Optimal Wavelength Allocation and Flow Assignment for Optical Networks for Profit Maximization

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Abstract -- **Automated Switched Optical Networks (ASON) are based on control strategies that determine the optimal distribution of flows over different wavelengths, increase the profit, by allowing service providers to define and deploy new service offers. In this paper, we examine a demand elasticity based model for wavelength and flow assignment in multiwavelength optical networks. The model assumes that the physical and logical topology of the optical network, the maintenance cost for all physical links, and the traffic demands are known parameters. A mixed integer optimization is employed to determine wavelength allocation and flow assignment of the requested traffic demand. One of the novelties of this work is the optimization cost function, used for the profit maximization of the transport service supplier. A case study is presented, showing how the bandwidth demand affects the supplier's profit. Also, a comparison between the profitability of the proposed profit maximization and shortest path routing is provided.**

Keywords – **wavelength allocation, mixed integer programming, demand elasticity, profit maximization**

I. INTRODUCTION

Wavelength-division multiplexing (WDM) has been used extensively in existing transport networks. The deployment of optical cross-connects (OXCs) and add-drop multiplexers (ADMs) is the next step in developing reconfigurable optical networks. These networks have the potential to provide on-demand establishment of high-bandwidth connections, also called lightpaths. The deployment of these optical network components led to the *Wavelength Routed Optical Networks* (WRON). Of particular interest are the optical mesh networks, which are seen as the future design of optical networks. An optical mesh network [10] consists of optical OXCs interconnected by DWDM links. Associated with these OXCs are controllers that facilitate communications among them. These controllers may be internal or external to the controlled OXCs. An optical channel (OCh) connection through the optical transport network (OTN) is established along a route of available capacity (wavelength availability) between its designated ingress and egress points. The OCh connection between the source and the destination OXCs is comprised of a series of OXCs interconnected by OCh link connections. The establishment of OCh connections using appropriate wavelengths is known as Routing and wavelength assignment (RWA) [2].

The RWA can be cast as an *optimization problem* [1], [2], [3] and can approached in a number of different ways, using various cost functions. In the related papers the approaches followed are: establishing all connections using a minimum number of wavelengths; establishing all connections using minimum path lengths; maximizing the number of the connections subject to a constraint on the number of wavelengths and/or the path lengths or their combinations [2]. The novelty in the presented RWA is that the cost function is defined as the *profit of operating the network*. To the best of our knowledge, there is no work in the open literature, addressing the RWA in this fashion. Only optical networks, optimally operating in terms of profitability, can satisfy the increasing demand for bandwidth.

A. *An overview of topological design problems*

The main design problem addressed in this paper is to find the proper connectivity and traffic routing strategy within the optical network that maximizes revenue and satisfies requests. The network traffic is given as a logical (virtual) topology that has to be mapped on the optical network. Transport network routing [8] procedures typically utilize explicit routing, where the path selection can be done either by an operator or by software-scheduling tools in resource management systems. This problem addresses mainly a backbone provider who runs a high capacity network and has connections to other backbone providers and Internet service providers. This business entity is defined as infrastructure layer [7]. The *design objective* is to maximize the network service supplier profit and compute the actual set of flows through the network. In a switched optical network, end-to-end optical channel connections are requested with certain constraints. Path selection for a connection request should employ constrained routing based algorithms that balance multiple objectives, while conforming to physical constraints such as network topology and load balancing of network traffic in order to achieve the best utilization of network resources.

II. ECONOMIC CONSIDERATIONS

In order to achieve the design objective, a transport service provider, in addition to the technical aspect of the flow assignment and routing, has to deal with economic considerations such as service demand, profit maximization, pricing of services etc. In this section, economic terms necessary for the formulation of the allocation strategy are introduced and explained.

A. *Demand and elasticity*

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In [7], [12] the definitions for demand elasticity and demand potential can be found. For every commodity on the market there is a *demand* '*d*' and *price* "*p*". The *demand elasticity* "*E*" is defined within a time interval as a negative ratio of the percentage change in demand and the percentage change in the price during that interval. Thus, for Δd denoting the change in demand and Δp denoting the change in price, $E = -\frac{\frac{\Delta d}{d}}{\frac{\Delta p}{p}}$ [7].

Assuming constant demand elasticity *E* for all *p* and *d*, the general form for the *demand function model* is $d(t) = Ap(t)^{-E}$ where *A* is a constant denoting the *demand potential* [7],[13]. For simplicity, we shall omit the dependence of the various functions on time *t*. The *revenue*, denoted by "*R*", is the product of the price and the demand, henceforth, $R = p.D$.

B. Supplier's revenue

We assume that a network service provider is operating as ***monopolist*** [13], which means that he is the sole provider of services in an unregulated monopoly. We define the *demand vector* $d = (d_1, \ldots, d_k)$ as *k* customer requests for bandwidth, $A = (A_1, \ldots, A_k)$ as their *demand potential* and $p = (p_1, \ldots, p_k)$ as their *price vector* for charging these requests. We assume that the services *y*, which the provider offers to the *k* different customers, meets the demand *d*. This kind of service is a ***bandwidth allocation service for requested optical connections***. Taking into consideration the dependence between demand and pricing [13], and assuming that the elasticity *E* of the optical network services is equal for all *k* customer demands, we can derive [13] the ***supplier's revenue*** as:

$$\sum_{i=1}^{k} p_i \cdot d_i = \sum_{i=1}^{k} \left(\frac{d_i}{A_i} \right)^{-\frac{1}{E}} \cdot d_i = \sum_{i=1}^{k} d_i^{\frac{E-1}{E}} \cdot A_i^{\frac{1}{E}} \tag{1}$$

The ***supplier's profit*** or ***payoff*** is determined by the ***cost*** of operating the network and the ***physical constraints*** associated with the network. The payoff is introduced in the next section.

C. ROUTING AND CHANNEL ASSIGNMENT IN OPTICAL NETWORKS

The formulation of the RWA problem as an optimization problem can be done in different ways using various cost functions [2], [3]. The network topology [2] is modeled by a set of nodes, $N = \{1, 2, \ldots, N\}$ and by a set of optical links $L = \{l_{xy}\}$, where l_{xy} denotes the unidirectional link from node *x* to node *y*. Every optical link l_{xy} is associated with utilization cost p_{xy}. The set of available wavelengths is denoted by $\Lambda = \{1, 2, \ldots, W\}$. The network traffic is given as a logical (virtual) topology $V = \{v_k\}$. A logical connection v_k has wavelength demand d_k and is associated with wavelengths and a sequence of optical links. Based on this, we can designate the network parameters and variables, used for routing and wavelength allocation. The *network parameters* are: v_k, the logical topology we want to realize; d_k, the number of wavelengths (or bandwidth), demanded by customers for every logical channel; f_{xy}, the number of fibers (link capacity) on the link l_{xy}; p_{xy}, the utilization cost for every link. The *network variables* are: $b_{w,xy}^{k}$, the flow variable which is equal to one if a logical connection v_k is carried on link l_{xy} over fiber with wavelength *w* and zero otherwise; the binary variable Ω_w^k, which is equal to one if connection v_k is carried on wavelength *w* and zero otherwise. Using these network parameters and variables, we can define the ***supplier's profit*** for operating the optical network, based on the ***bandwidth demand*** and its elasticity in a monopoly market environment as follows [13]:

$$\sum_{i=1}^{k} d_i^{\frac{E-1}{E}} \cdot A_i^{\frac{1}{E}} - \sum_{i=1}^{k} \sum_{j=1}^{W} \sum_{l_{xy} \in L} p_{xy} \cdot b_{j,l_{xy}}^{i} \tag{2}$$

The routing and wavelength assignment can be formulated now as ***maximizing the profit*** (2), imposed on ***constraints*** (3), (4), (5), (6) given by the network topology [13]:

Flow conservation constraint: $$\sum_{j\neq x} b^{k}_{w,xj} - \sum_{j\neq x} b^{k}_{w,jx} = \begin{cases} +\Omega^{k}_{w} & \text{if } x \text{ is source of } v_k \\ -\Omega^{k}_{w} & \text{if } x \text{ is destinatio n of } v_k \\ 0 & \text{otherwise} \end{cases} \quad \text{for every node } x \tag{3}$$

Capacity constraint: $$\sum_{i=1}^{w} \sum_{j=1}^{k} b^{j}_{i,xy} + \sum_{i=1}^{w} \sum_{j=1}^{k} b^{j}_{i,yx} \leq f_{xy} \tag{4}$$

Constraint for one traffic direction over single wavelength: $$b^{k}_{w,xy} + b^{k}_{w,yx} \leq 1 \tag{5}$$

Traffic demand constraint: $$\sum_{i=1}^{w} \Omega^{k}_{i} = d_k \qquad b^{k}_{w,xy} \in \{0,1\} \quad , \Omega^{k}_{w} \in \{0,1\} \tag{6}$$

Equation (3) is the flow conservation equation, which states that a connection v_k entering node x on wavelength w must leave the node on the same wavelength, thus ensuring wavelength continuity. If x is the source (destination) node for the traffic component v_k, then the flow conservation relation is accomplished by including the term Ω^{k}_{w}, which takes into consideration the direction of the flow (s) (entering or leaving the network). Inequality (4) specifies the capacity limit of every optical link. Equation (5) implies that the links are bi-directional, but on a single wavelength the communication is only in one direction. Equations (6) ensures that the requested bandwidth demand, interpreted as the number of wavelengths for every optical connection, is actually allocated throughout the network [13].

III: ROUTING AND WAVELENGTH ASSIGNMENT AS OPTIMIZATION PROBLEM: CASE STUDY I

In the example below we consider a simple virtual topology (Fig.1), realized on an optical network (Fig.2). The desired virtual topology (Fig.2) consists of two optical channels v_1 and v_2 with requested wavelength bandwidths $d_1 = 3$ and $d_2 = 2$. The optical network topology and parameters are given in Fig. 2.

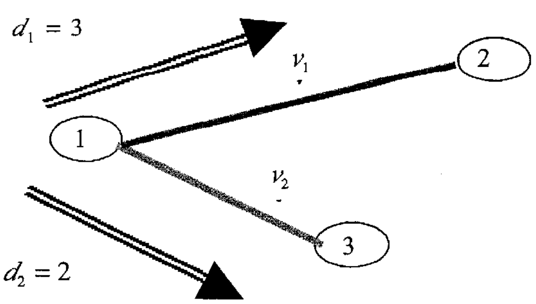

Fig. 1 Virtual topology

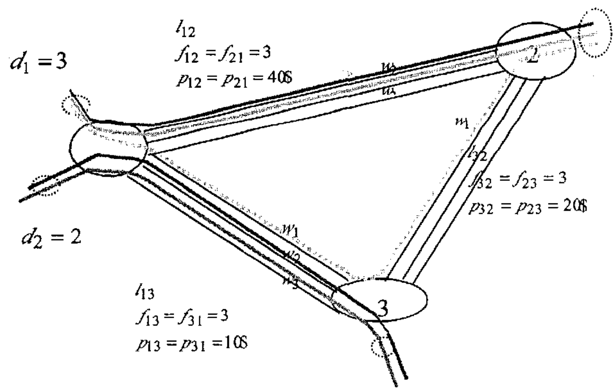

Fig. 2 Optical network

The RWA is carried out for the case where the service provider is a *monopolist* (see Section B). The solution of the optimization yields the wavelength allocation and corresponding optimal profit, cost and pricing (prices p_1 and p_2 are respective revenues for the service supplier) for the optical connections v_1, v_2. Throughout is assumed that the *demand potentials* A_1 and A_2 are already known. According to [7], the demand elasticity for optical networks is *E=1.5*. Based on equation (2), the optimization function for the network (Figs. 2 and 3) has the form $d_1^{0.33} \cdot A_1^{0.67} + d_2^{0.33} \cdot A_2^{0.67} - \sum_{i=1}^{k}\sum_{j=1}^{w}\left(40 \cdot b^{i}_{j,12} + 40 \cdot b^{i}_{j,21} + 10 \cdot b^{i}_{j,13} + 10 \cdot b^{i}_{j,31} + 20 \cdot b^{i}_{j,23} + 20 \cdot b^{i}_{j,32}\right)$, subject to constraints (3), (4), (5) and (6). Fig.2 shows a non-optimal RWA solution.

Simulation results:

The simulation is carried out using the algebraic modeling language *AMPL*, trade mark of *ILOG Corp*, which is algebraic modeling language for linear and nonlinear optimization problems, in discrete or continuous variables. The optimization solver, used in the simulation, is *CPLEX 7.0*, which is a trade mark of *ILOG Corp.* The optical network shown in Fig.2 is taken as example. Different bandwidth demands (*d1* and *d2*) are required from the two optical channels *v1* and *v2* (see Fig. 1). It is assumed that the scaling constants (demand potentials) are known. Their values are ad hoc chosen as $A1=164.31$ and $A2=207$. Table 1 summarizes the results after optimization. Columns 1 and 2 provide the bandwidth demand for virtual channels *v1* and *v2*; column 3 shows the optimal connections; column 4 provides the revenue from operating the network; column 6 shows the maximum revenue of the transport service provider for the corresponding bandwidth demand, calculated according to the *profit maximization* algorithm. Columns 5 and7 show the cost of all connections and the profitto be made when operating the network using the *shortest path routing* [1] algorithm.

Table 1. Demands, routing and wavelength allocations, associated costs and profits for *profit maximization algorithm* compared to the costs and profits for *minimum path length algorithm*.

Bandwidth, required for optical channel *v* in number of wavelengths *d*		Allocated links (optical channel, wavelength, links) using profit maximization algorithm	Cost of all connections		Profit from operating the network	
V2, D2	V1,D1		**Profit max.**	Shortest path	**Profit max**	Shortest path
0	1	V1: w1:(N1,N3),(N3,N2)	**30**	30	**0**	0
0	2	V1: w1,w2:(N1,N3), (N3,N2)	**60**	60	**-22.21**	-22.21
0	3	V1:w1,w2,w3: (N1,N3),(N3,N2)	**90**	90	**-46.74**	-46.74
1	0	V2:w3:(N1,N3)	**10**	10	**24.99**	24.99
1	1	V1:w2(N1,N3), (N3,N2) V2:w1:(N1,N3)	**40**	50	**24.99**	14.99
1	2	V1:w1,w2:(N1,N3), (N3,N2) V2:w3:(N1,N3)	**70**	90	**2.79**	-17.21
1	3	V1:w1,w2:(N1,N3), (N3,N2), w1: (N1,N2) V2:w3:(N1,N3)	**110**	130	**-31.75**	-51.75
2	0	V2:w1,w2: (N1,N3)	**20**	20	**24.08**	24.08
2	1	V1:w3:(N1,N3), (N3,N2) V2:w1,w2:(N1,N3)	**50**	60	**24.8**	14.8
2	2	V1:w1,w2:(N1,N3), w1:(N1,N2) V2:w1,w2: (N1,N3)	**90**	110	**-8.12**	-28.12
2	3	V1:w1(N1,N3), w1,w2:(N1,N2) V2:w1,w3: (N1,N3)	**130**	160	**-42.65**	-72.65
3	0	V2:w1,w2,w3: (N1,N3)	**30**	30	**20.47**	20.47
3	1	V1:w1(N1,N3), V2:w1,w2,w3: (N1,N3)	**70**	70	**10.46**	10.46
3	2	V1:w1,w2(N1,N3), V2:w1,w2,w3: (N1,N3)	**110**	110	**-21.74**	-21.74
3	3	V1:w1,w2,w3: (N1,N3), V2:w1,w2,w3: (N1,N3)	**150**	150	**-56.27**	-56.27

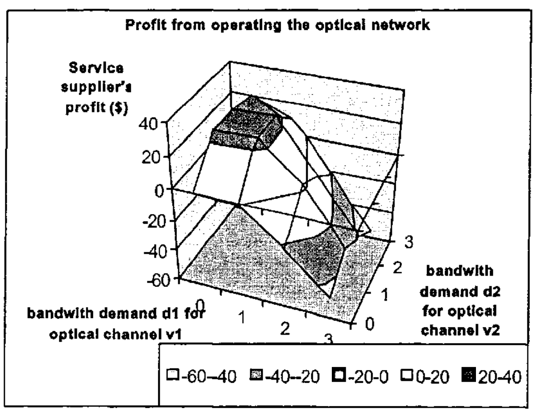

Fig. 3 Profit depending on demands *d1, d2*

On Fig.3 a graphic representation of columns 1, 2 and 6 of Table 1 helps us to draw some conclusions for operating a transport network. It can be seen that for this case study that the network can be operated profitably with low traffic load.

The simulation results lead to the following conclusions:

- profit maximization algorithm is more effective compared to shortest path algorithm with respect to profit
- full load of the available bandwidth resource does not provide maximum profit
- a call admission control, based on profit/loss consideration is necessary for a service provider in order to remain profitable
- the profit from operating a network is not necessarily proportional to demand

The simulation (routing for a certain traffic demand) takes a maximum of 0.0200288 seconds on a PC with tact frequency 1 GHz.

IV: ROUTING AND WAVELENGTH ASSIGNMENT AS OPTIMIZATION PROBLEM: CASE STUDY II

In the example below we consider another virtual topology (Fig. 4) implemented on optical topology (Fig.5). The demands for the virtual channels are *d1*, *d2* and *d3*. It is assumed that the demand elasticity for bandwidth is *E=1.5* [7]. It is also assumed that the scaling constants (demand potentials) are *A1=252.98*, *A2=164.31* and *A3=353.55*. The number of different traffic demand combinations is not 16 as in table 1, but 64, because there are 3 virtual channels (see Fig. 4). The profit for these demands is depicted graphically on Figs. 7 to 10.

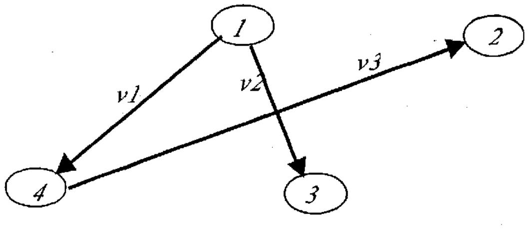

Fig. 4. Virtual topology

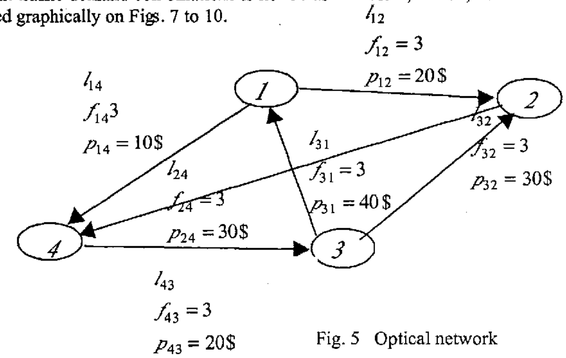

Fig. 5 Optical network

There are demands which cannot be satisfied, for example *d1=3*, *d2=3* and *d3=3*. One of the optimal solutions (where demands are *d1=3* , *d2=2* and *d3=1*) is shown on Fig. 6 (compare with Fig. 4).

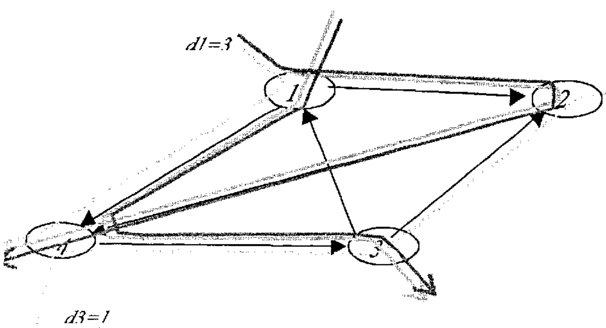

Fig. 6. Optimal wavelength allocation for demands *d1=3*, *d2=2* and *d3=1*.

Figs. 7, 8, 9, 10 show the dependence between supplier' s profit and bandwidth demands *d1*, *d2* and *d3* for the network, displayed in Fig.6. Similarly to the simulation in section III, we draw the following conclusions:

- not all demands can be satisfied (fig. 8, fig. 9, fig. 10)
- satisfaction of more traffic demand does not mean more profit for the supplier (compare fig. 7 (demands d1=2, d2=3, d3=0) with fig.8 (demands d1=2, d2=3, d3=1)
- a call admission control, based on profit/loss consideration is necessary for a service provider in order to preserve the profitability.

The simulation (routing for a certain traffic demand) takes a maximum 0.0300432 seconds on a PC with tact frequency 1 GHz.

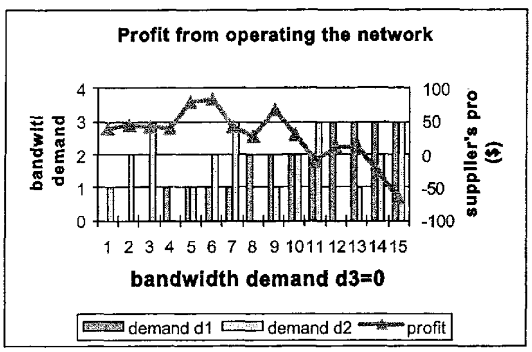

Fig. 7 Profit depending on demands *d1*, *d2*

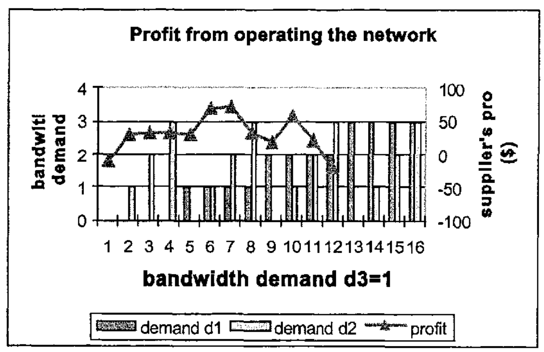

Fig. 8 Profit depending on demands *d1*, *d2*.

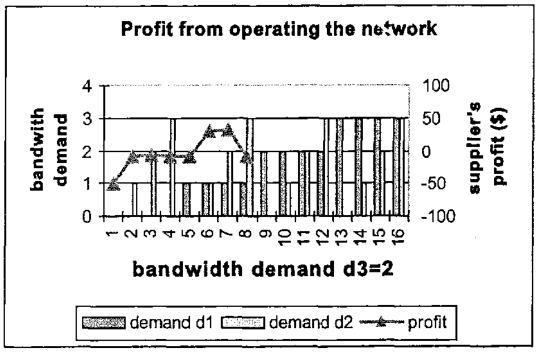

Fig. 9 Profit depending on demands *d1, d2.*

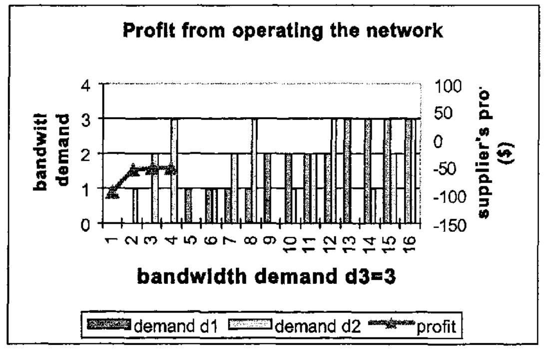

Fig. 10 Profit depending on demands *d1, d2.*

Conclusion

This paper considers a Mixed Integer Programming Formulation (MIP) for Routing and Wavelength Allocation (RAW) in an optical network. The work is based on an economic feasibility study for a service provider, acting as monopolist on the market, offering transport network services [13]. This novel formulation lead to a solution, which achieves better utilization of the existing resources of a network carrier, improves the network planning, provisioning and admission control with respect to market effectiveness for the transport service carrier. An important conclusion of this case study is that full load of the available bandwidth resources does not necessarily provide maximum profit. A call admission control, based on profit/loss considerations, is necessary for a service provider in order to preserve the profitability. We also conclude that the profit from operating a network is not necessarily proportional to the demand. In addition, not all demands in an optical network can be satisfied, although the demands do not exceed the bandwidth capacity of the internodal physical links in the network.

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