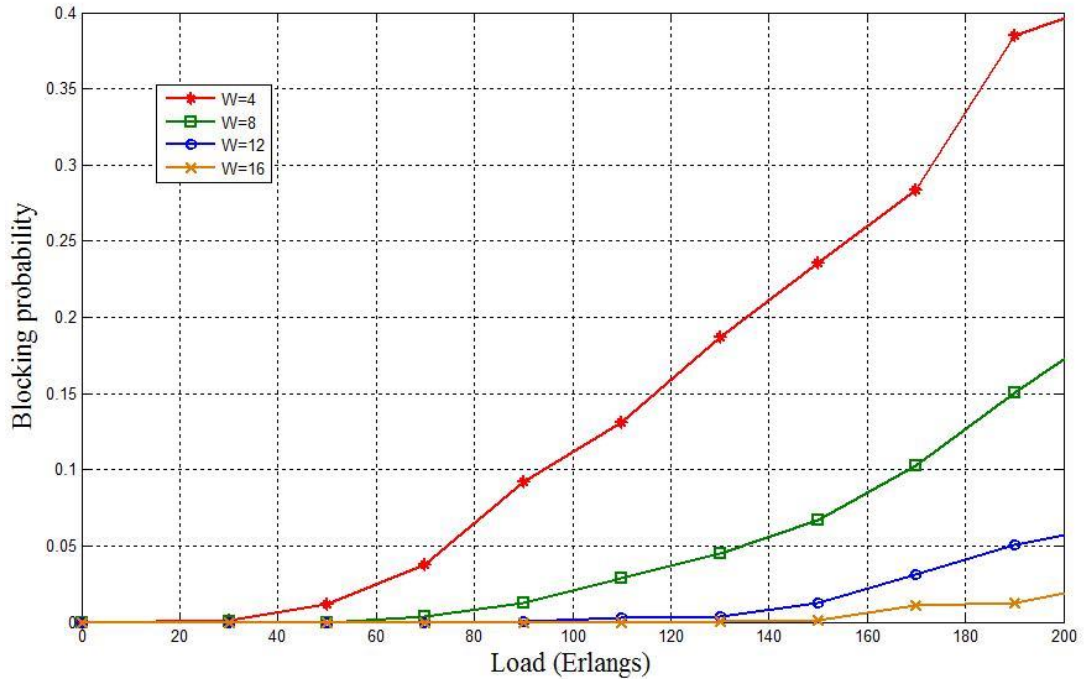
at μ= 10 sec

Figure 25 The blocking probability at different values wavelength W at SimpleNet
at μ= 20 sec

In the following, the impact of varying the number of wavelength in the blocking probability is introduced.

Figures 5.16 & 5.17 shows the blocking probability at different values of W as a function of call arrival rate at first network topology (6 nodes). It is observed that as W decreases, the blocking probability increases rapidly. This because the routs will not find sufficient wavelength for the lightpath to go through and so more call will be blocked. The service rate at figure 5.16 and 5.17 is set to be 10 sec and 20 sec respectively.

The effect of changing the service rate can be noticed when comparing results of figures 5.16 & 5.17. It can be shown that when the service rate increases the blocking rate increases because the channels will release faster and so more routes will be available for new call request.

Similar results can be obtained from figures 5.18 & 5.19 for second network topology and figures 5.20 & 5.21 for third network topology.

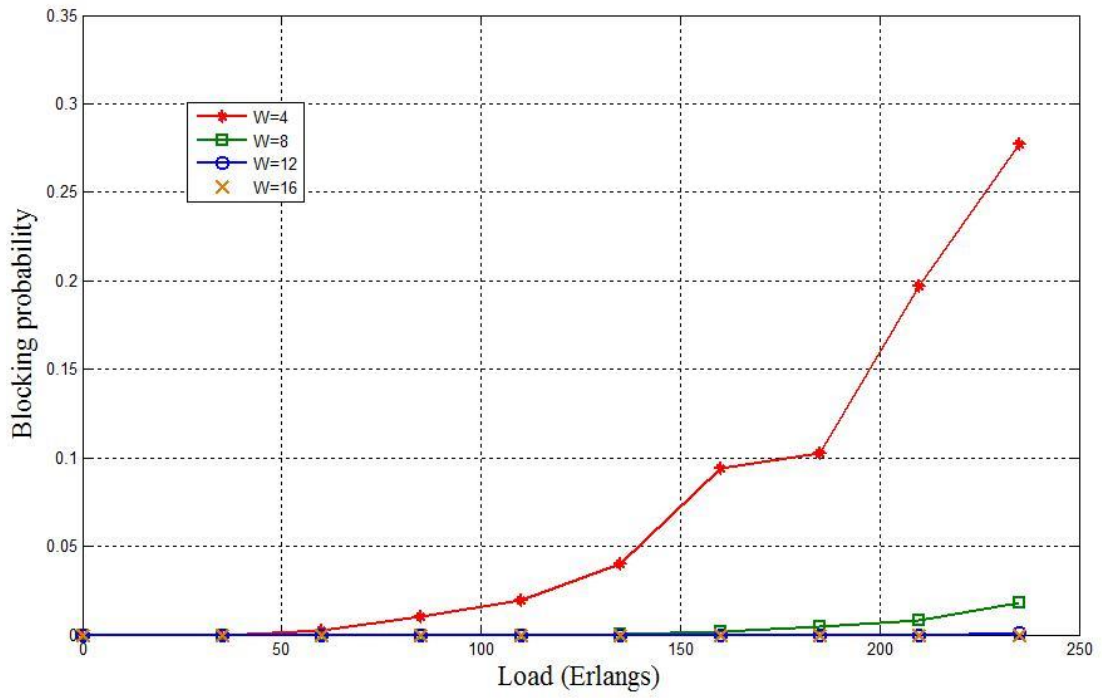**Figure 26** the blocking probability at different values wavelength W at NSFNet at
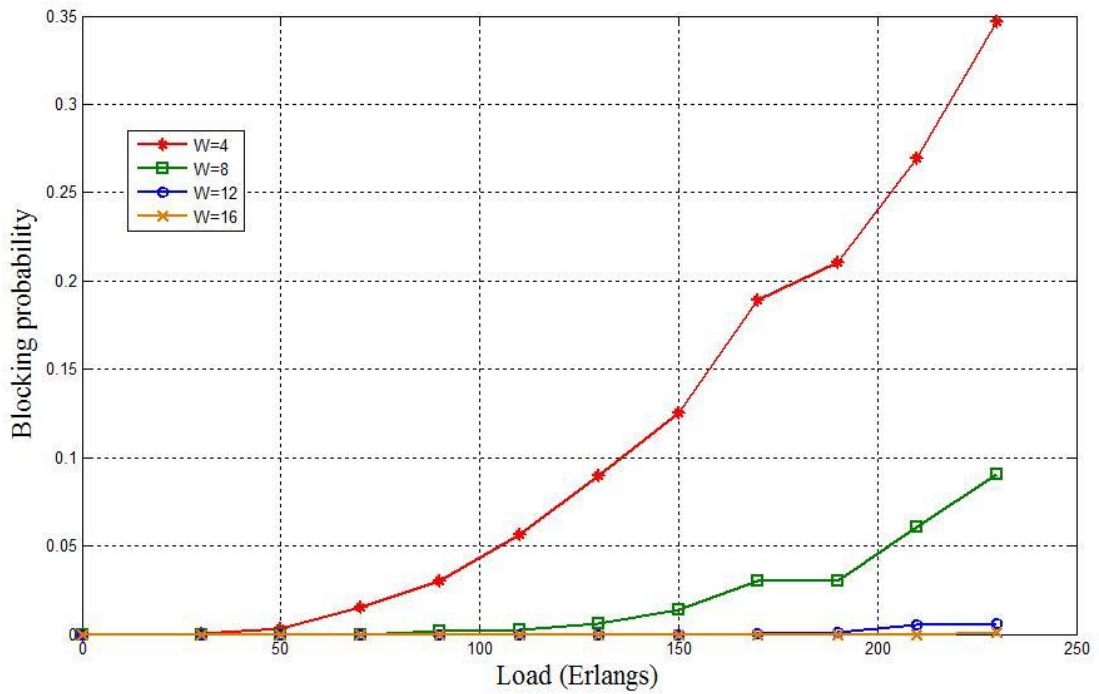
μ= 10 sec

Figure 27 The blocking probability at different values wavelength W at NSFNet at
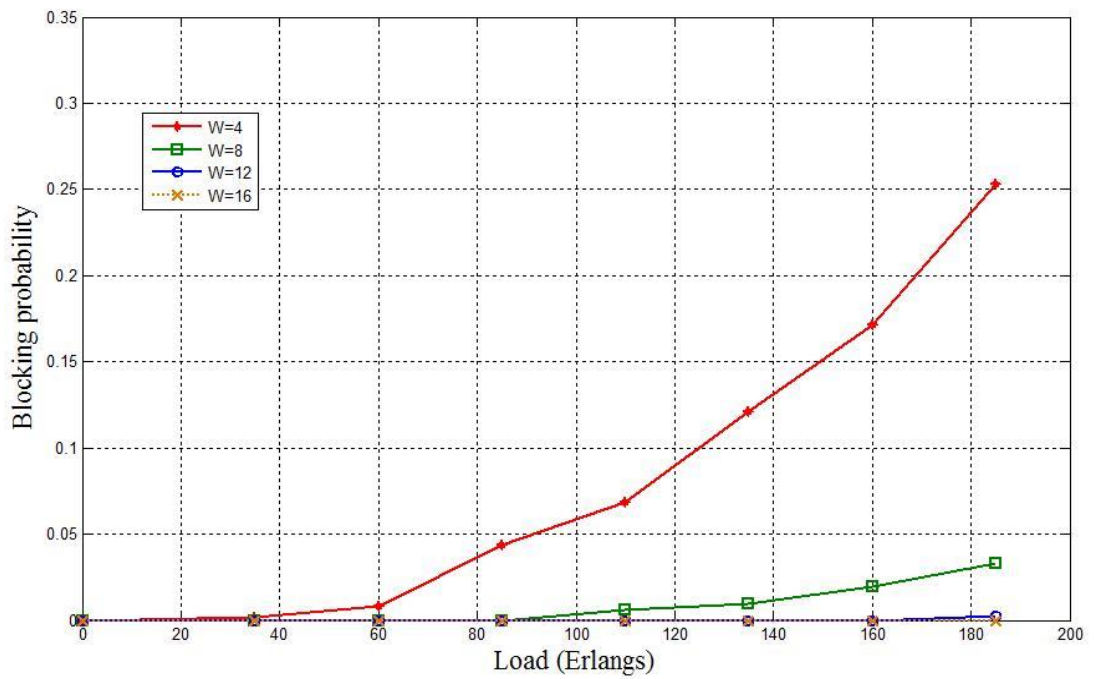
μ= 20 sec

Figure 28 The blocking probability at different values wavelength W at ARPA-2 at
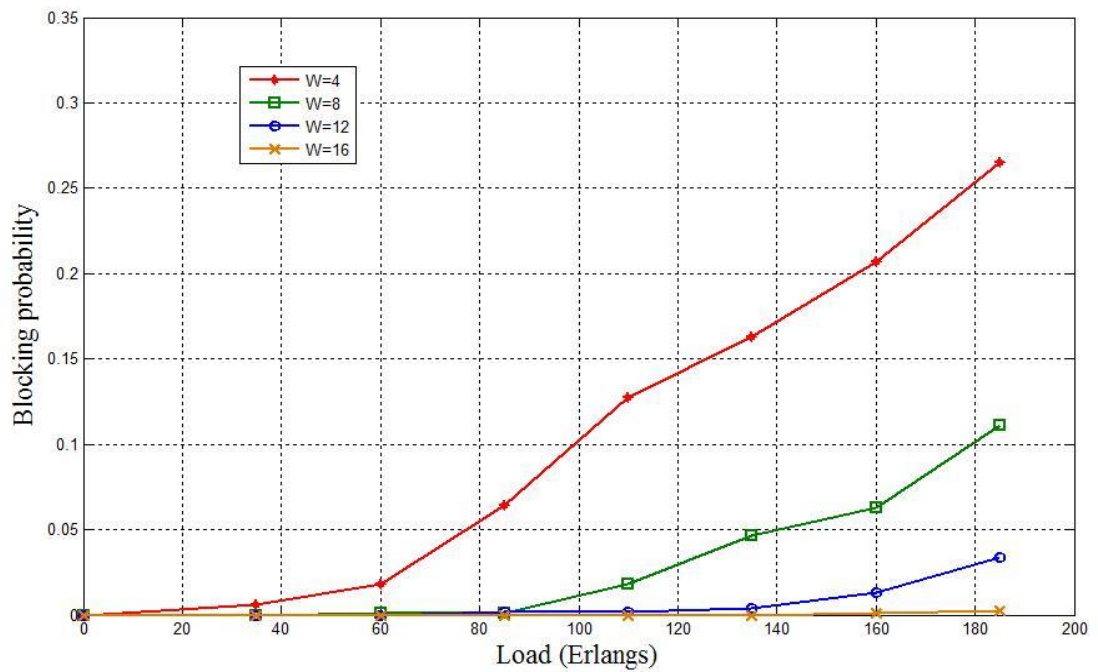
μ= 10 sec

Figure 29 The blocking probability at different values wavelength W at ARPA-2 at

μ= 20 sec

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

In the current work, Multi-Node Optimized Ant Colony Algorithm (M-NOACA) is proposed to solve the RWA (routing and wavelength assignment) problem in AON (All Optical Networks) by simulating traffic with the routing and wavelength assignment (RWA) algorithms on all-optical WDM networks. In this thesis, a study is done to implement M-NOACA with an optimum set of parameters for an ant based algorithm to solve RWA problem. The main milestones of this work can be concluded in the following points:

- A complete model for M-NOACA with wavelength assignment is developed using MATLAB. The proposed algorithm is generic and is designed to be valid with any number of nodes and an optimal setting of pheromone parameters is deduced.

- A new contribution to obtain the optimal setting of Ant Colony algorithm parameters is introduced.We have created

- A co-operation between MATLAB and OPNET is created to allow MATLAB to use its strong mathematical functionality and OPNET to use its ability to manipulate simulations.

- The performance and behavior of the network and different synario is analysed and evaluted.

- For comparison and verification, a shortest path first model is built in different three scenarios by using OPNET and its routs are fed into MATLAB model for accurate verification to the proposed model

- A performance metrics in terms of blocking probability with different number of wavelength assignment is developed and a comparison with OSPF

algorithm is introduced. The impact of deposing a pheromone trails in each node routing table is evaluated.

Through numerical results and analysis the following can be concluded:

- The ACO approach is an effective technique in getting optimal routs. This approach includes the routing mechanisms,table structures used by the ACO algorithm and the way they get updates depending on exploring the network using a suitable number of ants.
- Simulation results show that the ant colony optimization based algorithm provides significant improvements over the traditional shortest path first algorithm, and also performs significantly better than other dynamic load based routing algorithm.
- The proposed algorithms significantly reducing setup delay. In addition, this algorithm is flexible in the sense that to achieve a better performance.
- Extensive simulation results upon different network topologies indicate clearly that ant-based algorithm consistently outperforms the other dynamic load-based routing algorithm in different network topologies.
- These attractive properties make this ant-based dynamic (RWA) algorithm very promising for the next generation of WDM networks.

6.2 Future Work

In this model, the first fit wavelength assignment is considered. Other mechanism like mostly used and random method is left for future work. In addition, the pheromone control parameters are not considered in this work. An optimization in setting these control parameters is deeply needed which greatly has a great impact in routing updates and so in the overall network performance. This optimization can be adopted in future work. In this work, three familiar network topologies is studied and analyzed. Further research can be conducted in more complicated network topologies.

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