Elastic Bandwidth Allocation in Flexible OFDM-based Optical Networks
(Invited Paper)

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Abstract—**Orthogonal Frequency Division Multiplexing (OFDM) has recently been proposed as a modulation technique for optical networks, because of its good spectral efficiency, flexibility, and tolerance to impairments. We consider the planning problem of an OFDM optical network, where connections are provisioned for their requested rate by elastically allocating spectrum using a variable number of OFDM subcarriers and choosing an appropriate modulation level taking into account the transmission distance. Using algorithms developed in our previous works, we evaluate the spectrum utilization gains that can be obtained by utilizing the elastic bandwidth allocation of OFDM, when compared to a traditional WDM network.**

Index Terms— **Optical OFDM, planning (offline) problem, Routing Modulation Level and Spectrum Allocation.**

I. Introduction

The continuous growth of consumers 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-effective 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 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, they still exhibit a major drawback due to their rigid and coarse granularity. 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. Wavelength level granularity leads to inefficient capacity utilization, a problem expected to become even more significant with the deployment of higher capacity WDM networks (i.e., systems of 40 and 100 Gbps per channel).

The need for flexibility and efficiency requires an adaptive network that would have a fine granularity so as to elastically provide the required capacity to sub- or super-wavelength demands. Approaches such as optical burst switching (OBS) and optical packet switching (OPS) that meet these requirements can only be viewed as long-term solutions since their enabling technologies are not yet mature [2][3].

Recently, Orthogonal Frequency-Division Multiplexing (OFDM) has been proposed 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 adjacent subcarriers can overlap, since they are orthogonally modulated, increasing the transmission spectral efficiency. Moreover, optical OFDM can provide fine-granularity capacity to connections 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 Spectrum-sLICed Elastic optical path network (“SLICE”) [7]-[9].

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. 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 1).

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 (remember that OFDM uses overlapping orthogonally modulated adjacent subcarriers). In this context, the wavelength continuity constraint of traditional WDM networks is transformed to a spectrum continuity constraint. Also, note that in OFDM many properties of the transmitted signal are determined in the electrical domain and can be managed by software. A feature that is particularly important for further increasing the flexibility and efficiency of an OFDM network is the choice of the number of modulated bits per symbol for each subcarrier (or for the set of subcarriers corresponding to a connection). To address these issues, new Routing, Modulation Level and Spectrum Allocation (RMLSA) algorithms as well as appropriate extensions to network control and management protocols have to be developed.

The problem of planning a flexible OFDM-based optical network has only recently received some attention. The spectrum allocation problem in an OFDM-based core network, in a slightly different setting than the one considered here, has been examined in [11]. In particular, the authors in [11] use shortest path routing and do not account for the requirement of contiguous spectrum allocation for the OFDM subcarriers. An OFDM-based access network (OFDMA) and OFDMA sub-wavelength spectrum assignment to form fixed-grid WDM wavelengths are presented in [12]. The planning of an opaque

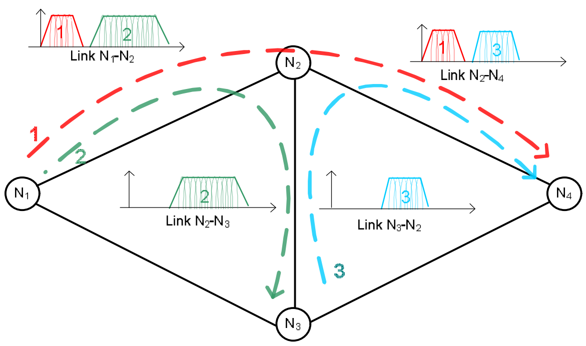

Fig. 1: Spectrum flexible OFDM-base optical network.

point-to-point OFDM-based network with adaptive modulation levels based on transmission distance restrictions has been examined in [13]. A comparison of the number of transponders required to design a bandwidth flexible OFDM network using fixed 50 GHz spaced grid to that of a traditional 50 GHz fixed-grid and rigid bandwidth WDM network is presented in [14]. Although not yet studied in depth, the flexibility of OFDM is also expected to offer significant benefits in a dynamic network environment with time-varying connection rates as well as in dynamic restoration scenarios.

We consider the planning phase (offline problem) in OFDM-based elastic optical networks, where we are given a traffic matrix with the requested transmission rates of all connections. Our objective is to serve the connections and minimize the utilized spectrum under the constraint that no spectrum overlapping is allowed among these connections. To serve the connections efficiently, we exploit the two degrees of flexibility provided by OFDM, namely, the elastic spectrum allocation and the modulation level adaptation. In our previous works [17][18], we have formulated the Routing Modulation Level and Spectrum Allocation (RMLSA) problem and presented various algorithms to solve it; ranging from combinatorial optimization algorithms based on integer linear programming (ILP) formulations and a heuristic algorithm that sequentially serves the connections, combined with appropriate ordering policies and simulated annealing. Using these algorithms, we present here a short study in which we evaluate the spectrum utilization benefits that can be obtained by the flexible utilization of bandwidth enabled by OFDM, when compared to a typical, fixed-grid WDM network.

II. OFDM-Based Optical Network

In this section we shortly present the basic elements of the elastic OFDM optical network envisaged in our study.

In OFDM, data is transmitted over multiple orthogonal subcarriers. This technology has been widely implemented in various systems, such as wireless local area network (LAN) and asymmetric digital subscriber line (ADSL). Recently, research efforts have focused on an optical version of OFDM (OOFDM) as a means to overcome transmission impairments [4]-[6]. In addition to the advantages that stem from the low symbol rate of each subcarrier and the coherent detection that both help to mitigate the effects of physical impairments, OFDM also brings unique benefits in terms of spectral efficiency, by allowing the spectrum of adjacent subcarriers to overlap thanks to their orthogonal modulation. Moreover, OFDM enables elastic bandwidth transmission by allocating a variable number of low-rate subcarriers to a transmission.

OFDM provides an additional degree of flexibility as described next. Typically, digital signal processing (DSP) are used at the transmitter and the receiver, to create the OFDM signal in the RF domain, while I-Q modulators and corresponding receivers are used to upconvert/downconvert the signal to the optical domain [6] [13]. Digital processing provides the capability to adapt many properties of the transmitted signal, in contrast to hardware implementations of 10/40/100 Gbits transponders in traditional WDM networks. In particular, each OFDM subcarrier can be modulated individually using, for example, single bit per symbol binary phase-shift keying (BPSK), QPSK (2 bits per symbol), 8QAM (3 bits per symbol), or 16QAM (4 bits per symbol), etc., while using the same I-Q modulator for the transmission. In contrast, in traditional WDM networks, changing the modulation level/ format would require the use of a different transponder [15].

The choice of the modulation level has to take into account the required Quality of Transmission (QoT) of the connection. A common assumption in optical OFDM ([9][13][14]) is that the transmission distance of the optical path is the sole QoT factor of interest. Transmissions over shortest optical paths are able to utilize higher modulation levels. Under this assumption, we can find the higher modulation level that can be used over a path if we are given its length

A related issue is the choice of the spectral and capacity characteristics of the subcarriers. For example, consider a 50 Gbps connection that is served by an OFDM optical path consisting of 10 subcarriers, 5 GHz spaced, using QPSK to transmit 5 Gbps per subcarrier. Assume also that we can use a shorter path that supports 16 QAM modulation format with acceptable QoT, using 10 subcarriers of 2.5 GHz and 5Gbps each, or 5 subcarriers of 5 GHz and 10 Gbps each, or another combination. In the literature [9][13] and our previous works [17][18], it is assumed that a subcarrier always utilizes a constant spectrum F GHz, irrespectively of the modulation format. Thus, for constant subcarrier spectrum F, the capacity of the subcarrier is defined by the modulation level choice.

Based on the above, a connection requesting a specific rate has two degrees of flexibility, the modulation level and the spectrum. Once these have been determined, the signal transmitted over the optical path is routed through bandwidth variable wavelength cross-connects (BV WXCs) towards the receiver. In this routing process, only the spectrum domain is essential. Every bandwidth variable WXC on the route allocates a cross-connection with the corresponding spectrum to create an appropriate-sized end-to-end optical path. To do so, the BV WXC has to configure its spectral switching window in a contiguous manner according to the spectral width of the incoming optical signal. MEMS or liquid crystal-based wavelength-selective switches (WSSs) can be employed as bandwidth variable WXC switching elements [10]. To avoid interference effects between adjacent optical paths, appropriate spectrum separation, implemented by spectrum guardbands, is required [9].

A. Transmission rate service guarantees

Although the transmission rate of a connection may 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 translates to the requirement for non-overlapping spectrum allocation to all connections for their requested rates. Although planning a network in this way may result in some waste of resources, when the connections under-utilize their provisioned bandwidth, there are still major gains that can be obtained over the traditional WDM networks. These gains include (i) the high spectrum efficiency because of the orthogonally modulated overlapping subcarriers, (ii) the fine granularity at the low-rate subcarrier level, (iii) the adaptable modulation level, (iv) impairment tolerance due to OFDM properties, and (v) a possible reduction in power consumption by partially deactivating the transmitters, adjusting them to the rate at a specific time. Note that, at a specific time, unused spectrum could be shared and allocated to connections that surpass their requested transmission rates or to best-effort traffic, but this spectrum will be de-allocated when the initially provisioned connection requires it.

Additional gains in spectrum efficiency can be obtained by network planning based on time scheduling, using information on the traffic time-variations, or by allowing overlapping spectrum allocation based on stochastic traffic models. For example, connections with transmission rates that are complementary in time, in the sense that when the rate of a connection increases, the opposite tends to happen to that of another one, could be served by shared spectrum slots. The operational phase of the network, where online algorithms are used to serve dynamic traffic, is also an interesting and future topic of study.

B. *RMLSA requirements*

Routing and wavelength assignment (RWA) algorithms devised for fixed grid WDM systems are not applicable to OFDM networks, even when the modulation level is fixed. To see that note that the OFDM routing and spectrum allocation (RSA) problem can be transformed into a typical RWA formulation, by viewing a subcarrier in the RSA problem as a wavelength of equal capacity in the RWA problem. Although a typical RWA algorithm is able to find a route for a connection requiring a number of subcarriers (wavelengths in the RWA context), the wavelengths that will be found by the RWA algorithm are not generally going to be contiguous. Allocating contiguous subcarriers is crucial in OFDM networks, since the spectrum of adjacent subcarriers must overlap to enable higher spectral efficiency.

Moreover, the majority of RWA algorithms proposed in the literature utilize variables and constraints that depend on the number of wavelengths, which in a typical WDM network seldom exceeds 80, beyond which the operators have to install additional fibers per link. The high number of OFDM subcarrier limits the applicability of traditional RWA algorithms. Finally, in the RMLSA problem, we also have to choose a modulation level per subcarrier and connection. This problem in a slightly different setting has been recently examined for mixed line rate (MLR) WDM systems [15].

From the above discussion it is clear that RMLSA requires the development of new algorithms that will (i) serve a connection utilizing a contiguous and elastic spectrum, (ii) formulate the problem using variables and constraints that do not depend on the number of subcarriers, and (iii) enable the choice of the modulation level for each connection.

In our previous works [17][18] we have developed such algorithms. We have presented an optimal combinatorial optimization algorithm and a decomposition approach (that breaks the problem into (a) routing and modulation level allocation and (b) spectrum allocation) based on integer linear programming (ILP) formulations. We have also presented a sequential heuristic algorithm that uses a pre-ordering phase and then a heuristic RMLSA algorithm designed for serving single demands, to sequentially serve all the demands one-by-one.

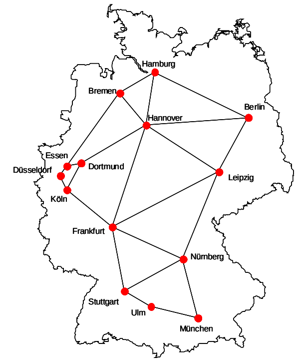

Fig 2: The generic DT network topology, with 14 nodes and 46 directed links.

III. SPECTRUM EFFICIENCY STUDY

We evaluate the spectrum utilization benefits that can be obtained through the elastic allocation of bandwidth of the envisioned OFDM-based optical network when compared to a typical fixed-grid WDM network.

For planning the OFDM network we used the simulated annealing meta-heuristic with 1000 iterations presented in [18]. We assume that a subcarrier utilizes F=5 GHz spectrum, single bit per symbol modulation (BPSK) capacity per subcarrier is C=2.5 Gbps, and the required guardband G=2 subcarriers. Regarding OFDM adaptive modulation levels we assume that BPSK can be used for transmissions up to 3000km, QPSK can be used up to 1500 km, etc. using the half distance law of [13]. For the RWA we used the LP-relaxation algorithm of [16], and we do not consider interference physical impairments, but when we utilize a mixed line rate (MLR) WDM system (Fig. 4) we use transmission reach constraints. We used the generic DT topology of Fig. 2 and a realistic traffic matrix for this network provided for 2009, as reported in deliverable D2.1 in www.diconet.eu/deliverables.asp. In this matrix, the average rate between nodes is around 15 Gbps. We uniformly scaled this realistic traffic matrix so as to obtain traffic matrices up to 8 times larger than the reference matrix of 2009.

In the experiments presented in Fig 3 we assume that the WDM network uses 40 Gbps wavelengths with QPSK in a 50 GHz grid. Thus, when QPSK is used in both OFDM and WDM networks, they both have equal spectrum efficiency per 50 GHz WDM wavelength. As mentioned, OFDM provides two flexibility degrees: (i) the elastic spectrum allocation and (ii) the adaptive modulation level. At light loads, the elastic spectrum allocation (first degree of flexibility) is quite efficient due to the finer granularity of the OFDM network, and yields high spectrum gains. As the load increases the gains from the elastic spectrum allocation decrease, since the finer granularity of the OFDM network (5 Gbps as opposed to 40 Gbps) is not that important. Although the spectrum gains of the elastic spectrum allocation decreases as the load increases, this is compensated by the improving effects of the adaptive modulation level (second degree of flexibility) that become more dominant at heavy load. At heavy load high-rate connections are served over shorter paths using higher modulation levels, improving the spectrum efficiency of the OFDM network. This, yields significant spectrum utilization gains as the load increases.

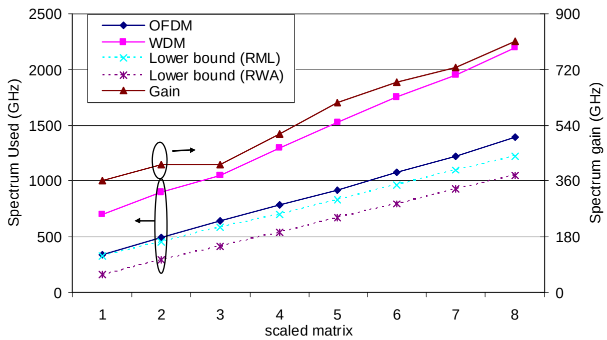

Fig. 3: Spectrum utilization of a 40 Gbps WDM network with spectral efficiency per wavelength (50 GHz) of 0.8 bit/s/Hz and an OFDM-based network with flexible spectrum allocation and adaptive modulation levels.

In Fig. 4 we the compare the OFDM with a mixed-line rate (MLR) WDM system. For the WDM network we assumed that 10 Gbps, 40 Gbps, or 100 Gpbs wavelengths are able to transmit with acceptable quality up to 3000 km, 1500 km, and 500 km, respectively. The modulation level restrictions of the OFDM-based network were as previously, resulting in almost the same spectral efficiency per wavelength as the WDM network for the same transmission distance. Comparing the results of Fig. 3 and Fig. 4 we see the improvements obtained in the WDM network when utilizing MLR (the performance of OFDM is the same in both figures). Still, the performance of OFDM with flexible spectrum allocation and adaptive modulation levels is superior and the spectrum improvements are maintained even for heavy traffic loads. Note that adapting the modulation level in the OFDM network can be performed by software, while in the MLR WDM network changing the wavelength capacity requires the utilization of different transponders, constraining the adaptability to traffic changes.

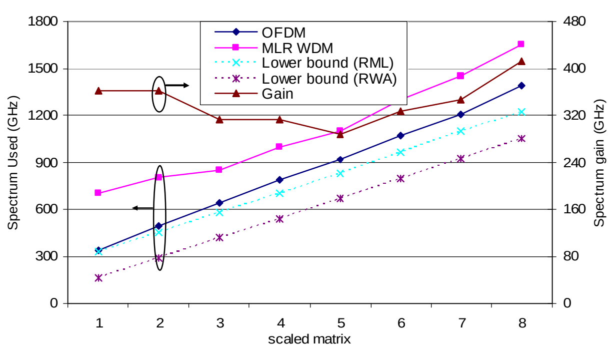

Fig. 4: Spectrum utilization of a mixed-line rate (MLR) WDM network with wavelength capacity of 10, 40 and 100 Gbps and an OFDM-based network with flexible spectrum allocation and adaptive modulation levels.

An OFDM network would have better spectral characteristics per wavelength than a WDM network, because of the overlap of adjacent orthogonally modulated subcarriers. Moreover, due to low subcarrier rates, the reach of the OFDM network is expected to be higher than that of a WDM network. These attributes were not used in the above study, but instead we assumed similar spectral and reach characteristics for both OFDM and WDM networks in order to evaluate the gains that can be obtained by OFDM flexibility. When these characteristics are taken into account, combined with the flexibility benefits as presented here, the performance advantages of an OFDM-based network would be even more pronounced.

IV. Conclusions

Optical OFDM is receiving recent attention as a spectrum-efficient modulation format that can provide elastic bandwidth transmission. We considered the problem of planning an OFDM-based optical network where connections are provisioned based on their requested transmission rate and assuming no spectrum overlapping between them. OFDM provides two degrees of flexibility, namely, elastic spectrum allocation and modulation level adaptation. Our results showed that the OFDM-based network has significant spectrum benefits over a typical fixed-grid WDM network, indicating that the OFDM architecture offers a promising solution for future high capacity transport networks.

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