Energy Efficiency in Telecom Optical Networks

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***Abstract*—Since the energy crisis and environmental protection are gaining increasing concerns in recent years, new research topics to devise technological solutions for energy conservation are being investigated in many scientific disciplines. Specifically, due to the rapid growth of energy consumption in ICT (Information and Communication Technologies), lot of attention is being devoted towards "green" ICT solutions. In this paper, we provide a comprehensive survey of the most relevant research activities for minimizing energy consumption in telecom networks, with a specific emphasis on those employing optical technologies. We investigate the energy-minimization opportunities enabled by optical technologies and classify the existing approaches over different network domains, namely core, metro, and access networks. A section is also devoted to describe energy-efficient solutions for some of today's important applications using optical network technology, e.g., grid computing and data centers. We provide an overview of the ongoing standardization efforts in this area. This work presents a comprehensive and timely survey on a growing field of research, as it covers most aspects of energy consumption in optical telecom networks. We aim at providing a comprehensive reference for the growing base of researchers who will work on energy efficiency of telecom networks in the upcoming years.**

***Index Terms*—Energy, efficiency, telecom, optical, networks.**

I. INTRODUCTION

ENERGY conservation is gaining increasing interest in our society in recent years. There is growing consensus on the necessity to put energy conservation at the top of the research agenda, as one of the most compelling and critical current research issues. Today, traditional energy resources, such as hydrocarbon energy, provide most of the energy demand, e.g., 85 percent of primary energy of USA's electricity [1], but this kind of energy is not renewable, and it is expected to be finally used up in the not-too-distant future. Besides, the combustion of hydrocarbon materials releases large amounts of Green House Gases (GHG), a major cause of Global Warming.

Two research directions are being explored to address this situation. First, renewable energy is being harnessed to replace traditional hydrocarbon energy. This not only gives the opportunity to reduce the carbon footprint, but also it paves the road towards a sustainable and environment-friendly societal development [2]. Second, energy-conservation approaches are being investigated in many science and technology areas - low-energy equipment and components are being developed, not only to decrease the energy cost, but also to help to save our environment. In almost all scientific disciplines where technological development may allow to reduce the amount of energy needed to support human activities, research efforts are ongoing to devise new solutions for energy conservation.

ICT (Information and Communication Technology) is one of the most promising areas for pursuing energy conservation. ICT is widely used in most aspects of our society and has traditionally had an environment-friendly image. This good reputation comes mostly from the fact that worldwide telecom networks have transformed our society and provided practical means to reduce the human impact on nature (consider, for example, telecom applications for telework, videoconference, e-commerce, and their impact on human movements). There is however a downside of ICT. The ubiquitousness of ICT in daily life (both private and professional) brings another issue - the energy consumption of computers and network equipment is becoming a significant part of the global energy consumption [3], [4], [5].

As the coverage of ICT is spreading rapidly worldwide, the energy consumption of ICT is also increasing fast, since more equipment and components for networks and communications are being deployed annually. From the data of 2009, ICT consumes about 8% of the total electricity all over the world [6]. Telecom networks, which represent a significant part of the ICT, are penetrating further into our daily lives. The traffic volume of broadband telecom networks is increasing rapidly and so is its energy consumption. Figure 1 reports a prediction of the energy consumption growth (by percentage) of telecom networks in the coming years [7], [8]. Considering both the growing energy price (expected with the decline of cheap availability of fossil fuels) and the increasing concern on the Green House effect which is being translated in government policies, the energy consumption of ICT is already raising questions, and it is imperative to develop energy-efficient telecom solutions. We need to design new networking paradigms so that ICT will maintain the same level of functionality while consuming a lower amount of energy in future [3], [9].

Among the various network technologies, in this paper, we mainly focus on energy efficiency of optical networking technologies. Optical technologies are widely used in telecom networks, and currently they constitute the basic physical network infrastructure in most parts of the world, thanks to their high speed, large capacity, and other attractive properties [10]. Optical networking technologies have also improved significantly in the recent decade. Different characteristics of optical networks have been investigated and many approaches have been proposed to improve the performance of optical networks. For instance, routing, wavelength assignment, and traffic grooming strategies have been proposed to make the optical network more cost-efficient [11]. Survivability of optical networks has also been thoroughly investigated because a failure of an optical link or node can cause a significant

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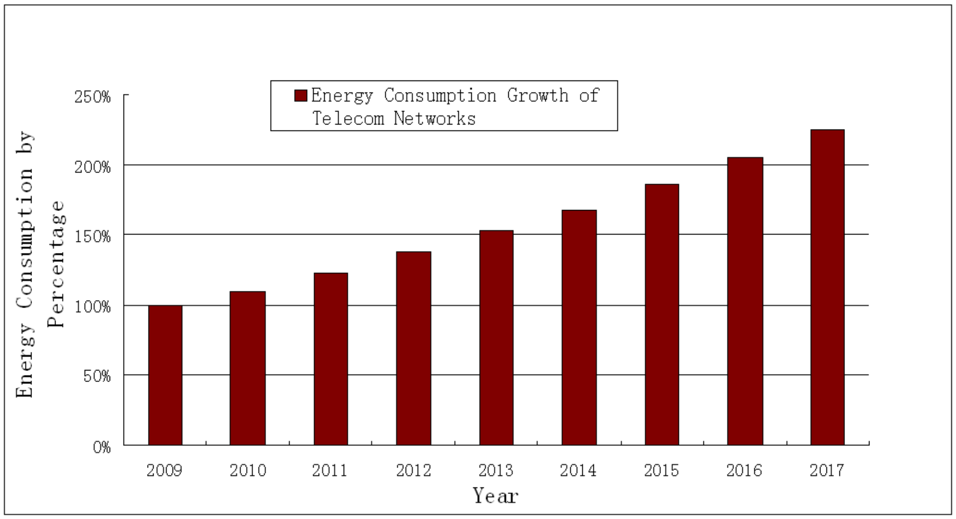

Fig. 1. Energy consumption forecast of telecom networks [7], [8].

loss due to the large bandwidth of an optical communication channel [12].

Nevertheless, the energy-efficient optical network is a new concept, which is being investigated in recent years. More research groups are starting to focus on it since energy-efficient optical networks will contribute to save the energy consumed by ICT, and further reduce the energy consumption of our society and protect our environment.

Minimizing energy consumption of optical networks can be generically addressed at four levels: component, transmission, network, and application. At the component level, highly-integrated all-optical processing components such as optical buffers, switching fabrics, and wavelength converters are being developed, which will significantly reduce energy consumption [13], [14]. Optical Switching Fabric (OSF) is more energy-efficient than electronic backplanes and interconnects [15], [16]. At the transmission level, low-attenuation and low-dispersion fibers, energy-efficient optical transmitters and receivers, which improve the energy efficiency of transmission, are also being introduced [17]. Energy-efficient resource allocation mechanisms, green routing, long-reach optical access networks [18], etc. are being investigated at the network level to reduce energy consumption of optical networks. At the application level, mechanisms for energy-efficient network connectivity such as “Proxying” [19] and green approaches for cloud computing [20] are being proposed to reduce the energy consumption.

Here, our objective is to mainly survey the energy-saving approaches at the network level. Typically, a telecom network can be subdivided into three domains: core, metro, and access. Optical technologies play a relevant role in each of these domains, and we survey the research efforts to improve the energy efficiency of optical network solutions in all three domains.

As shown in Fig. 2, the core network is the central part of the telecom hierarchy, and it provides nationwide or global coverage. Links in the core network span long distances – a link (employing optical fibers) could be a few hundreds to a few thousands of kilometers in length, e.g., links providing connections between the main cities of the Unites States. Typically, core networks rely on mesh topologies that provide increased protection flexibility and efficient utilization of network resources. The metro network typically spans a metropolitan region, covering distances of a few tens to a few hundreds of kilometers and is dominantly based on a deep-rooted legacy of SONET/SDH optical ring networks. The access network connects the end users to their immediate service provider. The access network enables end users (businesses and residential customers) to connect to the rest of the network infrastructure, and it spans a distance of a few kilometers. Optical access networks are usually based on tree-like topologies.

In this paper, energy consumption data and energy-conservation approaches are surveyed in all three network domains. We also review some relevant energy-saving approaches in the application layer and energy-efficient architectures in the data centers because these domains: (i) involve network elements that consume significant energy in a telecom network, and (ii) they largely involve optical networking technologies.

A comprehensive survey on new solutions for energy-efficient optical networks is a very timely and useful contribution since researchers working on energy-efficient optical networks may benefit from having a handy collection of basic information on the energy consumption of the various components of an optical network as their background of research, and also a comprehensive classification with comments on current efforts and approaches can inspire researchers to have new ideas on energy-saving research. Our survey includes these two aspects and anticipates possible future research areas. Also, note that various international standardization organizations, such as ITU (International Telecommunication Union), IEEE (Institute of Electrical and Electronics Engineers), and others, are currently working on developing new standards to strengthen research on this topic [21]. In this paper, we also include a summary of these standardization efforts.

The rest of the paper is organized as follows. Section II classifies the network domains on which optical technologies are employed, and provides energy consumption data for

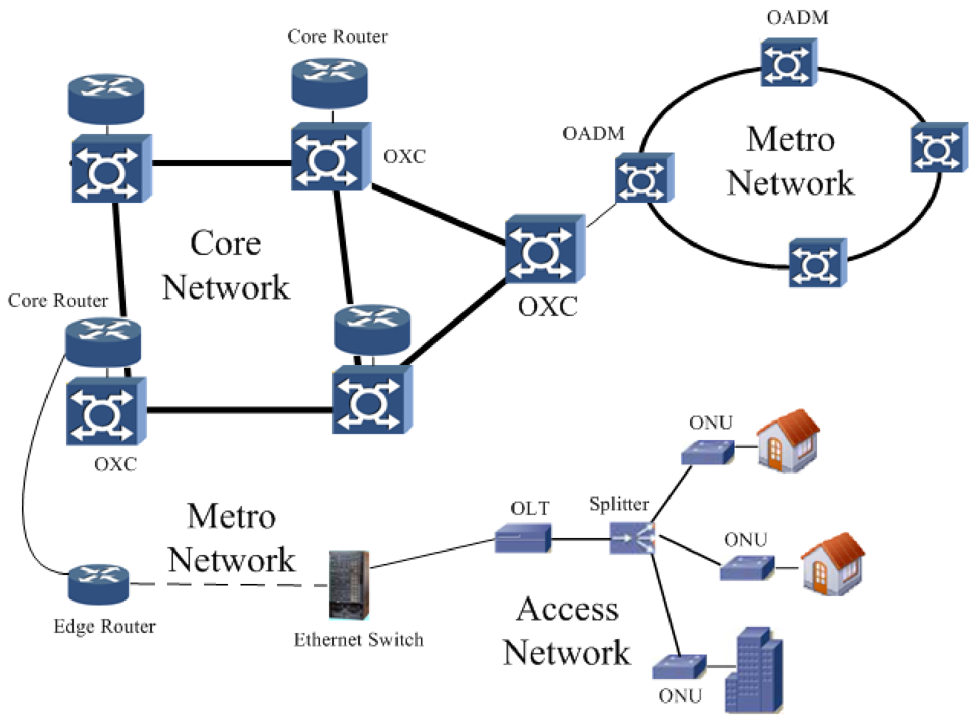

Fig. 2. Telecom network hierarchy.

the optical components and systems used in various network domains. Section III summarizes the standardization efforts for energy-efficient telecom network design. Section IV provides an overview of techniques and architectures for energy-consumption minimization in core networks, while Section V provides the corresponding treatment for optical metro and access networks. Section VI describes some recent approaches on how optical networking technologies can be employed to increase the energy efficiency in data centers and in the application layer. Finally, Section VII concludes the paper, outlining possible future research topics on energy-efficient optical networking.

II. Network Domains

Telecom networks can be divided into three network domains: core, metro, and access in all these network domains in order to support higher transmission rates and more cost-effective data transfer. In this section, we describe the three network domains and introduce the most important network elements of each domain. For each of these network elements, we also provide representative data and references regarding their energy consumption.

A. Core Network

By core network, we usually refer to the backbone infrastructure of a telecom network, which interconnects large cities (as network nodes), and spans nationwide, continental, and even intercontinental distances. The core network is typically based on a mesh interconnection pattern and carries huge amounts of traffic collected through the peripheral areas of the network. So, it needs to be equipped with appropriate interfaces towards metro and access networks which are in charge to collect and distribute traffic, so that users separated by long distances can communicate with one another through the core (backbone) network.

In the core network, optical technologies are widely used to support the basic physical infrastructure and achieve high speed, high capacity, scalability, etc. To intelligently control and manage the optical network, several high-level management equipment and technologies have been developed. For example, network architectures based on IP (Internet Protocol) over SONET / SDH (Synchronous Digital Hierarchy), IP over WDM (Wavelength-Division Multiplexing), or IP over SONET/SDH over WDM have been deployed over the past two decades [22], [23]. As core networks exhibit multi-layer network architectures, energy consumption of the core network should be considered at both of the network layers, i.e., the optical layer and the electronic layer.

Let us consider an IP-over-WDM network as an example, as shown in Fig. 3 - energy consumption of its network components can be found in the switching (routing) level and also in the transmission level. In the switching (routing) level, the main energy consumers are Digital Cross-Connects (DXC) and IP routers for switching electric signals at the electronic layer, while Optical Cross-Connects (OXC) are used to switch optical signals in fibers at the optical layer. In the transmission systems, WDM is a technology which multiplexes multiple optical carrier signals on a single optical fiber by using different wavelengths of laser light to carry different signals. As shown in Fig. 3, a WDM transport system [24] uses a multiplexer at the transmitter to join the signals together, and a demultiplexer at the receiver to split them apart. Transponders are used for transmitting and receiving signals. The booster is a power amplifier which can compensate the power loss caused by the multiplexer. The pre-amplifier is used

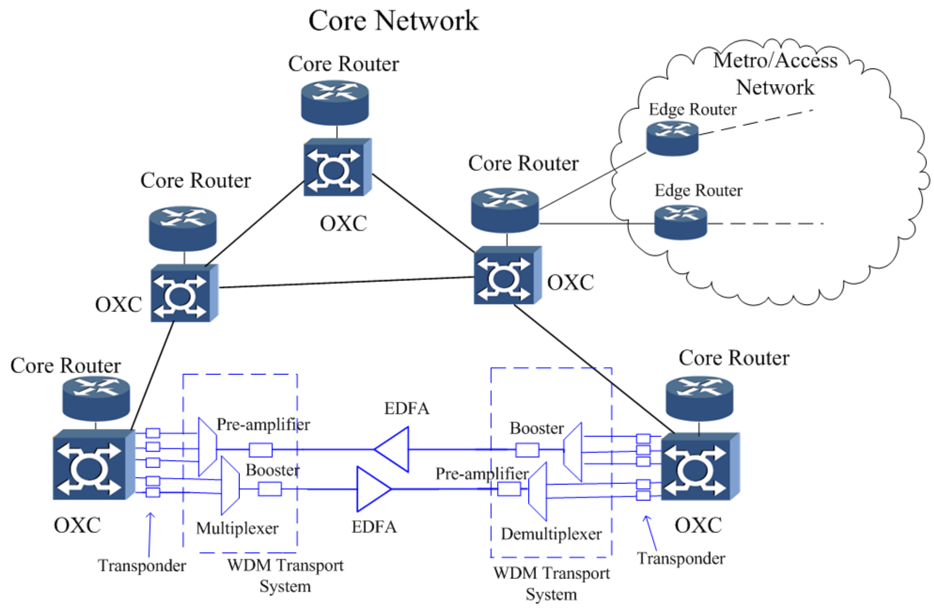

Fig. 3. Core network.

to amplify the power of optical signals so as to increase the sensitivity of the receiver. All these components of a WDM transmission system consume energy. Erbium-Doped Fiber Amplifiers (EDFAs), which are used for amplifying optical signals in the optical fiber, also consume energy: the energy consumption of an optical amplifier and how to measure it may depend on the way the optical amplifier is operated [25].

Next, we provide some typical data on energy consumption of the most important network components in core networks. Table I shows the energy consumption data of these components. The power values reported in Table I are associated with the maximum load that the corresponding equipment can serve, except for all-optical equipment where, due to the transaprency of the system to the bit rate, power value at a specified aggregate rate is difficult to calculate. Nonetheless, the above-mentioned property of transparency makes optical equipment more scalable (to increase capacity) than electronic equipment. By analyzing these data, it clearly emerges that energy consumed by the electronic layer is much larger than that of the optical layer. In other words, optical switching is more energy-efficient than electronic switching which is one of the basic ideas for energy-efficient network design by exploiting optical technology.

B. Metro Network

The metro network is the part of a telecom network that typically covers metropolitan regions. It connects equipment for aggregation of residential subscribers' traffic (e.g., it provides interfaces to dispersed access network, such as various flavors of Digital Subscriber Line (xDSL) and Fiber-to-the-Home or Fiber-to-the-x (FTTx)), and it provides direct connections to the core network for Internet connectivity. Different networking technologies have been deployed in different metro areas across the world. As shown in Fig 4, SONET (Synchronous Optical Networking), Optical WDM ring, and Metro Ethernet are three dominant technologies in metro networks. As an example, Metro Ethernet is a commonly-used metro network infrastructure which is based on the Ethernet standard [35] - edge routers, broadband network gateways, and Ethernet switches are its basic components. Energy consumption data of some Metro Ethernet equipment are shown in Table I.

Metro WDM ring networks have also been proposed to take the advantages of optical technology, such as higher speed and more scalability [36]. In metro WDM ring networks, energy consumption comes mainly from OADMs (Optical Add-Drop Multiplexers) which are used to add and drop optical signals. SONET ring architectures are also widely deployed in metro networks, which can aggregate low-bit-rate traffic of metro networks to high-bandwidth pipes of core networks [10]. SONET ADM (Add-Drop Multiplexer) is used to add and drop network traffic. Energy consumption of a SONET ADM is shown in Table I.

C. Access Network

The access network is the "last mile" of a telecom network connecting the telecom CO (Central Office) with end users. Access network comprises the larger part of the telecom network. It is also a major consumer of energy due to the presence of a huge number of active elements [7].

There are several access technologies proposed and deployed in the market such as xDSL (Digital Subscriber Line), CM (Cable Modem), Wireless and Cellular networks, FTTx, WOBAN (Wireless-Optical Broadband Access Network), etc. These technologies can be broadly classified into two categories – (a) wired (such as xDSL, CM, FTTx, etc.) and (b) wireless.

The enhanced copper or xDSL systems cover various technologies such as ADSL (asymmetric DSL), VDSL (very-high-speed DSL), and HDSL (high-bit-rate DSL). xDSL technologies use existing PSTN (Public-Switched Telephone Network) infrastructure to provide Internet service. Cable modem technology uses co-axial cable to provide Internet service along

TABLE I
TYPICAL ENERGY CONSUMPTION DATA OF DIFFERENT COMPONENTS IN TELECOM NETWORKS.

Network Domain	Component	Capacity	Energy Consumption
Core Network	Core Router (Cisco CRS-1 Multi-shelf System)	92 Tbps	1020 kW [26]
	Optoelectronic Switch (Alcatel-Lucent 1675 Lambda Unite MultiService Switch)	1.2 Tbps	2.5 kW [27]
	Optical Cross-Connect (MRV Optical Cross-Connect)	N/A	228 W [28]
	WDM Transport System (Ciena CoreStream Agility Optical Transport System)	3.2 Tbps	10.8 kW [24]
	WDM transponder (Alcatel-Lucent WaveStar OLS WDM Transponder)	40 Gbps	73 W [29]
	EDFA (Cisco ONS 15501 EDFA)	N/A	8 W [29]
Metro Network	Edge Router (Cisco 12816 Edge Router)	160 Gbps	4.21 kW [30], [31]
	SONET ADM (Ciena CN 3600 Intelligent Optical Multiservice Switch)	95 Gbps	1.2 kW [32]
	OADM (Ciena Select OADM)	N/A	450 W [33]
	Network Gateway (Cisco 10008 Router)	8 Gbps	1.1 kW [31]
	Ethernet Switch (Cisco Catalyst 6513 Switch)	720 Gbps	3.21 kW [26], [31]
Access Network	OLT (NEC CM7700S OLT)	1 Gbps	100 W [34]
	ONU (Wave7 ONT-E1000i ONU)	1 Gbps	5 W [34]

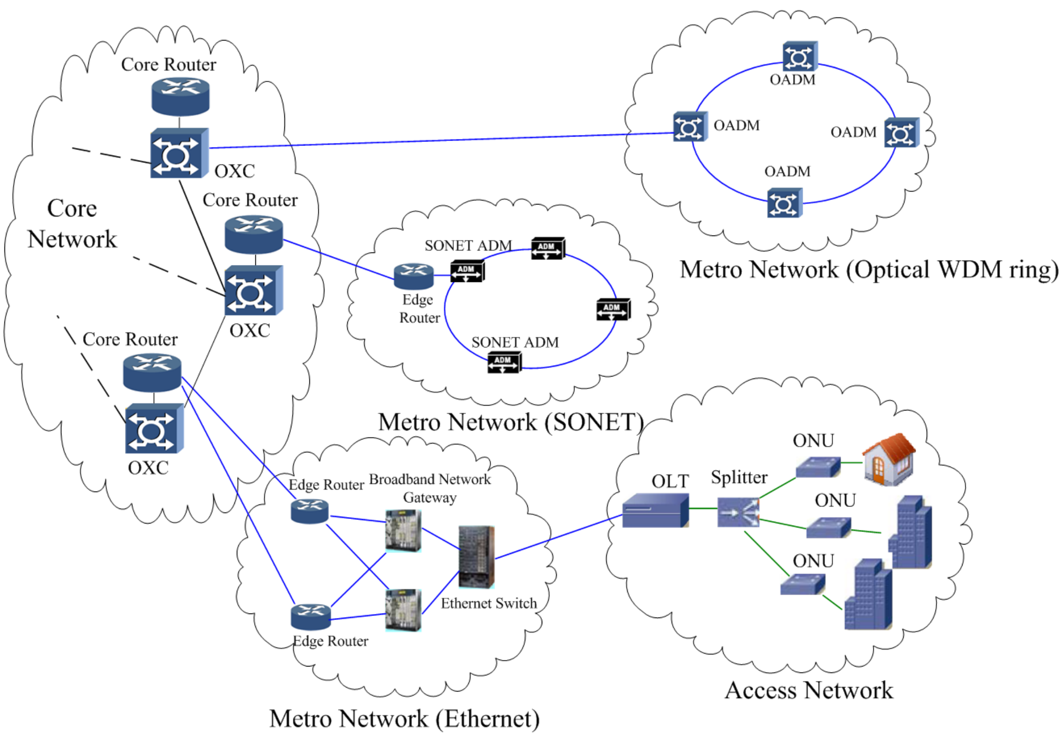

Fig. 4. Metro and access networks.

with digital TV. FTTx has different underlying technologies, such as direct fiber, shared fiber, and the most dominant one - PON (Passive Optical Network).

PON is the leading choice for fiber access network deployment because it has only passive elements in the fiber plant (see Fig. 4). Table I reports energy consumption data for the two main network elements in a PON architecture: OLT (Optical Line Terminal), located at the CO, and ONU (Optical Network Unit), located at (or close to) the end customer. Wireless access technologies include WiFi (Wireless Fidelity), WiMAX (Worldwide Interoperability for Microwave Access), and Cellular data service (such as LTE (Long Term Evolution), etc.). WOBAN is a novel access architecture which consists of a wireless network at the front-end supported by an optical backhaul, and can provide high-bandwidth service.

III. Standardization Efforts

The importance of energy efficiency in networking has also been acknowledged by a number of new workgroups in international standards organizations. Several of them, such as ITU (International Telecommunication Union), IEEE (Institute of Electrical and Electronics Engineers), ETSI (European Telecommunication Standard Institute), TIA (Telecommunication Industry Association), ATIS (Alliance for Telecommunications Industry Solutions), ECR (Energy Consumption Rating) Initiative, TEEER (Energy Efficiency Requirements for Telecommunications Equipment), etc. are working on new standards for energy-efficient networks [21]. They are developing novel concepts for green networking and their activity can provide guidance to researchers on the practicality of their research.

As part of a major initiative on Green Networks, ITU is organizing Symposia on ICT and Climate Change [37]. These symposia bring together key specialists in the field: from top decision makers to engineers, designers, planners, government officials, regulators, standards experts, and others. Topics presented and discussed include the adaptation and mitigation of the effects of climate change in the ICT sector and in other sectors, "green" ICT policy frameworks, and the use of ICT in climate change science and in emergency situations. The ITU Telecommunication Standardization Sector has also announced the establishment of SG- (Study Group) 15 on energy-conservation techniques. The technologies considered in the list include optical transport networks and access network technologies such DSL and PON. Together, these technologies represent a significant consumption of energy worldwide.

IEEE is developing a standard on Energy-Efficient Ethernet - IEEE P802.3az [38]. Its objectives are (i) to define a mechanism to reduce power consumption during periods of low link utilization for the PHYs (Physical layer protocol), (ii) to define a protocol to coordinate transitions to or from a lower level of power consumption which do not change the link status or drop frames, and (iii) to define a 10 megabit PHY with a reduced transmit amplitude requirement so that power consumption can be decreased. This effort is expected to be completed by September 2010.

ETSI Green Agenda is one of ETSI's major strategic topics [39]. This effort will implement the ISO 14001:2004 and 14004:2004 standards which are the Environmental Management Standards. In addition, ETSI Green Agenda includes Environmental Engineering, which consists of (i) "DTR/EE-00002" Work Item: reduction of energy consumption in telecommunications equipment and related infrastructure; (ii) "DTR/EE-00004" Work Item: use of alternative energy sources in telecommunication installations; (iii) "DTS/EE-00005" Work Item: energy consumption in Broadband Telecom Network Equipment; (iv) "DTS/EE-00006" Work Item: environmental consideration for equipment installed in outdoor location; and (v) "DTS/EE-00007" Work Item: energy efficiency of wireless access network equipment. In addition, ETSI ATTM (Access, Terminals, Transmission, and Multiplexing) "DTR/ATTM-06002" Work Item, which is about power optimization of xDSL transceivers, is under standardization. In the DTS/EE-00005 Work Item, which is the most closely related to the topic of this paper, ETSI leads the effort to define energy consumption targets and measurement methods for both wired and wireless broadband-telecom-network equipment. In the first phase, DSL, ISDN (Integrated Services Digital Network), etc. have been considered. In the second phase, energy consumption for WiMAX, PLC (Power Line Communication) will be investigated [39].

TIA started a "Green Initiative" in 2008, called EIATRACK [40]. It offers companies a way to strategize their future growth and environmentally-conscious initiatives in new markets. Its key product-compliance issues are about Take-back, Batteries, Restricted Substances, Design for Environment, and Packaging. More than 1,500 pieces of legislation are tracked, from proposal through implementation, which cover all major regions of Europe, Asia Pacific, North America, and South America. It contains accurate, up-to-date content provided by a wide range of international legal and technical subject-matter experts, and EEE (Electrical and Electronic Equipment) and RoHS (Restriction of the use of certain Hazardous Substances) experts in Europe and other jurisdictions.

ATIS has set up a committee named NIPP (Network Interface, Power, and Protection Committee), which is working on developing standards and technical reports covering Network Interfaces, Power, Electrical, and Physical Protection [41]. The "Green" activities of the NIPP committee are focused on: (i) producing standards that may be used by Service Providers to assess the true energy needs of telecom equipment, (ii) RoHS in electronic equipment, and (iii) investigating methods to reduce the power consumption of DSL modems at both network and customer ends of the line [21]. The NIPP has also established the TEE (Telecommunications Energy Efficiency) subcommittee which develops and recommends standards and technical reports related to the energy efficiency of telecommunication equipment. They are making efforts to define energy-efficiency metrics, measurement techniques, as well as new technologies and operational practices for telecommunications components, systems, and facilities [42]. In summary, like the standardization organizations listed above, ATIS is also focusing on "Green" technologies at both the physical and the network layers.

The concept of ECR (Energy Consumption Rating) has also been initiated recently. Since governments and corporations around the world are tightening energy consumption and carbon emission budgets, telecom equipment manufacturers are claiming to develop new and energy-efficient equipment. Verifiable data is needed to support these "green" marketing claims. ECR is defined to measure the energy efficiency of network equipment which is expressed in Watts/Gbps. As a primary metric, ECR is expressed to measure the ratio of power consumption and transmission bandwidth. New criteria are also used to define the practical aspects of energy efficiency for the networking industry [43].

TEEER Metric Quantification (Energy-Efficiency Requirements for Telecommunications Equipment) has been achieved from the Verizon energy-efficiency initiative, VZ.TPR.9205. The purpose of this program is to set Verizon technical purchasing requirements and to foster the development of energy-efficient telecom equipment, thereby reducing GHG emissions. TEEER is defined as an average rating of the power consumption of an equipment at multiple utilization levels. TEEER metric applies to all new equipment purchased by Verizon after January 1, 2009 [44].

IV. Core Network

In core networks, energy is mostly consumed in network transmission and switching equipment such as routers, OXCs

(Optical Cross-Connect), EDFAs, and transponders. Based on the data of Section II, the amount of energy consumed by core networks is huge. However, current network architectures and operation schemes generally do not pay much attention to energy efficiency. Therefore, many recent research efforts focus on energy-efficient core network. The approaches to reduce energy consumption in core networks can be divided into four categories: (i) selectively turning off network elements, (ii) energy-efficient network design, (iii) energy-efficient IP packet forwarding, and (iv) green routing.

A. Selectively Turning Off Network Elements

A major approach to save energy in the core network consists of selectively switching off idle network elements when traffic load decreases (e.g., at night), while still maintaining the vital functions of the network in order to support the residual traffic. If we consider a representation of the network hierarchy as in Fig. 2, we can see that there is often enough redundancy in the network so that some of the nodes can be completely turned off when they are not used as source or destination of traffic, and they are not essential also as transfer nodes. In this context, a node can be turned off (i) only when it is totally unused, (ii) when the traffic goes below a given threshold, leaving the responsibility to reroute the residual traffic to upper layers, and (iii) after proactively rerouting the traffic along other routes, in order to avoid traffic disruptions. These three approaches involve a wide range of burdens as far as control, management, and operation of the network are concerned. While the first approach requires no or minimal additional network control and the second only requires to gather congestion information, the third approach can be applied only in a network that has some form of automatic provisioning and/or reprovisioning in place.

In a similar manner, links can be switched off when there is no traffic on them, or when traffic goes below a given threshold, or when it is possible to re-route the traffic flowing along them. Unfortunately, most of the elements in a core network can not be just shut down without affecting the performance of the network. Shutting down an intermediate core node may cause the connection to be rerouted over a longer route, which may sometimes not be acceptable due to various reasons: congestion, extra delay, etc. So, the possibility of turning off nodes or links has to be carefully evaluated under connectivity and QoS (Quality-of-Service) constraints.

This problem has been modeled in [45] over a specific case study network - in order to maximize energy saving, one has to identify the maximum number of idle nodes and links while still supporting the ongoing traffic. This problem has been proven to be a NP-hard problem and can be formulated as a MILP (Mixed Integer Linear Program). Since the problem is computationally intractable, heuristics have been proposed in [46]. Moreover, traffic load varies at different hours of the day. Assuming that traffic demand at off-peak time is up to 60% lower than that at peak time, it is possible to reduce the percentage of powered nodes to 17% and links to 55% in the off-peak hours by switching off idle nodes and links, while ensuring that the resource utilization is still within a given threshold [47]. In [48], [49], the authors discuss the relationship between network robustness, performance, and Internet power consumption based on data collected from Internet sources.

In [50], the authors deduce energy-efficiency limit of adaptive networks. They develop several traffic models based on real traffic observations. If networks can follow these traffic models during resource allocation where resources will be allocated according to the traffic demands, energy efficiency of such networks can improve significantly from current constant-power networks. In [51], a scheme is proposed to shut down idle line cards (and the corresponding optical circuit or lightpath) when the traffic load is low. In this scheme, the physical topology is not changed and energy is saved by only changing the virtual connectivity. Similarly, in [52], the authors have also proposed a scheme to save energy by shutting down idle line cards, and also chassis, of IP routers in IP-over-WDM networks when the traffic load is low. In addition, this scheme minimizes the potential traffic interruption when the line cards and chassis are being shut down.

B. Energy-Efficient Network Design

Another possible way to achieve energy efficiency is to devise energy-efficient architectures directly during the network-design stage. For example, in [29], the authors consider a design approach for an IP-over-WDM network where the energy consumption of IP routers, EDFAs, and transponders is jointly minimized. The results show that different schemes of traffic grooming have a significant impact on energy-efficient design [29]. In this paper, heuristics have also been proposed to minimize the energy consumption of network equipment. The authors considered two possible ways to implement IP-over-WDM networks, i.e., lightpath non-bypass and bypass. Under lightpath non-bypass, all the lightpaths incident to a node must be terminated, i.e., all the data carried by the lightpaths is processed and forwarded by IP routers. But the lightpath bypass approach allows IP traffic, whose destination is not the intermediate node, to directly bypass the intermediate router via a cut-through lightpath. Results show that lightpath bypass can save more energy than non-bypass, deriving the fact that the number of IP routers can be decreased while using the lightpath-bypass scheme in designing an energy-efficient core network. Besides, the authors also estimated the energy consumption of routers, EDFAs, and transponders separately. It is shown that the total energy consumption of routers is much more than that of EDFAs and transponders in IP-over-WDM networks.

Line cards and chassis of core routers consume considerably higher amount of energy in core networks. Different line card/chassis configurations, i.e., different fill levels of the chassis, result in different energy consumption. The higher the fill level is, the more energy-efficient the network will be [53]. This is because even an empty chassis without line cards consumes a large amount of energy. Therefore, a chassis with higher fill level has lower energy consumption per transferred bit than the ones with lower fill levels. Besides, even if two chassis have the same throughput, the chassis which supports higher-speed line cards tends to consume less energy than the one which supports lower-speed line cards [54]. Therefore, energy-efficient line card/chassis reconfiguration can be a novel way to reduce energy consumption.

Existing optical backbone networks support 10-40 Gbps line rate, and demands for higher bandwidth are growing. Recently, a major social networking site claimed that it could use 100 Gbps line rate right now, if available. Hence, a future optical backbone network will be required to support MLR (Mixed Line Rates) (e.g., 10/40/100 Gbps) over its links. In [55], the authors present a mathematical model to determine the energy efficiency of a MLR optical network. They compare the energy consumption of both MLR and SLR (Single Line Rate) networks using their model. The results indicate that a MLR network performs better than the SLR networks by reducing the networkwide energy consumption.

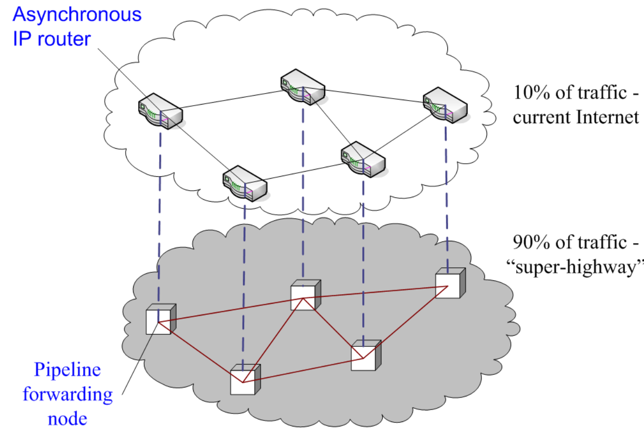

Fig. 5. Parallel networks on the same fiber infrastructure.

C. Energy-Efficient IP Packet Forwarding

Energy-aware packet forwarding has been proposed to lower energy consumption at the IP layer. In [54], the authors show that the size of IP packets impacts the energy consumption of routers. For a constant-bit-rate traffic scenario, the smaller the IP packets the routers transfer, the more energy they consume. Thus, new IP packet forwarding schemes can be designed to be energy-efficient. The size of IP packets can be optimized to save energy when they are being forwarded through routers. However, a tradeoff exists between packet switching delay and energy-efficient IP packet forwarding.

Another approach for energy-efficient IP packet forwarding is pipeline forwarding [67]. It is a “time-based” IP packet-switching scheme (also referred to as Time-Driven Switching), and it enables to extend the energy-efficient time-based IP packet switching all the way to the edges of the network. Based on pipeline forwarding, a network architecture which includes two independent, tightly-integrated, parallel subnetworks is proposed in [56]. The two subnetworks are the current Internet and “super-highways” where pipeline forwarding of IP packets is deployed (Fig. 5). Besides carrying typical traffic, such as mail, low-priority web browsing, and file transfers, asynchronous IP routers are used to transport the signaling required to set up synchronous virtual pipes in the pipeline forwarding parallel network which carries traffic requiring a deterministic service, such as phone calls, video on demand, video conferencing, and distributed gaming. Large bandwidth is required by most of such video-based services, which is the expected case for more than 90% of future Internet traffic. The pipeline forwarding parallel network is a “super-highway” as it will carry a large part of the traffic with deterministic performance as packets will flow faster and smoothly through it. Optical implementation of the Time-Driven Switching paradigm promises to enable even more significant energy savings [68].

D. Green Routing

In core networks, energy-aware routing is proposed as a novel routing scheme, which uses energy consumption of network equipment as the optimization objective. The authors in [54] propose an energy-aware routing scheme which considers line card/chassis reconfiguration in IP routers. Compared to the traditional shortest path or non-energy-aware routing scheme, energy-aware routing is expected to save a large amount of energy. This is because line cards and chassis are major energy consumers in core network and they are not configured and utilized energy-efficiently in traditional routing schemes. In this energy-aware routing scheme, energy consumption of IP routers in core networks is minimized. In addition, future energy-efficient routing schemes may tend to be more dynamic, which can reroute the traffic and save energy according to the traffic variation during the day or the season. A study on how to adapt OSPF (Open Shortest Path First) to include this kind of green routing feature can be found in [69].

While energy efficiency may be part of the solution, recent research [57] has also raised the concern that, given the rate of growth in demand for ICT products and services, an increase in efficiency will not be sufficient to counterbalance the growth in the ongoing deployment of new equipment and services. As well, the tendency of users to increase consumption of goods (in our case, energy) when the price of these goods decreases (phenomena referred to as the Khazzoom-Brookes postulate [70] or Jevons paradox) may mitigate any efficiency gains, i.e., it has been demonstrated that, paradoxically, increased efficiency results in increased consumption. So, depending solely on increased equipment efficiency may not result in any significant reduction in GHG emissions from computers and network equipment.

Under this perspective, since the target is essentially to reduce the carbon footprint, we can devise approaches to decrease energy consumption, targeting directly the reduction of GHG, which can help to solve Global Warming and related environmental problems. Therefore, renewable energy has gained more attention these days. An idea to reduce carbon footprint is to establish core servers, switches, and data centers at locations where renewable energy can be found, and then to route the traffic to the “Green areas” [58]. Since many network elements which consume energy will be deployed at the locations of renewable energy, zero carbon footprint can be realized. In this case, elements from other part of the network may have to request the equipment in “Green areas” to transfer their traffic demand by remote control, as shown in Fig. 6. This approach sets up a connection between the energy-efficient

TABLE II
COMPARISON OF GREENING EFFORTS IN CORE NETWORKS.

Paper	Algorithm	Energy Cost	Retrofit	Degree of Energy Savings	Extra Signalling and Control	Approach
L. Chiaraviglio et al. [45], [46], [47]	MILP & Heuristics [45], [46], Heuristics [47]	Minimized	Compliant	High (shutting down idle nodes)	Yes	Selectively turning off network elements
F. Idzikowski et al. [51]	MILP	Minimized	Compliant	High (shutting down idle line cards of routers)	Yes	Selectively turning off network elements
Y. Zhang et al. [52]	MILP	Minimized	Compliant	High (shutting down idle line cards and Chassis of routers)	Yes	Selectively turning off network elements
C. Lange et al. [50]	N/A	Non-minimized	New	High (adaptive networks)	Yes	Selectively turning off network elements
G. Shen et al. [29]	MILP & Heuristics	Minimized	Compliant	High (energy minimizing in two layers)	No	Energy-efficient network design
P. Chowdhury et al. [55]	MILP	Minimized	New	High (Mixed-Line-Rate networks)	No	Energy-efficient network design
L. Ceuppens [53]	N/A	Non-minimized	Compliant	Low (chassis re-configuration)	No	Energy-efficient network design
M. Baldi et al. [56]	N/A	Non-minimized	New	Medium (pipeline forwarding)	Yes	Energy-efficient IP packet forwarding
J. Chabarek et al. [54]	MILP	Minimized	Compliant	Medium (energy minimizing in IP layer)	Yes	Energy-efficient IP packet forwarding & Green routing
S. Figuerola et al. [57]	N/A	Non-minimized	New	High (renewable energy utilization)	Yes	Green routing
B. St. Arnaud [58]	N/A	Non-minimized	New	High (renewable energy utilization)	Yes	Green routing
E. Yetginer et al. [59]	MILP	Minimized	Compliant	Medium (traffic grooming)	No	Green routing
M. Xia et al. [60][61]	Heuristics	Non-minimized	Compliant	Medium (traffic grooming)	No	Green routing
B. Puype et al. [62]	Heuristics	Non-minimized	Compliant	Medium (traffic grooming)	No	Green routing
S. Huang et al. [63]	MILP & Heuristics	Minimized	Compliant	Medium (traffic grooming)	No	Green routing
Y. Wu et al. [64]	MILP & Heuristics	Minimized	Compliant	Medium (routing and wavelength assignment)	No	Green routing
M. Hasan et al. [65], [66]	Heuristics	Non-minimized	Compliant	Medium (traffic grooming)	No	Green routing

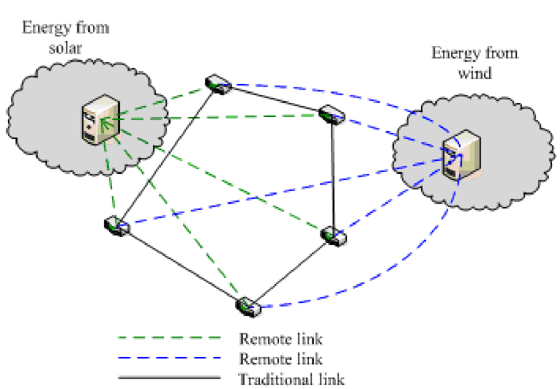

Fig. 6. Green routing with availability of renewable energy.

network and renewable energy utilization, which should gain more research interest in the near future.

Finally, traffic grooming is considered as a key functionality of WDM networks, in which, multiple low-speed traffic requests are groomed onto a high-capacity lightpath (wavelength) [11]. Energy-aware traffic grooming approaches may also help to reduce the energy consumption of an optical core network. Since network equipments consume a considerable amount of energy even without any traffic flow [54] and the energy consumption of most types of switching and transmission elements depends on the traffic load to a certain extent, energy-aware traffic grooming can be an approach to optimize the energy consumed by network elements.

In [59], total energy consumption of an optical WDM network is modelled in terms of the energy consumed by individual lightpaths. Then, an ILP (Integer Linear Program) formulation of the energy-aware grooming problem is defined. Due to computational complexity, numerical solution of the formulation is based on a small network, which indicates that significant energy savings can be achieved with energy-efficient traffic grooming. In [63] and [64], the authors propose both an MILP and a heuristic approach to do routing and wavelength assignment to minimize the number of interfaces of lightpaths to minimize their energy consumption. In [60] and [61], the authors consider energy consumed by network operations while grooming traffic in optical backbone networks. Energy consumption of every operation in traffic grooming is investigated, and an auxiliary-graph based model is proposed to identify the energy consumed by the operations. Results show that energy-aware traffic grooming saves a significant amount of energy compared to the traditional traffic grooming scheme. Authors in [62] also present a traffic engineering scheme based on the idea that traffic grooming at the lightpath layer can improve the energy efficiency of the network. They studied how multilayer traffic engineering affects energy efficiency, and their rationale is the IP/MPLS (Internet Protocol/Multi Protocol Label Switching) processing is more energy consuming than the lightpath (optical) layer. In [65] and [66], the authors focus on energy-aware dynamic traffic grooming problem in optical networks. Based on the traffic profile variation during different hours of the day, the authors minimize energy consumption of the devices in the network.

Table II shows the comparison of greening efforts in core networks. We compare the existing works in terms of the types of algorithms, energy cost of the network, necessity of retrofit (whether network architecture needs to changed), degree of energy savings, and extra signalling and control.

V. Access and Metro Network

In this section, we review the research contributions on energy conservation in access and metro networks. Most of the work in these areas deal with access networks - some preliminary investigations on metro network will be discussed at the end of this section.

A recent estimation [7] shows that access networks consume around 70% of overall Internet energy consumption. Hence, reduction of energy consumption in access networks will lead to significant Internet energy consumption reduction.

As bandwidth demands increase, access networks are becoming more heterogeneous in nature as different access technologies are being combined together. For example, current versions of xDSL use fiber as backhaul, and CM access networks use HFC (Hybrid Fiber Coax) technology as the network plant. Hence, developing energy-efficient fiber access technologies will lead to future energy-efficient access networks. In this section, we review the research efforts and recommendations aimed to build energy-efficient wired (fiber and other) access networks.

The wireless networking community has been developing energy-efficient wireless technologies for quite some time as extending the battery life in a wireless device is a very important problem. These research efforts can be summarized as a separate survey. In our current paper, we mainly focus on optical networking technologies for energy-efficient access networks.

A. Energy Consumption Estimation

There are several publications which provide approximate estimations of energy consumption in different types of access networks. The authors of [34] present a basic energy-consumption model for generic access networks. They use the model to compare the energy consumption of point-to-point optical links, PON, FTTN (Fiber To The Node), and WiMAX.

The efficiency of an access network can be defined as the energy consumed per bit of data transferred [34]. In fiber-based access networks, energy per bit drops as the average data rate increases. The per-user energy consumption data shows that, for access rates below 300 Mbps, PON is the most energy-efficient access network. Access networks with FTTN and VDSL technologies (where per-user data rate is limited to 100 Mbps) consume two to three times more energy than PON due to the presence of active remote nodes in the plant. WiMAX has the highest energy consumption among all these access technologies at access rate above 1 Mbps, and its date rate is limited to around 20 Mbps per user. For data rates above 300 Mbps, the point-to-point fiber access network becomes more energy efficient compared to PON as statistical multiplexing gain in PON does not apply anymore. Hence, it is concluded that PON and point-to-point optical networks are the most energy-efficient access alternatives.

The authors of [71] extended the energy-consumption model of [34] and studied the energy consumption of different FTTx network variants with respect to the average access bit rate. Their results also conform with the findings in [34] - up to certain data rate, PON-based FTTx are more energy efficient than point-to-point FTTx networks, and after that rate, point-to-point FTTx networks are more energy efficient.

The authors of [72] measure the energy consumption of a content delivery network such as an IPTV network. They develop a simple energy-consumption model for IPTV storage and distribution. This model can provide guidelines for energy-optimized IPTV network design. It is suggested that, for reducing energy consumption, frequently-downloaded materials should be replicated at many data centers near the users and less-frequent materials should be kept in a few data centers.

B. Energy-Aware Access Networks

In the previous subsection, we summarized results from publications which estimated the energy consumption of access networks. Now, we focus on different recommendations and research ideas on developing energy-efficient access networks.

1) PON: There are two popular variants of PON – (a) EPON (Ethernet PON), which uses Ethernet as the underlying transport mechanism, and (b) GPON (Gigabit PON), an evolution of Broadband PON (BPON) standard. While GPON standard is popular in Europe and North America, EPON dominates the huge market in Asia. At the system level, PON technologies are being improved for energy efficiency by (a) improved IC (Integrated Circuit) technologies such as smaller silicon size, (b) better devices such as burst-mode laser drivers, (c) energy-efficient chips which shut down inactive functions on the fly such as smart embedded processors, etc. [73]. Although neither PON standard incorporated any energy efficiency features initially, after several proposals and deliberations, there are some recommendations on building energy-efficient EPON and GPON. Below, we give an overview of these recommendations. Although these recommendations are written separately, they can be incorporated in both standards.

TABLE III
COMPARISON OF GREENING EFFORTS IN PON.

Approach	Standardized/ Proposed	Network Compliance/ New Network Architecture	Extra Signalling and Control	Implementation Complexity
Low-power state for ONU [74], [75], [76], [77]	Proposed	New	No	Moderate
Handshaking protocol for coordinated sleeping [75], [77], [78]	Proposed	Compliant	Yes	Moderate
Shedding power in UNI [73]	Standardized	New	No	Moderate
Shedding speed of UNI [73]	Proposed	New	Yes	High
Shedding power in ANI [73]	Proposed	New	No	Moderate
Shedding speed of ANI [73], [77]	Proposed	New	Yes	High

- **EPON:** Current IEEE 802.3ah/802.3av EPON standards do not define any low-power state for the optical components such as OLT or ONU [74]. However, during IEEE 802.3av task force meetings, proposals have been circulated to include low-power states for ONU so that it can go to sleep during network idle time [74]. It is estimated that, during sleep state, power consumed by an ONU is at least 10 times less than an active ONU [74]. Hence, there is a significant scope of energy savings by putting idle ONUs to sleep. A proper handshaking protocol is needed to arrange this coordinated sleeping while not impacting service quality. In [78], the authors propose such an adjustable-timer-based multi-point handshaking protocol. Authors of [77] propose two energy-saving mechanisms for 10G-EPON - one is sleep control function which switches modes (active or sleep) of ONU depending on traffic variability, and the other is adaptive link-rate mechanism which switches the link rate between OLT and ONU to conserve power.
- **GPON:** It is possible to shed power in the UNI (User Network Interface) (which connects ONU to user equipment) by turning it off when not in use. This process is described in G.983.2 and G.984.4 recommendations and is supported by some existing products [73]. However, it is difficult to detect when the UNI is not active as connected devices (such as computers) always communicate. It is also possible to slow down UNIs that are not used fully, a process known as UNI speed shedding [73]. Throttling back UNI speed in a seamless way can however be challenging.

  We can also save energy by power shedding in the ANI (Access Network Interface) which connects ONU to OLT. This technique basically turns off the whole ONU. It may have huge service quality impact and may block incoming calls. Another technique can be ANI speed shedding, i.e., slowing down the PON during low utilization. This technique can be very complex to implement. Coordinated scheduling of ONU shutdown based on time of the day can also be explored for building energy-efficient PON [73]. Implementation of sleep mode in GPON is described in ITU-T G.su45 GPON power conservation standard [79]. Some GPON products have already included the power-saving mode which reduces up to 95% of the ONU power consumption during power outages and standby periods [80].

In [75], the authors present several power-saving modes for a TDM-PON ONU and their advantages and disadvantages. They present a ONU sleep-mode system architecture. A sleep-mode control protocol has also been described in the paper. The authors of [76] demonstrate how sleep mode can be realized in a TDM-PON ONU and energy can be conserved.

Once incorporated, the above techniques can save energy for both the PON standards. Table III summarizes the comparison of the greening efforts in PONs on the basis of standardization efforts, network architecture, degree of energy savings, requirement of extra signalling and control, and implementation complexity.

2) xDSL: xDSL is the most dominant broadband access technology in the USA, where 66% of the customers use DSL for accessing the Internet [81]. One of the main communication challenges in xDSL is reducing electromagnetic interference known as *crosstalk* which occurs due to signal interference of different lines in the same cable bundle. Crosstalk can hugely deplete the DSL line's available bandwidth, and by decreasing crosstalk, it is possible to increase the operating efficiency and energy efficiency of DSL lines.

There are two different ways for reducing the crosstalk in DSL lines: (1) Smart DSL and (2) DSM (Dynamic Spectrum Management). Smart DSL is a proprietary technology developed by Alcatel-Lucent which introduces low-level noise in DSL lines to mask the crosstalk [82]. One can also combine Layer-2 Power Mode with smart DSL to improve energy efficiency of ADSL2+ deployments. This combination cancels out power fluctuations, decreases crosstalk, and creates a more stable network [82].

The other alternative – DSM – curbs crosstalk rather than masking it out. DSM coordinates the spectrum and/or signals from all users to reduce crosstalk [83]. Regular DSM design can be extended to add constraints on transmit power so that overall power consumption by DSL lines gets minimized [83]. Low transmit power will eventually reduce the power consumed by DSL modems. Low transmit power will also lead to less crosstalk between DSL lines. All of these features can be combined to make DSL "green" and energy-efficient [84].

It is estimated that there are opportunities for up to 50% energy savings while achieving 85% full-power data rate performance in real DSL network scenarios [83]. There are several solutions for reducing transmission power in DSL systems such as adaptive startup and L2 mode [85]. Implementations of constrained maximum transmission power and modes exploiting traffic-dependent transmission power are also being considered [85].

3) WOBAN: WOBAN is a proposal for an optimal combination of an optical backhaul (e.g., PON) and a wireless front-end (e.g., WiFi and/or WiMAX) [86]. In WOBAN, a

PON segment (headed by OLT) starts from the telecom CO and serves several ONUs. One ONU can serve several wireless gateways which, in turn, gather traffic from the wireless mesh front-end. There is a capacity mismatch between the wireless front-end and the optical backhaul. The redundant capacity in the optical backhaul provides enhanced reliability during a network failure so that traffic can be rerouted through alternate paths in the wireless front-end. This flexibility provided by the wireless front-end can be exploited during low-load hours to enable energy savings in the optical part of WOBAN [87], [88].

Traffic load on an access network fluctuates at different hours of the day. During low-load hours, the under-utilized part of WOBAN can be put to sleep while rerouting the affected traffic through other parts of the network. For the wireless front-end of WOBAN, coordinated sleeping techniques from mobile ad-hoc networks research can be adopted to reduce wireless router energy consumption. For the optical part, the OLT can manage a centralized sleeping mechanism to put low-load ONUs to sleep [87]. To reroute the affected traffic while not impacting the service quality, an energy-aware routing algorithm is devised in [87]. The objective of the routing algorithm is to "use the already-used paths" while keeping the average path length comparable with shortest-path routing.

4) Long-Reach PON: LR-PON (Long-Reach PON) is proposed as a cost-effective solution for future broadband optical access networks. LR-PON extends the coverage span of PONs (from traditional 20 km range) to 100 km and beyond by exploiting Optical Amplifier and WDM technologies [18]. In this way, LR-PON consolidates several remote central offices into a central one, thereby reducing the energy usage of future access networks. In LR-PON, each PON segment has the traditional tree topology, and the OLT is connected to those PON segments by a fiber ring and remote nodes (RN). The authors of [89] present a dynamic wavelength allocation scheme for LR-PON. This scheme assumes wavelength sharing among several RNs and reduces energy consumption of LR-PON by minimizing wavelength requirements and putting idle transmitters to sleep.

5) Energy Conservation in Metro Networks: There is limited research on energy conservation in metro networks. The authors in [90] deal with energy-efficient design of network architectures for metro networks. They consider three architectures for a unidirectional WDM ring network, i.e., FG (First-Generation) optical network, SH (Single-Hop) network, and MH (Multi-Hop) network. In a FG optical network, every node must electronically process all the incoming and outgoing traffic, including the in-transit traffic. In a SH optical network, every node electronically processes only the traffic that goes into or out of the network at that node. A MH network lies somewhere between the FG and SH networks.

The MH architecture makes use of both lightpaths and electronic traffic multiplexing, performed at few selected intermediate nodes. A power-saving network design is proposed aiming at minimizing the energy required by both optical and electronic components. The energy consumption for the three architectures is optimized using ILP formulations. The authors show that, when the unidirectional WDM ring network has uniform traffic, the power consumption of the MH network is lower than that of the FG network, not only when traffic load of optical components is low, but also when connection rate is close to the wavelength capacity. The authors also show that, when the connection rate is low, the MH network outperforms the all-optical SH network, because the MH network has more flexibility to perform traffic multiplexing in an energy-efficient way.

VI. Data Centers and Applications

A. Data Centers

Data centers are vital to support many of today's data-intensive telecom applications. The huge amount of data to be managed by these applications has been posing scalability issues for the data center infrastructures, and optical technologies represent a key enabler for data centers to support all of these traffic.

Specifically, optical networks play a relevant role in both data center inter- and intra-connections. At the inter-connection level, moving and delivering the ever-increasing amount of traffic to be supported by data centers can be effectively done using reconfigurable optical networks: note that the flexibility of the inter-connection pattern of core transport network, which is promised to be provided by emerging automatic control plane suites such as GMPLS (Generalized Multi-Protocol Label Switching) and ASON (Automatically Switched Optical Network), will be an important means to transfer data load among various sites, as envisioned in most of the works which are reviewed in this section [91], [92].

At the intra-connection level (connecting boards, chips, and memories of the data servers inside the data center), optical technology can also play a fundamental role for data center scalability: optics could solve many physical problems of intra-connections, including precise clock distribution, system synchronization (allowing larger synchronous zones, both on-chip and between chips), bandwidth and density of long interconnections, and reduction of power dissipation. Optics may relieve a broad range of design problems, such as crosstalk, voltage isolation, wave reflection, impedance matching, and pin inductance. It may allow continued scaling of existing architectures and enable novel highly-connected or high-bandwidth architectures [93].

Since servers and associated equipment consume a considerable part of energy used in telecom networks, several recent studies have focused on the estimation of the energy consumption in data centers. As an example, the total power used by servers in data centers represented about 0.6% of the total U.S. electricity consumption in 2005. When cooling and auxiliary infrastructure are included, this number grows to 1.2%, which is an amount comparable to that for televisions [94]. Therefore, energy-conservation technologies for data centers are being developed.

The author in [95] has proposed an approach for power control of high-speed network intra-connection (inside data centers), which focus on reducing the energy consumption of communication links. The author claims that communication links can support three types of power control: (i) usage of one or more low-power states, (ii) link width control, where only a portion of the link is put into a low-power mode, and (iii) multiple operational speeds [95]. The author focuses on method (ii). The width control algorithm decides how to transit between certain feasible widths in a multilane link, which involves energy-efficient design of networking fabrics, as well as interconnects that proliferate inside a server, e.g., CPU core interconnects, processor-memory interconnects, PCI-E (Peripheral Component Interconnect Express) links connecting NICs (Network Interface Controllers), graphics card, SATA (Serial Advanced Technology Attachment) adapters, etc. Results show that, when link width grows but traffic demands stay the same, power consumption can be brought down after power control. This is because links with higher width have higher probability of holding spare resources than the ones with lower width.

Another aspect of power-conservation technologies in data centers is about load distribution across data centers in different locations. A framework for optimization-based request distribution is proposed in [91]. Leveraging the combination of different time zones (where different data centers may be located), variable electricity prices, and some data centers being powered by green energy, an optimal load-distribution scheme across data centers is proposed. Mathematical optimization formulations and heuristics are proposed to minimize the cost and energy consumption of the collection of data centers. Since traffic demands vary at different locations during time of the day, after a specific request distribution, energy and cost can be minimized by the energy-efficient framework. This approach also provides a novel way to better utilize renewable energy.

Along the lines of the previous concept, another approach for energy conservation based on traffic load redistribution consists in locating servers at sites where renewable energy is available and then connecting these servers with the rest of the network by using optical transport systems. As an example, considering location availability of renewable energy, some institutions are about to launch a $100M "green" data center in the city of Holyoke, where there is a ready source of cheap, relatively-clean hydroelectric power [96]. This project promises to be very helpful to reduce the carbon footprint of data centers in the eastern United States. Google's "project 02" and Microsoft are also using hydroelectric facilities to build data centers to utilize renewable energy [92]. IBM, Syracuse University, and New York State have entered into an agreement to build and operate a new data center on the Syracuse University's campus. They will incorporate advanced infrastructure and smarter computing technologies to make it one of the most energy-efficient data centers in the world. The data center is expected to use 50 percent less energy than a typical state-of-the-art data center. The key element is an on-site electrical co-generation system that will use natural-gas-fuelled micro-turbine engines to generate all the electricity for the center and provide cooling for the computer servers [97]. On this topic, still a lot of research is needed on devising new Internet architectures with servers, computers, and storage collocated at remote renewable energy sites such as hydro dams, windmill farms, etc. Also, new routing and protection strategies for optical networks are sought for rapid and massive network-wide reconfiguration of the network interconnection between data centers according to current availability of renewable (e.g., sun or wind) energy to power routers and servers [58].

In the management of data center networks, a single administrative control domain is proposed for energy conservation of data centers [98]. The authors envision a centralized network power controller program running on a server within the data center. The energy-efficient algorithms can be *link-state adaptation*, *network traffic consolidation*, and *server load consolidation*. In these schemes, the placement algorithms take network traffic specifications of the job, the current network utilization, and the connectivity into consideration before assigning various servers for a job. Then, the controller communicates with all the switches and performs actions such as turning off unused switches, disabling unused ports, and adapting link capacity to save energy.

The authors in [98] also propose a power benchmarking framework for network devices in data centers. They build and describe a benchmarking suite that will allow users to measure and compare the power consumed for a large set of common configurations in any switch or router of their choice. They also propose a network energy proportionality index to compare power consumption behaviors of multiple devices. In their scheme, the network device to be benchmarked is connected to the power outlet via a power meter. Then, the device configurator modifies the various configuration states of the device according to the benchmarking requirements. The traffic generator loads the device with varying traffic patterns. The benchmark orchestrator coordinates the various components in order to synchronize the configuration, the workload, and the measurements from the power meter. The collected information is then processed by an analyzer to generate various energy proportionality indices and other power-related metrics [99].

B. Applications

While storage, memory, processor, and communication bandwidth tend to become relatively abundant and inexpensive as time progresses, electricity usage will become a growing expense in the operation of telecom networks [100]. In the application layer of computers and, more generally, telecom networks, turning idle devices to sleeping mode appears to be the most plausible way in which energy conservation can be well achieved. However, in order to implement algorithms for sleeping, several aspects have to be considered, e.g., (i) software should be designed to enable hardware of network equipment to sleep, (ii) Internet routing protocols, such as TCP/IP, need to be modified to adapt to energy-efficient design, and (iii) hardware of network equipment needs to be reconfigured to accept control signals from the software [101]. Several approaches have been identified that satisfy the above requirements, and they target energy conservation at the application layer. Broadly, we can identify three main proposals: "Proxying", Green TCP/IP protocol, and Green Grid Computing.

Below, the first two areas of research are quickly outlined for the sake of completeness, since they are not specifically related to optical network technologies. A longer discussion

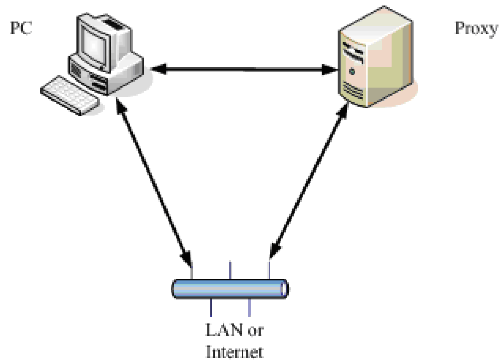

Fig. 7. Network connectivity "Proxying".

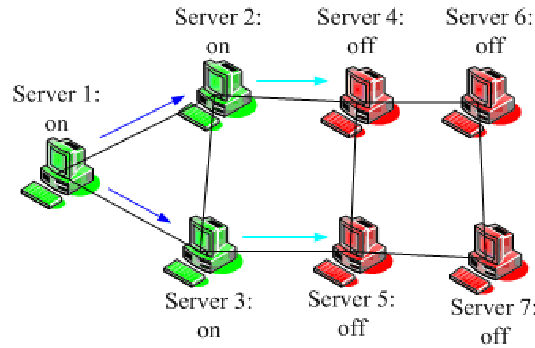

Fig. 8. Grid Computing job scheduling mechanism.

will be provided on green grid computing because of its close relation to optical networks. In fact, the computational resource sharing and virtualization enabled by optical grid networks (also referred to as lambda grids) is raising a lot of interest as practical means to reduce energy consumption. In [102], the authors analyse the energy saving opportunities of the thin client paradigm where a thin client terminal (with less functionalities) consumes less power, and more efficient use of resources in the server is possible due to virtualization.

1) Proxying: A first possible approach for reducing power consumption at application layer consists of using network connectivity "Proxying". Since much of the network connectivity should be maintained at all times to allow remote access and/or operations of network-centric applications, the PCs and servers involved have to be kept always on (day and night). In this case, a large amount of energy will be consumed. However, these PCs and servers are probably idle for significant durations of time. The authors in [9] propose a "Proxying" scheme that enables idle PCs to use sleeping mode. The structure of this "Proxy" scheme is shown in Fig. 7.

When a PC becomes idle, it transfers its network presence to the proxy before going to sleep, and then the proxy responds to route network traffic for the sleeping PC. When the PC is needed, the proxy wakes it up. In this case, the energy consumption of the system can be reduced because the proxy consumes much less energy than the monitor, hard disk, or CPU of a PC does. At the same time, TCP connections can be kept alive during the PC's sleep period by using a SOCKS-based (Protocol for sessions traversal across firewall securely) approach called green SOCKS (gSOCKS) as part of the Network Connectivity "Proxying" [19].

2) Green TCP/IP Protocol Design: At the application layer, protocols for IP routing determine the operational performance of the network to some extent, such as transmission delay or energy consumption. Many PCs are kept on in corporate offices at night, even when no applications or network activities are running on them, while in residential areas, many people keep their PCs on when they leave their house for work or holiday. In this way, a large amount of energy is wasted. In [103], a green TCP/IP protocol is proposed, which enables existing TCP/IP connections to be "put to sleep" to save energy. The green TCP/IP protocol also helps servers to block network connections between servers and clients when client PCs are sleeping. Network connections can automatically resume when the client PCs wake up.

3) Green Grid Computing: Grid computing combines computing resources from multiple administrative domains for a common goal [104]. Distributed grid computing, in general, is a special type of parallel computing that relies on computers connected to a network. Grid computing was originally started for Internet-related services such as search engines. Today, many other services, applications, and tasks that used to reside on an end user's terminal or computer get transferred to the grid. Software such as Sun Grid Engine, GridWay, etc. are developed to meet the requirements of next-generation grid computing. The underlying network architecture building the foundation for grid computing consists of interconnected server farms within data centers and a high-speed transport network providing connectivity to remote and backup sites. These high-speed connections form the backbone of the grid network and are required to run at highest bandwidth with lowest transmission latency - in particular, high-speed grid optical networks, such as National LambdaRail [105], promise to revolutionize the way that we approach grid computing, providing a scalable, reconfigurable, and cost-effective platform to support grid services [106].

In recent years, grid computing is also dealing with large experimental bulk data obtained from large-scale scientific instruments (e.g., radio telescopes used in the VLBI (Very Long Baseline Interferometry) experiments), high-end physics experiments at CERN (European Organization for Nuclear Research), or large-scale data processing results. In order to meet these huge computational and storage demands, computational cluster centers (e.g., supercomputers) are interconnected via networks to achieve a huge common resource pool to process the tasks [20]. Grid-based applications are also the hallmark of the twenty-first century global e-Science, which is defined as global, large-scale scientific collaborations enabled through distributed computational and communication infrastructure. In [107], the authors reviewed related open research issues on optical network control plane for the grid community to meet the requirements of high-bandwidth connectivity for supporting high-end supercomputers and highly dynamic operation. GMPLS-based Traffic Engineering is also proposed in [108] to analyze the performance of infrastructure service provisioning. The results show that the majority of performance improvements (such as efficiency of resource utilization) can be obtained with a controlled usage of multi-layer resource visibility and with a more flexible interconnection architecture between domains. Load balancing is also a crucial issue for the efficient operation of grid computing environments in distributing the sequential tasks. The authors in [109] propose a novel combination of static and dynamic load-balancing strategies which helps to reduce the system response time and to perform rapid task assignments.

As grid computing is being widely investigated in recent research, power-aware grid computing schemes have also been proposed. Recent studies of the usage of grid resources shows that the usage of a grid site may significantly vary (between less than 20% to over 90%) during the time of day [110]. Therefore, there is an opportunity for using energy-saving mechanisms to automatically switch on and off servers to match the available server capacity to actual computational demands. In grid systems, users do not really care about where exactly their jobs ultimately get executed; the job can be offloaded to a remote site with an available processor, rather than turning on a new server, which can reduce energy consumption of the whole grid system. To reduce energy consumption, a grid system needs a power-aware job scheduling mechanism, and a power-saving strategy to decide when to turn servers on/off.

As Fig. 8 shows, the job scheduling mechanism first considers the servers which were already powered on (server 2 or 3). Only if none is available, the mechanism then turns on one among those servers which were powered off using a shortest-path strategy (server 4 or 5). To decide when to turn servers off, a straightforward approach is proposed: every server will be turned off for a fixed time D after a job is finished, if during that time it is not running any other job or being used as the intermediate server for other working servers [20]. In this way, grid computing will not be interrupted when idle servers are turned off during the computation, and a large amount of energy will be saved during the time idle servers are turned off.

VII. Conclusion and Future Directions

Energy efficiency in telecom networks is a recent research topic, but it is gaining rapid recognition in the research community, motivated by the concern for the ever-increasing energy consumption of ICT. This survey reviewed energy-conservation protocols and energy-efficient architectures over the different domains of telecom networks, namely core, metro, and access networks, with a specific emphasis on telecom networks employing optical technologies. Important applications running over optical networks such as grid computing and data centers networks were also considered. Besides, standardization efforts toward energy efficiency by various telecommunication organizations were summarized, which may provide practical references to researchers. We provided useful references for researchers interested in energy-efficient telecom networks, which can be helpful to develop future directions on "green-networking" research.

Many possible extensions can be devised on the research lines that have been described in this paper, as well as many new paths of investigation can also be developed. Including energy conservation among the most important design objectives (together with cost and performance) represents a paradigm shift in the way network design, traffic engineering, and network engineering have been carried on so far. Most of the existing techniques for optical telecom networks investigated and developed in the past decade in optical core networks, say, e.g., protection and traffic grooming, should be re-thought under this new perspective. While some preliminary studies on energy-efficient network design have appeared, how to energy-efficiently operate the network with given equipment is an open research problem. The energy-savings methods in access networks can be quite diverse due to the existence of different access network architectures (e.g., ring or bus or tree): extending the coverage span of PONs using the recent concept of LR-PON [18], which can consolidate the metro-access network architecture and decrease the number of active components, is also a promising proposition for a "greener" broadband access network.

References

[1] Energy Information Administration Brochures, "Greenhouse gases, climate change, and energy," http://www.eia.doe.gov/bookshelf/brochures/greenhouse/Chapter1.htm, May 2008.

[2] "Report of the IUCN renowned thinkers meeting, the future of sustainability: Re-thinking environment and development in the twenty-first century," http://cmsdata.iucn.org/downloads/iucn_future_of_sustanability.pdf, Jan. 2006.

[3] W. Vereecken, L. Deboosere, D. Colle, B. Vermeulen, M. Pickavet, B. Dhoedt, and P. Demeester, "Energy efficiency in telecommunication networks," *European Conference on Networks and Optical Communications & Optical Cabling and Infrastructure (NOC'08)*, July 2008.

[4] M. Pickavet, W. Vereecken, S. Demeyer, P. Audenaert, D. Colle, C. Develder, and P. Demeester, "Contribution and role of network architectures in the footprint reduction of ICT," *NOC/OC&I'09*, Valladolid, Spain, June 2009.

[5] M. Pickavet, W. Vereecken, S. Demeyer, P. Audenaert, B. Vermeulen, C. Develder, D. Colle, B. Dhoedt, and P. Demeester, "Worldwide energy needs for lCT: the rise of power-aware networking," *International Symposium on Advanced Networks and Telecommunication Systems (ANTS'08)*, Bombay, India, Dec. 2008.

[6] P. Leisching and M. Pickavet, "Energy footprint of ICT: Forecasts and network solutions," *OFC/NFOEC'09, Workshop on Energy Footprint of ICT: Forecast and Network Solutions*, San Diego, CA, Mar. 2009.

[7] C. Lange and A. Gladisch, "Energy consumption of telecommunication networks - a network operator's view," *OFC/NFOEC'09, Workshop on Energy Footprint of ICT: Forecast and Network Solutions*, San Diego, CA, March 2009.

[8] C. Lange, D. Kosiankowski, C. Gerlach, F.-J. Westphal, and A. Gladisch, "Energy consumption of telecommunication networks," *European Conference on Optical Communication (ECOC'09)*, Vienna, Austria, Sept. 2009.

[9] B. Nordman, "ICT, networks, and energy: The energy perspective," *OFC/NFOEC'09, Workshop on Energy Footprint of ICT: Forecast and Network Solutions*, San Diego, CA, Mar. 2009.

[10] B. Mukherjee, *Optical WDM Networks*, Springer, 2006.

[11] K. Zhu and B. Mukherjee, "Traffic grooming in optical WDM mesh networks," *IEEE J. Sel. Areas Commun.*, vol. 20, no. 1, pp. 122–133, Jan. 2002.

[12] S. Ramamurthy and B. Mukherjee, "Survivable WDM mesh networks. part I-protection," *IEEE INFOCOM'99*, New York, NY, pp. 744–751, Mar. 1999.

[13] R. S. Tucker, "The role of optics and electronics in high-capacity routers," *J. Lightwave Technol.*, vol. 24, no. 12, pp. 4655–4673, Dec. 2006.

[14] R. S. Tucker, "Green optical communications - part I: Energy limitations in transport," *IEEE J. Sel. Topics Quantum Electron., Special Issue on Green Photonics*, 2010 (to appear).

[15] E. Bonetto, D. Cuda, G. A. Castillo, and F. Neri, "The role of arrayed waveguide gratings in energy-efficient optical switching architectures," *OFC/NFOEC'10*, San Diego, CA, Mar. 2010.

[16] E. Bonetto, L. Chiaraviglio, G. A. Castillo D. Cuda, and F. Neri, "Optical technologies can improve the energy efficiency of networks," *ECOC'09*, Vienna, Austria, Sep. 2009.

[17] R. S. Tucker, "Green optical communications - part II: Energy limitations in networks," *IEEE J. Sel. Topics Quantum Electron., Special Issue on Green Photonics*, 2010 (to appear).

[18] H. Song, *Long-Reach Passive Optical Networks*. PhD Dissertation, University of California, Davis, 2009.

[19] M. Jimeno, K. Christensen, and B. Nordman, "A network connection proxy to enable hosts to sleep and save energy," *IEEE International Performance Computing and Communications Conference*, pp. 101–110, Dec. 2008.

[20] C. Develder, M. Pickavet, B. Dhoedt, and P. Demeester, "A power-saving strategy for grids," *Gridnets'08*, 2008.

[21] D. Zuckerman, "Green communications - management included," *IEEE International Conference on Communications Workshops (GreenComm'09)*, Dresden, Germany, June 2009.

[22] N. Ghani, S. Dixit, and T. S. Wang, "On IP-over-WDM integration," *IEEE Commun. Mag.*, vol. 38, no. 3, pp. 72–84, Mar. 2000.

[23] J. Manchester, J. Anderson, B. Doshi, and S. Dravida, "IP over SONET," *IEEE Commun. Mag.*, vol. 36, no. 5, pp. 136–142, May 1998.

[24] "Ciena white paper - Optical Transport System - CoreStream Agility," http://www.ciena.com/files/Optical_Transport_System_PB.pdf.

[25] P. Chaitanya and D. Datta, "Some schemes for controlling gain dynamics of EDFA chains in wavelength-routed optical networks," *IEEE International Symposium on Advanced Networks and Telecommunication Systems (ANTS'09)*, New Delhi, India, pp. 1–3, Dec. 2009.

[26] R. S. Tucker, "Energy footprint of the network," *OFC/NFOEC'09, Workshop on Energy Footprint of ICT: Forecast and Network Solutions*, San Diego, CA, Mar. 2009.

[27] "Alcatel-Lucent 1675 Lambda Unite MSS datasheet," http://www.alcatel-lucent.com/wps/DocumentStreamerServlet?LMSG_CABINET=Docs_and_Resource_Ctr&LMSG_CONTENT_FILE=Data_Sheets/22131_1675_LambUnMSS_R_9.1_ds.pdf.

[28] "MRV Optical Cross Connect datasheet," http://www.mrv.com/datasheets/MCC/PDF300/MRV-MCC-OCC_A4_HI.pdf.

[29] G. Shen and R. S. Tucker, "Energy-minimized design for IP over WDM networks," *IEEE/OSA J. Optical Commun. Netw.*, vol. 1, no. 1, pp. 176–186, June 2009.

[30] J. Baliga, K. Hinton, and R. S. Tucker, "Energy consumption of the Internet," *COIN - ACOFT'07*, Melbourne, Australia, June 2007.

[31] J. Baliga, R. Ayre, K. Hinton, W. V. Sorin, and R. S. Tucker, "Energy consumption in optical IP networks," *Journal of Lightwave Technology*, vol. 27, no. 13, pp. 2391–2403, July 2009.

[32] "Ciena 3600 datasheet," http://www.ciena.com/products/products_cn3600_technical_info.htm.

[33] "Ciena Select OADM datasheet," http://www.ciena.com/files/Select_OADM_DS.pdf.

[34] J. Baliga, R. Ayre, W. V. Sorin, K. Hinton, and R. S. Tucker, "Energy consumption in access networks," *OFC/NFOEC'08*, San Diego, CA, Feb. 2008.

[35] Metro Ethernet Forum, "Metro ethernet services - a technical overview," http://metroethernetforum.org/PDF_Documents/metro_ethernet_services.pdf.

[36] P. P. Iannone, K. C. Reichmann, M. Birk, N. J. Frigo, R. M. Derosier, D. Barbier, C. Cassagnettes, T. Garret, A. Verlucco, S. Perrier, and J. Philipsen, "A 160-km transparent metro WDM ring network featuring cascaded erbium-doped waveguide amplifiers," *OFC/NFOEC'01*, 2001.

[37] "ITU symposia on ICTs and climate change," http://www.itu.int/ITU-T/worksem/climatechange/index.html, 2009.

[38] "IEEE P802.3az energy efficient ethernet task force," http://www.ieee802.org/3/az/index.html, 2009.

[39] B. Dugerdil, "ETSI green agenda," http://www.itu.int/dms_pub/itu-t/oth/06/0F/T060F0000090032PDFE.pdf, 2009.

[40] "TIA environment," http://tiaonline.org/environment/, 2009.

[41] "ATIS NIPP," http://www.atis.org/0050/index.asp, 2009.

[42] "NIPP-TEE," http://www.atis.org/0050/tee.asp, 2009.

[43] A. Alimian, B. Nordman, and D. Kharitonov, *Network and Telecom Equipment Energy and Performance Assessment - Test Procedures and Measurement Methodology*. ECR Initiative, 2008.

[44] Verizon, "TEEER metric quantification," http://www.verizonnebs.com/TPRs/VZ-TPR-9207.pdf, Jan. 2009.

[45] L. Chiaraviglio, M. Mellia, and F. Neri, "Energy-aware networks: Reducing power consumption by switching off network elements," *GTTI'08*, Rome, Italy, May 2008.

[46] L. Chiaraviglio, M. Mellia, and F. Neri, "Reducing power consumption in backbone networks," *IEEE ICC'09*, Dresden, Germany, June 2009.

[47] L. Chiaraviglio, M. Mellia, and F. Neri, "Energy-aware backbone networks: a case study," *IEEE International Workshop on Green Communications (GreenComm'09)*, Dresden, Germany, June 2009.

[48] B. Sanso and H. Mellah, "On reliability, performance and Internet power consumption," *IEEE DRCN'09*, Washington, DC, Oct. 2009.

[49] H. Mellah and B. Sanso, "Review of facts, data and proposals for a greener Internet," *BroadNets'09*, Madrid, Spain, Sept. 2009.

[50] C. Lange and A. Gladisch, "Energy efficiency limits of load adaptive networks," *OFC/NFOEC'10*, San Diego, CA, Mar. 2010.

[51] F. Idzikowski, S. Orlowski, C. Raack, H. Woesner, and A. Wolisz, "Saving energy in IP-over-WDM networks by switching off line cards in low-demand scenarios," *Conference on Optical Network Design and Modeling (ONDM'10)*, Kyoto, Japan, Feb. 2010.

[52] Y. Zhang, M. Tornatore, P. Chowdhury, and B. Mukherjee, "Time-aware energy conservation in IP-over-WDM networks," *Photonics in Switching'10*, Monterey, CA, July 2010.

[53] L. Ceuppens, "Planning for energy efficiency: Networking in numbers," *OFC/NFOEC'09, Workshop on Energy Footprint of ICT: Forecast and Network Solutions*, San Diego, CA, Mar. 2009.

[54] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, and S. Wright, "Power awareness in network design and routing," *IEEE INFOCOM'08*, Phoenix, AZ, pp. 1130–1138, 2008.

[55] P. Chowdhury, M. Tornatore, and B. Mukherjee, "On the energy efficiency of mixed-line-rate networks," *OFC/NFOEC'10*, San Diego, CA, Mar. 2010.

[56] M. Baldi and Y. Ofek, "Time for a greener Internet," *IEEE International Conference on Communications Workshops (GreenComm'09)*, pp. 1–6, June 2009.

[57] S. Figuerola, M. Lemay, V. Reijs, M. Savoie, and B. St. Arnaud, "Converged optical network infrastructures in support of future internet and grid services using IaaS to reduce GHG emissions," *IEEE/OSA J. Lightwave Technol. (JLT)*, vol. 27, no. 12, pp. 1941 – 1946, June 2009.

[58] B. St. Arnaud, "CANARIE: Research networks to help reduce global warming," *OFC/NFOEC'09, Workshop on Energy Footprint of ICT: Forecast and Network Solutions*, San Diego, CA, Mar. 2009.

[59] E. Yetginer and G. N. Rouskas, "Power efficient traffic grooming in optical WDM networks," *IEEE GLOBECOM'09*, Honolulu, HI, Nov. 2009.

[60] M. Xia, M. Tornatore, Y. Zhang, P. Chowdhury, C. Martel, and B. Mukherjee, "Greening the optical backbone networks: a traffic engineering approach," *IEEE ICC'10*, Cape Town, South Africa, 2010.

[61] M. Xia, M. Tornatore, Y. Zhang, P. Chowdhury, C. Martel, and B. Mukherjee, "Green provisioning for optical WDM Networks," *IEEE J. Sel. Topics Quantum Electron., Special Issue on Green Photonics*, 2010 (to appear).

[62] B. Puype, W. Vereecken, D. Colle, M. Pickavet, and P. Demeester, "Power reduction techniques in multilayer traffic engineering," *International Conference on Transparent Optical Networks (ICTON'09)*, Azores, Protugal, June 2009.

[63] S. Huang, D. Seshadri, and R. Dutta, "Traffic grooming: a changing role in green optical networks," *IEEE GLOBECOM'09*, Honolulu, HI, pp. 1–6, 2009.

[64] Y. Wu, L. Chiaraviglio, M. Mellia, and F. Neri, "Power-aware routing and wavelength assignment in optical networks," *ECOC'09*, Vienna, Austria, Sep. 2009.

[65] M. Hasan, F. Farahmand, and J. Jue, "Energy-awareness in dynamic traffic grooming," *OFC/NFOEC'10*, San Diego, CA, 2010.

[66] M. Hasan, F. Farahmand, A. Patel, and J. Jue, "Traffic grooming in green optical networks," *IEEE International Conference on Communications (ICC'10)*, Cape Town, South Africa, May 2010.

[67] C.-S. Li, Y. Ofek, and M. Yung, "Time-driven priority flow control for real-time heterogeneous Internetworking," *IEEE INFOCOM'96*, San Francisco, CA, Mar. 1996.

[68] D. Grieco, A. Pattavina, and Y. Ofek, "Fractional lambda switching for flexible bandwidth provisioning in WDM networks: principles and performance," *Photonic Network Communications*, vol. 9, no. 3, pp. 281–296, May 2005.

[69] A. Cianfrani, V. Eramo, M. Listanti, M. Marazza, and E. Vittorini, "An energy saving routing algorithm for a green OSPF protocol," *IEEE INFOCOM'10, Traffic Management and Monitoring Workshop*, San Diego, CA, March 2010.

[70] H. D. Saunders, "The Khazzoom-Brookes postulate and neoclassical growth," *The Energy Journal*, vol. 13, no. 4, pp. 130–148, Oct. 1992.

[71] C. Lange and A. Gladisch, "On the energy consumption of FTTH access networks," *OFC/NFOEC'09*, San Diego, CA, Mar. 2009.

[72] J. Baliga, R. Ayre, K. Hinton, and R. S. Tucker, "Architectures for energy-efficient IPTV networks," *OFC/NFOEC'09*, San Diego, CA, 2009.

[73] F. J. Effenberger, "Opportunities for power savings in optical access," http://www.itu.int/dms-pub/itu-t/oth/09/05/T09050000010006PDFE.pdf, Feb. 2008.
[74] J. Mandin, "EPON powersaving via sleep mode," IEEE P802.3av 10GEPON Task Force Meeting, www.ieee802.org/3/av/public/2008-09/3av_0809_mandin_4.pdf, Sept. 2008.
[75] S.-W. Wong, L. Valcarenghi, S.-H. Yen, D. R. Campelo, S. Yamashita, and L. G. Kazovsky, "Sleep mode for energy saving PONs: Advantages and drawbacks," *IEEE GLOBECOM Workshops'09*, Honolulu, HI, pp. 1–6, Dec. 2009.
[76] S.-W. Wong, S.-H. Yen, P. Afshar, S. Yamashita, and L. G. Kazovsky, "Demonstration of energy conserving TDM-PON with sleep mode ONU using fast clock recovery circuit," *OFC/NFOEC'10*, San Diego, CA, Mar. 2010.
[77] R. Kubo, J. Kani, Y. Fujimoto, N. Yoshimoto, and K. Kumozaki, "Sleep and adaptive link rate control for power saving in 10G-EPON systems?" *IEEE GLOBECOM'09*, Honolulu, HI, Dec. 2009.
[78] H. Yuanling and M. Hajduczenia, "Adjustable timer value for power saving," IEEE P802.3av 10GEPON Task Force Meeting, www.ieee802.org/3/av/public/2008-09/3av_0809_hajduczenia_power_Saving.pdf, Sept. 2008.
[79] GPON Power Conservation, "ITU-T G-Series Recommendations - Supplement 45 (G.sup45)," May 2009.
[80] "PMC-Sierra GPON ONT SOC," http://www.pmc-sierra.com/products/details/pas7401/.
[81] DSL Forum, "DSL dominates global broadband subscriber growth," Technical Report, http://www.broadband-forum.org/news/download/pressreleeases/YE06_Release.pdf, Mar. 2007.
[82] "AlcaLu paints its MSAN green," http://www.lightreading.com/document.asp?doc_id=178722#msgs, July 2009.
[83] P. Tsiaflakis, Y. Yi, M. Chiang, and M. Moonen, "Green DSL: Energy-efficient DSM," *IEEE ICC'09*, Dresden, Germany, June 2009.
[84] J. M. Cioffi, S. Jagannathan, W. Lee, H. Zou, A. Chowdhery, W. Rhee, G. Ginis, and P. Silverman, "Greener copper with dynamic spectrum management," *AccessNets'08*, Las Vegas, NV, Oct. 2008.
[85] L. Humphrey, "Opportunities and techniques for power saving in DSL," BT, UK, http://www.itu.int/dmspub/itu-t/oth/09/05/T09050000010003PDFE.pdf, Feb. 2008.
[86] S. Sarkar, P. Chowdhury, S. Dixit, and B. Mukherjee, *Broadband Access Networks: Technologies and Deployment*, ch. Hybrid Wireless-Optical Broadband Access Network (WOBAN). Springer, 2009.
[87] P. Chowdhury, M. Tornatore, S. Sarkar, and B. Mukherjee, "Towards green broadband access networks," *IEEE GLOBECOM'09*, Honolulu, HI, Dec. 2009.
[88] P. Chowdhury, M. Tornatore, S. Sarkar, and B. Mukherjee, "Building a green wireless-optical broadband access network (WOBAN)," *IEEE/OSA J. Lightwave Technol. (JLT), Special Issue on Very High Throughput Wireless over Fiber Technologies and Applications*, 2010 (to appear).
[89] L. Shi, S. S. Lee, and B. Mukherjee, "Energy-efficient long-reach passive optical network: A dynamic wavelength allocation scheme," *Photonics in Switching'10*, Monterey, CA, July 2010.
[90] I. Cerutti, L. Valcarenghi, and P. Castoldi, "Power saving architectures for unidirectional WDM rings," *OFC/NFOEC'09*, San Diego, CA, Mar. 2009.
[91] K. Ley, R. Bianchiniy, M. Martonosiz, and T. D. Nguyeny, "Cost and energy-aware load distribution across data centers," *HotPower'09*, Big Sky, MT, Oct. 2009.
[92] B. St. Arnaud, "CAnet - news," http://emperor.canarie.ca/pipermail/news/2009/000720.html, June 2009.
[93] D. A. B. Miller, "Rationale and challenges for optical interconnects to electronic chips," *Proc. IEEE*, vol. 88, no. 6, pp. 728–749, June 2000.
[94] J. G. Koomey, "Estimating total power consumption by servers in the U.S. and the world," Technical Report, Lawrence Berkeley National Laboratory, Feb. 2007.
[95] K. Kant, "Power control of high speed network interconnects in data centers," *Workshop on High-Speed Networks (HSN'09)*, 2009.
[96] Green Computing, "Cisco, EMC team with MIT to launch $100m green data center," http://www.greenercomputing.com/news/2009/06/11/cisco-emc-team-mit-launch-100m-green-data-center, June 2009.
[97] "IBM, Syracuse University, New York State to build one of the world's most energy-efficient data centers," http://www-03.ibm.com/press/us/en/pressrelease/27612.wss, May 2009.
[98] P. Mahadevan, P. Sharma, S. Banerjee, and P. Ranganathan, "Energy aware network operations," *IEEE Global Internet Symposium (in conjunction with IEEE INFOCOM'09)*, Rio de Janeiro, Brazil, Apr. 2009.
[99] P. Mahadevan, P. Sharma, S. Banerjee, and P. Ranganathan, "A power benchmarking framework for network devices," *IFIP Networking Conference*, Aachen, Germany, May 2009.
[100] K. J. Christensen, C. Gunaratne, B. Nordman, and A. D. George, "The next frontier for communications networks: power management," *Elsevier Computer Communications*, vol. 27, no. 18, pp. 1758–1770, Aug. 2004.
[101] M. Gupta and S. Singh, "Greening of the Internet," *ACM SIGCOMM'03*, Karlsruhe, Germany, pp. 19–26, Aug. 2003.
[102] W. Vereecken, L. Deboosere, P. Simoens, B. Vermeulen, D. Colle, C. Develder, M. Pickavet, B. Dhoedt, and P. Demeester, "Energy efficiency in thin client solutions," *International ICST Workshop on Green Grids*, Athens, Greece, Sep. 2009.
[103] L. Irish and K. Christensen, "A "green TCP/IP" to reduce electricity consumed by computers," *IEEE Southeastcon*, Orlando, FL, pp. 302–305, Apr. 1998.
[104] I. Foster and C. Kesselman, *The grid: blueprint for a new computing infrastructure*, Morgan Kaufmann Publishers, 2004.
[105] National Lambdarail, "The network for advanced research and innovation," http://www.nlr.net/.
[106] W. Feng, M. K. Gardner, G. Karmous-Edwards, J. Sobieski, and M. Veeraraghavan, "When optical networking meets grid computing?" *International Conference on Computer Communications and Networks (ICCCN'06)*, pp. 138–138, Oct. 2006.
[107] A. Jukan and G. Karmous-Edwards, "Optical control plane for the grid community," *IEEE Commun. Surveys Tutorials*, vol. 9, no. 3, pp. 30–44, July 2007.
[108] S. Tomic and A. Jukan, "Performance analysis of infrastructure service provision with GMPLS-based traffic engineering," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 5, pp. 881–894, June 2007.
[109] Y. Li, Y. Yang, M. Ma, and L. Zhou, "A hybrid load balancing strategy of sequential tasks for grid computing environments," *Future Generation Computer Systems*, vol. 25, no. 8, pp. 819–828, Sept. 2009.
[110] A.-C. Orgerie, L. Lefevre, and J.-P. Gelas, "How an experimental grid is used: The Grid5000 case and its impact on energy usage," *IEEE Intnerational Symposium on Cluster Computing and the Grid (CCGrid'08)*, May 2008.

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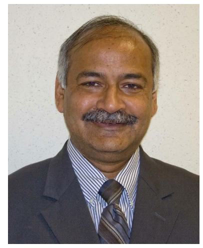

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