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Optical Multi-band OFDM Switching Technology

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Abstract— With the continuing growth in the amount of traffic, improving the flexibility and the transparency of optical networks is a very important problem facing operators today. In this paper, we present a networking technique based on optical multi-band Orthogonal Frequency Division Multiplexing. The optical multi-band OFDM approach enables optical switching at fine granularity in a highly spectrum-efficient manner. We study the performance of this approach in term of blocking compared to mono-band opaque and mono-band transparent OFDM technologies in an optical core network. We show that the flexibility offered by optical multi-band OFDM is efficient in term of blocking and that the sub-band granularity has an important impact on the blocking ratio.

Keywords: All-optical network, multi-band optical Orthogonal Frequency Division Multiplexing, Wavelength/sub-band conversion, optical aggregation/disaggregation, wavelength continuity constraint.

I. INTRODUCTION

The telecommunication area has been marked in the last years by an important increase in traffic, doubling every two years approximately [1]. The massive emergence of new services with high capacity requirements, like audiovisual services such as video on demand, will certainly sustain this growth in the next years. To support this growth, optical core networks have to increase their link capacity up to 100 Gbps per optical channel. Around a hundred of WDM channels per fibres that is becoming the next standard for optical transmission systems.

In order to support the regular traffic growth, optical networks have already evolved towards wavelength routed networks, introducing Reconfigurable Optical Add Drop Multiplexers equipment and dynamicity thanks to a control plane. However, in a wavelength-routed network, the minimum granularity of an optical connection is the capacity of a wavelength. With capacity growing up to 100 Gbps per wavelength, this granularity is even larger than it was from traffic flows generated by users. Thus the requirement for aggregation into the wavelength “tunnels” is expected to grow. Today, this aggregation is done at the end points thanks to electrical switching [2]. But with traffic increase, the use of electrical switching generates an important growth in power consumption and network cost [3]. Network operators aim thus to find solutions that offer such functionality with reduced impact on power consumption and cost. These

solutions should switch in the optical layer which may indeed provide these reductions thanks to the corresponding savings of optical-electrical conversions.

In this context optical multi-band OFDM (orthogonal frequency division multiplexing) technology can be an interesting candidate for future optical core networks. Optical multi-band OFDM can handle ultra high bitrates (as high as 100 Gbps and above). It benefits from an access to finer granularity than the aggregated 100 Gbps data rate while remaining in the optical domain. Using adequate add and drop sub-band functions in nodes, optical multi-band OFDM offers all optical switching and aggregation flexibility at granularities finer than the original generated 100 Gbs data stream. OFDM technology appears to be a particularly well adapted technology to sub bands generation thanks to a low modulation rate per sub-carrier leading to very square sub-band spectrums [4]. We have introduced this concept in [5]. In this paper, we analyze the performance of this solution in terms of blocking probability compared to legacy scenario based on mono-band opaque or mono-band transparent techniques.

The paper is organized as follows. First we describe the concept of the optical multi-band OFDM technique and present the major network flexibilities offered by this approach. We then explain the advantages of the concept with respect to state of the art solutions. In Section III, we describe the network model and the reference scenarios used to evaluate the proposed solution. In Section IV, we present the network performances of the optical multi-band OFDM approach compared to the reference scenarios. Section V concludes the paper.

II. OPTICAL MULTI-BAND OFDM NETWORKING TECHNIQUE

In this part, we present the concept of optical multi-band OFDM networking approach. Then we discuss the other technologies that can compete the optical multi-band OFDM technique.

A. Concept

The principle of OFDM is to split a high-rate data stream into a number of lower-rate data streams that are transmitted over a number of sub-carriers. Compared to “simple” optical OFDM, the optical multi-band OFDM approach consists to “slice” the channel spectrum in

fine separable and independent sub-bands. Each sub-bands is made of several sub-carriers. As said before, the spectrum shape of the sub-band has a square shape thanks to the OFDM modulation. Moreover the low rate data streams carried by the sub-carriers achieve a high sub-band density per optical channel. The optical multi-band OFDM channel simplified structure is shown in Figure 1 (-).

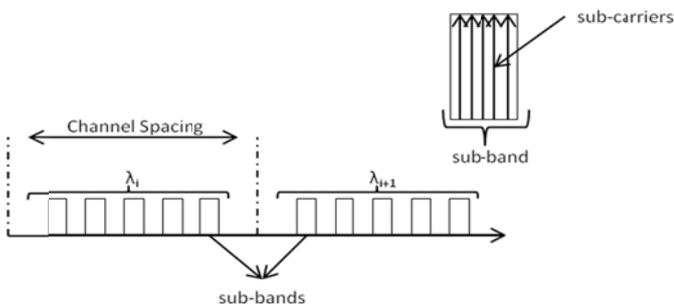


Figure 1 Typical Optical Multi-band OFDM Spectrum

The hierarchy of the optical multi-band OFDM approach is similar to the waveband concept [6], however at a different scale; waveband considers a band of optical channels when optical multi-band OFDM considers a band of sub-bands, each sub-band constituting one optical channel. However, the major difference is on the multi-band OFDM transponders. A single optical multi-band OFDM transponder can generate or receive simultaneously all the sub-bands of an optical channel that can be routed independently from each other in the network.

In an optical multi-band OFDM transponder in the core of the network, the optical switching of the sub-bands is performed thanks to very selective optical filters. They allow aggregation/disaggregation of sub-bands in the optical domain. As a result, sub-bands of different WDM channels going to the same destination (even when coming from different sources) can be optically aggregated together into the same optical channel (wavelength). Sub-bands coming from the same source and going to different destination can be optically disaggregated.

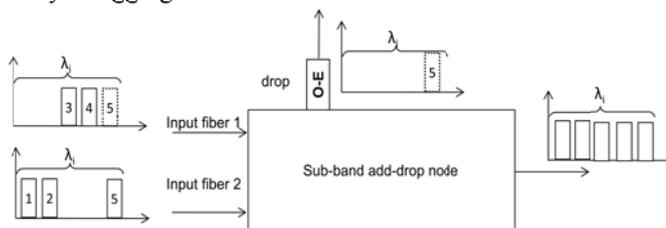


Figure 2 Example of sub-band add-drop and switching

The maximum number of sub-bands is thus highly dependant on the filter thickness and steepness and the channel spacing. As an example, tunable optical filters with fine bandwidth as low as 4 GHz are now commercially available [7]. They could allow to divide the usual optical channel bandwidth of 50 GHz into at least 4 sub-bands with adequate guard bands. Future progresses in the area of optical filtering will probably exceed this number in the next few years. Figure

2 shows an example of the all optical aggregation/disaggregation of 2 input optical multi-band OFDM channels. In this example the 2 input fiber channels (λ_1 on Fiber 1, λ_2 on Fiber 2) are composed of 5 potential sub-bands. In the sub-band add-drop node, the sub-band 5 of channel λ_1 of fibre 1 (in dashed points) is dropped in the node and other sub-bands 3 and 4 of channel λ_1 of fibre 1 are grouped with the sub-bands 1, 2 and 5 of channel λ_1 of fibre 2 then routed to the output port associated with fiber 3. The sub-bands that are grouped in the node must come from WDM channels occupying the same wavelength position in the input fibers and must also have disjoint spectral position in the channels; otherwise they can't be grouped together in the same channel. These continuity constraints can be by-passed by using sub-band or wavelength conversions. The sub-band add-drop node can extract a single or a group of sub-bands and can route it (or them) on one of the node output port.

Beside this all-optical aggregation capability, OFDM technology also offers opportunities to improve the sub-band flexibility itself by making the sub-band data-rate tuneable within limited technological challenges. Similarly to radio communication, optical OFDM sub-bands could adapt their data-rate under certain limits to the traffic requests or/and transmission conditions. For example sub-bands with very short paths could benefit from more capacity than the nominal data rate, or reversely sub-band lightpaths experiencing long paths with higher transmission impairment should decrease their data rate to support the transmission conditions and avoid regeneration [5]. In this paper we only evaluate the sub-band aggregation flexibility without considering such a data-rate adaptation.

B. State of the art

Optical multi-band OFDM offers fine granularity switching in its principle similar to SDH (Synchronous Digital Hierarchy) or OTN switching (Optical Transport Network) but in the optical layer. Indeed, multi-band OFDM offers the sub-band "hierarchy" to aggregate traffic. Compared to SDH or OTN, the switching granularity may be larger (25 Gbps for 4 sub-bands compared to 155 Mbps in SDH or 1 Gbps for OTN)[8].

It is also comparable to spectrum-sliced elastic optical path network (SLICE) [9] with respect to the "slicing" of the channels into sub-bands. The aim of SLICE as defined in [9] is to provide spectrum-efficient transport of 100 Gbps services and beyond also based on OFDM modulation format. It offers a flexible frequency approach instead of the fixed ITU-T frequency grid; considering super-channels, made of spectrum slots. Thanks to this slot approach, the SLICE technique is able to allocate the optical spectrum depending on the demand volume and physical constraints on each lightpath request. This requires a bandwidth-variable transponder which is used to generate an optical signal using just the necessary spectral resources. Bandwidth variable wavelength cross connects allocate the appropriate spectrum along the optical path.

Bandwidth adaptation is the major contribution of SLICE in term of flexibility, however, SLICE doesn't allow to access

to the slot entities independently. In this respect, SLICE is not suitable for all optical aggregation purpose.

Thanks to the OFDM modulation, multi-band optical OFDM can offer flexibility and adaptability of SLICE within the limit of technological constraint. In addition the multi-band optical OFDM approach allows access to sub-wavelength entities.

III. NETWORK MODEL PERFORMANCE STUDY

As explained in the previous section, optical multi-band OFDM switching technology can be viewed as a way to virtually multiply the number of independent optical channels with fine granularity. On a networking point of view, this approach is expected to improve transparency. In this section, we compare the network performance of multi-band optical OFDM switching technology to two extreme switching technology: purely mono-band opaque and purely mono-band transparent networks. The optical switching technologies are defined as follow.

Mono-band opaque switching technologies: this switching technology corresponds to an OTN case where O-E-O convertors are systematically deployed at intermediate nodes of the network. In this opaque network, we have thus the total flexibility to aggregate/disaggregate the carried traffic. Each demand is then aggregated to occupy a minimum of channels on each link. As a result, tributaries coming from different sources and going to the same destination are aggregated in the intermediate nodes. In the same way, purely transit traffic is also systematically converted. In the following studies, we suppose that the minimum granularity switched/aggregated by the network is 1 Gbps. Optical channels are thus expected to be well filled. However traffic is expected to undergo a high number of OEO conversions (one at each switch along the lightpath).

Mono-band transparent switching technologies: In mono-band transparent switching, O-E-O (optical-electrical-optical) conversions are not used to aggregate/disaggregate demands and the mono-band structure of the optical channel does not allow to access to any sub-wavelength granularity. Each demand uses a dedicated wavelength channel. Depending on the traffic distribution (for example if the traffic is made of many small demands), optical channels are not well filled in this kind of network which can cause a waste of optical resources.

Optical multi-band OFDM switching technologies: In optical multi-band OFDM switching. Each demand can use a sub-band or a group of sub-bands of the optical channel. Thanks to optical switching, demands can be aggregated in the same optical channel while remaining in the optical domain. Optical multi-band OFDM can be considered as a trade-off between opaque networks and transparent networks.

The performance of the three previous network scenarios is evaluated using an event driven simulator based on OMNeT++ [10]. The following assumptions are made.

A. Assumptions

- The bit-rate of each optical channel is 100 Gbps, except for the multi-band OFDM where it depends on the number of sub-bands effectively. The maximum bit-rate of multiband OFDM is 100 Gbps.
- Every link is composed of maximum 10 optical channels (arbitrary limit selected to reduce simulation times).
- Links are bidirectional.
- Duration of connections: we assume that the connections have a finite duration. The duration of connections is drawn randomly following an exponential law with parameter values ... and
- The probability of appearance of a demand between two nodes is drawn randomly following a uniform law with parameter values ... and ... and ...
- A connection between two nodes is deactivated at the end of the communication and the resources are released.
- Generated demands have a bit-rate between 1Gbps and 100 Gbps. The bit-rate of each request is drawn randomly with a uniform law with parameter values ... and
- Routing algorithm: a shortest path algorithm is used to calculate the path of each request. The shortest path is calculated based on the number of hops in a path.

For the transparent case:

- Wavelength continuity is assured. This means that each request must use the same wavelength along its path. Wavelength conversion is not used except when specified.
- Connections are setup based-on first fit wavelength assignment.

For multi-band optical OFDM technology, we suppose that:

- Sub-band continuity is assured. Each request must use the same sub-bands along its path. Sub-band conversion is not used except when specified.
- Connections are setup based-on first fit wavelength and sub-band assignment on a chosen path. A connection is established using the shortest path and the first available continuous sub-band on this path. If no continuous sub-band is found, the connection is blocked.
- The optical channel is composed of n sub-bands.
- The bit-rate of each sub-band is at maximum $100/n$ Gbps (and since we do not consider data rate adaptation bit-rate of each sub-band is fixed to exactly this maximum).

The study is made on NSFnet network topology. The NSFnet network is composed of 14 nodes and 22 unidirectional links [11]. This network topology is one of the most used topology for similar studies. We suppose that each node of the network receives/transmits traffic from/to all other nodes.

Based on these assumptions we evaluate the performance of the proposed scenario.

IV. RESULTS

A. Optical Multi-band OFDM performance with $n=4$ sub-bands and without wavelength conversion

The performance metric is the blocking ratio. The blocking ratio is defined as the ratio of the number of blocked demands over the number of generated demands.

We suppose first that for optical multi-band OFDM network, the optical channel is composed of $n=4$ sub-bands.

For each simulation a total of 200000 demands were generated. The performances metrics are averaged over 20 randomly generated set of runs. The standard deviation of the blocking ratio was around 3%.

Figure 3 depicts the blocking ratio of the three proposed switching technologies. The blocking ratio is showed as a function of network load. The network load is defined as the amount of simultaneous connection demands and normalized by the maximum link capacity.

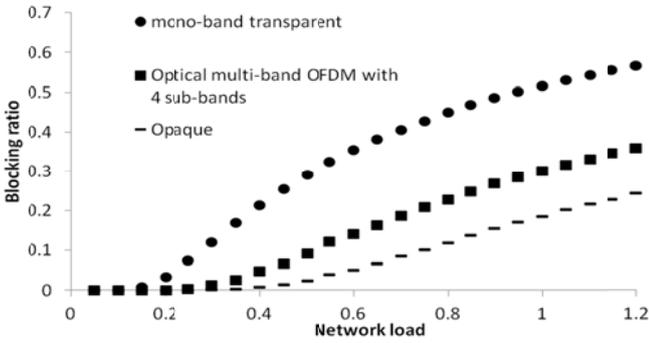


Figure 3 Blocking performance of proposed optical switching technology

As expected, the blocking ratio is higher in mono-band transparent network than in optical multi-band OFDM network and mono-band opaque network. This is due to the fact that in mono-band transparent switching, each requests uses an entire optical channel, while in the case of optical multi-band OFDM switching and the mono-band opaque switching an optical channel can be shared by multiple requests.

Opaque switching is the most efficient switching technology, thanks to the systematic electrical switching that allows to get rid of the continuity constraint and also aggregates traffic on the minimum number of wavelengths.

In order to explain this, we consider the example shown in Figure 4. In this simple example, we assume that each link carries only up to one optical channel. Two demands must be routed on the network: a demand from A to D with 90 Gbps traffic and one from B to D with 10 Gbps traffic. In the optical multi-band OFDM case, since the maximum bit rate per sub-band is 25 Gbps, the first demand must use in total the 4 sub-bands to satisfy the demand, leaving no place for the B-D demand. Hence B-D must be blocked.

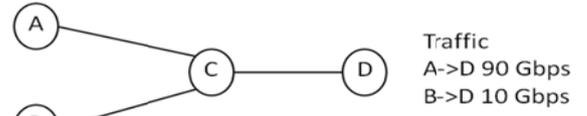


Figure 4 Example of blocking with optical multi-band OFDM switching technology

Reversely, in the opaque case the demands are aggregated in the node C using electrical grooming and both demands can be transported over the network.

We call the blocking obtained with the multi-band network case the granularity constraint.

B. Impact of the deployment of wavelength conversions on optical multi-band OFDM node

The previous example showed that the resulting blocking ratio for the multiband case not only accounts for resource unavailability but also for both wavelength continuity constraint and granularity constraint. In Figure 5 we have separated the different sources of the blocking ratio due to the continuity constraint and blocking ratio due to resource unavailability or granularity constraint.

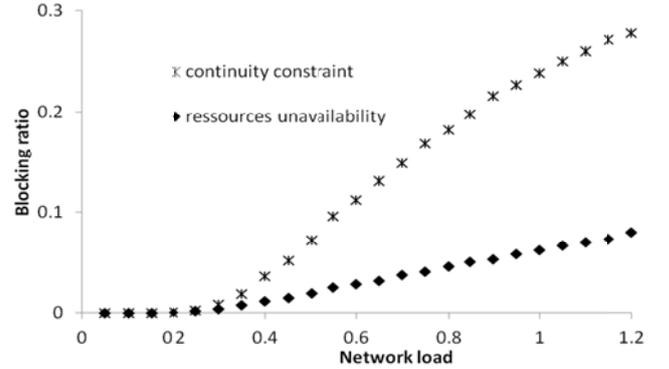


Figure 5 Cause of blocking in optical multi-band OFDM network

We remark that the blocking is mainly caused by the continuity constraint. For this reason, we expect that using wavelength and sub-bands conversions probably reduces the blocking ratio of optical multi-band OFDM approach.

We have thus simulated the addition of wavelengths and sub-band converters in each node. Results are plotted on Figure 6 in the case of optical multi-band OFDM switching technology.

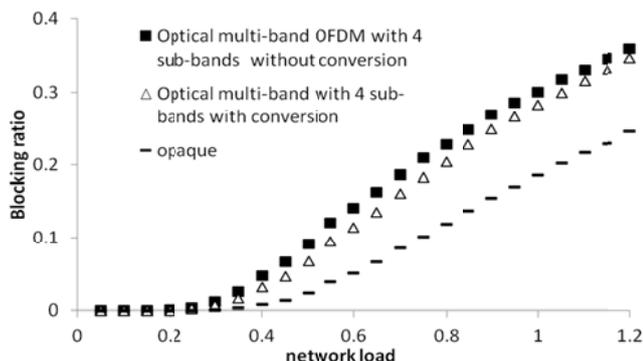


Figure 6 performance of optical multi-band OFDM with wavelength conversion

We observe that optical multi-band OFDM switching technology with wavelength conversion performs slightly better than without wavelength conversion (at most 16% improvement).

With respect to our initial guess, this result is due to the fact that wavelength conversion now favours demands with more than one hop. However, multiple hops demands occupy more resources which in turns reduce the amount of useable resources.

We conclude that wavelength/sub-band conversion does not improve significantly optical multi-band OFDM performance.

C. Playing on the number of sub-bands

In the previous results, we have considered a multi-band OFDM switching technology with 4 sub-bands. Wavelength and sub-bands conversion have also been investigated to improve the network performance. Now we propose to increase the number of sub-bands per optical channels to access to finer granularities, still keeping the 100 Gbps bit-rates of the channel. In Figure 7, we plotted the performance of optical multi-band network with 10 sub-bands.

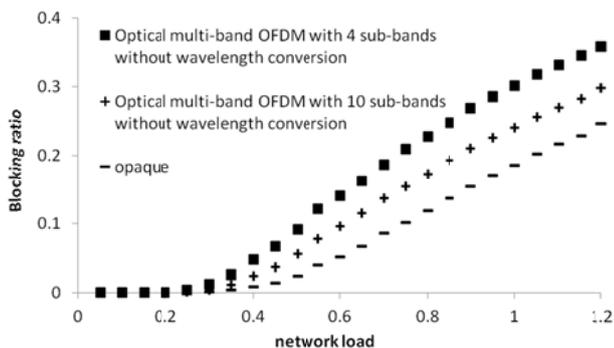


Figure 7 Blocking performance of optical multi-band OFDM with 10 sub-bands

We remark that the performance is improved by around 36% compared with the use of 4 sub-bands. This result tends to prove that increasing the number of sub-bands is more

efficient than implementing complex and costly wavelength conversion

However, the problem of increasing the number of sub-band is directly related to technological limits. By increasing the number of sub-bands, we decrease the bandwidth of each sub-band. So we need very selective optical filters to aggregate-disaggregate the sub-bands. Number of sub-bands is thus a trade-off between technical constraint and demands granularity.

V. CONCLUSION

Using simulations, we studied first the performance of optical multi-band OFDM switching technology compared to mono-band opaque and mono-band transparent switching technology. Optical multi-band OFDM approach is not as efficient in term of blocking ratio as opaque solution, however, it provide better result than mono-band transparent without resorting to electronics at intermediate nodes. Unexpectedly, wavelength/sub-band conversion does not improve much its performances and less than increasing the number of sub-bands in the optical channel. Filtering fineness and steepness fix the limit of the feasibility of the multi-band switching, but already filters as fine as 8 GHz exist that could be used for sub-band grooming.

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