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Online Resource Allocation in Dynamic Optical Networks

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***Abstract*—This paper presents a synopsis of ongoing research in the field of resource allocation in dynamic optical networks. This type of networks are envisioned to serve connections with random arrival and holding times and with fast connection setup requirements. Based on this, we model resource allocation as a mechanism that includes network control functions for routing and spectrum assignment (RSA), connection admission control (CAC) and grade of service (GoS) control. The goal is to efficiently assign spectrum resources to connections so as to attain optimum performance. For that, the network is modelled as a stochastic loss system subject to spectrum continuity and contiguity constraints. The theory of Markov decision processes (MDP) is then applied to formulate an algorithm that performs fast, adaptive and state-dependent RSA, CAC and GoS control. The proposed algorithm can easily be integrated with existing protocols for fast connection setup. Moreover, we discuss the cost efficiency of selected network implementations which are based on basic, colorless and colorless and directionless optical nodes.**

Keywords—Dynamic optical networks, resource allocation, routing and spectrum assignment, connection admission control, Markov decision processes

I. INTRODUCTION AND MOTIVATION

Current optical transport networks are circuit-switched systems that carry customer demands on optical connections. For that, fixed-grid Wavelength Division Multiplexing (WDM) is implemented in the optical layer. A connection is a lightpath that consists of an optical channel established on a route between two network nodes. Today, setup times for optical connections are in the order of weeks as in most cases manual labour is required for the provisioning of resources. Once established, connections remain active for months or years. This inflexible and static design of the optical layer was conceived for constant bit-rate connections that do not require fast connection setup. A typical use case of this type of connectivity is the transport of Internet protocol (IP) traffic: operators overprovision capacity in the optical layer (via high-speed, constant-bit rate connections) to cope with the burstiness of IP traffic. According to [1], in 2005 it was observed that the lightpaths used to serve IP traffic had around 25 percent average utilization in the US Internet. This trend continues today, which evinces that optical capacity is not used efficiently, as it is underutilized at the expense of high network deployment costs.

The constant IP traffic growth together with the emergence of grid computing and cloud-based services are imposing new connectivity requirements on the optical layer. There is raising awareness on the need for a changeover to dynamic optical networks. As argued in [2-4], besides capacity benefits, dynamic optical networking enables the provisioning of bandwidth on demand (BoD) in the optical layer. Hence, instead of supplying long-term installed, constant bit-rate connectivity, dynamic optical networks are expected to serve connections with different bit-rate requirements, and with random arrival and holding times. Furthermore, connections may need to be set up and torn down rapidly. According to [2-3], to cope with the connectivity needs of grid computing and cloud-based services, optical networks will have to serve connections with interarrival and holding times ranging from seconds to hours.

In Fig. 1 an architecture for dynamic optical networks is shown. In order to provide fast BoD connectivity, the architecture has to comprise a powerful (software defined) control plane. Ongoing research has identified flex-grid WDM [5], reconfigurable optical add/drop multiplexers (ROADMs) [6-7], and bandwidth variable/tunable transponders [8] as key technology drivers that enable a flexibly configurable network. In particular, the Core Optical Networks program (CORONET) [2] has adopted these three drivers to create two contributions: a directionless/colorless ROADM architecture [9-10] that interworks with a shared pool of transponders [10-12], and a 3-way handshake (3WHS) signalling protocol that enables setup times in the range of milliseconds to seconds [10], [12-14]. The idea behind the CORONET proposal is that the network must be installed with enough capacity to cope with an expected demand growth without manual interaction. For that, the nodes are designed with ROADMs equipped with pools of shared transponders (see Fig. 1). Hence, instead of installing dedicated transponders for each connection (like traditional fixed-grid WDM networks do today), the dimensioning of the number of transponders and the installation of pools is performed before the network gets operational. Then during operation, the customer connections are assigned - on demand - to transponders in the pool, thereby avoiding manual configuration.

By having sufficient installed capacity in the nodes, the 3WHS protocol was then proposed as the most efficient strategy to perform fast connection setup. For a connection request, the 3WHS protocol - unlike the generalized multiprotocol label switching (GMPLS) mechanisms for connection setup - probes resources on different paths simultaneously, and therefore, it can provide real time information for fast resource allocation. Furthermore, as discussed in [10], the protocol performs well at

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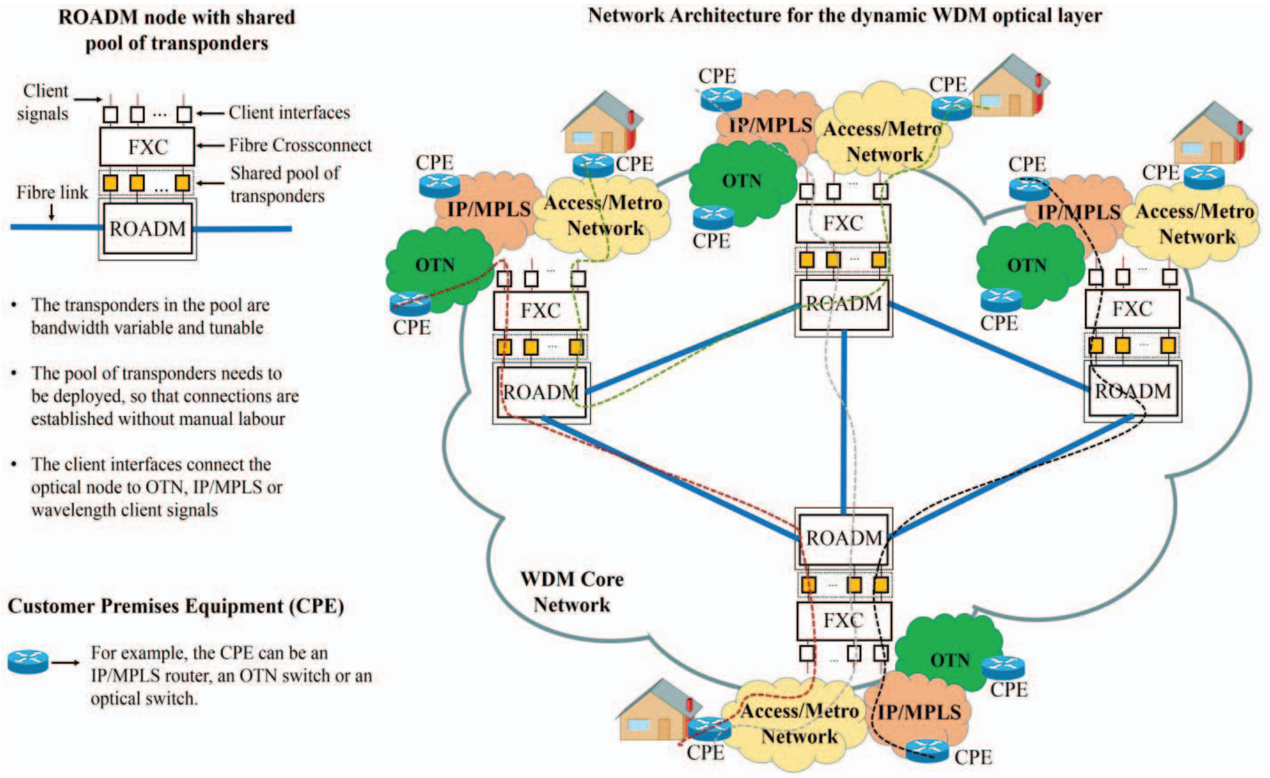

Fig. 1. Dynamic optical network architecture.

minimizing backward blocking (i.e. the blocking arising from concurrent connection requests trying to seize the same resources on a given path). These capabilities render the 3WHS protocol more efficient than GMPLS. A thorough discussion of the advantages of the 3WHS protocol over GMPLS can be found in [10], [12].

The aforementioned innovations represent an important step towards the deployment of dynamic optical networks. However, further work is needed regarding the development of strategies for optimum resource allocation. In dynamic optical networks, connections may arrive and depart randomly. Hence, given that the traffic matrix is unknown, the network has to resort to online control functions to efficiently assign the installed capacity on demand. This means that every connection request submitted to the network has to be checked w.r.t. its impact on the network performance. Therefore, in dynamic optical networks, resource allocation should be tackled as an online optimization problem. In this paper we present a synopsis of the dissertation work in [15] which addresses this problem by assuming a network architecture as shown in Fig. 1.

This paper is organized as follows. In Section II the problem of online resource allocation is defined. Section III cites relevant publications on the subject. Section IV outlines relevant research contributions. Section V concludes the paper.

II. PROBLEM STATEMENT

Network planning and traffic engineering play a relevant role in the design of efficient network infrastructures. In particular, in dynamic optical networks, network planning relies on proper demand forecasting to perform the dimensioning of links, ROADMs and transponders (i.e. it guarantees that sufficient resources are deployed to provide BoD without manual intervention). On the other hand, traffic engineering ensures that the installed capacity is efficiently assigned to the connections. For that, online resource allocation is performed by implementing functions for routing and spectrum allocation (RSA), connection admission control (CAC) and grade of service (GoS) control.

Assuming a network with ROADMs equipped with pools of transponders as shown in Fig. 1, blocking of a connection request may occur either if transponders are unavailable in the pools of the source and destination ROADMs, or if a suitable lightpath cannot be found in the network. Low transponder-related blocking can be accomplished by proper dimensioning of the transponder pools, see for example the method outlined in [10]. On the other hand, the control of the blocking (i.e. the GoS) due to the unavailability of lightpaths is a task of online resource allocation. We refer to online resource allocation as the mechanism whereby the network assigns, on demand, spectrum resources to connections (besides link spectrum slots this includes transponders and ROADM resources as well). Such a mechanism basically relies on a decision making process whereby for every connection request, a decision is provided on admission, routing and spectrum assignment. The decision depends on two factors, namely, the requirements of the connection request (e.g. bit-rate, holding time) and the network state at the time of the connection arrival. Thus, for a committed

GoS, upon arrival of a connection request, the resource allocation mechanism has to run an online RSA algorithm in order to calculate candidate lightpaths. Then, a CAC algorithm applies admission decision rules to determine the lightpath which is appropriate for the connection. Besides performing GoS control, resource allocation needs to fulfil three requirements to efficiently supply BoD. First, the RSA and CAC algorithms used must be fast, adaptive and state-dependent. Secondly, algorithms for online resource allocation must be designed to interwork with connection setup protocols as connection setup involves resource allocation. Therefore, the design and implementation of RSA and CAC algorithms needs to be aware of the connection setup signalling protocol. And third, instead of solely minimizing blocking probability, resource allocation algorithms should allow for the optimization of other desired objectives, e.g. economic revenue maximization or cost minimization.

The design of online resource allocation algorithms that meet these requirements is an open issue. Today, research on this field has predominantly been focused on the design of online RSA algorithms. Existing approaches, e.g. [16-19], aim at minimizing the overall blocking probability, and do not allow GoS control of individual connection classes. (Remark: here the term class is used to refer to a group of connections which have similar properties such as bandwidth requirements and holding times.) In reality, a dynamic optical network should be capable of serving different connection classes with individual committed GoS. Thus, online approaches that solely minimize overall blocking need to be extended in an appropriate way. This problem is addressed in the dissertation work [15].

III. PUBLICATIONS

The research contributions in [15] tackle the problem of resource allocation in dynamic flex-grid optical networks. The main concepts, mathematical models, algorithms and findings are published in nine papers [20-28]. Another publication related to the topic can be found in [29]. In what follows, a brief description is given concerning the most relevant contributions published in the cited literature.

IV. RESEARCH CONTRIBUTIONS

In [15] the theory of Markov decision processes (MDP) [30] is applied to formulate resource allocation as an online reward-based optimization problem. The idea behind the concept of reward is quite simple: connections are categorized into classes, for each class, a reward parameter (whose meaning and actual value is defined by the network operator) is assigned. The reward parameter quantifies the benefit that a connection request yields to the network if it is admitted. The goal is to find the resource allocation policy that maximizes the rate at which reward is earned from carried connections. The advantage of this approach is that the reward parameters can be set either to optimize any desired objective (e.g. blocking minimization, maximization of carried traffic or economic revenue) or to equalize or prioritize the GoS offered to different connection classes.

A resource allocation policy is a collection of decisions that define the course of action to be taken when a connection request arrives in a given network state. More specifically, a policy can be modelled as a two-dimensional matrix. The number of rows equals the size of the network state-space, and the number of columns equals the number of connection classes. A matrix entry represents a policy decision. Upon arrival of a connection request, the network has to retrieve from the matrix the entry that matches the current network state (row) and the connection class (column). That entry indicates whether to accept the request or not. If accepted, the entry further specifies the configuration of the lightpath allocated to the connection (i.e. the route and the spectrum slots of the optical channel). Thus, any definable policy determines how to handle connection requests. The calculation of the policy decisions, i.e. of the matrix entries, involves online algorithms for RSA, CAC and GoS control.

MDP theory provides the mathematical method to calculate the optimum resource allocation policy. To apply this theory to the design of control algorithms for a specific network type (such as a WDM network), it is mandatory to define first a suitable stochastic network model. This includes the definition of both the network state and the set of constraints for the optimization problem. With the model defined, the time evolution of the network state is represented as a stochastic process. Then MDP theory is used to control this process by calculating a policy that achieves the desired optimization objective. This methodology was successfully applied to the design of adaptive and state-dependent routing in telephone and multiservice networks [31-38]. However, these algorithms are not applicable to optical systems since they assume networks which are not subject to spectrum continuity and contiguity constraints. In [15] these constraints are considered so as to apply MDP theory for the calculation of resource allocation policies for optical networks. The main contributions made in [15] to accomplish this goal are summarized in the following.

A. Formulation of an Exact Resource Allocation Algorithm

A method is proposed whereby dynamic flex-grid optical networks are modelled as large-scale stochastic loss systems. The network state is defined as the configuration of the optical spectrum over all network links. This configuration is given by the connections carried in the network, and hence, the state is defined by the spectrum configurations of lightpaths that fulfil the contiguity and continuity constraints. (Remark: in flex-grid systems, a lightpath consists of contiguous spectrum slots centered at the same frequency on each link used by the lightpath.) The time evolution of the network state is modelled as a continuous-time stochastic process. By applying MDP theory to control this process, resource allocation is formulated as a reward-based online optimization problem. The solution is calculated by a policy iteration algorithm (PIA) that determines the optimum resource allocation policy. This policy is a set of state-dependent decisions on RSA and CAC that tell the network how to handle each connection request. The approach guarantees that if the policy is used to allocate resources, the network reward rate is maximized. Since the policy calculation is performed online, its decisions are adaptive to changing traffic conditions. Besides, the approach optimizes any desired objective, and if needed, it allows GoS control by properly defining the reward parameters. The proposed algorithm extends the applicability of MDP theory to the control of stochastic loss systems subject to contiguity and continuity constraints.

B. Approximate Resource Allocation Algorithm

A well-known drawback of state-dependent control is that the computational complexity grows with the size of the network state-space. That is the case for the exact reward-based algorithm mentioned before, which is unsolvable for large-size networks. To circumvent this problem, a link decomposition approach is used whereby the rate at which the network earns reward from connections is approximated as the sum of the link reward rates. By this strategy, the optimization problem is decomposed into separate problems (one for each link) by assuming statistical independence of the link state distributions. As result of this, an approximate PIA is proposed that reduces the computational complexity. Furthermore, to improve the adaptability to varying traffic conditions, this PIA implements a method to estimate from online measurements the statistical properties of the traffic. This allows the network to adapt the policy decisions to the traffic conditions.

The link independence assumption reduces mathematical complexity, but it might be oversimplifying. In reality, any carried connection induces state correlations among links. The extent to which the assumption is valid is strongly dependent on the network topology, as networks that route connections on multi-link paths are prone to induce more correlations than those which use many direct link paths (e.g. highly meshed networks). To counteract the lack of accuracy of the link independence assumption, in [15] it is shown that the performance of the policy can be improved by admission decision rules that intend to reduce the correlations among links [15], [24]. To illustrate this, consider the optical network in Fig. 2a which serves two connection classes, namely, narrowband and wideband connections. Furthermore, consider the following four admission decision rules, which are denoted as MDP, MDP-SP (Shortest-Path), MDP-PG (Positive-Gain) and MDP-PGMC (Positive-Gain-Maximum-Capacity) [24]. Upon arrival of a connection request, the PIA determines a set of candidate lightpaths. For each lightpath a reward gain is calculated which can be positive or negative. This gain depends on the network state and on the class of the connection request. Based on this, the admission decision rules work as follows: the MDP rule admits the connection on the lightpath with the highest reward gain. The MDP-SP rule admits the connection on the shortest path (w.r.t. the number of links) if it has an available lightpath. If this path is full, the MDP rule is used to place the connection on another lightpath. The MDP-PG rule selects the lightpath with positive gain which is routed on the path with shortest length (w.r.t. the number of links). The MDP-PGMC rule selects the lightpath with positive gain routed on the path with maximum available capacity. The performance of the rules depends on the spectrum allocation scheme, e.g. first-fit (FF), random-fit (RF) [17], used to determine optical channels for lightpaths. For the network in Fig. 2a, the reward losses obtained by the approximate PIA are depicted in Fig. 2b for the four rules under different traffic loads. The results are shown for the case where FF and RF are used as spectrum allocation schemes. As can be seen, the PIA performs better (i.e. it yields lower reward losses) with FF. Besides, the MDP-PGMC rule provides the best performance. The importance of this result is that simple admission decision rules can be defined to improve the performance of the policy calculation method.

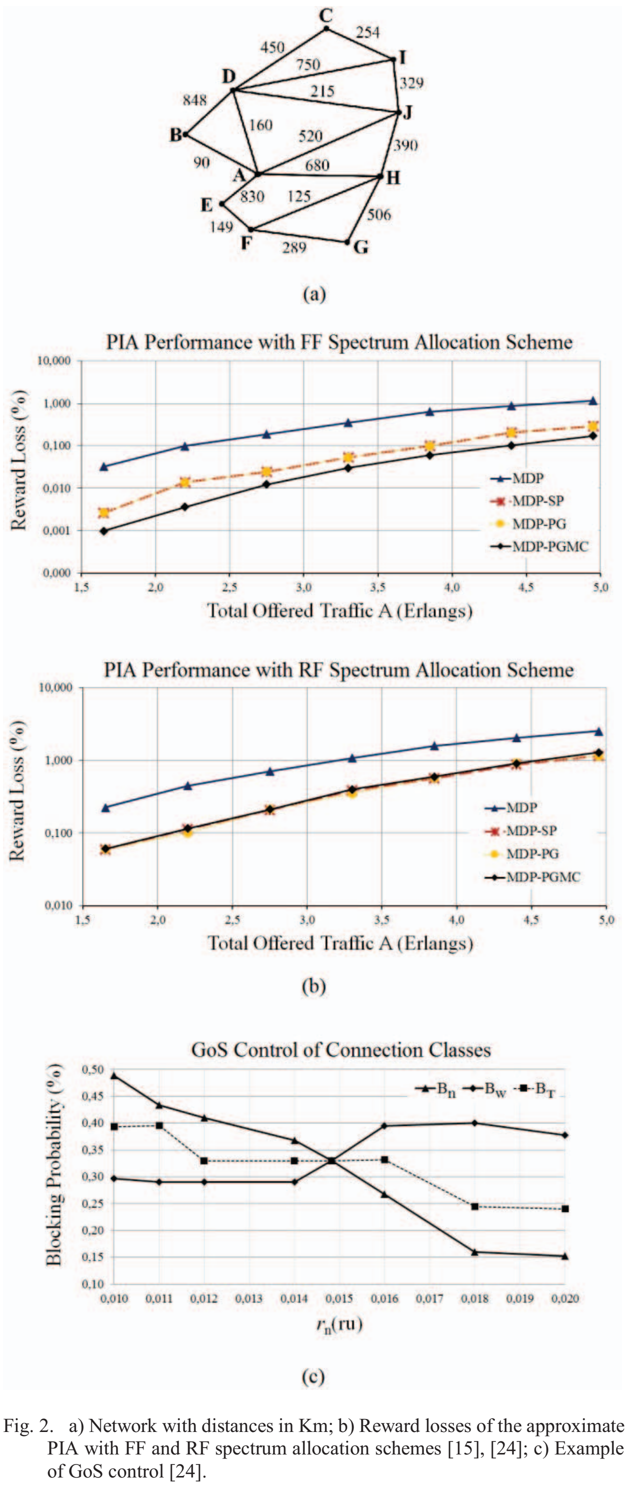

Fig. 2. a) Network with distances in Km; b) Reward losses of the approximate PIA with FF and RF spectrum allocation schemes [15], [24]; c) Example of GoS control [24].

Another important capability of the PIA is that it can perform GoS control by tuning the reward parameters of the connection classes. For the network in Fig. 2a, this is illustrated in Fig. 2c, which shows the blocking B_n of narrowband connections, the blocking B_w of wideband connections, and the overall blocking

B_T as function of the narrowband reward parameters r_n - given in reward units (ru). The reward parameters can be tuned to either equalize blocking so that $B_n = B_w = B_T$, or to prioritize classes. For example, in Fig. 2c, large values of r_n reduce the blocking B_n of narrowband traffic while increasing the blocking B_w of broadband traffic.

C. Definition of an Implementation Scenario

Resource allocation is part of the connection setup procedure implemented by the control plane of the network. In that respect, the 3WHS protocol for connection setup is adapted to perform resource allocation with the approximate PIA [15], [24]. In the proposed implementation, the node that receives the connection request starts the connection setup process whilst the destination node calculates the policy decisions, and triggers the resource allocation procedure. The process is coordinated by a centralized control plane. The signalling mechanisms of the 3WHS protocol guarantee setup delays in the range of milliseconds to seconds. The proposed approach can be realized via a software define networking (SDN) based implementation or as an extension to GMPLS.

D. Analytical Approach to Evaluating Connection Setup Delay

An analytical method to estimate the connection setup delay of the 3WHS protocol is proposed in [15], [26-27]. For that, the protocol is modelled as a task graph that represents the signalling latency during the connection establishment phase. By using reduction techniques, the graph is simplified so as to obtain a performance model that estimates the mean connection setup delay. The analytical model provides precise estimates of the connection setup latencies. An example of this is depicted in Fig. 3, where a comparison is made between the analytical and the simulated (plotted with 95% confidence intervals) connection setup delays obtained for the network shown in Fig. 2a. This network has 45 node-pairs. The results in Fig. 3 show the mean setup delay for connections established between the node pairs. For all node pairs, the delays estimated by the analytical model are within the 95% confidence intervals.

The advantage of the task graph reduction approach is that it is applicable to any connection setup protocol operating with arbitrary resource allocation algorithms. Therefore, the analysis in [15] and [26-27] can easily be extended to estimate latencies in different implementation scenarios for resource allocation.

E. Evaluation of Infrastructure Costs

A cost model for the evaluation of the infrastructure costs of dynamic optical networks is provided in [15], [25], [28]. Given the traffic demand, the cost model uses a bottom-up approach for the dimensioning of ROADMs and their corresponding pools of transponders. Then the infrastructure costs are determined as sum of the costs of ROADMs, transponders and optical in-line amplifiers (OLAs). The approach is applied to the calculation of the network costs for three ROADM implementations, namely, basic (B), colorless (C) and colorless & directionless (CD). As an example, in Fig. 4 the costs are shown for the network in Fig. 2a. The costs are expressed in strongest cost units (SCU). As defined in [39], an SCU is the cost of a 10 Gbps transponder with transparent reach of 750 km in the year 2012. The results show that the lowest costs are obtained when the network installs colorless ROADMs. However, it is worth noting that with this solution the network cannot automatically re-route connections in case of link failures. This deficiency is overcome by adding the directionless property to colorless ROADMs. Although the resulting solution is more costly, it allows a more efficient utilization of the network resources. More specifically, as seen in [15], a colorless & directionless architecture substantially reduces the number of transponders required to serve an expected traffic demand.

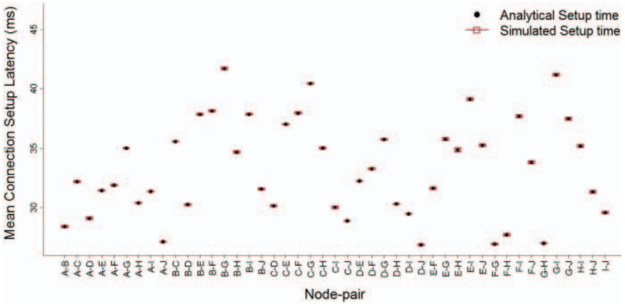

Fig. 3. Comparison of analytical and simulated connection setup delays [27].

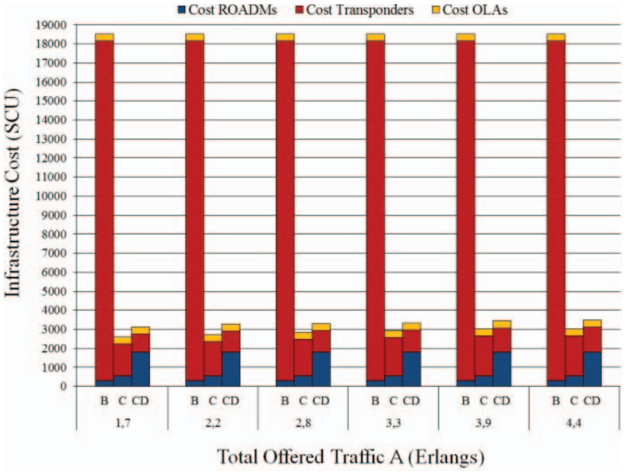

Fig. 4. Infrastructure cost evaluation for differente traffic loads [15].

V. CONCLUSION

The research work outlined in this paper extends the body of knowledge in the field of communication networks in different directions. First, it formulates a stochastic network model which is applicable to optical communication systems with continuity and contiguity constraints. Secondly, it extends the applicability of MDP theory to the control of optical networks. Thirdly, it provides a comprehensive framework for the design of network control functions for RSA, CAC and GoS control. In particular, the framework integrates the design of these functions with the signalling mechanisms used to perform connection setup. Last, the work provides network design guidelines for the planning of cost efficient dynamic optical networks.

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