



D1.5 Final Report for the IRA “Comparison of circuit versus packet switching paradigm in terms of energy efficiency”

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Project Coordinator: Name: Marco Ajmone Marsan
Phone: +39 011 5644032
Fax: +39 011 5644099
e-mail: ajmone@polito.it

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Editors:	Achille Pattavina – CNIT (PoliMi) Francesco Musumeci – CNIT (PoliMi)

Abstract:

This deliverable presents the activities within the Integrated Research Action (IRA) 1.2 of the TREND Network of Excellence (NoE). The energy-efficiency of circuit and packet switching paradigms is first investigated in the context of optical networks. Then, a hybrid circuit-packet switching paradigm, the Time Driven Switching, is considered, and its energy benefits are evaluated in comparison to traditional solutions. Next, the energy efficiency of VoIP and PSTN have been compared, evaluating also several energy-wise schemes conceived to reduce their energy consumption. Furthermore, continuous and burst transmission mode have been analyzed in the case of ADSL lines. In particular, it has been investigated the achievable savings that can be obtained by adopting burst transmission mode ADSL modems, and implementing sleep mode policies, with respect to employing continuous transmitting devices.

The final outcomes of this IRA are summarized as conclusion.

Keyword list: Packet Switching, Circuit Switching, Internet Protocol, Wavelength Division Multiplexing, Optical Networks, Time Driven Switching, Voice over Internet Protocol, Public-Switched Telephone Network, Burst transmission mode, ADSL modem, Sleep mode

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Executive Summary

This deliverable shows the results obtained by partners and Collaborating Institutions (CIs) of the TREND FP7 Network of Excellence (NoE), in the framework of the Integrated Research Action (IRA) 1.2, titled “Comparison of circuit versus packet switching paradigms in terms of energy efficiency”.

This IRA is part of the TREND Work Package (WP) 1 “Assessment of power consumption in ICT” and its key goal is to compare the circuit switching and packet switching paradigms from an energy perspective.

The core part of this document can be identified with the following topics.

The circuit and packet switching paradigms are first compared in the context of optical networks in Section 2. We will refer to Internet Protocol (IP) over Wavelength Division Multiplexing (WDM) networks, where layer 3 data units, i.e., IP packets, are transported through optical fibers at the optical WDM layer. A comparison between the two switching paradigms is carried out from the point of view of equipment cost and power consumption. Moreover, we also investigate the effect of various parameters, such as network topology and devices line rate, on the energy efficiency of the two switching paradigms.

In Section 3 an innovative switching paradigm, known as Time-Driven-Switching (TDS), is reported. This switching architecture can be identified as a “virtual circuit” switching paradigm, as it provides the capability of establishing end-to-end optical circuits switched by network nodes on a slotted-time basis. This enables the possibility of grooming traffic belonging to different source/destination pairs *directly in the optical domain*, and taking further energy advantages as electronic processing, accomplished in IP routers, can be avoided when performing traffic grooming. In this report, the power consumption of TDS networks is compared to traditional solutions, and its performance is also evaluated from the cost and blocking probability point of view.

In Section 4, the telephone networks services Public-Switched Telephone Network (PSTN) and Voice over Internet Protocol (VoIP) are analyzed in terms of energy consumption by means of measurements on the PoliTo campus systems, modelling and actual experiments. In this report, furthermore, the main lines of intervention to introduce energy efficiency in the two telephone networks are proposed.

The energy efficiency of continuous and burst transmission mode is investigated in Section 5. We have evaluated the energy consumption reduction that can be achieved by introducing burst mode ADSL modems which can implement sleep mode policies. After introducing two different sleep mode policies, we have evaluated the achievable energy and monetary savings using actual traffic profiles.

Finally, Section 6 summarizes the outcome of this IRA in terms of publications and the conclusions of the activity are drawn in Section 7.

1. Introduction

Telecommunication networks have historically been dominated by a circuit switching paradigm. However, the last decades have seen a clear trend towards packet switched networks, thanks to their flexibility in providing capacity to the end users at reasonable costs, also adjusted according to the kind of service required by customers. Nonetheless, besides the traditional evaluation of costs (e.g., in the devices deployed in the network) and network performance (e.g., in the quality of service provided), the power consumption issue has become stringent recently, when doing both the design and operation of telecommunication networks and, more generally, in the whole Information and Communication Technology (ICT) sector.

The aim of the TREND IRA 1.2, “Comparison of circuit versus packet switching paradigms in terms of energy efficiency”, presented in this deliverable is to go one step further in the comparison between circuit and packet switching, by assessing the benefits of both paradigms from the energy consumption viewpoint.

According to Ref. [1], the ICT currently consumes about 1% of the total world electricity and telecommunication networks represent about 25% of this amount. More recent estimations [2] have shown that the worldwide electricity consumption of telecommunication networks (including operator networks, office network equipment, and customer premises network equipment) has been estimated to be 350 TWh in 2012, accounting for 1.8% of the total worldwide electricity consumption in the same year.

Currently, the highest power consumption in telecommunication networks is attributed to the wired and mobile radio access network, while the backbone network, in contrast, is estimated to account (in 2012) for only about 8% of the total network consumption [3]. However, the energy consumption in access networks is proportional to the number of connected subscribers, while the consumption in the backbone network is proportional to the traffic volume [3]. With the expected increase in traffic volume, the highest consumption growth rate is expected in the backbone networks. For this reason, in large part of this activity we have focused our analysis in the energy consumption comparison of circuit and packet switching, considering optical backbone networks.

This document consists of the following main parts: Sections 2-to-5 represent the core part of the deliverable, where technical contributions are reported. The outcomes of the IRA, in terms of papers are reported in Section 6, while the conclusion of the activity is drawn in Section 7.

Most of the studies presented in this deliverable have been performed through joint activities between TREND partners and/or CIs, and several publications have been produced in this context or are planned for the near future. Each activity is presented with a short “ID card” indicating the topic, factual results and papers generated, as well as the involved partners/CIs.

The authors that contributed to this document are listed below:

Partner/CIs short name	Name of authors
CNIT (PoliMi)	Achille Pattavina, Francesco Musumeci
iMinds	Ward Van Heddeghem
PoliTo	Edoardo Bonetto, Faheem Khuhawar
TUB	Filip Idzikowski

2. Energy-Efficiency Comparison of Circuit and Packet Switching Architectures in the Context of Optical Networks

In this section the circuit and packet switching paradigms are compared in the context of optical networks. We will refer in this context to Internet Protocol (IP) over Wavelength Division Multiplexing (WDM) networks, where layer 3 data units, i.e., IP packets, are transported through optical fibers at the optical WDM layer. In this scenario, the circuit and packet switching solutions are also referred to as bypass and non-bypass architectures, respectively. Two contributions are reported in this section.

In the first part of this section, the comparison between the two switching paradigms is carried out from the point of view of Capital Expenditure (CapEx) and Operational Expenditure (OpEx), which is basically driven by the power consumed by the network.

In the second part of this section, we investigate the effect of various parameters, such as network topology and devices line rate, on the energy efficiency of the two switching paradigms.

2.1 CapEx/OpEx Evaluation of Circuit vs Packet Switched Optical Networks

Summary: A power and cost comparison of circuit and packet switching paradigms is carried out in the context of IP-over-WDM networks. For both paradigms, we provide a network design strategy that minimize either the CapEx (cost) or OpEx (power consumption) and then we quantitatively identify and discuss under which conditions (network size, load, etc.) one paradigm is more convenient than the other from a cost and/or power consumption perspective.

Publication: This work is published in the Proceedings of *ONDM 2013 Conference* with the title “CapEx/OpEx Evaluation of Circuit vs Packet Switched Optical Networks” [4].

Contributing partners: PoliTo, CNIT (PoliMi)

2.1.1 Circuit vs Packet Switching

In IP-over-WDM networks, the circuit switching paradigm is implemented by establishing end-to-end optical circuits (called lightpaths) for every traffic demand between two IP routers. In this case, the established optical circuits are maintained at the optical layer from the source to the destination node, without performing electronic switching or grooming of traffic flows belonging to different source-destination pairs into a given lightpath. Thus, as shown in Figure 1(a), the intermediate IP routers are optically bypassed (hence, this paradigm is commonly referred to as optical-bypass) via Optical Cross-Connects (OXC), which perform signal switching at the WDM layer, i.e., at the wavelength granularity. We assume that at each node, transit lightpaths are regenerated using WDM transponders.

On the other hand, the packet switching solution can be identified with the so-called non-bypass scenario. Here, the wavelengths carried by optical fibers are converted into the electrical domain and traffic is electronically switched at each node (see Figure 1(b)), where IP packets are processed by the routers and multiplexed into optical channels (i.e., traffic demands are groomed) to be optically sent towards the next node in the network.

To evaluate the power consumption and cost of the two switching paradigms, the IP-over-WDM nodes have been modeled according to Refs. [5] and [6].

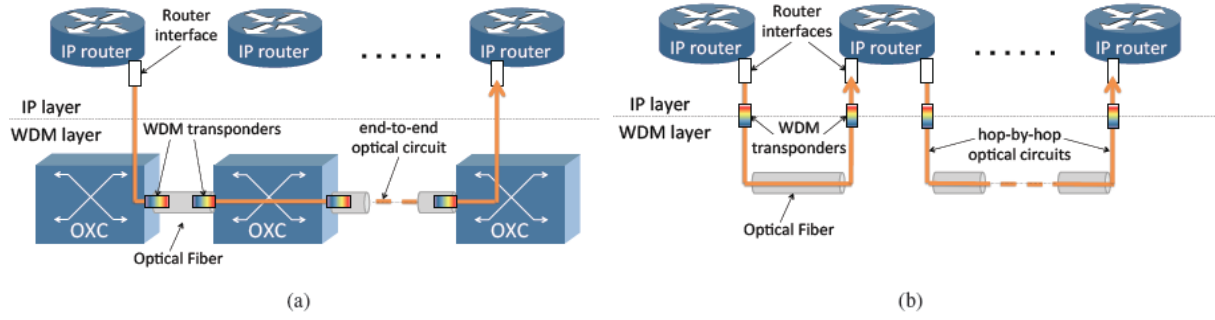


Figure 1 (a) Circuit Switched (bypass) architecture; (b) Packet Switched (non-bypass) architecture.

The IP router is modeled according to the *Cisco CRS* router series. The main building block of the router is the Basic Node (BN), which is in charge of the switching, control and management functions and also includes the power-supply and cooling functionalities. The BN has a modular structure, composed by either one Line Card Shelf (LCS) or by several LCSs interconnected using one or more Fabric Card Shelves (FCSs), if more switching capacity is needed. The FCS contains the switching fabric required to interconnect the LCSs. A single FCS can connect up to 9 LCSs. If more LCSs have to be connected, the required number of FCSs can be computed as $\lceil \text{LCS}/9 \rceil$. Each LCS can host up to 16 Line Cards (LCs), which provide the physical connectivity of the basic node to the network. Thus, the number of required LCSs is equal to $\lceil \text{LC}/16 \rceil$. A LC is composed by one Slot Card (SC) and by one Port Card (PC), all operating in full duplex. The SC implements the Layer 3 Forwarding Engine, while the PC is the physical interface of the LC. We consider SC operating at 40 Gbit/s and as PC we employ a Short Reach Interface (SRI), namely the Cisco CRS Single-Port OC-768c/STM-256c POS Interface Module. Finally, the long haul transmission is performed using a WDM transponder operating at 40 Gbit/s.

The two switching paradigms differ for some distinctive characteristics related to the node model. The differences regard the number of LCs to install at the routers, the number and the positioning of the WDM transponders and the presence or not of OXCs. In the following, we outline these characteristics for both network architectures.

1) Circuit switching: in this architecture the number of LCs to be installed at a router is equal to the maximum between the number of lightpaths that are generated and those that are terminated at the node. We denote with Y_{ij} the number of lightpaths generated at node i and destined to node j . Thus, being N the set of all network nodes, the number of LCs required at the router of node i can be computed as:

$$LC_i = \max \left(\sum_{\substack{j \in N \\ j \neq i}} Y_{ij}, \sum_{\substack{j \in N \\ j \neq i}} Y_{ji} \right)$$

In the bypass architecture transit lightpaths are switched at the WDM layer, so an OXC is co-located at each node. We consider that an OXC has a maximum number of fiber ports T equal to 10, as in Refs. [5] and [6], and we denote with d the number of network-side fiber ports, while the number of fiber ports connected to the router is indicated with a (thus, $T = a + d$). As we consider an opaque bypass solution (no wavelength continuity is considered), other than from transmitting or receiving the lightpaths generated or terminated at a node, WDM transponders are employed also to regenerate transit lightpaths. Thus, it is necessary to install a number of transponders equal to the total number of lightpaths flowing on all the fibers connected to the node. In particular, for each fiber, the number of lightpaths is computed considering the maximum number of lightpaths flowing in both directions, as WDM transponders operate in full duplex. Then, denoting with L_{ij} the number of lightpaths

flowing on the fiber from i and j , the maximum number of WDM transponders for the fiber i - j is $\max(L_{ij}; L_{ji})$. Instead, the total number of WDM transponders at node i , given that N_i represents the set of nodes that are connected to node i , is given by:

$$TSP_i = \sum_{j \in N_i} \max(L_{ij}; L_{ji})$$

2) Packet switching: in this case, the optical channels are converted into the electrical domain at each node. Thus, no OXCs are installed at the nodes, and the number of installed LCs is equal to the number of WDM transponders. Since both LC and WDM transponder are full duplex, the number of devices required to support the communication between a pair of adjacent nodes is equal to the maximum between the number of lightpaths flowing in the two directions between two pair of nodes i and j , thus:

$$LC_i = TSP_i = \sum_{j \in N_i} \max(Y_{ij}; Y_{ji})$$

2.1.2 Cost and Power Consumption Models

(a) IP Routers

The cost and the power consumption of the router installed at a generic node i , $C_{Router,i}$ and $P_{Router,i}$, depend on the number of LCSs, FCSs and LCs equipped in the router. They can be computed considering the contributions of the BN and Line Cards, i.e.:

$$\begin{aligned} C_{Router,i} &= C_{BN} + C_{LineCards} \\ P_{Router,i} &= P_{BN} + P_{LineCards} \end{aligned}$$

where we indicate with C_{BN} (respectively, P_{BN}) and $C_{LineCards}$ (resp., $P_{LineCards}$) the cost (resp., power consumption) of the BN and of the LCs.

To compute the cost and power consumption of the BN, we take into account the number of LCSs and FCSs, denoted with LCS and FCS , respectively. Moreover, C_{FCS} (respectively, P_{FCS}) and C_{LCS} (resp., P_{LCS}) indicate the cost (resp., power consumption) of FCCs and LCSs. Thus we obtain:

$$C_{BN} = \begin{cases} C_{LCS} & \text{if } FCS = 0 \\ LCS \cdot (C_{LCS} + 12.494) + FCS \cdot C_{FCS} & \text{otherwise} \end{cases}$$

which is extrapolated from Ref. [6], and

$$P_{BN} = \begin{cases} P_{LCS} & \text{if } FCS = 0 \\ LCS \cdot P_{LCS} + FCS \cdot P_{FCS} & \text{otherwise} \end{cases}$$

The cost and power consumption of the installed LCs are computed as:

$$\begin{aligned} C_{LineCards} &= LC_i \cdot (C_{SC} + C_{SRI}) \\ P_{LineCards} &= LC_i \cdot (P_{SC} + P_{SRI}) \end{aligned}$$

where LC_i represents the number of LCs installed at the router of node i , C_{SC} (respectively, P_{SC}) and C_{SRI} (resp., P_{SRI}) are the cost and the power consumption of a SC and a SRI.

(b) WDM links

At the WDM layer, we take into account the power consumed in all the used fiber links. Each fiber is assumed to support 40 wavelengths.

The power consumed by a fiber link is determined by the number of Optical Line Amplifiers (OLAs) installed and by the two WDM terminals (one for each edge of the fiber), including a WDM multiplexer/demultiplexer and a booster- or a pre-amplifier. We consider that one OLA is deployed every 80 km. One OLA system includes an optical amplifier (erbium-doped fiber amplifier (EDFA) or Raman) and some additional electronics [5]. Thus, being d_{ij} the distance in km between nodes i and j , the link power consumption is:

$$P_{link,ij} = \left(\left\lceil \frac{d_{ij}}{80} \right\rceil - 1 \right) \cdot P_{OLA} + 2 \cdot P_{WDMterm}$$

(c) Total Network Cost and Power Consumption

The total network power consumption, P_{NET} , is computed as:

$$P_{NET} = \sum_i (P_{Router,i} + TSP_i \cdot P_{TSP}) + P_{OXC} + P_{links}$$

where TSP_i is the number of WDM transponders used at node i , P_{TSP} is the power consumed by one transponder, P_{OXC} is the power consumed by all the OXCs (neglected in the case of packet switching architecture) and P_{links} includes the power consumed by all the OLAs and WDM terminals of the used fiber links.

The total network cost, C_{NET} , is computed as:

$$C_{NET} = \sum_i (C_{Router,i} + TSP_i \cdot C_{TSP}) + C_{OXC}$$

where C_{TSP} is the cost of a WDM transponder and C_{OXC} represents the total cost of the all OXCs installed in the network. Note that the cost associated to WDM links is not included in the circuit vs. packet switching comparison, as we assume that the number of deployed fibers and the related equipment (OLAs and WDM terminals) do not depend on the switching paradigm under consideration.

2.1.3 Results

To perform the CapEx/OpEx comparison of the circuit vs. packet switching paradigms, we exploited a heuristic approach based on genetic algorithms (GA), which has been validated by comparing the results obtained with an Integer Linear Program (ILP) formulation over two network topologies. The algorithms perform the network design under static traffic conditions (i.e., given a static traffic matrix of demands between source-destination pairs we design the network which is able to accommodate all the demands), aiming at the minimization of the total network cost or power consumption.

The two switching paradigms have been evaluated over several different realistic network topologies, as detailed in Ref. [4], where the power consumption values considered for the various network devices are also indicated. For each topology, we perform the CapEx/OpEx comparison between the two switching paradigms, considering increasing traffic loads. Traffic matrices have been randomly generated and the value of each traffic demand is chosen uniformly between 0 and a maximum value M , which varies according to the traffic scenario. We consider values of M in the range 10-100 Gbit/s with a granularity of 10 Gbit/s. We report in Figure 2 the results obtained for the 22-nodes GÉANT topology [7] exploiting the heuristic approach.

It is evident that the factor that most influences the network performance is the traffic load for both the CapEx and OpEx point of view. For low traffic loads, the packet switching paradigm is the most convenient architecture. As the traffic load of the network increases, the circuit switching paradigm is preferable. The fact that packet switching has to be preferred at low loads depends on its capability of aggregating traffic demands. In these traffic scenarios,

the lightpaths established in the circuit switching scenario are characterized by a very low utilization, since traffic demands are not groomed, but they are directly sent from sources to the destinations. Instead, the packet switching performs effectively traffic grooming while the electronic switching required at each hop does not change the power consumption, because the amount of transmitted traffic is low. As the traffic grows, circuit switching performs better

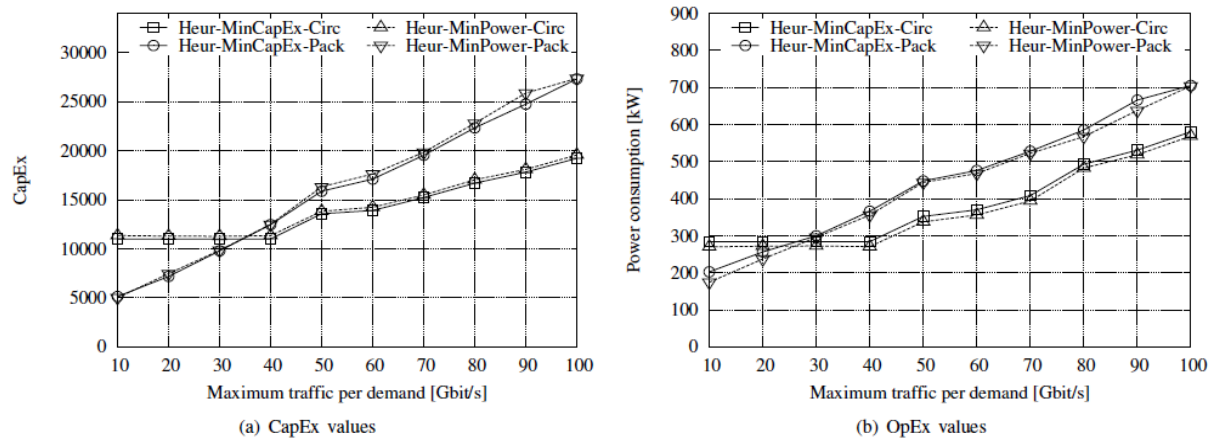


Figure 2 Circuit vs Packet Switching comparison for the GEANT network topology: (a) CapEx; (b) OpEx.

since it avoids the electronic switching exploiting the optical transparency provided by the OXC. Thus, packet switching is less efficient due to the large amount of resources required to electronically switch the traffic.

Moreover, it is worth noting that the difference between minimizing the power consumed by the network (i.e., the OpEx) and the CapEx is modest (minimizing network resources cost induces also a power efficient solution), yet not negligible.

2.2 On the Effect of Network Topological Parameters and Devices Line Rate Capacity on the Power Consumption of Circuit and Packet Switching in Optical Backbone Networks

Summary: A power consumption comparison of circuit and packet switching paradigms in the context of optical networks is carried out considering the effect of network topology features, such as network size and mesh degree, and transport line rates. We assess under which conditions (topology/traffic) each paradigm is the most energy-friendly.

Publication: This work has been submitted to the *Online GreenComm 2013 Conference* with the title “Power Consumption Evaluation of Circuit-Switched versus Packet-Switched Optical Backbone Networks” [8].

Contributing partners: iMinds, CNIT (PoliMi), TUB

2.2.1 Network and Power Model

Similarly to Section 2.1, we refer to IP-over-WDM backbone networks to compare the circuit and packet switching paradigms. An optical WDM layer, consisting of OXCs interconnected via optical fibers, provides the physical connectivity between IP routers placed at an upper IP layer, as shown in Figure 3.

IP routers are equipped with line cards, providing short reach interfaces. Different line rates granularity are considered for the various router interfaces: local clients connect to the router using 1 Gbit/s interfaces, while the network-side interfaces work either at 2.5 Gbit/s, 10 Gbit/s or 40 Gbit/s (which we refer to as 2.5G, 10G and 40G). Depending on the demand bit

rate, one or more interfaces can be required per demand. In the WDM layer, long reach transponders (TXPs) with the same capacity as the IP layer line cards (i.e., 2.5G, 10G or 40G) provide WDM optical signals, switched via OXCs. A mux/demux (included in the OXC) aggregates/separates up to 40 channels on/from a fiber. A booster and pre-amplifier (included in the OXC) amplify all channels in a fiber pair respectively upon leaving and entering one

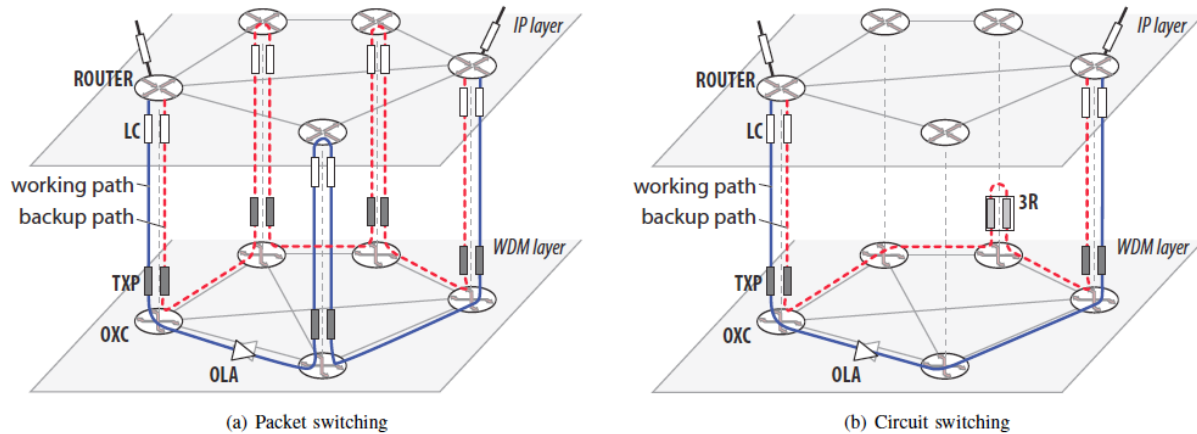


Figure 3 (a) Packet and (b) circuit switching architectures. End-to-end demands are served establishing both the bidirectional working path (solid lines) and backup path (dashed lines) under a 1+1 protection scheme.

node. Within optical fiber links, one OLA is placed every 80 km and amplifies all channels carried by the fiber. For link lengths longer than the regenerator span, taken to be 1500 km, the signal is switched by the OXC to pass through a 3R regenerator, which can be identified by a couple of back-to-back transponders.

Under the packet switching paradigm (see Figure 3(a)), all the traffic in a node (not only the originating and terminating, but also the transit traffic) is processed by the IP router. Doing so provides the opportunity to groom traffic of demands from different sources that are destined to the same outgoing link, thus wavelengths can be more-efficiently filled.

Under the circuit switching paradigm, dedicated optical circuits are set up between the source and destination IP routers, as shown by the solid line in Figure 3(b). This allows the transit traffic to remain in the optical domain and thus bypass the IP router. Note that, depending on the ratio between the traffic demand bit rates and the channel line rate, lightpaths might not be optimally used. For a given set of demands, this might result in a higher number of channels required compared to packet switching.

In both switching cases, we assume a 1+1 protection scheme at the IP layer. Under this scheme, a backup connection (dashed line in Figure 3) is *simultaneously* routed over a link-disjoint path with respect to the primary one, so that if the working path fails, the traffic can be instantaneously switched over to the backup path.

The power consumption values assumed for each equipment type are taken from Ref. [5], with the exception of the 40G coherent transponder data, which is based on Ref. [9]. The power-per-port values for the IP router include both the power consumed by the line card and the basic node (i.e. router chassis and shelves). The OXC degree is defined as the number of network-side bidirectional fiber ports, assuming that all fiber ports are added/dropped at the tributary side (i.e., towards the IP layer). The power consumption value used for the OXC includes mux/demux stages as well as pre and booster-amplifiers. In addition to the total power consumed by the devices, we assume that an equal amount of overhead power is consumed for site cooling and power supply losses. This additional power is typically taken into account by considering a multiplying factor for the devices power consumption, i.e., the Power Usage Effectiveness (PUE), assumed as equal to 2 in this study.

2.2.2 Topologies Definition

To understand the influence of the connectivity degree and network size (intended as total number of nodes) on the power consumption of the two switching paradigms, we consider a total of nine artificially generated topologies, ranging from minimally meshed (ring), over medium-meshed (half-mesh) up to maximally meshed (full-mesh) networks. For all of the networks, the IP topology is taken identical to the WDM topology, and all links are bidirectional. For each of these variations we consider networks with the number of nodes N equal to 10, 15 and 25. We define the mesh degree M of a network as the ratio of the average node degree of the network under consideration (d), and the node degree of a full-meshed network having the same number of nodes as the considered network ($d_{mesh}=N-1$), so we get $M=d/d_{mesh}$. The half-mesh networks have a mesh degree of $M=0.5$, resulting in a node degree $d_{half-mesh}=(N-1)/2$. To generate these half-mesh networks we (a) start from a ring network with the required number of nodes N and number of links $L_{ring}=N$, (b) then calculate the number of links to add to have the average degree $d_{half-mesh}$, (c) then add these links distributed evenly across the ring (connecting the most distant nodes, based on the hop count, first). Note that the number of links in such a half-mesh networks is given by $L=L_{ring}+N*(d-2)/2= N*(N-1)/4$.

For the link lengths, which influence the power consumption of the OLAs and 3R regenerators, we assume that each of the generated networks cover a geographical area with a diameter of 2500 km (which is comparable to a country-sized network). The link lengths are then taken to be 2500 km divided by the number of links in a ring network. For the half-meshed and full-meshed networks we take all other links to have the same length (though this is topologically unrealistic).

2.2.3 Network Design Methodology

We compare the circuit vs. packet switching networks by performing the IP-over-WDM network design, carried out with a java-based dimensioning tool. Given a static traffic matrix, i.e., a set of demands between source/destination nodes along with the required traffic, the Routing, Fiber and Wavelength Assignment (RFWA) is performed for all the demands. Then we evaluate and compare the power consumption of the two switching paradigms.

In order to achieve 1+1 protection at the IP layer, the two shortest link-disjoint paths between the source and destination nodes are selected using a minimum cost flow algorithm, where we assume the overall path length, expressed in number of hops, as cost. For each demand, wavelength and fiber assignment is accomplished in a first-fit fashion. From the node port counts we derive the power consumption of IP routers, transponders and OXCs. From the link and connection lengths we calculate the number of required OLAs and regenerators, and subsequently their power consumption. For each link, we assume an unlimited number of fibers to be available.

2.2.4 Results

For all the network topologies described above, we generate uniform traffic matrices, i.e., traffic required by every node pair is identical, and obtain the power consumption values under the two switching paradigms considered. Moreover, we also obtain results by varying the demands bit rate, from 1 Gbit/s up to 25 Gbit/s per demand.

In Figure 4 we show the results obtained for the 15-nodes topologies (ring, half-mesh and full-mesh cases) for increasing traffic and considering the various devices line rates (2.5G, 10G and 40G).

It is evident that sparser topologies (i.e., more ring-like) consume more power than topologies with higher mesh degree. This is due to longer paths needed both in the circuit and

packet switching, which causes a much higher number of electronic interfaces in use in the packet switching paradigm. Furthermore, for higher traffic demands the packet switching architecture (dashed lines) consumes more power than the circuit switching architecture (solid lines). On the other hand, for lower traffic the most power efficient architecture of the two depends on the mesh degree and channel capacity.

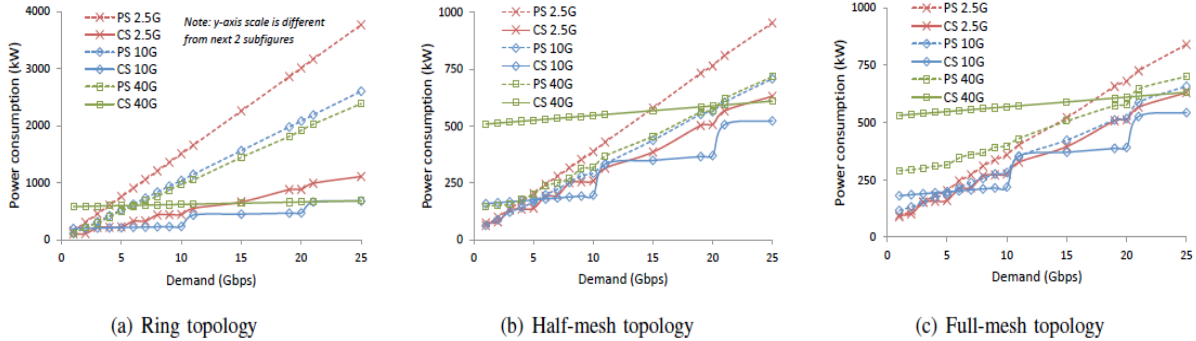


Figure 4 Total power consumption of ring/half-mesh/full-mesh 15-nodes topologies for different devices line rates and increasing average node-to-node traffic demand (CS=Circuit Switching; PS=Packet Switching).

It can be also observed from Figure 4, that the circuit switching architecture exhibits a very minor linear component (e.g., the CS-10G curve is almost flat for demands bit rate values between 12 Gbit/s and 20 Gbit/s), due to the fine granularity of the 1G IP client side ports, and a much more pronounced stepwise component due to the coarser granularity of the IP network side add/drop ports. Such power consumption steps occur when the demand bit rate reaches a multiple of the transmission capacity (2.5G/10G/40G). These dual components make the circuit switching solution preferable only for higher traffic values and, as the devices line rate increases (e.g., considering 40G devices), the cross-point between packet and circuit switching solutions (i.e., the *minimum* demands bit rate value for which the circuit switching has lower consumption than the packet switching) is higher. Further results and more detailed discussion can be found in Ref. [8].

3. Time Driven Switching: a Green Approach for Future Optical Networks

As shown in Section 2, the best solution from the power consumption viewpoint, between circuit and packet switching is not always univocal. In fact, the most energy efficient solution depends on the traffic and topology under consideration. For this reason, it is generally preferable to adopt hybrid solutions, able to exploit the circuit switching capability of optically bypassing power hungry electronic IP routers, and the opportunity of performing traffic grooming as in packet-switched networks, to more efficiently exploit wavelength capacity, especially in low traffic situations.

In order to achieve this compromise and obtain further energy benefits, a recently proposed paradigm, known as Time-Driven-Switching (TDS), has been studied.

This switching architecture can be identified as a “virtual circuit” switching paradigm as it provides the capability of establishing end-to-end optical circuits switched by network nodes on a slotted-time basis, thus enabling the possibility of grooming traffic belonging to different source/destination pairs *directly in the optical domain*, and taking further energy advantages as electronic processing, accomplished in IP routers, can be avoided when performing traffic grooming.

In the following we provide in Section 3.1 a power consumption evaluation of TDS networks and compare it with a hybrid circuit/packet switching IP-over-WDM architecture, where optical circuits between source and destination nodes can be eventually interrupted in some intermediate nodes in case traffic grooming with other flows is useful to reduce the overall energy consumed by the network. Moreover, we provide a performance evaluation for TDS networks from a cost and blocking probability point of view in Section 0.

3.1 Energy Efficiency of Time Driven Switching (TDS)

Summary: We compare the TDS network power consumption with that of traditional IP-over-WDM transport architectures by developing an ILP formulation for the power-minimized network design in both cases.

Publication: The results and considerations shown in the following are published in the Proceedings of *ICC 2011 Conference* with the title “On the Energy Efficiency of Optical Transport with Time Driven Switching” [10] and in the *IET Optoelectronics Journal*, with the title “Energy-Efficiency of All-Optical Transport through Time Driven Switching” [11].

Contributing partners: CNIT (PoliMi), FW

3.1.1 Time Driven Switched Networks

TDS is an optical switching technique which uses a global Common Time Reference (CTR) for implementing the so-called Pipeline Forwarding (PF) of data inside the network [12]. The necessary condition for implementing the PF technique is to have the same clock reference in all switching elements. In TDS networks the so-called Fractional Lambda Switches (FLS) are used and, as they are synchronized with a CTR, such as the Global Positioning System (GPS), they can identify a basic time period called Time Frame (TF). TFs are “virtual containers” for data units and they are switched independently by reconfiguring the optical switches at the end of each TF based on the global time synchronization. By doing

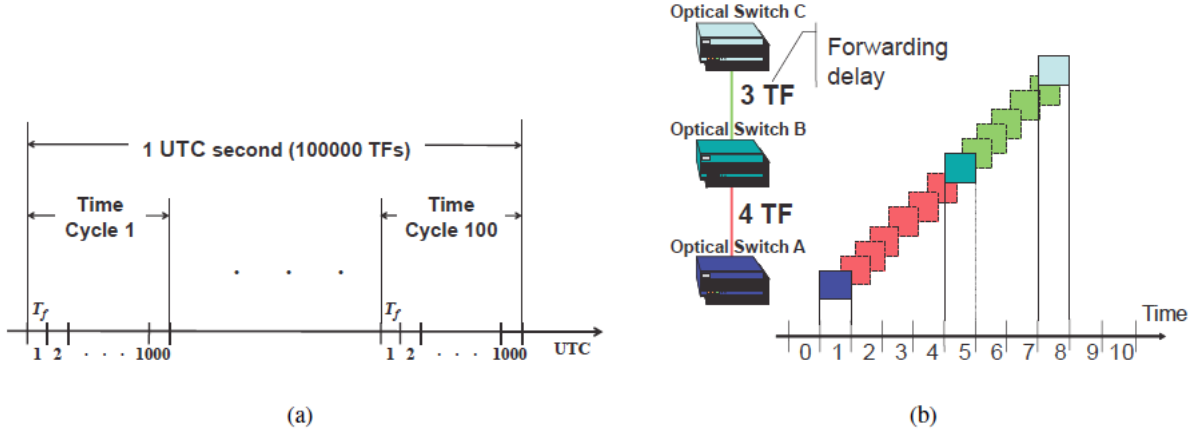


Figure 5 TDS features: (a) common time-reference structure and (b) switching of a Synchronous Virtual Pipe.

so, the aggregation or separation of “fractions” of the optical channel (grooming and degrooming operations) can be performed directly at the optical layer.

TFs are grouped into Time Cycles (TCs), which are further grouped into super cycles, each lasting one Universal Coordinated Time (UTC) second, as shown in Figure 5(a), where we assume that one UTC second is composed by a set of 100 TCs, each consisting of 1000 TFs of duration T_f . TFs are partially or totally reserved for each flow during a resource-reservation procedure; the TC sets the periodicity of the reservation. This results in a periodic schedule, repeated every TC, for packets to be switched and forwarded, which is called Synchronous Virtual Pipe (SVP) [12]. Figure 5(b) shows how an SVP is switched and forwarded along three optical switches A, B and C: the propagation delay among the switches is expressed in terms of multiples of TFs.

Each SVP transports data of one protocol, such as IP packets or Asynchronous Transfer Mode (ATM) cells. However, SVPs transported over the same wavelength on a certain link may carry data of different protocols, as TDS is “transparent” to modulation and bit-rate since data is always maintained in the optical domain.

The architecture of a TDS node and the devices used therein are shown in Figure 6. An upper layer made up of IP routers is placed over an optical layer consisting of OXCs and optical fiber links, connected to the OXCs through multi/demultiplexing stages. The interconnection between the IP routers and the OXCs is performed through WDM transponders, i.e., router ports, which provide the Optical-Electrical (OE) and Electrical-Optical (EO) signal conversion. In order to implement TDS in the optical domain, optical switches must support a very fast reconfiguration time matching the very short duration of a TF (i.e., the smallest granularity to be switched in TDS, which is on the order of 10 μ s, according to Figure 5(a)). Thus, switching fabrics based on Semiconductor Optical Amplifiers (SOAs) are used to cope with this issue. The structure of such SOA-based OXCs is shown in Figure 6(b), where we assume that the switching operations are performed through a multiple-plane switching architecture, where each plane operates over demultiplexed signals with a certain wavelength. A generic node is reached by N (bidirectional) WDM links, each carrying up to W different wavelength channels. When an optical signal arrives at the input of the node through the optical fiber link, the different wavelengths are demultiplexed and sent towards the appropriate SOA-based switch planes, which provide for switching of signals coming from (going to) a specific input (output) link. Up to N additional inlets/outlets per plane need to be taken into account, since an IP router can be source/destination for up to N (one for each input/output link) SVPs over the W wavelengths. Therefore, we consider $2N \times 2N$ switching matrices, which can be obtained using elementary SOA-based switches implemented through

a broadcast-and-select structure (see Ref. [11] for the details of the SOA switching architecture).

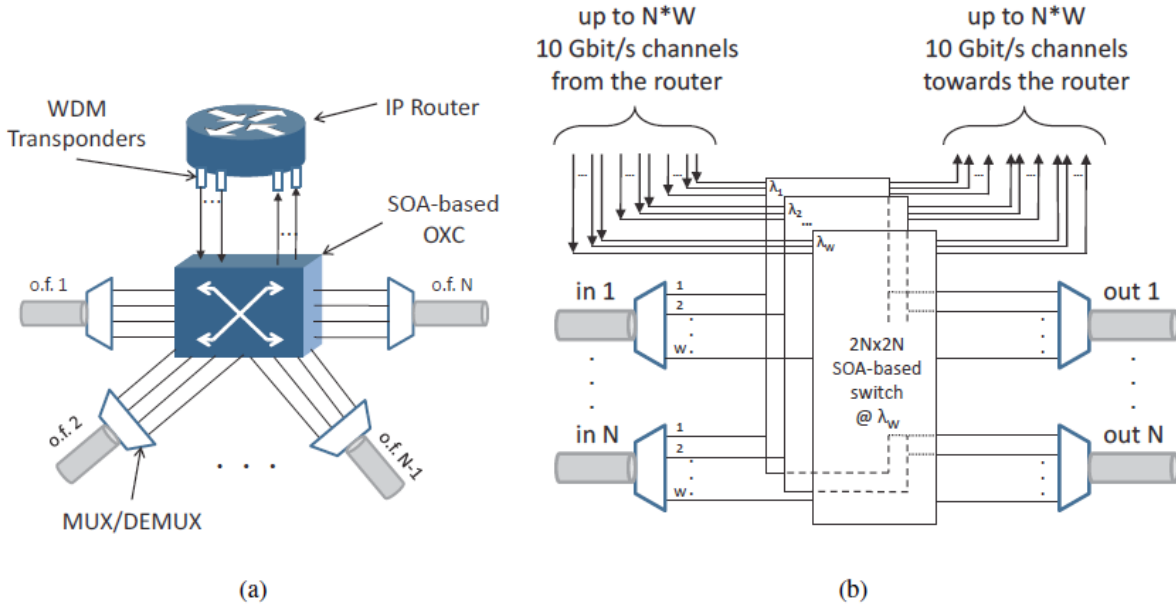


Figure 6 TDS node architecture with incoming/outgoing optical fiber (o.f.) links; (b) structure of the SOA-based OXC within the node.

3.1.2 Comparison between TDS and IP-over-WDM Networks

The power consumption of TDS networks has been compared to a traditional IP-over-WDM network scenario. This is intended as a hybrid solution, which is able to exploit the circuit switching capability of optically bypassing electronic IP routers, and the opportunity of performing traffic grooming as in packet-switched networks, to more efficiently exploit wavelength capacity, especially under low traffic conditions.

We consider several contributors to total power consumption, i.e.: 1) electronic traffic processing at the IP routers to perform signal switching, regeneration and, in the case of traditional IP-over-WDM case, also traffic grooming; 2) WDM transponders; 3) optical switching, performed by OXCs either based on SOAs or Micro-Electro-Mechanical-Systems (MEMS) mirrors, as in TDS or traditional IP-over-WDM networks, respectively (see Refs. [10] and [11] for the detailed power consumption values). Figure 7 shows the IP-over-WDM and TDS architectures compared in this study, as well as the routing of three connection requests (continuous arrows) over different lightpaths (dashed arrows).

For both architectures, signal regeneration is accomplished in the IP-router (left node). Add/drop operations, performed for both architectures in the right node, are differently accomplished. Unlike the TDS case, where grooming can be performed directly in the optical domain, in the IP-over-WDM case signal add/drop is accomplished by terminating the established lightpath and performing grooming in the IP router, thus electronic processing is needed. However, when neither regeneration of signals nor traffic grooming are needed, also in the IP-over-WDM architecture optical bypass of IP routers is implemented (not shown in the figure).

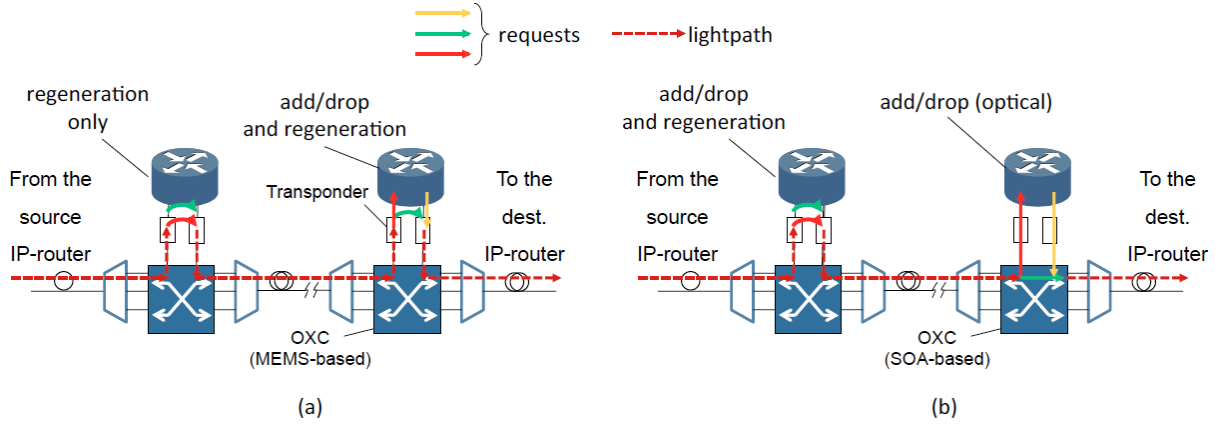


Figure 7 Compared architectures: (a) IPoWDM: traffic grooming is accomplished by terminating lightpaths and performing electronic processing; (b) TDS: traffic grooming is accomplished in the electronic domain through the establishment of SVPs.

The power consumption comparison between the TDS and IP-over-WDM networks has been carried out by developing two ILP formulations to accomplish a power-minimized network design. In other words, given a double-layer network consisting of IP routers placed over an optical WDM layer (OXCs connected by optical fiber links) and a set of traffic demands among the nodes, we aim at minimizing the power consumed by the network, satisfying three main sets of constraints: *i*) all the requests must be routed in the network, *ii*) each fiber carries a limited number of wavelengths (capacity constraint) and *iii*) each lightpath is maintained at a certain wavelength (wavelength-continuity constraint). Furthermore, in our power consumption evaluation, we impose that for each lightpath, the signal quality, expressed in terms of the end-to-end Optical Signal-to-Noise Ratio ($OSNR_{e2e}$), is maintained above a certain threshold, taking into account the physical length of the fibers (thus, the number of EDFAs) and the number of nodes (i.e., the number of OXCs) traversed by the lightpath (physical impairment constraints) [11].

3.1.3 Results

The power consumption of the two aforementioned architectures has been compared over the NSFNET topology, consisting of 14 nodes and 22 bidirectional links, where we considered a non-uniform traffic matrix with a total amount of traffic of 180 Gbit/s, on the line of Ref. [13]. We considered mono-fiber network links with 11 wavelengths per fiber (i.e., the minimum number of wavelengths which guarantees the feasibility of the solution for both architectures), where each wavelength has capacity 10 Gbit/s. Moreover, we also evaluate the power consumption of the two scenarios for increasing traffic, i.e., we scale the bit rate required by each demand by a factor of 2, 3, 4 and 5 (accordingly, we set the number of wavelengths per fiber as equal to 15, 23, 30 and 37, respectively).

Table I shows, for increasing values of the traffic matrix scaling factor, the comparison between the power consumed by IP-over-WDM and TDS networks, considering four different cases for the $OSNR_{e2e}$ threshold, i.e., from 20 to 17 dB.

We observe that TDS power consumption is maintained always below the consumption of the IP-over-WDM architecture and for increasing traffic amounts the gap between the two architectures remains nearly unchanged, mainly due to the limitation imposed by the physical impairment constraint, which implies higher amount of electronic processing and transponders needed. When the constraint on the $OSNR_{e2e}$ is relaxed (i.e., lowering its threshold value), we observe that the energy advantage of TDS is increased (up to 55% of savings are obtained with respect to the IP-over-WDM case), thanks to its

opportunity to perform traffic grooming in the optical domain, thus implementing optical bypass more than the traditional hybrid packet/circuit IP-over-WDM scenario.

A further comparison between the two architectures has been carried out considering a power consumption improvement envisioned in IP routers technology for the near future. In other words, we considered that the power consumed by WDM transponders and for electronic traffic processing are reduced by a factor of 10% and 20%. Results obtained in these two cases have shown that the TDS architecture still outperforms the IP-over-WDM one, especially for lower bandwidth granularity and for less strict physical impairment constraint, when we can obtain up to about 60% of power saving [11].

Table I Power Consumption Values (kW) in the two scenarios for increasing traffic and different values of $OSNR_{e2e}$ threshold.

Traffic matrix scaling factor	$OSNR_{e2e} \geq 20$ dB		$OSNR_{e2e} \geq 19$ dB		$OSNR_{e2e} \geq 18$ dB		$OSNR_{e2e} \geq 17$ dB	
	IPoWDM	TDS	IPoWDM	TDS	IPoWDM	TDS	IPoWDM	TDS
1	5.478	5.122	4.107	3.688	3.585	2.114	3.135	1.357
2	10.479	9.957	7.273	6.098	5.813	3.953	4.596	2.661
3	15.372	14.805	10.163	8.647	8.112	5.325	6.176	3.82
4	20.194	19.466	13.258	10.3	10.185	7.09	7.489	5.097
5	24.867	24.224	15.78	12.178	11.981	8.7	8.377	6.24

3.2 TDS Networks Performance Evaluation

Summary: In order to evaluate the potential of TDS as a promising architecture, we evaluate its performance in both static and dynamic traffic scenarios. We propose a network design strategy aiming to minimize the network cost, intended as the number of wavelengths or the number of transponders used in the network. Moreover, we develop different routing and resource assignment algorithms for the performance evaluation of TDS networks in terms of SVP-request blocking probability.

Publication: This work is published in in the Proceedings of *HPSR 2012 Conference* with the title “Dynamic Routing and Resource Allocation in Time-Driven-Switched Optical Networks” [14]. We also plan to submit part of the studies in this section (i.e., the TDS performance evaluation under static traffic conditions) to relevant international journal publication.

Contributing partners: CNIT (PoliMi), FW

3.2.1 TDS Features

Before going into the details of the TDS performance analysis, we first provide the description of some features of TDS networks, that is, the techniques used to forward data along the network, either using optical buffers or not, and the different routing strategies to establish the SVPs, which can exploit single or multiple wavelengths and use one or more physical routes between source and destination nodes.

1) Forwarding techniques. The establishment of an SVP, i.e., the reservation of the TFs along the path between a source/destination pair, is related to the specific forwarding technique adopted by TDS nodes. According to the possibility of introducing a certain delay

within the node, two techniques are allowed: *Immediate Forwarding (IF)* and *Non-Immediate Forwarding (NIF)*.

Assume that data units of a given connection arrive at a node in TF i : (a) in the IF case, they are “immediately” moved to the output in TF $(i+1)$; (b) in the NIF case, data is sent to the proper output port in TF $(i+d)$, where $1 \leq d \leq B \leq C$, B is the maximum allowed buffer size and C indicates the number of TFs per TC (for the case $B=C$ we refer to Full Forwarding).

Using optical buffers provides higher flexibility to TDS networks, since more paths can be exploited to route connections. However, optical buffers, e.g., based on Fiber Delay Lines (FDLs), are unpractical with current technology, so that implementing NIF highly increases the node complexity.

2) Routing Strategies. To route a connection in a TDS network, since each connection can be served using more than one TF, we identify three different routing scenarios:

- Single Path – Single Wavelength (SP-SW): all the TFs belonging to a single connection have to be routed along a unique physical path (single SVP) over a single wavelength.
- Single Path – Multiple Wavelength (SP-MW): all the TFs belonging to a single connection have to be routed along the same path (single SVP), but can use different wavelengths¹.
- Multiple Path (MP): the TFs belonging to the same connection can be routed over different physical paths (different SVPs) and wavelengths.

The SP-SW scenario is the more constraining, so it is likely to have higher blocking probability with respect to the other cases, and it typically needs to use larger buffers to achieve acceptable performance. As a consequence, data is usually buffered within the node before it can find the proper TF at the output of the switch, so in this scenario the connections usually experience large delays and the technological complexity increases due to the needs for FDLs.

In the MP scenario there is a higher flexibility in finding free TFs in the network, hence it is likely to provide the lowest blocking probability. Thanks to this, in the MP scenario smaller buffers are needed, and the SVPs may experience lower delay. Nevertheless using different paths for the different TFs of the same connection may causes latency jitter, due to the fact that different physical paths can be constituted by a different number of links, each with a different propagation delay.

The SP-MW scenario is an intermediate case between the aforementioned scenarios from the blocking probability, buffer requirements and jitter points of view, since it avoids the main term of jitter related to diversity of paths, but it still incurs in the jitter due to the recombination of flows received over different line cards (as in other inverse multiplexing techniques), due to the possible wavelength-diversity for TFs.

3.2.2 Cost-Minimized TDS Network Design

In TDS networks connection requests are served by scheduling the corresponding traffic into one or more SVPs, constituted by a set of TFs along the links composing the end-to-end path. Therefore, beside the traditional Routing and Wavelength Assignment (RWA), the TFs allocation is also performed, i.e., a complex problem of Routing, Wavelength and TF Allocation (RWTa) must be solved.

We developed an ILP formulation for the design of TDS networks where we aim at minimizing the network cost, expressed as either the number of wavelengths or the number of

¹ Note that we assume TDS nodes are not equipped with wavelength converters, so a TF assigned to a certain wavelength at the starting node is routed over the same wavelength in all the links composing the path.

transponders used. In addition, with respect to the power-minimized design shown in Section 3.1, in this study we also take into account the scheduling of connections into TFs. Therefore, we must face the problems arising with the time issue, i.e., we account for the time needed to perform switching operations within a TDS node, the propagation delay in the links, etc. Note that, according to its length, each link has a different propagation delay, so a different TF allocation is accomplished in every link. Remind that, one SVP is obtained by reserving one or more TFs along the end-to-end path, and that the reserved TFs are periodically used in every TC, until the connection is ended. So the needed capacity can be determined only by the number of TFs per TC. For instance, considering 10 Gbit/s wavelengths and assuming that one UTC second consists of T TFs per TC and c TC per second, as the same TF is periodically used in each TC, then one SVP which exploits one TF per TC correspond to a channel at $10/T$ Gbit/s, independently from the value of c . Therefore, in the following we will ignore the knowledge of the number of TCs per second, without loss of generality. To deal with scalability issues which makes the ILP problem intractable when dealing with large networks, we provide a heuristic approach to perform the network design.

We here report a brief description of the heuristic algorithm developed to carry out the TDS network design with minimized number of used wavelengths. The design procedure is composed by two main phases: 1) an initial RWTA; 2) an optimization cycle used to minimize the number of used wavelengths.

Step 1: RWTA

In the initial RWTA step, we start considering the network as unloaded, i.e., no connection requests are routed into the network. All the connection requests are set up one by one until all have been provisioned. To do this, the network resources are initially oversized, i.e., each link carries a very large number of wavelengths W (e.g., equal to the total number of wavelengths which would be needed if all connections were between the same source-destination pair and were routed over the same physical path). In this way we are guaranteed that the RWTA for every connection requests is feasible. Before being accommodated, all the connection requests are sorted, starting from the connection requiring the highest number of TFs per TC. After the initial sorting, the demands are accommodated one by one. Each demand is routed along the path which uses the lowest number of wavelengths (i.e., basically the path with minimum number of hops) as long as it satisfies the demands TFs requirement. A first-fit criterion has been adopted for the wavelength assignment, though several other criteria are possible, e.g., promoting the most or the least used wavelength in the path. Similarly, the first-fit selection is also adopted for the TFs assignment. Whenever a demand is routed and the corresponding TFs are allocated, the occupied resources are set as unavailable. Therefore, the next demand is accommodated exploiting the residual network capacity (TFs).

Step 2: Optimization cycle

After the initial RWTA phase has been completed, all the unused wavelengths are assumed as pruned (i.e., eliminated) from the network. Correspondingly, all the TFs of the pruned wavelengths are “disabled”. Then the optimization iteration takes place. An optimization counter k is initialized to 1. On every link, the wavelengths containing only k occupied TFs² is detected. Let us identify these wavelengths as “ k -wavelengths”. Then the SVPs using one or more TFs in a k -wavelength are sequentially considered. Every SVP is temporarily deallocated (i.e., all the TFs belonging to that SVP are deallocated, including those routed over the other wavelengths). Thus, the k -wavelength is temporarily disabled. All the deallocated SVPs are reallocated again by following the routing criteria of step 1 (RWTA). Now, there is no guarantee of success of the reallocation, since the physical network has been deprived of the unused capacity. If all the deallocated SVPs can be re-

² Being T the total number of TFs for each wavelength, then $T-k$ is the number of *unused* TFs.

routed, then the wavelength is permanently disabled (pruned), otherwise, the original routing of the disabled SVPs are restored and the k -wavelength is preserved.

3.2.3 Results (TDS Network Design)

We utilized the heuristic algorithm described above to evaluate the impact of different key parameters on TDS networks performance. Specifically, we evaluate the impact of the different routing strategies (SP-SW, SP-MW and MP) and forwarding techniques (IF and NIF), as well as the effect of the TF granularity on the TDS network performance. Here we show the results, i.e., the number of used wavelengths, when performing the cost-minimized network design, considering that the SP-MW routing strategy is adopted in both the IF and NIF scenarios, and assuming three possible values for the TF granularity, i.e., 50, 20 or 10 TFs per TC (see Figure 8). For this study we considered the USA-24 network topology, consisting of 24 nodes and 43 bidirectional links [14] and a base traffic matrix with 453 connection requests and a total amount of traffic of about 100 Gbit/s (we also obtain results for different values of the base matrix scaling factor).

For the NIF case, we consider that the maximum allowed buffer size Z is equal to the 20% of the TC capacity, in terms of number TFs. For higher traffic loads, i.e., when the single connections require higher capacity, the three curves tend to superpose, since small TFs (i.e., for higher number of TFs per TC) are not useful since no fine bit-rate requests are present. On the other hand, for low traffic load, the granularity of 50 TFs per TC shows a remarkable reduction in the number of wavelengths used, up to about 42% and 66% lower than the 20 or 10 TFs per TC cases, respectively. The figure also shows that the TF granularity has a stronger effect in minimizing the number of wavelengths if compared to the usage of buffers. This is due to the fact that the TF granularity has a direct impact on network resources while buffering helps to use them efficiently.

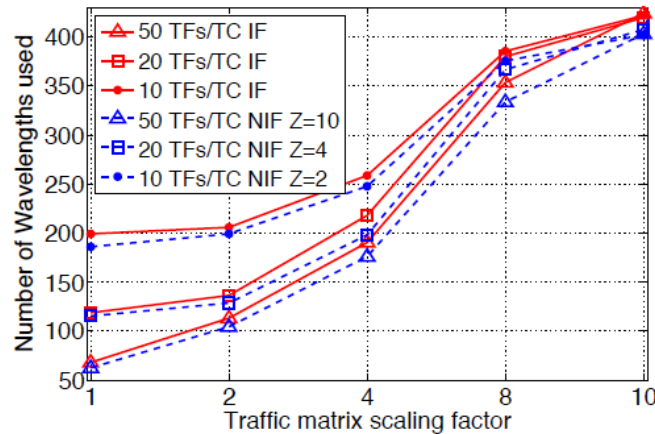


Figure 8 Effect of the TF granularity on TDS network performance (number of used wavelengths) in the IF and NIF scenarios for increasing values of the traffic matrix scaling factor.

3.2.4 TDS Blocking Performance Evaluation

To evaluate the performance of TDS networks under a dynamic traffic scenario, we provide algorithms for the routing and resource allocation for randomly-arriving connections. In this regard, the performance evaluation in terms of blocking probability of a TDS network needs to take into account the contribution of the so-called *time blocking*, which arises when there is no feasible TFs allocation in two (or more) consecutive links along the path. Specifically, several contributions to blocking must be considered, i.e.:

- **call blocking** occurs when no resources are available; this is a classical problem in any circuit switched network;
- **space blocking** happens when resources are available at the output, but the internal structure of the switch prevents connecting the input and the output;
- **time blocking**: this is a specific feature of TDS networks and occurs when resources are available, and each switch along the end-to-end path can be configured to connect one input with one output, but it is impossible to find a feasible schedule mapping the input TF to the output TF.

We focus on the combined effect of time blocking and call blocking, neglecting the contribution of space blocking, as we assume that switches are constituted by non-blocking matrices. We explore several aspects of the dynamic RWTa problem, i.e.: the use of various routing strategies (SP-SW, SP-MW and MW), the possibility of using optical buffers in TDS nodes, and the proper buffer size to adopt; the impact of the TF dimension over network performance.

The RWTa with FDLs problem is a NP-hard problem as it contains another NP-hard problem (the RWA) as a subroutine. Therefore, to deal with such problem complexity, we split the online RWTa process in two steps [14]:

(1) **Admissible Paths Discovery**: we first find a set of admissible paths having an available capacity of at least one TF. For each path of this set a certain wavelength is assigned as well as one TF in every link composing the path, chosen according to a first-fit criterion. The obtained paths are collected in a set called *Paths*.

(2) **Resource Allocation**: the effective capacity (expressed in number of TFs) required by the connection is now taken into account, so we explore the set *Paths* to find the proper path (or paths) having the desired available capacity. For this step, we develop one algorithm for each of the three routing strategies (SP-SW, SP-MW and MP).

For each connection, if no feasible routes (with the proper available bandwidth) are found, the connection is considered blocked, otherwise it is routed and the resources are allocated and successively released when the connection ends.

3.2.5 Results (Dynamic RWTa)

To evaluate the blocking performance of TDS networks, we developed an event-driven simulator implementing the RWTa algorithms and applied it to the USA-24 topology, used also for the cost-minimized TDS network design. We considered mono-fiber links, having 8 wavelengths with capacity 10 Gbit/s each. Connection arrivals are Poisson-distributed and their duration is distributed as a negative exponential function normalized to unity. Source and destination nodes of the requests are uniformly chosen at random among the 24 nodes. The bandwidth required by each connection is chosen among four different Optical Carrier (OC) rates, i.e., 155.52 Mbit/s (OC-3), 622.08 Mbit/s (OC-12), 2.488 Gbit/s (OC-48) and 9.95 Gbit/s (OC-192), with probabilities 6/19 for the cases OC-3, OC-12 and OC-48, and 1/19 for the OC-192 case. Simulation runs of 10^4 connection requests are repeated until the estimated P_b shows a statistical confidence of 95% and a 5% error interval.

In Figure 9 we show the values of P_b for increasing connection arrival rate, in the SP-SW and SP-MW cases, when the maximum allowed buffer size (in number of TFs) is varied from $|Z|=0$ (IF case) to $|Z|=50$. We consider 100 TFs per TC, where one TC corresponds to 1 second. As expected, the values of P_b for the SP-SW scenario are remarkably higher than those for the SP-MW case, especially for low arrival rates, since the SP-MW routing strategy is more flexible in finding routes from source to destination. As the offered traffic increases, i.e., for arrival rates approaching to 600 connections per second, the difference between the

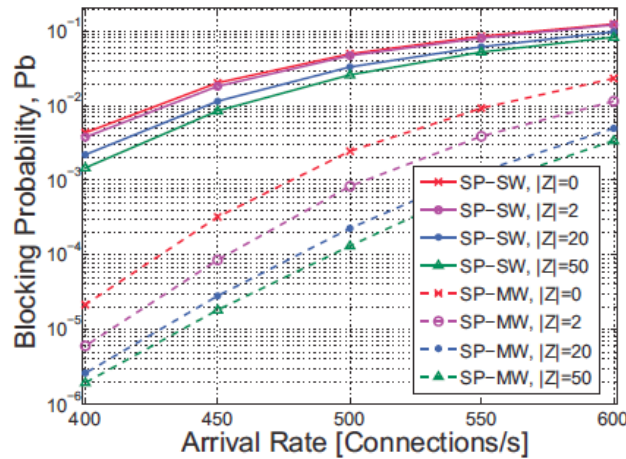


Figure 9 Comparison between SP-SW and SP-MW with variable maximum buffer size $|Z|$ for increasing connection arrival rate ($C=100$ TFs per TC).

two routing strategies decreases as the network is highly occupied and in both scenarios the values of P_b tend to converge. Moreover, increasing the value of $|Z|$ (i.e., allowing higher buffer size) the benefits obtained in the SP-MW case (P_b is reduced by a factor 10) are more evident with respect to the SP-SW scenario (P_b is almost halved). Also, even for high buffer size ($|Z|=50$), the SP-SW routing strategy is still outperformed by SP-MW, even in the case of SP-MW where no buffers are allowed ($|Z|=0$). This means that the benefit obtained allowing the usage of multiple wavelengths is substantially higher than the advantage provided by employing optical buffers, from both the P_b and the technological complexity point of views.

Further results, e.g., the comparison between SP-MW and MP scenarios and the effect of varying the number of TFs per TC can be found in Ref. [14].

4. Energy Efficiency in VoIP and PSTN Networks

The aim of this section is to compare the energy efficiency of two well known architectures used for voice communication: the traditional Public Switched Telephone Network (PSTN), based on circuit-switched technology, and the Voice over Internet Protocol (VoIP) which is based on IP network. These technologies follow two opposite design choices. On the one hand, complex structured circuit-switched technology PSTN utilizes centralized switching and group switching among Private Branch Exchanges (PBX) which implement all intelligence and interconnect very simple phone devices. On the other hand, the VoIP technology uses simple Ethernet switches and a gateway to interconnect intelligent phones that implement all the advanced features.

In the following, we investigate which is the most energy efficient architectures and in particular we evaluate if some power savings are possible by implementing VoIP. To target these issues, the two architectures are compared in terms of energy consumption using real or actual power consumption data. Next, those measurements are used to develop a simple mathematical model to estimate the power consumption per user. Given that, we estimate the energy consumption for any given number of users for either PSTN or VoIP systems. Lastly, possible energy savings schemes, along with their results, are described.

4.1 Comparison of Energy-Efficiency in PSTN and VoIP systems

Summary: Two telephone networks namely traditional Public-Switched Telephone Network (PSTN) and Voice over Internet Protocol (VoIP), are extensively examined in terms of energy consumption by means of measurements, modelling and actual experiments on the PoliTo campus systems. Results indicate that VoIP solution is energy hungry unless any energy saving scheme is deployed.

Publication: This work is published in the Proceedings of *Future Energy Systems: Where Energy, Computing and Communication Meet (e-Energy)*, 2012 Third International Conference with the title “Comparison of Energy Efficiency in PSTN and VoIP Systems” [15].

Contributing partner(s): PoliTo

4.1.1 Private Voice Systems

Traditional Circuit Switched System

We consider the telephone system of the PoliTo university campus as reference to compare VoIP and PSTN architectures. The configuration implemented at PoliTo PSTN consists of 14 PBXs, serving 3120 phones. These phone lines are divided into 2787 analog and 333 digital lines. All 14 PBXs are connected to the Group Switch (GS), which acts as a gateway providing connection between all 14 PBXs and the external telecom network. The maximum capacity of each PBX is around 500 phones with the possibility to increase the number of phones by inserting new line cards. Each line card can handle up to 16 phones. Line card for analog phone line is different from the line card for digital phone line, with also different power consumption values.

VoIP System

The VoIP system deployed at Istituto Superiore Mario Boella, a research center close to PoliTo campus, is considered as reference for the VoIP network. Interestingly, the

architecture is simple and it does not require large scale infrastructure like in the case of the traditional phone system. It consists of 4 Power over Ethernet (PoE) switches (3 switches with 24 ports and one with 48 ports) and a PC with Asterisk software to act as a communication server. The referenced architecture serves around 120 users with the capability to make phone calls, and also to provide data services. This means that the VoIP architecture utilizes shared Ethernet infrastructure which provides data services, that seems to be a good option in terms of energy saving.

4.1.2 Measurement and Modelling

Measurement Setup

The measurement of power consumption values of PBX or VoIP switches are carried out locally at regular intervals by local devices. Later, the measurement data is transmitted to a central server through a wireless transmitter connected to the measurement device. The collected data are then stored in a database for statistical analysis. This measurement activity involves the collection of certain parameters like Real/Reactive Power, RMS Voltage/Current.

PBX Measurements

Two PBXs (namely LIM9 and LIM13) out of 14 PBXs are kept under power measurement. The monitoring of power consumption of these two PBXs collected over the span of two weeks (4-15/04/2011) for the weekdays is shown in Figure 10. Similarly, Figure 11 shows the power consumption during weekends. The three curves with green, black and red colour represent, respectively, the maximum, average and minimum power consumption samples for 24 hours collected over a span of weekdays or of weekends. Power consumption is constant during weekends and it's around 137 Watts in case of LIM 9, even if there is no user activity. During weekdays, and when the system is carrying phone calls, the system consumes around 10% more of the overall consumption. Note that the measurements are vendor specific (Ericson model in our case), so the results we provide may not be representation for every scenario, but rather could be generalized to provide good estimates. For example, similar experiments were conducted over AASTRA's new generation PBX, where empty PBX (no phones or line cards connected) resulted with 66 Watts of consumption.

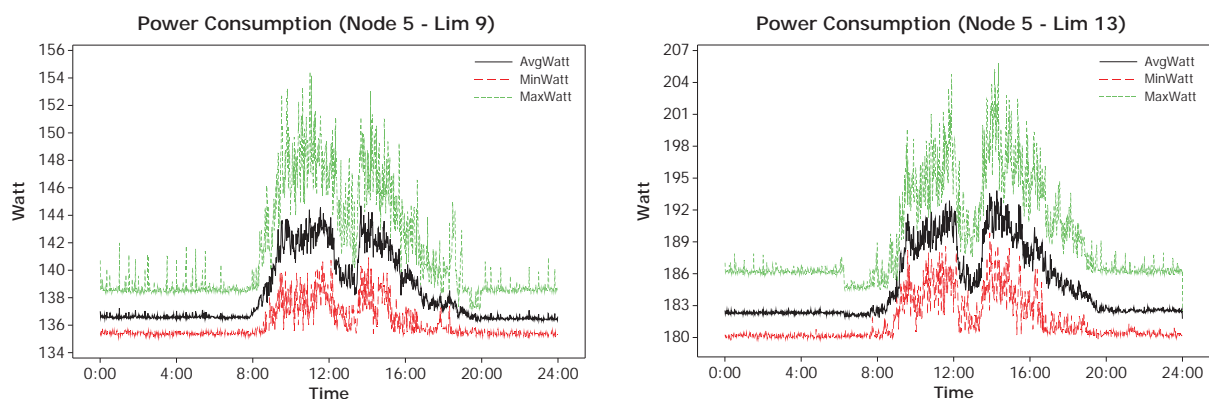


Figure 10 PSTN: Power consumption – Weekdays.

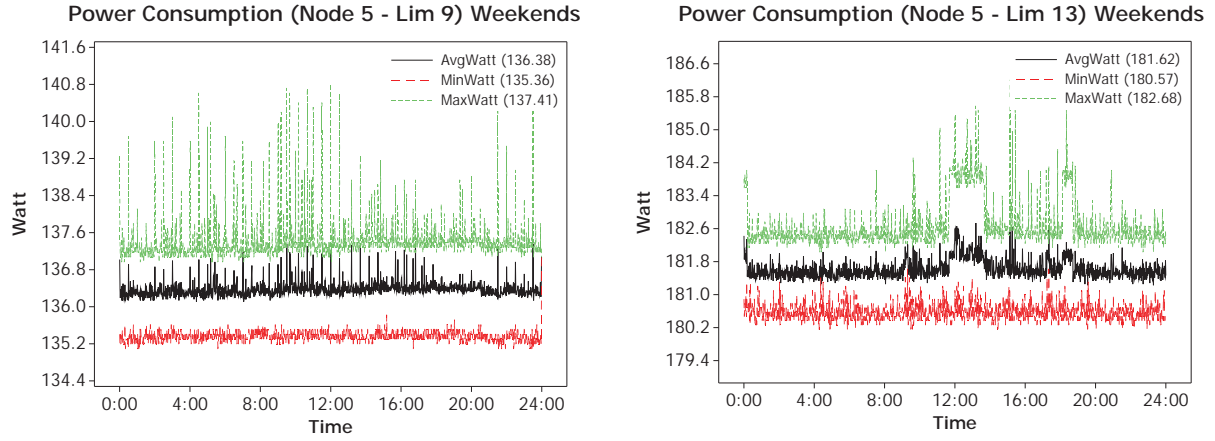


Figure 11 PSTN: Power consumption – Weekends.

PSTN Power Modelling

A simple mathematical model is extrapolated from the acquired real measurements to estimate the per user consumption. Using this estimate, it is possible to approximate an overall consumption for a given number of users in any campus or corporate scenario.

Considering minimum power consumption when the system is idle, we assume that the power consumed by analog/digital line cards, as well as phones, is approximately the same:

$$P_{PBX} + X \cdot P_{lc} + K \cdot P_{ph} = P_{TOT_{PBX}} \quad (1)$$

The above expression divides total power consumption as the sum of minimum constant PBX power consumption, P_{PBX} , plus the power consumed by line cards P_{lc} and phone lines P_{ph} . X and K represent respectively the number of line cards and phone lines connected to specific PBX. Based on the number of interfaces and phone lines connected to each PBX, we obtained the following two equations:

$$\begin{cases} LIM\ 9, & P_{PBX} + 11P_{lc} + 158P_{ph} = 135.10W \\ LIM\ 13, & P_{PBX} + 18P_{lc} + 242P_{ph} = 180.06W \end{cases} \quad (2)$$

In order to solve the equations we need to know the value of one of the variables. For that purpose, we decided to directly measure the power consumption of phones lines by adding ten new phones to the PBX and observe their effect on the PBX power consumption. We observe the average power consumption by single phone user (ON-hook) to be, $P_{ph} = 0.53W$. By solving (2), we find the power consumption of the line card and of the PBX:

$$\begin{cases} P_{PBX} = 50.6686W \\ P_{lc} = 0.0629W \end{cases} \quad (3)$$

VoIP Measurements

Two switches (namely SW-2 and SW-3 which are used exclusively for connecting VoIP phones) with model HP Pro-Curve are kept under power measurement in the VoIP system. The distribution of the number of phones on SW-2 consists of 12 non-PoE phones and 5 PoE phones. SW-3 has 9 non PoE phones and 12 PoE phones. The monitoring and collection of power consumption data is done as mentioned above. The 24 port switch under measurement can provide up to 370 watts of power to PoE devices, which in turn means all 24 ports deliver at an average of $370/24=15.4$ watts per port. Figure 12 shows the actual

power consumption behaviour of PoE switches observed over the same duration of two weeks (4-15/04/2011). Differently from the PSTN system, we observe constant power consumption, which is independent on user activity (notice the range of the y-axis of the plot).

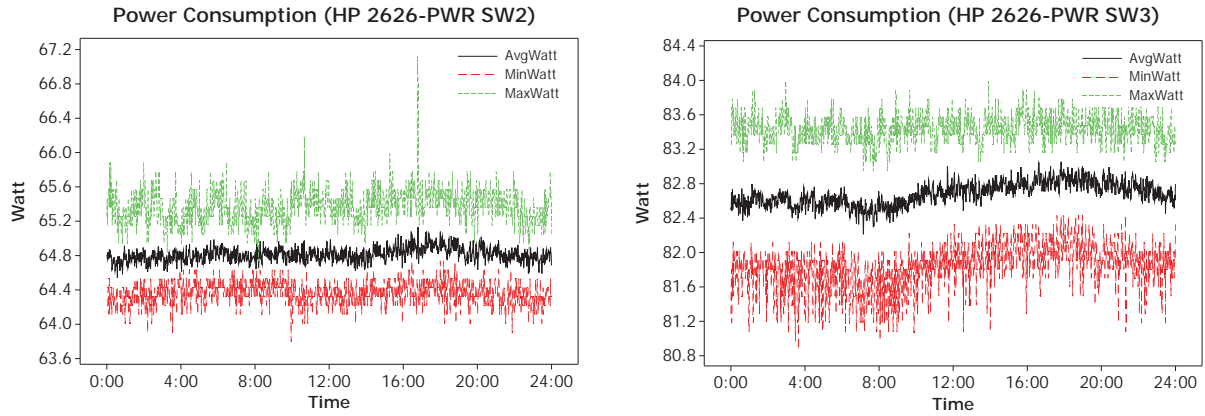


Figure 12 VoIPs Power consumption.

Formulation

Similarly to the previous case, we extrapolate a simple mathematical model to estimate the per user consumption. Thus, we have that the total power consumption is the sum of the minimum constant power consumption of the Ethernet switch (P_{SW}), plus the power consumed by the number of PoE and non-PoE phones. Whereas, P_{PoE} and $P_{non-PoE}$ represent the power consumption figure of PoE and non-PoE phones. Assuming non-PoE phones do not require power from the switch, we have, $P_{non-PoE} \approx 0$.

$$\begin{cases} SW2, & P_{SW} + 5P_{PoE} = 64.81W \\ SW3, & P_{SW} + 12P_{PoE} = 82.67W \end{cases} \quad (4)$$

Solving the equations, we have $P_{SW} = 51.88W$ and $P_{PoE} = 2.6W$. In order to verify the results, we conducted another experiment in which SW-3 offered connectivity to only 16 PoE phones and SW-2 to only 19 non-PoE phones. The results showed that SW-2 and SW-3 gave 53.2 W and 90.7 respectively. These numbers complied with the results derived from previous calculations.

4.1.3 Analysis

Using the formulation mentioned above for both the architectures, a rough estimate of the power consumption for a generic PSTN system is computed from:

$$P_{PSTN} = \left[\frac{N_{T_{lines}}}{N_{users}/PBX} \right] P_{PBX} + P_{ph} N_{T_{lines}} \quad (5)$$

Where $N_{T_{lines}}$ is the number of phone lines and N_{users}/PBX is the number of phones a PBX can host (500 in our case). Similarly, P'_{VoIP} is the equivalent estimated power consumption of the VoIP system:

$$P'_{VoIP} = \left[\frac{N_{T_{lines}}}{N_{ports}/switch} \right] P_{SW} + P_{PoE} N_{T_{lines}} \quad (6)$$

Where $N_{ports}/switch$ is the number of ports available on a specific switch (24 in our case). Note that (5) and (6) represent a lower bound on power consumption since they assume to fill completely a switch before adding a new one.

Energy Saving Schemes

The power consumption of PBX and of the equivalent VoIP architecture for some specific numbers of users is computed using (5) and (6). The results consider the total average consumption of the system during 24h time period. Figure 13 (*notice the ylog-scale*) reports the comparison of power consumption of PBX (black line with legend PSTN) and equivalent VoIP architecture (with legend VoIP) along with the comparison between energy saving VoIP scenarios. The results clearly indicate that VoIP solution consumes more power for the considered architecture, but this is strongly dependent on the devices used for implementing the phone infrastructure. Yet, VoIP systems have the flexibility to be made energy efficient by adding some sort of energy-wise schemes.

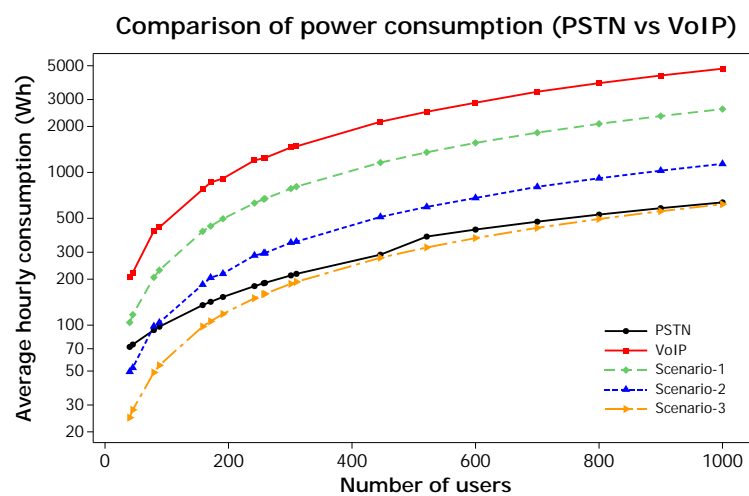


Figure 13 PSTN and VoIP energy consumption

Scenario-1,2,3 describe the different energy saving schemes implemented on VoIP architecture. Further details can be found in Ref. [15].

Results

Results show that VoIP architecture is energy hungry, unless aggressive energy efficient schemes are in place. For example, referring to the Figure 13, the remarkable difference in the power consumption observed in scenario-3 is due to the fact that it considers only the power consumption of VoIP phones (not the switches) and sleep mode is aggressively exploited.

5. Energy-Efficiency of continuous and burst transmission mode

In this section, the energy-efficiency of devices adopting the continuous or the burst transmission mode has been compared. In particular, it has been investigated the case of ADSL access networks.

Choosing a continuous or a burst transmission mode device depends mainly on the traffic profile of the transmission line. Indeed, burst mode transmitters can save energy if there are long time periods in which no traffic requires to be transmitted. In these periods, the burst mode transmitter can enter a sleep mode state in which the power consumption is reduced. Instead, continuous transmission mode devices have to transmit continuously, even if no data has to be sent, and thus they always consume the maximum amount of power.

In the following, we first analyze the traffic activities of about ten thousands ADSL lines in order to evaluate which is the average effective utilization of an ADSL line. Secondly, we propose two different sleep mode policies which determine with different approaches when ADSL modems can enter the sleep mode state. Finally, we evaluate the achievable energy and monetary savings in the case that burst mode ADSL modems are employed and the proposed sleep mode policies are implemented. Results are retrieved for the actual traffic profiles of the users that we monitored.

5.1 Energy consumption savings with burst-mode transmission in ADSL lines

Summary: We evaluate the convenience of continuous or burst-mode transmission in the ADSL lines case. We analyze the line activity of about ten thousand users to understand which is the typical line activity behaviour. We propose two sleep mode policies, employed to determine when burst mode modems can enter a sleep mode state, and we estimate the achievable energy and monetary savings in the case that burst transmission mode ADSL modems implement the proposed sleep mode policies.

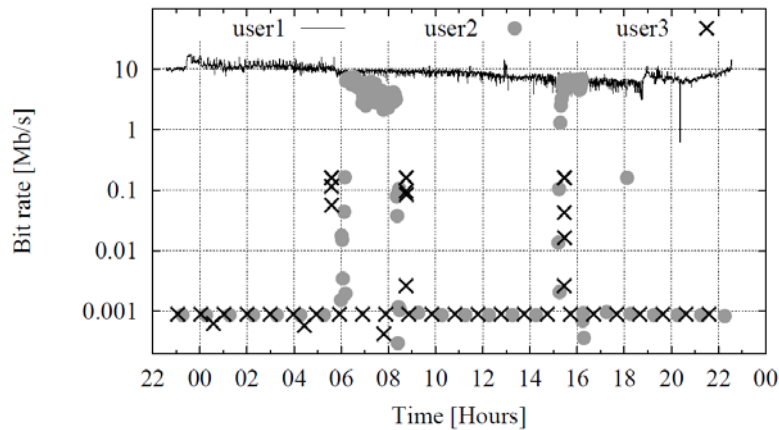
Publication: This work is published in the Proceedings of *Networks 2012* with the title “Sleep Mode at the Edge: How Much Room is There?” [16].

Contributing partner(s): PoliTo, FW

5.1.1 ADSL lines activities

We collect traffic data of about ten thousand ADSL residential lines associated to the same Point of Presence for 24 hours. The collected data consist in the number of bytes, $bytes_U(i)$, sent and received by the user U in the i^{th} time interval of $\Delta=10$ seconds. These samples have been collected using the traffic monitoring tool Tstat [17]. We compute the average line rate, expressed in bit/s, as $bytes \cdot 8 / \Delta$.

Some examples of users' activity are reported in Figure 14, which reports the line rate for a period of 24 hours. Notice the logarithmic scale on the y-axis. Three different usage



patterns are exposed: *user1* is always connected constantly exchanging a large volume of traffic (as typical of users running P2P applications); *user2* has two activity periods in the early morning and afternoon during which the bit rate is very large; few other low bit rate activity periods are possibly due to the usage of Voice over IP (VoIP) services; finally, *user3* shows only three significant traffic events during which the bit rate is limited which are possibly due to VoIP as well.

Figure 14 Examples of the evolution of the line rate for three different users.

Interestingly, both *user2* and *user3* exhibits several traffic events, in an almost periodic way, characterized by very low bit rate. Those correspond to traffic automatically generated by applications for control purposes, e.g., the DHCP traffic due to the modem itself, or applications that check for the availability of updates. In the following, we refer to this type of traffic activity as *background traffic*. Note that during time periods in which only *background traffic* is present, no users is actually actively accessing the network. Thus the line could enter into a sleep mode state in order to save energy.

Then, in the case that the users' habits are similar to *user2* and *user3*, the use of burst mode ADSL modems and the deployment of sleep mode policies can be an effective method to reduce the energy consumed in access networks. Instead, if the majority of users has habits similar to *user1*, burst mode ADSL modems would not bring any advantage with respect to continuous transmission mode ADSL modems. Thus, the effectiveness of the burst mode transmission depends on which is the typical user behaviour.

In the following, we characterize the typical ADSL line behaviour by exploiting our measurements. We define as "activity period" the time during which the rate of a line is above a certain threshold *MinRate*. We consider that all the traffic events for which the line rate is below *MinRate* are not due to user's activity, but they represent *background traffic*.

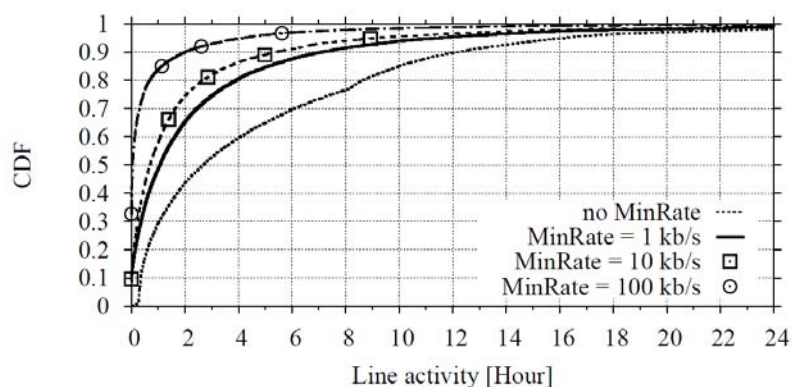
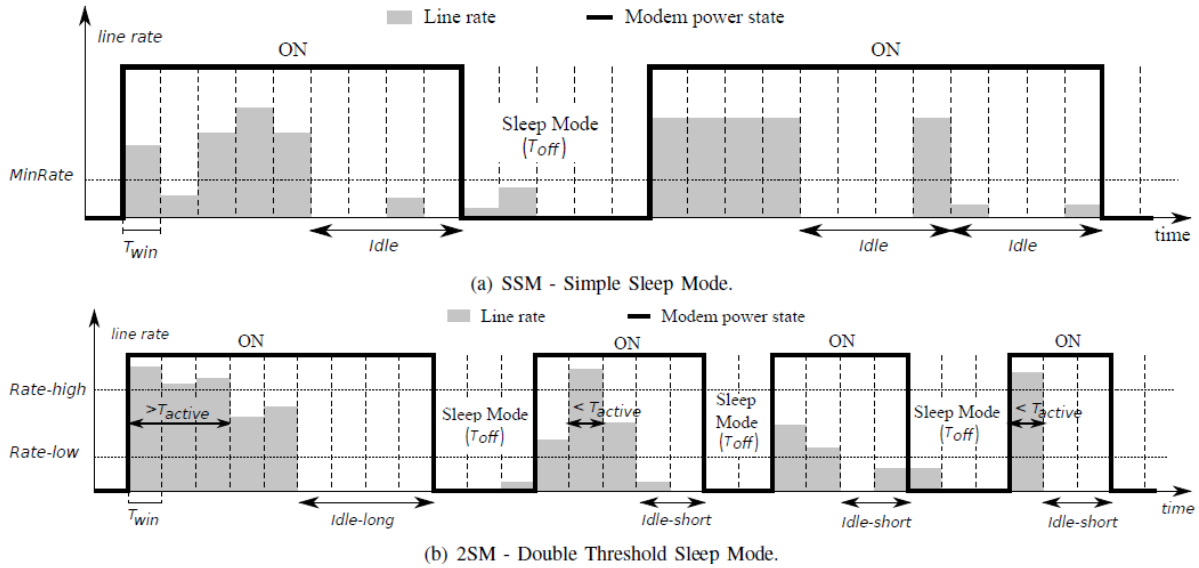


Figure 15 CDF of the total activity of the monitored lines during the day.

Considering a 24h time interval, Figure 15 reports the CDF of the total line activity period for different values of *MinRate*. Overall, the average line utilization is very limited. For instance, if no threshold is applied, only 50% of the lines is active for more than 2.5 hours, and only 10% of lines exchanges traffic for more than 12 hours. Considering *MinRate*=1 kb/s, 50% of the lines are active for less than 1 hour in the entire day. Even more



impressive, we have that about 50% of the lines never exceed *MinRate*=100 kbit/s in the whole day. This means that it may be worth to use burst mode ADSL modems, since most of customers actually generate traffic for typically short periods, with their access line that carries only *background traffic* for most of the time.

Figure 16 Example of evolution of the line rate and the modem power consumption obtained using two sleep mode policies.

5.1.2 Sleep mode policies at the ADSL modems

In the following, we describe two possible policies that, according to the traffic profile of a given ADSL line, determine when the modem can enter the sleep mode state.

Simple Sleep Mode (SSM) policy

We start considering a simple policy that we called *Simple Sleep Mode* (SSM) which exploits a single line rate threshold, namely *MinRate*, to identify when the modem can enter the sleep mode. Figure 16(a) depicts the strategy reporting an example of line rate evolution over time. The modem monitors the line activity measuring the line rate. If the rate does not exceed *MinRate* for *Idle* seconds, then the line is assumed to be inactive and the modem enters sleep mode. As soon as the line rate is above *MinRate*, the modem has to be woken up and to become fully operative.

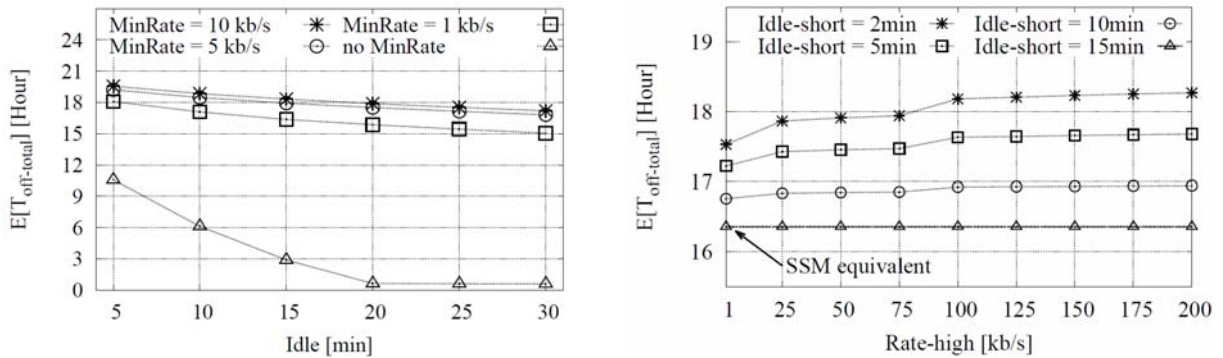
Double threshold Sleep Mode (2SM) policy

The SSM policy is very conservative. When the modem is woken up for traffic events, the modem has to wait for *Idle* seconds before enter sleep mode again. In case *background traffic* is present, the line would remain active for long time even if little traffic is exchanged. Therefore, it may be better that the modem, after sending background traffic, re-enters quickly the sleep mode state. The *Double Threshold Sleep Mode* (2SM) policy exploits two traffic thresholds to distinguish between users' activity and *background traffic*. Figure 16(b) shows an example of line rate evolution controlled by the 2SM policy. Similarly to before, as

soon as the rate is higher than *Rate-low*, the modem is turned ON. Another threshold, *Rate-high*, is used to decide for how long the modem has to wait before entering the sleep mode. If the line rate is above *Rate-high* for at least T_{active} seconds, then the user is assumed to be active and the sleep mode can be entered only after an *Idle-long* inactivity period. This means that the modem is left ON for *Idle-long* seconds even if the rate goes below *Rate-high* in a second moment. Otherwise, we assume that the traffic is likely to be related to background information and a fast sleep mode idle time, $Idle-short \leq Idle-long$, is used to enter sleep mode.

5.1.3 Results

The evaluation of the effectiveness of adopting burst mode ADSL modems and implementing sleep mode policies in the ADSL lines is based on the metric $T_{off-total}(l)$, that is the total time spent in the sleep mode by the line l , corresponding to $T_{off-total}(l) = \sum_i T_{off}(i; l)$, where $T_{off}(i; l)$ is the duration of the i^{th} sleep mode interval for the line l .



- a. Comparison of the average duration of total silent time $T_{off-total}$ using the SSM policy with different *MinRate*.
- b. Comparison of the average duration of total silent time $T_{off-total}$ using the 2SM policy with *Rate-low* = 1 kbit/s and T_{active} = 2 min.

Figure 17 Average duration of total silent time $T_{off-total}$ for SSM and 2SM policies with different settings.

The results of the SSM policy are reported in Figure 17. We report in Figure 17(a), the average time spent by the N users of our data set in the sleep mode state, that is

$$E[T_{off-total}] = \frac{\sum_{l=1}^N T_{off-total}(l)}{N}$$

We consider different values of *MinRate* in order to see the effect of *background traffic*. Recall that a modem can enter in sleep mode only if the line rate has not exceeded *MinRate* for *Idle* seconds. In case no *MinRate* is applied (e.g., *MinRate* = 0 kbit/s), the average time spent in the sleep mode state is very limited. This can be clearly seen in Figure 17(a). As *Idle* is higher than 15 minutes, $E[T_{off-total}]$ is almost zero, meaning that *background traffic* is generated periodically and idle time periods are not long enough to allow the modem to entering sleep mode. Instead, for *MinRate* greater than zero, even a low value such as 1 kbit/s brings significant improvements. Indeed, in the worst case with *Idle* equal to 30 minutes, we have $E[T_{off-total}]$ equal to 15 hours. Decreasing *Idle* it is possible to gain up to 3 hours of sleep mode considering *MinRate* equal to 1 kbit/s. If we further increase *MinRate*, no significant advantages are introduced; indeed, comparing 1 kbit/s and 10 kbit/s thresholds, the latter achieves a $E[T_{off-total}]$ about 2 hours longer in the best case. Thus, the value of *MinRate* is not strongly affecting the time spent in the sleep mode state, provided it is larger than zero.

Considering the 2SM policy, the evaluation of $E[T_{off-total}]$ is shown in Figure 17(b) for different settings. We consider *Rate-low* = 1 kbit/s, *Idle-long* = 15 min and we set T_{active} equal

to 2 min. Notice that the values of $E[T_{off-total}]$ are almost constant with respect to *Rate-high*. Instead, decreasing *Idle-short*, it is possible to spend more time in the sleep mode state. In particular, using *Rate-high* = 100 kbit/s and *Idle-short* = 2 min, a line is silent for 18.2 h/day in average. For comparison, the SSM policy guarantees 16.3 h/day (highlighted in the plot for comparison). This means that with more aggressive settings it is possible to save more energy. However, the 2SM setting introduces more state transitions (i.e., change from the sleep mode to the ON state) with respect to the SSM case. This means that the 2 hours of additional savings implies additional impairments. More conservative settings could represent a better performance/gains compromise.

Finally, we evaluate the energy consumption for the SSM and 2SM policies and we compare them with respect to the case in which ADSL modems adopt continuous mode transmission and thus lines are always active. We take into account the power consumption of ADSL modems located at the users' and at the operator's side. We assume that the power consumption of a DSLAM modem port is around 1 W while an user modem consumes about 5 W according to the values reported in Refs. [18] and [19]. The power consumption of modems in the sleep mode state depends strongly on their implementation. Characterizing the implementations details of the sleep mode policies is out the scope of this work. Those are strictly related to the modem hardware and technological constraints. We just assume that the modems have enough buffering resources to compensate the variations of the line rate introduced by the sleep mode policies. In the following, we consider two possible cases for the power consumption of the sleep mode state: (i) the modem is completely switched OFF, thus consuming approximately 0 W, (ii) the modem supports some basic functionalities with a reduced power consumption.

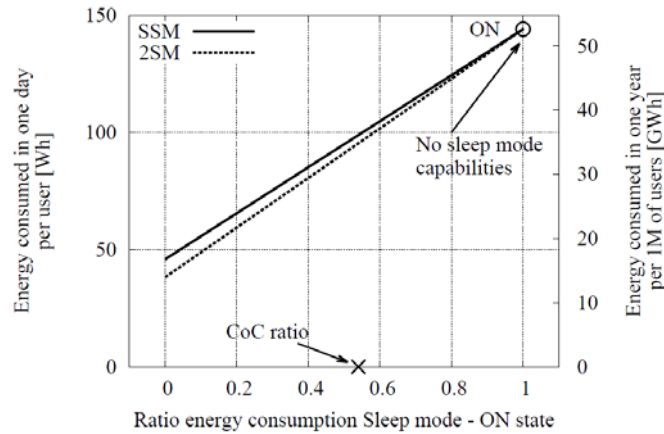


Figure 18 Average energy consumption per users. SSM policy with *MinRate* = 1 kbit/s and *Tidle* = 15 min. 2SM policy with *Rate-low* = 1 kbit/s, *Rate-high* = 100 kbit/s, *Idleshort* = 5 min, *Idle-long* = 15 min and *Tactive* = 2 min.

We select the following settings for the policies which represent the best trade-off between time spent in the sleep mode state and number of transitions: for SSM policy *MinRate* = 1 kbit/s and *Idle* = 15 min, for 2SM policy *Rate-low* = 1 kbit/s, *Rate-high* = 100 kbit/s, *Idle-short* = 5 min, *Idle-long* = 15 min, *Tactive* = 2 min. Using these settings we obtained the energy consumption reported in Figure 18. The x-axis reports the ratio between the energy consumed by the modem in the sleep mode state and the energy consumed in the ON state. Thus, x=0 is the case in which the modem is powered OFF when it enters sleep mode. When this ratio is equal to 1 it means that the system does not support sleep mode. The figure reports for comparison the amount of energy consumed by modems for the SSM and for the 2SM policies. The energy is evaluated with two different scales. Left y-axis reports the average amount of energy consumed per user in one day considering the average values

obtained from analysis of the dataset. Instead, right y-axis reports the energy consumed in one year assuming 1 million customers. These results are obtained assuming the monitored users are representative for a wider population and power consumption is similar in different days.

We can notice that the energy consumed by the two strategies is very similar, with 2SM performing a little better. Indeed, the decrease of the energy consumption guaranteed by the simple SSM policy is very large. Considering as reference for the ON and the sleep mode states the power consumption values reported in the “Code of Conduct on Energy Consumption of Broadband Equipment”, the Sleep mode - ON state ratio is about 0.54, and we have that the SSM allows to easily save about the 35% of energy, which consists to save 18 GWh in one year for a population of 1 million users. Note that, since the DSLAM modem accounts for 1/6 of the energy consumption of a line, an operator that is willing to implement a sleep mode strategy only at DSLAM can save at least 3 GWh, which corresponds to about 330 kEuro per year, assuming a price of electricity equal to 0.112 Euro/kWh. If we consider the best scenario (i.e., the modem does not consume during the sleep mode), the energy saved is about 38 GWh, guaranteeing to double the savings.

6. Summary of the papers

6.1 Published/submitted papers

Involved partners /CIs	Authors	Title	Conf/journal	Date of presentation / publication
PoliMi	F. Musumeci, F. Vismara, V. Grkovic, M. Tornatore, A. Pattavina	“On the Energy Efficiency of Optical Transport with Time Driven Switching”	<i>International Conference on Communications (ICC) 2011, Kyoto, Japan</i>	June 2011
PoliTo	F. Bota, F. Khuhawar, M. Mellia, M. Meo	“Comparison of Energy Efficiency in PSTN and VoIP Systems”	<i>e-Energy 2012 Conference, Madrid, Spain</i>	May 2012
CNIT (PoliMi), FW	F. Musumeci, L. Hernandez, L. Zapata, M. Tornatore, M. Riunno, A. Pattavina	“Dynamic Routing and Resource Allocation in Time-Driven-Switched Optical Networks”	<i>International Conference on High Performance Switching and Routing (HPSR) 2012, Belgrade, Serbia</i>	June 2012
CNIT (PoliMi), FW	F. Musumeci, M. Tornatore, G. Fontana, M. Riunno, S. Bregni, A. Pattavina,	“Energy-Efficiency of All-Optical Transport through Time Driven Switching”	<i>IET Optoelectronics Journal, Special Issue on Green Photonics, vol. 6, issue 4, pp. 173-182</i>	August 2012
PoliTo, FW	E. Bonetto, A. Finamore, M. M. Munafò, R. Fiandra	“Sleep Mode at the Edge: How Much Room is There?”	<i>Networks 2012, Rome, Italy</i>	October 2012
PoliTo, CNIT (PoliMi)	A. Bianco, E. Bonetto, F. Musumeci, A. Pattavina, M. Tornatore	“CapEx/OpEx Evaluation of Circuit vs Packet Switched Optical Networks”	<i>International Conference of Optical Networks Design and Modeling (ONDM) 2013, Brest, France</i>	April 2013
iMinds, CNIT (PoliMi), TUB	W. Van Heddeghem, B. Lannoo, D. Colle, M. Pickavet, F. Musumeci, A. Pattavina, F. Idzikowski	“Power Consumption Evaluation of Circuit-Switched versus Packet-Switched Optical Backbone Networks”	submitted to <i>Online GreenComm 2013 Conference</i>	

6.2 *Planned papers*

Involved partners/CIs	Topic	Targeted conf/journal	Planned date
PoliTo, CNIT (PoliMi)	CapEx/OpEx Evaluation of Circuit vs Packet Switched Optical Networks	TBD (journal)	Oct. 2013
CNIT (PoliMi), FW	Cost performance analysis of Time Driven Switching under static and dynamic traffic	TBD (journal)	Oct. 2013

7. Conclusions

In this deliverable the energy efficiency of circuit and packet switching paradigms has been evaluated. As a first comparison between the two paradigms, we evaluated the energy consumption in both scenarios in the context of optical IP-over-WDM networks. We found that, in general, circuit switching is preferable from both the power consumption and cost perspective, especially considering the envisioned traffic increase in telecommunication core networks, as this switching paradigm can take high benefit from establishing direct end-to-end optical lightpaths to reduce the number of power hungry router interfaces and other electronic devices. Only when the traffic carried by the network is low, i.e., below a certain threshold depending on the considered network topology and devices line rate (transmission rate of WDM transponders and router line cards), the packet switching solution provides higher efficiency, due to its ability in aggregating/separating traffic flows coming from (or going towards) different source (destination) nodes. To this end, hybrid circuit/packet switching architectures, which are able to perform traffic grooming and, when useful, optical bypass of IP routers, represent the most energy-friendly solutions to cope with multiple network and traffic situations.

Thus, such hybrid solution has been compared to a novel switching paradigm, the Time Driven Switching (TDS), which allows to perform traffic grooming directly in the optical domain thanks to the time-synchronization of all network elements. With such scenario, power savings can be also obtained when performing traffic grooming, since electronic operations are no more needed as in the packet-switching (or even hybrid circuit/packet switching) solutions.

Following, we investigated the energy efficiency of PSTN and VoIP telephone networks using actual data. Results show that the VoIP architecture is energy hungry and thus requires, to be competitive in terms of energy efficiency, the implementation of aggressive energy saving schemes.

Finally, energy efficiency of continuous and burst transmission modes has been investigated in the case of ADSL lines. We first evaluated that ADSL lines are usually active for limited periods of time or present a very low bit rate. We thus quantified the achievable energy savings and we found that burst mode ADSL modems, implementing sleep mode policies, can effectively reduce the energy consumption of access networks.

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List of Acronyms

ATM	Asynchronous Transfer Mode
BN	Basic Node
CapEx	Capital Expenditure
CI	Collaborating Institution
CTR	Common Time Reference
EDFA	Erbium Doped Fiber Amplifier
EO	Electrical-Optical
FDL	Fiber Delay Line
FLS	Fractional Lambda Switches
GA	Genetic Algorithm
GPS	Global Positioning System
GS	Group Switch
ICT	Information and communication technologies
IF	Immediate Forwarding
ILP	Integer Linear Programming
IP	Internet Protocol
IRA	Integrated Research Action
MP	Multiple Path
NIF	Non-Immediate Forwarding
NoE	Network of Excellence
OE	Optical-Electrical
OEO	Optical-Electrical-Optical
OpEx	Operational Expenditure
OSNR	Optical Signal-to-Noise Ratio
OXC	Optical cross-connect
PBX	Private Branch Exchange
PF	Pipeline Forwarding
PoE	Power over Ethernet
PSTN	Public-Switched Telephone Network
SP	Single Path
SP-MW	Single Path - Multiple Wavelength
SP-SW	Single Path - Single Wavelength
SSM	Simple Sleep Mode
SVP	Synchronous Virtual Pipe
TC	Time Cycle
TDS	Time Driven Switching
TF	Time Frame
VoIP	Voice over IP

WDM	Wavelength Division Multiplexing
WP	Work Package
2SM	Double threshold Sleep Mode