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Supporting the Evolution to the Future Internet

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Published in:
The Future Internet

Link to article, DOI:
10.1007/978-3-642-30241-1_20

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Tomkos, I., Angelou, M., Barroso, R. J. D., de Miguel, I., Toledo, R. M. L., Siracusa, D., ... Tafur Monroy, I. (2012). Next Generation Flexible and Cognitive Heterogeneous Optical Networks: Supporting the Evolution to the Future Internet. In The Future Internet: Future Internet Assembly 2012: From Promises to Reality (pp. 225–236). Springer. (Lecture Notes in Computer Science, Vol. 7281). DOI: 10.1007/978-3-642-30241-1_20

Next Generation
Flexible and Cognitive Heterogeneous Optical Networks
Supporting the Evolution to the Future Internet

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Abstract. Optical networking is the cornerstone of the Future Internet as it provides the physical infrastructure of the core backbone networks. Recent developments have enabled much better quality of service/experience for the end users, enabled through the much higher capacities that can be supported. Furthermore, optical networking developments facilitate the reduction of complexity of operations at the IP layer and therefore reduce the latency of the connections and the expenditures to deploy and operate the networks. New research directions in optical networking promise to further advance the capabilities of the Future Internet. In this book chapter, we highlight the latest activities of the optical networking community and in particular what has been the focus of EU funded research. The concepts of flexible and cognitive optical networks are introduced and their key expected benefits are highlighted. The overall framework envisioned for the future cognitive flexible optical networks are introduced and recent developments are presented.

Keywords: Optical Networks, Optical Transport, Cognitive Networks, Flexible Optical Networks.

1 Introduction

After the establishment of the first fiber-based telecom networks in the 1980s, it was the emergence of Wavelength Division Multiplexing (WDM) a decade later that enabled the current expansion of Internet. In these early steps of WDM networks though, each optical channel had to be converted to the electrical domain and then back to the optical at every node even if the optical channel was not destined for that

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node; these networks are commonly referred to as opaque networks. Later on, the idea of avoiding all these costly O/E/O conversions triggered the development of Optical Add-Drop Multiplexers (OADMs) that, in turn, allowed the establishment of transparent networks, where the signal propagates all-optically from source to destination throughout the network. In transparent networks, the regeneration-related costs of opaque networks are eliminated [1] achieving up to 50% of cost saving when compared with opaque networks [2]. Furthermore, reconfigurable OADMs (ROADMs) and Optical Cross-Connects (OXCs) were implemented to achieve a higher degree of flexibility and to enable networks to adapt remotely and on-demand to the potential traffic changes, thus reducing the associated operational costs. Moreover, the introduction of high data-rate transmission technology aims to provide large trunks so as to accommodate the bandwidth-intensive new multimedia applications. Nevertheless, not all traffic demands require such high bit rates and operators are seeking for networks that are not wasting resources but are cost-effective and therefore versatile. In this framework, existing 10 Gb/s optical networks may upgrade their infrastructure gradually migrating to heterogeneous networks that accommodate mixed 10/40/100 Gb/s traffic [3]. This new solution is known as Mixed Line-Rate (MLR), as opposed to the legacy one, also referred to as Single Line-Rate (SLR).

However, the above cited solutions provide limited flexibility and are not capable to scale to the envisioned capacities of the Future Internet. In fact they operate under added complexity and cost due to the rigid wavelength granularity of the systems currently deployed. Operators provide connections with capacity that fulfils the highest (worst case) demand (over-provisioning), while these connections remain underutilised for most of the time. To this account, the recent advances in coherent technology, software-defined optics and multicarrier transmission tecniques, such as Orthogonal Frequency Division Multiplexing (OFDM) [4]-[5] and Nyquist WDM (N-WDM) [6], have introduced the possibility to achieve a significantly high spectrum-efficiency providing a fractional bandwidth feature. In fact, thanks to these technologies it is possible to dynamically tune the required bit-rate and the optical reachability by appropriately choosing the allocation of the spectrum and the modulation format. Some of the terms often associated in literature to the optical networks exploiting these technological advancements are “flexible”, “tunable”, “elastic” or “adaptive”. Hence, flexibility means that the network is able to dynamically adjust the resources in an optimal and elastic way according to the continuous varying traffic conditions, These new concepts will enable a new network architecture where any two nodes can be connected with the amount of bandwidth required, either providing a sub-wavelength service or super-channel connectivity [7]-[8].

On the other side, the aforementioned emerging heterogeneous networks have introduced a new type of challenge in network design. In reconfigurable single line-rate networks, the resources at hand during the design phase were limited to the channels considered feasible according to Quality of Transmission (QoT) parameters (through physical-layer aware processes [9]) while the rate and the modulation format were fixed. The new heterogeneous network paradigms have introduced an additional level of flexibility, also interpreted as additional complexity. In this context, to serve a given traffic demand, the network manager has to select the route, the channel, the bit-rate and the modulation format [8]. Hence, traditional Routing and Wavelength

Assignment (RWA) algorithms are no longer applicable and it is transformed to a Routing, Modulation Level and Spectrum Allocation (RMLSA) problem where every connection request is assigned a spectrum fraction.

Once the network planning has taken place, an advanced control plane solution needs to be designed and developed in order to fully support all the aforementioned enhancements to the optical infrastructure. Literature presents some proposals on the control plane solutions for the physical-layer aware optical networks [9]-[11], while the study on the flexible networks is still on a early stage, both from the standardization (the Internet Engineering Task Force has recently published some internet drafts [12]-[13]) and the research point of view (very few works have been published, among them [14]). Through properly developed Generalized Multi-Protocol Label Switching (GMPLS) protocol extensions, the control plane is expected to be able to support the overall networking solution and allows the different building blocks to cooperate and run in an orchestrated manner. On the whole, the concepts of physical-layer awareness and of spectrum flexibility will require intelligent techniques to offer optimal static planning, dynamic configuration and management of optical signal with acceptable QoT. In such a context, the control and management planes will work in conjunction to provide dynamic routing and flexible spectrum assignment, management of sub-wavelength service or super-channel connectivity, performance and impairment monitoring, traffic monitoring, failure localization, etc. In turn, the information stemming from the data plane considered valuable to the various modules will be disseminated to the nodes of the network through properly enhanced control plane extensions.

A promising solution to tackle these challenges comes from exploiting cognition [15]. The use of cognitive techniques in optical networks brings about an extended level of “intelligence” to the optical layer by facilitating the adaptive tuning of various physical layer characteristics (modulation format, forward error correction, wavelength capacity, etc) and network layer parameters (bandwidth, number of simultaneous lightpaths, QoS, etc) depending on application or service requirements. Cognitive networks typically perform cross-layer design and multi-objective optimization in order to support trade-offs between multiple goals; thus they become a promising option to optimize the performance of optical networks in a cost- and energy-efficient way. This approach is fully aligned with a Future Internet vision where the role of an optical network is not just about providing fixed high-speed bandwidth between node pairs, but instead it enables network operators to finely tune these pipes among a set of nodes in order to provide an “application-specific” virtual network which complies delay and bandwidth constraints according to application requirements. As envisioned in projects more focused on Future Internet services like the ones currently pursued within the FI-PPP framework [16], these requirements can in fact be wildly different and thus deserve a highly adaptive transport layer. A cognitive optical network based on flexible-grid technologies will strengthen the link between the client (IP) and the transport (optical) layer [17] to an extreme degree thus providing a consistent contribution toward the EU vision of a future network infrastructure that support the convergence of heterogeneous broadband technologies as enablers of the Future Internet.

In this chapter, we present the approach followed within the FP7 European Cognitive Heterogeneous Reconfigurable Optical Network (CHRON) project [18], in which a cognitive architecture is proposed in order to realise a flexible optical Future Internet infrastructure. The investigated cognitive solution is expected to provide effective multilayer decisions on (i) how to efficiently route traffic over the network; and (ii) how to allocate the spectrum and choose the appropriate transmission/switching technique, optical launch power, modulation format, bit-rate, etc., thus relying in cross-layer design techniques. On the other hand, we also demonstrate the advantages of using heterogeneous flexible networks in terms of three parameters: the spectrum efficiency, the cost and the energy consumption.

2 Cognitive Optical Networking

A cognitive network is defined as "a network with a process that can perceive current network conditions, and then plan, decide, and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals" [15]. Therefore, a cognitive network should provide better end-to-end performance than a non-cognitive network. In fact, cognition has already been tested and proven to be an excellent solution for wireless networks [19].

However, cognitive networks are also applicable to wired communication architectures, and are especially appealing for optimizing performance in heterogeneous networks. Since cognitive networks typically perform cross-layer design and multi-objective optimization in order to support trade-offs between multiple goals, they also become a promising option to optimize the performance of heterogeneous optical networks in a cost efficient way.

In the area of optical communications, cognitive techniques are exploited in the framework of CHRON [18] project so to enable "intelligence" in the optical layer. In particular, CHRON should be able to provide effective decisions, by relying on cognition, on:

- how to route new traffic demands, either through existing optical connections (lightpaths), through new lightpaths or by triggering a reconfiguration process of the virtual topology (i.e., by rearranging existing connections);
- how to assign resources, not only wavelengths or spectrum, but also the most appropriate transmission/switching technique, modulation format, bit-rate, etc.;
- how to ensure energy-efficient operation;

and all while taking into account the Quality of Service (QoS) and Quality of Transmission (QoT) requirements of the demands.

According to the definition of cognitive networks given above, those decisions must be made by taking into account current status and knowledge acquired through previous experience. Thus, the core element of the CHRON architecture is the *cognitive decision system*. Such a system is complemented with a *network monitoring system*, which provides traffic status and optical quality of transmission measurements, and with a set of *control and management mechanisms* to implement the decisions that are made by the cognitive decision system and to disseminate the monitored information. The interaction of those building elements is detailed in Fig. 1.

Since the cognitive decision system must deal with very diverse tasks, it is composed by five different modules, all of them exploiting cognition. Thus, it includes a RWA/RMLSA module to process optical connection (lightpath) requests; a QoT estimator module to predict the QoT of the optical connections before being established (and thus helping the RWA/RMLSA module to ensure that quality requirements are met); a virtual topology design module, which determines the optimal set of lightpaths that should be established on the network to deal with a given traffic demand, and a traffic grooming module, which is in charge of routing traffic through the lightpaths composing the virtual topology. Last but not least, a network planner and decision maker module coordinates and triggers the operation of the other modules and handles the communications with other network elements.

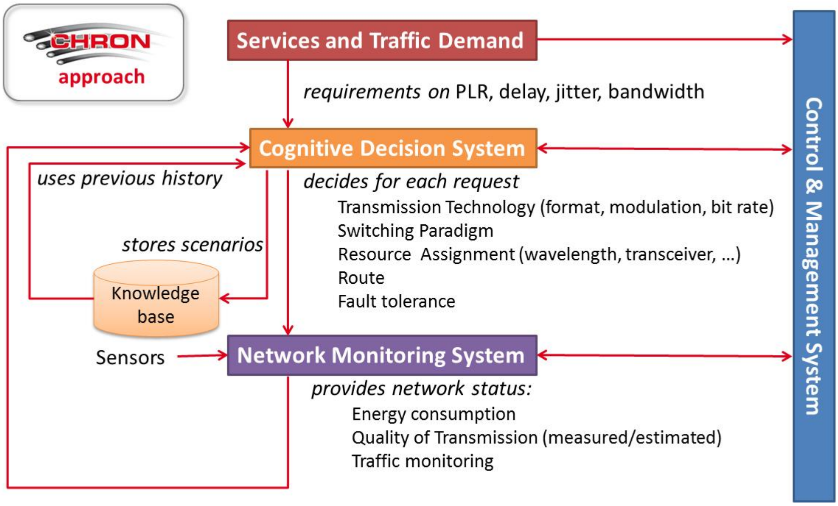

Fig. 1. Main elements of the CHRON approach

In the framework of this architecture, the advantages of cognition have already been demonstrated in a number of scenarios, such as on quickly and effectively assessing whether an optical connection (i.e., a lightpath) satisfies QoT requirements [20], or on determining which set of connections should be established on an optical network (i.e., the so-called virtual topology) in order to support the traffic load while satisfying QoT requirements and minimizing energy consumption and congestion [21].

In the former scenario, the utilization of Case-Based Reasoning techniques to exploit knowledge acquired through previous experiences leads to obtaining not only a high percentage of successful classification of lightpaths into high or low QoT categories (Fig. 2), but also to a great reduction in the computing time (around three orders of magnitude) when compared to a previous tool for QoT assessment which does not employ cognition [20].

In the latter scenario, the inclusion of cognition in a multi-objective algorithm to determine the optimal set of virtual topologies with different trade-offs in terms of throughput and energy consumption brings great advantages. Since a multi-objective algorithm provides a set of solutions (i.e., virtual topologies) in a single execution, we have joined the solutions provided by two versions of the same algorithm: one without cognition and the other with cognition. Then, the best set of solutions has been selected, which is called the common Pareto Optimal Set (POS). Fig. 3 shows that at the beginning (when there is no previous history that the cognitive method can exploit), both methods contribute approximately with the same number of solutions. However, once cognition really enters into play, i.e., when enough past history is used, most of the solutions contained in the common POS (i.e., the best solutions) are obtained by the cognitive method [21].

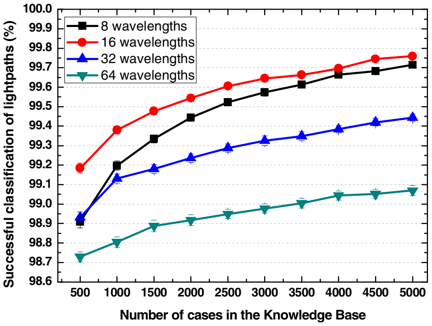

Fig. 2. Successful classification of lightpaths into high/low QoT categories

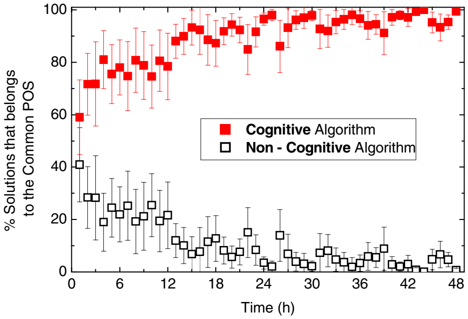

Fig. 3. Percentage of solutions in the common POS found by a method with cognition and the same method without cognition

3 Advantages of Mixed Line-Rate and Flexible Networks

Cognition is a useful tool capable of optimizing the design and control of an optical network. A cognitive network allows the introduction of a flexible transport to support the Future Internet, by pushing down to the optical layer some of the “intelligence” typically performed in the IP layer. However, a key element for operators seeking to migrate to the next-generation core is the evaluation of the trade-off between the extra capital investment that it requires and its performance. Moreover, in addition to the capital cost of the future core network, power consumption is another parameter that becomes relevant, mainly due to the operational economic implications, considering the pace at which traffic is increasing annually. The goal of this section is to discuss the new mixed line-rate and flexible core networks from a cost, spectral and energy perspective and give a comprehensive view of the potential of each solution. Focusing on the importance of spectrum as a resource, novel RMLSA algorithms for path and resource allocation in flex-grid networks are exploited herein [22].

Nevertheless, to realize the level of flexibility of the multi-carrier solutions, new network and transmission elements need to be introduced in the optical transport, implying extra capital investment. Software-defined transponders [23] and bandwidth-flexible optical nodes [24] employing spectrum-flexible Wavelength Selective Switches (SF-WSS) are the key enablers for the implementation of this architecture. The methodology presented in [25] is used to investigate the requirements in capital of the flex-grid networks over the fixed-grid solutions in correlation with the gained spectrum optimization. Following the optimized resource allocation, all solutions are evaluated under the prism of energy efficiency. The energy efficiency that each solution incurs is estimated considering the power consumption needs of the associated networking elements.

3.1 Spectrum Allocation Advantages

The analysis considers networking solutions that can deliver up to 400 Gb/s per channel in a fixed or flexible spectrum grid utilizing physical-layer aware algorithms to route and allocate the available spectrum [26], [4]. The study includes fixed WDM SLR networks that deliver either 40 Gb/s, 100 Gb/s or 400 Gb/s per channel and MLR [9] networks with data rates of 10 Gb/s, 40 Gb/s, 100 Gb/s and 400 Gb/s. Regarding the flex-grid solutions, two multi-carrier solutions have been considered; one refers to the technique reported in [4] (denoted as E-OFDM) while the other refers to the technique in [5] (denoted as O-OFDM). Both multi-carrier solutions can adapt the transmitted bit-rate from 10Gb/s-400Gb/s by modulating subcarriers with the necessary modulation level.

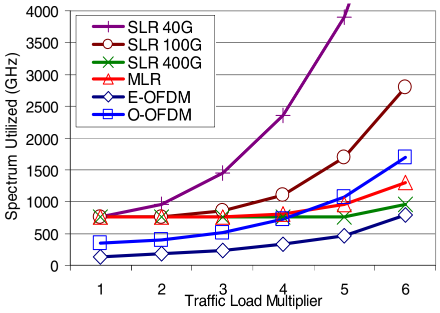

Fig. 4. Spectrum utilization for all solutions and different traffic loads

To calculate the bandwidth utilized by the various solutions the Deutsche Telekom core network (14 nodes, 23 bidirectional links) and the realistic traffic matrix of the DT network for 2010 scaled up to 11 times to obtain traffic ranging from 3.6 Tb/s up to 39.6 Tb/s has been utilized. Under the given assumptions, the flexible multi-carrier solutions offer the most efficient spectrum allocation as expected from the optimized packing of the connections in the frequency domain (Fig. 4).

3.2 Cost Efficiency Advantages

Spectrum utilization is not only used as a way to evaluate the networking solutions but also in the form of spectrum savings (considered here in 50GHz slots) that can be utilized for the provisioning of new traffic. Based on the methodology introduced in [25] the total cost of a system is modeled considering three cost parameters: the cost of transponders, the cost of node equipment and the one related to the number of “dark” 50GHz channel slots that are utilized and associated only with the link infrastructure cost.

Among the fixed-grid networks the distinctive component that determines the capital requirements is the type of the transponders. Fig. 5 illustrates the absolute number of transponders per networking solution. Fig. 6. shows the relative transponder cost of all fixed-grid solutions; the relative cost values are set at 1/2.5/3.75/5.5 for the 10 Gb/s, 40 Gb/s, 100 Gb/s and 400 Gb/s transponders respectively [27]. For MLR systems, two variations of the planning algorithm are reported; the first one seeks to minimize the number of utilized wavelengths, and the second one optimizes the transponder cost of the network.

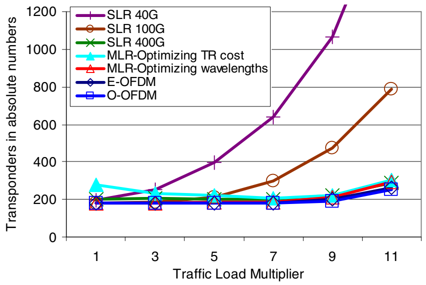

Fig. 5. Required number of transponders for all solutions to serve the different traffic matrices (in absolute numbers)

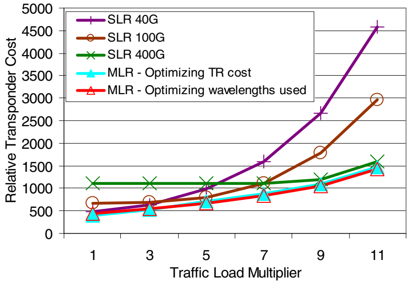

Fig. 6. Relative transponder cost for the fixed-grid networking solutions

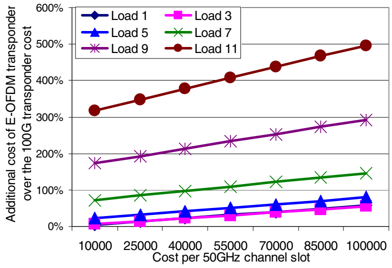

Fig. 7. Allowable additional cost for E-OFDM transponder compared to SLR 100G from spectrum savings for different traffic loads

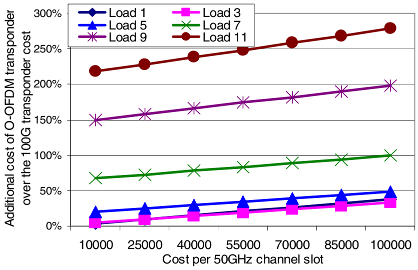

Fig. 8. Allowable additional cost for O-OFDM transponder compared to SLR 100G from spectrum savings for different traffic loads

However, reliable data for the cost of the flex-grid networks components, i.e., the software-defined transponders and bandwidth-variable nodes, are currently not available. To overcome this, the extra cost of the E-OFDM and O-OFDM transponders over the cost of a 100 Gb/s transponder so as to achieve total network cost equal to that of the related SLR network is examined. The comparison was focused on the cost of the E-OFDM and O-OFDM transponders as those rely on electronics for DSP. Fig. 7 presents the allowable additional cost for the E-OFDM transponder compared to the SLR 100 Gb/s transponder for different traffic loads. For a 50 GHz-channel cost that ranges from 10 k€ to 100 k€, an E-OFDM transponder may cost 3 to 5 times more when the traffic load is equal to 11 so as to achieve total network cost equal to that of the SLR network. For the lowest traffic scenario (load=1), where the spectrum savings of the flex-grid solution compared to the 100G SLR are less pronounced, the E-OFDM solution is preferable over the SLR network when the additional cost that is tolerable ranges between 6% to 50%. In a similar manner, Fig. 8 presents the results for the comparison between O-OFDM and 100G SLR. The O-OFDM transponder may cost approximately 2-3 times more for the highest traffic load scenario. The difference with the O-OFDM case is justified by its higher spectrum utilization as shown in Fig. 4. From the operators’ perspective, these results indicate how the spectrum savings of the flex-grid networks can be used to mitigate the additional cost of the new spectrum flexible transponders.

3.3 Energy Efficiency Advantages

In addition to the capital cost of the future core network, power consumption is another parameter that becomes relevant in network planning, mainly due to the operational economic implications but also the growing ecological awareness, considering the pace at which traffic is increasing annually. Following the resource allocation of all solutions, the energy efficiency is estimated considering the power consumption needs of the associated networking elements. Hence, the considered solutions were compared with respect to the power consumption of the associated network elements, i.e., transponders, optical cross-connects (OXCs) and optical line amplifiers.

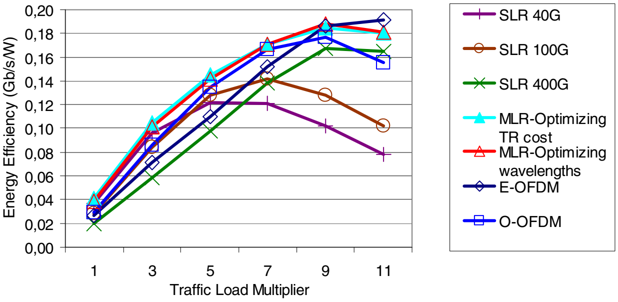

Fig. 9. Energy Efficiency achieved for all solutions and different traffic loads

The estimated energy efficiency (in Gb/s/W) for the various traffic loads is illustrated in Fig. 9. 400G SLR appears to be the least efficient for traffic load up to 5 although it tends to improve for higher loads. The other SLR solutions achieve better efficiency that decreases for high loads justified by the great number of transponders as depicted in Fig. 5. On the other hand, the granularity of 10G/40G/100G/400G in MLR and of the low-rate subcarriers in O-OFDM appears to be sufficient for the entire range of traffic loads optimizing the number and type of transponders and leading to low power consumption. Under the given power consumption assumptions, E-OFDM demonstrates lower energy efficiency for load up to 5. Moving up in traffic load, the transponders assumed run at higher bit rates leading to superior energy efficiency.

On the whole, in terms of the overall network energy efficiency, flex-grid solutions achieve low energy per bit as they use just the amount of network resources needed for given input traffic.

4 Conclusions

Optical networking developments allow the reduction of complex operations at the IP layer so as to reduce the latency of the connections and the expenditures to deploy and operate the networks. New research advancements in optical networking promise to further fortify the capabilities of the Future Internet. In this context, the CHRON project proposes a Cognitive Heterogeneous Reconfigurable Optical Network, which observes, acts, learns and optimizes its performance, taking into account its high degree of heterogeneity with respect to QoS, transmission and switching techniques. The aim of CHRON is to develop and showcase a network architecture and a control plane which efficiently use resources in order to minimize CAPEX and OPEX while fulfilling QoS requirements of each type of service and application supported by the network in terms of bandwidth, delay and quality of transmission, and reducing energy consumption.

The cognitive process and the consequent cross-layer proposed solutions have been extensively exploited to deliver connections at a single line-rate. Nevertheless due to their potential, flexible optical networking solutions have been investigated within the CHRON project, as well as their predecessor, the mixed line-rate (MLR) one. In order to demonstrate the potential of cognitive techniques, we have shown the performance advantages brought when cognition is used in two different scenarios: the estimation of the QoT of the lightpaths established (or to be established) in an optical network, and the design of efficient virtual topologies in terms of throughput and energy consumption. Then, the advantages of flexible optical networks have been evaluated.

As opposed to the rate-specific and fixed-grid solution of an MLR network, flexible optical networks, regardless of the employed technology, are bandwidth agnostic and have the ability to deliver adaptive bit-rates. The associated technologies and concepts that enable the vision of flexible optical networks include advanced modulation formats that offer higher spectral efficiency, the concept of a spectrum-flexible grid, software-defined optical transmission, single-carrier adaptive solutions and multi-carrier technologies. Nevertheless the increased level of flexibility imposes complex requirements with respect to the spectrum and capacity allocation.

Therefore, in this context, CHRON has evaluated the core networks of the Future Internet from a cost, spectral and energy perspective and has provided a comprehensive view of the potential of various technologies. This investigation has been carried out by taking into account the greatly different requirements of Future

Internet application as well as the need for energy-efficient future network infrastructures that support the convergence and interoperability of heterogeneous mobile, wired and wireless technologies, as envisioned in the EU FP7 research framework. The resource optimization achieved in MLR and flexible networks has been investigated under the prism of cost and energy efficiency. First a methodology has been introduced to explore the conditions under which the vision of flexible networking makes a good business case. Single and multi-carrier networks offering channel rates up to 400 Gb/s have been evaluated under realistic reach parameters. The aforementioned methodology has been applied to examine how the efficient spectrum utilization and fine bit-rate granularity of flex-grid core optical networks may affect the requirements in capital and power compared to fixed-grid solutions. It has been shown that the capability of the flex-grid networks to allocate efficiently the available spectrum counterbalances the additional capital expenditures that are required to migrate to a multi-carrier system. On the whole, in terms of the overall network energy efficiency, flex-grid solutions can achieve low energy per bit as they use just the amount of network resources needed for the given input traffic.

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