Spectrally/Bitrate Flexible Optical Network Planning

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Abstract *We consider the Routing and Spectrum Allocation (RSA) problem in an OFDM-based optical network with elastic bandwidth allocation*. We asses the spectrum utilization gains of this flexible architecture compared to a traditional fixed-grid rigid-bandwidth WDM network.

Introduction

The continuous growth of IP traffic in combination with emerging high-rate applications, such as video on demand, high definition TV, cloud computing and grid applications, require a cost-efficient and scalable networking infrastructure. To meet the increasing capacity requirements, recent innovations in optical communication systems, including advanced modulation formats and digital equalization in the electrical domain, have enabled per-channel bandwidths of 40 and 100 Gb/s with improved transmission distance.

Although wavelength routed transparent networks offer obvious advantages, they still have a significant drawback due to their rigid and coarse granularity. Currently, wavelength-routed networks require full allocation of a wavelength even when the traffic is not sufficient to fill the entire capacity. Wavelength level granularity leads to inefficient capacity utilization, a problem expected to become even more significant with the deployment of systems with 40 and 100 Gb/s capacity per channel.

The need for flexibility and efficiency requires the use of resources with subwavelength and super-wavelength granularity. Approaches such as optical packet switching (OPS) and optical burst switching (OBS) that meet these requirements have been proposed in the literature, but can only be viewed as long-term solutions due to their immaturity.

Recently, Orthogonal Frequency-Division Multiplexing (OFDM) has been proposed as a modulation technique in optical networks [1-3]. Enabling technologies, such as bandwidth-variable transponders and bandwidth-variable WXCs, have been designed and demonstrated in SLICE network [4-5].

We focus on the routing and spectrum allocation (RSA) problem in OFDM-based elastic optical networks. We consider the planning phase (offline problem) of such network, where we are given a traffic matrix with the requested transmission rates of all connections. Our objective is to serve the connections through adequate spectrum allocation, with the constraint that no spectrum overlapping is allowed among these connections, and minimize the utilized spectrum.

Network Architecture

Optical OFDM distributes the data over a high number of lower data rate subcarriers and, thus, can provide fine-granularity capacity to connections by the elastic allocation of subcarriers according to the connection demands (Fig. 1). The signal transmitted over the optical path, using just-enough spectrum, is routed through bandwidth variable WXCs towards the receiver (Fig. 2). MEMS- or liquid crystal-based wavelength-selective switches (WSSs) can be employed as BV WXC that configure their switching window in a contiguous manner.

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 rigid-bandwidth WDM network. However, this new concept poses new challenges on the networking level, since the routing and wavelength assignment (RWA) algorithms of traditional WDM networks are no longer directly applicable. The wavelength continuity constraint of traditional WDM networks is transformed to a spectrum continuity constraint. Moreover, a connection requiring capacity larger than one OFDM subcarrier has to be assigned a number of contiguous subcarrier slots.

Although the transmission rate of a connection can fluctuate with time, from the operators' perspective the network has to be planned to guarantee the service of a connection for a requested rate. This would translate to non-overlapping spectrum allocation to all connections for their requested rates. Although planning a network in this way may result in a waste of spectrum resources, when the connections under-utilize their provisioned bandwidth, there are still major gains compared to traditional WDM networks. The gains are (i) the high spectrum efficiency due to OFDM format, (ii) the fine granularity of low-rate subcarrier level, (iii) impairment tolerance due to OFDM features, and (iv) a possible reduction in power consumption by partially deactivating the transmitter, adjusting it to the specific rate at a given time. In the future we

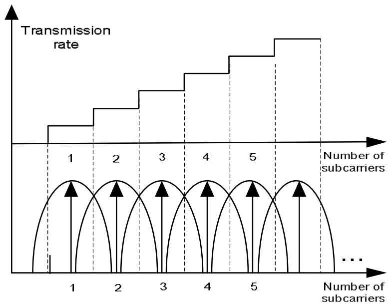

Fig. 1: Variable bandwidth transmission by elastically allocating OFDM subcarriers.

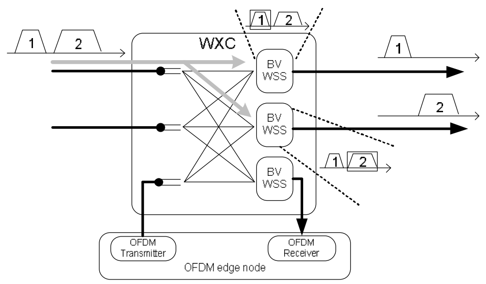

Fig. 2: Spectrum flexible WXC

plan to examine planning methods for OFDM networks where spectrum overlapping is allowed (between non-overlapping time periods), based on time or probabilistic traffic models, as a way to further improve spectrum utilization efficiency.

Routing and Spectrum Allocation Algorithm

We assume an OFDM optical network as presented in the previous section and [4]. The spectral granularity of the transmitters and WXCs is one subcarrier corresponding to *F* GHz. We assume that elastic OFDM transmitters can be tuned to utilize a given number of subcarriers forming a continuous spectrum with a step of *F* GHz. In this context, the spectrum is divided in subcarrier slots of *F* GHz, and each subcarrier is mapped to an integer number. To route the paths through the WXC a guardband of *G* subcarriers has to separate adjacent spectrum paths. Serving a connection *i* that requires T_i subcarriers is translated to finding a starting subcarrier frequency f_i after which it can use T_i contiguous subcarriers (in addition to the guardbands).

A network topology is represented by a connected graph *G*=(*V,E*). *V* denotes the set of nodes, which we assume to be equipped with bandwidth variable WXCs. *E* denotes the set of (point-to-point) single-fiber links. The planning (offline) version of the RSA problem assumes an a-priori known traffic scenario given in the form of a matrix of non-negative integers *T*, called the spectrum traffic matrix. Then T_{sd} denotes the number of subcarriers required for the communication between source *s* and destination *d*. We assume that for connection (*s*,*d*) we utilize a continuous spectrum (a continuous set of subcarriers), so that T_{sd} subcarriers are allocated over a single path.

In the following, we present an integer linear programming (ILP) formulation to solve the Routing and Spectrum Allocation (RSA) planning problem in elastic OFDM-based optical networks. We assume that physical layer impairments (PLI) are not significant for network considered in this study (due to the low symbol rate of OFDM subcarriers and coherent detection) [3], and thus are not accounted for in the algorithm.

For each connection (*s*,*d*) we pre-calculate *k* paths (e.g., using a *k*-shortest path algorithm or variations of it). Let P_{sd} be a set of candidate paths for (*s*,*d*) and $P=\bigcup_{(s,d)} P_{sd}$ be the total set of candidate paths.

Variables:

x_p: Boolean variable that denotes the utilization of path $p\in P$ (x_p equals to 0 if path *p* is not utilized, and 1 if *p* is utilized)

f_{sd}: Integer variable that denotes the starting frequency (subcarrier) for connection (*s*,*d*). Assuming $T_{total}=\sum_{(s,d)} T_{sd}$, we have $0 \le f_{sd} < T_{total}$.

$\delta_{sd,s'd'}$: Boolean variable that equals 0 if the starting frequency of connection (*s'*,*d'*) is smaller than the starting frequency of connection (*s*,*d*) (i.e., $f_{s'd'}<f_{sd}$), and 1 otherwise (i.e., $f_{sd}<f_{s'd'}$).

c: maximum utilized spectrum slot

ILP RSA formulation:

minimize *c*

subject to the following constraints:

- Cost function:
  $c \ge f_{sd} + T_{sd}$, for all (*s*,*d*) pairs (1)
- Single path routing constraints:
  $\sum_{p\in P_{sd}} x_p = 1$, for all (*s*,*d*) pairs (2)
- Starting frequencies ordering and non-overlapping spectrum allocation constraints:

For all commodities (*s*,*d*) and (*s'*,*d'*) that have $p_i\in P_{sd}$ and $p_j\in P_{s'd'}$, with p_i and p_j sharing at least one common link *l*, we employ the following constraints:

$\delta_{sd,s'd'} + \delta_{s'd',sd}=1$, (3)

$f_{s'd'} - f_{sd} < T_{total} \cdot \delta_{sd,s'd'}$, (4)

$f_{sd} - f_{s'd'} < T_{total} \cdot \delta_{s'd',sd}$, (5)

$f_{sd}+T_{sd}+G-f_{s'd'} \le (T_{total}+G) \cdot (3-\delta_{sd,s'd'}-x_{pi}-x_{pj})$, (6)

$f_{s'd'}+T_{s'd'}+G-f_{sd} \le (T_{total}+G) \cdot (3-\delta_{s'd',sd}-x_{pi}-x_{pj})$. (7)

The above ILP algorithm finds the paths *p* (corresponding to x_p=1) and the starting frequencies f_{sd} of the connections over those paths so as to minimize the total used spectrum *c*. Spectrum continuity constraint is translated to non-overlapping spectrum allocation. Thus, the starting frequencies of the connections that utilize a common link are ordered so that their allocated spectrums do not overlap (accounting also for the required guardbands *G* in-between).

Since the above ILP formulation cannot be solved efficiently for very large networks, we are also working on designing alternative heuristic RSA algorithms; these heuristics fall outside the scope of the present brief paper, which aims at introducing the problem, its optimization formulation and obtaining insight in it through results obtained through ILP using a small of candidate paths (i.e. *k*=1 in our experiments).

Performance results

We compared the performance of an OFDM-based elastic optical network to that of a typical fixed-grid, rigid-bandwidth WDM network. To do so we evaluated the performance of the proposed RSA algorithm to that of a typical RWA algorithm through simulation experiments. For the RWA algorithm we have used the LP-relaxation algorithm presented in [6] without considering physical layer impairments, at least for this study.

We have used the generic Deutsche Telekom topology consisting of 14 nodes and 46 directed links [7] (please consider D2.1 in www.diconet.eu/deliverables.asp). We scaled up the realistic traffic matrix of this network (average rate between nodes around 20 Gb/s) to obtain traffic matrices up to 8 times larger than the reference matrix.

We assume that the typical WDM network uses wavelengths of fixed capacity equal to (a) 40 and (b) 100 Gb/s, in a fixed 50 GHz ITU grid, so as to have 0.8 and 2 bit/s/Hz spectral efficiency per wavelength, respectively. The granularity of the OFDM-based network is 5 GHz per subcarrier each of (a) 5 and (b) 12.5 Gb/s capacity, respectively, and the required guardband is 2 subcarriers. Assuming that 10 (8 plus 2 guardband) subcarries are fitted in 50 GHz, this results in the same spectral efficiency (a) 0.8 and (b) 2 bit/s/Hz, respectively. These values were chosen the same for both networks so as to have a fair comparison and evaluate the gains that can be obtained by the flexibility of OFDM. However, OFDM with overlaping orthogonally modulated subcariers is expected to have almost double spectral efficiency than a typical WDM network.

In Fig. 3a we present the performance results for case (a), in which the WDM network uses 40 Gb/s wavelenghts and the OFDM network 5 Gb/s subcarriers. We can observe that the OFDM network has much better pefrormance in terms of spectral utilization. The performance difference of the two networks decreases as the load increases. For the realistic load (scale value equal to 1) the improvement is 95% that is reduced to 5% for the matrix scaled 8 times. This is expected, since for high loads (i.e. average rate between nodes 160 Gb/s) the finer granularity of the OFDM network (5 Gb/s as opposed to 40 Gb/s) is not anymore important. In Fig. 3b we present the performance results for case (b), in which the WDM network uses 100 Gb/s wavelenghts and the OFDM network 12.5 Gb/s subcarriers. In this case the OFDM-based network exhibits even higher performance gains that are also significant for higher loads.

Note that, in this set of experiments we have uniformly scaled the traffic matrix. Higher gains are expected in a more unbalanced traffic case with high traffic churn. Moreover, as stated above, OFDM modulation format is expected to have higher spectral efficiency than a WDM network. When this is combined with the flexibility benefits as presented here, the improvents of an OFDM-based network would be even more pronounced.

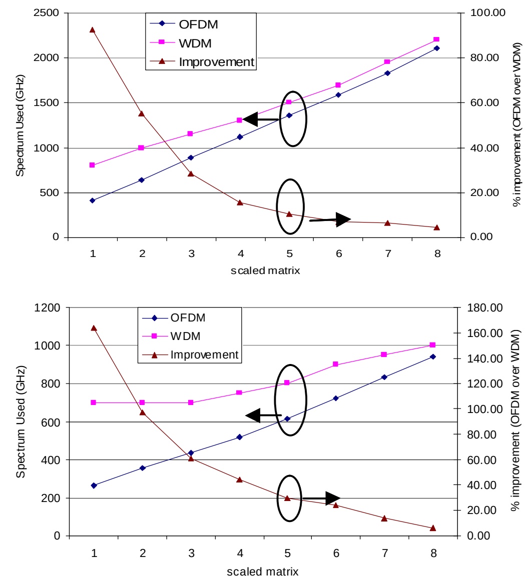

Fig. 3: Spectrum utilization of a WDM and OFDM-based network with spectral efficiency per WDM wavelength (50 GHz) (a) 0.8 bit/s/Hz and (b) 2 bit/s/Hz.

Conclusions

Recently, research has focused on optical OFDM as a spectrum-efficient modulation format that can provide elastic bandwidth transmission. We introduced the Routing and Spectrum Allocation (RSA) problem in an OFDM-based elastic bandwidth optical network and presented an algorithm to solve it. Our performance results showed that important spectrum benefits can be obtained by using this networking architecture when compared to a typical fixed-grid, rigid-bandwidth WDM network. This work has been partially supported by the E.U. through DICONET.

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