Dynamic Bandwidth Allocation in Flexible OFDM-based Networks

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Abstract: We propose a general policy to allocate subcarriers to time-varying traffic in a flexible OFDM optical network. We compare the OFDM network performance to that of a fixed-grid WDM network using simulations.
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1. Introduction

Recent innovations in optical communication systems, including advanced modulation formats and digital equalization in the electronic domain, have enabled per-channel bandwidths of 40 and 100 Gbps with improved transmission distance in traditional fixed-grid single carrier WDM networks [1]. Although wavelength routed WDM networks offer well-known advantages, their rigid and coarse granularity leads to inefficient capacity utilization, a problem expected to become increasingly significant with the deployment of systems with 40 and 100 Gbps per channel. This is because, currently, wavelength-routed networks require full allocation of a wavelength to a connection even when the traffic between the end nodes is not sufficient to fill the entire capacity, and also this allocation is usually static even if the traffic is varying with time. Approaches such as optical burst switching (OBS) and optical packet switching (OPS) that would meet the flexibility, granularity and efficiency requirements of future networks can only be viewed as long-term solutions, since their enabling technologies are not yet mature [2][3].

Recently, Orthogonal Frequency-Division Multiplexing (OFDM) is being considered as a modulation technique in optical networks [4]-[6]. Optical OFDM distributes the data on several low data rate subcarriers (multi-carrier system). The spectrum of orthogonally modulated adjacent subcarriers can overlap, increasing transmission spectral efficiency. Optical OFDM can serve connections with fine-granularity by the elastic allocation of low rate subcarriers according to the connection demands. Enabling technologies, such as bandwidth-variable (BV) transponders and bandwidth-variable WXCs, have been demonstrated in the SLICE network [7]. To achieve high spectral flexibility a bandwidth-variable OFDM transponder generates an optical signal using just enough spectral resources, in terms of subcarriers with appropriate modulation level, to serve the client demand (see figure 1a). Since, typically, the OFDM signal is generated at the RF domain, many transmission properties can be determined, enabling the choice of the number of modulated bits per symbol of the subcarriers. To establish a connection, every BV WXC on the route allocates a cross-connection with sufficient spectrum to create an appropriately sized end-to-end optical path (see figure 1b).

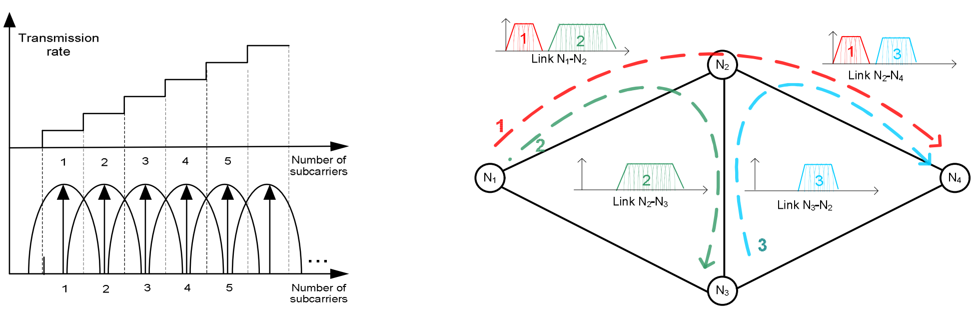

Fig. 1: (a) Variable bandwidth transmission by controling the number of OFDM subcarriers, (b) Spectrum flexible optical OFDM network.

The use of optical OFDM as a bandwidth-variable and highly spectrum-efficient modulation format can provide scalable and flexible sub- and super-wavelength granularity, in contrast to the conventional, fixed-grid WDM network. However, this new concept poses additional challenges on the networking level, since the routing and wavelength assignment (RWA) algorithms of traditional WDM networks are no longer directly applicable. A connection requiring capacity larger than that of an OFDM subcarrier has to be assigned a number of contiguous subcarrier slots for increased spectral efficiency.

In our previous works [11] we have considered the offline problem of planning an OFDM-based optical network, where we are given a traffic matrix with the requested transmission rates of all connections, and we allocate paths and spectrum resources to serve the connections so as to minimize the utilized spectrum, with no spectrum overlapping on any given link allowed among these connections. For other works related to the planning phase we refer the reader to [8]-[10]. In this study we turn our attention to the online, dynamic spectrum allocation problem. We focus on the operational phase of the OFDM network in which the rates of the connections change dynamically as a function of time. We propose a number of policies to assign OFDM subcarriers to dynamic changing traffic and perform simulation experiments to evaluate these policies. To the authors best knowledge this is the first work that considers the problem of allocating subcarriers/spectrum in a way that is dynamic with time in an OFDM network.

2. Dynamic Allocation of Subcarriers

We start with a working network in which connections have already been established (using, for example, a planning algorithm [11]), or with an empty network in which connections will be established. In either case we assume that the traffic between the source-destination nodes of the network fluctuates dynamically with time. For each source-destination pair, we assume that we have a probabilistic traffic model that describes the traffic between these two nodes, and that we also have information on its current traffic rate. In particular, we assume that we know the average rate a_{sd} for each source destination pair *s-d*, an upper bound u_{sd} on the instantaneous rate between *s* and *d* (given, e.g., by the maximum rates of the local/access networks connected to these nodes) and a burstiness parameter b_{sd} , which is a metric to characterizes the way that the traffic fluctuates. For each *s-d* pair we can calculate a set P_{sd} of *k*-shortest paths, which are viewed as the candidate paths over which the connection will be served. We denote by h_{sd} the number of hops of the shortest hop path that connects *s* and *d*. We assume that the network utilizes bandwidth-variable OFDM transponders that can adapt the number of subcarriers allocated to each connection according to its desired rate. Given the above model, we would like to design a policy that allocates/de-allocates subcarriers to the connections so as to follow their traffic fluctuations.

Based on the traffic and path parameters for each source-destination pair (*s*,*d*) in the network, we pre-reserve a number of contiguous subcarriers $R_{sd}=f(a_{sd}, u_{sd}, b_{sd}, h_{sd})$, where *f* is a function that is meant to describe the policy used for determining the guaranteed reserved rate for the *s-d* pair, given its characteristics (it could also be a function of the its desired QoS level) It is desirable that these subcarriers be contiguous in the spectrum domain in order to obtain the spectral efficiency advantages of overlapping orthogonally modulated subcarriers. Even when the instantaneous rate of *s-d* falls below the capacity of the R_{sd} subcarriers, these subcarriers are not de-allocated, but are always reserved for that *s-d* pair. Note that this formulation also includes the special case R_{sd}=0, where no subcarriers are pre-reserved. Thus, in our model, there are two types of subcarriers in the network: (a) those that are pre-reserved by the connections ("guaranteed" or reserved subcarriers) and (b) those that are not pre-reserved, but are shared on a demand basis, and can be allocated/de-allocated to the connections according to their time-varying requirements ("best effort" or shared subcarriers).

The rate of an *s-d* connection changes dynamically with time, but as long as it remains below R_{sd}, no additional resources are required for it. At certain instances, however, the rate of the connection may exceed that of the R_{sd} subcarriers provisioned for it, in which case an effort is made to allocate to it the additional subcarriers required.

Consider a connection *s-d* that requires at a given point in time an additional subcarrier. To address this demand we implement the following policy for the dynamic allocation of the shared subcarriers. We initially calculate the availability of the subcarriers over the candidate paths in P_{sd}. Under the spectrum continuity constraint, we consider only the subcarriers that are available over all the links comprising a path. We also keep track the utilization state *U* of all subcarriers in the network and, consequently, of the range of subcarriers T_{sd} that have been allocated to that connection (the pre-reserved R_{sd} subcarriers and, possibly, the additional subcarriers that have been allocated to it subsequently). Given the above we apply an optimization function or policy $g(h_p, U, T_{sd})$ to select the path and the additional subcarrier to allocate to the connection. Intuitively, optimization function *g* should favor shorter paths (paths with small h_p), subcarriers that have been fairly utilized in the network (according to the most used wavelength –MUW approach of traditional RWA algorithms), and also subcarriers that are adjacent to previously assigned subcarriers so as to be able to obtain a higher spectral efficiency due to the OFDM characteristics. The reverse process is followed when the rate of a connection decreases and a previously allocated subcarrier is freed.

3. Dynamic OFDM Network Example

In our simulation experiments we assumed the DT network topology [11]. The instantaneous rate of each connection is assumed to follow an independent Markov continuous time process. When a connection is at state *i*, the rate of the connection is C_i,; in our experiments, we take $C_i = i \cdot 2$Gbps. The rate intensity from state *i* to state *i*+1 is equal to λ, and from state *i* to state *i*-1 is equal to $i \cdot \mu$. In other words, there is an increase in the desired rate of a connection by 2Gbps every 1/λ sec, and a decrease in the requested rate by 2Gbps every 1/($i \cdot \mu$) sec on the average. The upper bound u_{sd} on the connection rate corresponds to the highest possible state of the Markov chain. The average rate a_{sd} can be easily calculated as a function of parameters λ and μ, and the burstiness parameter b_{sd} can be defined as a function of the same Markov continuous time process parameters.

In our comparisons we consider, on the one hand, a WDM network with 10 Gbps wavelengths, with *W* wavelengths per link and 50 GHz grid, and on the other hand, an OFDM network in which each subcarrier supports 2 Gbps in 12.5 GHz spectrum (including the guardband). Note that the spectral efficiencies of a single subcarrier and of a single wavelength are 0.16 and 0.2 bit/s/Hz, respectively. However, when we utilize adjacent subcarriers in OFDM we obtain some gains due to subcarrier overlapping. In particular, two adjacent subcarriers have a capacity of 6 Gbps, three adjacent subcarriers have capacity of 10 Gbps, and so on. Given the above parameters, we assume for the OFDM network that it has $4 \cdot W$ available subcarriers per link, for the comparison to be fair. At any given instance the number of wavelengths and subcarriers allocated to the connection must have at least enough capacity to satisfy the connection rate. An increase in the transmission rate (corresponding to a transition from state *i* to state *i*+1) that cannot be served by the network is counted as a blocking. Since we have the same a_{sd}, u_{sd}, b_{sd} parameters for all *s-d* pairs, we graph the performance for specific values R_{sd}=1, 2, 3, 4 (therefore, the curves on each figure correspond to a different amount of pre-reserved/guaranteed capacity of 2, 6, 10 and 14 Gbps for each connection).

In Fig. 2a we present the results for different values of the average holding time $1/\mu$; one can view $1/\mu$ as a measure of the time-scale or of the dynamicity of the sources A first observation is that the OFDM network exhibits performance that is superior to that of the WDM network in terms of the blocking rate. For low values of $1/\mu$ better performance is obtained if we pre-reserve R_{sd}=2 subcarriers. As expected, as the values of $1/\mu$ increase, the load of the connections increase and we observe that we have better performance when we increase the number of pre-reserved subcarriers (for $1/\mu$=5 R_{sd}=3 has better performance while for $1/\mu$=9, R_{sd}=4 performs better). In Fig. 2b we graph the performance as the number of wavelengths (or corresponding subcarriers) increase. As expected the performance of all algorithms improves as we increase the number of wavelengths. For the parameters of $1/\mu$ and *u* considered here, R_{sd}=3 seems to have the best performance. Finally, in Fig. 2c, we present the performance for different values of the upper bound on the connection traffic. Again the OFDM network exhibits a lower blocking probability than the WDM network. Similarly to Fig.2a. as the value of the upper bound *u* on the traffic rate increases, the average load of the connection increases, and better performance can be obtained by increasing the number of subcarriers that are pre-reserved.

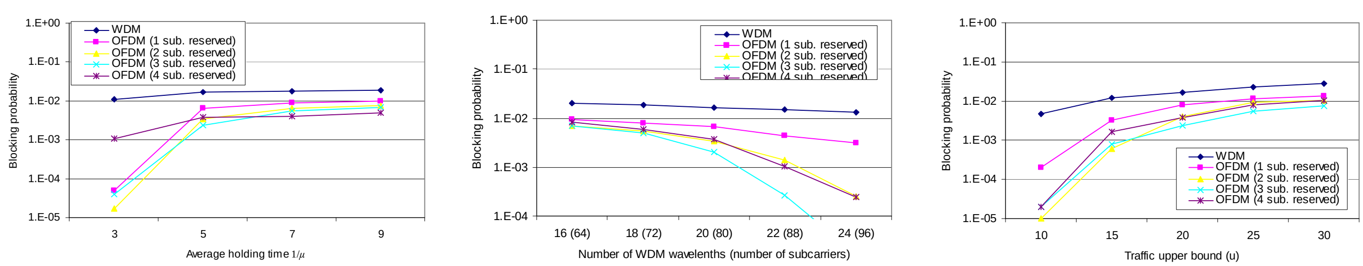

Fig. 2 Blocking probability as a function of: (a) the average holding time $1/\mu$, assuming traffic upper bound u_{sd}=20 Gbps and 20(80) wavelengths (subcarriers), (b) the number of available wavelengths (subcarriers) assuming holding time $1/\mu$=5 and upper traffic bound u_{sd}=20 Gbps, and (c) the traffic upper bound u_{sd}, assuming average holding time $1/\mu$ =5 and 20(80) wavelengths(subcarriers).

4. Conclusions

We considered the problem of the dynamic allocation of spectrum in an OFDM-based transport network, and proposed a general policy to allocate subcarriers to connections whore rate fluctuates as a function of time. We presented a case study in which we compared the OFDM network to a traditional fixed-grid WDM network and observed that the flexibility of the OFDM network can decrease the overall blocking probability.

5. References

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