Dynamic Operation of Flexi-Grid OFDM-based Networks

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Abstract: Routing in dynamic OFDM-based optical networks by simultaneous optimization of allocated spectrum and transponder reach is proven beneficial when flexi-grid technology is used regarding blocking performance and spectral efficiency when compared to standard-grid counterpart.

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1. Introduction

The abundance of core network fiber capacity presents an excellent opportunity for handling the continuously growing core traffic, which remains unexplored due to the fixed transmission grid imposed on Wavelength Division Multiplexing (WDM) by the Non-Return to Zero modulation format (MF). Flexi-grid transmission exploits the "void" fiber bandwidth [1]-[3], especially with the advent of coherent MFs that allows spectral packing of WDM channels. Among the various candidates Orthogonal Frequency-Division Multiplexing (OFDM) is promising due to its enhanced spectral efficiency (SE), ability to tailor transmission properties and cost efficient upgradability to higher bitrates. As a multi carrier format the channel capacity is divided in several low data rate subcarriers while their MF can be chosen according to the required SE. Simultaneously, in Wavelength Switched Optical Networks (WSONs) optical WDM lightpaths are utilised to interconnect egress and ingress IP routers through multi-degree reconfigurable optical add-drop multiplexers (ROADM) to overcome hop-by-hop optoelectronic processing. As OFDM can provide fine-granularity capacity to connections by the flexible allocation of sub wavelength carriers, WSON networks may become *elastic* by moving away from the rigid ITU grid. Hence OFDM-based networks may offer fine granularity by allowing sub- and multi wavelength capacity allocation. Going away from the typical "wavelength" lightpath as the main granularity however imposes constraints on both physical and network layer. The added flexibility of variable bandwidth (VB) OFDM puts an extra burden on the routing engine that now has to serve a specific connection request between two nodes by assigning the most spectrally efficient MF which can extend to the requested distance while considering that the reach of a transponder varies with the SE and bit rate [4].
In this work we are investigating path establishment in an elastic optical network environment with VB, flexi-grid (FG), distance adaptive OFDM physical layer capability with respect to a standard grid (SG) counterpart. A novel routing engine is developed that coordinates allocations of just enough transmission resources by simultaneously optimizing the allocated spectrum and the path length in a dynamic networking environment while considering physical degradation through a new OFDM empirical model.

2. Variable bandwidth, distant adaptive OFDM transmission

In VB OFDM, data is transmitted over multiple orthogonal subcarriers. An optical signal using just enough spectral resources with appropriate MF is generated by the transponder to serve the connection request. For the scope of our work, a model that can give an accurate estimate of the transponder's reach is developed. In [4], the reach of OFDM transponders employing polarization multiplexing for different MF is investigated. By fitting the data therein, we have developed an accurate empirical model and in turn calculates the transmission reach for different bit rates as a function of the spectral efficiency. By optimizing the values of the constants we obtain the following equation that fits well the data in [4]: $L = 145.741 + (n - 14.0344)(60.2196\ln(BR) - 465.82)$ with L in km, n in bit/s/Hz and bit rate (BR) in Gb/s. We then obtained the look up table of Fig. 1 (a) that is used for routing purposes.

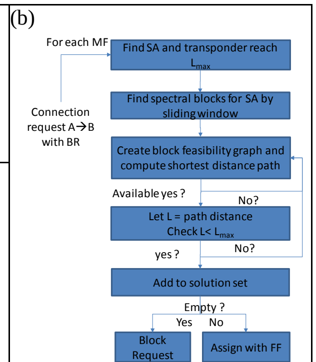
3. Routing in Flexi-Grid OFDM-based Networks

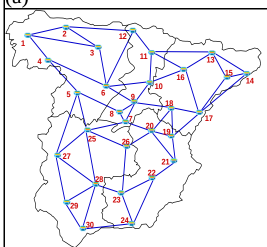
Routing in VB OFDM based dynamic network is expected to be different than conventional WDM ones as it should coordinate path establishment, MF assignment and spectrum allocation (SA) [2]. In Fig 1 (b) the routing engine for elastic networks is illustrated. The available spectrum is divided into elementary spectrum slots (ESS). A connection request between nodes A and B for a specific BR arrives. The routing engine maps BR to the lowest index MF (4 = QPSK, 3 = 16QAM, 2 = 32QAM and 1 = 64QAM see Fig 1(a)) and it is in turn translated to an aperture equal to the SA of this MF. For each SA a feasibility graph is constructed and a shortest distance path is computed. The mapping procedure starts with the most spectrally efficient MF (here QAM-64) and groups of contiguous ESSs (blocks) are computed by a sliding window running over the spectrum with group population equal to SA. The process is analogous to the wavelength continuity constraint check in WDM networks where the aperture is always 1 and the SSEs are identified as wavelengths. The physical feasibility of the computed path is checked by comparing its physical length, to transponder reach for the specific MF at the requested BR. The engine keeps a list of all successful candidates and assigns the best solution with first fit, making sure that just enough resources are allocated.

bit rate request (Gb/sec)	Lmax (KM)	SA (ESS)	MF index	bit rate request (Gb/sec)	Lmax (KM)	SA (ESS)	MF index	bit rate request (Gb/sec)	Lmax (KM)	SA (ESS)	MF index	bit rate request (Gb/sec)	Lmax (KM)	SA (ESS)	MF index
40	685	1	1	40	1024.0	1	2	40	1677.9	1	3	40	2585.2	2	4
100	546	2	1	100	847.2	2	2	100	1342.5	3	3	100	2007.3	5	4
160	475	3	1	160	756.5	4	2	160	1170.5	4	3	160	1710.9	8	4
400	335	7	1	400	579.6	8	2	400	835.1	10	3	400	1133.0	20	4
600	274	10	1	600	501.4	12	2	600	686.7	15	3	600	877.3	30	4

(a)

(b)





(c)

Scenario	Scenario 1 SG-QPSK	Scenario 2 SG-64QAM	Scenario 3 FG-FF
Description	Fixed standard grid with ESS=50GHz	Fixed standard grid with ESS=50GHz	Flexi-grid with ESS=5GHz
Modulation Format (MF)	QPSK	64QAM	OFDM with flexible format (FF) capability among QPSK, 16QAM, 32 QAM, 64 QAM
Spectral Efficiency (SE)	4 bits/sec/Hz	12 bits/sec/Hz	Varying depending on MF [4]
Bit rate (BR) request and Spectral Allocation (SA)	10-160Gb/sec→ 1wavelength (50GHz) 400Gb/sec→ 2wavelengths (100GHz) 600Gb/sec→ 3wavelengths(150GHz)	10-600Gb/sec→ (50GHz)	Varying depending on MF see Table in (a)

(d)

Fig. 1: (a) The look up table utilized by the routing engine- SA is expressed in closest integer number of ESSs (b) The flow chart of the routing engine (c) the TID reference network and (d) the three scenarios under investigation

4. Reference network and simulation scenarios

For our study we used the Telefonica national network topology (Fig.1 (c)). The links of the network are bidirectional, capable to transport capacity of 4THz comprising either 80 WDM channels or 800 ESSs. We assume that connection requests have constant service time and inter-arrival times have an exponential distribution, while destination requests are uniformly distributed. Connection requests have BR uniformly selected among 40, 100, 160, 400 and 600Gb/s values. All nodes in the network are assumed colorless, non-directional, contentionless ROADMs.

In this work we investigate a) the performance of our routing engine that utilizes just enough network resources b) the efficiency of FG elastic networking. Methodologically this dictates comparison of our case study with SG counterparts that lack MF/transponder reach choice flexibility. We thus choose 3 scenarios which comparison highlights the benefits of abolishing the ITU grid. In the first case the physical layer comprises an SG VB OFDM optical network deploying QPSK. Assuming SE of 4 bits/sec/Hz depending on the requested BR, the allocated spectrum will be 50 GHz (1 wavelength), 100 GHz (2 consecutive wavelengths) or 150 GHz (3 consecutive wavelengths) (see Fig 1 (d)). For the second scenario the SG OFDM optical network deploys only 64QAM hence for all BR 50GHz is sufficient. This case is used for benchmarking purposes only, as the limited reach of 64QAM is expected to affect its performance. Comparison with fixed bandwidth technology is not included due to the spectrum allocation induced deterioration. The 3rd scenario corresponds to the FG/flexi format (FF) case where channels are allocated with just enough resources by our developed routing engine.

5. Simulation Results

A number of metrics have been utilized in order to investigate the three different scenarios. As illustrated in Fig. 2 where blocking probability (BP) is used as a means of network performance evaluation, the FG scenario outperforms the others. It is evident that especially as load grows the FG network manages to “discover” or efficiently utilize resources in the network and blocking does not deteriorate significantly with respect to S1. S2 exhibits very poor performance as expected due to the small reach of 64QAM transponders. This is explained by Figures 2 (b) and (c) where the rejection probability is calculated. As rejection probability we define the inability of a candidate solution to enter the feasible solution set which is attributed to either the lack of sufficient contiguous spectrum (rejection probability due to spectrum) or due to the length of the path being longer than the feasible OFDM length (rejection probability due to path length). It is evident that S2 suffers from the fact that the 64QAM cannot achieve long reach, while S1 and FG/FF cases are more vulnerable to the spectrum unavailability or fragmentation. In Fig.2 (d) utilization i.e. the topological mean of utilized fiber resources as a percentage of the overall resources, is plotted and the trend of the three cases proves that the FG performance lies between S1 and S2, indicating that slightly less resources could have been used. In Fig. 2(e) we have plotted the average allocated spectrum per connection request where the main benefit of flexi grid is revealed. The spectrum required here is only 40% of the spectrum allocated in S1 and 60% of the S2 case. By assuming that the average spectral efficiency of each connection request will be <spectral efficiency>=<bit rate>/<allocated spectrum> for all established connection requests, we have calculated that S1 and S2 exhibit similar average SE of 3.5bit/s/Hz for the various load while the flexi grid scenario exhibits 8.7 bit/s/Hz which is more than two-fold improvement as shown in Fig. 2 (f).

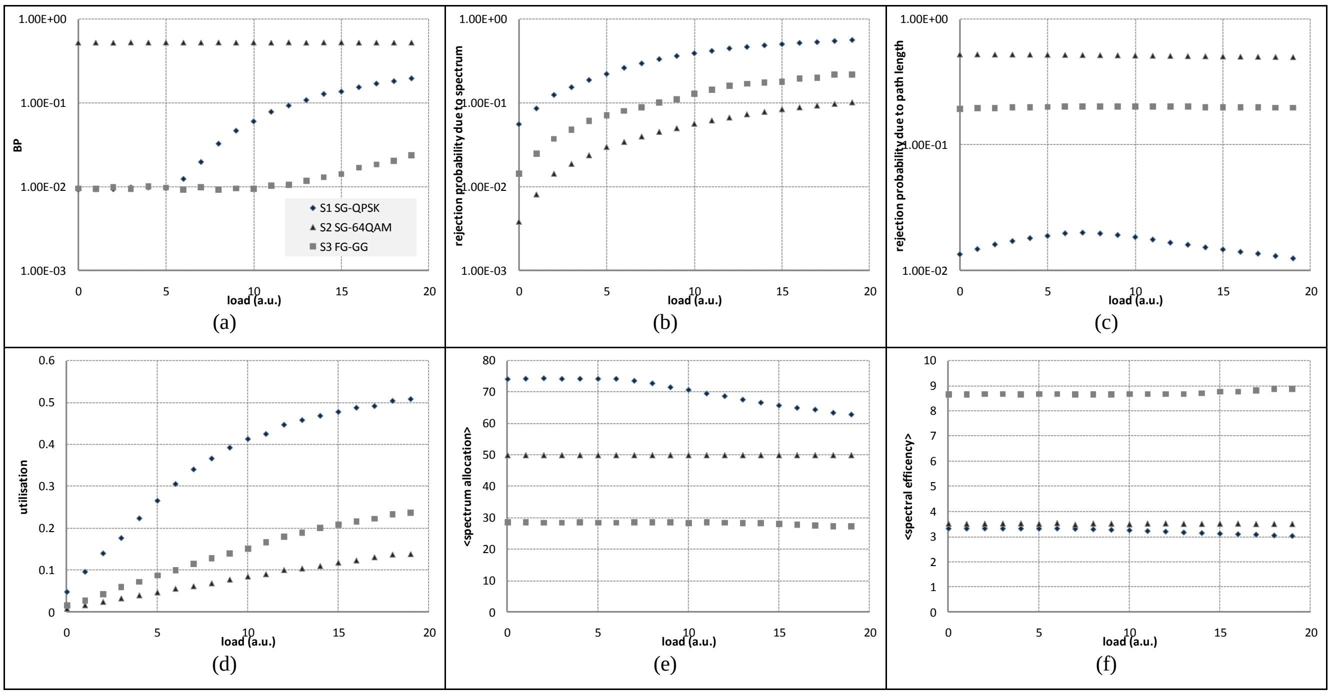


Fig. 2: (a) BP (b) rejection probability due to spectrum (c) rejection probability due to path length (d) utilization (e) average allocated spectrum per connection request (f) average spectral efficiency for three cases shown in legend of (a)

6. Conclusions

Elastic networking based on flexi-grid technology has been proposed as means to utilize the optical spectrum flexibly. It is shown here that resources that are released due to the non-rigid spectrum allocation allow better spectrum utilization and better blocking performance. In this work we have developed a routing engine that can utilize “just enough” resources by deploying variable bit rate OFDM technology exhibiting better blocking probability and more than two fold average spectral efficiency enhancement with respect to standard grid, fixed modulation format counterparts making elastic networking a promising candidate for multi granular future networks.

7. Acknowledgment

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8. References

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