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Abstract:

This document is the second deliverable of the new WP21 on Green Optical Networks. The deliverable reports progress of the planned activities into this workpackage (running from January 2009 until December 2010) and the research results obtained so far (until October-November 2009).

At the time of submission of this Deliverable there are 15 partners involved in the 6 joint activities that have been proposed in this workpackage. Currently, 4 mobility exchanges and 6 joint papers have been reported under WP21.

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 second deliverable of the Topical Project on Green Optical Networks. This report contains the first results of joint activities in 2009.

At the time of submission of this Deliverable there are fifteen partners involved in the six joint activities that have been proposed in this WP:

JA1: Estimating the Footprint of ICT and Identifying the Main Contributors

JA2: Power Consumption and Supply of Individual Network Elements

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

JA4: Green Routing Protocols

JA5: Innovative Powering Strategies by Renewable Sources

JA6: Energy-Efficient Optical Network Design

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.

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. Introduction

This document is the second deliverable of the Topical Project on Green Optical Networks. This report contains the first results of joint activities in 2009 and 2010.

At the time of submission of this Deliverable there are 15 partners involved in the 6 joint activities that have been proposed in this workpackage.

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.

JA1: Estimating the Footprint of ICT and Identifying the Main Contributors

This joint activity reports on detailed studies to estimate the impact of ICT on the environment and predict how this will evolve in the future. From this survey important conclusions for the future of ICT industry and the internet are drawn, and challenges and research directives are deduced.

The future energy consumption of ICT worldwide has been estimated in this study. For 2007, the footprint of ICT (complete life cycle) is about 4% of the overall primary energy consumption. Without considerable measures, this percentage is expected to grow to about 8% in 2020.

The results of this JA 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.

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.

During this period, the JA is reporting power dissipation studies of network elements and particularly optical switches. The power consumed by large switches and routers has been increasing with the overall switching capacity, and has become one of the most stringent limits to the design of larger switches. The expected increase of line rates to 100 Gb/s will further stress these limits. Results indicate significant advantages of optical technologies with respect to electrical technologies when information is transmitted and/or switched at higher bit rates and over longer distances. Indeed, a strong driver for the successful deployment of fiber optics in telecommunication has been a reduced need for power supply, e.g. in submarine cables, or in WDM long haul links.

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. During this period, the JA reports on several correlated contributions stemming from the complementary expertise of involved partners. In order to underline the energy saving potential the networks can offer, PoliTo includes here a practical implementation of a distributed web-based system to manage the uptime of unused PCs in its campus. Several studies and surveys on the power consumption of commercial electronic/optical communication equipment have been performed by TUB, which also considered and evaluated the energy savings for different degrees of freedom in reconfiguring an IP network. PoliTo proposed several heuristics to help improve the power efficiency of networks: energy-aware backbone networks with traffic concentration on the minimal set of network resources on one side, and solution of the routing and wavelength assignment problem with energy-saving targets in wavelength routing WDM networks. Furthermore, IBBT faces the energy saving problem by using multilayer traffic engineering, including power-dependant metrics in algorithms and traffic variations. Currently, KTH and AIT are working together in the energy budget impact of protection networking resources. FUB analysed an European transport network by means of simulation, trying to turn off links carrying less traffic and accounting for signal regeneration costs in the analysis. Several complementary expertises have been identified to the moment; SSSUP is planning to use GMPLS in future research, which seems an opportunity to match the GMPLS support identified by IBBT work, or using heuristics proposed by PoliTo.

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 layer2 carrier grade Ethernet networks.

In the next period, the JA aims to investigate possible implementation of the proposed routing algorithms in GMPLS-based networks by means of proper extensions of the current protocols, in Mesh and interconnected-ring topologies and finally in networks with partly transparent optical nodes.

JA5: Innovative Powering Strategies by Renewable Sources

This joint activity concentrates on the possible advantages of using renewable energy sources for the powering of telecommunication networks. In this activity, the primary objective is not energy-efficiency, but limited carbon footprint. The variety of renewable energy sources (solar, wind, hydro, etc.) is investigated, and it is examined how the energy sources of today’s and tomorrow’s networks can be altered to lead to low footprint solutions.

JA6: Energy-Efficient Optical Network Design

This joint activity focuses on optical network design taking into consideration the energy-consumption as an additional constraint and aims at providing network solutions optimized against power dissipation. This energy-efficient planning approach is based on realistic equipment power consumption models.

More specifically the JA is focusing on detailed network planning and dimensioning taking into account traditional considerations relating to cost-efficiency and capacity availability while including energy-consumption as an additional constraint. The JA also aims to optimize jointly network performance with energy and cost efficiency and identify associated trade-offs

3. Participants

There are 15 partners collaborating in this work package.

Table **JA0.1** shows the list of participants involved.

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

Table JA0.1: Work package participants in the WP21 joint activities

4. Workpackage structure

No	Joint Activity Title	Responsible person	Participants	Deadline
1	Estimating the Footprint of ICT and Identifying the Main Contributors	Mario Pickavet (IBBT)	IBBT, GET	M24
2	Power Consumption and Supply of Individual Network Elements	Slavisa Aleksic (TUW)	TUW, BME, PoliTo, UNIMORE, UoP, UPCT, USWAN, FUB	M36
3	Energy Saving Potential by Selective Switch-off of Network Elements	Fabio Neri (PoliTo)	PoliTo, KTH, FUB, IBBT, TUB, GET, AIT, SSSUP	M36
4	Green Routing Protocols	Reza Nejabati (UEssex)	UEssex, GET, KTH, AIT, SSSUP	M36
5	Innovative Powering Strategies by Renewable Sources	Michel Morvan (GET)	GET, AIT, FUB	M36
6	Energy Efficient Optical Network Design	Anna Tzanakaki (AIT)	AIT, KTH, UoP, SSSUP	M36

Table JA0.2: Summary list of the planned joint activities

5. Planned Joint Activities and Research Results

5.1 JA1 Estimating the Footprint of ICT and Identifying the Main Contributors

Participants:

IBBT (Mario Pickavet - Mario.Pickavet@intec.ugent.be, Willem Vereecken - Willem.Vereecken@intec.ugent.be), GET (Bruno Fracasso - bruno.fracasso@telecom-bretagne.fr, Philippe Gravey - philippe.gravey@enst-bretagne.fr)

Responsible person:

Mario Pickavet (IBBT)

Description :

As Information and Communication Technology (ICT) is becoming more and more wide-spread and pervasive in our daily life, it is important to get a realistic overview of the worldwide impact of ICT on the environment in general and on energy and electricity needs in particular. This joint activity JA1 (2008-2009) reports on a detailed study to estimate this impact today and to predict how this will evolve in the future. From this survey important conclusions for the future of ICT industry and the internet will be drawn, and challenges and research directives will be deduced.

5.1.1 Introduction

ICT has a rather environmentally friendly image to the public community. This is largely correct: the worldwide communication via datacom and telecom networks has transformed society drastically and has opened opportunities to reduce the human impact on nature. Some typical examples are the rise of e-commerce, tele-working, tele- and video-conferencing, reducing the worldwide traveling of both people and goods and hence the consumption of petroleum and the emission of greenhouse gases. A quite different example is the use of environmental sensors. Through wireless sensor network technology, different parameters like temperature, sun light and humidity can be measured and exploited to optimize the energy management in buildings. This ICT revolution has only just begun, and will have an ever stronger impact in the years to come.

However, some dark clouds are looming at the horizon. The high penetration of ICT in our daily lives has as a drawback that the energy consumption of computers and network equipment is becoming a significant portion of the energy consumption worldwide and this portion is expected to grow steeply over the coming years. This energy consumption contains many obvious and less obvious facets. Of course electricity consumption of the ICT equipment during the operational lifetime is important. But also the complete manufacturing process to produce ICT equipment (with in many cases limited economical lifetimes) and the disposal process afterwards are having a large impact.

5.1.2 General Energy Statistics

To assess the environmental impact of ICT, a worldwide view on the energy production and consumption flows is essential. Detailed energy statistics and forecasts are collected by the U.S. Energy Information Administration [1]. Based on this, the estimated situation for 2007 is depicted in Fig. JA1.1.

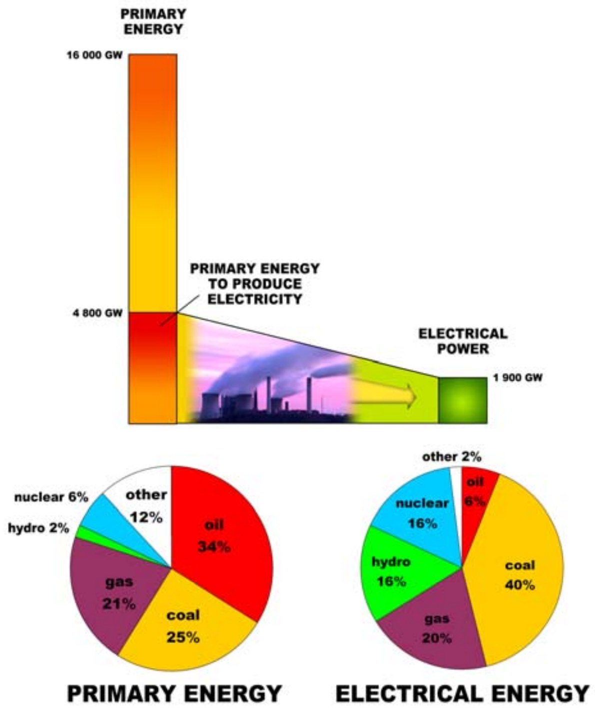

Fig JA1.1: Worldwide energy production and consumption in 2007 and share for electrical energy.

The primary energy consumption throughout the year is about 500 EJ (= 500×10^{18} J), this comes down to an average power throughout the year of 16000 GW. About 4800 GW or 30% of this primary energy is consumed to produce electrical energy in the power plants around the world. With an average yield of about 40% in power plants, this leads to about 1900 GW of electrical power. As shown in Fig. JA1.1, the major share of this power is produced by conventional thermal power plants, i.e. by burning fossil fuels (coal being the most important, but also gas and oil).

Note that the limited yield factor of power plants implies that 1 J of electrical energy corresponds (on average) with 2.5 J of primary energy. A similar multiplication factor applies also for the CO_2 emission. If we take into account the different energy sources (cf. pie diagrams in Fig. JA1.1), it can be calculated that on average 1 J of electrical energy causes the same CO_2 emission as 2.1 J of primary energy.

By examining the evolution of the energy figures during the last years and predictions for the years to come [1], an annual growth rate of 2% p.a. for the total primary energy and 3% p.a. for the electrical energy consumption can be expected. Due to the increasing scarcity and the steeply rising prices of fossil fuels, together with a growing pressure to reduce the emission of greenhouse gases, significant price augmentations for primary energy and electrical energy during the coming years will most probably be inevitable.

5.1.3 Energy for ICT: Current Situation

In contrast with the general energy statistics worldwide, where clear and comprehensive figures are carefully kept up to date, it is far more difficult to accurately estimate the share that is used for ICT purposes. Because it is crucial to get a good view on this in order to detect possible improvements, the authors have carried out an extensive survey to assess the major energy consumption factors in ICT.

A5.1.3.1 Electricity consumption of ICT equipment during use

The most obvious ICT effect is the electricity consumption of all kinds of ICT equipment during operational lifetime. A first important factor is of course the power consumption of devices during active mode. Some typical values are shown in Table JA1.1.

Equipment type	Power consumption during active mode (average load)
desktop PC with LCD display	100 W
desktop PC with CRT display	150 W
laptop PC	30 W
CRT TV	150 W (0.34 W per square inch)
LCD TV	190 W (0.29 W per square inch)
Plasma TV	330 W (0.34 W per square inch)
Gaming console	190 W
Volume server[1]	220 W
Mid-range server[2]	700 W
High-end server[2]	10000 W
Core routers and switches[2]	5 W per Gbit/s throughput
Access routers and switches	> 10 W per Gbit/s
Home gateway	7 W
GSM Base Station	700 W
WiMAX Base Station	400 W

Table JA1.1: ICT equipment and corresponding power consumption.

A second important factor is the number of devices in use worldwide. This can vary considerably, for instance the number of high-end servers worldwide is about 60 thousand, while there are about 30 million volume servers and about 1.5 billion TVs. Also the percentage of time in active mode has a large influence, ranging from being active 24 hours and 7 days a week for some servers to devices where the standby electricity consumption is even larger than the active electricity consumption (for instance for infrequently used audio installations).

[1] Infrastructure energy for cooling, UPS, etc. not included
[2] E.g. IP routers, SONET/SDH cross-connects and add-drop multiplexers, Ethernet switches

To estimate the total electricity consumption of ICT equipment during operational lifetime, the following five main categories were distinguished:

1. Data centers: including servers, storage devices, network equipment at data centers, but also cooling, backup power infrastructure like UPS systems, and so on.
2. PCs, i.e. both desktop and laptop PCs, including computer screens, network interfaces in PCs, etc.
3. Network equipment, including datacom and telecom networks, but excluding network equipment inside data centers or built-in in PCs.
4. TV sets, including video and DVD players.
5. Other ICT equipment, containing all ICT equipment not contained in the first 4 categories, such as audio equipment, telephone handsets, gaming consoles, printers, copiers and fax machines.

For the estimation of total power consumption in data centers worldwide, various sources can be found that are more or less in agreement. A recent and quite extensive study can be found in [2]. Based on these studies, a yearly average of about 26 GW can be expected for data centers worldwide in 2007. Remarkable in this figure is the large contribution of cooling equipment. Due to the miniaturization of servers, the heat dissipation per rack is increasing steeply, compelling for more sophisticated and more power consuming cooling solutions.

The estimation of PC power consumption is mainly based on the number of PCs used worldwide – which is close to 1 billion today – , the average power consumption of different desktops, laptops and computer screens when in active / standby / off mode and the average weekly ratios of these 3 modes for professional and residential users. After critical comparison of these results with previous estimations in literature, the 2007 estimation is about 28 GW.

Due to its distributed character and wide diversity in network equipment types (routers, switches, modems, line cards, etc.), a direct estimation of network equipment power consumption worldwide is notoriously difficult. However, based on many inventory surveys (e.g. [3]) in the past, together with annual power growth estimates and comparison with the power consumption of data centers and PCs in the same surveys, a reasonable estimation can be made, leading to a worldwide network equipment consumption of about 22 GW.

In the case of TVs, the estimation is mainly built upon the number of used TVs worldwide, the average power consumption during active/standby/off mode for different TV types (mainly CRT, LCD and plasma) and the average number of hours per week in each mode. After matching with previous surveys in some countries, we concluded that the total power consumption of TV sets worldwide is about 40 GW.

A lot of other ICT equipment types are not falling within the 4 categories mentioned above. For example the power consumption of audio installations worldwide is estimated to be slightly less than 50% of the requirements for TVs. Also office equipment like printers, copiers and fax machines represent considerable power consumption. As in many previous country-specific survey studies, we have combined all remaining ICT equipment types in a fifth category. Typical estimations here are in the same range as the contribution of TVs, i.e. about 40 GW.

The main results of this survey have been summarized in Fig. JA1.2. This leads to a total of about 156 GW, which is more than 8% of the global electricity consumption. Note that this corresponds to about 2.5% of the worldwide primary energy consumption. As a comparison, the contribution of aviation today represents about 2% of the worldwide primary energy consumption.

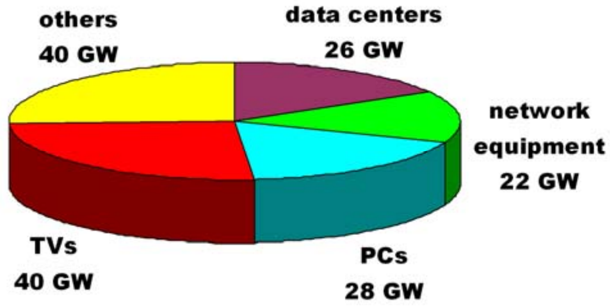

Fig. JA1.2: Electricity consumption of ICT equipment during operation worldwide (yearly average 2007).

A5.1.3.2 Energy consumption for manufacturing of ICT equipment

Electricity consumption during the use phase may be the most obvious energy demand of ICT equipment, it is definitely not the only one. A regular PC for instance requires considerable energy sources before it is plugged in for the first time: the production of PCs is a manufacturing process with high energy needs. Estimating these energy needs is a highly complex task, because it involves the modeling of the complete manufacturing process, from the extraction of the raw constituting materials, via the different steps to produce the building blocks and the transportation of all kinds of components between different geographical locations, to the final product: a PC ready to use. In [4] this modeling exercise has been carried out in detail, leading to an average of 1550 MJ of electrical energy and 4850 MJ of non-electrical primary energy sources to manufacture a typical PC configuration. Taking into account the average yield factor of 40 % for electricity production, 1550 MJ of electrical energy requires 3875 MJ of primary energy. Together with the non-electrical contribution, this leads to a total of about 8700 MJ per produced PC.

It is instructive to compare this figure with the primary energy needs of a PC during the use phase. If we assume an economical lifetime of 4 years, then the average PC consumption during the use phase is about 8800 MJ.[3] This means that the energy needs during the manufacturing phase are of the same order of magnitude as during the use phase! Of course, this conclusion depends on the type of equipment, especially on the energy intensity of the manufacturing process and on the expected economical lifetime. For example the economical lifetime of network equipment will in many cases be higher than for PCs. Taking all influencing factors into account, the complete life cycle of ICT equipment is probably responsible for about 4% of the worldwide primary energy consumption.

[3] The disposal phase (after the operational life of the PC) was not taken into account here, as the energy needs of this phase are typically much smaller than for the production and use phases. Note that this study concentrates on the energy needs of the involved processes. Other environmental impacts, such as consumption of rare materials, toxic chemicals, water supply for manufacturing, e-waste, etc. were not modeled in detail.

5.1.4 Energy for ICT: Future Trends

To judge where we are heading to, the absolute numbers of ICT energy use today are important, but even more crucial is to predict how these numbers will evolve in the next years. For the main categories of ICT equipment, it will be estimated how much the electricity consumption during use will change in the years after 2007. This evolution will be characterized by estimating the annual growth rate, as explained below.

For data centers, detailed recent studies [2] indicate that the overall power consumption of data centers worldwide is expected to grow by 12% p.a.. This considerable growth is mainly caused by the ever growing data volumes to be processed, stored and accessed, and the associated power for cooling.

The growth rate for PCs power consumption worldwide is expected to be somewhat lower: about 7.5% per year. This is mainly caused by the growing number of PCs that are used worldwide (growing by about 10% p.a.) and the ever rising data volumes to be processed by a PC. On the other hand, the gradual trends to replace CRT by LCD screens and to replace desktop by laptop PCs have a positive impact on the power consumption.

For network equipment, the power consumption growth rates are typically in the same range as for data centers: about 12% per year overall. Especially the growing wireless access infrastructure (for mobile phones, wireless computer access, etc.) and the quick rise of home networks are responsible for steeply growing power consumption rates.

For the other ICT equipment types, large differences in growth rates can be noticed. Worldwide power consumption of TVs is growing considerably (estimated growth rate of 9% p.a.), mainly due to the gradual replacement of CRT technology by (more power consuming) flat screens. On the other hand, worldwide power consumption of audio equipment is stagnating. On average, an annual growth rate of 5% p.a. is probably a reasonable estimate.

Based on these growth rates and the absolute power consumption values from section III, the electricity consumption in the coming years can be estimated. The results are shown in Fig. JA1.3.

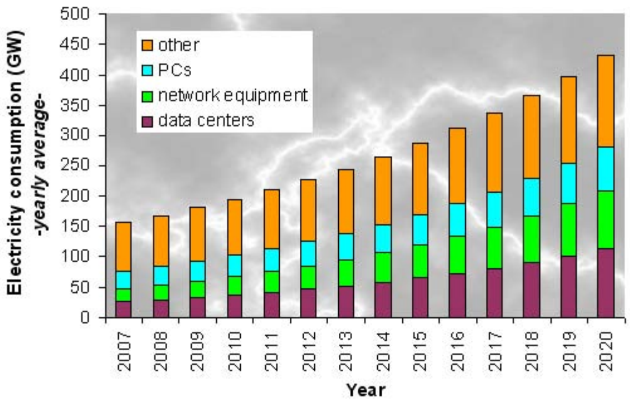

Fig. JA1.3: Electricity consumption forecasts for 2007-2020 of ICT equipment during use.

From this figure, a key conclusion can be drawn. The overall power consumption of ICT equipment is growing steadily, from 156 GW in 2007 to about 430 GW in 2020. Even if we assume a 3% electricity consumption growth of all other (non-ICT) equipment, this comes down to a relative contribution of ICT in electricity consumption from 8.2% in 2007 to more than 14% (i.e. 1/7) in 2020! Note that the manufacturing energy for ICT equipment is not even included in these figures.

5.1.5 Research Challenges

From these forecasts, it is clear that the pressure on power- efficiency for ICT will become more and more prominent in the coming years. The relative importance of power consumption in the total cost of ownership (TCO) of ICT infrastructure will grow significantly, and become a key cost factor. For ICT industrial players, it it crucial to anticipate to this trend by initiating research actions as soon as possible.

Today, power-efficiency is already a crucial research issue for wireless devices such as laptops, mobile phones, PDAs, sensors, etc. This attention is mainly caused by the direct consequences of power consumption on the battery autonomy of the device. In sharp contrast with this, the power optimization for wired devices has received little research attention so far. But this will change drastically in the coming years. Many power-efficiency measures are possible and research in this direction will be driven by economical motives, as soon as the awareness in the ICT sector of the large and quickly growing impact on electricity consumption will become prominent.

A5.1.5.1 Hardware of individual devices

One of the key measures is the power optimization of individual devices. Perhaps the most striking example here is the comparison of laptop and desktop PCs. The power consumption of a laptop PC is typically only a small fraction of a desktop PC, for basically the same functionality. This shows that there is clearly room for making desktop PCs much more energy-efficient, if there is a real driving force.

From Fig. JA1.2 and JA1.3 it is also clear that the ICT footprint on power consumption will not be dominated by one equipment type: data centers, PCs, network equipment and TVs are all representing a considerable share of the overall power consumption. Diverse measures will be needed to improve the overall situation drastically, ranging for instance from more power-efficient chip design for CPUs to better technologies for TV and computer screens.

A5.1.5.2 Software optimizations

Although software is only indirectly linked with power-efficiency, its impact can be considerable. A typical example here is the impact of a new version of operating system on the upgrade towards more power-consuming PCs. A power-friendly operating system would allow considerable savings on electricity consumption during the PC’s lifetime. Furthermore, it would allow longer economical lifetimes of PCs, reducing the manufacturing energy footprint. Another possible software optimization is more intelligent power management of computers and screens, adapting to the user behaviour. Also in server parks significant power savings can be realized, for instance through virtual server configurations, allowing to switch off most servers during night hours and only using the full capacity of servers during peak hours.

A5.1.5.3 New network paradigms

Whereas the previous measures concentrate typically on one type of equipment, it is crucial to consider also the big picture of various terminals all around the world interconnected via a common network infrastructure. New, clean-slate network paradigms could change the energy footprint of ICT drastically, leading to lower power consumption for both network infrastructure and terminal devices.

For instance, the so-called 'Thin Client' concept [5] could severely reduce power needs. The key idea here is to outsource most or all of the processing and storage tasks from a regular PC client to servers. This allows replacing the PC by a much smaller and simpler client machine (the Thin Client) that is communicating frequently with the servers via the network. This reduces the electricity consumption of the client machine (at the expense of more consumption in the network and on the servers) and moreover allows a much longer economical lifetime of the client machine, hence reducing manufacturing energy [6].

Another important initiative on the network level was taken by the IEEE Study Group on Energy-efficient Ethernet in 2006 [7]. The Study Group explores the realization of an Adaptive Link Rate, allowing to temporally reduce the bandwidth and hence also the power consumption of Ethernet links during quiet hours and to return quickly to full bandwidth when needed. A similar concept can be applied to ADSL access networks, or to keep PCs connected to the LAN while sleeping [8].

The power-efficiency of information transport also highly depends on the physical medium, with optical fibers being more efficient than copper and much more efficient than air interfaces (for wireless applications). New, clean-slate network architectures could drastically reduce the power consumption when taking this into consideration wherever possible.

A5.1.5.4 Policy supporting studies

Estimating the energy and environmental footprint of alternative ICT solutions is a key element to define clear future goals. This holds both from the viewpoint of an ICT equipment vendor, who wants to distinguish his product from the crowd by emphasizing the low power costs and green characteristics of the product, and from the viewpoint of a government or regulatory body, that wants to promote environmentally friendly products through financial stimulation, product labels (like the Energy Star label for computers [9]), etc.

However, as already pointed out in the previous sections, estimating the footprint accurately is in many cases a highly complex problem. Further and more extensive research is definitely needed in this area.

5.1.6 Case Study 1: Storage versus Transmission Energy Consumption

As explained in the previous section, architectural and organizational choices in future networks can have a large impact on power consumption. A typical example is the optimization of the content delivery process, where the choice can be made to concentrate all information on a central server that will be accessed by users from all around the world or rather to duplicate the (frequently asked) content on a number of mirror servers all around the world. The latter (distributed) architecture implies that, in case of new content versions, updates must be sent from the central server to the mirror servers. The two architectures are illustrated in Fig. JA1.4.

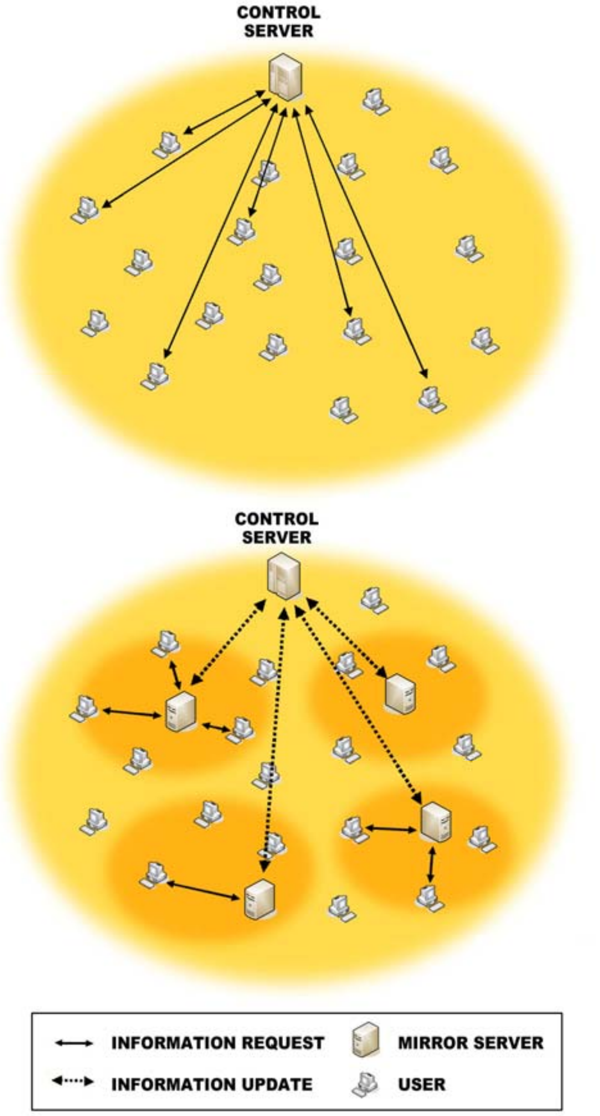

Fig. JA1. 4: Content delivery through a central server (top) or via distributed mirror servers (bottom).

A key advantage of the central architecture is the conceptual simplicity, without update synchronization, whereas the distributed architecture will typically lead to lower delivery delays.

But also in terms of power consumption, the two options can be quite different. The three main differentiating factors are:

- Content storage: the total energy to store a particular content grows as the content is duplicated on more mirror servers.
- Content updates: if mirror servers are used, then the content on all mirror servers should be updated every time a new version is released. This leads to higher transport energy needs.

- Content requests: if a user requests a particular content, this content will be delivered by the mirror server closest to the user. The energy related to the transport of content from the mirror server to the access network where the user belongs to will typically be lower if the content is spread over more mirror servers.

Based on the energy needs of the involved equipment, and by taking into account the relative share that is used for a particular content, the average power consumption for the three differentiating factors above can be estimated. The result will be more or less proportional to the size of the considered content. Moreover, the power consumption will depend on the content update frequency, the content request frequency and the number of used mirror servers. The results are depicted in Fig. JA1.5: the case of one server replica shows the central architecture, whereas the cases with more than one server replica correspond to distributed architectures.

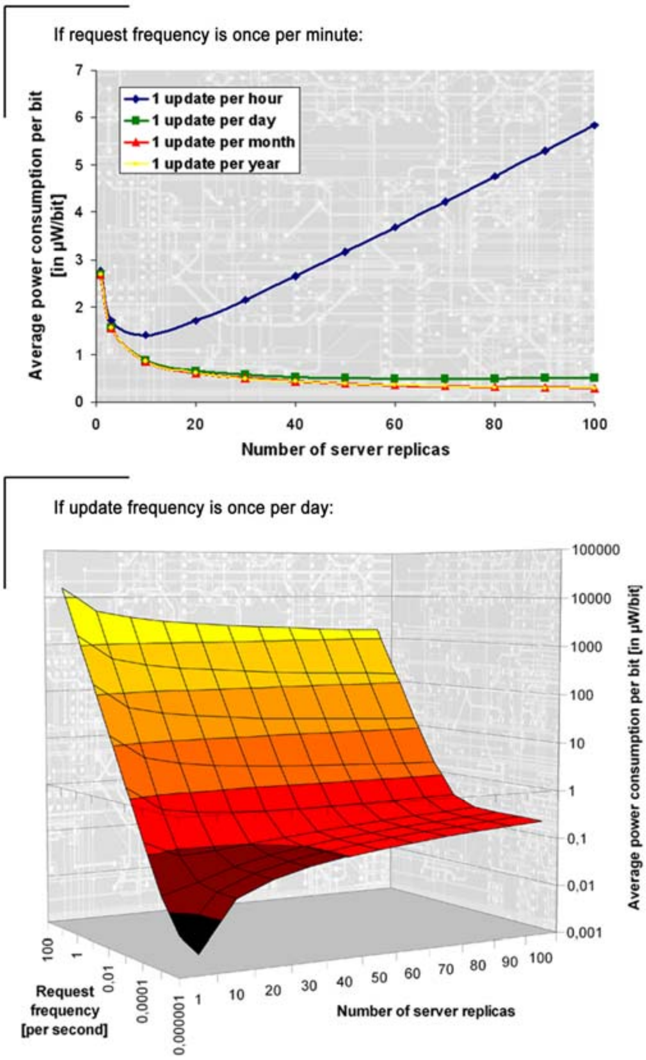

Fig.JA1. 5: Power consumption of content distribution and delivery for varying number of server replicas, depending on the request and update frequencies.

Fig. JA1.5a shows the case where the content is requested by some user once per minute (on average), for different update frequencies: once an hour, once a day, once a month or once a year. If the content needs updating every hour, it is clear that a large number of replicas should be avoided, since it causes excessive energy to transport the content updates. If the updating is less frequent (once a day or less), the power consumption is almost constant over a large range of the number of used servers (as soon as the number of servers is above 10). In this case, the update energy is rather limited: the dominating factor is the energy to transport the requested content to the user.

The typical situation of one update per day (cf. newspaper) is considered in detail in Fig. JA1.5b. From this figure, it is clear that the transport of requests has a large impact on the power consumption. For high values of the request frequency, it is important to have many replicas to minimize the request energy. For low values of the request frequency, the number of replicas must be low as the storage and update energy are then the dominating factors. For values in between (one request per 100 or 1000 seconds), an optimal trade-off value for the number of replicas can be noticed, where modest request energy is combined with modest storage and update energy.

5.1.7 Case Study 2: Energy Footprint of Home Networks

While present electricity consumption of the Telco networks is 2-3% of the overall consumption, with a large part devoted to access and mobile networks, the increasing number of services and devices in home networks have lead to a dramatic increase in power consumption due to personal multimedia use. This network segment being rather new (less than 5 years) and currently oriented towards performance and services, only very few studies have been performed to date on the corresponding energy consumption. We try to present here a few elements on that topic.

A5.1.7.1 Use mode

The diagrams in figure JA1.6 show the evolution of electricity consumption in European households (about 3000 kWh per year) during the last ten years [10]. The main idea to be noted is that the obvious reduction of energy consumption for different household equipment classes (like fridge, ovens, washers, lighting etc…) is totally cancelled by the increase in energy consumption of the multimedia segment (including PCs).

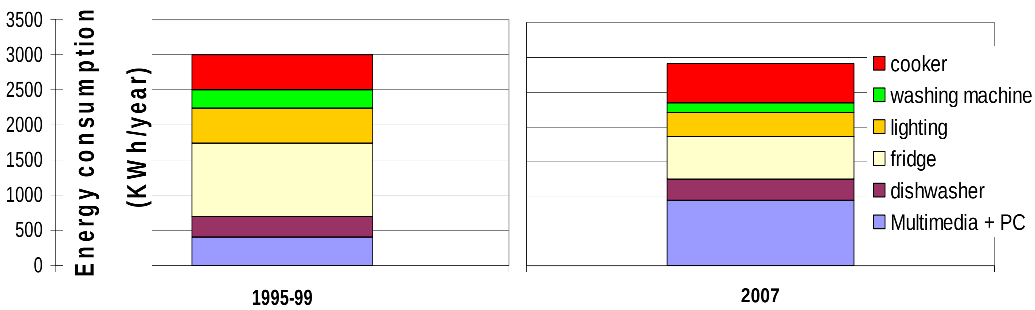

Fig JA1.6 Evolution of the average electricity consumption per European household within 10 years. From [10]

In December 2008, the European Commission re-insisted on the necessity to reduce the overall energy consumption in Europe by an amount of 20% within ten years. However, this goal might be difficult to reach if the home/multimedia ICT energy consumption still continues to grow by a rate of 8-10% per year, in a general framework that imposes a decrease of more than 2% per year.

An interesting study published by Deutsche Telekom [11] estimated the overall energy consumption of a German "new generation" multimedia broadband home, including the possible "stand-by" modes of the different devices. The estimated total energy per day was 2600 Wh, with about 40% originating from PC and TV screens (i.e. displays). Considering about 38 million households in Germany, this leads to an amount of 36 TWh per year, representing about ten times the average energy production of a power plant in Germany ! The corresponding carbon footprint must be calculated taking the electricity production mode into account. Table JA1.2 gives the correspondence for different electricity sources.

Electricity Production mode (1 kWh)	*Hydro*	*Nuclear*	*Wind*	*Photo-Voltaic*	*Natural Gas*	*Fuel*	*Coal*
CO_2 emissions per kWh (in grams)	4	6	3-22	60-150	880	890	980

Table JA1.2. Carbon footprint of different electricity production modes. Source : ACV-DRD study

At any country level, an average electricity/carbon rate must be calculated over the different power plant technologies. This gives 0,6 for Germany and 0,09 for France. Hence, an overall carbon footprint for the whole home network segment of the two countries can be estimated, as shown in table JA1.3. To explain this large difference, it is to be noted that 80% of the French electricity production originates from nuclear plants.

	Number of households (millions)	*Daily Overall Electricity consumption of home networks (GWh)*	*Average CO_2 emission (kg) per kWh produced*	*Estimated daily CO_2 emissions due to home networks (kT)*
Germany	38	99	0,6	59,4
France	28	73	0,09	6,6

Table JA1.3. Compared estimations of the overall CO2 emissions due to home networks in Germany and France.

The electricity consumption of home networks may further increase in the future as a consequence of three driving parameters : i) network pressure, ii) bit-rate and iii) displays.

The network pressure is the increased energy used by electronic devices by the unique fact of their being networked. In many cases, PCs and other multimedia devices are left on (when they would be turned off) just to make them accessible over the network. In the near future, we will see many more networked devices, many of which will practically require continuous network presence to provide acceptable functionality to end users. The extreme case is illustrated by sensor networks, for which energy consumption is a real issue.

A second major trend is the increasing bit-rate of network links, driven here by optical access network high-speed techniques (FTTX). Most present-day PCs have 10/100 Mbit/s Ethernet network interfaces, but 1 Gbit/s are increasingly common and 10 Gbit/s will be a standard to transmit such services as HDTV. Higher speeds require more power-consumptive interfaces, and the 10 Gbit/s type may consume 10 W at each link end. If this power level is maintained during times of moderate activity, there is a substantial source of increasing energy consumption.

The expected third source of home networks increased energy consumption is displays, or monitors. The transition from CRT-based to flat panel displays makes them much easier to deploy in homes, offices and public spaces. Some statistics on their energy consumption can be given here :

- Old CRT-based TVs have sizes (diagonal) between 19” and 42”, with an average value at 27”. The average use time per day is 5.5 h and the average energy consumption (over all sizes) per device is 144 kWh/year.
- LCD-based TVs have sizes between 22” and 46”, but some 60” (and more !) panels are being introduced commercially. The average size to date is 37”. The average use time per day is 6.5 h and the average energy consumption is 230 kWh/year., which is significantly higher than CRT-based devices. New lighting technologies such as LED are expected to decrease the energy consumption of LCD displays, provided that they can be massively diffused.
- Plasma-based TVs have sizes between 42” and 62”. The average use time per day is 6 h and the average energy consumption is 490 kWh/year.

Two additional criteria tend to show that future displays might generate more energy consumption in the future :

1. more flexible wired and wireless network interfaces make it easier to provide content for the displays, that could be installed almost everywhere,

2. The definition (and hence the complexity and consumption) of display panels will increase, as some companies are currently working on the next-generation HDTV. As an example, the Japanese national broadcasting company NHK is presently conducting the development of Super Hi-vision (SHV) [12], which might be commercially introduced in 2020., as a successor of HDTV. SHV has a resolution of 7680x4320 pixels (i.e. 16 more times than HDTV). Because of its very large bandwidth, new (and low energy consuming) techniques will have to be found to broadcast the channels, either wire- or wireless based.

A5.1.7.2 Production mode

Like other ICT segments, the estimation of the overall energy footprint of home networks is complicated and must take the overall life cycle of the addressed devices into account. In addition, it should be noted that it is rather difficult to obtain reliable figures in all the countries involved in the ICT market. In some case, the error margin reaches 30%. The figures concerning the device production largely comprise the CO_2 volume emitted related to the energy production in the country to be concerned. However, the emitted CO_2 per MWh rate varies widely amongst the different countries. From a recent study [13], the worldwide average figure is 450 kg/MWh, to reach 84 kg/MWh in France. Considering that most multimedia devices are produced in different Asian countries, it has been estimated that the production of a desktop computer with a CRT screen corresponds to 680 kg of CO_2, and jumps to 1280 kg for a LCD-panel screen. An estimation based on the weight ratio can be performed for lap-top computers, leading to the figure of **800 kg of CO_2** to produce the “average” PC unit. The same procedure applied to TV displays leads to 1390 kg for a 32” LCD panel., and only 100 kg for a 22” CRT display. This gives an overall estimation of 41,3

Mt of CO_2 for the TV sets contained in the 28 millions of French households, yielding 5,9 Mt/year if a 7 years lifetime is considered. This figure must be complemented by 8 million additional devices owned by professional companies and public institutions. The conclusion of that is the carbon footprint due to the production of TV sets (mainly in Asia) located in France is 6.8 Mt. At the same time, the electrical consumption corresponding to all these devices can be estimated to 1,38 Mt of CO_2, i.e. five times less. Again, this result is very typical to the French electricity production system, based on nuclear plants. In the EC, where the ratio is about 400 kg/MWh, the production and use carbon footprints (in Mt of CO_2) of TV sets are of the same order of magnitude. This conclusion is important and shows that minimising the energy consumption during the use time is useless if the production (and re-cycling) stages still generate high carbon emissions.

A5.1.7.3 What to do ?

There is a real public issue in reducing energy use within home networks, but relatively little activity to address these problems. Unlike core or access-networks which are operated by private companies, there seem to be a vacuum of responsibility for this topic, from the citizen to the state level. In addition to this, the potential increase of home network traffic (and hence its power consumption) will be driven by the increase of the internet traffic, with such services as intensive video transfer (P2P, Youtube), which, in a near future, might be proposed in high definition standards. It is simply not realistic to expect manufacturers, operators and service providers to put a brake on technological developments that are energy consuming. An alternative solution would be to develop end-user education on how to buy and efficiently use home network equipment.

5.1.8 Conclusion

The future energy consumption of ICT worldwide has been estimated in this study. For 2007, the footprint of ICT (complete life cycle) is about 4% of the overall primary energy consumption. Without considerable measures, this percentage is expected to grow to about 8% in 2020.

From these figures, together with increased scarcity of energy sources and the likely price augmentations for electricity in the coming years, it is clear to the authors that power-efficiency of ICT equipment will become crucial in the near future. This will have an impact on regulatory measures, customer behaviour, the worldwide internet and the complete ICT industry. Large research efforts to increase power-efficiency will be needed to support and prepare this turn without jeopardizing the technological advances in ICT. Some possible research directives are proposed in this joint activity, going from hardware and software optimizations to new network paradigms that could fundamentally change the way the internet works and consumes energy.

5.1.9 *References*

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5.2 JA2 Power Consumption and Supply of Individual Network Elements

Participants:

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Responsible person:

Slavisa Aleksic (TUWien)

Description:

Power dissipation is a very important task when planning and designing network elements for the future Internet. On the one hand, it is expected that switches and routers within the core area will need to provide a very high capacity of hundreds of Terabits or even several Petabits in the near future. Besides the high capacity they also need to be highly reliable. The power consumed by large switches and routers has been increasing with the overall switching capacity, and has become one of the most stringent limits to the design of larger switches. The expected increase of line rates to 100 Gb/s will further stress these limits. Beyond monitoring the scaling trends of current commercial switching devices, it is therefore important to identify switching architectures and protocols that minimize power consumption. A significant advantage of optical technologies with respect to electrical technologies is better scaling of power consumption when information is transmitted and/or switched at higher bit rates and over longer distances. Indeed, a strong driver for the successful deployment of fiber optics in telecommunication has been a reduced need for power supply, e.g. in submarine cables, or in WDM long haul links.

On the other hand, in the access area, the current growth of both the total number of users and the average bandwidth per user set new requirements on implementation and maintaining of such highly heterogeneous networks with a high number of network termination points. Thus, the increased capacity and introduction of new technologies will open new questions and problems related to power consumption and supply as well as protection.

Concerning power consumption, some fundamental aspects regarding access networks, where the most expensive investments will be carried out in next years, have to be addressed. Optical fiber to the home/building is a well accepted solution for high density inhabitant locations. In the opposite case, the use of copper (VDSL) and radio is still under exam, especially for rural regions. These choices should be analyzed also from the energy consumption point of view since xDSL and radio solutions have higher power consumption with respect to the technologies based on optical fibers.

5.2.1 Contribution UoP:

Power consumption in switch architectures has always been an area of major research since they may affect the OPEX of a specific network scenario and hence would be detrimental for the technology choice of an operator. In that sense the interplay between the networking scenario the switch architecture and the switch fabric technology is essential when discussing about the power consumption of a switching subsystems. For example when discussing optical packet switching scenarios one has to take under consideration the fast switching fabrics, In this section we discuss this interplay with respect to the overall power consumption of system that comprises a number of fibres and wavelengths.

A5.2.1.1 Considered switching devices

As far as the switching fabrics are concerned there are a number of options that are commercially available, however three are the most promising ones: Micro-Electro-Mechanical Systems (MEMS), semiconductor optical amplifiers (SOAs) and transponders combined with Arrayed Waveguide Gratings (AWGs). These are indicative technologies for low loss, low crosstalk switching with switching times of msec/nsec, indicating the network scenario that these technologies might be applicable to. As far as the wavelength converters are concerned we assume that only O-E-O transponders are readily available. It is noted that the O-E-O converters (transponders) act as 3R regenerators to the physical layer, and therefore cascadeability is not an issue. Specifically for the λ-S-λ switch a λ module is required for the purpose of switching that is assumed to be constructed by transponders with AWGs. In order to measure the power consumption of the above architectures we use the methodology developed in [1] extended to cover for all possible architectures etc. Assuming a line rate of 10 Gb/s, the power consumption of the individual elements was:

- SOA-gates: 3W;
- tunable transponders: 11W;
- fixed transponders: 7W.
- MEM switches: 35W for 32 port- and 80W for 64 port- devices;
- IP routers: 237 W/port.

A5.2.1.2 Switch architectures

Here we compare some of the most promising architectures and components with respect to their performance and power consumption. We base our results on previous work related to the power consumption of specific components [1]. Although large integrated platforms are technologically feasible, single stage switches have long been abolished as architectural solutions for high port count switches. Large crossbar switches are not the most efficient architecture beyond a certain port count. Hence three-stage architectures have been proposed and studied and in this work we focus on two: the three-stage Clos and the λ-S-λ architectures. In [1] it was widely discussed that the second architecture is modular and can support multicasting.

We assume that the switch has N input fibres and M wavelengths per fibre and a channel rate of 10 Gbps. For the Clos architecture to be strictly non blocking we assume that in the first stage each of the N fibres is connected to a $M\times(2M\text{-}1)$ switch, the second stage consists of $2M\text{-}1$ $N\times N$ switches and the output stage consists of N $(2M\text{-}1)\times M$ switches, each connected to an output fibre. The λ-S-λ architecture, as discussed in [1], requires MN^2 switches (on-off gates). It is assumed that wavelength conversion is assumed for all the switching nodes independently of the networking scenario.

In Fig. JA2.1 we have calculated the power consumption of each node with respect to the number of wavelengths per fibre for *N*=64. Evidently the network technology dictates the switch fabric that is best suited assuming that all the other functionalities will be accounted for as well. For example if we assume an OTN network for example MEMS switches with 'slow' reconfiguration time are sufficient. For OBS and OPS switches 'fast' switching elements must be deployed. If slotted/synchronous OPS/OBS scenarios are assumed, quickly reconfigurable strictly non blocking switches are required (Clos) otherwise a λ-S-λ architecture can be assumed. Furthermore for the OPS scenario a transponder per wavelengths is assumed in each node for processing the header. For the CANON scenario slotted frames are utilized for the intracluster traffic and the re-arrangably nonblocking modular λ-S-λ architecture can be utilized as the MN. These results will be combined with physical layer evaluations and network wide evaluations as well.

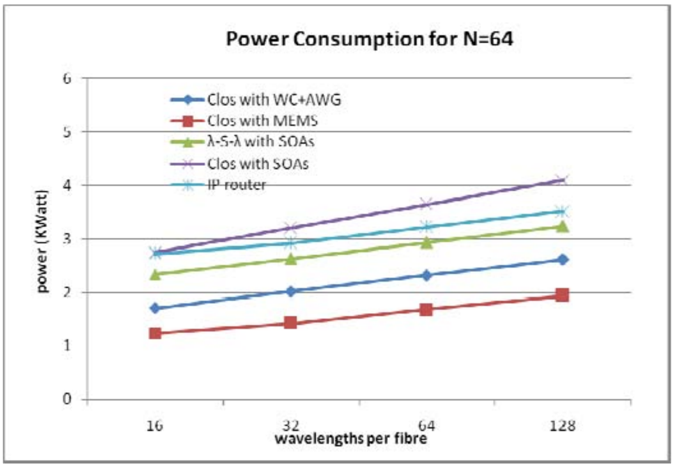

Fig. JA2.1: Power consumption of the different architectures combined with different switching technologies. (The three-stage Clos architecture and the λ-S-λ architecture)

5.2.2 Contribution PoliTo:

A5.2.2.1 Power Consumption of Current Commercial Switching Devices

In this research work, PoliTo faces three main fronts: i) assessing the power consumed by electronic switching devices which are employed in the core network, ii) proposing new optical architectures for high-end switches and routers and iii) estimating and optimizing their power consumption. The long-term aim is to compare optical and electronic devices in order to identify their power efficiency trends and to try to bring evidence to the advantages of optical technologies in terms of power consumption. Power consumption data of electronic and optical components currently available on the market are taken from the power supply declared in their technical data sheets.

Today, the switching devices utilized in the backbone segment of the network are mainly core routers. Core routers are required to handle an aggregate bandwidth ranging from few Gbps up to several tens of Tbps. In order to understand the power trends depending on both the aggregated capacity and time, power consumption of different generations of core routers was assessed. The evolution of power requirements was performed interpolating the data collected from the technical data sheets of commercial equipment. Fig. JA2.2 shows the power supply needed by router families of major router vendors. This analysis shows that power consumption figures are rather consistent across different vendors, and that the power consumption scales almost linearly with their total aggregate bandwidth. PoliTo used the Energy Scaling Index (ESI) as a metric to compare the efficiency of switching devices; the ESI corresponds to the switched aggregate bit rate offered for each Watt of energy budget. Fig. JA2.3 shows the ESI values for several classes of network devices, from which switches and routers are the most energy-efficient devices.

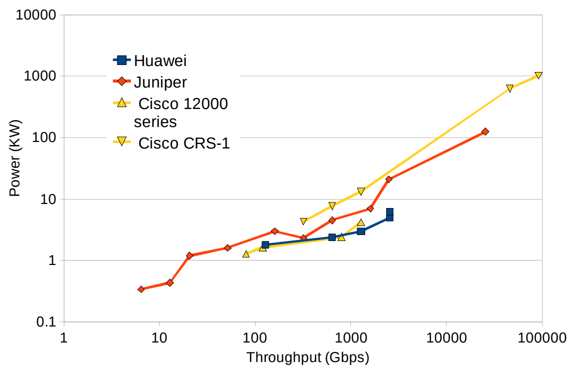

Fig. JA2.2: Router power consumption trend related to their aggregated capacity

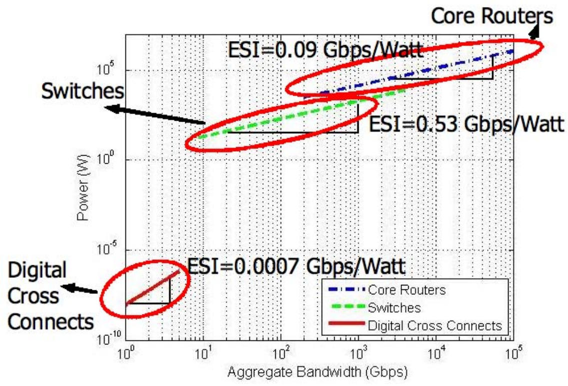

Fig. JA2.3: Comparative Energy Scaling Index (ESI) for different electronic network switching devices

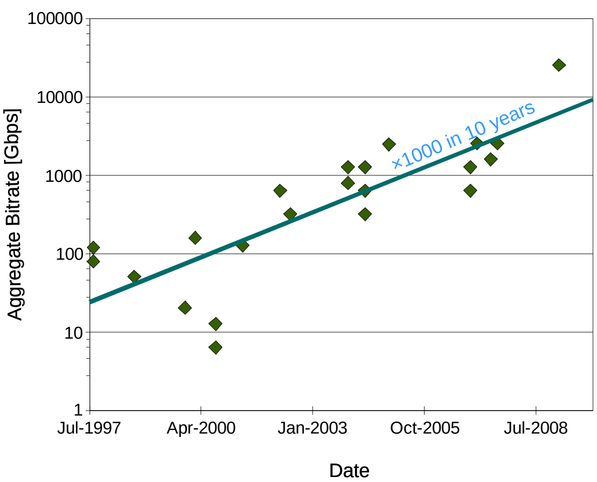

Fig. JA2.4: Router capacity evolution with time

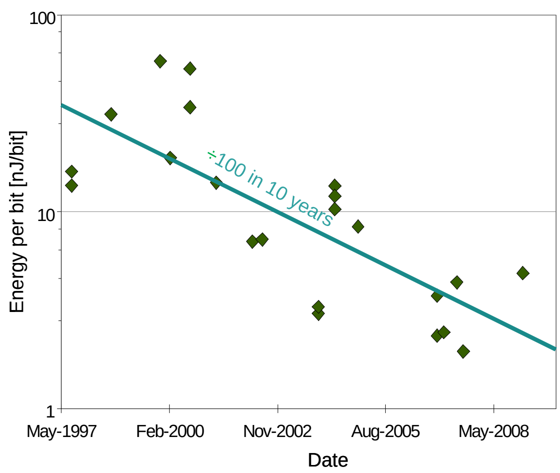

Fig. JA2.5: Evolution of the Energy Scaling Index (ESI) with time

It is also interesting to study the time evolution of the ESI. Fig. JA2.4 shows the aggregate capacity of top-performance core routers as a function of the date of their first appearance on the market. Approximately a ×1000 max capacity increase is observed over a 10 years time span. The ESI (measured in nJ/bit) for different routers as a function of time is instead shown in Fig. JA2.5. We observe that technological improvements (in electronic technologies) reduce the amount of energy needed to switch one unit of information, but this reduction over the same time frame of Fig. JA2.4 is only be a factor 100.

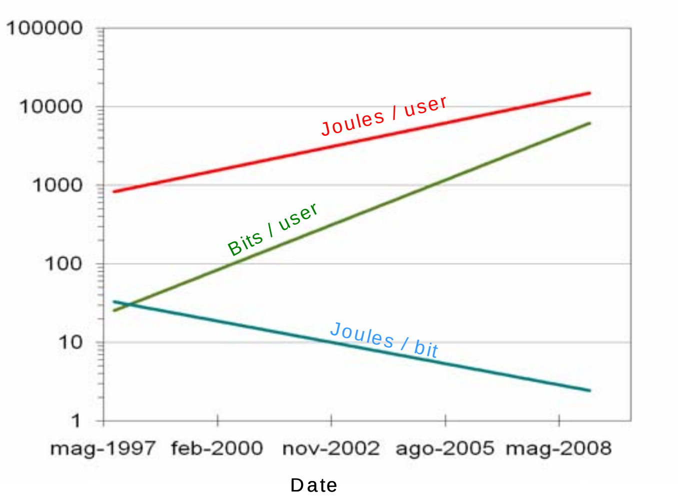

Fig. JA2.6: Evolution with time of the amount of energy needed to switch the network traffic

If we take the aggregate capacity of large routers as a good indication of the user traffic requirements, we could claim that the amount of energy needed to switch user information in the Internet (J/user) has been increasing approximately 10 times in the last 10 years (see Fig. JA2.6). More conservatively, we can claim that technological advancements of electronics have not been capable of fully compensating the growth of traffic in terms of power consumption. If this trend is maintained, new disruptive approaches to switching and networking need to be taken.

A5.2.2.2 Optical Switching Fabrics

Because of the unsustainable growth of power requirements for core routers and thanks to the breakthroughs made in integrating photonic devices, optics is gaining interest to build switching fabrics able to carry high information densities and to interconnect large linecard counts.

Optical fibers are already used to interconnect line cards, for example belonging to different racks or pieces of equipment, but their use in implementing forwarding back planes is not widespread. Optical interconnects help reducing routers' power requirements since their performance are at a first approximation independent from the bit rate, and can cover larger distances than their electronic equivalents (i.e. by reducing the number of regenerators required along the signal path).

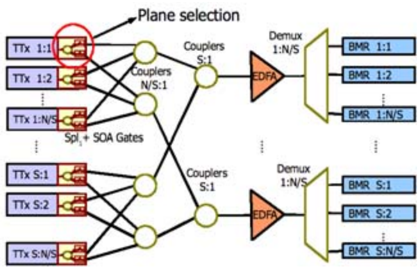

Fig. JA2.7: Multiplane Couple-Amplify-Demultiplex (MCAD) architecture

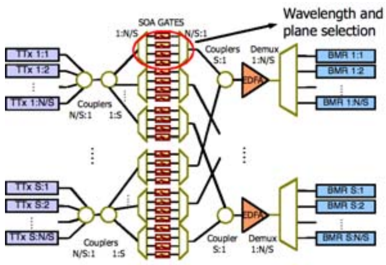

Fig. JA2.8: Wavelength SelectiVe (WSV) architecture

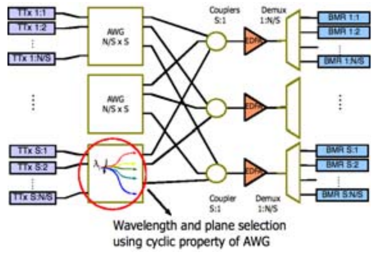

Fig. JA2.9: Wavelength Routing Space (WRS) architecture

PoliTO proposed and studied several optical architectures for interconnecting linecards inside large packet switches, based on the well known tunable-transmitter fixed-receiver paradigm (see Fig. JA2.7, Fig. JA2.8, Fig. JA2.9). These architectures, called MCAD, WSV and WRS, were formerly studied in [2]. Switching is performed at the input linecards exploiting both the wavelength and the space dimension in order to reach the output destination. MCAD uses wavelength tunability (N/S wavelengths, with N destination ports over S switching planes) and space switching by means of semiconductor optical amplifiers (SOAs); WSV uses wavelength tunability and selection using SOAs; and WRS uses full wavelength tunability (N wavelengths) exploiting the AWG cyclic routing property. More details in [2].

The physical limitations to the scalability of these architectures is given by the optical noise accumulation through the fabric, caused by the nominal noise aggregation from all transmitters, being coupled on the common optical media. The feasibility of these fabrics was modelled in order to configure them so as to achieve of the maximum aggregate capacity. Up to several Tbps were shown to be possible. Assuming low noise figures for tunable lasers, the WRS architecture scales best both in aggregate bandwidth and in power efficiency (Watts/bit); the main reason for this is that WRS architecture is mostly passive from the earliest switching stages (AWGs, couplers), introducing less noise (despite it accumulates noise in higher proportion respect to MCAD and WSV) [3],[4].

A5.2.2.3 Power Consumption of Optical Switching Fabrics

Based on these architectures and their construction rules to optimise scalability, the power consumption of the considered optical interconnections was computed starting from individual optical components' consumption, which was modelled as a function of the linecard's bit rate for each component. A reference block model scheme for this analysis is shown in Fig.JA2.10 ; all the components contributing to power consumption are depicted in a generic transmission system for a switching fabric.

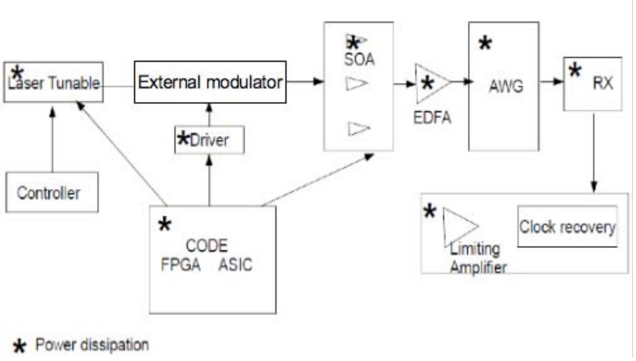

Fig.JA2.10. Typical component scheme in an optical switching fabric

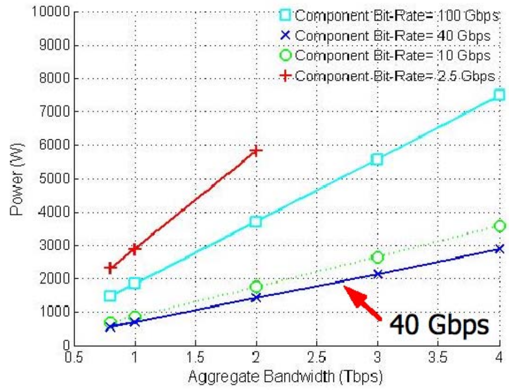

Fig. JA2.11. Example of power consumption of MCAD architecture.

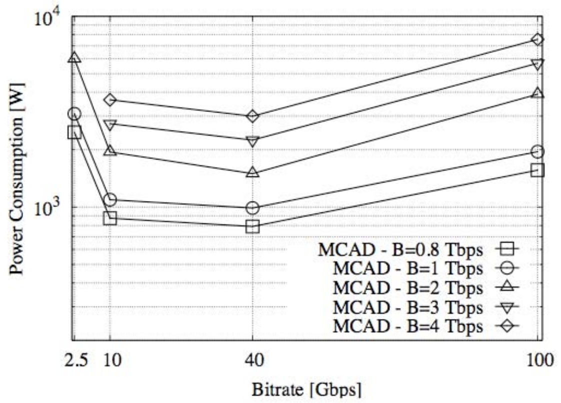

Fig. JA2.12. Power versus line-card bit-rate for the MCAD architecture.

The behaviour of the power consumption strongly depends on the bit rate, and therefore on the transmission technology used. Indeed, technologies for low bit rates (e.g., 2.5 Gb/s) can be now considered consolidated and almost obsolete, whereas for the highest bitrates (such as 100 Gb/s) technologies are not mature yet. As results show in Fig. JA2.11 and Fig. JA2.12, the minimum power consumption occurs when using intermediate available and mature technologies. Indeed, they indicate that the optical architectures operating with interfaces at 40 Gbps are the less power consuming than higher or lower bit rates.

As a further step, PoliTo compared the power consumption trends of the considered optical fabrics with the consumption attributed to the electronic switch fabric cards of core routers (in particular, the Cisco CRS-1 and its switching fabric, which is reported to consume 15% of the total router power). As plotted in Fig. JA2.13, the outcome was quite favourable to the optical solutions; indeed, optical switching fabrics consume less power and their trend is more power-efficient since their power/bandwidth ratio is lower than their electronic counterpart.

The individual contribution of each component to the total power consumption of the proposed optical fabric was analysed. The results show that the lasers have the highest power consumption contribution.

A5.2.2.4 Power-Efficient Variations of the Optical Switching Fabrics Architectures

Thus, in order to reduce the impact of transmitters on the total power consumption, PoliTo studied possible variations of to the original architectures. The most promising solution was to reduce the number of tunable lasers employing a unique source of optical CW signals which is constituted by an array of lasers instead of one laser per line card; the modification to the architectures is depicted in Fig. JA2.14. Exploiting the distribution stage, optical signals are distributed to line cards, where they are switched and modulated.

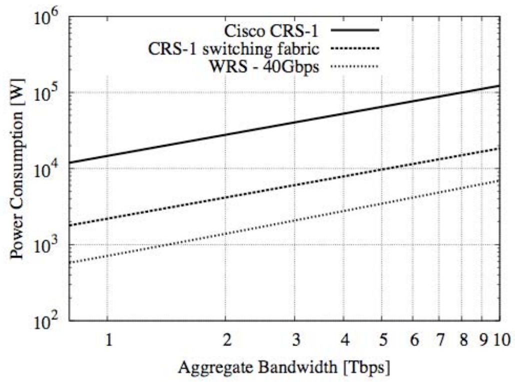

Fig. JA2.13. Comparison between Cisco CRS-1 Router and optical WRS fabric.

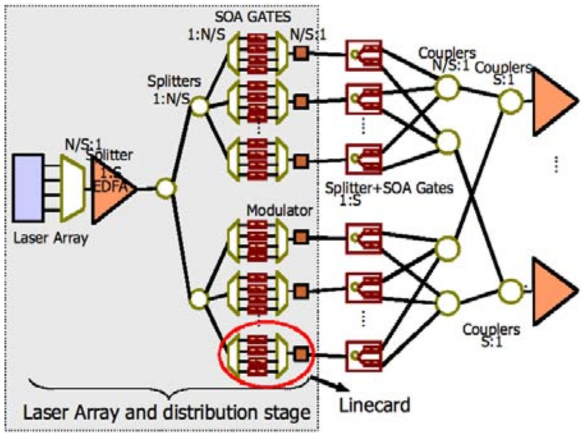

Fig. JA2.14. Proposed laser array technique to reduce overall power consumption (i.e. for MCAD architecture).

The total number of lasers is then reduced and the total power consumption is decreased. Although the strategy slightly reduces the overall switch scalability, it helps reducing the power consumption by at most 10% for MCAD and WSV architectures; for WRS the laser array technique is not convenient since the number of lasers required is not reduced considerably and its aggregate bandwidth scalability is reduced.

As a general result, we can claim that optical technologies are more energy-efficient and better scaling in terms of energy/bit than the electronic ones. Results obtained are based on the components commercially available today on the market and they should be considered as a rough estimate, since some power optimisation is still possible. Note that, this gain is expected to be higher moving from architectures based on discrete components (as considered up to now) to integrated designs and properly engineered implementations.

5.2.3 Contribution UNIMORE:

The current focus of UNIMORE's activities is on the following issues:

- power consumption comparison between electronic vs. optics;

- MEMS vs. SOA in optics, and

- single stage vs. multistage in optics with MEMS or SOA.

Currently, UNIMORE has some preliminary results that will be reported in the next deliverable. UNIMORE also intends to do some integration on the above mentioned topics.

5.2.4 Contribution TUW:

Within the scope of this JA, TUW concentrated on estimation of power consumption of different types of high-capacity nodes for use in the core and the metropolitan area networks. Fig. JA2.15 shows power consumption of electronic packet-switched routers currently available on the market for capacities up to 100 Tbit/s. The largest multishelf configuration of the Cisco CRS-1 router having a total capacity of 92 Tbit/s and requiring 80 racks to carry the networking equipment would consume about 1 MW of power. Figure JA2.15 shows additional examples of current high-performance routers, namely Black Diamond 20808 from Extreme Networks and Juniper's M320 and T-series as well as several implementations of all-optical and hybrid (electronic/optical) packet routers that have been reported very recently [6]. It is evident that the optical routers consume lower power than the electronic ones with the same total capacity, but they do not comprise all the functions that are usually implemented in electronic high-performance routers.

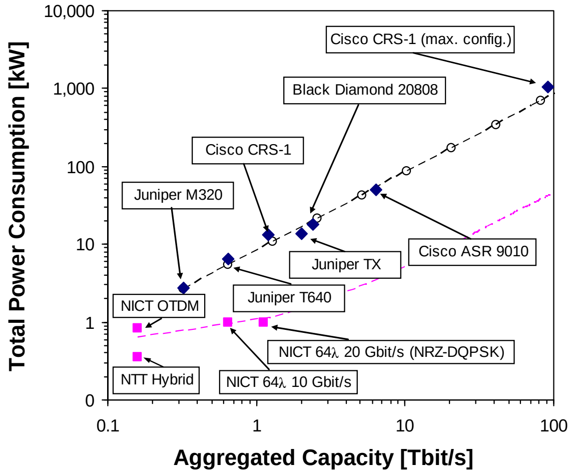

Fig. JA2.15: Examples of current high-performance electronic IP routers and some recent demonstration of high-speed optical packet routers [7].

We estimated the total power consumption of four core node architectures including examples for possible realizations of high-capacity network nodes using electronic and optical technologies as well as circuit and packet switching. Fig. JA2.16 shows the results for electronic core node architectures [8]. It is evident that the power consumption increases with increasing aggregated switching capacity. For example, state-of-the-art packet-switched electronic routers with capacities of approx. 1 Tbit/s consume about 8 - 11 kW. The total power consumption exceeds 900 kW when we scale electronic packet routers to capacities of 100 Tbit/s and beyond. Moreover, footprint of such high-capacity routers increases too, and thus, a 100 Tbit/s router requires more than 80 racks to house the equipment. If we scale packet routers to 1 Pbit/s, than the total power consumption approaches 9 MW. Such large power consumption and high number of line cards would raise requirements on power supply, room cooling, and interconnection infrastructure that today and in near future hardly can be met. The most power consuming part is the subsystem for data processing and packet forwarding that consumes more than half of the total power supplied.

One could try to reduce the large complexity and the huge buffer size of electronic packet routers by transmitting data through core nodes in a rather circuit-switched manner. Thus, smaller buffers would be required and paths through the cross-point switch could be set for longer time periods so that data processing within line cards could also be extremely simplified. Thus, no high-performance traffic processors would be needed. Additionally, the structure of switching devices would be simpler too and instead of complex and power-hungry packet processing, routing, and switching elements, large cross-point devices can be used. Together savings in total power consumption of up to 70% could thereby be achieved. However, the reduction of processing complexity, and thus, the lower power consumption comes at a certain cost: network edge node's tasks become more complex and the utilization #of available network resources likely more inefficient if not planned well in ahead. The estimated power consumption of such a 100 Tbit/s circuit-switched electronic core node is approximately 300 kW, which seems practically feasible, but a 1 Pbit/s circuit-switched node would still consume about 3 MW. According to the ITRS predictions, both size and power consumption of future high-capacity electronic routers should significantly shrink. Applying that, we can expect that an electronic packet-switched 100 Tbit/s node would consume no more than 45 kW, a circuit-switched node of same capacity about 26 kW, a packet-switched 1 Pbit/s router about 440 kW, and a corresponding circuit-switched one approximately 250 kW. That is, if the predictions become reality, then even packet routers with capacities of 1 Pbit/s could be realized using electronics and current approaches.

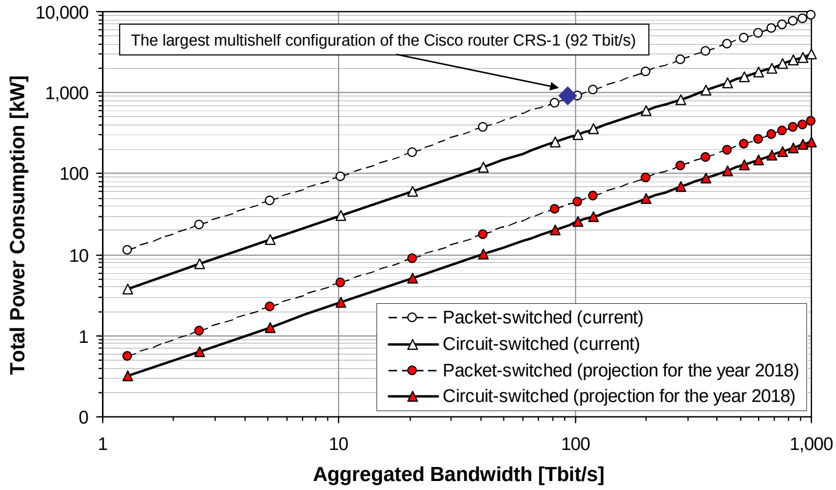

Fig. JA2.15: Total power consumption of electronic packet- and circuit-switched nodes.

The estimated power consumption of the two optical core node variants is shown in Fig. JA2.16. One can observe only slight differences in power consumption between the two realizations using 400-kbit and 40-Mbit FDL buffers; however the footprint of the 40-Mbit buffers option would be much larger. We assumed all-optical wavelength converters at the fabric inputs and 3R regeneration of the optical signal within the switching fabrics of an optical packet switch. The estimated power consumption of a 100 Tbit/s optical router using SOA-based switching and signal processing structures and 400 kbit optical buffering per port is slightly less than 68 kW, and for 1 Pbit/s about 784 kW. When using 40-Mbit buffers based on fiber delay lines (FDLs), the consumption increases slightly to 69 kW and to 794 kW for 100 Tbit/s and 1 Pbit/s, respectively. Due to the fact that the required length of a 40-Mbit optical buffer at 40 Gbit/s is about 200 km, the required total length of FDLs in a 100 Tbit/s optical router is 500,000 km. The main limiting factor for packet-switched optical routers is thus not their power consumption but the physical size of optical buffers.

When taking a look at the results regarding the high-capacity optical circuit-switched core nodes, it can be concluded that they would consume the lowest power and would also occupy the lowest area in the premises of network providers. A 100 Tbit/s node without wavelength conversion would consume slightly more than 2 kW and that with 1 Pbit/s aggregated capacity no more than 21 kW. However, as with electronic circuit switching, the reduction in power consumption comes at the cost of more complex edge node tasks and potentially less efficient bandwidth utilization. When employing all-optical wavelength conversion for contention resolution, the power consumption increases noticeably.

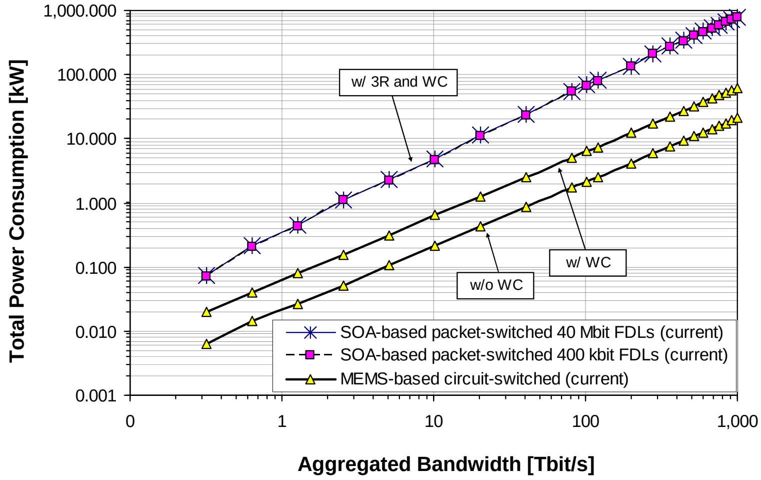

Fig. JA2.16: Estimated total power consumption of optical core nodes.

Recently, there have been significant research and standardization efforts to specify and implement 40 and 100 Gigabit Ethernet systems (40GbE and 100GbE). The proposals for the physical layer range from parallel transmission using a number of optical fibers or a number of wavelength channels within a single fiber to serial transmission over a single wavelength channel by exploiting advanced modulation formats and high-speed data processing. It is of particular interest to see if the proposed 40Gbit/s and 100Gbit/s Ethernet physical-layer transport options could contribute to reduce the total power consumption of high-performance networking and storage systems.

We investigated energy efficiency of different realization options for large Ethernet switches (see Fig. JA2.17) comprising ports at 40Gbit/s and 100Gbit/s by considering five different realizations of line cards, three of them comprising 100GbE ports and two other comprising 40GbE ports.

The 100GbE options include parallel transmission over either 10 wavelength channels (10x10G) or 4 channels (4x25G) as it is expected to be defined in the future IEEE 802.3ba standard [9]. For the implementation of serial transmission at 100 Gbit/s (1x100G) we consider single-polarization differential quadrature phase shift keying (DQPSK) format [10]. Similarly, 40GbE systems include both serial option (1x40G) that comprises electronic 1:4 muxes and demuxes and parallel transmission over 4 channels (4x10G). We estimated total power consumption of those systems by using a model that includes all functional blocks needed to implement Ethernet line cards and switches as well as realistic data of power consumption obtained from components' specs, research papers, and documents of the IEEE 802.3 Ethernet Task Force.

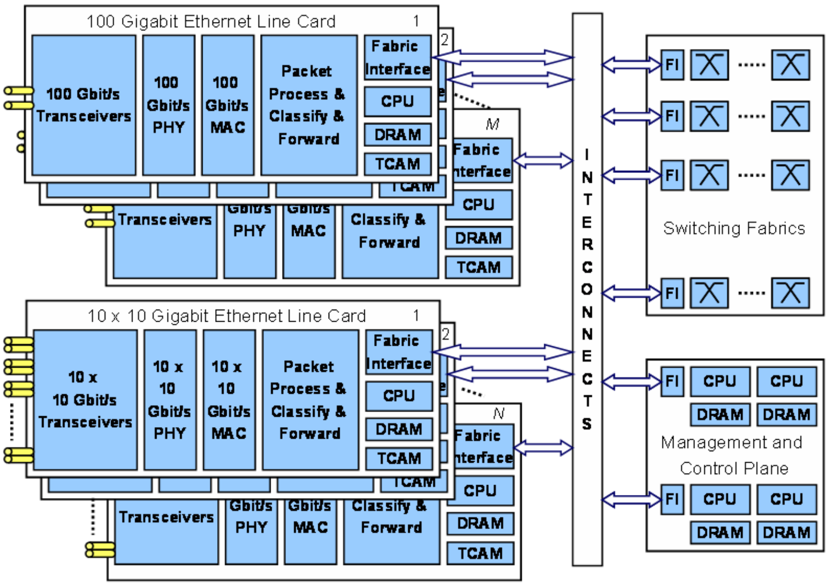

Fig. JA2.17: Generic diagram of a large Ethernet switch

Fig. JA2.18 shows energy efficiency of large Ethernet switches when using the five options for the implementation of the physical layer [11]. It is evident that switches equipped with 40GbE or 100GbE line cards are more energy efficient than those having only 10GbE ports. Here, a reduction in energy consumption of more than 2 nJ per bit and relative power savings of more than 20% can be achieved. The relative power savings decrease exponentially when increasing the aggregated switch capacity (*C*) and by using a fixed number of either 40GbE (*P*) or 100GbE (*M*) ports together with a large number of 10GbE ports (*N*). For large switch capacities of more than 20Tbit/s, the power savings shrink to values below 3%.

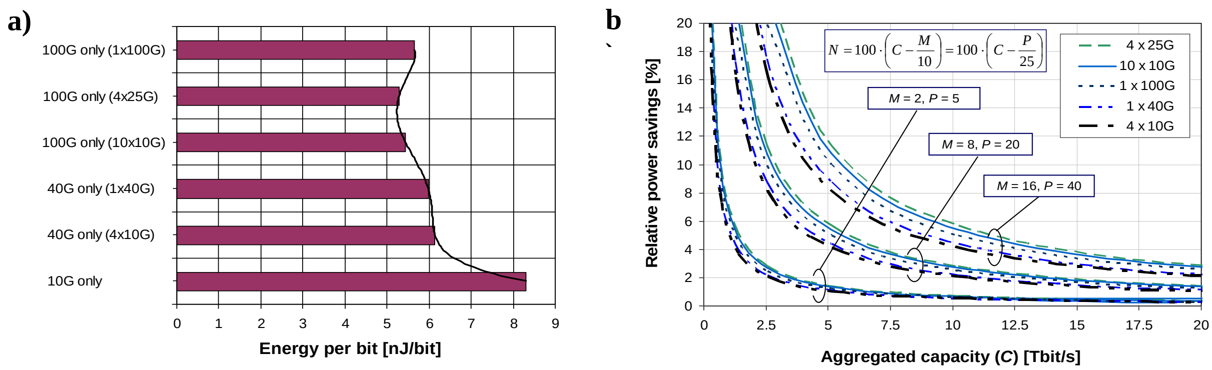

Fig. JA2.18: Comparison of different 40GbE and 100GbE realization options a) with respect to energy consumption per bit and b) regarding achievable power savings when using a number of 100GbE or 40GbE ports instead of 10GbE ports in a large Ethernet switch.

5.2.5 References

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5.2.6 Publications

[1] Stavdas, C. (T) Politi, T. Orphanoudakis, and A. Drakos, "Optical packet routers: how they can efficiently and cost-effectively scale to petabits per second", OSA Journal of Optical Networking, Vol.7, No. 10, pp. 876-894, 2008.

[2] E. Bonetto, L. Chiaraviglio, D. Cuda, G. Gavilanes Castillo, F. Neri, "Optical Technologies Can Improve the Energy Efficiency of Networks", ECOC 2009, invited, Vienna, September 2009.

[3] E. Bonetto, D. Cuda, G. Gavilanes, F. Neri, "The Role of Arrayed Waveguide Gratings in Energy-Efficient Optical Switching Architectures", 34th Optical Fiber Communication (OFC/NFOEC 2010) Conference, (submitted paper), San Diego, CA, USA, March 2010.

[4] S. Aleksic, "Analysis of Power Consumption in Future High-Capacity Network Nodes", IEEE/OSA Journal of Optical Communications and Networking, Vol. 1, No. 3, pp. 245 - 258. 2009.

[5] S. Aleksic, "Power Efficiency of 40 Gbit/s and 100 Gbit/s Optical Ethernet", 11th International Conference on Transparent Optical Networks (ICTON2009), Ponta Delgada, Azores, Portugal (invited); paper We.B2.2, 2009.

5.2.7 Remark

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.

5.3 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)

Description:

The driving criterion to design packet switching networks and the Internet has always been to minimize the utilization of available resources, which are typically over-provisioned in order to provide a best-effort service (in the case of Internet); the whole network infrastructure (ADSL lines, wireless base stations and access points, switches, routers, links, protection resources) is permanently powered on, and user terminals are sporadically switched off when not used. This widespread attitude of redundant equipment contributes consequently to a waste of energy.

A more conscious powering strategy for network devices may lead to significant savings in energy consumption (a telecom operator easily uses some TWh per year): in a energy-aware (or green) network, the operation criteria should be changed from evenly spreading traffic over available resources for congestion minimization to concentrating traffic on the minimal subset of available resources that guarantee service delivery with the desired quality level.

5.3.1 Approach

Part of deployed resources can be powered-off or kept in a low-power stand-by mode, thereby reducing energy consumption. This policy can be effectively applied also to protection resources, possibly loosening the requirements in terms of fault recovery latencies.

Optical technologies can play a significant role in greening telecommunication infrastructures, as they scale, in terms of power consumption, better with the capacity×distance product with respect to their electronic counterparts.

5.3.2 Possible research areas

- Joint routing and topology design to minimize power consumption
- Strategies to selectively switch off inactive coverage cells in wireless-over-fiber (WoF) and optical wireless access/home networks
- Definition of management protocols to control the powering state of network devices
- Evaluation of the power savings achievable by turning off the network periphery (e.g., ONUs in PONs), and proposing new, energy-efficient PON architectures
- Optimization of transmission elements, using fiber capacity to avoid regeneration

5.3.3 First research results from partners

The following sections report on several correlated contributions stemming from the complementary expertise of involved partners. In order to underline the energy saving potential the networks can offer, PoliTo includes here a practical implementation of a distributed web-based system to manage the uptime of unused PCs in its campus. Several studies and surveys on the power consumption of commercial electronic/optical communication equipment have been performed by TUB, which also considered and evaluated the energy savings for different degrees of freedom in reconfiguring an IP network. PoliTo proposed several heuristics to help improve the power efficiency of networks: energy-aware backbone networks with traffic concentration on the minimal set of network resources on one side, and solution of the routing and wavelength assignment problem with energy-saving targets in wavelength routing WDM networks. Furthermore, IBBT faces the energy saving problem by using multilayer traffic engineering, including power-dependant metrics in algorithms and traffic variations. Currently, KTH and AIT are working together in the energy budget impact of protection networking resources. FUB analysed an European transport network by means of simulation, trying to turn off links carrying less traffic and accounting for signal regeneration costs in the analysis. Several complementary expertises have been identified to the moment; SSSUP is planning to use GMPLS in future research, which seems an opportunity to match the GMPLS support identified by IBBT work, or using heuristics proposed by PoliTo.

A5.3.3.1 PoliTo – Energy cost in IT infrastructures of organizations

According to several studies, the largest majority of power consumption in the ICT is today due to the billions of terminals in both households and companies. Furthermore, with the current proliferation of networked devices that are continuously power on, it is becoming urgent to think about simple and effective ways to reduce their power consumption, not only by reducing the energy consumed while they are active, but by turning them off when left unused. In particular, the power consumption of a PC is far from being negligible, and today a simple desktop PC requires about 100W to be simply up, despite its much more energy efficient design (with respect to the past). However, people generally leave their PC on, even if not used.

In this work, PoliTo considered the problem of reducing the power consumption due to PCs in a mid-size Campus scenario. PoliTo tried to answer to questions like “What is the energy cost that today a medium University has to face due to the number of PCs that are present?” “Is that a negligible cost, or is it possible to reduce it, by implementing some smart energy efficient solutions?” by precisely quantifying the energy cost of networked devices in PoliTo's Campus. It was experimentally observed that the large majority of users do not turn off their PCs at the end of the day, which causes a large energy waste. This is mainly due to two dominant factors: i) the little sensibility people have versus the cost of keeping a PC on, and ii) the cost both in terms of time and technical skill to properly and quickly power down and up a PC. These somehow surprising facts suggested us to design a solution that controls the power state of PCs in the Campus, explicitly targeting the ease of use. The result is PoliSave, a centralized web-based architecture which allows users to schedule power state of their PCs; a PoliSave server remotely triggers power-up and power-down events by piloting a custom software which has to be installed in each PC. The client software handles all the tasks of correct PC configuration, enabling Wake-On-Lan (WoL) on network cards and the hibernation feature on the OS. To the best of our knowledge, this is the first work which quantifies the energy waste due to PCs left on during non working periods in large Campuses, a timely problem which was explicitly targeted by proposing a simple solution whose primary goal is to minimize the installation and management problems for users.

All the functionalities of PoliSave have been implemented, together with a rich set of monitoring and analysis tools (see http://www.polisave.polito.it), and a deployment trial has been studied. In particular, PoliTo installed PoliSave on a trial of 70 users of the Electrical Engineering Department (EEDept). The aim was i) to test the software implementation on a real environment, ii) to assess the possible power-saving and iii) to collect feedbacks from actual users.

0compares the average on time of PCs with and without PoliSave. The histograms represent the probability distribution functions (pdfs) of the time in which the PCs are left on during a day. Normally, about 53% of PCs without PoliSave are always on, while with PoliSave this percentage falls to less than 6%, with most of PCs that are alive for less than 12h. The average daily uptime of PCs managed by PoliSave is 9.7h, while the average daily uptime for other PCs is 15.9h. This corresponds to an average saving of more than 6h per working day, or an annual saving of about 219 kW/year per PC (about 100,000 Euros per year using current electricity costs considering the PCs in PoliTo campus, which is around 4000). The savings achieved including weekends, for which PoliSave PCs result off for the whole day with probability 0.93, amount to more than 250,000 Euros per year.

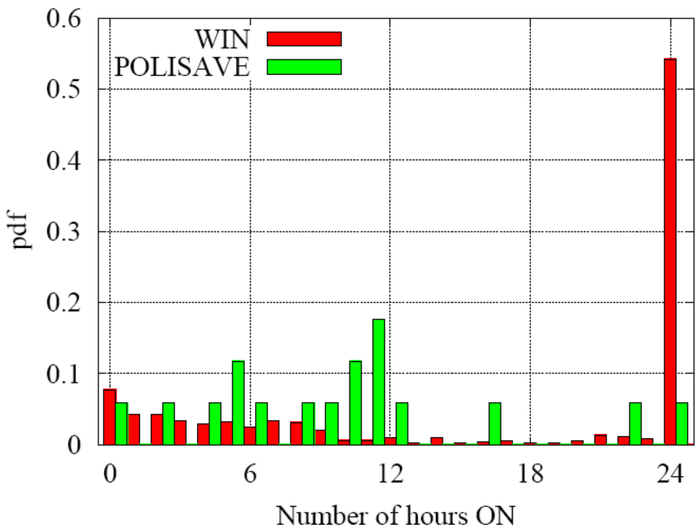


Fig. JA3.1 Average on-time for PCs with and without PoliSave.

Results show that the possible saving is huge, with negligible impacts on users' habit. At the time of writing, results are so encouraging that PoliSave is being extended to the whole set of Campus PCs, and other Italian Universities are considering to deploy it. Software is also made available as Open Source from www.polisave.polito.it

A5.3.3.2 PoliTo – Study case of energy-aware backbone networks

The Information and Communication Technology sector (ICT) consumes from 1% to 10% of the worldwide energy consumption. Among the main ICT sub sectors, 37% of the total ICT emissions are due to the Telecom infrastructures and devices, while data centers and user terminals are responsible for the remaining part. Considering the network infrastructure alone, its power consumption accounts for an average 0.1 GW of power worldwide. To this extent, routers consume the large majority of energy, while including air conditioning and cooling can almost double the energy consumption of a network. In Italy, for example, Telecom Italia is the second largest consumer of electricity after the National Railway system, consuming more than 2TWh per year. It is therefore not surprising that Internet Service Providers (ISPs) are trying to reduce the energy consumption of their networks, although the problem is faced with different motivations.

In this work, PoliTo aimed at studying how to reduce the overall power consumption of a backbone ISP network, considering it as a single, large distributed system. The focus is not at reducing the power consumption of each device, but rather at controlling the whole network, so to find the minimum set of devices that must be used to meet the actual traffic demand. Traditionally, networks have been designed to be able to serve a given maximum traffic demand, e.g., peak hour traffic, subject to Quality of Service (QoS) constraints, e.g., maximum links load or robustness to device failures. Minimizing the overall monetary cost (both capital –CAPEX- and operational –OPEX-expenditures) has been the traditional objective function. The intuition however suggests that such approach, while being optimal during peak hour traffic, results in a over-provisioning of resources, causing waste of resources, including energy to keep the whole network up and running. In addition, the coarse granularity of today's transmission technology often forces the network provider to install high-bandwidth links that most of the time are lightly loaded. Spare resources are also present to provide a reliable service, so that additional links and nodes are deployed to guarantee to recover from occasional failures. Keeping all these additional equipments always powered on is a clear waste of energy.

Let consider a scenario in which network devices can be selectively turned on and off to meet the actual traffic demand, and to be quickly activated in case of failures. This intuition has been already proposed in the literature, but in this work, PoliTo goes a step further, by i) precisely formulating the problem, ii) providing efficient heuristics in case larger networks are considered, and iii) assessing the effectiveness of the proposed approach considering a real test case, showing that power saving can be significant, e.g., typically larger than 35%.

The problem was formulated as an Integer Linear Programming (ILP) problem in [2]. Howver, since the optimal formulation of the problem is viable up to a small number of nodes, PoliTo proposed and studied different heuristic approaches to solve the problem also for large networks. In particular, the heuristic algorithms start by considering a network in which all elements are powered on; then the algorithms check iteratively if a given element (either a node or a link) can be turned off without violating QoS constraints. At each iteration, the considered element is powered off, and traffic is then re-routed on the residual network. If Quality of Service constraints are still verified, then the selected element is definitively powered off.

The algorithms implemented here share the same intuition: the energy saving achieved by turning off nodes is higher than by switching off single links, and switching off a node is more difficult than switching off a single link. Algorithms therefore try to turn off nodes first, and then links are possibly powered off in a second iteration.

The proposed heuristics were tested in [2] using data from a real network (considering real network parameters and configuration of a major Italian operator). 0reports the comparison of the energy spent for each bit by an energy-aware network and a standard network during a whole day. The energy-aware network exploits the algorithm to minimize the total power consumption, while in the standard network all the devices are always powered on. Traffic flowing in both networks is supposed to follow a day/night trend, as normally happens. The energy per bit represents the energy spent for transporting each bit in the network. The figure reports also the efficiency gain computed as the relative percentage of the energy-aware network and the standard network. The plot shows that with the energy-aware network design it is possible to reduce the cost of transporting information during the whole day, with higher gains during the night time, since traffic is lower and so a higher number of devices can be switched off. Indeed, during the night time, the saving is higher than 30% of the energy needed to transport a single bit.

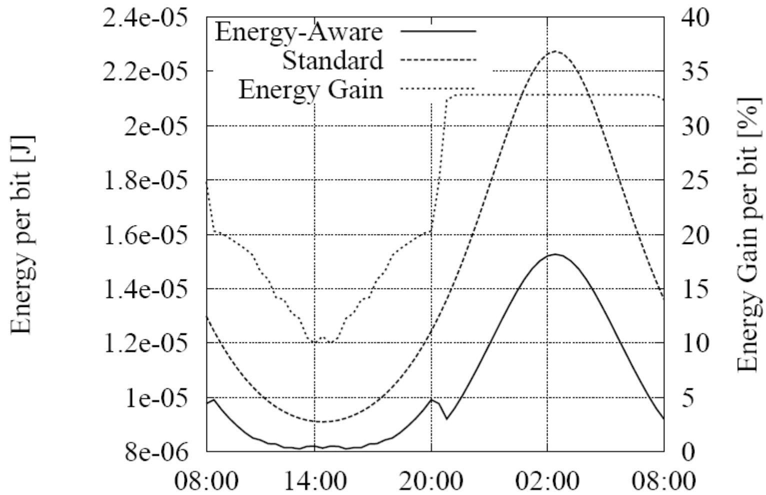


Fig. JA3.2 Energy efficiency comparison between the energy-aware network and a standard network

A5.3.3.3 PoliTo - Power-Aware Routing and Wavelength Assignment in Optical Networks

The role of optics in reducing the energy wastage can be significant. Regarding the core segment, Wavelength Routing (WR) networks offer the flexibility of designing a “logical topology”, comprising lightpath requests, over a physical topology, configured with Optical Cross Connect devices (OXCs) and links with many fibers each. Each fiber accommodates several wavelengths using WDM techniques.

The Routing and Wavelength Assignment (RWA) problem is well known in the literature: its goal is to assign a route and a suitable wavelength in the physical topology for each lightpath of the logical topology. Traditionally, RWA algorithms spread lightpaths over available resources. Hence, the solutions obtained from the standard RWA algorithms lead in general to a waste in the power required to keep up and running both OXCs and optical amplifiers along fiber links.

In [4] the target is the minimization of power consumption when solving the RWA problem, by making maximum usage of powered-on devices, e.g., by reusing the same fiber along the same path as much as possible, in contrast to spreading lightpaths on available fibers and paths. After precisely formulate the PA-RWA problem, PoliTo proposed some simple heuristics to solve it. Simulation results show that a significant amount of power can be saved, reducing up to 5 times the energy needed to operate a WR network.

As an example, 0 reports the total power consumption as the number of nodes N in the test network increases, considering the different heuristics implemented. A lower bound (LB) is reported to better assess the impact of heuristics on power consumption. In particular, the LCP-FF (Least Cost Path - First Fit) heuristic is almost energy-unaware, so that the power grows notably as N (number of nodes) increases. Indeed, both the MUP-FF (Most Used Path-First Fit) and OLMUP-FF (Ordered Lightpaths Most Used Path-First Fit) heuristics, which mainly consider the power consumption, are quite close to the lower bound, thus clearly improving the energy-efficiency of the network.

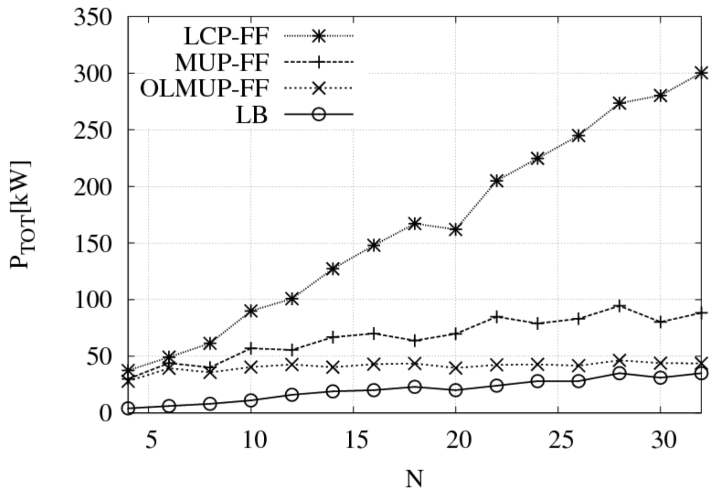


Fig. JA3.3 Power Consumption of different heuristics for an increasing number of nodes N

A5.3.3.4 TUB - Influence of the rerouting on energy saving potential in IP over WDM networks in low-demand scenarios

IP-over-WDM networks offer the potential to save energy by switching off line cards in low demand scenarios. The virtual topology in the IP layer consists of links corresponding to lightpaths in the WDM layer (0). Utilization of the lightpaths in a static network varies depending on the changing traffic. There is room to benefit from the dynamic traffic characteristics and deactivate the empty lightpaths together with the corresponding line cards, where each line card consumes up to 500 W.

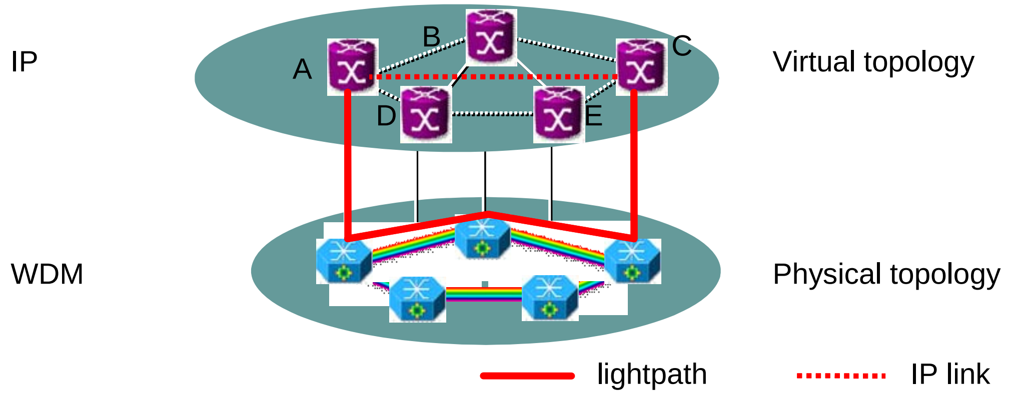


Fig. JA3.4 Network modelConsidered approaches to save energy

TUB focused on the following three approaches, which correspond to different levels of freedom in rerouting IP demands over the virtual topology and rerouting of lightpaths over the physical topology:

1. 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)
2. 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.
3. 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.

TUB did not consider the Fixed Upper Dynamic Lower approach, since the IP routing would not be able to react to changes of the virtual topology in such a case. The aim of the work at TUB is to compare the three approaches in dependence of the load scenario with respect to the maximum potential gain. Flow splitting among parallel multi paths in the virtual topology, colored line cards and wavelength conversion capability were assumed.

Methodology

TUB use a CAPEX minimized network as a base for these investigations. This static base network determines the number of installed fibers, IP routers and line cards in the network together with their capacities and power consumption. The network is designed to accommodate peaks of all demands in the network. Mixed Integer Linear Program (MILP) was used to calculate this network [9]. The MILP has the following variables: flow variables, number of lightpaths installed on a given pre-calculated physical path, number of fibers installed on a physical link, and type of router installed at a given node.

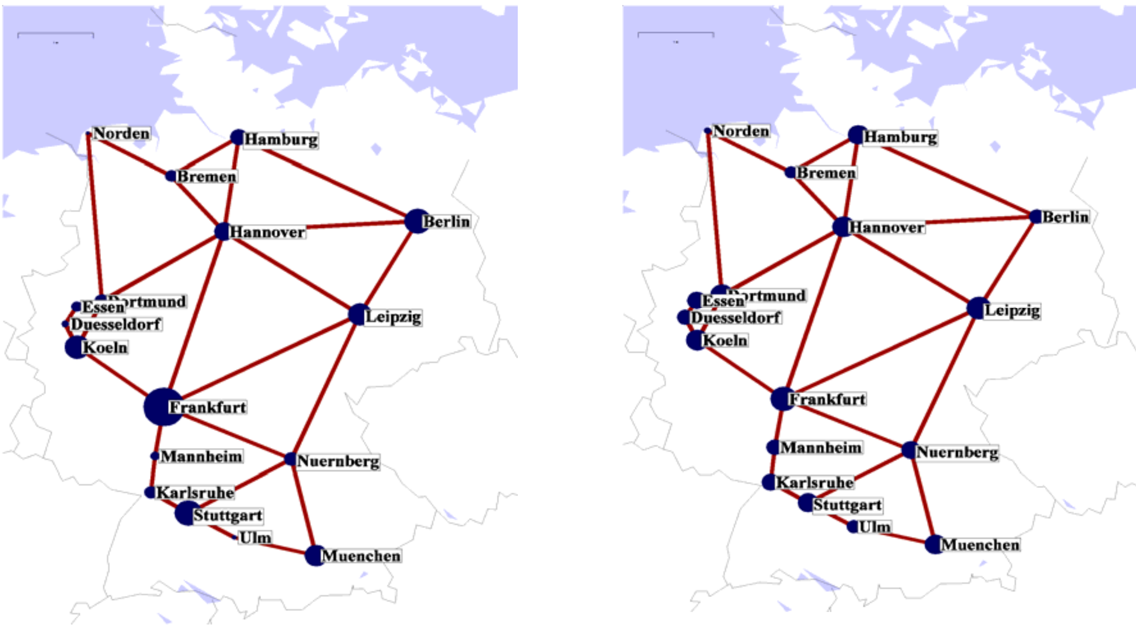
MILP variations were used to evaluate the energy savings in the considered approaches. Additional constraint for the fixed number of installed equipment is needed for DUDL, and one more constraint on the fixed IP routing is needed for DUFL. FUFL does not require any optimization model, since both the routing of the IP demands over the virtual topology, and the routing of lightpaths over the physical topology is fixed. A simple script is sufficient in this case.

Considered network scenario

TUB made this study as realistic as possible with regards to the power consumption [1] and to the cost of network elements [10], network topology [10], and traffic demands [16]. A capacity of 40 Gbps per each wavelength channel was assumed and 80 wavelengths per fiber. Consequently, a 40 Gbps colored line card is assumed with the power consumption of 500 W according to the 4-port 10-GE Tunable WDMPHY PLIM and Modular Services Card by CISCO [1]. Nine different types of IP routers accommodating 16-208 line cards with a capacity of 640-8320 Gbps (CISCO CRS-1 single- and multi-shelf systems) can be used. The costs of all network elements (routers, line cards, optical line amplifiers, dynamic gain equalizers, dispersion-compensating fibers, WDM multiplexers and optical crossconnects (OXCs)) are taken from the cost model developed in the European NOBEL project [10].

The network topology originates from the same project. It is a German backbone network (ger17) with 17 nodes and 26 links (0). A lightpath between two nodes can take one of the 50 pre-calculated shortest paths, not longer than 1500 km though.

Different sets of demands with different temporal and spatial distributions were considered. TUB covered different time scales (every 15 minutes, every day, every month), and different maximum total demands (sum of the maxima for each demand over time equal to 1, 3 and 5 Tbps, which cover also different granularities of the capacity of the wavelength channels). The measurements used were taken in the national research backbone network operated by the German DFN-Verein [16]. Another set of demands was generated according to the Dwivedi-Wagner (DWG) model [12]. In order to get a traffic matrix for each time period, TUB applied the relative demand changes in the DFN demands to the static DWG model. The resulting DWG demands are less centralized, as shown in 0 (the area of the node is proportional to its emanating demand). Moreover, the domination effects caused by single demands in DFN measurements are ruled out [9].



(a) ger 17, DFN (b) ger 17, Dwivedi-Wagner

Fig. JA3.5 Physical topology and source traffic distribution. The size of a node represents its emanating demand.

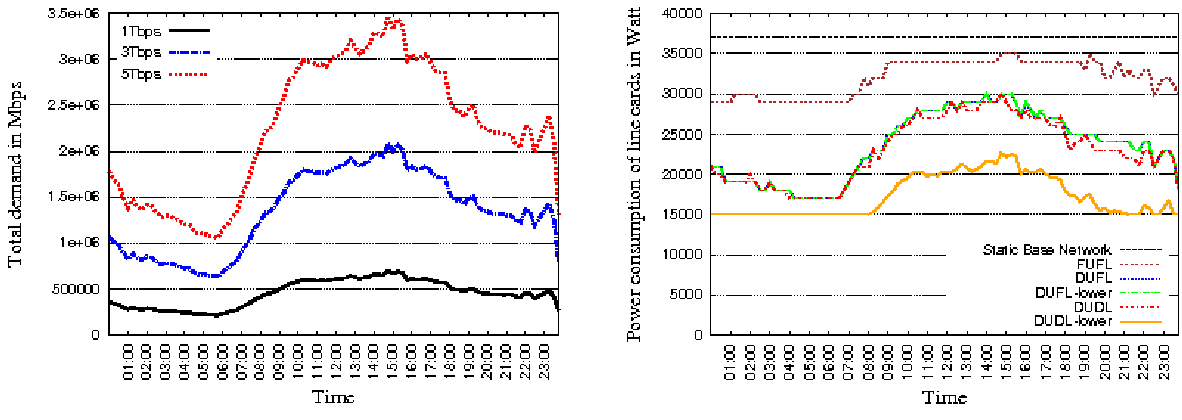
Results

Since all the considered scenarios gave similar results, the main focus was on the 96 DFN traffic matrices with the time granularity of 15 minutes, and the maximum total demand equal to 1, 3 and 5 Tbps. TUB focused on the comparison of the energy savings between FUFL, DUFL and DUDL. Since the static base network is over-provisioned (peak demands do not occur all at the same time), the energy savings compared to it could be overestimated.

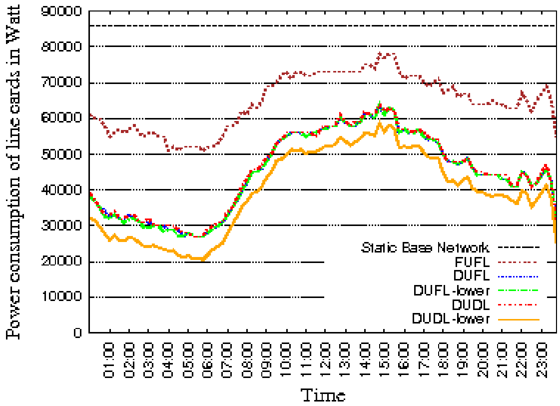
Some optimizations (mostly DUDL runs) hit the time-limit of the optimization (1 hour). Therefore the lower bounds of power consumption are shown together with the optimization results in the 0(b)-(d). All the comparisons are made using the lower bounds since they correspond to the upper bound of the maximum saving of the power consumption (the aim of this study).

0(b)-(d) illustrate the power consumption (of the line cards only) for the static base network (constant over time), the power values obtained with FUFL, and the values and dual bounds for DUFL and DUDL. The power consumption generally follows the total demand curve. As expected, DUFL brings much higher savings than FUFL (0.77/1.55/2.32 MWh for FUFL and 0.57/1.07/1.59 MWh for DUFL for 1/3/5 Tbps), however DUDL does not bring much more additional profits 0.41/0.95/1.51 MWh for 1/3/5 Tbps). Notice that the power consumed by line cards constitute only 23.1/22.5/24.5 % of the total power of line cards and IP routers for the static base network with 1/3/5 Tbps maximum total demand, respectively.

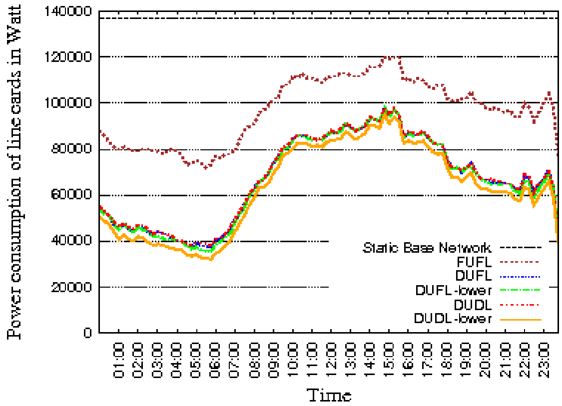
All the approaches bring benefits when the power consumption in the high demand hour and in the low demand hour is compared. It is especially important for FUFL, since FUFL is the least complicated approach to implement (decisions to deactivate line cards may be taken locally at the routers). It (as well as FUFL and DUFL) shows also significant energy savings against the over-provisioned static base network.



(a) Total demand, 1/3/5 Tbps, DFN *(b) Power consumption of line cards, 1 Tbps*



(c) Power consumption of line cards, 3 Tbps



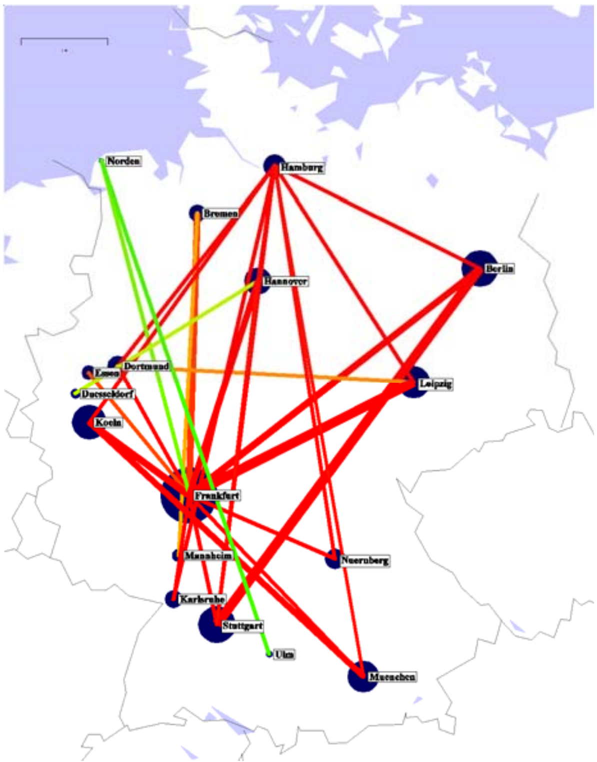
(d) Power consumption of line cards, 5 Tbps

Fig. JA3.6 Power consumption of line cards in ger17 network, DFN traffic, 1/3/5 Tbps, every 15 minutes on February 15, 2005.

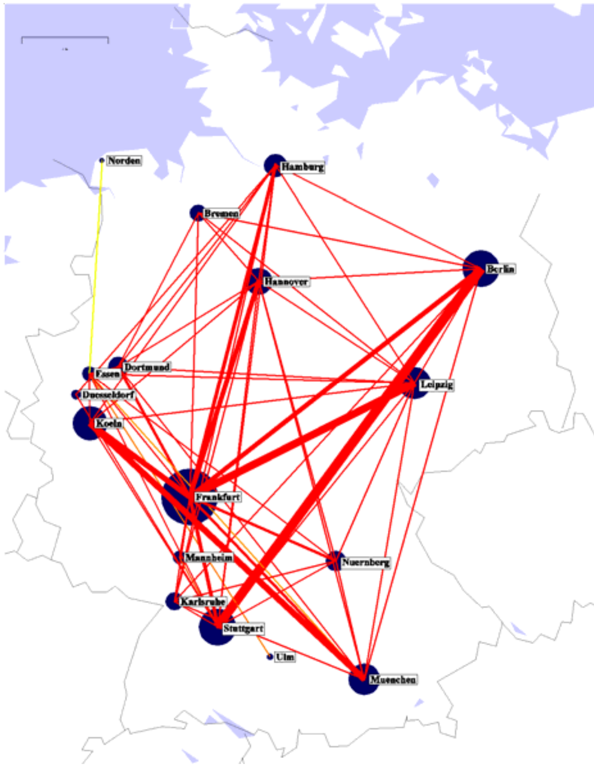
The disappointing performance of DUDL in comparison to DUFL may be explained in the following way. Firstly, the static base network, which serves as a starting point for all the approaches, is highly interconnected (virtual topology) under heavy load (more than 5 Tbps of the maximum total demand, see e.g. Fig.JA3.8(d)). Therefore the capability of DUDL to establish lightpaths that do not exist in the reference network is of little importance. Secondly, under low load, the virtual topology shrinks down to a tree, where the realization of which is irrelevant (Fig.JA3.8(a) and (b)). DUFL can choose any virtual links from the static base network to build a tree (Fig.JA3.8(c)). Thirdly, TUB allowed flow splitting in the IP layer, which allows DUFL to fill up the established lightpaths (Fig.JA3.8(a) and (b)). Moreover, the spatial distribution of traffic demands does not drastically vary over time. It is the change of the spatial distribution of the traffic demands that allows benefiting from the dynamic establishment of new lightpaths non-existent in the static base network.

(a) ger 17, DUFL, DFN, 1 Tbps, 5:30 am

(b) ger 17, DUDL, DFN, 1 Tbps, 5:30 am

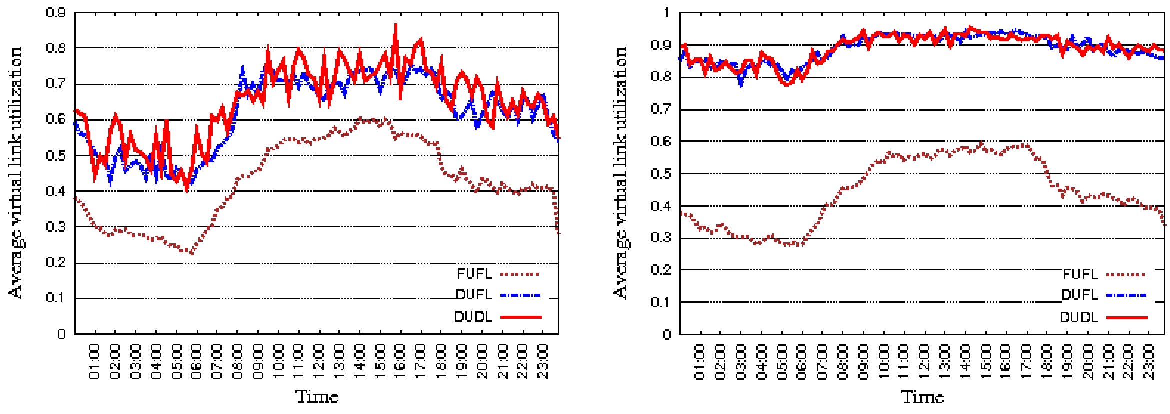


(c) ger 17, static base network, DFN, 1 Tbps



(d) ger 17, static base network, DFN, 5 Tbps

Fig. JA3.7 Virtual topology. The size of a node represents its emanating demand, the width of the links corresponds to their capacities, color indicates the link utilization (the darker the color, the higher the usage of the link)



(a) 1 Tbps *(b) 5 Tbps*

Fig. JA3.8 Average virtual link utilization over all active virtual links for ger17, DFN, 1 and 5 Tbps, every 15 minutes.

Conclusions and future work

TUB estimated the potential energy savings that can be achieved using three approaches FUFL, DUFL and DUDL, which correspond to different levels of freedom in dynamic rerouting of IP demands and dynamic adaptation of the virtual topology to the changing traffic demands. TUB found out that all the approaches yield the energy savings in the considered realistic scenarios, however it is the change of the IP routing that contributes the most to these savings. Although FUFL does not bring as substantial benefits as DUFL or DUDL, it is much simpler to realize in practice.

TUB is going to check the realistic energy savings that can be achieved using the three approaches mentioned above. Heuristics instead of the optimization are going to be applied. Moreover, one of the plans in the future is to investigate the influence of flow splitting on the results presented above.

A5.3.3.5 KTH, AIT - Impact of protection resources on the overall energy budget a WDM network

This WORK was carried out at KTH Sweden in collaboration with Anna Tzanakaki and Kostas Katrinis from the Athens Information Technology (AIT) in Greece.

The focus of this activity is to investigate and quantify the (possible) consumption reduction from switching off protection resources. With this objective in mind, a study was conducted where the total energy consumption of a transparent WDM network was compared in the following two cases:

- Protection resources are always ON
- Protection resources are turned OFF when they are not needed.

The study considered a scenario with dynamic traffic where connection requests comes and goes without prior knowledge. Preliminary results are encouraging and both partners, KTH and AIT are going to submit them for publication in the coming weeks to the Photonic Technology Letters.

A5.3.3.6 SSSUP – Plans for research activities

SSSUP is planning to address research considering an optical GMPLS network with distributed control plane. For saving energy, during periods of low utilisation (e.g., at nights) SSSUP will consider the opportunity to switch off selected network lines and thus reroute the traffic on the other links of the network, in an energy-efficient way. There are plenty of open issues to study including:

- Which policy to choose the network elements to selectively switch off (e.g., the least loaded)?
- When and for how long to switch-off them (e.g., schedule the switch-off)?
- How to avoid data losses while rerouting the traffic for the sake of energy-efficiency?
- How to implement the power-consumption support awareness in GMPLS (e.g., new GMPLS messages or objects may need to be proposed)?
- How to achieve power reduction while ensuring that blocking probability is not degraded?

A5.3.3.7 IBBT – Energy consumption model for multilayer backbone networks

Optimizing resource usage, reducing costs and increasing overall performance of backbone networks has been a research topic for a long time. The multilayer network, typically IP over optical, allows for cost-reduction by shifting packet-switched traffic from the IP layer to the optical layer. This has resulted in logical topology design schemes that provision capacity for the IP layer optimally. The advent of automatic optical switching has brought with it faster dynamic grooming (allowing longer-term periodic reconfiguration) and in particular multilayer traffic engineering (MLTE) which is used to adapt the network to changing traffic demands on a very short timescale (minutes or hours). Although originally envisioned for cost and performance optimization, IBBT seek to leverage MLTE for energy saving as well.

In order to optimize flexible multilayer networks towards energy efficiency, IBBT first looked at the main elements dictating power requirements in multilayer networks, and identified how energy consumption can be reduced. Optical layer switching provides for economy-of-scale and as such is very cost-efficient in switching large amounts of traffic. It turns out that it is also very energy-efficient. Additionally, the actual energy consumption for optical circuit switching techniques is largely independent of actual (IP-layer) traffic processed or switch configuration. In fact, energy dissipated in the optical switching layer is typically only around 1% of total multilayer IP-over-optical network power requirements. This means that most energy optimization can be achieved in the IP/MPLS layer.

IP/MPLS equipment processes packets at very high rates; both IP routing and MPLS forwarding. The power that is required for the electronic layer switching is related to the total volume and also to the characteristics of the processed traffic [13]. Line cards in the router chassis connect out to the optical switching layer. These line cards shift the traffic from the electronic domain (packets), into circuits which exist inside the optical domain. Power requirements for IP/MPLS equipment are typically rated for both the router chassis and any line cards installed on the chassis. The model adopted by IBBT for the energy consumption assumes a constant idle power, and an energy consumption term that varies with traffic volume. The idle power term amounts to 90% of total power requirement for current IP/MPLS router equipment. It was assumed the following to be true:

- router idle power is a constant term which cannot be optimized by merely reconfiguring IP/MPLS router connectivity;
- line cards carrying no traffic can be shut down;
- router traffic processing is directly related to line card traffic volume;
- terminated client interface volume is fixed (or varying over time, but well-defined for the scenario) and cannot be optimized;
- terminated client volume cannot be subtracted from line card volume since interface power characteristics are non-linear.

These assumptions allows us to optimize for energy consumption by either optimizing traffic volume over multiple line cards (on multiple IP/MPLS nodes), or in the extreme case switch of line cards altogether by deviating traffic away from them. Changing line card traffic volume of course requires optimizing the IP/MPLS traffic routes; switching off line cards requires reconfiguration in the optical layer. Reconfiguring the logical topology (i.e., switching off some IP/MPLS links and establishing some new ones) may further help with reducing energy consumption. This will be the task of a MLTE strategy that is aware of energy efficiency.

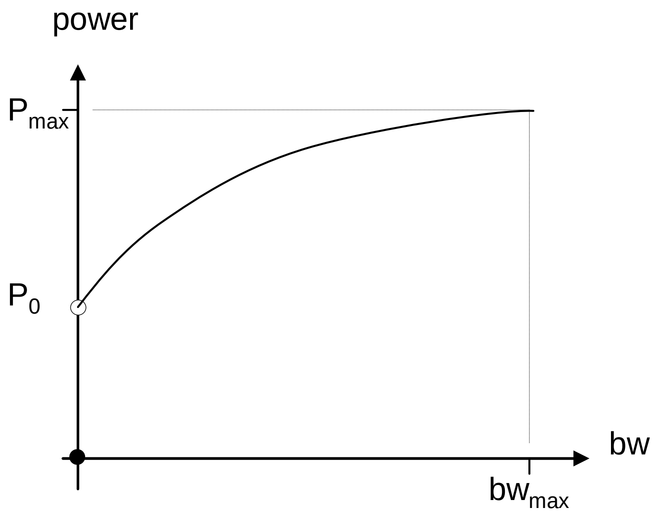


Fig. JA3.9 Non-linear power characteristic model (power req. vs. bandwidth usage)

The power characteristic model adopted for a line card is shown on 0. It is non-linear, or at least non-proportional (since there is always a non-zero idle power P_0, which is some fraction of the maximum rated power P_{max}). Energy consumption rises as carried bandwidth increases. A power requirement of 0 when shutting off the line card was assumed (which is only possible if the line card carries no bandwidth).

Multilayer TE for energy efficiency

The multilayer traffic engineering algorithm [6] used for the below results uses a routing cost function (not to be confused with the power characteristic which is used to calculate power requirement after a MLTE solution is found) as shown on 0.

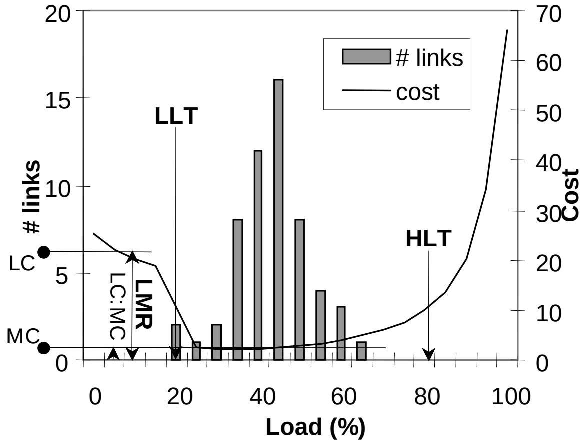


Fig. JA3.10 Bandwidth dependent routing cost for MLTE strategy

The routing cost function is dependent on IP/MPLS link load, and is such that an optimal cost is seen for links between a certain range LLT – HLT (Low and High Load Threshold respectively). High costs beyond HLT avoid overloading IP/MPLS links; a cost 'bump' is added in order to raise costs for links with load below LLT. This makes sure that no lightly loaded links are present in the network. In fact, when routing separate traffic streams, any IP/MPLS links that have their load drop below LLT will eventually will become more and more costly, leading to all traffic being deviated from those links. When applying such an algorithm on a full mesh, this leads to some of the links not carrying any traffic, with many streams being routed along multihop paths on the remaining links. The algorithm can route over a virtual full mesh first; the subset of links that do carry traffic after the MLTE finished is then matched on the actual multilayer IP-over-optical network, using flexible optical switching and lightpath setup. Links not carrying traffic do not need setup, which is how the strategy optimizes logical topology (as well as routing). Consequently, this is how switch-off of line cards (= IP/MPLS links) for some traffic scenarios is triggered through the MLTE strategy).

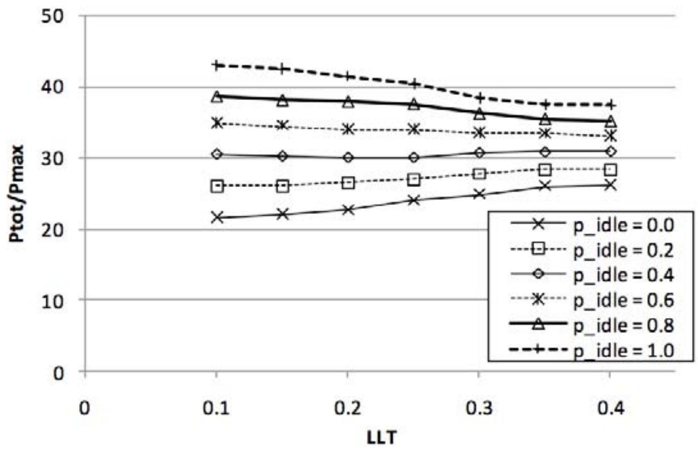


Fig. JA3.11 Influence of LLT parameter on total network power requirement for different line card idle power figures

0shows the influence of the LLT parameter on resulting total power requirement of the logical topology and routing solution for the same sample traffic pattern over 14 nodes. Power requirement is normalized against P_{max}. The typical value of LLT is 0.2 [6]. By varying LLT, the MLTE strategy will groom more or less aggressively; higher LLT yields longer multi-hop paths and vice versa.

For equipment with high P_{idle}, higher LLT leads to a sparser logical topology and lower energy consumption. However, the exact opposite is the case when using interfaces offering low idle power requirements. These are very efficient at low bandwidth utilization rates, and therefore it is OK to set up a lot of lightly loaded IP links in the logical topology. In fact, multi-hop routing merely increases total transit traffic volume in this case, which explains the higher total power requirement. Note that typical current router equipment has a P_{idle} of 0.9 (of P_{max}).

A5.3.3.8 IBBT – Switch-off during diurnal traffic variations

Although MLTE is suited for very large traffic variations, a typical pattern seen in access as well as core networks is a daily alternation between peak and off-peak volumes. Obviously, a large part of the background off-peak volume is always-on traffic such as P2P services. Peak (day) traffic largely consists of more interactive services, which need increasingly larger bandwidths (e.g., consider gaining popularity of on-demand streaming video), making for a stronger diurnal traffic oscillation. Off-peak/Peak rate may be anything from 50% down to 10% (e.g., for a network servicing smart phones).

From the above result (0), there is clearly room for specific optimization by somehow modifying the MLTE strategy. For the case of optical layer resource usage, IBBT used a so-called optical metric in [17]. In the study presented here, this approach was repeated for a power based metric: take the interface power characteristic (0) and multiply it with the original cost function (0) to reach a new cost function yielding automatic energy efficiency optimization.

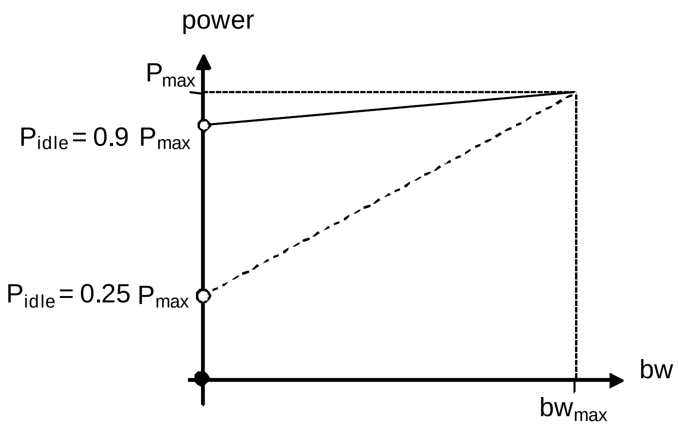


Fig. JA3.12 Linear power characteristics for normal and energy-efficient line cards

0shows total power requirement (normalized to line card P_{max}) for a 14 node network, where 4 nodes have power efficient line cards (P_{idle} = 25% of P_{max}). Source-destination traffic is uniformly distributed between 0 and 50% maximum link bandwidth. IBBT assumed full mesh routing or any of two types of MLTE regimes, and also for peak and off-peak traffic volume (with a bottom/peak rate of 25%).

The full mesh regime requires an IP/MPLS link to be setup between any two of the 14 IP/MPLS nodes; some small reduction was noticed in power requirement for the off-peak volume, but since the idle power is quite substantial for most line cards, this saving is minimal (15%). It does however set a benchmark figure for the difference between peak and off-peak power requirements.

As for the MLTE regimes, the first, called 'slow', has logical topology updates slower than the diurnal variations, this may in fact be some kind of dynamic grooming which on a large time-scale (months). For the 'fast' variant, it is possible to perform MLTE actions in-between peak and off-hour periods, but this requires protocol support (e.g., GMPLS) for resource reservation and performing the lightpath actions. The 'slow' variant optimizes for peak volume (so there is always enough bandwidth available for carrying traffic), which is why power requirements are equal for 'slow' and 'fast' during peak hours (and 30% lower than the full mesh peak case). For off-peak hours, power requirements are 45% lower (vs. full mesh off-peak) for 'slow' MLTE simply because of lower traffic volume (similar to the full mesh case). For 'fast' MLTE, the MTLE optimization yield additional energy savings (drop of 70% vs. full mesh off-peak)

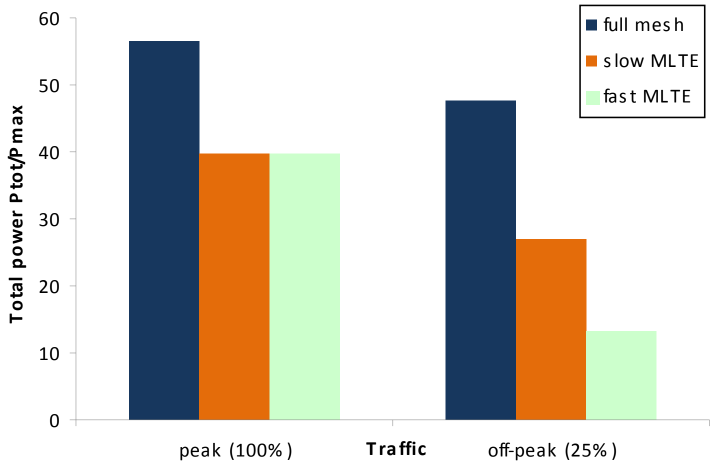


Fig. JA3.13 Peak vs. off-peak power requirement for three TE scenarios

Next, IBBT ignored the full mesh scenario and instead look again at the 'slow' and 'fast' MLTE cases, but in this case incorporated the power metric in the MLTE strategy. The power metric allows energy consumption optimization by taking into account the energy-efficiency of links, and configures optimal traffic loads for each type of line card.

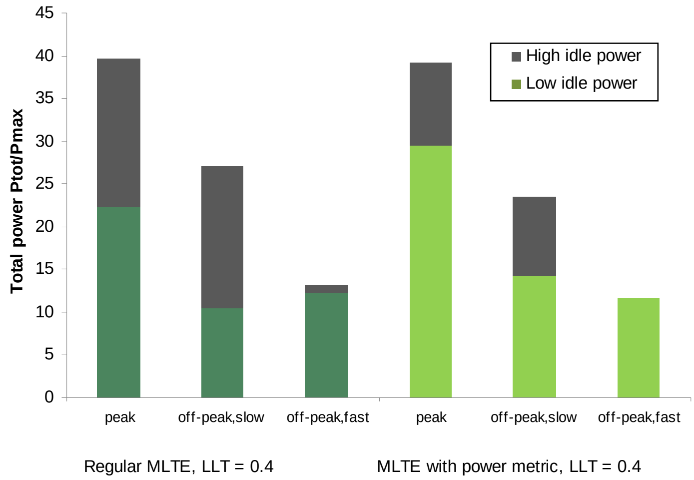


Fig. JA3.14 Comparison of regular MLTE and MLTE with power metric

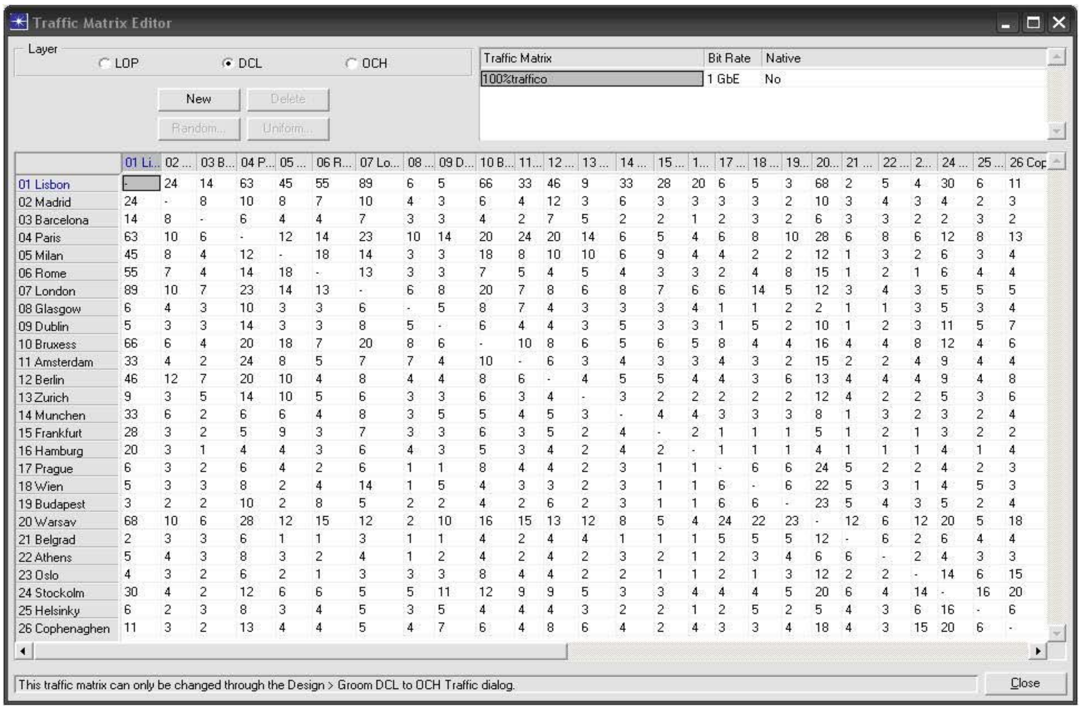
In 0, for the same network and traffic scenario, the darker (top) part of each bar shows power required by line cards with high P_{idle}. It can be seen that the power metric enabled scheme tends to avoid and shut down these inefficient line cards (links), especially at off-peak ('low') volumes. Although the slow regime offers no reconfiguration at off-peak volumes, avoiding inefficient line cards leads to better scaling of total power requirement with traffic volume.

For the 'fast' regime and regular vs. power metric, a reduction of 12% in power is seen for off-peak hours (13% for the 'slow' regime). The difference for peak traffic is minimal as no interfaces are run near their idle operating point, so differences in power efficiency are minimal also.

A5.3.3.9 FUB - OPNET Simulations

This work was carried out by FUB using the OPNET™ (OPtimum NETwork performance) SP Guru Transport Planner code (version 12.0). Starting from a matrix describing the traffic among the nodes and from the available fibre links among the nodes, this simulation tool allows us to design optical transport networks and, in particular, to assign the wavelength channels in fibre links optimising the traffic grooming; the simulation model also evaluates the protection paths.

The simulation tool allows us to achieve the complete network design in terms of optical fibre links, optical amplifiers, wavelength channels (including protection paths) and 3R regenerators. The channel bit rate, the amplifiers and the in-line 3R spacing are data that have to be provided as input to the simulation tool; such data can be found either in literature (for an instance in [14]) or by means of transmission simulation tools.



	01 Li...	02 ...	03 B...	04 P...	05 ...	06 R...	07 Lo...	08 ...	09 D...	10 B...	11...	12 ...	13 ...	14 ...	15 ...	1...	17 ...	18 ...	19...	20...	21 ...	22 ...	2...	24 ...	25 ...	26 Cop
01 Lisbon	-	24	14	63	45	55	89	6	5	66	33	46	9	33	28	20	6	5	3	68	2	5	4	30	6	11
02 Madrid	24	-	8	10	8	7	10	4	3	6	4	12	3	6	3	3	3	3	2	10	3	4	3	4	2	3
03 Barcelona	14	8	-	6	4	4	7	3	3	4	2	7	5	2	2	1	2	3	2	6	3	3	2	2	3	2
04 Paris	63	10	6	-	12	14	23	10	14	20	24	20	14	6	5	4	6	8	10	28	6	8	6	12	8	13
05 Milan	45	8	4	12	-	18	14	3	3	18	8	10	10	6	9	4	4	2	2	12	1	3	2	6	3	4
06 Rome	55	7	4	14	18	-	13	3	3	7	5	4	5	4	3	3	2	4	8	15	1	2	1	6	4	4
07 London	89	10	7	23	14	13	-	6	8	20	7	8	6	8	7	6	6	14	5	12	3	4	3	5	5	5
08 Glasgow	6	4	3	10	3	3	6	-	5	8	7	4	3	3	3	4	1	1	2	2	1	1	3	5	3	4
09 Dublin	5	3	3	14	3	3	8	5	-	6	4	4	3	5	3	3	1	5	2	10	1	2	3	11	5	7
10 Bruxess	66	6	4	20	18	7	20	8	6	-	10	8	6	5	6	5	8	4	4	16	4	4	8	12	4	6
11 Amsterdam	33	4	2	24	8	5	7	7	4	10	-	6	3	4	3	3	4	3	2	15	2	2	4	9	4	4
12 Berlin	46	12	7	20	10	4	8	4	4	8	6	-	4	5	5	4	4	3	6	13	4	4	4	9	4	8
13 Zurich	9	3	5	14	10	5	6	3	3	6	3	4	-	3	2	2	2	2	2	12	4	2	2	5	3	6
14 Munchen	33	6	2	6	6	4	8	3	5	5	4	5	3	-	4	4	3	3	3	8	1	3	2	3	2	4
15 Frankfurt	28	3	2	5	9	3	7	3	3	6	3	5	2	4	-	2	1	1	1	5	1	2	1	3	2	2
16 Hamburg	20	3	1	4	4	3	6	4	3	5	3	4	2	4	2	-	1	1	1	4	1	1	1	4	1	4
17 Prague	6	3	2	6	4	2	6	1	1	8	4	4	2	3	1	1	-	6	6	24	5	2	2	4	2	3
18 Wien	5	3	3	8	2	4	14	1	5	4	3	3	2	3	1	1	6	-	6	22	5	3	1	4	5	3
19 Budapest	3	2	2	10	2	8	5	2	2	4	2	6	2	3	1	1	6	6	-	23	5	4	3	5	2	4
20 Warsav	68	10	6	28	12	15	12	2	10	16	15	13	12	8	5	4	24	22	23	-	12	6	12	20	5	18
21 Belgrad	2	3	3	6	1	1	3	1	1	4	2	4	4	1	1	1	5	5	5	12	-	6	2	6	4	4
22 Athens	5	4	3	8	3	2	4	1	2	4	2	4	2	3	2	1	2	3	4	6	6	-	2	4	3	3
23 Oslo	4	3	2	6	2	1	3	3	3	8	4	4	2	2	1	1	2	1	3	12	2	2	-	14	6	15
24 Stockolm	30	4	2	12	6	6	5	5	11	12	9	9	5	3	3	4	4	4	5	20	6	4	14	-	16	20
25 Helsinky	6	2	3	8	3	4	5	3	5	4	4	4	3	2	2	1	2	5	2	5	4	3	6	16	-	6
26 Cophenaghen	11	3	2	13	4	4	5	4	7	6	4	8	6	4	2	4	3	3	4	18	4	3	15	20	6	-

Fig. JA3.15 Traffic matrix of the European transport network

The European transport network was studied with a traffic matrix reported in Fig.JA3.15 and with the fibre links shown in Fig.JA3.16.

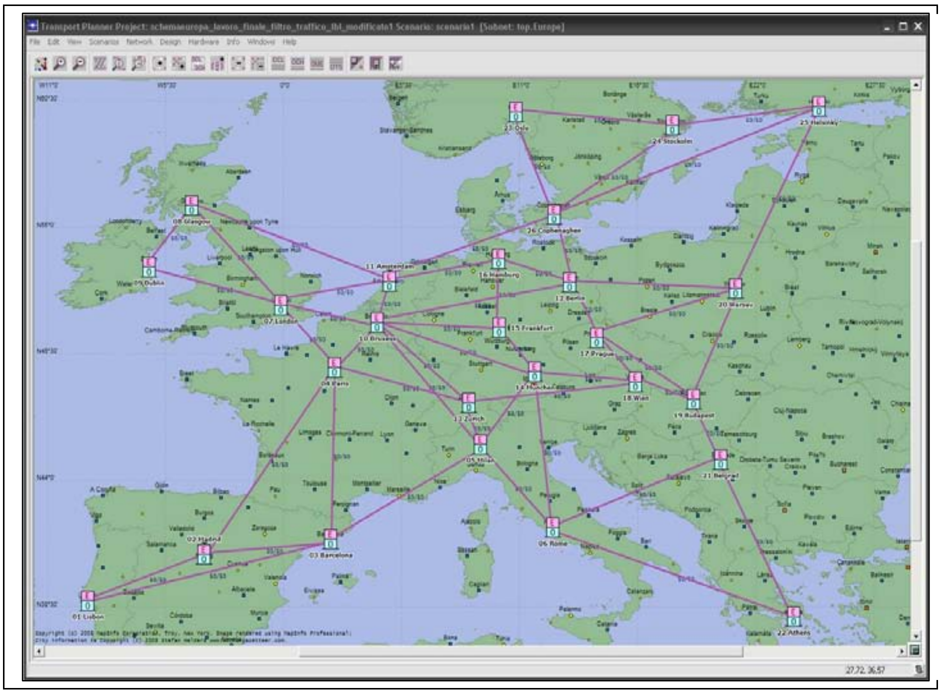


Fig. JA3.16 European network topology

In presence of a traffic reduction, a switch off of the links carrying less traffic can be achieved, and the traffic that has to be carried in such a links can be groomed in the wavelength channels operating in the remaining links. It has to be pointed out that protection paths are established between each pair of nodes also after switching off.

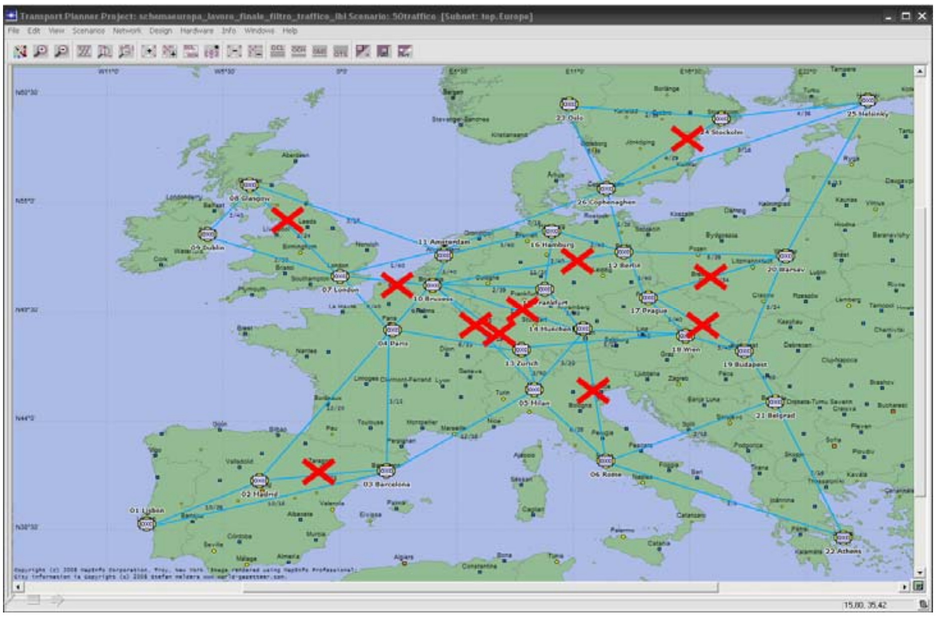


Fig. JA3.17 Link switch off in the presence of a traffic reduction (50% of 0).

Two possible scenarios were considered: in the first one, a traffic reduction of 50% is assumed with respect to the one reported in Fig.JA3.15. Fig.JA3.17 reports an example of switch off of links when the traffic reduces at 50%: this operation allows an energy saving of about 200 kW. By reducing the traffic at 20% of Fig.JA3.15, optical links can be switched off with an energy saving of about 300 kW. The energy saving could be much higher if we also consider the consumption of other equipment as, for an instance, air-conditioning.

It has also to be pointed out that the links that have to be switched on in conditions of higher traffic can be efficiently fed with solar cells, since the traffic load occurs mainly during the day time. For instance, panels of some square meters can generate power for some kW [15]. Therefore, a network design that takes into account both the reduction of transmission elements and the use of renewable energies can give an important contribution in terms of non renewable energy saving.

A5.3.3.10 FUB – Next Activities

Referring to a transport network, FUB would evaluate and compare the energy saving that can be achieved in different scenarios considering:

- absence of protection for client flows
- different protection techniques to ensure reliability to client flows (1+1, path sharing, link based, etc).

More in detail, FUB proposes to perform such evaluation starting by the heuristic algorithms proposed by PoLiTo [2]. Here, a static traffic matrix is considered and a simple algorithm is proposed to power off a node (or a link) and then to reroute the whole traffic matrix. Nodes and links are ordered according to different criteria (Least-Link, Least-Flow, Random) and eliminated, step-by-step, from the network graph. Only QoS constraints are considered in terms of maximum link load, regardless to protection issues.

Furthermore, it is expected that, when protection techniques are considered, algorithm performances will decrease due to the disjoint path constraint.

The basic idea is to perform a simulation in which constraints of different protection techniques are considered, and to compare the respective results. In order to obtain a valid comparison, it should be considered for each scenario:

- the same physical topology;
- the same network capacity;
- the same total traffic load (including both working and protection paths).

However, the protection traffic is not the same for different protection scenarios when the same working traffic matrix is considered. That makes it difficult to define a traffic matrix so that the resulting total traffic load is the same for every scenario.

In order to obtain an independence with respect to the total traffic load, FUB proposes for each scenario:

- to define the same network topology
- to consider a variable traffic matrix (for example a sinusoidal traffic load with a one-day period)
- to route traffic depending on protection scenario
- to dimension the network capacity on the basis of the peak load (that will be different for each scenario, and that will include working and protection traffic)
- to evaluate the percentage of nodes and links that can be powered off during a day.

In this way, the traffic matrix considered (the client traffic matrix) may be the same and scenarios will be compared in terms of percentage of nodes and links powered off versus the percentage traffic reduction, with and without traffic protection.

Such a study can be useful for different reasons:

- when a transport network is considered protection issues have a great importance and can't be ignored due to the small time of restore required and to the large amount of traffic;
- the additional load required for protection purpose also impose a disjoint path constraint and can not be treated as a simple additional traffic;
- when protection is considered, the results obtained in [11] for each heuristic may be different. For example, considering nodes heuristics, Least-Link may perform better than Least-flow because of the biggest number of routes available in the network.

Finally, FUB also proposes to realize such a study by means of OPNET Transport Planner software

5.3.4 Publications

[1] Technical report: F. Idzikowski (TUB), *Power consumption of network elements in IP over WDM networks*, TU Berlin, TKN Group, Tech. Rep. TKN-09-006, 2009

[2] L. Chiaraviglio (PoliTo), M. Mellia (PoliTo), F. Neri (PoliTo), *Reducing Power Consumption in Backbone NetworksIEEE* International Communications Conference (ICC 2009), Next Generation Networking Symposium, Dresden, Germany, June 2009

[3] L. Chiaraviglio (PoliTo), M. Mellia (PoliTo), F. Neri (PoliTo), *Energy-aware Backbone Networks: a Case Study*, First International Workshop on Green Communications(GreenComm'09), Dresden, Germany, 18 June 2009 [in conjunction with IEEE ICC 2009]

[4] Yong Wu (PoliTo), L. Chiaraviglio (PoliTo), M. Mellia (PoliTo), F. Neri (PoliTo), *Power-Aware Routing and Wavelength Assignment in Optical Networks*, 35th European Conference on Optical Communication (ECOC 2009), poster paper P5.12, Vienna, Austria, Sept. 2009

[5] B. Puype (IBBT), D. Colle (IBBT), M. Pickavet (IBBT), P. Demeester (IBBT), *Energy Efficient Multilayer Traffic Engineering*, European Conference on Optical Communication (ECOC 2009), Vienna, September 2009.

[6] B. Puype (IBBT), W. Vereecken (IBBT), D. Colle (IBBT), M. Pickavet (IBBT), P. Demeester (IBBT), *Power Reduction Techniques in Multilayer Traffic Engineering*, 11th International Conference on Transparent Optical Networks (ICTON 2009), Sao Miguel (Portugal), July 2009

[7] A. Silvestri (FUB), A. Valenti (FUB), S. Pompei (FUB), F. Matera (FUB), A. Cianfrani (UniRoma1), *Wavelength Path Optimization in Optical Transport Networks for Energy Saving*, ICTON 2009, July 2009

[8] A. Silvestri, A. Valenti, S. Pompei, F. Matera, A. Cianfrani, *Wavelength path optimization in optical transport networks for Energy saving* in proc. of ICTON 09, Ponta Delgada, June 29-July 2

[9] F. Idzikowski, S. Orlowski, C. Raack, H. Woesner, A. Wolisz, “Saving energy in IP-over-WDM networks by switching off line cards in low-demand scenarios", accepted for ONDM 2010.

[10] “NOBEL – Next generation Optical networks for Broadband European Leadership,” http://www.ist-nobel.org, 2004–2007.

[11] Luca Chiaraviglio, Marco Mellia, Fabio Neri, “Energy-Aware Networks: Reducing Power Consumption By Switching Off Network Elements”, FEDERICA-Phosphorus tutorial and workshop (TNC2008), Brugges, BE, 18 May 2008

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[13] J.Chabarek et al., Power Awareness in Network Design and Routing, IEEE Infocom’08, 457-465

[14] F. Matera, et al: Numerical Investigation on Design of Wide Geographical Optical Transport Network based on n x 40 Gbit/s transmission, J. of Lightwave Technlogy, Vol. 21, pp 456-465, February 2003

[15] http://www.fvgenergy.com/photovoltaic_eng/home_eng.html

[16] “Deutsche Forschungsnetz Verein,” http://www.dfn.de, DFN.

[17] B.Puype et al., Optical Cost Metrics in MLTE for IP-over-Optical Networks, Proc. ICTON ’04, 1, 75-80

…

5.4 JA4 Green Routing Protocols

Participants:

AIT (Anna Tzanakaki), GET (Philippe Gravey), KTH (Paolo Monti), SSSUP (Alessio Giorgetti), UEssex (Reza Nejabati)

Responsible person:

Reza Nejabati (UEssex)

5.4.1 Scope

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 layer2 carrier grade Ethernet networks. The important factor that will be considered in development and investigation of routing algorithms and protocols are:

- Node characteristics (e.g. optical transparency),
- Geographical location of nodes and links,
- Instantaneous load of the nodes
- Length of the links
- Bit-rates, loss and other physical layer impairments

Finally this JA aims to investigate on possible implementation of the proposed routing algorithms in GMPLS-based networks by means of proper extensions of the current protocols, in Mesh and interconnected-ring topologies and finally in networks with partly transparent optical nodes.

5.4.2 Current and planned activities

So far there are two joint research activities have been proposed in this JA of which one is in progress and the other one will start early 2010. Some JA participants have also expressed their intention for starting relevant joint research activities in 2010. This section will report on these two joint research activities:

A5.4.2.1 Green RWA

This is a joint research activity between AIT and KTH.

Participants are: A. Jirattigalachote, K. Katrinis, A. Tzanakaki, L. Wosinska, and P. Monti

The aim of this activity is to address the problem of energy efficiency in the provisioning of services identifying alternative approaches that can support service provisioning with reduced energy consumption compared to the conventional routing and service provisioning schemes. The approach taken by this activity is based on identifying appropriate resilience mechanisms and routing schemes in order to minimize the overall network energy budget over time. In this context this activity aims to address the following challenges:

- Current RWA solutions commonly optimize network resource utilization without considering the associated power consumption. This activity aims to develop methods that will enable the provisioning of paths in a power-aware manner.
- This activity also aims to define a method for determining the efficiency bounds of the proposed approaches in real networks.
- Currently the choice of the suitable resilience schemes applied in various types of WDM optical networks do not take into consideration the associated energy consumpition. This joint activity will consider the performance of the various possible resilience schemes in terms of network availability, resource utilization but also power consumption and will try to identify optimum resilience schemes with respect to these requirements and discover associated trade-offs. A study of the suitable routing schemes for both working and protection traffic will be also performed.
- Methods that can support the reorganization of provisioned paths considering power-awareness will be also explored.

The plan for the next year is to continue addressing the research challenges described above. In addition KTH will also extend the trade-off study (between saved energy and blocking probability) to other green RWA techniques that are necessarily limited to switching off protection resources.

All this activities are on-going and there are, up to this date, no results or mobility action to report. The plan is to have one journal publication (JOCN or Communication Magazine).

It is planned to carry out one mobility action between AIT and KTH in the framework of this work and produce a conference paper either at ECOC 2010 or OFC20011.

A5.4.2.2 Corss-Layer Energy Optimization for eScience Applications

This is a newly joint research activity proposed by UEssex. Some JA4 participants expressed their interest to participate in this activity form 2010. The expected start data of this activity is Jan 2010.

Aim of this work is to address network energy efficiency for e-science applications. e-science applications required coordinated computing resources interconnected by a dynamic high-performance optical networks. In such an infrastructure, computing resources controlled by a application middle-ware and network resources are controlled by network control plane (e.g. GMPLS). Both computing and network resources are major energy consumption resources. In this task the objective is to design a cross-layer mechanism that consider energy consumption at both network and computing domain by inter-acting with network control plane and application middle-ware.

This activity has not started yet. The planned start date is January 2010. The activity will be based on close collaboration between IBBT and UESSEX with possibility of joining more partners. A method will be developed for joint energy-ware resource allocation and reservation at middle-ware and network control plan. The proposed method and it’s efficiency will be evaluated with a Grid networking simulator (Phosphorus simulator) available in UEssex and IBBT. The result is expected to generate paper suitable for publication in ONDM 2011.

5.5 JA5 Innovative Powering Strategies by Renewable Sources

Participants:

Michel Morvan (GET)
Francesco Matera (FUB)
Siamak Azodolmolki (AIT)

Responsible person:

Michel Morvan (GET)

Description:

The subject of JA5 is quite complex. It requires not only a good understanding of the wide and complex energy topic but also a deep knowledge of the telecom area in a transversal way.

So, in a general context where everybody worries about energy; the scope of the activity has to be defined as clearly as possible from a telecom perspective.

The effort has been first put on the definition of an action plan addressing the various aspects to be explored. Here below are topics expressed in terms of questions that have to be answered in the scope of the activity. The questions are numbered from data collection issues to more open topics related to the telecom area itself.

- what are the characteristics of renewable power sources with respect to conventional ones? Do they exhibit specific advantages, drawbacks or requirements for use in the telecom area?
- how telecom networks are currently powered: what are the current power strategies and what change could be brought?
- how can renewable power sources be in a short term used in telecom network in a smart and green way i.e. without any major change in the network?
- how could telecom network architectures evolve in the context of a structural and lasting power shortage or price increase?

The specific objectives of JA5 consist in answering these questions

- To identify the different ways telecom networks could use renewable energy sources in a specific way, if any.
- To identify potential evolution ways of telecom network architectures which would not only consume few energy but in a way adapted to renewable energy sources.

5.5.1 Question 1: Characteristics of renewable power sources

Renewable energy sources in the common understanding designate the mechanical or thermal power that can be extracted from natural forces like wind, water, sun and earth. We focus on electricity generation.

Geothermal power is very little used in a massive way. Only some specific countries with high volcanic activity like Iceland. This energy source is also very seldom used to produce electricity.

Hydroelectric power has long been used all over the world (cf. Fig. JA5.1), either using flowing rivers (continuous power) or dams (power on demand). Most sites have already been equipped in Europe. Hence, there is very little progression to be expected. This is not the case in developing countries where dams can still be built. One thing to be mentioned is that hydroelectric power plants are not seen as green as they may appear at first sight. They present also some drawbacks with respect to the environment.

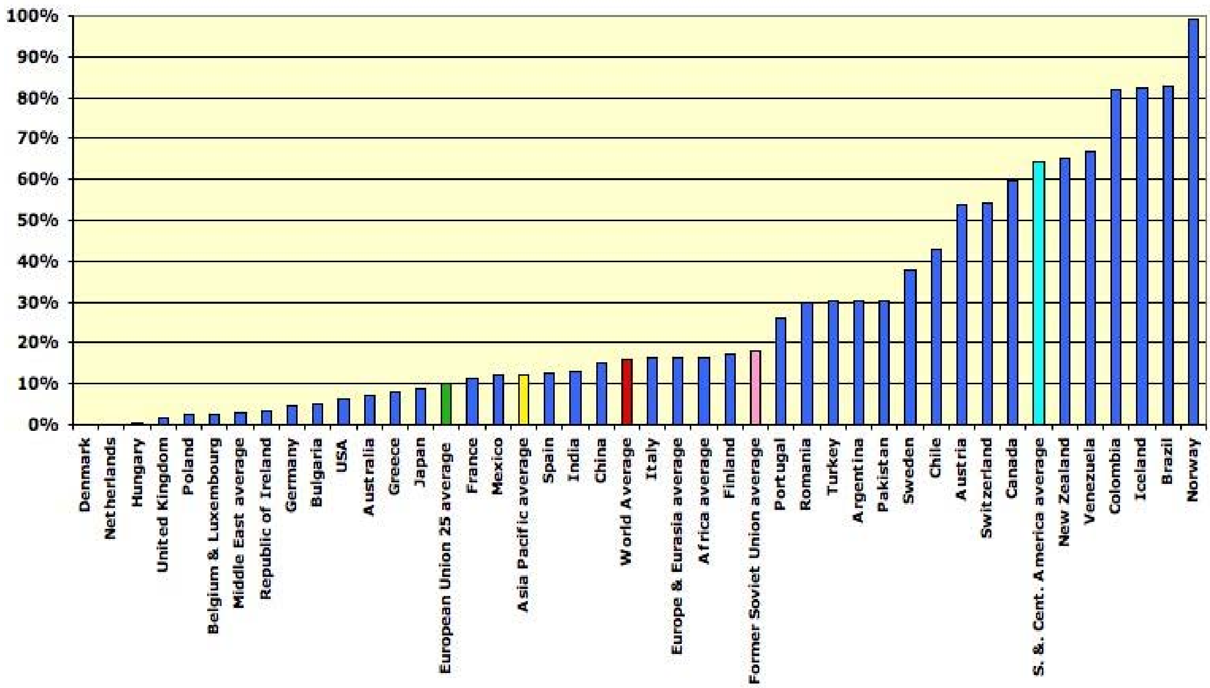


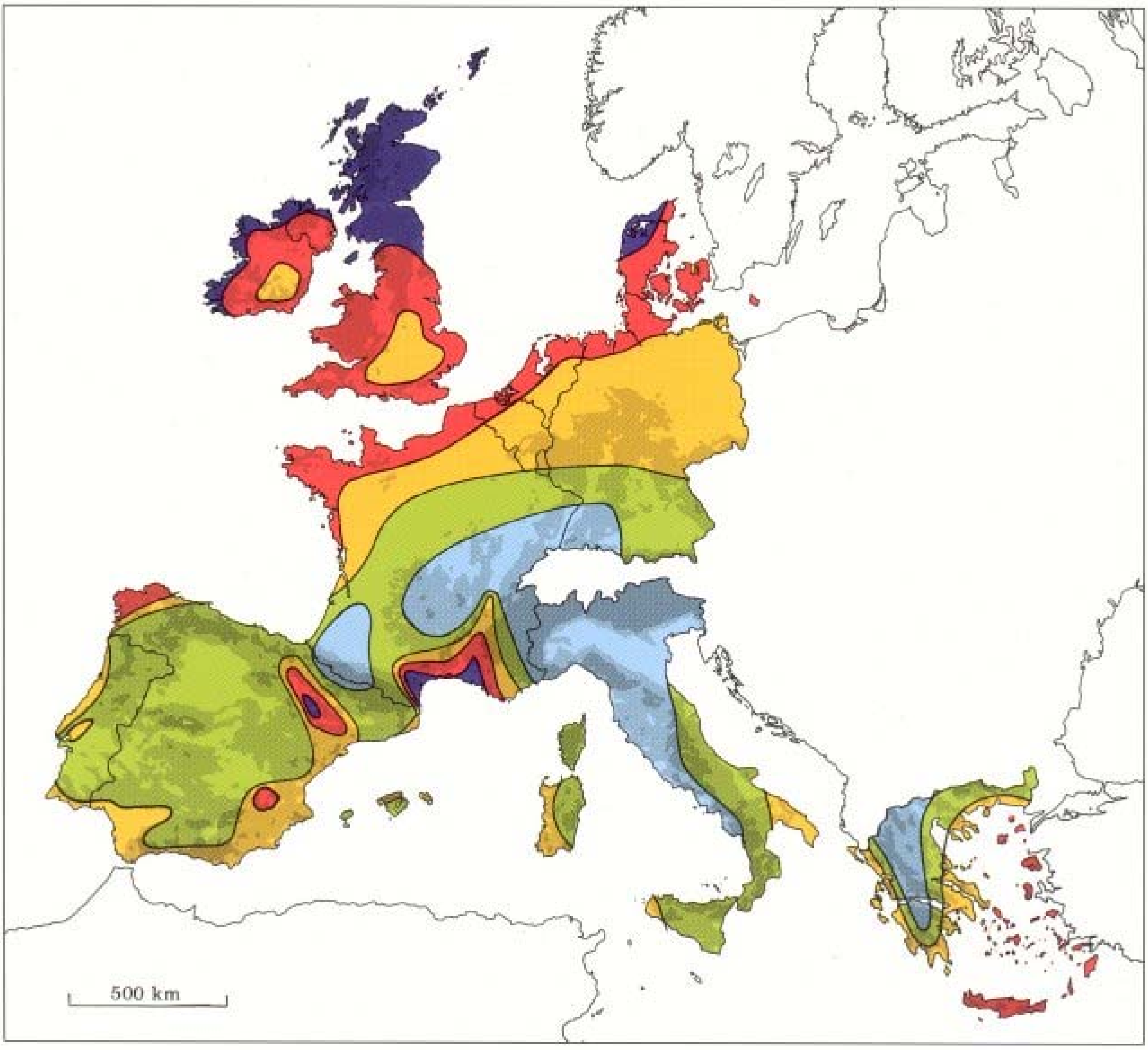
Fig. JA5.1: part of hydroelectricity in the country's total electricity production

Source: BP statistical review 2005

Wind power is starting to get a significant part of energy production (several percents of the total production in some countries like Denmark) but suffers from its intrinsic dependency on weather conditions. A windmill can deliver the equivalent of 2000 hours at full power per year in regular windy sites, mainly along the sea shore (cf. Fig.JA5.2). Due to the relatively weak power of wind with respect to flame, domestic power plants can only offer moderate power supply with windmills of reasonable size.

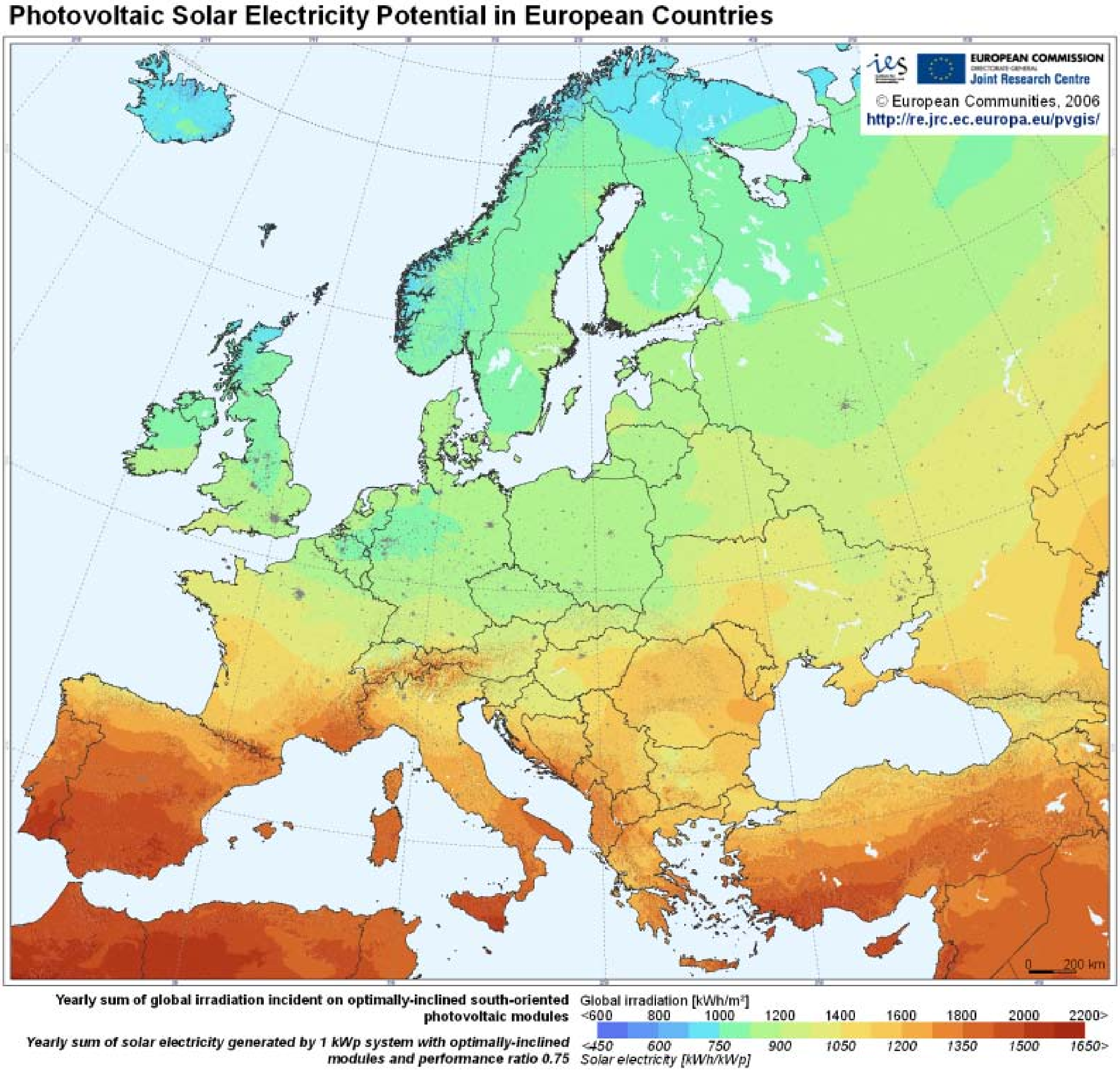
Sun power (photovoltaic) is getting more and more traction for domestic used as well as for power companies. As wind, photovoltaic electricity producing is also depending on latitude and climate. A good figure of photovoltaic panel area per kW power production is about 7 square meters per kW in Europe. Then depending on sun exposition, the total energy can be computed all over the year for every location (cf. Fig.JA5.3).

Unlike conventional thermo electric or nuclear power plants that are concentrated on relatively small areas, windmill or photovoltaic power farms or even hydroelectric dams do not have the same power/footprint ratio. Green power plants have then to be quite big to achieve the same power about the same power than conventional power plants. They are hence more adapted to a local production distributed all over the territory.



Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Fig.JA5.2: Wind resources at 50 metres above ground level for 5 different topographic conditions
Source : *European Wind Atlas*. Copyright © 1989 by Risø National Laboratory, Roskilde, Denmark



Source: Photovoltaic Geographical Information System http://re.jrc.ec.europa.eu/pvgis/

5.5.2 Question 2: Power strategies of telecom networks

Current power consumption of telecom equipment and telecom networks

Up to now, equipment compactness (expressed in terms of port, rack and bay densities) has been one of the main criteria in choosing telecom equipment. Power consumption is then derived from the traffic managed by the piece of telecom network equipment. It strongly depends on the amount of electronic processing. Hence, higher layer equipment does consume more power than lower layer and switching do consume more power than transmission (cf. Fig. JA5.4).

The power consumption of a telecom network for a medium size country of several tens of inhabitants has to be counted in GW and represents a considerable amount of money. Power companies provide the primary power source of telecom networks. A secondary power source (usually generators and batteries) is installed by telecom operators in the main nodes to face power breakdowns. All central offices, transmission network nodes and data centres are equipped with such emergency power sources that can supply power for 24 up to 48 hours. So, the network is power secured from the core to the access.

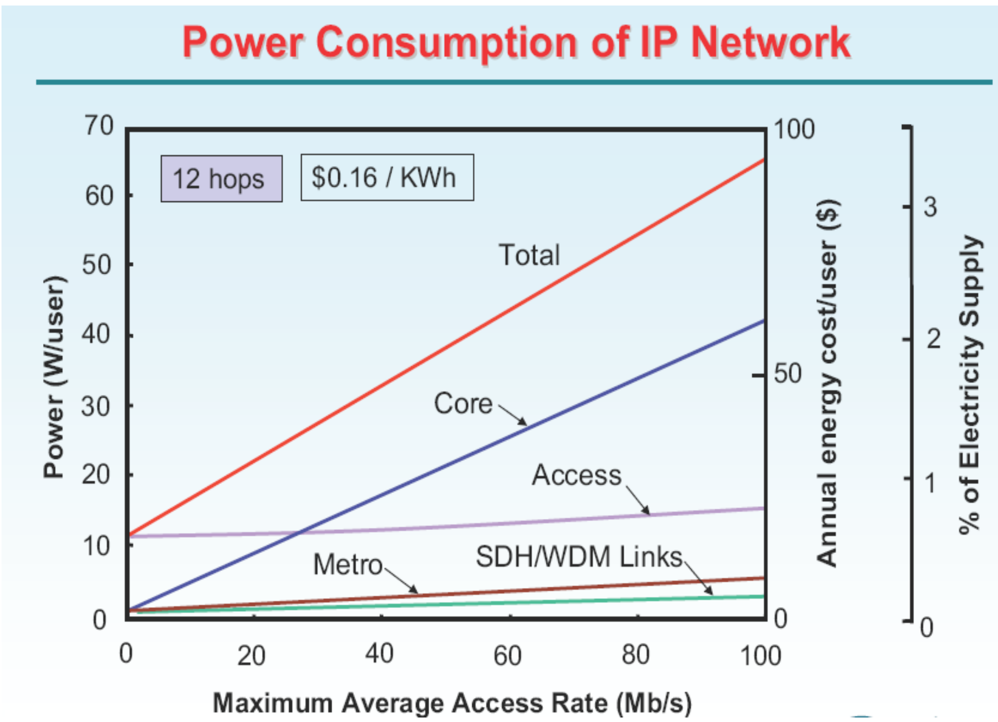


Fig. JA5.4: Power consumption of IP network
Source: R Tucker (OFC 2008)

As the aggregation and core networks do process considerable amount of concentrated traffic, their power consumption is mainly dependent on this parameter. The situation in access networks is different as access network is not mutualised by nature. The power consumption is there mainly dependent on the number of subscribers. The access network absorbs about one third of the total power, but in the context of growing traffic, the core and aggregation networks share in the total network power consumption will continue to increase [ref: Lange et al, paper 5.5.3 ECOC '09].

The immediate strategy for example, FTTH could lower the power consumption by 40% with respect to ADSL [Ref: Baliga et al OFC'08 paper OthT6].

On the customer side of access network, alternative power strategies of the CPE are part of the general home power strategy. The situation is very similar to the one encountered for the aggregation /core network; unless operators want to come back to the old POTS power strategy when telephones set-ups were remotely powered.

Only in-line telecom equipment of the access network may benefit directly from an autonomous powering strategy, which has to be defined properly. This concerns in particular wireless access networks where base stations can be placed in remote locations with no power available on site. The case of wired networks has to be also addressed, although not as critical for remote power strategies are possible.

5.5.3 Question 3: Innovative power strategies (with no major architecture changes)

We have to define what changes renewable energy sources could bring in a green way, i.e. by reducing CO_2 footprint and not harming environment another way (e.g. by the use of polluting batteries, etc…). The often neglected latter point has to be included in order to make a fair statement.

In the case of the primary power source provided by the general electrical power network, the operator strategy or should we say the policy is at least to choose the power vendor offering the maximal amount of green electricity.

When it comes to the secondary emergency power source of network nodes, the telecom operator has more choice regarding the power generation. Considering the non green conventional current solution (fuel powered generators), green power sources can be used as long as the amount of power is producible locally. This is not always possible, depending on the footprint needed. A contradiction appears here between the need for reduced footprint and room space and the need for space for local green power plants. The study has to be done using results of WP21 JA1 and JA2.

5.5.4 Question 4: Network architecture changes in the context of power shortage

This more prospective topic questions traffic growth, equipment power consumption, mutualisation of power sources, network and service architecture modifications, protocol changes, etc…Two topics can be first addressed :

- In the case of structural and lasting power shortage and/or high energy price, the telecom powering strategies could be refunded completely towards more stringent energy saving solutions. One solution could be a comeback to more layer 1/2 processing at the expense of layer 3 packet processing. So, network simplification consisting in expansion of access network transmission and distributed server localizations are ways to be explored. In particular, the use of power efficient optical technologies and the reduction of individual packet processing are ways to reduce the power consumption in the access/metropolitan area network. OBS network architectures are hence good candidates.

- The search for distributed network architectures built based on low consumption /low traffic equipment could also be another way to cope with the energy issue. Avoiding high power consumption nodes, these architectures would rely on many nodes powered by medium sized green power plants.

This activity is more related to JA3 and JA4.

5.6 JA6 Energy-Efficient Optical Network Design

Participants:

Anna Tzanakaki (AIT), Kostas Katrinis (AIT), Lena Wosinska (KTH), Paolo Monti (KTH), Tanya Politi (UoP), Isabella Cerutti (SSSUP)

Responsible person:

Anna Tzanakaki (AIT)

Description:

It is true to say that conventional network design approaches commonly try to optimize specific metrics such as e.g. maximize network resource utilization, minimize blocking probability in an effort to minimize the overall network cost. This entails the development and consideration of specific cost models describing the cost associated with the available network resources and technologies. However, the issue of energy efficiency as an additional constraint that can be considered during the network design phase has not been considered extensively to date. This joint activity focuses on optical network design taking into consideration the energy-consumption as an additional constraint and aims at providing network solutions optimized against power dissipation. This energy-efficient planning approach is based on realistic equipment power consumption models.

More specifically the objectives of this JA are to:

- Focus on detailed network planning and dimensioning taking into account traditional considerations relating to cost-efficiency and capacity availability
- Include energy-consumption as an additional constraint
- Optimize jointly network performance with energy and cost efficiency and identify associated trade-offs

As mentioned above the energy-efficient planning approach will be based on:

- realistic equipment power consumption figures available in the literature
- network equipment specifications and relevant models

In the context described above relevant activities have already been initiated by specific partners and framework for collaborative work are currently being planned. More specifically:

5.6.1 Contribution AIT

A WDM optical network design tool has been developed. This is modeled as a set of OXCs interconnected with fibre links. A Linear cost model has been used to formulate the dimensioning problem as an Integer Programming Problem (ILP). A static input traffic matrix has been used. The cost factors that have been considered are:

- Trenching
- Termination equipment
- Fibre link cost
- OXC dimensions
- Regenerator cost

This initial tool has been enhanced to address energy efficiency considerations. An energy consumption model has been developed using network equipment specifications. This model has been incorporated in the WDM optical network design tool with the aim to provide network design supporting minimized energy consumption. Comparisons and identification of trade-offs between cost and energy optimized network designs can be also performed. This work is still ongoing and the models are currently being finalized.

5.6.2 Contribution KTH

KTH is currently investigating the impact of energy efficiency in the network design problem. KTH plans to take full advantage of the network design tool developed by AIT to study and develop energy efficient network design algorithms/heuristics that will aim at reducing the overall network cost. The proposed algorithms will then be compared, for benchmarking purposes, against the optimal solution provided by the ILP formulation (developed at AIT) and will represent a viable network design approach to be used in very large networks.

5.6.3 Contribution SSSUP

Has worked on “Designing Energy-Efficient WDM Network with Traffic Grooming Capabilities”

Some initial work of JA6 was carried out at SSSUP (Italy) concerning the design of energy-efficient WDM networks with traffic grooming capability. During this year, the work focused on unidirectional ring topologies.

Two architectures that are widely studied are the First-Generation (FG) optical network and Single-Hop (SH) network. In a FG optical network, every node must electronically process all the incoming and outgoing connection traffic, including the in-transit traffic. In a SH optical network, every node electronically processes only traffic that is inserted into or extracted from the network at that node. Electronic processing of the transit traffic is avoided by using wavelength circuits, also referred to as *lightpaths*, that connect the source-destination node pair. Data traffic transmitted on a lightpath propagates all-optically across multiple fibers and nodes up to the intended destination.

A (hybrid) multi-hop (MH) network architecture approach was proposed as a compromise between the FG and SH network. MH architecture makes use of both lightpaths and electronic traffic multiplexing that is performed at few selected intermediate nodes. In MH networks, a tributary signal is allowed to be transmitted through a sequence of lightpaths and may undergo Optical-Electrical-Optical (OEO) conversion, signal regeneration, and electronic switching at only some selected intermediate nodes. MH networks provide some advantages over the FG and SH networks. First, data traffic can be multiplexed (or groomed) in the electronic domain to efficiently exploit the coarse bandwidth of the outgoing lightpaths. Moreover, the OEO conversion occurring at these nodes constitutes an electronic 3R regeneration (Reamplification, Reshaping, and Retiming) of the optical signals. This signal regeneration overcomes the power losses and the degradation due to various transmission impairments. Thanks to the aforementioned advantages, MH networks require a lower CAPEX compared to FG and SH networks, as shown in [1] for different cost scenarios (e.g., fiber costs and line terminal costs), traffic loads, and network topologies.

However, when considering OPEX due to power consumption of the network, the cost-effectiveness of the different architectures may need to be re-evaluated. The design of a unidirectional WDM ring based on either a FG, SH, or MH architecture is optimized, with the objective of minimizing the OPEX cost due to power consumption. Power consumption of the equipments required in the network, such as line terminals, and add-drop multiplexers (ADMs), is quantified according to [3]. The designs at minimal power consumption are compared for various connection rate, ring size, and various scenario of power consumptions in the optical and electronic components of the ADMs.

A5.6.3.1 Network Architecture Power Budget

This section describes the node architecture model that is adopted to evaluate power consumption in FG, SH, and MH networks. In MH rings, the node architecture is based on a hybrid ADM. It includes an Optical ADM (OADM) [4] and a Digital cross-connect (DXC). In the OADM, lightpaths can be transparently transmitted, added or dropped. When bypassing a lightpaths, a wavelength selective switch (WSS) fabric, along with wavelength converters and a line power amplifier, are required. When adding a lightpaths, a tunable transmitter (i.e., E/O converter) is required. When dropping a lightpath, a receiver (i.e., an O/E converter), that might be preceded by a low-noise amplifier, is required. Electronic input and output buffers are necessary for add and drop functionalities, respectively.

In the DXC, connection traffic can be electronically switched from the electronic input ports to the electronic output ports. Thus, traffic can be either re-groomed on a different lightpath, or can be dropped at the local port. Once received by the DXC, signal is 3R regenerated.

Nodes of FG rings consist of DXC only. Nodes of SH rings consist of OADM only.

Given one of the above node and network architectures, the problem of evaluating (and minimizing) the overall power consumption in a WDM unidirectional ring, while satisfying all the connection requests can be formulated as an integer linear programming (ILP) problem. ILP formulation accounts for the above mentioned electronic and optical components and is derived from [1]. Power consumption of the electronic switch fabric in DXC and of the WSS fabric in the OADM is assumed to be proportional to the number of ports. Number of ports is defined as the maximum among the input or output ports, that are required for terminating lightpaths and local ports in a DXC or for bypassing, adding, and dropping lightpaths in a WSS.

A5.6.3.2 Results

A WDM network with unidirectional ring topology operating at 40 Gb/s channels is considered. A connection is required between each node pair. Link lengths are such that power amplification is required only at the nodes (e.g., below 100 km). Optimal results are obtained by solving the ILP formulation with a commercially available solver.

Power consumption of network equipment is derived from [3]. Transmitter power consumption is 108 mW and includes a high power E/O converter (100 mW) and a buffer (5 mW). Receiver power consumption is 23 mW and includes an O/E converter (10mW), a buffer (5mW), and a low-noise pre-amplifier (5mW). Per-port power consumption of the DXC is indicated as *Pe*, and accounts for power consumption of the electronic switch fabric. Per-port power consumption of the OADM is indicated as *Po* and accounts for power consumption of the WSS, line power amplifier, and low-noise preamplifier.

Fig. JA6.1 shows the total (network) power consumption versus the connection traffic rate (from 3 to 40 Gb/s) in a 6-node ring and 10-node ring, respectively, for FG, SH, and MH architectures. In the figures, power consumption for the electronic and the optical switch fabric are, respectively, *Pe* = 189 mW and *Po* = 197 mW per port [3]. For such traffic loads, SH architecture requires always one lightpath for each connection. Thus, power consumption is independent on the load. In FG and MH architectures, power consumption increases with the load as a large number of lightpaths is required. The breakpoint between FG and SH indicates that the use of just optics may save power at high load, i.e., when traffic grooming may not help to further reduce the resources utilization and, thus, resource power. MH architecture achieves power saving in the 10-node ring. In the 6-node ring, MH power consumption is higher or comparable to FG power consumption. This controversial result is due to the more complex (hybrid) ADM architecture in MH networks, consisting of both DXC and OADM. This lead to power consumption for both the electronic and the optical components and may lead to a higher overall power consumption.

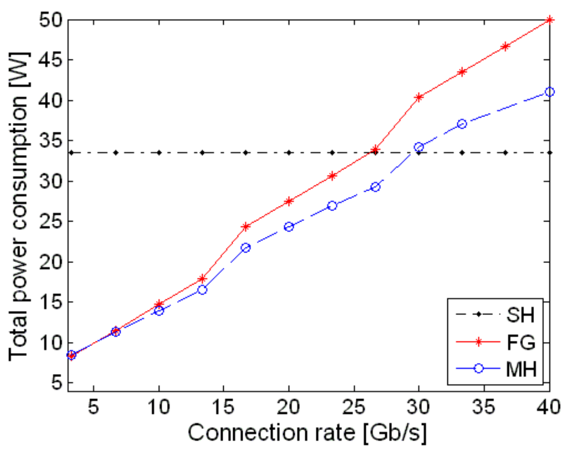


Fig. JA6.1: Total power consumption vs. connection rate in a 10-node ring for *Pe* = 189 mW, *Po* = 197 mW

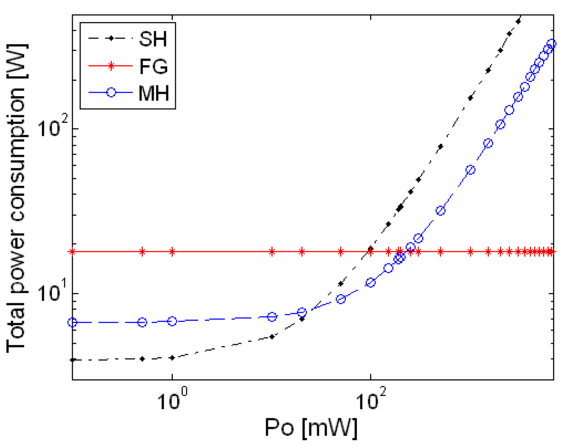


Fig. JA6.2: Total power consumption vs. *Po* in a 10-node ring for *Pe* = 189 mW

Fig. JA6.2 shows the total power consumption in the network as a function of *Po* for the three architectures, when *Pe* = 189 mW and the connection rate is 1/3 of channel rate (40 Gb/s). Power consumption in FG architecture is constant and given by electronic components only. Power consumption in FG and MH increases with *Po* at a similar rate. At low values of *Po*, MH power consumption is higher than SH power consumption, as MH nodes require both OADM and DXC. However, at higher values of *Po*, MH is more power-efficient than SH, as optimal MH design can make use of the less-expensive electronic components.

A5.6.3.3 Conclusion

The presented study is one of the first works on power saving network architectures. Power saving network designs are achieved by minimizing the network power required for both, optical and electronic, components. Both the power consumption of electronic-versus-optical components and the traffic load are shown to drive the power-efficiency of the different architectures. Power consumption of all-optical (SH) networks is lower than that of first-generation (FG) networks, not only when power consumption of optical components is low, but also when connection rate is close to the wavelength capacity. In most scenarios, multi-hop (MH) network outperforms SH and FG networks, thanks to MH capability to exploit optical transparency and perform traffic. However, under some scenarios of cost and traffic, the more complex (hybrid) ADM architecture, having both optical and electronic components, may turn the advantages of MH architectures into a higher power-consumption.

5.6.4 Future plans

It is planned to carry out one mobility action between AIT and KTH in the framework of this work and produce a conference paper either at ECOC 2010 or OFC20011 and a journal paper.

5.6.5 References

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