SEVENTH FRAMEWORK PROGRAMME

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Abstract:
This document is the final deliverable of WP21 on Green Optical Networks. The deliverable reports on the 2010 activities of WP21 and the research results obtained so far (until October-November 2010). In total, 15 partners were involved in the WP21 joint activities.

Keyword list:
energy efficiency, power consumption, carbon footprint, GHG emissions, optical networks, network-wide solutions, network elements

Disclaimer

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1. Executive Summary

This document is the final deliverable of the Topical Project on Green Optical Networks. This report contains the 2010 results of the defined joint activities, concentrating on the following four major themes:

- Power Consumption and Supply of Individual Network Elements (JA2)
- Energy Saving Potential by Selective Switch-off of Network Elements (JA3)
- Green Routing Protocols (JA4)
- Energy-Efficient Optical Network Design (JA6)

The topics covered by this WP address a wide range of issues: from power consumption and power management of individual network elements and network segments, to routing protocols for energy optimization and proposals for new power strategies to improve energy efficiency.

There have been carried out a number of collaborative actions. Most of the collaborating partners took part in informal meetings during the year that have been held at the conferences ICTON 2010 (Munich, Germany), OFC 2010 (San Diego, CA, USA), EU Future Networks & Mobile Summit (Florence, Italy), ECOC 2010 (Torino, Italy) as well as at the BONE Summer and Master School (Budapest, Hungary). Results of WP21 were also presented at the EU Future Networks & Mobile Summit.

The results of this WP provide an understanding of the energy footprint of ICT today and in the coming decade. These results allow evaluating the relative importance of different network segments and technologies (with a focus on optical technologies) in terms of energy consumption and energy optimization and therefore to identify which technical approaches need to be further investigated.

2. Overview

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Whereas the joint activities JA1 and JA5 were active in 2009 only, four joint activities have also been active in 2010:

JA2: Power Consumption and Supply of Individual Network Elements

This JA is under the common umbrella of the workpackages WP14 (Virtual Centre of Excellence on Optical Switching Systems) and WP21 (Topical Project on Green Optical Networks), providing the bridge between both domains. This positioning is crucial to allow for input from optical switching systems experts into the WP21 activities on power consumption.

The joint work resulted in three joint publications and ten single-partner papers of which two papers are published in refereed journals (see Section 5.1.7). The collaborative work concentrated mainly on three particular areas, namely on energy efficiency in optical access networks (TUW, UPC, and ISCON), power consumption and performance evaluation of optical hybrid switching nodes (UNIMORE and TUW) and solar-powered optical passive networks (USWAN and TUW). The first and the third collaborative works are mainly within the scope of WP21 while the second work is mainly related to WP14. Also contribution of PoliTo is mainly related to WP14, in which a set of scheduling algorithms were proposed and compared in order to solve the energy aware scheduling problem through a frame-based approach. Additionally, PoliTo studied the power efficiency of AWG-based optical switching architectures. A mobility action was performed between UNIMORE and TUW, in which MSc student Matteo Fiorani spent more than four months at TUW working on implementation of a model for evaluation of energy efficiency in optical hybrid switching networks.

JA3: Energy Saving Potential by Selective Switch-off of Network Elements

JA3 is studying powering strategy for network devices with the view to achieve significant savings in energy consumption. Different degrees of freedom in the operation of optical networks can be used for the sake of energy efficiency switching off networking resources.

TUB efforts showed the impact of IP routing in energy saving, assuming to be able to switch-off unused linecards, distinguishing between upper (IP) and lower layer (WDM) routing dynamicity; the dynamics in the upper layers is important to achieve lower power consumption even when lower layers are less dynamic.

In wavelength routing networks, the heuristic approach proposed by PoliTO and FUB (PA-RWA) for routing and wavelength assignment appears as a promising alternative to achieve power savings within the optical domain, since very simple power-aware network planning algorithms help improving the link usage; a power reduction of 5 times with respect to a non power-aware wavelength routing network was observed.

Energy awareness can be considered when analysing the availability of network resources: FUB analysed the availability of paths when switching-off entire fibers with the aim of saving energy. On the other hand, network provisioning can deal with availability and power savings. The way lightpaths requests are served under protection requirements offers opportunities to save energy; this can happen by properly establishing policies to deal with protection resources. Given that these protection resources can be activated only when they are required, a trade-off rises to balance power consumption (where differentiation is made between main and protection paths) and path availability (which is larger if no differentiation is made).

In general, the switching-off of network elements challenges the actual paradigm of the design of telecommunication networks, for example, proper integration of switching-off techniques with network control (i.e., GMPLS) offers a feasible evolutionary path towards energy efficient optical networks; this is also true from a multilayer (IP, GMPLS, WDM) perspective.

The results presented for JA3 match the research areas planned for this joint activity and underline the possibility of power savings thanks to the flexibility offered by optical technologies. Several papers, among which two joint papers, were published by BONE partners within the JA3 of WP21.

JA4: Green Routing Protocols

The overall scope of this JA is to study novel energy aware routing protocols and algorithms for optimizing Energy consumption in path computation. In particular this JA focuses on investigating routing algorithms, protocols and procedures suitable for layer 1 optical and layer 2 carrier grade Ethernet networks.

There were two main research activities in this JA, the first focused on investigating a new energy aware routing protocols which can potentially have considerable effect on the reduction of the overall network energy consumption. The second activity, proposed a novel IT+optical network resource scheduling and allocation solution for future Optical Internet where energy reduction problem is addressed on joint selection and joint allocation of both IT and network resources.

JA6: Energy-Efficient Optical Network Design

The work performed in the framework of this JA is attempting to quantify the overall network power consumption of the future European network as well as identify and propose approaches, methodologies and algorithms that can be used to design energy efficient optical networks. Results indicate that taking into consideration the energy consumption of the optical network during the design phase results in significant overall savings.

In order to provide a realistic basis for the calculation of the energy consumption of the Pan-European telecommunications network was examined as a test case for three different time periods: today, in the next five and ten years. In each time period the Pan-European network was dimensioned, using traffic predictions based on realistic data generated by the BONE optical networking roadmap. A wavelength routed WDM optical network based on either transparent or opaque node architectures was examined considering exclusively either 10Gbit/s or 40Gbit/s per channel data rates. The results manifest that transparent optical networking technologies are expected to provide significant energy savings of the order of 35% to 55%. It was also shown that the migration towards higher data rates, i.e. from 10Gbit/s to 40Gbit/s, is assisting to improve the overall energy efficiency of the network.

In addition, an energy-efficient planning strategy for survivable WDM networks was proposed, that exploits the sleep mode of devices supporting protection lightpaths. The network planning problem is defined through an integer linear programming formulation and is solved in a real case scenario. The optimal results show that significant power savings are achieved by properly routing the lightpaths so that a number of links carry only protection lightpaths. In this way, link devices, such as amplifiers, can be set in sleep mode, until a fault occurrence requires a prompt re-activation. Sleep mode of links permits to achieve power savings up to 25% when optimized during the planning phase. Sleep mode at nodes was also considered, but its effectiveness is restricted to very low loads. The achieved benefits are calling for support of sleep mode in optical devices.

The work reported in this JA has resulted to a number of publications that were jointly produced among several BONE partners.

3. Participants

There are 15 partners collaborating in this workpackage:

Partner No	Member
1	IBBT
2	TUW

5	TUB
14	UPCT
18	GET
19	AIT
23	UOP
24	BME
27	FUB
30	POLITO
31	SSSUP
33	UNIMORE
41	KTH
47	UEssex
48	USWAN

4. Workpackage structure

WP21 contains 6 joint activities:

No	Joint Activity Title	Responsible person	Participants
1	Estimating the Footprint of ICT and Identifying the Main Contributors	Mario Pickavet (IBBT)	IBBT, GET
2	Power Consumption and Supply of Individual Network Elements	Slavisa Aleksic (TUW)	TUW, BME, PoliTo, UNIMORE, UoP, UPCT, USWAN, UPC, ISCOM, FUB
3	Energy Saving Potential by Selective Switch-off of Network Elements	Fabio Neri (PoliTo)	AIT, IBBT, TUB, KTH, FUB, GET, SSSUP, POLITO
4	Green Routing Protocols	Reza Nejabati (UEssex)	AIT, GET, KTH, SSSUP, UEssex
5	Innovative Powering Strategies by Renewable Sources	Michel Morvan (GET)	GET, AIT, FUB
6	Energy Efficient Optical Network Design	Anna Tzanakaki (AIT)	AIT, KTH, UoP, SSSUP, UoE, IBBT

5. Final results of joint activities

In this section, the 2010 activities and obtained results are described in more detail.

5.1 JA2 Power Consumption and Supply of Individual Network Elements

Remark:

This joint activity (JA) is under common umbrella of WP21 and WP14. Therefore, the results of collaborative actions within JA2 are reported in both work packages. There is a clear statement for each particular contribution about whether it is rather related to WP14 or to WP21.

Participants:

TUW (Slavisa Aleksic), PoliTo (Fabio Neri, Guido Gavilanes) UNIMORE (Maurizio Casoni), UoP (Tanya Politi), UPCT (Pablo Pavon), BME (Szilárd Zsigmond), USWAN (Karin Enser), UPC (Josep Prat, Jose A. Lazaro), ISCOM (Giorgio M. Tosi Beleffi), FUB (Francesco Matera).

Responsible person:

Slavisa Aleksic (TUW)

5.1.1 Contribution from UPC, ISCON and TUW (mainly within WP21)

A5.1.1.1 Energy efficiency of long-reach optical access networks

Within this JA, TUW, UPC and ISCON carried out a study on energy efficiency of long-reach optical access networks. Power efficiency of various optical access networks was modelled and investigated in three scenarios that refer to different uplink capacities of the central office (CO), namely for a theoretically unlimited uplink and considering two limitations of 320 Gbit/s and 100 Gbit/s. The considered access networks are reach-extended versions of conventional passive optical networks (PONs) and optical P-t-P Ethernet networks providing 1 and 10 Gbit/s data rates. A special focus was dedicated to the SARDANA network, whose power efficiency is analyzed through two cases. The first one includes the measured power consumption of the existing SARDANA test bed, while the second one is an estimation including more market-ready devices with optimized power consumption values. The second case (SARDANA 2) behaves similarly to the 10G-EPON offering very good efficiency. According to the results, it can be observed that the power consumption of 1G PONs, i.e., GPON and EPON, is not being affected by considered uplink limitation for up to 1,000 users. However they provide the lowest data rate per user among all considered access options.

A5.1.1.2 Description of the model

All considered networks are long-reach access options. Fi depicts basic topology differences of considered networks. All networks are FTTH variants including various realizations of passive optical networks, optical point-to-point (P-t-P) Ethernet connections and the hybrid ring-tree TDM/WDM PON as proposed in the SARDANA project.

We consider reach extension of access networks by means of optical amplifiers and optoelectronic repeaters. All types of considered PON options use doped fibre amplifiers, which can extend the transmission span from 20 km that are specified in PON standards to an extended distance of 100 km. For 1G and 10G P-t-P Ethernet networks we take into account power efficient optical-electrical-optical (OEO) repeaters and semiconductor optical amplifiers (SOA), respectively [1]. Thus, the reach of each separate P-t-P Ethernet line is extended with one bidirectional doped fibre amplifier (DFA), while in PON, reach extender is connected to only one shared feeder fibre, as shown in Fi.

The power efficiency of the whole network is estimated by taking into account all contributing elements and peculiarities of each technology such as topology, typical configuration and realization, and maximum data rates in downstream (DS) and upstream (US) directions. Additionally, we model the bandwidth per user as a function of several parameters. These parameters include the number of users connected to the access network, the maximum available DS and US data rates and the aggregated uplink throughput in the central office. These factors influence the performance of the system and set some limitations for considered scenarios. In this paper, we especially investigate how the uplink capacity in the central office affects the power efficiency, which we define as power consumption per Gbit/s of user's bandwidth. We consider three different scenarios:

1. Uplink bandwidth in the CO is theoretically unlimited, so that every user can achieve the maximum possible upstream and downstream data rate.
2. Uplink capacity (CU) is limited to 320 Gbit/s.
3. Uplink capacity (CU) is limited to 100 Gbit/s.

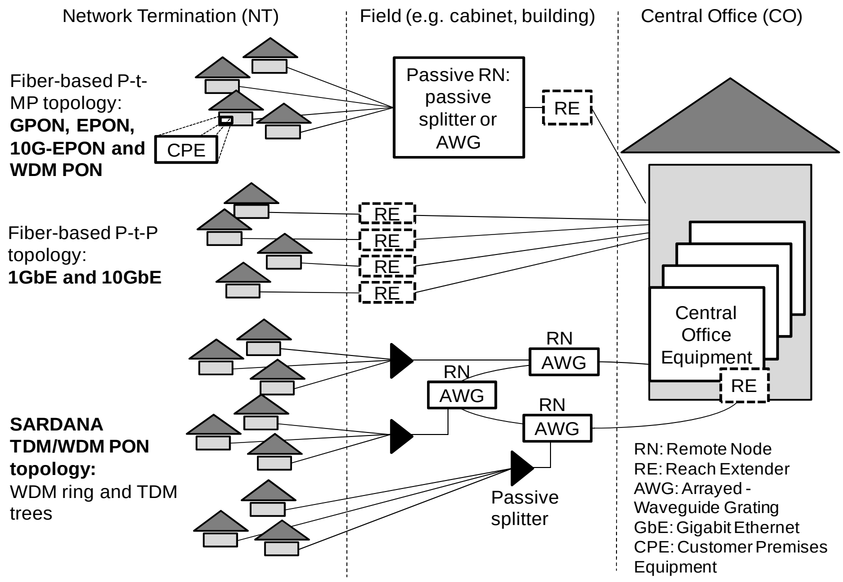

Figure 0: Considered access network topologies

The network elements are modelled at the chip level. That means first generic structures for both network-side and user-side elements are specified and then their total power consumption is calculated by summing up values for consumption of individual functional blocks. The CO equipment is modelled as an aggregation switch with a number of downlink ports, Ethernet or PON ports, and a number of 10G Ethernet uplink ports, as shown in figure 0. Detailed structures of considered OLT and Ethernet line cards are depicted on the right side of figure 0. It shows main functional blocks of optical line terminals firstly in the case of TDM PON, i.e., GPON, EPON and 10G-EPON, secondly in the case of WDM PON, thirdly for the SARDANA network, and finally for P-t-P Ethernet. Additionally, the figure depicts the considered structure of customer premises equipment (CPE) with a user interface consisting of a number of Fast Ethernet ports and/or a number of 1 GE ports, which are modelled on the chip level analogue to the CO equipment. The consumption values of network elements, number of users per CO and uplink capacity (CU), are the input to the model used for calculation of power efficiency. The output of the model is power efficiency presented by Watt per user per bit/s of user's data rate. Due to the fact that users of passive optical networks connected to the same OLT have to share both US and DS data rates, they can not reach the maximum data rates unless there is only one user per OLT.

In all three scenarios we assume that the number of users connected to a CO can rise up to 1,000 and that all users are active and consume the maximum data rate they can get. The considered data rates for different technologies are net line data rates exclusive coding overhead, for instance in the case of P-t-P 1GE we assume 1 Gbit/s (w/o the overhead associated with the 8B/10B coding) in both directions, unless it is limited by the uplink of the aggregation switch in the CO. In other words, both protocol inefficiency and user behaviour are not taken into account because it would make the comparison much more complex. In the case of PONs, we assume that every user can receive the maximum downstream data rate, while upstream data rate is shared among all users connected to the particular OLT, i.e., to a TDM tree. The average data rate per user is then calculated according to:

$$R_{user} = R_{DS,\max} + R_{US,\max} \frac{N_{OLT}}{N_{user}} \tag{2.1}$$

where $R_{DS,max}$ and $R_{US,max}$ are the maximum downstream and upstream data rates, respectively. N_{user} is the total number of active users connected to a CO and N_{OLT} denotes the number of OLTs needed for the given number of users, while according to the standardized splitting ratio, 32 users can be connected to one OLT. For P-t-P networks, we assume that all users can achieve the maximum data rate unless there is another limiting factor. The data rate per user in P-t-P options can be only limited by the maximum capacity of the aggregation switch to which they are connected and by the maximum uplink capacity of the corresponding CO.

For the SARDANA network, we assume 32 wavelength channels, each with a TDM tree comprising 32 ONUs, which could provide access to 1024 users. However, we assume the same maximum number of users as for other access network options, i.e., up to 1,000 users per CO. SARDANA provides 10 Gbit/s of DS and 2.3 Gbit/s of US net data rate per TDM tree. In our power efficiency analysis, we introduce two SARDANA cases. The first one refers to the existing test bed in which values of power consumption are real measured values of the devices that are deployed in the test bed. The power consumption of the test bed equipment is not optimized in terms of power savings and improved efficiency as it would be in some degree done in commercial equipment. In the second case, we assume that the network is equipped with market-ready components, i.e., with components which can provide required performance and are optimized for deployment in the field. Such components would provide remarkably lower power consumption. However, electronic devices for 10G PONs are still hardly commercially available, therefore we collected available data about power consumption and formed a database that refers to many scientific papers and some product data sheets. According to those values, we were able to estimate the power consumption of future 10G PON devices that could be used for SARDANA. For more detailed information about the model and the values used as the input to the model please refer to [1].

The following diagrams show the results obtained for the three previously mentioned scenarios. Figure 1a shows the power consumption per Gbit/s of the considered technologies in the case of an unlimited uplink in the CO. Generally, the highest power consumption is observed for the 1 GE P-t-P network. For a large number of users and unlimited uplink, the power efficiency of 1 GE P-t-P, WDM PON and EPON becomes similar. This is evident from figure 1a as the three highest curves are closely placed around 10 W/Gbit/s. Opposite to these curves, there is the lowest band of curves referring to 10 GE P-t-P network, SARDANA 2, and 10G-EPON. They are the most power efficient networks in the given scenario. SARDANA 1 and GPON are in the middle range.

Figure 1b shows the results for the case where the limitation in the CO is set to 320 Gbit/s. In this scenario, a remarkable increase in power per user per Gbit/s can be observed for higher numbers of users. This effect can be explained as follows. A growing number of users imply an increase in required number of network terminals, i.e., higher total power consumption. At the same time, the data rate per user decreases due to the bandwidth limitation in the CO, i.e., users can not exploit their maximum data rates anymore. Consequently, an increase of power per Gbit/s, or equivalently, a decrease of power efficiency is caused.

Although 10 GE P-t-P network performs very well for up to several tens of users, it becomes the most inefficient one for more than 60 users due to the bandwidth limitation as shown in figure 1b. Also 1 GE P-t-P network and WDM PON, which are relatively power-inefficient for small number of users, become even less efficient when the number of users increases. The power efficiency of EPON and GPON remains the same as in the previous scenario because they are not affected by the limitation, i.e., the CO uplink with 320 Gbit/s is sufficiently large to provide the maximum possible data rate to 1,000 users. SARDANA is generally not affected by this limitation until 800 users per CO. For 1,000 users, SARDANA 2 is the most power efficient network providing 3 W/Gbit/s. Apart from that, it bears great resemblance to 10G-EPON regarding power efficiency over a large interval.

Finally, figure 1c represents the results obtained for the case where we set an even stronger uplink limitation, i.e., 100 Gbit/s. The general trend of increasing power consumption per bandwidth consumed can be observed for all technologies except for EPON and GPON, which still remain unaffected by the limitation even for 1,000 users. 10 GE P-t-P network becomes strongly limited in terms of available bandwidth, and accordingly least power efficient, already for more than 5 users per CO. For a very high number of users it can be seen that GPON becomes the most power efficient, while SARDANA 2 shows the highest efficiency up to 400 users.

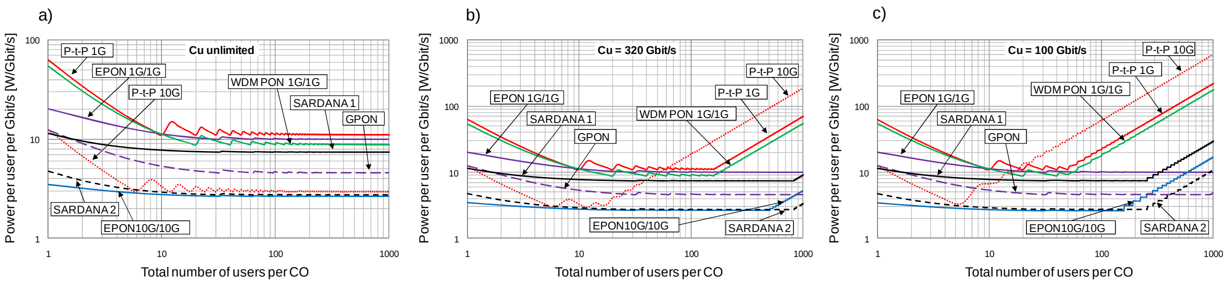

Figure 1: Results for a) unlimited uplink, b) uplink limitation of 320 Gbit/s and c) uplink limitation of 100 Gbit/s

5.1.2 Contribution from UNIMORE and TUW (mainly within WP14)

A5.1.2.1 Optical hybrid switching node

The collaboration between UNIMORE and TUW has concentrated on developing and application of a simulator for an optical hybrid core node that can be used to study both node performance (achievable throughput and loss probabilities) and power consumption. Thus, the simulator is able to provide an estimation of power consumption depending on different factors such as node architecture, realisation, aggregate capacity, achievable throughput, different load levels and traffic patterns. An integrated control plane for the considered optical hybrid switching node has been defined and implemented [2]. In the following, we briefly describe the integrated control plane, considered node architectures, implementation of the simulator and some preliminary results. This collaboration resulted in a mobility action between UNIMORE and TUW, in which Matteo Fiorani form UNIMORE spent more than four months at TUW in order to complete the above mentioned tasks described.

A5.1.2.2 Definition of a novel integrated control plane for HOS

HOS is a switching paradigm that aims to combine optical circuit switching (OCS), optical burst switching (OBS) and optical packet switching (OPS) on the same network. In the first part of the project we defined: the format of the data (circuits, bursts and packets) handled by the HOS node, the format of a unified control packet able to carry the control information for all data types, and the structure of the scheduler. Also, we defined three possible architectures for the node to be managed by the proposed control plane.

Format of data units: The node is supposed to handle time division multiplex (TDM) circuits. In a TDM-circuit, time is divided in frames, each of which is divided in a fixed number of time-slots. Different traffic flows, sharing the same circuit, use different time-slots in a time-domain multiple access (TDMA) manner. The core node can fill unused slots in a frame with optical packets of suitable length that have the same destination as the circuit.

Aiming to increase the network efficiency, an offset time was defined for circuits. This offset time informs the nodes along the path about the exact time in which data are going to arrive at the input ports of the switch, so that the nodes reserve the resources only for the actual duration of the circuit. The circuit offset time is defined to be greater than the sum of the maximum burst-offset and the maximum burst-length, thus circuits results to have higher priority over bursts and packets.

Regarding switching of optical bursts, the JET reservation mechanism was chosen for its high efficiency. The offset time gives bursts a prioritized handling in comparison to packets.

Format of the control packet: The format of a control packet able to carry the control information for all the considered data types was introduced. The two main fields of the control packet are the routing information and the bandwidth reservation. The routing information field is used to route the control packet from source to destination node. The bandwidth reservation field carries the information needed by the core nodes to deploy the data scheduling, and it is divided into five subfields: type, length, offset, free-slots, and slot-length.

The type subfields inform the node about the type (circuit, burst or packet) of the incoming data. The length and the offset subfields contain the length (expressed in kByte) and the offset time (expressed in µs) of the incoming data, respectively. The free-slots and the slot-length subfields are used to schedule optical packets into unused slots of circuits. The free-slots subfield contains number and position of the unused slots in the frame. The slot-length contains the length of a slot.

Scheduler: The proposed control plane employs a suitable scheduling algorithm for each incoming data type.

Circuit scheduling: because circuits have the highest priority, a new circuit is scheduled on the first output channel in which no other circuit has been previously scheduled.

Burst scheduling: two different algorithms for burst scheduling have been implemented and compared, the first fit unscheduled channel with void filling (FFUC-VF) and the best fit with void filling (BF-VF). In FFUC-VF, the scheduler keeps track of all the void intervals and assigns a new burst to the first suitable void, which is found by checking all the available wavelength channels in a sequential manner. In BF-VF, when a suitable void is found, the scheduler computes the difference between the arriving time of the burst and the starting time of the void, and the difference between the ending time of the void and the ending time of the burst. The BF-VF algorithm selects the void in which the sum of these values is lower. BF-FV is more efficient than FFUC-VF but introduces higher complexity and processing time.

Packet scheduling: when a new packet reaches the node, firstly the scheduler tries to insert it on a free TDM-slot of an already established circuit. If there is no circuit able to host it, the packet is then scheduled on the first output channel in which no reservation has been made for the time required for transmission. Firstly, the performance has been evaluated without providing any buffering space for packets contention resolution. Afterwards, aiming to reduce the packet loss probability, optical buffers have been implemented.

A5.1.2.3 Considered node architectures

We proposed three node architectures: all-optical hybrid, optical/electronic hybrid and all-electronic.

All the architectures are composed of an electronic control unit and a switching fabric. The control information associated to each wavelength channel is extracted and sent to the control unit, while the corresponding data are sent towards the switching fabric. The control unit converts the control signal into the electronic domain and processes it in order to select the proper output port for the corresponding data. It is divided in two functional blocks: the routing unit and the scheduler.

In the hybrid architectures, the switching fabric is divided in two parts: a slow and a fast switch. The slow switch is used for switching “slow” traffic (i.e. circuits and long bursts), the fast switch is used for switching “fast” traffic (i.e. packets and short bursts). In the all-optical hybrid architecture both the slow and fast switch are realized using optical switching elements. The fast switch is realized using semiconductor optical amplifiers (SOA), while the slow switch is realized using micro electro-mechanical systems (MEMS). Also in the optical/electronic hybrid architecture the slow switch is realized using MEMS, whereas the fast switch is realized using fast electronic switching elements. Finally, the all-electronic architecture is given by a unique fast electronic switch.

A5.1.2.4 Development of the simulation model

In the second part of the project, we developed a simulation model for the analysis of the proposed node. The simulation model is a time-discrete C++ simulator. Time is divided in simulator clock-times, each of which has been set to be equal to the time needed for the transmission of 1 kByte of data. Considering a data-rate of 40 Gbps, each clock-time corresponds to 0.2 μs. One traffic source is connected to each input port of the node.

In each clock-time sources generate a new control packet with a probability belonging to a Poisson distribution with mean defined by the user. After generating a control packet, the source goes in an idle state for a fixed period of time, in which it does not generate any new control packet. The scheduler receives the new generated control packets and schedules the corresponding data on the output channels using the scheduling algorithms previously described. The simulator produces outputs for both performance and power consumption analysis.

A5.1.2.5 Performance and power consumption evaluation

The evaluation of performance and power consumption of the node was carried out by changing one parameter per time. The parameters that have been varied are: input load, traffic pattern, aggregate node capacity and wavelength converters capacity.

The figures utilized to measure the node performance are: normalized throughput, packet loss probability, burs loss probability and circuit establishment failure probability.

To compare the power consumption of the different proposed architectures the concept of “increase in power efficiency” was introduced. Consequently, the figures utilized in the power consumption analysis are the increase in power efficiency between all-optical hybrid and optical/electronic hybrid architectures ($IE_{O,O/E}$) and the increase of efficiency between optical/electronic hybrid and all-electronic architectures ($IE_{O/E,E}$).

The results regarding packet and burst loss ratios as well as node's power consumption for different realization possibilities and varying traffic pattern were obtained. An example of such a result for different loads and percentages of resources reserved for the circuit-oriented traffic is shown in figure 2.

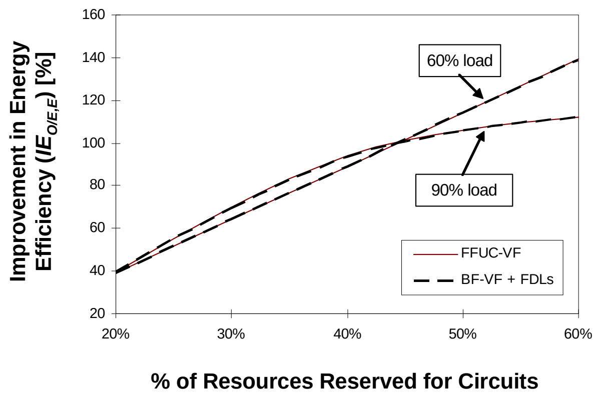

Figure 2: Improvement of energy efficiency when a dynamically adaptive hybrid optical/electronic switch is used instead of a pure electronic packet switch (a conventional IP router).

From the figure it can be observed that the increase in energy efficiency between a hybrid optical/electronic and a pure electronic implementation, $I_{O/E,E}$, exceeds 100% if in average more than 45% of the active switching ports are slow ones, i.e., if 45% of the available resources is reserved for circuits. At moderate loads of 60% and higher percentages of circuit-oriented traffic, the $IE_{O/E,E}$ increases up to about 140%. For very high loads of 90% and above, the achievable improvement of energy efficiency is limited to approximately 110% because both burst and packet losses become high at very high loads and when a large portion of the resources is reserved for circuits. Although an implementation of FDLs and efficient scheduling algorithms may have a strong impact on switch performance, i.e. on the burst and packet loss probabilities, it has, however, a very low, almost negligible influence on the achievable improvement of energy efficiency as it is evident from figure 2. This is because an addition of optical buffers and more effective scheduling algorithms usually leads to a higher achievable throughput, but at the same time it causes an increase in the total power consumption.

5.1.3 Contribution from USWAN and TUW (mainly within WP21)

A5.1.3.1 Techno-economic feasibility studies for greener Access Network

This contribution presents a techno-economic feasibility study to use solar energy as a renewable energy to power the passive optical network. The focus is on the requirements and sources of power for the active components of the Passive Optical Network (PON). To ensure continuous reduction of the carbon footprint while advancing towards purely passive optical networks, we have emphasized the need for alternative, renewable and greener sources to supply the required power. Solar power would be used as the default power source while mains are used as backup or a standby source. This is because solar power can be harvested and stored with less carbon footprint.

A5.1.3.2 Broadband access network growth and demand

As the demand for speed and bandwidth rise, so are the requirements on network elements. Jointly with this growth and demand come the requirements to support and maintain the operations and running of access networks. It becomes crucial to consider the power needed to run and meet the growing demands of the infrastructure. The global growth for demand of Internet, Broadband and associated services continues to grow exponentially and the number of Internet users is estimated to reach 120 Millions per annum [3].

A5.1.3.3 Methods to reduce the power consumption in broadband access networks

There are a number of methods proposed for reduction of power consumption in access networks. Especially for mobile devices, a very low consumption is of great importance because the batteries have limited capacity, size and weight. Additionally, because wireless technologies use shared transmission medium, there is a strong interference at the receivers that needs to be mitigated by using advanced modulation formats and coding schemes as well as intelligent control of the transmitter power by combining efficient channel selection algorithms together with power-aware transmission and routing protocol [4][5]. Similar to wireless sensor networks, also radio access networks are designed a priori for low consumption. Although there has been a lot of progress towards energy efficient mobile devices and base stations [6][7][8] there is still some room for additional improvement; especially when looking into radio base stations, a huge reduction of energy losses of about 75% may be possible [6].

The requirements on low power consumption in wired access networks are not as high as in wireless networks. Here, network terminals are usually supplied by the power grid and capacity, size and weight of batteries does not play a significant role. The most common options for a wired access are different versions of digital subscriber line (xDSL) systems, hybrid fiber/coax (HFC) network or an optical fiber-based solution (FTTx). Although radio and wireless access solutions have made a lot of progress towards energy efficiency and there are many new highly efficient components and systems for power supply and transmission in copper-based technologies such as xDSL, the most promising technology concerning high performance and low power consumption for the access area seems to be a solution based on optical fibers [9][10]. Since the contribution of access networks to the total power consumption of global networks is large, the deployment of energy-efficient components and systems for access area will have a large impact on the overall power consumption. Therefore, one should concentrate on methods for improving the energy efficiency of components and systems within the access area.

Optical transmission and processing technologies are generally able to provide both low power consumption and high data rates. For a large number of users, high access rates, and delivering of broadcast services such as standard-definition (SD) and high-definition (HD) television, which is a realistic situation in the access area today and in the near future, the passive optical networks is one of the most efficient solution. Indeed, very large number of subscribers in urban and suburban areas can be connected to a single central office of a network provider when using a reach-extended PON. Additional to the very large number of users connected to a single OLT port (> 1000) and long reaches (~ 100 km), reach-extended PONs also provide the highest energy efficiency [11]. Different methods such as remote amplification and remote powered extender box [12] can be used to further improve the already high energy efficiency. Protocols for access networks can be adapted to allow dynamic resource allocation and to make possible to adjust performance and power consumption to actual needs by taking into account the actual network utilization. The energy savings can be then achieved by either using low-power modes or switching off inactive devices. It has been shown recently [13] that if 60% of end users are not active then up to 27% (or up to 58%) of power can be saved when inactive equipment is operating in the low-power state (or CPE is switched off).

A5.1.3.4 Solar power energy and system selection

The equipment at the subscriber premises represents a small value of power consumption in the overall domestic energy consumption. Therefore the study focuses on supplying renewable solar energy for the Optical Line Terminal (OLT) which belongs to the operators. The OLTs are usually placed in the metropolitan area and connected to the core network by the Point-of-Presence (POP). This equipment belongs to the operator and when summed all the OLT’s power consumption of the entire network the total value is significant large.

To power the 200W OLT to supply 256 subscribers with broadband, a minimum of a 200W solar power module/panel would be required. A possible module to use is a module supplied by Sanyo, which supplies 215 W at 42 V. This module is approximately 16.1 kg in weight and has dimensions of 1580 mm tall by 798 mm wide and a depth of 46 mm [14]. The cost of this module is $900 (approximately £605). This module would require a regulator that is capable of controlling up to 48 V. The batteries required for this task would need to have a current of at least 4.93A. A Surrette battery has a 100 hours capacity rate; at 5.32A (amps); with an overall capacity of 532 AH (ampere-hours). This would mean that the battery would be capable of powering the system for 100 hours when fully charged [15]. The cost of this battery is $343 (approximately £230), which has a weight of 58 kg and an expected lifetime of ten years.

A5.1.3.5 Discussions and conclusions

The number of solar panel modules required per OLT depends on the solar energy harvest. As an example, we consider the city Swansea in United Kingdom. Let’s consider the energy harvest by the 215W solar panel over the year in Swansea. The minimum number of modules required per OLT is six; this would power the OLT continuously for the months May, June and July. However in December there would be required thirty-three modules [16]. This indeed will vary with the geographic location and period of the year. One could install an average number of modules to cover partially the yearly needs and obtain a reduction of carbon emissions. Assuming that each OLT has 250 subscribers in operation to serve 1 Million users, it will be necessary 4000 OLTs. If an average number of panels per OLT is used, e.g., 13 panels, the total panels required will be a total of 52000 solar panels.

The cost of implementing solar power includes the fittings, the solar system and associated components including a battery is roughly £6200 per OLT [19]. It is important to recognize that this is a one-off cost and the price will potentially be reduced when large quantities are bought.

There are various methods of generating electricity, each producing a different amount of CO_2 per kWh. Therefore, by calculating a weighted average, the amount of CO_2 released in to the atmosphere is 0.54kg for every kWh of electricity generated [17]. The carbon emission of Photovoltaic cells is approximately 58g /kWh. This value is exclusively from the manufacture of the cells, as there are no carbon emissions when the system is in use [18]. This leads to a significant reduction of carbon emission by using solar panels to feed the telecom equipments.

Solar panels are designed to be installed outdoors and have weather resistant covers which help to retain their reliability. Another relevant issue is to maximize the system efficiency. There are many ways however the best is to check the cost per kWh. To increase the efficiency of the whole system the modules should be closed to the OLT to avoid lost of energy during travelling.

Vandalism is always a concern when installing anything in metropolitan areas where there are higher population densities. A possible solution is to install special designed modules with an impact resistant acrylic. It is recommended that the OLT is connected to the photovoltaic system and the national grid. This will allow the system to continue operating even when the solar system stops or the mains has a fault.

In conclusion, the use of solar power within broadband network is theoretically feasible. At present there is a large initial cost associated with the implementation of the solar system. This could be reduced by increasing the efficiency of the solar technology and its demand. The benefits for the environment are significant due to very large carbon emission reduction.

5.1.4 Contribution from PoliTo (mainly within WP 14)

A5.1.4.1 Frame Scheduling for Input-Queued Switches with Energy Reconfiguration Cost

The growth of energy consumption in core router/switches is one of the most critical design problems, mainly due the thermal issues that require complex cooling systems. As a consequence the next generation of high-end core routers/switches will have to deliver maximum performance at minimum power requirements. In this research work, PoliTo focused on minimizing the energy consumption in a slotted input-queued switch with a crossbar-like switching fabric while preserving high throughput.

Typically a switching fabric is placed on a single chip and its energy consumption can be strictly related on the technology used. On the one hand, the energy consumption can be *i)* bit rate dependent (as it typically happens for electronic switching fabric families) or *ii)* it can be independent of the number of transported bits (as it can be assumed for optical switching fabric families). The family of optical switching architectures is very promising to face energy scalability issues because the energy consumption depends on the number of rearrangements in the switching configuration between consecutive time-slots, and not on the volume of switched traffic.

The energy aware scheduling problem can be addressed through the fulfilment of the following targets:

- Change the switching fabric configuration to serve all queues in order to maximize the throughput.
- Minimize the variations between two consecutive switch configurations to minimize the energy consumption.

PoliTo [20] proposed and compared a set of scheduling algorithms to solve this problem through a frame-based approach. For each frame the problem can be solved combining two independent classes of algorithms: i) a configuration selection algorithm to maximize the throughput and ii) a frame sorting algorithm to reduce the variations between two configurations so as to minimize the energy consumption.

PoliTo considered four different algorithms to define the set of matchings composing a frame. The first three are iterative algorithms (BvN, GMax, GMin), exploiting the proposed generic decomposition algorithm Gen-DEC; they are based on the Birkhoff-Von Neumann decomposition, and on maximum and minimum weight matching respectively; the last one (Diag) is a simple decomposition algorithm based on a precomputed set of diagonals.

A sorting algorithm (aware of the energy/reconfiguration trade-off) is used to order the previously selected matchings with the aim of minimizing the energy consumption due to reconfigurations in consecutive time-slots. This problem reduces to a Travelling Salesman Problem (TSP) [21], which is NP-complete, but can be well approximated with heuristics. The effect of the different sortings was examined using 3 cases: no sorting at all (NS), Best sort (BS) and Worst sort (WS), corresponding to lowest and highest energy cost.

The impact of frame sorting algorithms is shown in Table 1 each row represents the achievable (normalized) energy consumption per packet obtained from a configuration selection algorithm with a particular frame sorting algorithm for a 64×64 input-queued switch. The impact of frame sorting allows reducing the achievable energy per packet consumption.

Configuration Select Alg	*Worst Sort*	*No Sort*	*Best Sort*
BvN	0.87	0.81	0.74
GMax	0.45	0.41	0.37
GMin	0.72	0.045	0.05
GExa	0.87	0.02	0.02
Diag	0.02	0.02	0.02

Table 1. Energy consumption comparison per packet for different algorithms

The energy performance was assessed with an ad-hoc event driven simulator. Figure 3 shows the energy-throughput trade-off obtained by GMin-NS by varying the number of switch ports *N*. It is interesting to observe that, regardless of the switch size, the maximum sustainable load is always significant, and the increase in the energy per packet as a function of *N* is marginal. Figure 4 shows the trade-off between the maximum sustainable load and the achievable energy consumption per packet. Each point represents the average value considering the best combination between matching selection and a frame sorting selection algorithms; the horizontal and vertical bars show the maximum and the minimum values obtained.

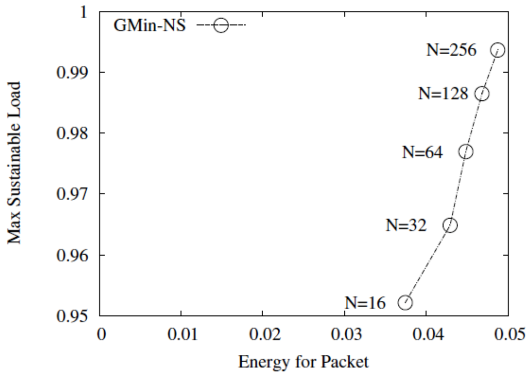

Figure 3: Throughput and energy trade-off for the GMin algorithm (with no sorting) for Uniform traffic.

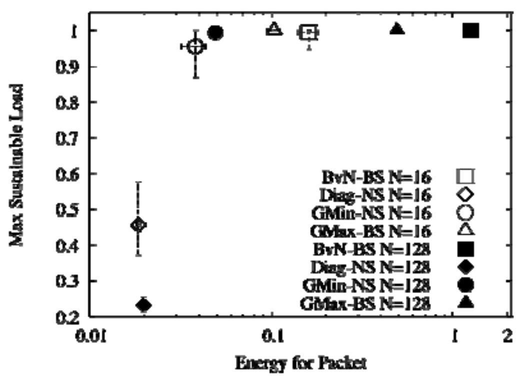

Figure 4: Throughput and energy trade-off for a number of ports N=16 and 128

It can be observed that the energy consumption per packet may vary by almost two orders of magnitude depending on the chosen algorithm. Even if BvN with best sort is a well-known optimal algorithm for energy-oblivious frame decomposition, it is also the least efficient among the studied algorithms in terms of energy consumption, further requiring a high computational complexity. GMin with no sorting appears to provide the best compromise between sustainable load (always very close to the maximum) and energy consumption (very close to the observed minimum). Diag is very good in energy consumption, but provides too low throughputs. In general this work assesses the reduction of power consumption of switching fabrics, by properly controlling the scheduling applied to control the switch, through a proper separation in two individual simpler problems.

A5.1.4.2 The power efficiency of AWG-based optical switching architectures

PoliTO has studied several Optical Switching Fabrics (OSFs) for high performance packet switches in [22]. Three OSF architectures were introduced: Multiplane-Couple-Amplify-Demultiplex (MCAD), Wavelength-SelectiVe (WSV) and Wavelength-Routing-Space (WRS) architecture, which were reported in [23] and [24].

In the research work reported in [22], PoliTO focused on the WRS architecture, which is based on Arrayed Waveguide Gratings (AWGs); AWGs are passive optical devices and can have large aggregated bandwidth and lower power requirements with respect to other optical interconnection architectures based on active components.

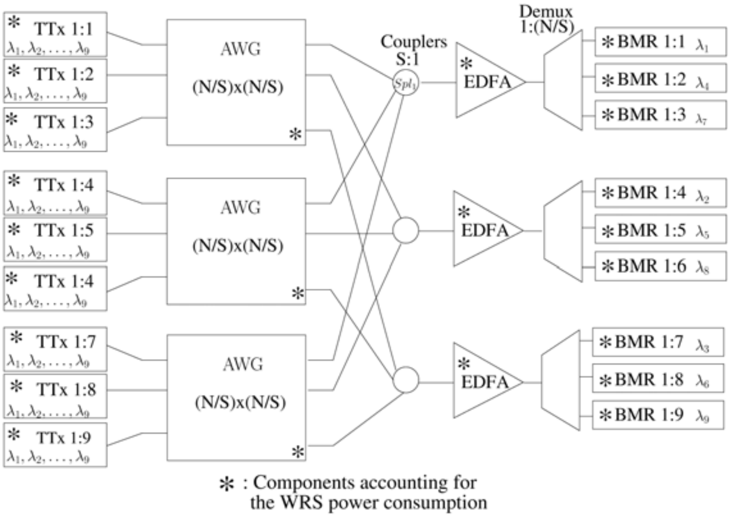

Figure 5: WRS switching fabric architecture

The WRS architecture is depicted in figure 5; it is based on the AWG cyclic property, by which wavelengths in homologous positions of different Free Spectral Ranges (FSRs) lead to the same input/output signal routing. This property is used to perform both the plane and the destination selection. Being S the number of planes and *N* the number of linecards, each Tunable Transmitter (TTx) needs to tune *N*/*S* wavelengths on *S* different FSRs; hence requiring a total tunability range equal to *N*. 0shows a 9x9 WRS OSF with *S* = 3.

In [23] it is showed that the scalability of AWG-based OSFs can be limited by coherent crosstalk when too many AWG inputs use the same wavelength at the same time. These crosstalk limitations can however be solved either at *i)* an architectural level, or *ii)* by using a proper scheduling algorithm. In [24] a version of the WRS architecture named WRS-zc (zero crosstalk) was analyzed, that takes the former approach. In WRS-zc, by equipping each linecard with a TTx spanning over a different set of *N* wavelengths, the reuse of the same wavelength in different parts of the fabric can be avoided. On the other hand, in [25], the authors proved that it is possible to design scheduling algorithms able to select input-output matchings that minimize wavelength reuse.

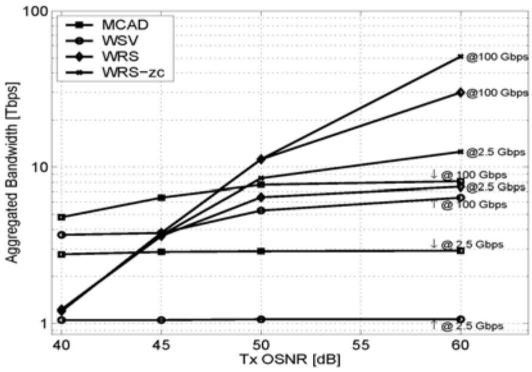

Figure 6: Aggregated bandwidth as a function of

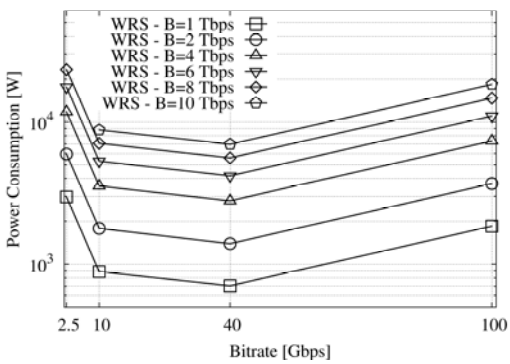

Figure 7: Power consumption trends of WRS OSF.

the transmitter $OSNR_{TX}$

PoliTO has assessed the scalability and the power consumption for each one of the WRS, MCAD and WSV architectures. Physically the WRS is highly penalized by the lasers' optical noise ($OSNR_{TX}$) as shown in figure 6, since AWGs accumulate N source contributions instead of N/S for the other architectures; however, typical values of $OSNR_{TX}$ near 50 dB are possible and this allows the WRS architecture to scale in aggregate capacity comparably to MCAD and WSV. By imposing realistic sensitivity and signal-to-noise-ratio constraints at receivers, it was observed that OSFs based on commercially available components of today achieve aggregate bandwidths of several Tb/s.

Regarding the power consumption of WRS, 0reports the total power consumption as a function of the bitrate for the WRS architecture when $OSNR_{TX}$ = 50 dB for several aggregate bandwidths. The behaviour of the power consumption strongly depends on the bitrate, hence on the technology used. Indeed, technologies for low bitrates (e.g. 2.5 Gb/s) can be now considered consolidated and almost obsolete, whereas for highest bitrates (as 100Gb/s) technologies are not mature yet. The minimum power consumption occurs when using available and mature technologies.

The MCAD and WSV OSFs exhibit power requirements similar to the WRS OSF for the same aggregate bandwidth, but both the MCAD and the WSV architectures support lower switching capacity than the WRS solution.

The AWG is therefore a promising device to build OSFs able to scale to ultra-high capacities while ensuring significant power savings. Comparing the power consumption of the WRS architecture and the power consumption of the CRS-1 Cisco router (which is one of the largest packet switching devices offered on the market today), the power consumed by WRS OSF is lower than the power needed by the CRS-1 switching fabric, which is declared to be the 15% of total router power consumption. It is important to note that this gain in power efficiency is expected to be much higher moving from architectures based on discrete components (as PoliTo considered in this work) to integrated designs and properly engineered implementations.

5.1.5 JA Conclusion

There have been a number of collaborative actions carried out in JA2. The most of the collaborating partners took part in informal meetings and discussions that have been held at the conferences ICTON 2010 in Munich, Germany, OFC 2010 in San Diego, CA, USA, EU Future Networks & Mobile Summit, Florence, Italy as well as at the BONE Summer and Master School in Budapest, Hungary. Some results of JA2 were also presented at the EU Future Networks & Mobile Summit. Since JA2 is under common umbrella of WP21 and WP14, some of the activities are more related to WP21 and other to WP14. The joint work resulted in three joint publications and ten single-partner papers of which two papers are published in refereed journals (see Section 5.1.7). Additionally, three other joint journal papers are under preparation for submission. The collaborative work concentrated mainly on three particular areas, namely on energy efficiency in optical access networks (TUW, UPC, and ISCON), power consumption and performance evaluation of optical hybrid switching nodes (UNIMORE and TUW) and solar-powered optical passive networks (USWAN and TUW). The first and the third collaborative works are mainly within the scope of WP21 while the second work is mainly related to WP14. Also contribution of PoliTo is mainly related to WP14, in which a set of scheduling algorithms were proposed and compared in order to solve the energy aware scheduling problem through a frame-based approach. Additionally, PoliTo studied the power efficiency of AWG-based optical switching architectures. A mobility action was performed between UNIMORE and TUW, in which MSc student Matteo Fiorani spent more than four months at TUW working on implementation of a model for evaluation of energy efficiency in optical hybrid switching networks.

5.1.6 References

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5.1.7 Publications

1. (joint paper) A. Lovrić, S. Aleksić, J. A. Lazaro, G. M. Tosi Beleffi, F. Bonada, and J. Prat, Influence of Broadcast Traffic on Energy Efficiency of Long-Reach SARDANA Access Network", accepted for publication in OFC/NFOEC 2011, Los Angeles, CA, USA, March 2011.
2. (joint paper) A. Lovrić, S. Aleksić, J. A. Lazaro, G. M. Tosi Beleffi, J. Prat, and V. Polo "Power Efficiency of SARDANA and Other Long-Reach Optical Access Networks", accepted for publication in 15th International Conference on Optical Network Design and Modeling (ONDM 2011), Bologna, Italy, February 2011.
3. K. Ennser, B. Devlin and S. Mangeni, "Towards greener optical access networks", in Proc. International Conference on Transparent Optical Networks – ICTON'10, Munich, Germany, 2010, invited paper Tu.B1.1.
4. (joint paper) K. Ennser, S. Mangeni, S. Taccheo, S. Aleksic, "Techno-economic feasibility studies for solar powered passive optical network", in Proc Conf. Broadband Access Communication Technologies V as part of SPIE Photonic West Symposium on OPTO: Optical Communications: Devices and Systems, USA, 2011, paper 7958-21.
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6. S. Aleksić, „Energy-efficiency of Electronic and Optical Network Elements", in Journal of Selected Topics in Quantum Electronics, IEEE, (invited), scheduled for publication in March 2011.
7. S. Aleksić, "Design Considerations toward Low-Power-Consuming Optical Network Elements", (invited), to be published in Asia Communications & Photonics Conference & Exhibition (ACP 2010), Shanghai, China, paper SI2, December 2010.
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5.2 JA3 Energy Saving Potential by Selective Switch-off of Network Elements

Participants:

AIT, IBBT, TUB, KTH, FUB, GET, SSSUP, POLITO

Responsible person:

Fabio Neri (PoliTo)

5.2.1 *Energy-aware Optical Wavelength Routing Networks*

A5.2.1.1 Energy-aware WDM networks - FUB

The role of optical networking technologies in core networks has gained interest thanks to the flexibility provided in designing virtual topologies at the upper layer. Energy saving strategies at the electronic layer lead to a higher number of requested lightpaths as a consequence of the end-to-end grooming strategy. In this scenario and for wide area optical networks the power consumption becomes significant also in the optical domain. The work in publication [26] aims at reducing the power consumption of a transparent multi-fibre optical network by using a subset of optical fibres deployed in the network with the goal to put optical amplifiers along them in idle state.

Starting from the approach proposed by PoLiTo and considering some specific issues of optical networks, like protection requirements requested by upper layers and the wavelength continuity constraints, the problem was formulated as an Integer Linear Programming problem and new heuristic criteria were proposed and tested for properly selecting optical fibres to switch-off. Results in [26] showed some performance difference among heuristic criteria indicating as major constraining factor the availability of a path in the network when switching off a fibre.

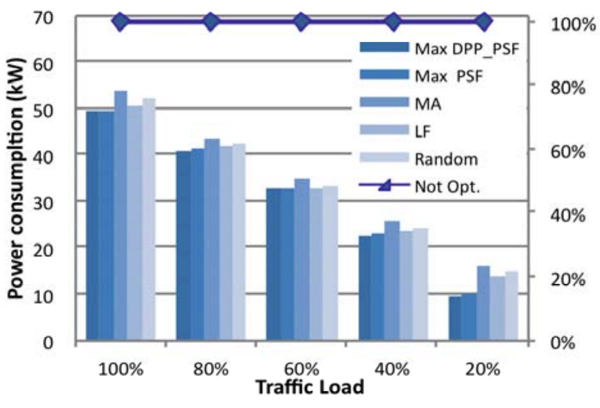

Figure 9: Optical link power consumption versus traffic load for different heuristic fibre selection criteria. N=18; W=40; D=0.25.

Considering a sinusoidal traffic load during a day, FUB results showed that, by switching off fibres on the basis of the traffic load, it is possible to save approximately 35% of the total energy consumed at the optical layer, also considering the energy due to O/E/O conversion performed by transponders.

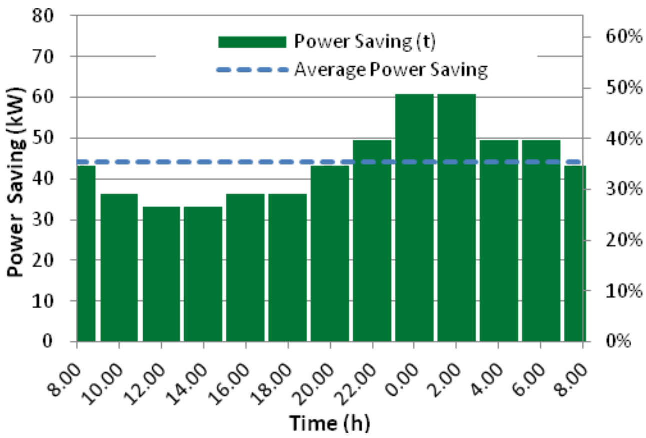

Figure 10: Power saving versus time; Max DPP_PSF heuristic; N=18; W=40, D=0.25

In the work in [28] (submitted to IEEE Communication Letters) FUB extended the results provided in [27] by investigating the impact of network design parameters on the power consumption of the network and on the efficiency of the proposed mechanism. Results showed that by increasing the number of wavelengths of WDM systems it is possible to achieve good energy efficiency even with a small connectivity degree. Moreover, from the energy consumption point of view, applying the proposed mechanism corresponds to increasing the number of wavelengths of about 50%.

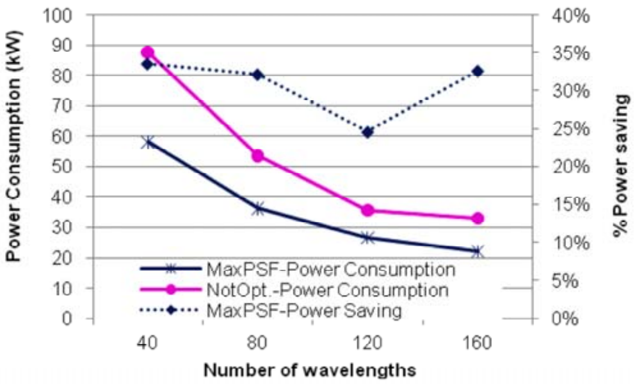

Figure 11: Link power consumption vs. *W*. *N*=20; *D*=0,3.

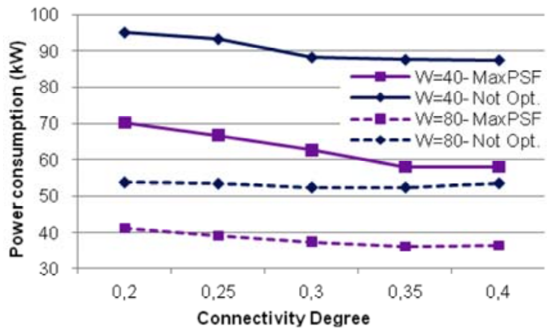

Figure 12: Link power consumption vs. *D*, for optimized and not optimized cases; (*W*=40 and *W*=80); *N*=20.

In Publication [29] (submitted to ICC 2011) FUB proposed a Power-Aware Routing and Wavelength Assignment (PA-RWA) algorithm with the objective to establish lightpaths so that the power required by the network is minimized. Unlike other works in the literature, this work considers a dynamic traffic scenario; a heuristic routing algorithm, called Load Based Cost (LBC), and a modified version of the First Fit (FF) wavelength assignment algorithm, called Least Additional Power-FF (LAP-FF), have been proposed. The proposed algorithm has been compared with other routing algorithms, such as Least Congested Path (LCP), Shortest Path (ShP) and Most Used Path (MUP), recently proposed by PoLiTo. The basic idea of LBC is to use a cost function to assign link weights considering the load of each fibre. In fact we observed that, by applying a null cost to the used fibres, path lengths increase very much, leading to a huge bandwidth waste. Moreover, when fibre loads are high, the probability to find an available wavelength along the whole path rapidly decreases due to the wavelength continuity constraint, determining the need to power on an additional fibre on some links of the chosen path during the wavelength assignment phase. This pointed out the need to design a cost function that increases with the load of each fibre. On the other hand, when the fibre load is low, the probability to power-off is high and then a higher cost should be assigned to such a fibre in order to avoid its utilization. The previous observations have suggested the definition of a class of functions, called V-Like functions, composed of two branches: the first decreases for increasing values of load until it reaches a value equal to W/2; the second increases in the interval [W/2, W], where W is the number of wavelengths of each link.

Results showed that LBC allows reducing the power consumption for any traffic load, especially when LAP-FF is used, and that it outperforms MUP when traffic load grows.

MUP shows good performance when the traffic load is low, reducing the power consumption by a factor of 5 with respect to ShP for the minimum considered traffic load. On the contrary, when traffic load increases, MUP power consumption rapidly increases and exceeds ShP one.

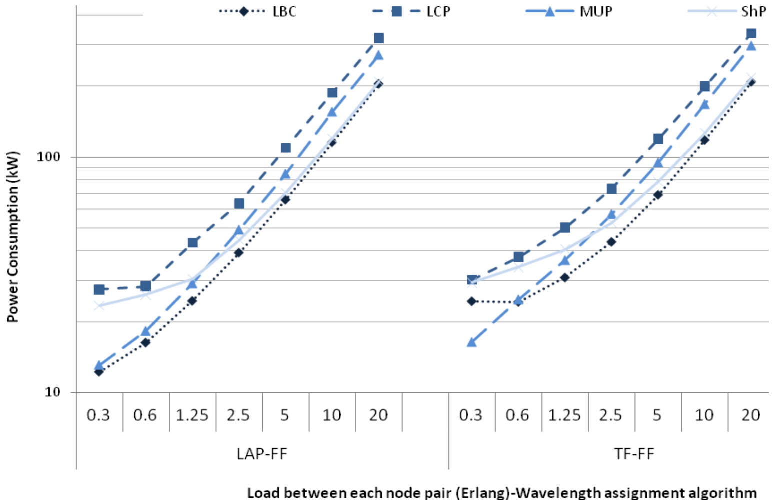

Figure 13: Power consumption of different PA-RWA algorithms

A5.2.1.2 Influence of rerouting on energy saving in IP over WDM networks in low-demand scenarios – TUB

TUB focused on the following three energy-saving approaches in IP over WDM networks [30], which correspond to different levels of freedom in rerouting IP demands over the virtual topology and rerouting of lightpaths over the physical topology:

- Fixed Upper Fixed Lower (FUFL) – no possibility to change the virtual topology (Fixed Lower) and IP routing (Fixed Upper) over time. Traffic can be shifted only between the parallel lightpaths that correspond to the same physical path. Line cards can be switched-off once the corresponding lightpath is empty (only due to a decrease of the load).
- Dynamic Upper Fixed Lower (DUFL) – it is possible to dynamically change the IP routing over the fixed virtual topology. The routing is changed in such a way that the number of idle lightpaths is maximized, so that the corresponding line cards can be switched off.
- Dynamic Upper Dynamic Lower (DUDL) – both the virtual topology and the IP routing can be changed over time with the same goal as above. The number of installed cards at each node is fixed though.

In order to investigate the sensitivity of previous results obtained by TUB against input data, the following parameters (kept as realistic as possible) were stressed [31]:

Network Topology: TUB evaluated the potential of power savings on three different network topologies: Germay17, Abilene and GÉANT, using corresponding traffic matrices originated from measurements. The results obtained for these topologies were similar to each other. DUFL brings more power savings than FUFL, and additional flexibility of changing the virtual topology (DUDL) does not bring substantial benefits against DUFL. Although the simple strategy FUFL provides lower power savings than DUFL, it still shows significant improvements against the static base network.

Time Scale: TUB also considered different time scales of traffic demands, i.e. additionally to the 15-minute demand matrices over a day, aggregated measurements for every day over a month were considered, and every month over a year. The results are similar for all considered time scales.

Demand Patterns: Structure of demands was changed by applying the Dwiwedi-Wagner (DWG) model into DFN (national research backbone network operated by the German DFN-Verein) traffic matrices. The main result that DUFL brings comparable power savings to DUDL does not change. In contrast, FUFL brings only marginal power savings against the base network when demands are more evenly distributed over space than in the traffic matrices originating from measurements. This is due to the fact that there are only few parallel lightpaths in the base network, and line cards are more evenly distributed (according to the traffic demands) over the network nodes. Since FUFL assumes no reconfiguration of the virtual topology, it has to keep lowly utilized lightpaths for connectivity reasons.

Demand Scalings: TUB scaled the traffic demands so that the maximum total demand equaled 1, 3 and 5 Tbps. This changed also the ratio between the capacity of a WDM channel and the size of demands. Similarly to changing the structure of demand patterns, the success of FUFL depends on the size of the demand. Decreasing the demand size with constant capacity of the WDM channel decreases the power savings achieved with this simple strategy.

The main result obtained by TUB with this work is that rerouting of demands over the virtual topology in the IP layer (DUFL) contributes the most to the power savings. The extensive computational study performed strongly suggests that this result is independent from the demand scaling, network topology, time scale and demand patterns. Simple monitoring of traffic and switching-off unnecessary line cards (FUFL) may bring substantial power savings. The success of FUFL depends on the size of demands compared to the capacity of a WDM channel as well as on the regional distribution of the demands.

5.2.2 Switch-off control via GMPLS – (FUB+SSSUP)

Second-level protocol layers can help also in the control of power consumption by optical networks. FUB and SSSUP have devised control schemes based on GMPLS to encourage switch-off or sleep mode in optical links.

The work in [27] (submitted to OFC 2011) provides a practical mechanism to reroute connections without experiencing flow interruption when switching off an optical fibre. To address this issue in [27] FUB proposed to use the GMPLS graceful shutdown procedure and adapted the algorithm adopted in [26] to be used together with the GMPLS mechanism. The main difference with respect to the algorithm in [26] is that, when performing the fibre switch-off and connections on that fibre must be rerouted, each connection can use only available resources in the network or resources reserved for itself on common links between the old and the new path but cannot use resources that will be released by other connections under rerouting. In [27] FUB also evaluated the impact of the switching-off procedure on the path length distribution demonstrating that it allows reducing the maximum path length for working paths and implies an increasing of the average path length for protection paths.

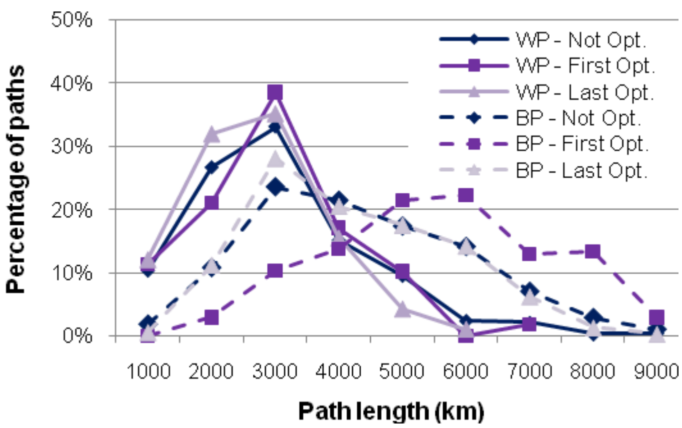

Figure 14: Path length distribution for optimized and not optimized cases

On the other hand, SSSUP has worked in the definition of a distributed strategy for selecting links to be set to sleep in a GMPLS optical network. The rationale is that the power drained by the in-line amplifiers remains the same whether few or a large number of lightpaths traverse the link (due to large overheads and inefficiencies of currently available optical amplifiers). Therefore when the network is scarcely loaded, it is possible to reduce the power consumption by setting the links (and thus all the optical amplifiers on the corresponding links) to sleep. The proposed strategy can be implemented locally at each node and should decide whether the outgoing links should be set to sleep and, in the positive case, should re-route the lightpaths supported by the link.

If the link is supporting at most *r* lightpaths (where *r* is a threshold value), the link is candidate for being switched to sleep mode. The node informs the source nodes of the *r* lightpaths, via RSVP-TE Notify messages. Upon receiving the notification, the source nodes trigger the lightpath re-routing. Lightpath re-routing is performed using a *make-before-break approach*: the old lightpath to be re-routed is still used while a new one is being established. Once established, the traffic is smoothly re-routed and the source node can tear down the old lightpath. When all the wavelength resources of the selected link are released, the link can be finally put to sleep. To avoid disruption of the already existing lightpaths (if re-routing is not successful) the old lightpath is preserved and thus the link is forced to operate in active mode. Sleeping links can be reverted to active mode when a newly requested lightpath is routed on such link (e.g., when the node receives a RSVP-TE Resv message specifying that the lightpath is reserving resources along the incoming link). Links support sleep mode either by:

- *Sleep Mode Unaware* (SMU) GMPLS, i.e., the current standard. The LSA messages of OSPF-TE advertise whether a link is active or off. Only nodes receiving a Notify message are aware of the link(s) in sleep mode. The other nodes consider the links in sleep mode as active.
- *Sleep Mode Aware* (SMA) GMPLS, i.e., extended for the support of link sleep mode. The LSA messages of OSPF-TE are extended to specify whether a link is in sleep mode. TED is updated accordingly and used for the path computation of incoming lightpath requests. Thanks to this information, all network nodes are informed about the operational mode of the links and can refrain from routing newly requested lightpaths on the sleeping links.

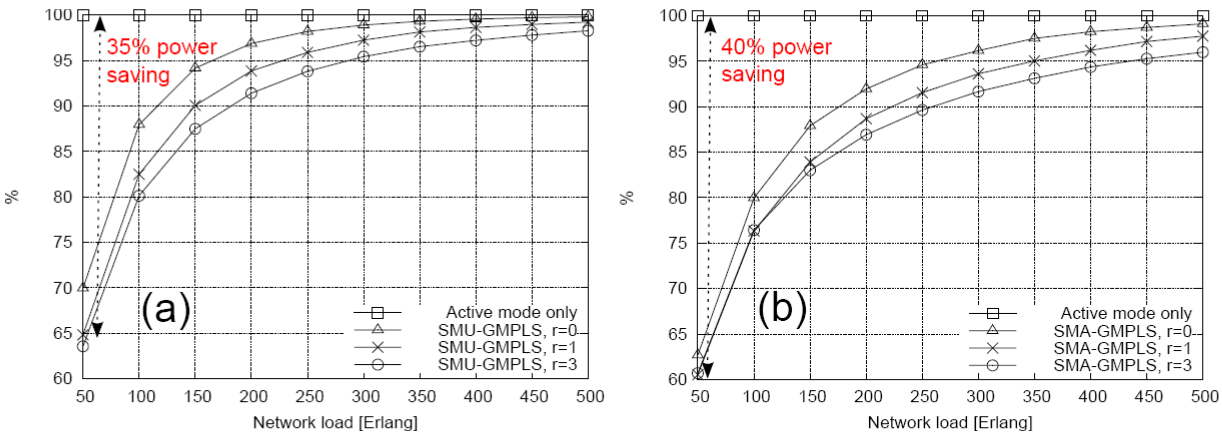

Figure 15: Normalized power consumption vs. load for SMU-GMPLS (a) and SMA-GMPLS (b).

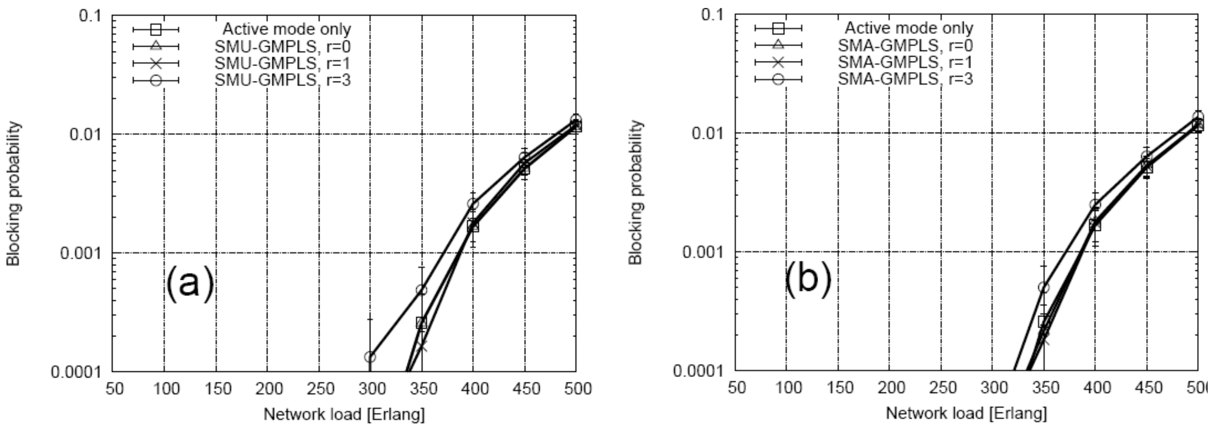

Figure 16: Blocking probability vs. load for SMU-GMPLS (a) and SMA-GMPLS (b).

The results achieved [34] in terms of power consumption and lightpath blocking probability are shown in figure 15 and 16, respectively. In the figures, the performance of SMU-GMPLS and SMA-GMPLS for different values of threshold *r* is compared against that of a reference GMPLS network without support of link sleep mode nor re-routing (i.e., links are always active). Performance evaluation has been carried out through simulations on the European network [34]. Results indicate that considerable power savings are achieved at low loads (up to 35% for SMU-GMPLS in figure 15(a)). By extending GMPLS for advertising link sleep mode (i.e., SMA-GMPLS in figure 15(b)), power savings improve by an additional 5%. More importantly, the network performance in terms of blocking probability of the requested lightpaths (figure 16) is not influenced by the proposed strategy. Also, the proactive re-routing of the lightpaths passing on the selected link avoids the disruption of the existing lightpaths (i.e., no increment of packet losses) and does not impose any tight requirement on the transition time between link operational modes. In summary, the main achieved results are that the proposed distributed strategy is effective: it leads to a significant decrease of power consumption at low loads without QoS impact. Such advantages are already achievable under the currently standardized GMPLS suite, but they could be increased by enabling the links sleep mode support, as proposed, into the GMPS control suite.

Finally, a centralized strategy for the link sleep mode support is currently under investigation and it is planned to be compared with the proposed distributed strategy in a journal publication.

5.2.3 Power efficiency in survivable WDM networks (KTH+AIT)

Protection resources are instrumental to guarantee resilience in WDM networks against component failures. They might be utilized in different ways, depending on the protection scheme used. In the case of 1:1 protection, regardless of the status of the primary path (i.e. failed or not), protection resources (e.g. optical amplifiers and node equipment) are always active (i.e. switched on) along the secondary path. Taking this into account and considering the fact that secondary paths are on average longer than their respective primary paths, it is clear that the power consumed by protection resources in WDM networks becomes a key issue. However, the solutions proposed in the literature so far to reduce the power consumed by the network infrastructure pay little or no attention to the role played by protection resources in the overall network power consumption [R1]-[R4].

One way to reduce the power consumed by protection resources is to switch-off (or set in a *sleep mode*) the network elements used for protection purposes [32]. The rationale is that these resources are redundant and need to be in an active state only after a failure in the network occurs. There are two issues that need to be addressed in order to make this approach effective. First, an assessment of the real benefits in terms of power reduction when protection resources are switched off is necessary. Secondly, only those network elements that are provisioned exclusively for protection purposes can be switched off, in order to not affect the primary lightpaths. In this context, the higher the number of secondary paths that are routed along already provisioned protection resources, the higher the probability for these network elements to be turned off.

The contribution of this study is two-fold. First the potential power savings achieved by setting protection resources in a sleep mode are assessed in a dynamic provisioning scenario [32]. Secondly, different energy-aware algorithms are proposed and compared to explore the potential power savings caused by the deactivation of protection resources [33].

With this rationale in mind, different energy-aware provisioning algorithms that trade energy minimization for blocking probability, while exploiting the sleep mode feature, are proposed. The first energy-aware dedicated path protection algorithm, with differentiation of primary and secondary paths (EA-DPP-Dif), focuses on energy minimization by forcing differentiation between the links used by primary and secondary paths. The second proposed approach based on energy-aware dedicated path protection with mixing secondary with primary paths (EA-DPP-MixS) relaxes the differentiation constraint between the links used by primary and secondary paths, while routing secondary paths. Finally, this study also presents an approach based on energy–aware dedicated path protection (EA-DPP) algorithm that tackles the energy minimization problem in a dynamic scenario when the sleep mode is not supported by the network devices.

To evaluate these energy-aware routing algorithms, both partners used the Pan-European test network topology (COST 239) [33] with 40 wavelengths per fibre link. A dynamic network environment was simulated where connection requests arrive to the system following a Poisson process and are sequentially served, with an exponentially distributed service time, without prior knowledge of future incoming connection requests. Source/destination pairs are randomly chosen with equal probability following a uniform distribution among all network nodes. The granularity of the demands considered is the wavelength. The wavelength continuity is a hard constraint, and for each demand a link-disjoint path pair has to be identified, where the secondary path is used as a dedicated-protection path.

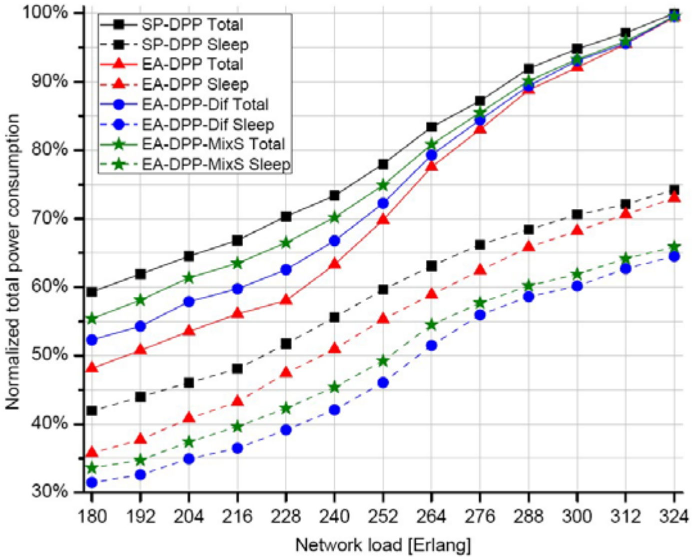

Figure 17: Normalized total power consumption vs. network load

Figure 17 shows the total network power consumption as a function of the offered network load in Erlangs. The figure presents the value of the total power consumption normalized with the highest value of power consumed as a function of the network load. The results show a significant reduction of power consumption with the proposed energy-aware survivable connection provisioning algorithms, when compared to the conventional Shortest Path with Dedicated Path Protection (SP-DPP).

According to figure 17 the algorithms able to efficiently exploit the sleep mode are EA-DPP-Dif and EA-DPP-MixS. These two algorithms show a very similar behaviour, and they both outperform EA-DPP and SP-DPP. By packing primary with primary and secondary with secondary paths, EA-DPP-Dif gives maximum reduction of the overall network power consumption.

When the sleep mode is not supported, i.e., both working and protection resources are active, the highest power savings can be achieved using the EA-DPP. The results show that up to 12% of power savings can be achieved over conventional SP-DPP routing. This is because EA-DPP does not take into account the sleep mode of operation during the routing phase, and it tries to maximize the energy reduction under the assumption that working and protection resources are both constantly active. On the other hand EA-DPP-Dif and EA-DPP-MixS are sleep-aware, i.e., they are both designed to minimize the energy consumption as protection resources can be set to sleep mode when not required to restore failed connections.

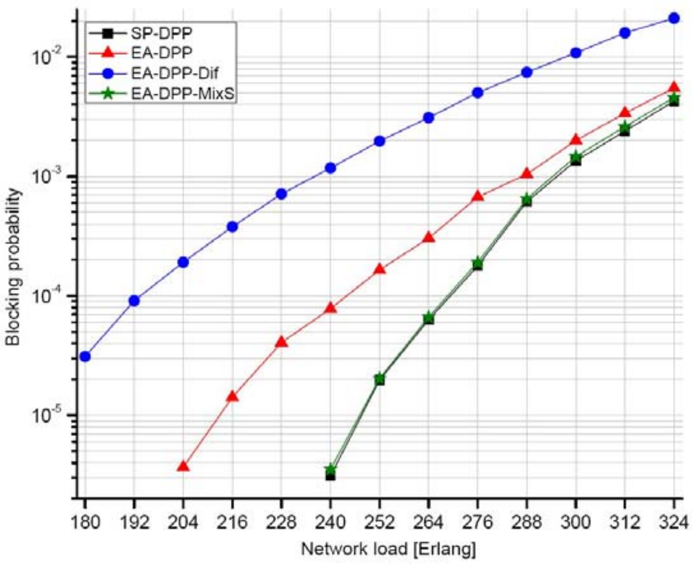

Figure 18: Network blocking probability vs. network load

The total blocking probability shown in figure 18 accounts for blocking due to insufficient resources, i.e., no wavelengths are available for primary or secondary paths. Figure 18 shows that EA-DPP-MixS is a promising solution, compared to other energy-aware approaches, in terms of blocking. It can be observed that the blocking performance of EA-DPP-MixS is similar to the SP-DPP routing. Note that both networks are analyzed for the same range of traffic loading. However, as confirmed by the power consumption results in figure 18, EA-DPP-MixS is still able to show significant energy savings even when the number of alternative paths per node is limited and when most of the resources are used. A condition in which it is challenging to save energy by finding resources that can be set into sleep mode.

5.2.4 Energy saving by switching off network elements in core networks (PoliTO)

PoliTO considered a wide area network scenario. Given the network topology and a traffic demand, the possibility of turning off some network elements (nodes and links) was considered under connectivity and Quality of Service (QoS) constraints. The goal was to minimize the total power consumption of a large network, in which usually resource over-provisioning is large, by using simple optimization algorithms.

During previous project reporting periods, PoliTO [36] proposed and evaluated different heuristics to solve the power minimization problem. In particular, the problem was first formulated as an optimization model. The objective function consisted in minimizing the total power consumption of the network, considering connectivity and maximum link utilization constraints to route the traffic requested by users. The problem was formulated using an Integer Linear Programming (ILP) formulation. However, ILP problems fall in the class of NP-Hard problems, which are known to be very complex to solve. Thus, finding a power-optimal solution resulted to be a viable approach only for very small networks. Therefore, PoliTO developed efficient heuristics to solve the problem also for large networks.

The proposed algorithms consider a network in which all elements are powered on. Each algorithm iteratively tries to switch off each element, considering different sorting criteria to select the devices to be powered off. In particular, devices are sorted considering: power consumption, quantity of traffic or a random ordering. Then, the proposed algorithms try to selectively power off devices. For each device, the current device is powered off. In the following step, connectivity and maximum link utilization constraints are checked by routing the traffic matrix. If the constraints are violated, the current device is repowered. Otherwise, the device is left off. The algorithms end after that all devices are considered.

To evaluate the performance of the proposed solutions, PoliTO started by considering manually generated topologies. In particular, a hierarchical topology model composed by transport and source/destinations nodes was assumed. Actually, traffic was generated among source/destinations nodes, so that these devices cannot be powered off. Differently random generated topologies were used, considering the variation of the network size and the percentage of transport nodes over the total number of nodes. The proposed algorithms were run on the generated topologies. Results show that it is possible to reduce the percentage of nodes and links actually powered on to up 30% and 50% respectively, while guaranteeing that the resource utilization is still below a given threshold. e.g., 50%.

In the second part of PoliTO's work [37], a real case-study was considered, using a topology very similar to the actual one deployed by one of the largest ISPs in Italy. Moreover, the power consumption of nodes and links was estimated using realistic figures derived from available products. A new algorithm was also proposed, which exploits nodes' and links' power consumption to select the set of elements that have to be turned off.

The obtained results show that that, while most network capacity has to be fully available during peak hours, traffic variation over time allows to improve the energy efficiency up to 34% during off peak hours. Considering instead the savings during the whole day, it was shown that it is possible to save more than 23% of total energy consumption, which corresponds to a saving of 3GWh/year.

During the last year of the project, PoliTO further investigated the problem of minimizing the total power consumption by devising optimal solutions that can scale up to medium-size networks [35].

In particular, the original formulation of the problem was modified in order to reduce the total computation time. More in depth, the work at PoliTO exploited: I) a simplified structure to describe how the traffic flows into the network, II) source/destination nodes cannot be powered off, and III) source/destination nodes connected to the same points of the transport network can be reduced into one equivalent node. It was thereby possible to simplify the original formulation of the problem while still providing an optimal solution. The heuristics proposed during previous years were extensively compared against the modified optimal formulation. It was possible to solve the optimal problem both for the synthetic topologies and for the real case-study. The obtained results show that the heuristics perform in general close to the optimal formulation, while requiring low computation times.

To give more insight, 0(left) reports the percentage of power saving comparing the proposed optimal formulation (OPT-V3), and the heuristics (MP-MP and LF-LF). MP-MP and LF-LF adopts different rules for sorting the devices. In particular, MP-MP tries to switch off devices consuming the highest amount of power, while LF-LF considers first the devices with the lowest quantity of traffic flowing through them. In this case a daily traffic variation of users' traffic, and the realistic ISP topology previously described, were considered.

The curve labeled “Maximal” refers to the maximal power saving achievable by the network when only the connectivity constraint is considered. Interestingly, Saving(t) is practically constant during the night, since the traffic is so little that only the connectivity constraint is effective: at night the achieved power saving is instead at its absolute maximum. Saving of 36% of power is possible using the optimal algorithm. MP-MP performs well, with a maximum gap of 1% during the night, while LF-LF performs consistently worse, reaching a maximum saving of only 23%.

During the day the power saving decreases as the traffic increases, since more capacity is required to guarantee the QoS constraint. In this case the maximum gap between OPTV3 and the heuristics is larger, though it is limited to the peak hours.

Considering the computation times, 0(right) shows that the optimal algorithm requires several hours to find the solution during the day. Indeed, finding good solutions is harder when the amount of over-provisioned resources is small, as confirmed also by the heuristics. During off-peak time, the set of constraints is easily met, and the optimal solution can be obtained in less than 20 s. Considering the heuristics, they both require less than 100 s, with higher times during peak hours: this is due to fact that the cost of running the shortest path algorithm increases as the traffic increases, since less devices are powered off.

In conclusion, these encouraging results are supporting the effort spent by the research community. In particular, they call for the availability of both devices that support different power states, and the design of distributed algorithms to allow the real implementation of an energy-aware control plane.

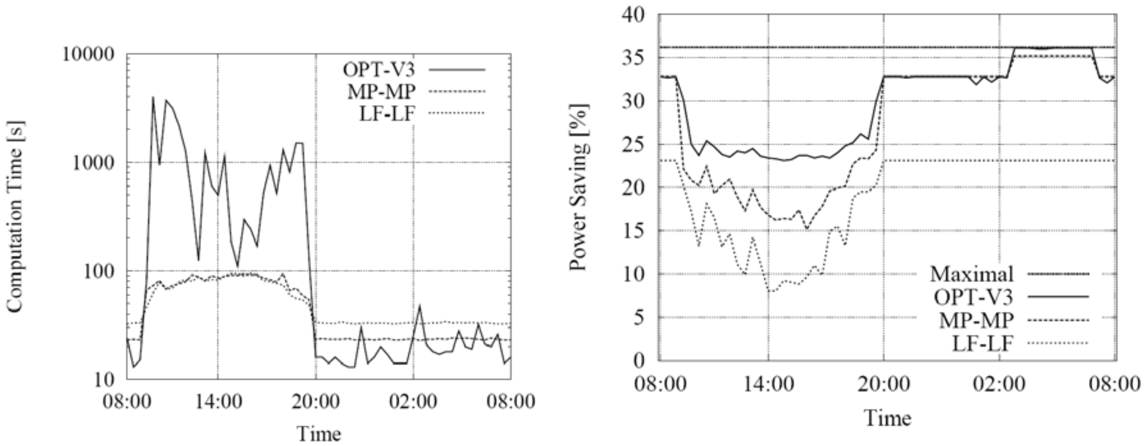

Figure 19: Power Saving versus time (left) and computation time (right), considering the optimal formulation and the proposed heuristics

5.2.5 JA Conclusions

Different degrees of freedom in the operation of optical networks can be used for the sake of energy efficiency switching off networking resources.

TUB efforts showed the impact of IP routing in energy saving, assuming to be able to switch-off unused linecards, distinguishing between upper (IP) and lower layer (WDM) routing dynamicity; the dynamics in the upper layers is important to achieve lower power consumption even when lower layers are less dynamic.

In wavelength routing networks, the heuristic approach proposed by PoliTO and FUB (PA-RWA) for routing and wavelength assignment appears as a promising alternative to achieve power savings within the optical domain, since very simple power-aware network planning algorithms help improving the link usage; a power reduction of 5 times with respect to a non power-aware wavelength routing network was observed.

Energy awareness can be considered when analysing the availability of network resources: FUB analysed the availability of paths when switching-off entire fibers with the aim of saving energy. On the other hand, network provisioning can deal with availability and power savings. The way lightpaths requests are served under protection requirements offers opportunities to save energy; this can happen by properly establishing policies to deal with protection resources. Given that these protection resources can be activated only when they are required, a trade-off rises to balance power consumption (where differentiation is made between main and protection paths) and path availability (which is larger if no differentiation is made).

In general, the switching-off of network elements challenges the actual paradigm of the design of telecommunication networks, for example, proper integration of switching-off techniques with network control (i.e., GMPLS) offers a feasible evolutionary path towards energy efficient optical networks; this is also true from a multilayer (IP, GMPLS, WDM) perspective.

The results presented for JA3 match the research areas planned for this joint activity and underline the possibility of power savings thanks to the flexibility offered by optical technologies. Several papers, among which two joint papers, were published by BONE partners within the JA3 of WP21.

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5.3 JA4 Green Routing Protocols

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5.3.1 JA4 scope

The overall scope of this JA is to study novel energy aware routing protocols and algorithms as well as resource allocation mechanism for optimizing Energy consumption in future networks. For this reporting period there are two research activates:

- Activity 1: Green Routing and Wavelength Allocation
- Activity 2: Energy-Aware Service for integrated Optical Network+IT Infrastructure

5.3.2 Activity 1: Green Routing and Wavelength Allocation (Green RWA)

Optical networks are a power efficient transport option able to play an important role in reducing the power consumption in the ICT sector. The main benefit of optical networks derives from their ability to transparently, i.e., all-optically, transmit data from source to destination, thus avoiding power hungry optical-electrical-optical (O-E-O) conversion [1]. Recently, several solutions have been proposed in the literature to further improve the power efficiency of transparent WDM networks. These approaches address the power consumption in both the network design [2] and the path provisioning phase [1]. Among these methods, solutions limiting the number of active network elements during normal network operations attracted a lot of attention.

These solutions are currently advocated in both static and dynamic provisioning scenarios. In a static paradigm [2-4] these methods are used to re-provision traffic in previously deployed network, where the objective is to lower the total network power consumption by having a minimum number of active elements. In a dynamic scenario [5] links with traffic below a certain threshold may be set to an off/sleep state and their traffic rerouted. Regardless of the provisioning scenario, the focus of these solutions is on power minimization only. Currently, in the literature little or no attention is paid to the effect that solutions tailored only to lower the power consumption has on other network metrics. For example, a pure power minimization provisioning strategy may have an adverse impact on the length of the routed lightpaths, i.e., in order to avoid to unnecessarily power on network elements, the provisioned paths are, on average, longer than the one found with traditional shortest path solutions. This is in contradiction with the goal of classical routing and wavelength assignment (RWA) algorithms that tend to minimize the resource usage within the network, in order to minimize the blocking probability.

Our study addresses this problem by investigating the impact that power minimization has on the overall network performance. With this purpose in mind, a non-conventional solution to the power-aware RWA problem is presented. This approach, referred to as Weighted Power-Aware RWA (WPA-RWA), is based on the intuition that in some cases relaxing the power minimization constraint can have beneficial effects on the overall network performance, i.e., it can contribute to the reduction of resource fragmentation in the network and lower the blocking probability. The proposed algorithm is very promising and leverages on a cost function that weights the power status of network elements versus information about the wavelength usage.

The proposed WPA-RWA strategy is based on a modified version of the k-shortest path algorithm [6], and it works as follows. For each connection request arriving at the network edge, up to k candidate paths are computed. The algorithm accounts for the current resource usage (i.e., wavelengths) in the network, where fiber links without available wavelengths are temporarily deleted from the network topology. When computing each candidate path, each fiber link l in the network is assigned a weight (C_l) as follows:

$$C_l = \begin{cases} \alpha \cdot P_{link,l}, \text{ fiber link } l \text{ in use} \\ P_{link,l}, \text{ fiber link } l \text{ not in use} \end{cases} \quad (1),$$

where $P_{link,l}$ represents the power necessary to operate the in-line power amplifier(s) along fiber link l, and α is a weighting factor with values between 0 and 1. Note that with values of α close to 0 WPA-RWA behaves as a pure power minimization approach, while for values of α close to 1 WPA-RWA tends to provision connection requests along shorter routes.

To evaluates the impact that the WPA-RWA strategy has on the blocking probability a set of simulations were run considering the COST 239 network topology with 11 nodes and 26 bidirectional fiber links [7]. It is assumed that each fiber carries a maximum of sixteen wavelengths and no wavelength conversion capability is considered in the network. Source destination pairs for the incoming connection requests are uniformly distributed among the networks nodes. Furthermore, it is assumed that the connection requests arrive according to a Poisson distribution with parameter λ, while the service time for each connection request is exponentially distributed with a mean holding time defined by 1/μ. The power consumption assumptions for the optical components are the following. In-line optical amplifiers (EDFAs) consume 12 W. A transceiver consumes 7 W (for a transmission speed of 10 Gbps), and an Optical Cross Connect (OXC) 6.4 W. A series of values for the power-weighting factor α are considered, starting from 1 down to values of α close to 0. In this study no more than k=3 candidate paths are computed for each connection request, while wavelengths are assigned using a First Fit approach.

Figures 20 and 21 show the values of the network blocking probability, and the average power saved per request, respectively. Both metrics are presented as a function of the network load. The average power saved per request is computed as the difference between the total network power consumption obtained when α=1 and the total network power consumption for any other given value of α.

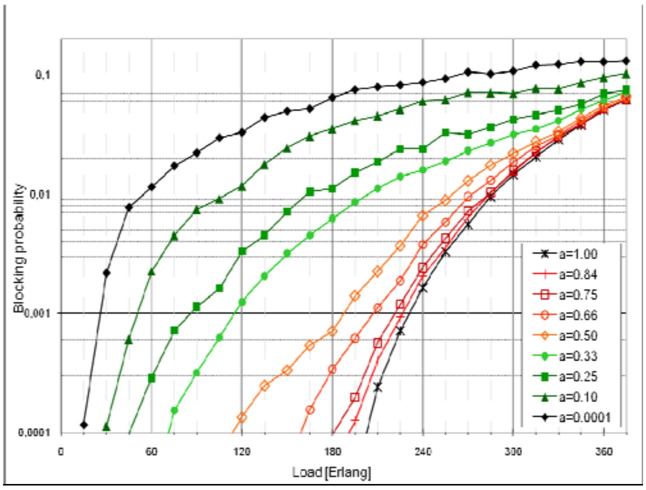


Figure 20: Network blocking probability vs. the network load.

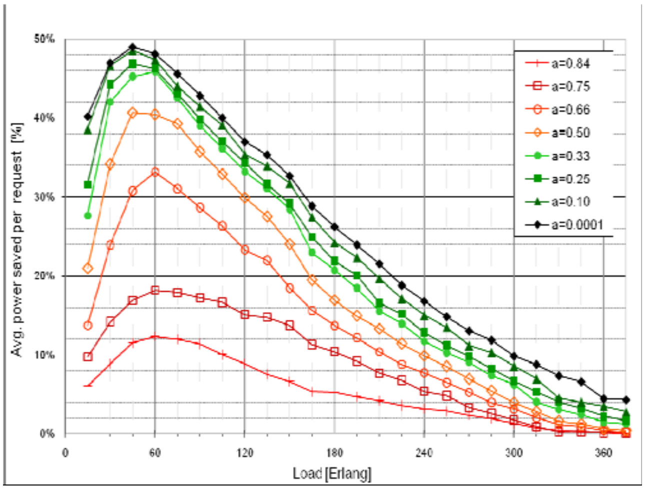


Figure 21: Average power saved per requests vs. the network load.

The figures show that considerable power savings (up to 50%) are achievable, but at the expense of a relevant increase in the network blocking probability. This confirms the earlier intuition that an approach that accounts only for the minimization of the network power consumption may not always be the best choice. The figures also show the possible trade-off results between these two metrics, should an operator be willing to compromise on the total network power expenditure. For example with values of α between 0.66 and 1, there is no significant impact on the blocking probability, but the power saved per request is still significant, e.g., between 30% and 15 % for low and medium traffic conditions.

A5.3.2.1 Relevant publications

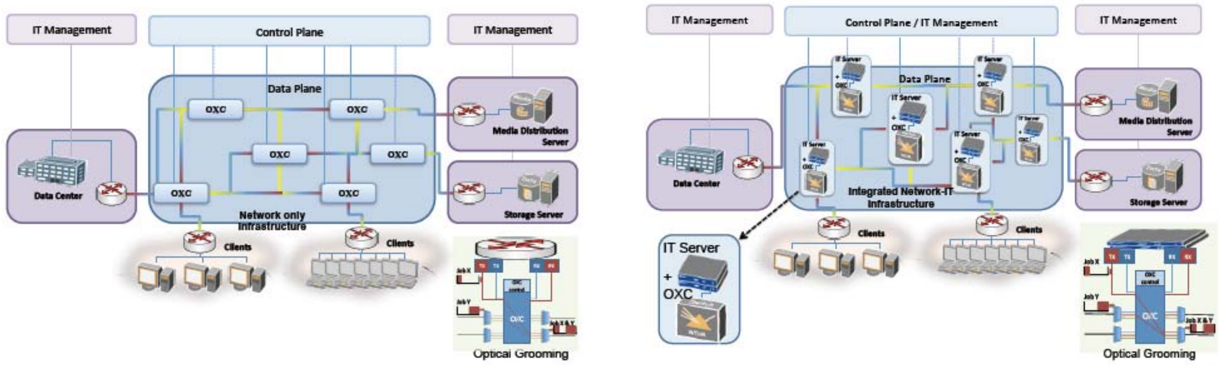
Pawel Wiatr, Paolo Monti, Lena Wosinska, "Green Lightpath Provisioning in Transparent WDM Networks: Pros and Cons", in Proc. of IEEE ANTS 2010

5.3.3 Activity 2: Energy-Aware Service for integrated Optical Network+IT Infrastructure

The advancement of the optical network and the introduction of the wavelength division multiplexing (WDM) technology have brought about a huge amount of readily available bandwidth. This has led to the emergence of demanding, bandwidth-hungry distributed applications such as ultra high definition television (UHD-TV), interactive 3D online gaming. High speed WDM optical network is currently the only transport network capable of supporting these high performance and high-bandwidth applications with strict IT (e.g. computing, storage and content) resource requirements.

As future Internet applications continue to develop, the number of IT and network equipments and data centres that need to be installed will rise, and in turn, the contribution of green house gas (GHG) emissions by ICT will increase. According to recent research [8], ICT is a one of the contributors to the GHG. Currently, the overall ICT power consumption is approximated as high as 10% [9]. Furthermore, the power consumption of the Internet is estimated at 0.4% of the total power consumption [10].

There has however been limited research [13] into the global consideration of the energy efficiency over network and IT resources. Thus, we propose a novel method on the holistic consideration of power consumption in the unified scheduling and allocation of network and IT resources in a collaborative manner. We also propose and analyse two infrastructure scenarios as illustrated in figure 22.



(a) Scenario I (b) Scenario II

Figure 22: Proposed Infrastructure Scenarios Evaluated for Energy Efficiency

The first is the typical Optical-IT infrastructure scenario that considers that large-scale IT resources (e.g. data centres) are placed at the edge of the core network interconnected via IP routers. The second is a novel approach that extends the first scenario by integrating limited footprint and capacity IT resources interconnected via add-drop ports using opto-electronic transceivers (e.g. OTN, Eth) directly to the optical switch, in addition to the data centres. These small IT resources are physically co-located with the OXC. Hence, network operators can benefit from the existing space, cooling and power switches of their existing point-of-presence. We call this integrated OXC-IT scenario, Scenario II.

In this report we propose a novel energy-aware resource selection method capable of locating andscheduling/allocating appropriate underlying network and IT resources for each application/service request such that a globally energy efficient solution is achieved. This may be achieved using a subset of IT and network devices, such that unused/minimally used devices can be put in sleep-mode thus consuming considerably less power. However, we do not consider switching off devices as a means of reducing overall power consumptions. This is because the start-up time for certain devices may be in the order of seconds, which is not practical in highly dynamic operational and provisioning scenarios.

The assumption for the proposed method is that a) each OXC is equipped with a GMPLS control plane and a network management system and each IT resource site is quipped with an IT management system, b) The control and management systems are holding database with resource-state information in the form of available resource capacities, available timeslots as well as energy-related parameters of each device and resource site which can be used by the proposed method, and (c) the low-level task scheduling and lightpath assignment over the resources selected by the proposed method.

To address energy efficient network + IT resource provisioning, we propose a novel Greedy Randomised Adaptive Simulated Annealing (GRASA) algorithm. GRASA combines the generalised Greedy Randomised Adaptive Search Procedure (GRASP) with the Simulated Annealing (SA) algorithm. GRASP is an iterative heuristic composed of two phases. In the first phase, construction phase, an initial solution is constructed. The second phase is the improvement phase. It improves the greedy randomized solution with a local search method. In this report, we use Simulated Annealing (SA) in the improvement stage. From the SA point of view, GRASP is used to create its initial solution. The construction phase creates a feasible solution by estimating a scheduling cost for each of the requests (network + IT request). We propose two algorithms to determine the scheduling cost.

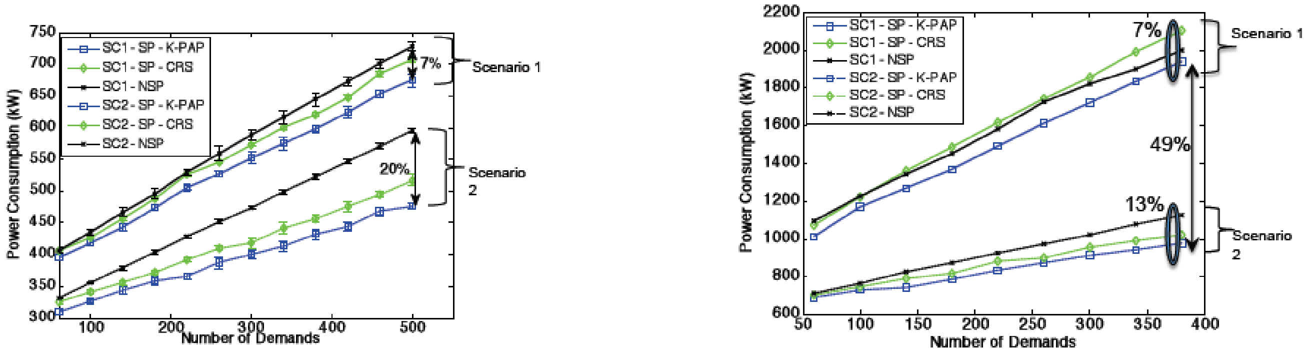
First is closest Resource Scheduling Cost Algorithm (CRS). CRS selects the closest IT resource nodes with sufficient IT resource capacity. This approach minimizes the number of devices used in satisfying a request. Thus, reducing the total power consumed.

Second is K-Power-Aware Paths Scheduling Cost Algorithm (KPAP). KPAP schedules requests by considering the power consumption of each resource-path pair for each request and selects the pair with the lowest energy consumption. The scheduling cost of each request-resource-path triplet is placed in a Candidate List (CL). A restricted candidate list (RCL) is formed which consists of all entries in the CL with scheduling costs according to a threshold parameter correspond to the lowest and highest scheduling costs in the CL. A solution is selected randomly from the request-resource-path triplets in the RCL to schedule the request.

The SA algorithm runs through a number of iterations, during which a new solution is obtained by a perturbation scheme. The perturbation scheme frees a number of demands and then attempts to re-schedule the demands using one of three algorithms: (a) random (b) greedy (closest-resource) (c) minimum scheduling cost.

We validate our service-oriented energy-aware algorithm over the 5-node mesh topology. We then evaluate the heuristic over a larger 14 node NSF Network with 42 unidirectional links. The capacity of each link in the evaluation topology is considered 40Gbps. Each network node is capable of grooming traffic at a granularity of 1Gbps. The PUE (Power Usage Effectiveness [12] PUE is a metric that indicates how much power is used by the IT resource site in relation to its IT equipment load) of each data-centre is randomly selected from the set {2:4; 5:0} and for integrated OXC-IT nodes is set to 1:2. We consider an infrastructure with unlimited resources (over provisioned infrastructure). This is to ensure an accurate and fair measurement and comparison the power consumption of the different algorithms and avoid inconsistencies due to blocking. For Scenario I, we consider disjoint IT resource sites at each edge. For Scenario II, we distribute the IT nodes across OXCs in the network. The total amount of IT resource remains the same for both scenarios.

In figure 23 we evaluate and compare the proposed algorithm against the non-energy-aware resource allocation (CRS) using a service plane approach as described in [13], and the NSP. NSP schedules resources in two stages. It uses least-free and constrained shortest path algorithms for IT and network scheduling respectively and iteratively searches for a resource-path pair until one is found. Figure 23a shows the power consumption over the 5-node for Scenarios I and II. For Scenario I, we observe a 3% improvement when we introduce the service plane, and a total of 7% improvement when using the energy-aware algorithm. Scenario II shows a 13% improvement when we introduce the service plane, and a total of 20% improvement when using the energy-aware algorithm. The NSF network topology (figure 23b) shows a 7% and 13% improvement for Scenarios I and II respectively. However in Scenario I, the NSP performs better than the CRS. This shows the unpredictability of non-energy aware algorithms on energy consumption. In this case, the nodes with higher PUE are closer to the peripherals of the network, and the requesting nodes. Thus are selected by the CRS, leading to an increased energy consumption.



(a) (b)

Figure 23: Evaluation of the Service-Oriented Energy Aware Algorithms against other algorithms: (a) 5-Node Topology (b) NSF Network

A5.3.3.1 Relevant publications

C. Abosi, G. Zervas, R. Nejabati, D. Simeonidou ," Energy-Aware Service Plane Co-Scheduling of a Novel Integrated Optical Network+IT Infrastructure", accepted for publication in ONDM 2011 proceedings, Feb 2011, Italy

5.3.4 JA Conclusion

This JA addressed the energy efficiency issue within two JAs. One JA focused on investigating a new energy aware routing protocols which can potentially make considerable effect on the reduction of the overall network energy consumption. The Other JA, proposed a novel IT+optical network resource scheduling and allocation solution for future Optical Internet where energy reduction problem is addressed on joint selection and joint allocation of both IT and network resources.

5.3.5 *References*

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5.4 JA6 Energy-Efficient Optical Network Design

Participants:

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Anna Tzanakaki (AIT)

5.4.1 Power Considerations towards a Sustainable Pan-European Network

Trying to follow a realistic approach in predicting the capacity required by the European Network of the Future, the BONE optical networking roadmap takes as input the access bandwidth as well as the services and applications available to the end users currently and their expected evolution in the next five and ten years on a per European country basis. The methodology of the roadmap can be found at [1] and was used to produce the traffic generated/terminated and supported by the various European countries under consideration. A percentage of this traffic is effectively fed and has to be supported by the Pan-European network. We assumed that 20% of the traffic that is generated within each country is fed and will be serviced by the Pan-European network. Based on this assumption a matrix was produced indicating the volume of traffic that will enter the Pan-European network. Each European country considered is represented by the corresponding capital as a source/destination node, thus forming the topology of the optical transport network under study. The source/destination information, in combination with the traffic data associated with it, is then converted into a conventional traffic matrix to be used for the Pan-European network dimensioning that will follow. This traffic matrix was obtained from the in-/out-bound traffic projections per source/destination site, assuming wavelength granularity of demands and uniform distribution of traffic to and from each node to all other nodes. Since the goal of the dimensioning study is to capture future trends rather than specify exact quantitative requirements, we consider only a subset of all potential European source/destination nodes of the core traffic. Specifically, the Pan-European reference network topology proposed by the COST 239 action was considered [2].

A WDM optical network architecture based on Wavelength Selective Switch (WSS) nodes without wavelength conversion is assumed, as it offers a scalable approach that can support the very high capacity requirements predicted for the near and more so the longer term future of the Pan-European network [1]. The switching technology assumed was Micro-Electrical Mechanical Systems (MEMS), while the input/output fibers of the OXC's are supporting a maximum of 40 wavelengths each. Two alternative OXC technology options are evaluated: one supporting a transparent optical network, where data remains in the optical domain while traversing the optical path without optoelectronic conversions at any intermediate node and one that supports the opaque network architecture, whereby the optical signal is converted into the electronic domain at every intermediate node along each lightpath. The opaque OXC architecture is identical to the transparent one with the only difference being the presence of transponders surrounding the optical switch fabrics. Regarding the fiber links a model comprising a sequence of alternating Single Mode Fiber and Dispersion Compensation Fiber spans, is assumed. Optical amplifiers based on Erbium Doped Fiber Amplifier technology are allocated at the end of each transmission span to compensate for the associated insertion loss. The energy consumption figures used for all active devices are typical consumption figures originating from datasheet and surveys. Additionally, we incorporated power dissipation due to cooling in the power estimation mode used and a 100% power overhead due to cooling is assumed [3].

The equipment energy consumption of the Pan-European network is calculated through a network dimensioning study that takes as input the predicted traffic demands produced by the BONE roadmap. The calculation of the dimensions of the European network is done for three different time periods and is performed by solving an instance of the network dimensioning problem referred to as "Brownfield Network Dimensioning". In this version of the problem, the geographical location of nodes is given together with the set of trenched physical links (ducts) connecting neighboring nodes. The output of the dimensioning process is the *optimal number of fibers per link* and *wavelengths per fiber* that need to be installed to serve the input traffic matrix at minimum cost, as well as the *optimal dimensions of optical switches* required to transparently route the input traffic. The adopted method employs a linear cost model incorporating fiber cost (fixed and length-dependent components), wavelength cost and size-dependent MEMS switch cost. In addition, all flow constraints are linear, thus admitting the formulation of the problem as a linear programming problem with integer solutions, similarly to the approach specified in [4]. Each source-destination demand (expressed at wavelength granularity) is served by k=3 candidate lightpaths according to the standard k-shortest path routing, whereby physical distance is used for assigning link weights during the routing process. For three input datasets of estimated aggregate traffic per site corresponding to three distinct time intervals, i.e., currently, in five years and in ten years from today, we generated traffic matrices assuming alternately 10Gb/s and 40Gb/s data rates per wavelength channel. Through this process, six input traffic matrices in total were obtained.

Using the dimensioning method and the input parameter set outlined above, we created instances of Integer Linear Programs and solved each instance to optimality. This enabled us to specify the minimum-cost dimensions of the European optical core network corresponding to the present, as well as to its projected future evolution.

Based on the dimensions of the European optical network derived as described above the calculation of its present and future energy footprint is performed as a post-processing step. The results clearly indicate that the transparent approach offers significant energy savings compared to its optoelectronic counterpart [5]. More specifically figure 24 illustrates the total network power consumption for the two OXC architectures under study, supporting two possible per channel data rates i.e. 10 Gb/s and 40 Gb/s. The results manifest that transparent optical networking technologies are expected to provide significant energy savings of the order of 35% to 55%. It was also shown that the migration towards higher data rates, i.e. from 10Gbit/s to 40Gbit/s, is assisting to improve the overall energy efficiency of the network. Figure 24 indicates that for both data rates the main power-dissipating elements are the transceivers followed by the EDFAs, while the least energy consuming elements are the optical switches.

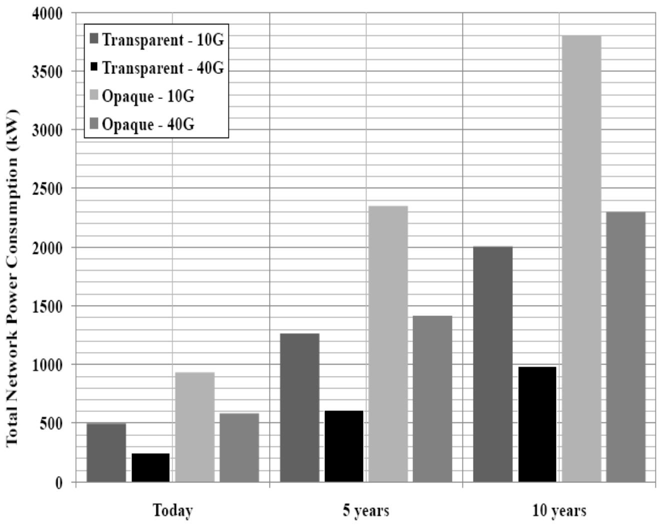

Figure 24: Total network power consumption for 10Gb/s to 40Gb/s per wavelength, for the transparent and opaque architecture

5.4.2 Energy-Efficient WDM Network Planning with Dedic. Prot. Res. in Sleep Mode

In wavelength division multiplexed (WDM) networks *redundant* resources are required to overcome service interruptions due to unpredictable failures [6]. Such resources are typically maintained active, independently of the network status, and thus consume power even in the absence of failures. However, the currently available strategies for energy-efficient planning [7]-[10] lack to address the issue of provisioning redundant resources and to account for their corresponding power consumption.

In this study, energy-efficient planning (i.e., static routing and wavelength assignment) of survivable WDM networks is considered for the first time. Energy-efficiency is achieved not only through a proper provisioning of the resources for working and protection lightpaths, but also through an innovative way of reducing the network power consumption of redundant resources. Since redundant resources are unused until a failure occurs, they can be set in *sleep mode*. Sleep mode represents a low-power, inactive state from which devices can be suddenly waken-up upon the occurrence of a triggering event.

In order to make sleep mode effective in survivable WDM networks it is necessary to ensure that working lightpaths are not supported by devices in sleep mode. Such issue requires a proper planning strategy. The problem of planning a WDM network with dedicated 1:1 path protection [6] and devices supporting sleep mode is considered in this study. For each connection request, a link-disjoint working and protection lightpaths need to be provisioned, in order to guarantee 100% single link failure survivability. The devices in links and nodes can be put in sleep mode only if they are used exclusively for protection purposes. With this rationale, good candidates for sleep mode are devices installed in the links (e.g., in-line optical amplifiers) and at nodes, if traversed only by protection lightpaths.

The planning problem is formalized as an integer linear programming (ILP) formulation [11], based on a general model for accounting the power consumption of the different operational modes of the devices. Such formulation is applied to an all-optical network with the aim to minimize the overall power consumption.

In this study the power consumption of various planning strategies is evaluated, namely: Minimum Power with Sleep mode (MP-S), Minimum Power (MP) and Minimum Cost (MC). The results are optimally found by running a commercially available ILP solver on the Cost 239 European network with 11 nodes and 52 unidirectional links using the formulations presented in [11].

Each link in the network supports 16 wavelengths. Given a fixed number of requested lightpaths, a set of lightpaths is generated by uniformly selecting the source and destination nodes. The sets of lightpaths are generated until the confidence interval of the optimal network planning results are less or equal to 6% for a confidence level of 90%.

A (sub)optimal solution for the proposed planning strategies is obtained considering three shortest paths for each node-pair. The parameters characterizing the power consumption are set according to [12] as follows: 150 W for the power drained by the electronic control at each node; 5.9 W for the power drained by transmitters and receivers; 1.757 W for power drained by the optical switch including wavelength conversion. It is assumed that each link has the same number of in-line power amplifiers and that 30 W accounts for their power consumption.

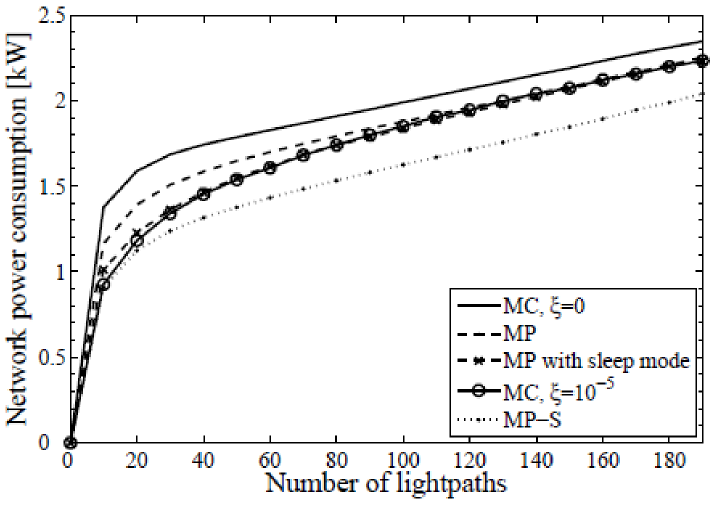

Figure 25: Network power consumption vs. number of lightpaths

Figure 25 shows the network power consumption as a function of the number of lightpaths to be provisioned in the network, for the three planning strategies mentioned above. For benchmarking purposes, a fourth strategy (MP with sleep mode) is also presented. In this latter strategy, routing is identical to MP planning, but sleep mode is enabled for redundant devices. Results for MC planning are obtained by setting $\xi=10^{-5}$ [12] (i.e., among the minimum cost solutions the one at minimum power is selected) and $\xi=0$ (i.e., any of the minimum cost planning solution is selected) as benchmarking. The figure shows that minimizing the power consumption (MP planning) is effective with respect to a network planning strategy at minimum cost (MC planning with $\xi=0$), leading to savings of up to 10%. Further reductions can be achieved by exploiting sleep mode. Indeed, exploiting sleep mode after provisioning lightpaths (i.e., MP with sleep mode) allows an additional 10% reduction of power at low loads only. If sleep mode is accounted in the planning (i.e., MP-S), savings of up to 15% at low loads and about 10% at high loads are achievable with respect to MP. This shows the significant savings that can be achieved by enabling sleep mode in redundant devices and the importance of accounting for sleep mode already during the network planning phase, rather than afterwards.

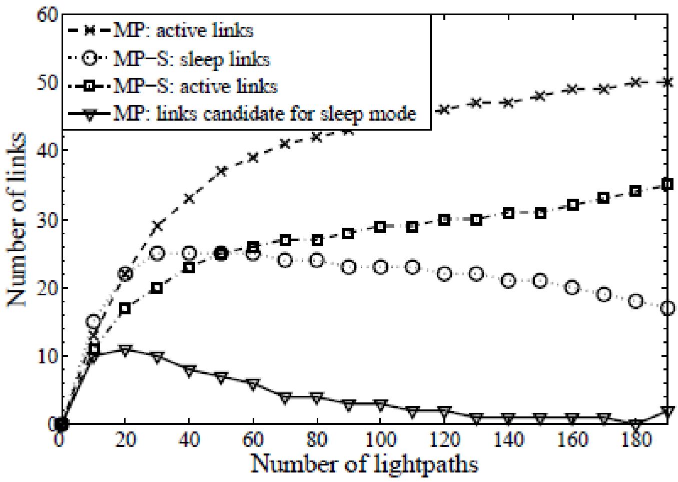

Figure 26: Total number of links in sleep and active mode vs. the number of lightpaths

The effectiveness of a network planning strategy that accounts for sleep mode is further analyzed by the results in figure 26. The figure shows the number of links whose devices are set in active and sleep mode (i.e., active or sleep links respectively) for MP-S and MP. In MP-S planning, a greater number of links is set in sleep mode, while in MP planning a large number of links is active and thus consuming more power than in MP-S. Results on the operational mode of the node devices are not reported, as only few (typically one or two) nodes are set to sleep mode in few experiments and for very low loads (i.e., 10 and 20 lightpaths), i.e., sleep mode of node devices is not exploited by the planning strategies.

5.4.3 JA Conclusion

The work performed in the framework of this JA is attempting to quantify the overall network power consumption of the future European network as well as identify and propose approaches, methodologies and algorithms that can be used to design energy efficient optical networks. Our results indicate that taking into consideration the energy consumption of the optical network during the design phase results in significant overall savings.

In order to provide a realistic basis for the calculation of the energy consumption of the Pan-European telecommunications network was examined as a test case for three different time periods: today, in the next five and ten years. In each time period the Pan-European network was dimensioned, using traffic predictions based on realistic data generated by the BONE optical networking roadmap. A wavelength routed WDM optical network based on either transparent or opaque node architectures was examined considering exclusively either 10Gbit/s or 40Gbit/s per channel data rates. The results manifest that transparent optical networking technologies are expected to provide significant energy savings of the order of 35% to 55%. It was also shown that the migration towards higher data rates, i.e. from 10Gbit/s to 40Gbit/s, is assisting to improve the overall energy efficiency of the network.

In addition, an energy-efficient planning strategy for survivable WDM networks was proposed, that exploits the sleep mode of devices supporting protection lightpaths. The network planning problem is defined through an integer linear programming formulation and is solved in a real case scenario. The optimal results show that significant power savings are achieved by properly routing the lightpaths so that a number of links carry only protection lightpaths. In this way, link devices, such as amplifiers, can be set in sleep mode, until a fault occurrence requires a prompt re-activation. Sleep mode of links permits to achieve power savings up to 25% when optimized during the planning phase. Sleep mode at nodes was also considered, but its effectiveness is restricted to very low loads. The achieved benefits are calling for support of sleep mode in optical devices.

The work reported in this JA has resulted in the following publications that were jointly produced among several BONE partners:

- Anna Tzanakaki, Kostas Katrinis, Tanya Politi, Alexandros Stavdas, Mario Pickavet, Peter Van Daele, Dimitra Simeonidou, Mike J. O'Mahony, Slavisa Aleksic, Lena Wosinska, Paolo Monti et al, "Power Considerations towards a Sustainable Pan-European Network", JWA061, OFC2011
- A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, P. Castoldi, A. Tzanakaki, "Energy-Efficient WDM Network Planning with Dedicated Protection Resources in Sleep Mode," in Proc. Globecom, December 2010.
- Anna Tzanakaki, Kostas Katrinis, Tanya Politi, Alexandros Stavdas, Mario Pickavet, Peter Van Daele, Dimitra Simeonidou, Mike J. O'Mahony, Slavisa Aleksic, Lena Wosinska, Paolo Monti et al, "Dimensioning the Future Pan-European Optical Network with Energy Efficiency Considerations, IEEE/OSA, Journal of Optical Communications and Networking, (submitted)

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