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Impact of transparent network constraints on capacity gain of elastic channel spacing

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Abstract: We compare fixed-grid network architectures with variable-spacing OFDM based solutions. We show that capacity gains can reach up to 50% but are strongly affected by physical and topological constraints of transparent networks and traffic statistics.
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1. Introduction

Due to the increase of traffic and the limited number of wavelengths per fiber, spectral-efficient transmission techniques are required. A first step towards enhancing the spectral efficiency of a network is to increase the data-rate per wavelength in combination with multi-level modulation formats, such as presently available in 100Gb/s products over 50GHz channel spacing grid. The next generation of optical networks is expected to accommodate a large variety of services ranging from low-capacity (like voice) to high-capacity (for instance 3D or ultrahigh definition television). The payload transported by a channel may thus be only a fraction of its capacity. This is especially the case in transparent networks where grooming is performed only when a connection is created [1]. Hence, to provide spectral efficient solutions we have to consider the transported payload versus the required spectral window.

The introduction of new modulation technologies like Orthogonal Frequency Division Multiplexing (OFDM), enabling the parallel transmission of data on a large number of low data-rate subcarriers, opens up new perspectives for optical communications like grid-less transmission [2]. Thanks to OFDM, a finer channel granularity (sub-carrier) is provided and the channel width does not depend any more on the constraints of a used grid (usually 50GHz) but on the capacity requirement of the demand. Examples of bandwidth-variable transponders and cross connects are proposed and demonstrated in the literature [2]. In the following we call elastic-channel spacing the capability to manage signals with different bandwidths, with central frequencies no longer aligned on the 50GHz grid; otherwise we talk about fixed grid.

In this work we firstly propose a new impairment-aware routing and spectral allocation algorithm, and then we compare the performance of elastic-OFDM versus fixed spacing 40Gb/s channels. In this work we show how the advantages of elastic-OFDM depend on transparent routing constraints (i.e. spectrum continuity and physical impairments) and on the traffic matrix characteristics.

2. Proposed routing algorithms for elastic channel spacing

2.A Physical model

We consider optical OFDM transmission systems with subcarriers spaced by 10GHz. Each subcarrier is modulated in Binary Phase Shift Keying carrying 10Gb/s. The maximum number of subcarriers per channel is obtained by considering the physical impairment occurring along the path. We assume that the performance of transmission systems is only limited by two factors: (i) the accumulation of Amplified Spontaneous Emission (ASE) noise, as a signal propagates along a transmission link, and (ii) the finite maximum power available for each channel. Under these assumptions, the channel bit-error rate (BER) is solely determined by the signal-to-noise ratio (SNR) seen by each of the subcarriers. If we assume an identical length for all fibre spans and identical Erbium doped fibre amplifiers (EDFA) exactly compensating for the span losses, the SNR measured in the bandwidth of a subcarrier is given by [3]:

$$SNR_{dB} = P_{channel,dBm} - 10\log_{10}(N_{sub}) - NF_{dB} - 10\log_{10}(N_{span}) - L_{dB} - 10\log_{10}(1000 h\nu \cdot \delta f)$$

where N_{sub} the number of subcarriers, NF_{dB} the noise figure of the EDFA (6dB), N_{span} the number of fiber spans in the transmission link, L_{dB} the optical loss of each span (100km-spans with 22dB loss), h the Plank constant (J.s), ν (Hz) the central frequency of the channel, δf the subcarrier spacing (Hz) and $P_{channel,dBm}$ is the maximum available channel power at the input of each span, and the factor 1000 is used to normalize the dBm. We set $P_{channel,dBm}$ to 0dBm, whatever the distance [4]. A connection is considered feasible if SNR_{dB}> $RSNR_{dB}$ (BER, format) where $RSNR_{dB}$(BER) is the required SNR to ensure a reference BER after propagation. $RSNR_{dB}$ (9.5dB for BPSK modulation and 10^{-5} BER) depends on the format chosen to encode the data on the subcarriers and can be derived from digital communication textbooks, e.g [5].

2.B Routing and spectral allocation routine

The proposed algorithm handles demands sequentially and jointly searches for the path and the spectral allocation associated to a connection demand, while minimizing the global spectral window per link. To reduce the amount of used spectrum, we sort the demands before routing. The ordering strategy considers the product of the demand capacity by the number of links composing the shortest path. Therefore we firstly route demands requiring more spectrum in the whole network.

To solve the spectrum allocation problem, we split the 4THz-wide C-band transmission window in 400 10GHz-wide slots and create a Boolean vector per link with 400 elements; the value '1' indicates that the slot is occupied, '0' otherwise. Between each pair of source-destination nodes we consider k-shortest pre-selected paths, with k=3. High capacity connections that are too long for transparent transmission are split into two or more contiguous connections. Moreover, [2] suggests the use of a guard-band (GB) separating OFDM channels in order to minimize the penalties due to both filtering functions and the channel cross-talk. While in transparent networks, increasing the GB width allows to pass through a larger number of filters, hence through more intermediary nodes, in opaque networks, GBs are needed just to isolate channels from each other at the receiver end. Thus, GBs are generally smaller in opaque scenarios than in transparent scenarios. In the following we investigate the maximum GB width such that the elastic channel spacing is still interesting compared to a fixed one. The bandwidth of a channel is given by the width relative to the total number of subcarriers plus the width of the GB. Naturally, if a request is split in several connections (because the distance to bridge is too long), a GB is associated to each of the created connections.

The fixed grid algorithm also performs the same sorting and routing approach than the previous one, but the minimum number of channels is now obtained by taking the ceil of demand capacity divided by the channel data-rate (40Gb/s). The transparent reach of the 40Gb/s channel is 2400km supposing that all channels are modulated with Polarization Division Multiplexing BPSK format, without dispersion management and with coherent detection [6].

3. Results

To investigate the advantages of elastic- versus fixed-channel spacing we consider both opaque and transparent networks. We gradually introduce the constraints relative to the transparency, i.e. first the spectral continuity and then physical impairments. At the same time we investigate the impact of guard-band width on spectral efficiency for both network types. The presented results are obtained considering a 21-node, 37 bi-directional-link network, whose characteristics are summarized in Table 1. All k-shortest paths are shorter than 2400km. The considered traffic matrices have 420 uni-directional demands with the following statistics on the channel capacity (Gaussian distribution): average capacity demands of 20, 40 and 60Gb/s and standard deviation of 5, 10 and 20Gb/s, for a total of 9 types of traffic matrices summed up in Table 2. Results are obtained by averaging the routing results of 100 traffic matrix draws.

Table 1: Characteristics of the studied network.

	min	average	max
Link length	139	294	567
Path length	139	985	2316

Table 2: Average traffic loads (Tb/s) of the different matrices obtained for the different channel capacity distributions.

		Standard deviation		
		σ=5	**σ=10**	**σ=20**
Mean	**m=20**	8.6	8.7	10.1
	m=40	17	17	17.2
	m=60	25.7	25.4	25.5

To perform the comparison, we compute the maximum spectral window over all links required to route all demands for both elastic- and fixed-channel spacing. In Fig. 1(a) we report the relative reduction of spectral usage of elastic- versus fixed-channel-spacing networks, as a function of the guard-band. We first observe that independently of the traffic assumption, the gains observed for opaque networks are higher than for transparent. This can be traced back to the spectrum continuity constraint in transparent networks which tends to fragment the transmission window. When no GB is considered, the gain due to the elastic channel spacing is around 50% when the average channel capacity is low (m=20Gb/s); this is mainly due to the poor filling of fixed 40Gb/s channels while the OFDM solution better adapts the channel width to its payload. On the other hand, if we increase the average channel capacity, the fixed 40Gb/s channels are better filled and the interest of elastic channel spacing decreases to 35% (m=60Gb/s). But to account for filtering effects, we introduce a GB which increases the spectral occupancy of OFDM channels. We observe, still on Fig. 1(a), that the elastic channel spacing solutions remain more interesting than fixed ones as long as the GB is narrower than 3 subcarriers.

The standard deviation of capacity distribution has little impact except for cases when the fixed 40Gb/s channels are poorly filled, that is for m=20Gb/s and to a smaller extend for m=60Gb/s.

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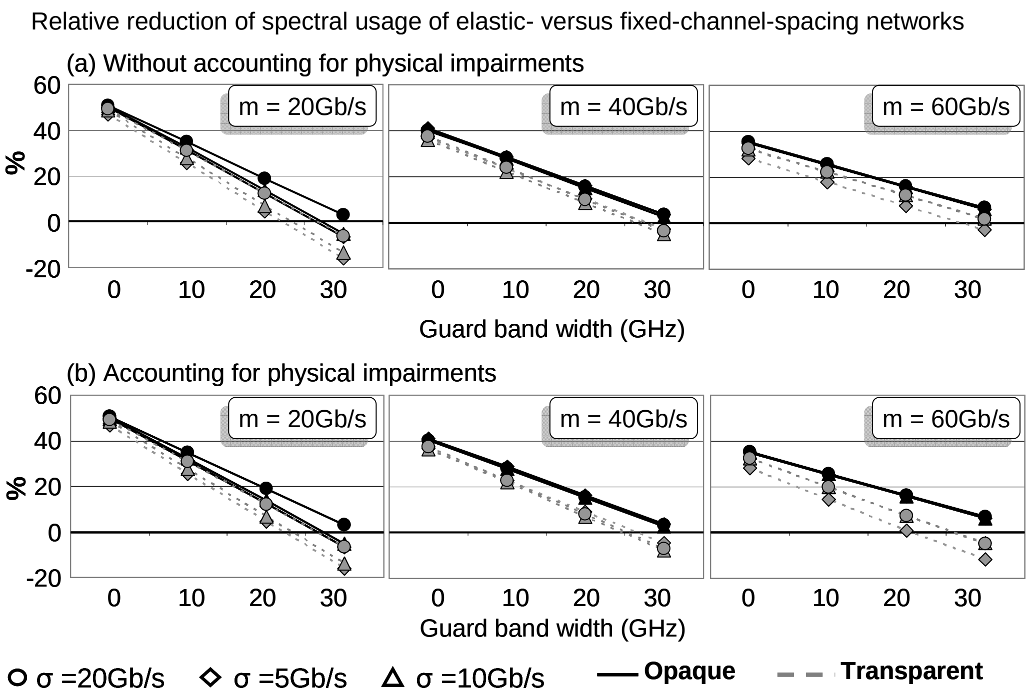

Figure 1: Relative reduction of spectral usage of elastic- versus fixed-channel-spacing networks, as a function of the guard-band width and demand capacity distributions (average m=20, 40, 60Gb/s and standard deviation σ=5, 10, 20Gb/s). .

With the introduction of physical constraints, we check for each demand that the covered distance is transparently feasible for a single OFDM channel and split the demand in two or more connections otherwise. The gain of elastic architectures versus fixed ones for this case is shown in Fig 1(b). Comparing with Fig. 1(a), we observe that opaque scenarios are almost unaffected by physical constraints because of the short link lengths. This is not the case for transparent networks where long transparent transmissions are required and a single OFDM channel cannot be used to transport high capacity demands. Splitting demands into several channels is penalizing when a non-zero GB separates the OFDM channels. This penalty is especially evident with the increase of the average channel capacity, because more high capacity demands covering long distances are generated, thus increasing the number of required GBs. For transparent networks the elastic channel spacing is more interesting than fixed-grid solutions only if the GB width does not exceed the limit of 2 subcarriers slots (i.e. 20GHz). This limit matches the minimum channel spacing recommended in [2] as a result of current technological constraints on filtering. This underlines the challenges associated to the successful implementation of elastic channel spacing in transparent optical networks. For low demand capacity the elastic-channel spacing is on average 7% more interesting than fixed (similar result with or without physical constraints), while for high demand capacity such interest drops to 5% (against 12% w/o physical impairments).

4. Conclusion

In this paper we compare the spectrum efficiency of elastic-channel spacing versus standard fixed (50GHz) ones. We have shown how the interests of elastic-channel spacing are strongly dependent on the traffic assumptions and physical impairments. If no guard-band is required between OFDM-channels, opaque and transparent networks have similar gains, decreasing from 50% to 35% when the capacity demand goes up because fixed 40Gb/s channels become more efficiently filled. On the other hand, if guard-bands are introduced and physical constraints are taken into account, the elastic channel spacing remains interesting in opaque networks if guard-bands do not exceed 30GHz, while for transparent networks it has to be at the most 10GHz.

5. References

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