Static and Dynamic Spectrum Allocation in Flexi-grid Optical Networks

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ABSTRACT

We consider the problems of both static and dynamic resource allocation in spectrum flexible (flexi-grid) optical networks. We present algorithms for planning such networks given the requested demand rates. We also present dynamic spectrum allocation policies to serve time-varying traffic and analyze their blocking performance for the dynamic operation of a flexi-grid network.

Keywords: spectrum flexible, routing and modulation level and spectrum allocation algorithms, spectrum expansion/contraction policies.

1. Introduction

Increasing the capacity and improving the efficiency of optical transport networks has been an important research challenge for many years. To cope with traffic increases of almost 40% per year extensive research efforts have been devoted on advanced modulation formats and digital equalization in the electronic domain to enable per-channel capacity of 40 and 100 Gbps with improved transmission distance for traditional WDM systems. However, despite the high transmission rates that can be achieved by wavelength routed WDM networks, their rigid and coarse granularity leads to inefficient capacity utilization, a problem expected to become increasingly significant with the deployment of the higher channel rate systems.

To achieve better efficiency, the Optical Burst Switching (OBS) and Optical Packet Switching (OPS) paradigms utilize the time domain to enable the sharing of the network resources. The statistical multiplexing of traffic over the time-shared resources can meet the efficiency requirements of future transport networks. However, OPS can be viewed only as long-term solution, since its enabling technologies are still maturing, while the few commercial OBS products have not yet found market success. In addition to the time domain, exploited in the OBS and OPS paradigms, the frequency is another domain that can be harvested to provide finer granularity and higher efficiency for the optical networks. Typically, wavelength routed WDM networks operate over the ITU-T grid, that is, a constant 100 or 50-GHz spaced grid. Taking a different approach, many efforts have lately focused on architectures that support variable spectrum connections. Spectrum flexible, elastic, tunable, adaptive, flexi-grid are few examples of the terms used by the research community to describe solutions that migrate from the fixed 50GHz grid systems to systems that support variable spectrum connections [1-6].

A number of networking paradigms that adopt the spectrum flexible approach have recently emerged. The Spectrum-sLICed Elastic optical path network ("SLICE") [2] utilizes optical OFDM to enable spectrum flexible transmissions. Optical OFDM distributes the data on several low rate subcarriers (multi-carrier system). The spectrum of adjacent subcarriers can overlap, since they are orthogonally modulated, increasing transmission spectral efficiency. A bandwidth-variable (BV) OFDM transponder generates an optical signal using just enough spectral resources with appropriately modulated subcarriers to serve the demand. Every bandwidth variable OXC on the route allocates sufficient spectrum to create an appropriately sized end-to-end optical connection. A Flexible-WDM architecture similar to SLICE is considered in [3]. Field trials of flexi-grid networks have been reported, while standardization activities are in progress in the ITU-T and OIF.

Focusing on the importance of the frequency (spectrum) as a flexible resource, we have studied the problem of resource allocation in the planning (offline) [4] and the operational (dynamic) [5] phases of a flexi-grid optical network. In [4] we proposed algorithms to solve the planning problem of transparent spectrum flexible networks, referred to as routing and spectrum allocation (RSA), or as routing, modulation level and spectrum allocation (RMLSA), when the modulation level of each connection can be also chosen elastically. In this paper we present an extension to the static RMLSA of [4] by considering realistic capacity-reach-spectrum-guardband parameters based on physical layer studies for OFDM-based networks [6]. Since these developed algorithms incorporate realistic transmission performance characteristics we refer to them as Impairment Aware (IA)-RMLSA planning algorithms. We also present a framework for serving time varying traffic in a flexi-grid network that exploits the dynamic spectrum sharing among connections to obtain statistical multiplexing gains [5].

2. Impairment-aware Routing, Modulation Level and Spectrum Allocation Planning

The planning problem of a spectrum flexible OFDM network is described as follows.

We are given a network $G=(V,E)$, where V denotes the set of nodes and E denotes the set of (point-to-point) single-fiber links. We are also given the actual (physical) lengths D_l of all links $l \in E$. We assume that the spectrum is quantized in spectrum slots of F GHz, where one spectrum slot is defined as the switching granularity of the flexible network elements and that of the flexible transponders. We assume an a-priori known traffic scenario given in the form of a traffic matrix of aggregated demands Λ in Gbps. To serve this traffic we utilize *flexible* OFDM transponders that have two flexibility degrees: (a) the choice of the modulation format and

(b) the choice of the spectrum (in contiguous spectrum slots) that they utilize. Adapting these, the flexible transponder can be tuned to transmit *c* Gbps over a path of distance *l* km using *b* spectrum slots and a guardband of *g* spectrum slots from the adjacent spectrum connections so as the transmission to exhibit acceptable transmission quality. Given the capabilities of the transponder (e.g., it can be tuned up to 64 QAM and 50 GHz), and since the modulation format and the spectrum that are utilized are selected from discrete sets, we have certain transmission configurations for the transponder. In particular we denote by the *tuple* $t=(c_t,l_t,b_t,g_t)$ a transmission configuration of the tunable transponder. Our algorithms will use the realistic capacity-reach-spectrum-guardband parameters that are based on physical layer studies for OFDM optical networks [6] so that they are impairment-aware (IA-RMLSA planning algorithms).

To serve a demand we establish one or more optical connections between the source and the destination. The number of connections depends on the demanded rate, the capabilities of the transponders and the transponder configuration tuple that will be used for the transmission. It is the role of the routing and spectrum allocation RSA (or IA-RMLSA) algorithm to identify how to serve each demand, and in particular decide how to break each demand into connection(s), select the configuration(s)/tuple(s) that the transponder(s) will use, and allocate path(s) and spectrum slot(s) to those connection(s) accordingly. In transparent networks each connection is a *transparent spectrum-flexible lightpath*. A spectrum-flexible lightpath is associated with a single flexible transponder and has to utilize the same spectrum segment (spectrum slots) throughout its path, what we call the *spectrum continuity constraint*. In translucent networks, where optical regeneration is performed at one or more intermediate hops, the spectrum-flexible lightpath is terminated at the regeneration point, and a new spectrum flexible lightpath is initiated at that point, to create an end-to-end *translucent connection*. Thus, a connection in a translucent network can be a single transparent spectrum-flexible lightpath or a sequence of spectrum-flexible lightpaths. In the planning (static) phase of the network, no spectrum overlapping is allowed among the transparent spectrum-flexible lightpaths, what we call the *non-overlapping spectrum assignment constraint*. To avoid interference effects between spectrum adjacent lightpaths and guarantee acceptable quality of transmission (QoT), appropriate spectrum separation, implemented by spectrum guardbands is required.

Extending our algorithms in [4] we developed algorithms to solve the planning problem for transparent and translucent networks based on OFDM under realistic physical layer constraints. The objective is to serve the traffic that are Pareto optimal with respect to the total amount of spectrum utilized and the number of transponders used. We developed algorithms based on ILP formulations for transparent and translucent networks and also heuristic algorithms that utilize simulated annealing to trade off performance with running time. Both ILP and heuristic algorithms use a pre-processing phase to calculate the set of Pareto optimal (non-dominated) path-tuple pairs that are considered as candidate solutions by the algorithms. In particular, after calculating a set of paths for each source-destination, based on the length of the paths, we identify the transponder configuration tuples that can be used to serve the demands over the paths, to form what we call path-tuple pairs. We remove the candidate path-tuple pairs that are dominated by others. For a given demand (s,d), suppose that over a specific path p we have a tuple t whose total spectrum utilization $S_{p,t}$ is less than the spectrum utilization $S_{p,t'}$ of tuple t', and the number of required transponders $N_{p,t}$ is also less than the number of transponders required for t', $N_{p,t'}$. Then path-tuple pair (p,t') cannot appear in the optimal solution, because we could always improve any potential solution containing t' by replacing t' with t, that is, use path-tuple pair (p,t) instead. This is because our cost objective is monotonically increasing with respect to each of these two parameters. The ILP and the heuristic algorithms take as input the set of Pareto optimal path-tuple pairs and select one to serve each demand. The objective that we want to minimize is: $W\cdot f+(1-W)\cdot n$, where f is the maximum utilized slot, n is the number of utilized transponders, and W is the objective weight, $0\leq W\leq 1$. $W=0$ corresponds to the case where we want to solely optimize the number of utilized transponders, while $W=1$ corresponds to the case where we want to solely optimize the spectrum utilization. Values $0<W<1$ results in a multiobjective optimization.

3. Dynamic Spectrum Sharing Framework for Serving Time Varying Traffic

We now turn our attention to serving time varying traffic in a flexi-grid optical network. The relatively few works that have studied the online problem (e.g. [3]), consider traffic changes as new connection requests and terminations. We envision an elastic and dynamic flexi-grid network where nodes communicate over adjustable-rate (elastic) end-to-end connections, without establishing/releasing connections unless specifically required. In our model, changes (usually smooth) in the requested rate happen dynamically, and have to be absorbed by the flexible transponders by changing their utilized spectrum in real time. This is done by expanding or contracting the continuous spectrum allocated to the existing connections.

In the framework for serving time-varying traffic we proposed in [5], each connection is assigned a route and a reference frequency by a dynamic RSA (or RMLSA) algorithm. The connection is allowed to expand and contract the spectrum used around this reference frequency so as to follow the required transmission rate and absorb the traffic variations, according to what we call a *spectrum expansion/contraction* (*SEC*) policy. No spectrum overlapping among connections is allowed at any given instant, but the spectrum can be shared among connections at different time instants, yielding multiplexing gains similar to those obtained by the time-sharing of resources in OBS or OPS networks. Fig.1 presents an example of the utilization of a link in such a network for two different time instants. We proposed two SEC policies. The first is a simple Constant Spectrum Allocation (CSA) policy that assigns the exclusive use of a set of spectrum slots to a connection. This policy, which is adaptive but offers no sharing among connections, is compared to a Dynamic High Expansion-Low Contraction (DHL) policy that enables the dynamic sharing of spectrum slots among connections. Under the DHL policy a connection starts from its reference frequency and expands toward higher slots until it reaches a slot that it is utilized by an upper spectrum adjacent connection. Then, if more spectrum is required by the connection, it expands toward lower spectrum slots until it reaches a slot that is utilized by a bottom spectrum adjacent connection. Spectrum contraction follows the inverse procedure. We developed models for calculating the network blocking probability for both the CSA and DHL policies, and used them to understand the performance of the policies and in our dynamic RSA algorithm.

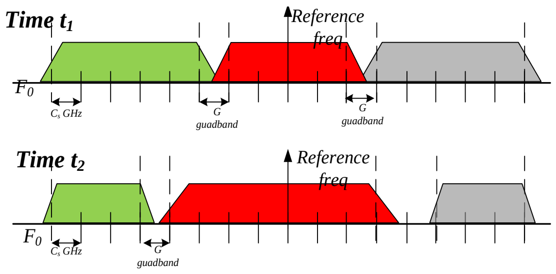

Fig. 1: Spectrum allocation of a link's bandwidth to variable rate connections. Two different time instants are displayed in (a) and (b). Spectrum guardabands of *G* slots separate the connections so that they are routed and received with acceptable BER.

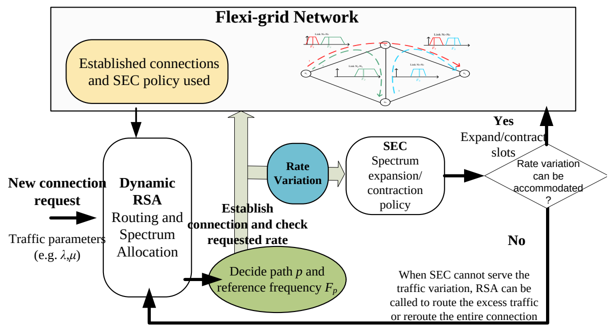

Fig. 2: Flow diagram for serving a connection request. Dynamic RSA is used to determine the path and reference frequency and SEC policy takes care of traffic variations.

The dynamic RSA algorithm serves the connection requests by assigning paths and reference frequencies to them so as to minimize the average network blocking, taking into account the specific SEC policy used. The SEC policy is responsible for accommodating the traffic variations of the connection. Fig. 2 presents the process of serving a connection. The RSA algorithm is also used when a connection needs additional spectrum slots on a regular basis (high blocking), or when the rate exceeds the transponder capabilities. Then, dynamic RSA is called to route the excess traffic over a new connection, or reroute the existing connection. In [5] we presented an iterative RSA algorithm that takes into account the SEC blocking model and calculates the paths and reference frequencies that should be used, with the objective of minimizing the overall blocking in the network.

Note that the proposed framework for serving time-varying traffic can be used in an OFDM or any other type of flexi-grid network, as long as transponders able to dynamically adapt their utilized spectrum are available.

4. Performance Results

4.1 Planning a flexi-grid Network

To evaluate the performance of the IA-RMLSA algorithms outlined in Section 2 we performed simulation experiments. We compared the flexi-grid network to a mixed-line-rate (MLR) WDM system that supports 10, 40, 100, 400 Gbps, with reach capabilities: 3200 km, 2300 km, 2100 km, 790 km and transponders' cost of 1,3,4,6 units, respectively. The cost of the OFDM transponder was assumed to be 6 units, reach and bandwidth requirements were taken from [6] but we have limited the OFDM transmission rates to maximum 400Gbps to evaluate under equivalent circumstances both networks. For the experiments reported here we used the 14-node generic Deutche Telecom (DT) network topology and assumed that its traffic increases uniformly by 40% each year. We set the objective weight W=1, so spectrum is the sole parameter of optimization in these experiments.

Table 1 presents the results. We can see that the performance of the flexi-grid network is superior to that of the MLR network. For low loads (up to year 2016), the MLR network utilizes mostly 10 and 40 Gbps transponders which have low spectral efficiency. Since the spectrum in the MLR system is inefficiently utilized, the spectrum required is substantially higher than that required for the flexi-grid network. As the load increases, MLR becomes more efficient, but still its performance is vastly inferior to that of the flexi-grid network. The improvement obtained by planning the network using the translucent algorithms is not substantial, since the network under study has small link and path lengths and can be planned efficiently with a (almost) transparent setting. Experiments with larger networks, e.g. the Geant topology, are not reported here due to length limitations, but note that for the planning of large networks the use of translucent algorithms is compulsory.

Table 1.Performance Results for the DT network for spectrum/wavelength minimization.

Load for years	OFDM flexi-grid transparent		OFDM flexi-grid translucent		MLR transparent		MLR translucent	
	Bw (GHz)	TR (cost)	Bw (GHz)	TR (cost)	Bw (GHz)	TR (cost)	Bw (GHz)	TR (cost)
2010	165	1001.0	135	1001.0	750	957.3	750	990.5
2012	210	1001.0	180	1001.0	750	953.8	750	990.5
2014	280	1001.0	245	1001.0	750	959.5	750	990.5
2016	365	1001.0	330	1001.0	800	975.8	750	994.0
2018	495	1094.5	485	1105.5	900	1103.5	750	1071.0
2020	810	1485.0	780	1485.0	1350	1529.0	950	1430.0

4.2 Serving time varying-traffic

In this section we present performance evaluation results for serving time-varying traffic in a flexi-grid network under the spectrum sharing framework outlined in Section 3. We used the 14-node generic DT network in our experiments. We assumed a single connection between all source-destination pairs. Spectrum slot requests for each connection *p* are generated according to a Poison process of rate λ_p and their duration is exponentially distributed with mean $1/\mu_p=1$. The arrival rate λ_p for each connection is drawn from an exponential distribution with mean λ. Thus, $\lambda|\boldsymbol{V}|\cdot(|\boldsymbol{V}|-1)$ is the network load in Erlangs. We graph the blocking performance of the CSA and DHL policies as calculated using the developed analytical models (exact for the CSA and approximate for the DHL policy). For the same traffic scenarios, we conducted full network simulation experiments. For comparison, we also present the blocking performance of a network that supports the full sharing of slots among connections. This can be viewed as a WDM network with spectrum slots corresponding to wavelengths, with the constraint of having to use guardbands in-between wavelengths. This reduces to a WDM network with $T/(1+G)$ wavelengths, where T is the number of supported slots. We set G=1, which is the minimum guardband requirement; the performance of the WDM network for higher values of G is expected to be worse.

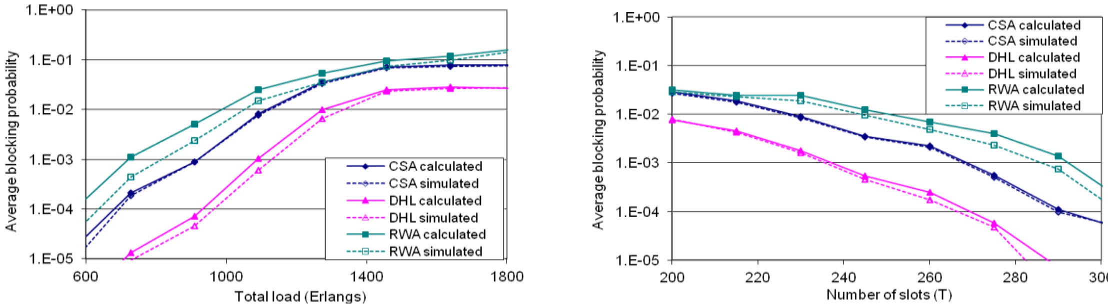

Fig. 6: Average blocking probability vs. (a) the total load, assuming T=250 slots and (b) the number of slots T, assuming 1000 Erlang load.

In Fig. 6a we graph blocking as a function of the total load (in Erlangs) assuming T=250. We observe that the proposed analytical models for calculating the blocking probabilities of the CSA and DHL policies are in very close agreement with the corresponding simulation results. The blocking model for the CSA policy, does not involve any approximating assumptions, and thus we expected to have such a good accuracy. The approximation model developed for the DHL policy is shown to be very accurate. The network blocking probability of the DHL policy is lower than that obtained for the CSA policy by more than one order of magnitude. This is the gain that we obtain by enabling spectrum sharing among spectrum-adjacent connections, as done with the DHL policy. The performance of the WDM network utilizing $T/2$ wavelengths (remember that G=1) is worse than the proposed solutions that follow our framework. Fig. 6b presents the performance of the network as a function of the number T of slots supported, assuming total network load of 1000 Erlangs. Again we observe that the proposed DHL policy outperforms the CSA policy and that the WDM system exhibits the worse performance.

5. Conclusions

Flexi-grid optical networks are considered one of the most promising architectures for next generation optical networks. In this paper we provided an overview of the algorithms that we have developed to plan and operate flexi-grid networks. In particular, we have developed Impairment-aware RMLSA algorithms for planning transparent and translucent flexi-grid networks that take into account realistic physical layer studies for OFDM-based networks. We have also proposed a framework for serving time varying traffic in flexi-grid networks that exploits the dynamic spectrum sharing among connections to obtain statistical multiplexing gains. In this framework, a connection is assigned a path and a reference frequency and expands/contracts its spectrum around that frequency to follow the traffic variations. Spectrum expansion/contraction policies and a dynamic RSA algorithm were developed and evaluated through simulations.

Acknowledgement

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