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Research challenges on energy-efficient networking design

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ABSTRACT

The networking research community has started looking into key questions on energy efficiency of communication networks. The European Commission activated under the FP7 the TREND Network of Excellence with the goal of establishing the integration of the EU research community in green networking with a long perspective to consolidate the European leadership in the field. TREND integrates the activities of major European players in networking, including manufacturers, operators, research centers, to quantitatively assess the energy demand of current and future telecom infrastructures, and to design energy-efficient, scalable and sustainable future networks. This paper describes the main results of the TREND research community and concludes with a roadmap describing the next steps for standardization, regulation agencies and research in both academia and industry.

1. Introduction

Telecommunication/computer networks have become a critical infrastructure for our societies: from an academic playground they have grown to become an essential enabler for information access and knowledge sharing, for electronic commerce and entertainment. Broadband Internet access has drastically changed the way we live and work. Just few examples: every student today finds on the Internet much more information than what could be found only on the most respected source of general information, such as the Encyclopædia Britannica, before the Internet; travel planning has become so much easier on the Internet that a large number of travel agencies are going bankrupt; movies and TV series can now be watched on the Internet with a much wider choice than with movie theatres or traditional TV programs. As a result, the access to the Internet is becoming a primary need for a large portion of the world population, up to the point that some groups advocate its introduction in the list of human rights, and that some forms of addiction are emerging.

From a technical perspective, this implies that the number of Internet users, and the amount of traffic they generate, keeps growing at an exponential pace. The famous Cisco Visual Networking Index report [1] forecasts that global average Internet traffic will grow at a compound annual rate of 23% from 2012 to 2017, and peak Internet traffic will increase even more rapidly. The annual global Internet traffic will reach 1.4 zettabytes by the end of 2017 (a figure which is far beyond our normal accounting habits), and the peak hourly Internet traffic will reach 865 Tbps by the same date, equivalent to 720 million people streaming a high-definition video continuously. Regarding equipment, end users are installing more and more networking devices in their homes and offices, and network operators need to react with a parallel increase in their network equipment and in its capabilities.

One of the consequences of this "race to networking" is that the amount of energy necessary to operate the installed equipment is growing to worrisome levels. The networking research community started realizing this issue in the first half of the last decade, and energy-efficient networking (or green networking) became a hot topic around 2007. Researchers started looking into key questions on energy consumption of communication networks, like: "*Is the current growth of energy consumption in telecom infrastructures sustainable?*"; "*Can we generate and transport enough electricity to provide high bandwidth access to everyone in metropolitan areas?*"; "*Are optical technologies more energy-friendly than electronics?*"; "*Is the Internet protocol suite needlessly wasting energy?*".

The European Commission was quick in realizing the relevance of this topic, which started appearing in the Work Programmes of its 7th Framework Programme (FP7). A pioneer FP7 project, EARTH (Energy Aware Radio and neTwork tecHnologies) [2], was launched in 2010, with the goal of "addressing the global environmental challenge by investigating and proposing effective mechanisms to drastically reduce energy wastage and improve energy efficiency of mobile broadband communication systems, without

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compromising users perceived quality of service and system capacity".

In 2011, FP7 activated the TREND (Towards Really Energy-efficient Network Design) Network of Excellence (NoE) [3], whose aim was "to establish the integration of the EU research community in green networking with a long term perspective to consolidate the European leadership in the field".

TREND has contributed during the last three years to the international research on green networking, establishing itself as one of the primary hubs for researchers in this field. Some of the most relevant achievements of TREND include:

- Collection of comparable data to assess the power consumption of terminals, devices and infrastructures, and identification of the power consumption trends in the field of networking.
- Identification of energy-friendly devices, technologies, algorithms, protocols and architectures and investigation of how they can be introduced in operational networks.
- Definition of new energy-aware network design criteria.
- Experimentations that prove the effectiveness of the proposed approaches.
- Identification of a roadmap for energy-efficient networking.

A holistic approach was taken, considering all network segments, from user terminals, to access networks, to metro and backbone networks, to applications, to data centers, both in evolutionary scenarios and in clean-slate designs.

Other projects have recently been proposed and developed, targeting challenging issues and aspects of green communications and networking. In the FP7 framework of the European Commission, some projects look at wireless networks. Among those more closely related to TREND, CONSERN (https://www.ict-consern.eu/) focuses on small scale wireless networks and, in particular, on two aspects: how to make the elements of the wireless network interact in an energy efficient way and how to make the network evolve in an energy efficient way. Thus, the project introduces the concept of energy-aware self-growing network. The project CROWD (http://www.ict-crowd.eu/) investigates dense heterogeneous wireless networks, in which the density of network nodes is needed to sustain the fast traffic growth; one of the objectives is to make traffic-proportional the network energy consumption. Wireless access technologies are also investigated in C2Power (http://www.ict-c2power.eu/), a project that proposes energy saving technologies based on a combination of cognitive radio and cooperative strategies.

Other projects focus on aspects related to the interconnection of the devices in the core and metro network. In the ECONET (http://www.econet-project.eu/) project, energy efficiency of wired devices is achieved by using low consuming standby modes and performance scaling capabilities that adapt active resources to current traffic loads. The objective of the STRAUSS (http://www.ict-strauss.eu/) project is to define an energy-efficient optical infrastructure for Ethernet transport, whose architecture is based on software defined networking principles. The main goal of FIT4Green (http://www.fit4green.eu/) is to optimize resources in data centers by turning off devices when unused due to load fluctuations.

The COST action project titled IC0804-energy efficiency in large scale distributed systems (http://www.cost804.org/) aims at proposing solutions for improving energy efficiency of large systems that share distributed resources; the approach consists in working in a complementary way at network, middleware and applications levels.

One of the prominent worldwide initiative is GreenTouch (http://www.greentouch.org/), a large forum that involves manufacturers, operators, research institutions, with the ambitious goal to increase network energy efficiency by a factor of 1000 with respect to 2010 levels in just five year. The organization investigates efficiency in a comprehensive way, including different technologies and network segments, and proposing architectures, specifications and roadmaps for energy efficiency improvement.

This paper describes some of the main achievements and contributions of the TREND NoE as well as some indications for future steps towards energy-efficient networking. The rest of this paper is organized as follows. Section 2 describes and explains the main insights of one the initial goal of the TREND researchers on collecting data on real electricity consumption of communication networks. Section 3 focuses on the segment of backbone networks, including aspects of network design and operation. Section 4 is devoted to energy-efficient data centers. The access part of the networks is discussed in Section 5 (wireless access networks) and Section 6 (optical access networks). Finally, Section 7 introduces a roadmap in energy-efficient networks covering aspects to be tackled by equipment designers, operators, standardization fora and networking researchers.

2. Worldwide electricity consumption of communication networks

Collecting data on real electricity consumption of communication networks has been one of the initial goals of the TREND researchers [4]. It is an essential first step in order to play with trusted data, share them with the research community, design energy aware networking solutions and finally assess the impact of introducing new energy efficient technologies.

Often-cited values of the footprint of communication networks and ICT in general date back from five to ten years ago or are extrapolations based on these values. A previous report [5] on the worldwide energy needs for ICT was based on data from 2007; in the Smart2020 report [6], which studied both the footprint of ICT and its enabling effect to reduce emissions, the network section of the analysis was based on reported energy consumption values of telecom providers in 2002. These values were then extrapolated based on the expected increase in subscriptions in 2002–2020. Another extensive study on greenhouse gas emissions and operational electricity use in ICT by Malmodin et al. [7] also provided estimates for 2007. In the past five years, the electricity consumption of networks was likely transformed by fiber rollout, smart devices requiring mobile Internet access and rapid customer base growth in emerging markets.

TREND contributed to energy consumption data collection and forecast with a top-down analysis of the total global electricity consumption in communication networks, based on results on recent data (2007–2011), aiming to obtain an updated estimate of the network share of the worldwide electricity consumption in 2012. The considered components of the communication networks are: telecom operator networks, office networks, and customer premises equipment. Only the in-use electricity consumption is taken into account: the energy consumption due to the manufacture and dismissal phases is not considered.

The results are summarized in Fig. 1. Telecom operator networks make up almost three quarters of the network electricity consumption, the remaining quarter is used by customer premises equipment and office networks. Among networks, the contribution of mobile networks is estimated to be between 40% and 60%.

The total worldwide electricity consumption of communication networks has increased from 219 TWh per year in 2007 to 354 TWh per year in 2012. This corresponds to an annual growth rate of 10%. When this is compared to the total worldwide electricity consumption [8], we see that the share of networks is becoming increasingly important (dotted line in Fig. 1). Where communication networks only consumed about 1.3% of worldwide electricity in 2007, their relative contribution has increased to 1.8% in 2012.

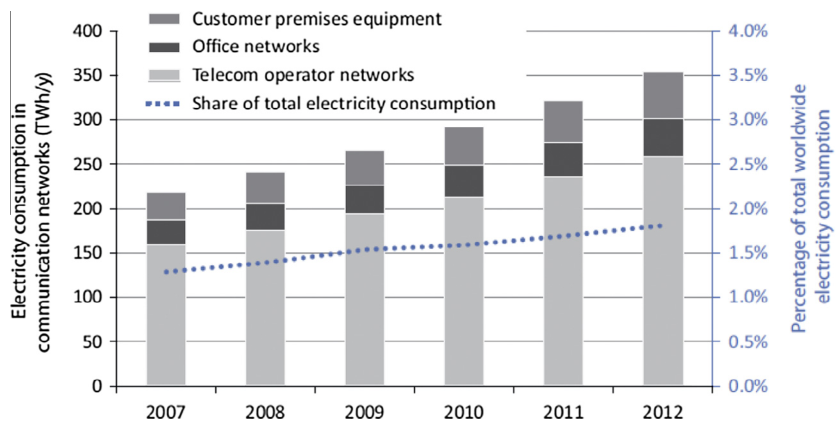

Fig. 1. Worldwide use phase electricity consumption of communication networks (columns, left axis) and share of networks in total worldwide electricity consumption (dotted line, right axis). Source: [4].

Since the electricity consumption in communication networks is growing at a faster pace (annual growth rate about 10% in the interval 2007–2011) than the overall electricity consumption (annual growth rate about 3% in the interval 2007–2011), the relative share of communication networks is increasing. Moreover, subscription numbers are forecasted to continue to grow exponentially in the next years; as we already mentioned, the Cisco Visual Networking Index report [1] forecasts that global average Internet traffic will grow at a compound annual rate of 23% from 2012 to 2017 and subscription numbers are globally predicted to grow at rates between 10% and 20% by the ITU, in the 2012 report "Measuring the Information Society" [9]. These data confirm the need to invest in more energy efficient network technologies.

These numbers suggest that the problem of the increase of energy consumption of communication networks, intuitively perceived as important by the scientific community only a few years ago, is going to become dramatically worse in the next years. Countermeasures to slow down this trend are necessary not only to achieve (important) cost reductions for network operators, but also to guarantee the sustainability of future communication networks. In this context, the wide set of solutions proposed by TREND becomes a strategic means for operators and rulers to tackle the problem.

For what concerns the breakdown of the energy consumption among the various segments and components of the networks, the analysis performed by TREND shows that energy consumption distributes among segments and components in a relatively fair way, meaning that it is necessary that all parts of the network are redesigned with energy efficiency as a fundamental objective. For this reason, the TREND consortium has developed new, comprehensive, energy-aware approaches to networking, including core, metro, access, and home networks (considering both wired and wireless technologies), as well as data centers.

In what follows, we will shortly review some of the main solutions proposed by TREND for the various network segments and related technologies. This will also give a view of how the networks of the future will operate to cope with the critical issue of sustainability.

The description of the solutions in the rest of this paper is organized into solutions for the backbone, the data centers and the access networks. A discussion of the next steps and some conclusions will be drawn at the end of the paper.

3. Energy-efficient backbone networks

The main results achieved by TREND for the backbone networks are described and discussed in Refs. [10,11]. The first paper is focused on optical networks including the access and core parts, while the second one deals with core and metro networks including data centers (Fig. 2).

From the energy perspective, data centers have already been identified as a critical segment [12]. Meanwhile, core networks are expected to generate the biggest increase in electricity consumption [13] because their equipment number grows almost proportionally to the data traffic. Assuming similar exponential growth [1] as observed over the last decade, the segment will also be critical on the 2020 horizon.

TREND objective has been then to provide solutions for energy-efficient future backbone networks capable of sustaining traffic growth with reduced energy consumption. The effort is twofold: on the one hand, more efficient networks and data centers architectures are proposed and investigated; on the other hand, a more energy efficient way to operate the networks is envisioned. In this paper, data centers will be discussed later in Section 4; here we focus on network design and operation.

3.1. Energy-efficient network design

In typical IP-over-WDM core networks, the IP nodes represent the largest share in the total power consumption. It has been shown to be as high as 60% of the total power consumption [14]. Therefore, any solution that allows reducing the average number of IP hops required to route a demand will usually decrease the power consumption of the core network. *Optically bypassing the IP routers* is a well-known technique to reduce the IP hop count. The idea is that traffic not intended for the IP node, remains in the optical layer and thus bypasses the IP, with the associated costs related to the conversion from the optical to the electronic domain and the electronic operations. This allows us to reduce load of the router and the associated power consumption.

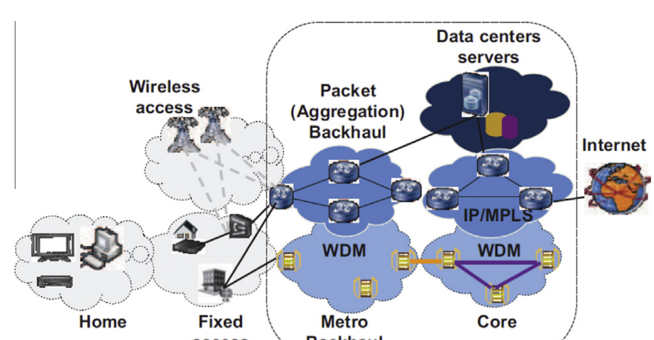

Fig. 2. Generic operator network architecture and domains studied within TREND. Source: [10,11].

For sufficiently large demands, this technique was shown in [14] to allow energy savings of up to 50% in the pan-European Géant network. A more extensive analysis in [15] shows that these savings are for a great deal depending on the mesh degree of the network, the ratio of the average demand over the line rate, and the average physical link length. High(est) savings are achieved for the combination of demands close to (but below) the channel line rate, sparsely meshed networks (corresponding to realistic networks with node degrees of around 3), and not very long links.

Besides trying to reduce the IP hop count, there are other possibilities to make the network design more energy efficient. In the design of the network, traditionally aiming at reducing capital expenditures (i.e., the costs of investments on the devices of the infrastructure) or maximizing the performance, energy consumption should be introduced as a new design variable [12] with respect to which network design should be optimized. Achievable energy savings that range from 10% to 30%, depending on the network topology and the traffic load, are feasible [16].

Another design choice concerns the routing of the traffic demands: single-path vs. multi-path routing. Adopting multipath routing requires that each traffic demand is split into several sub-demands routed independently, potentially following different paths from the source to the target node. Multi-path routing can achieve a more effective traffic grooming, resulting in some network interfaces that are underutilized and can be put in sleep modes resulting, as a consequence, in lower network energy consumption. Savings are significant only for low values of the traffic load, when grooming is possible and effective; otherwise the savings reach roughly 10% [16].

In summary, the energy consumption of core networks can be significantly reduced if appropriate choices are performed during the design phase. However, some of the energy wise choices may reduce network performance. For example, optical bypass may reduce network availability because in case of a failure, it prevents from re-routing at the intermediate router that has been bypassed; thus a trade-off between energy reduction and performance must be chosen.

A more energy efficient network can be achieved by properly adapting the design, as in the solutions mentioned above, but also by exploiting at best the potentiality of optical technologies. TREND has investigated to what extend optical technologies can be revisited with energy consumption reduction as a main goal. In particular, the benefits of both subwavelength photonic switching technologies and Optical Burst Switching have been considered.

As already mentioned, to reduce energy consumption, optical switching of lightpath should be used instead of electronic switching at intermediate network nodes so as to eliminate the need for optical to electronic to optical (O/E/O) conversion in the core nodes of the network. On the downside, this suffers from both scalability and efficiency issues especially in metro and backhaul networks, where there may be higher discrepancy between the effective traffic and the wavelength channel granularity. Aggregation is then needed to avoid dedicating a wavelength to a single source–target pair leading to severe bandwidth waste. In current networks, the bandwidth of every wavelength channel is dynamically shared among several source–target pairs thanks to electronic switching. Subwavelength photonic switching technologies are also providing this capability and might be very effective in substitution to electronic switching.

Optical Burst Switching (OBS) with reduced processing overhead and switching constraints may be an interesting solution for meshed networks. In OBS networks, incoming IP packets are aggregated into larger optical bursts at the edge of the OBS network. Unlike time-slotted solution, bursts of data may have variable length and can be sent asynchronously.

Several flavors of control exist and we showed that the most promising solutions are the ones that avoid burst loss [17]. By eliminating O/E/O conversion at intermediate nodes, OBS is likely to considerably reduce power consumption. TREND researchers investigate a recent proposal for sub-wavelength switching at burst granularity has shown by means of a detailed comparative study that subwavelength switching solutions are expected to reduce the energy consumption by some 50% when compared to today's [18].

In summary, energy efficiency increase in the backbone network though network design can be achieved mainly in two ways: by rethinking the network design so as to push a more intense use of the optical layer with respect to the electronic one and by relying on technologies that allow a reduction of electronic switching and ease traffic grooming.

3.2. Energy-efficient network operation

The previous section considered the energy consumption reduction that can be achieved by a proper network design. Once the network is deployed, additional savings are possible by properly operating it, or, in other terms, by making the actual active capacity *adaptive* to the traffic needs.

Network topologies in the core usually form a mesh, where more than one path is present between a node pair. Dynamic choice of the path for the traffic demands arriving at the network can be used to increase the number of idle or lightly loaded devices during the low demand hours [42]. It is difficult to switch off complete nodes of core networks, because there is usually (aggregated) traffic originating from or targeted to them. However, traffic can be rerouted from some links, and delivered to the target nodes via alternative paths. Furthermore, many IP links are composed of bundled links of the lower layer, so it is possible to temporarily decrease their capacity and deactivate the excessive resources. Furthermore, the rate of both the link and node equipment could be reduced to decrease its power consumption.

TREND researchers presented a wide set of adaptive routing solutions working in both the IP layer and the optical layer in Ref. [43]. An evaluation study based on a realistic network scenario provided by orange and forecast for the typical traffic values in year 2020 has shown that the different solutions utilizing adaptive routing in the IP layer achieve comparable savings. 39–45% of energy consumed by line cards over a working day can be saved with respect to the static base network.

Furthermore, we compared these savings with the savings of a simple solution called Fixed Upper Fixed Lower (FUFL), where no dynamic routing is used, but only dynamics of traffic is utilized. FUFL achieves energy savings of 15% in the considered scenario. The smaller savings in comparison to the results obtained by the more sophisticated solutions are balanced by the simplicity of application of this distributed solution, as it requires only local knowledge to make decisions about activation or deactivation of resources.

The percentage of energy savings achieved by the solutions in the optical layer (with respect to all devices targeted to be put into sleep mode) is similar or even higher. However, the absolute values of the savings in kW h are much smaller than those in the IP layer, as optical transponders consume significantly less power than the router line cards [14].

Recently, the concept of Elastic Optical Networking (EON), based on OFDM, for example, and coherent detection, has been introduced as a promising candidate for the operation of future optical transport networks. EON can bring significant advantages in terms of energy efficiency thanks to the variable lightpath capacity and the adaptive modulation formats. The finer granularity allows a better adjustment of the allocated capacity by expanding or contracting the channel bandwidth according to the actual user demand, whereas the adaptive modulation enables the choice of modulation format according to the demand and distance, thus minimizing the number of regenerations in the network. Furthermore, EON also improves the spectral efficiency and reduces the network blocking with respect to fixed-grid scenarios, which has also an impact on the energy efficiency of the network.

Studies in terms of energy efficiency for EON have been carried out by the TREND researchers, considering different network scenarios and conditions in Ref. [44] (i.e., different-sized network topologies, static and dynamic traffic operations, unprotected and protected networks, and different traffic loads). One of the main conclusions from the different studies is that EON can considerably benefit in terms of power efficiency when exploiting the traffic variations in the network. For instance, EON can specially benefit from novel protection schemes, proposed in Ref. [45], where the rate of the backup transponders is adapted to the current required bandwidth to reduce the energy consumption. In conclusions, network operation can be made more energy efficient by dynamically adapting capacity (and, hence, consumption) to the traffic load. This can be done both at IP and at the optical layer, with savings that depend on the traffic aggregation levels and variability.

3.3. Energy-efficient protection schemes

A proper network operation requires the support of protection schemes, often based on a significant redundancy of devices that corresponds to large energy consumption. Some solutions, as those discussed in this section, should be adopted to reduce this consumption.

In long-haul optical networks, the most common and secure strategy to provide resilience is implementation of a dedicated path protection DP 1 + 1, scheme, where the data is duplicated and transmitted on two link-disjoint paths. This scheme requires the reservation of twice the spectral resources for working and protection paths, and the deployment of redundant transponders, which are simultaneously active and consuming power. However, in many cases clients may not require such a high level of reliability for their service. Accordingly, the heterogeneity of protection requirements requested by clients could be exploited to enhance the energy efficiency of the network with respect to the conventional DP 1 + 1. A differentiated quality of protection (Diff QoP) was proposed in Ref. [45] and evaluated for both fixed grid WDM and flexible grid OFDM-based EON. The provisioning of Diff QoP is based on the definition of different QoP classes corresponding to different protection levels: DP 1 + 1, DP 1:1, shared protection and best-effort protection.

In the study, different traffic load conditions with different percentages of QoP traffic classes have been evaluated corresponding to the predominance of different types of client: (i) big corporations, (ii) small- and medium-enterprises and (iii) intermediate scenario. Energy savings up to 21% can be achieved with respect to DP 1 + 1 scheme. Even though power savings can be obtained for all the different traffic conditions, the degree of power savings strongly depends on the transmission technology, total traffic, and distribution of traffic classes. Savings are more significant at high traffic load, and for scenarios with lower percentage of client demands requiring maximum protection [45].

In this context, considering that protection resources (i.e., WDM transponders, IP routers line cards, etc.) can be set into a low-power sleep-mode, high energy benefits can be obtained. In Ref. [46], a comparison between different protection strategies has been carried out from the power consumption point of view, by accomplishing a power-minimized network design. Dedicated vs. shared as well as link vs. path protection strategies have been compared, developing for each of the four scenarios an Integer Linear Programming based formulation aiming at minimizing the network power consumption. It has been found in [46] that up to about 60% of power savings, according to the protection strategy and traffic scenario, can be obtained by setting protection devices into sleep-mode, especially thanks to the possibility of saving large amounts of the power spent in IP routers. Moreover, it has been also found that, by employing sleep-mode for protection devices, it is possible to guarantee network resilience for a small (1–2%) additional power expenditure compared to non-resilient scenarios.

3.4. Energy-efficient content distribution

Some further energy consumption reduction can be achieved by taking into account the characteristics of the applications that generate most of the traffic. For content distribution services, caching can be deployed by the service provider with the objective of reducing consumption; when, instead, the traffic originates from the end users, as in P2P services, it is the application itself that should be made energy aware. Recent studies [13] demonstrate that homes and organizations (i.e., end-hosts) are responsible for 75% of the overall Internet energy consumption.

Existing multimedia file distribution services such as peer-to-peer (P2P) file sharing applications, one-click-hosting services, software releases, etc., represent a major fraction of the current Internet traffic [20] and this traffic volume is expected to grow even further in the future. Much of this traffic is multimedia in nature. As an example, Cisco estimates that the sum of all forms of videos will represent 86% of the global consumer traffic by 2016 [1]. Thus, file-sharing and content distribution services are responsible for a significant fraction of the overall energy consumption in the Internet and proper solutions to improve their efficiency are needed.

TREND researchers have considered the case of improving the energy efficiency of content distribution architectures managed by an Internet Service Provider (ISP) in Ref. [19]. The aim is to find the best locations in the ISP topology where to place the content requested by users from the Internet Peering Points (PPs) in order to minimize the energy consumption of the ISP infrastructure including transport, storage caches and servers.

The decision about where to store the content is taken on the basis of the energy consumption and the content popularity. In fact, very popular content is likely to be placed close to users to minimize the cost of transporting information inside the network. However, a tradeoff exists since the more the content is placed close to the users, the higher the number of required replicas is. Results obtained over a realistic case study show that energy savings of more than 8% are achievable. These savings are obtained on the entire network of the ISP, ranging from the core to the access. At the same time, a 18% reduction of the bandwidth required at the PP is possible.

For what concerns file-sharing applications, the majority of previous studies in the area have mainly focused on optimizing the performance, i.e., minimizing the download time [21]. However, those algorithms, designed to minimize the download time, are not optimal in terms of energy consumption. Performance of energy-efficient file distribution algorithms was analyzed in Ref. [22] by TREND researchers. In particular, it was proposed to enhance the scheduling algorithm of the P2P content distribution so as to make it energy aware; an active peer should upload content so as to let other peers enter low consuming sleep modes. The proposed algorithms reduce the energy consumption of the file distribution process with respect to any centralized file distribution scheme, such as those widely used today, even in challenging heterogeneous or congested scenarios. These savings range between 50% and two orders of magnitude, depending on the centralized scheme under consideration.

Besides the saving obtained through a proper network design and operation, some additional, and large, saving can be achieved when the characteristics of the applications using the network are taken into account. The actual effectiveness of these approaches depends of the considered scenario.

4. Energy-efficient data centers

As previously mentioned, data centers consume huge amounts of energy. Indeed, the ever increasing demand for computing resources has led companies and resource providers to build large warehouse-sized data centers, which require a significant amount of power to be operated: 120 billion of kW h in the USA alone, as stated in the report published by the USA Environmental Protection Agency [24].

Many efforts have been devoted to the efficiency improvement of the physical infrastructure of the data centers. Indeed, only a fraction of the power that enters the data centers is actually used to support the workload, while a consistent amount of power is used by the facilities for power supply and distribution, and by the cooling infrastructure.

However, the physical efficiency is not enough to guarantee the overall efficiency of the data center that has to be also related to the computational efficiency, which, in its turn, depends on the workload distribution over the servers. A given load evenly distributed over a large number of servers that work at low utilization requires more energy than the same load groomed over a smaller number of servers that work at higher utilization.

This observation, combined with the possibilities offered by virtualization, has led to many approaches to consolidate load on as few servers as possible. The key issues are then the strategies to properly allocate virtual machines to servers, and the methods to face the possibility that servers, which work at high utilization, become overloaded due to fluctuations of the amount of resources requested by the running virtual machines.

To this end, TREND researchers have proposed a solution, called VMPlanner [23], to efficiently optimize the network power consumption in a cloud data center. VMPlanner performs two main tasks: the virtual machines (VMs) placement inside the data center, and the traffic flow routing between the VMs. At the end of this procedure, as many network elements as possible are switched off while guaranteeing Quality of Service (QoS) constraints. The problem is formulated as an Integer Linear Problem and solved suboptimally by decoupling in three different steps. In particular, first the VMs are grouped into sets that exchange a minimum amount of traffic. Then, as the second step, the VMs are mapped to the server infrastructure in order to minimize the traffic that is exchanged between the servers. Finally, the traffic generated by the VMs is routed in such a way that as many network elements as possible can be turned off. Results demonstrate the efficiency and efficacy of the proposed solution, with up to 60% of saving achievable compared to a solution in which all the network devices are always powered on [23].

The solution proposed in Refs. [25,26] consists of delegating part of the VM placement decision processes to the servers, so that the allocation and migration strategies are implemented in a distributed fashion, with the contribution of all servers. The servers use only the local knowledge about their own load, and make simple probabilistic decisions about their availability to host a new virtual machine or the need to migrate some virtual machine to other servers. The probability of accepting a new VM or migrating one depends on the server load, so that overload conditions can be avoided. By acting this way, the system, as a whole, naturally scales and adapts to the varying conditions. The achieved energy saving depends on the workload profile with time and, thus, on the degree of server consolidation that can be achieved. Average daily saving is typically between 30% and 40%.

5. Energy-efficient wireless access networks

Traditionally, up to a few years ago, energy efficiency aspects have been included in the wireless access networks design space only in the context of power control aimed at interference mitigation, and for the increase of the terminal battery lifetime. Energy consumption of network components has also, for a long time, not been considered as an issue, neither in equipment design, nor in network planning and management. Wireless access networks have traditionally been designed targeting performance maximization at full load. Indeed, the full load working condition is the most critical and challenging one in terms of efficient use of the available resources, and, consequently, of capital expenditure. However, most of the time, networks work at low to medium load. This is especially true for wireless access networks in which the user aggregation level is very limited: cells cover limited areas in which users tend to exhibit similar behavior, so that the load profile presents large variations between peak and off-peak values, with long periods of low load, as shown in the figure below for the traffic measured on cells of an Italian mobile network in operation (Fig. 3).

While the network is often under-utilized, the access devices exhibit low degrees of load proportionality, i.e., the devices consume when idle almost the same fraction (a fraction varying between 60% and 90%) of what they consume at full load. This has induced researchers to envision strategies for energy efficiency based on the idea of making the amount of active capacity (and, hence, consumption) adaptive to traffic needs. The research efforts in this field have taken two main directions. On the one hand, manufacturers are focusing on the design of devices whose consumption is more load proportional; on the other hand, new network architectures are being proposed to make the network as a whole consume less and provide *resources on demand*, either through management of the devices of a given network, or through the interaction with other networks, in a heterogeneous scenario.

5.1. Wireless network nodes management

In order to provide resources on demand with the objective to improve energy efficiency, several solutions have been proposed, based on the use of low consumption sleep modes of access network devices. The idea is that devices enter sleep modes whenever the traffic is low, i.e., when capacity is redundant. The use of sleep

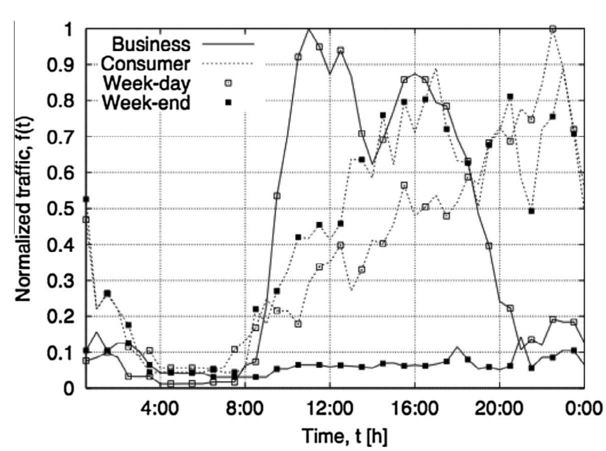

Fig. 3. Normalized traffic measured on cells of an Italian mobile operator in a cell of a business area (solid lines) and a cell of a consumer area (dashed lines).

modes for the devices corresponds to approximate at a slow timescale a load proportional behavior of the access network. TREND has devoted a large effort to the study and development of BS management schemes based on sleep modes, targeting energy efficiency.

Some activity focused on the development of centralized, distributed and pseudo-distributed control schemes [34] that can be implemented in an online and offline fashion, the trade-off typically being that larger saving can be achieved with dynamically reactive online approaches at the risk of some oscillation and possible misbehavior of the network. The considered scenarios include access points of WiFi networks [29–31] and base stations of cellular networks [32,33,47,48]. Some other work, instead of developing algorithms, focused on the evaluation of the potential achievable saving and relative bounds [34].

As a further case of resource-on-demand provisioning, cooperation among mobile network operators has been considered. In this case, resource-on-demand schemes apply to the resources of different operators providing connectivity on the same area. When traffic is low, the whole access infrastructure of one or more operators can be put to sleep, as far as the infrastructures that remain active can carry all the traffic, including the one roaming from other operators with their access network in sleep mode. Results show that this approach can lead to huge savings, whose actual value depends on many factors, such as the traffic profile and the relative size of the involved networks [35].

The results indicate that resource-on-demand approaches in the wireless access lead to significant saving, due to the high traffic variability between peak and off-peak time and the long duration of the low traffic periods that are typical of network segments close to the users and with limited traffic aggregation levels.

5.2. Access network architectures

Important opportunities for energy efficiency derive from the innovation of access network architectures. A very promising scenario is the one of heterogeneous networks, in which the coexistence of a few different access technologies in the same area allows the optimization of network performance with respect to several variables. This has been seen often as an opportunity for what is called *offloading*, a technique that aims at improving the performance of the network at peak traffic by exploiting capacity provided by the various overlapping networks. For example, data traffic movement from the cellular network BSs to IEEE 802.11 hotspots is one of the key techniques through which mobile operators intend to cope with the increasing traffic demand in cellular networks. Beside performance optimization, the same approach can be used to save energy [27]. In this case, during low traffic periods, the diversity of available technologies is used in combination with grooming techniques and sleep modes: traffic is groomed and carried through one network while the alternate technology that becomes underutilized is put to sleep. Clearly, the use of these techniques requires the design of proper protocols and procedures to guarantee connectivity and provide quality of service during all phases on the connections [28].

5.3. Saving energy on wireless transmission

While network-level approaches are fundamental to save energy through resource-on-demand approaches, additional saving can be achieved with physical layer solutions. In the TREND framework, several solutions have been proposed for different technologies and various aspects of transmission, from power control [36], to retransmission protocols for reliability [37], to resource allocation strategies, topic that, with the increase of traffic and bandwidth demand, still remains the key issue in wireless access [38–40]. The results of the research developed in this context show that a careful redesign of all the aspects of transmission is effective and should integrate network-level approaches.

In addition, the fact that the same area is increasingly covered by different technologies that provide connectivity and capacity can be exploited very effectively. As an example, the possibility to use WiFi in support of WiMAX is considered in [41] and proves to be promising. This is particularly interesting having long term scenarios of the future networks in mind.

6. Energy-efficient optical access networks

During the last years, massive Passive Optical Network (PON) deployments with optical fiber closer to the customer premises are taking place worldwide. PONs are a cost-effective way to increase the broadband access speed to customers, thus pushing the use of the Internet and information technology innovation, improving business efficiency and eventually increasing the Gross Domestic Product (GDP) of countries. A relevant characteristic of PON technologies is also their energy efficiency.

TREND identified several topics for enhancing the energy efficiency of PONs. First, a re-design of user premises equipment, both the Optical Network Terminals (ONT), and the Residential Gateway (RG), has been analyzed. Secondly, energy-aware PON dimensioning and optimization has also been studied for massive deployments, considering the access speed and Quality of Service (QoS).

New ONT design with optimized components adapted to the service model, such as single-port or Small Form-factor Pluggable (SFP) ONTs, can achieve relevant energy savings in the user premises. Additionally, the simplification of the user network, by providing higher-layer functionalities from the operator network, can also significantly reduce the power consumption per user in PONs [7,34,35].

Energy-aware PON dimensioning can be very helpful for network operators, allowing them to optimize the investment from the service perspective. As the access speed is increasing, and also considering the challenges of fixed-wireless convergence, migration to next-generation PONs in a cost-effective and energy efficient way can guarantee the massive adoption of ultra-high speed broadband access in countries as well as long-term energy sustainability of ICT [36–38].

7. TREND roadmap towards energy-efficient networks

The different energy saving schemes proposed by the TREND researchers could lead to the (estimated) energy consumption reductions summarized in Fig. 4. These numbers are provided only as indications, since their relative impact on the global energy consumption picture depends on the combination of approaches in different network segments, on the consumption of the segment they address, and on the considered network scenario. We can however realistically claim that a large majority of the energy consumed by networks today can be saved by a clever combination of the proposed schemes, say 60–80%.

However, in spite of these very interesting predictions, on which most researchers in the field agree, and of the associated substantial monetary savings in operational expenditures due to the reduction of the operators' energy bills, the adoption of energy-efficient networking approaches is slow in operational networks.

Several aspects should be considered on the side of standardization bodies and regulation agencies to accelerate the uptake of energy-efficient networking approaches:

- Definition of standards for energy-efficient network operation. This is already in progress, with several groups working in this area, for example at ETSI and ITU; the publication of preliminary

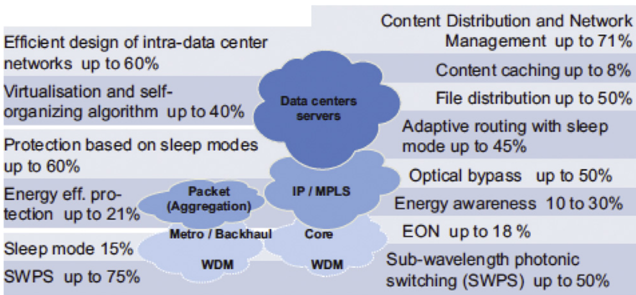

Fig. 4. TREND energy consumption reduction. Source: [10].

versions of these standards should happen rapidly, so that both manufacturers and operators can have clear indications about the paths to follow.

- Introduction of regulation to require manufacturers to publish reliable, complete, and standardized energy consumption data for their products. Indeed, if manufacturers had to fully characterize their equipment energy consumption and provide comparable data, they would be pushed to invest in energy-efficient options and, in their turn, network operators could reliably estimate the operational cost reductions achievable through the adoption of the new equipment and consequently make their choices.
- Definition of an "energy star" scheme for network equipment and for networks. A simple ranking of the energy performance of networks and equipment can be very effective in orienting the preferences of customers sensitive to the energy and environmental issues.
- Introduction of incentives and regulations to reward energy-efficient network operators. Several European countries already offer incentives for the replacement of older technologies with new, more energy efficient ones; they are considered an interesting support for technology replacement by operators; new approaches for the identification of the energy advantages of network management schemes should be introduced, in addition to those linked to new equipment.

From the point of view of researchers both in industry and academia, several topics in energy-efficient networking are interesting to tackle in the next few years:

- Definition of new energy-efficient architectures, which allow resource provisioning on demand. Some work in this direction is in progress, for example the GreenTouch project is investigating an architecture in which the resources for coverage and signaling are separated from the data plane resources.
- Development of equipment with better energy efficiency and switch on/off capabilities. This issue is on the agenda of most manufacturers, but an increased interest for the energy performance features of the equipment on the side of network operators could better motivate manufacturers and stimulate this area of research.
- Definition of resource management algorithms with positive effects on energy efficiency and minor sacrifices in terms of QoS. Much work has been done in this field, but much remains to be done, especially as regards the interaction of traffic flows with realistic characteristics – e.g., TCP connections – with network controls for energy efficiency; the key objective in these efforts is the improvement of proportionality between traffic and energy within equipment, and within networks, even with non-proportional equipment.
- Careful computation of the overall energy saving resulting from the adoption of energy efficient approaches in different sections of the network. It is necessary to account not only for the relative impact on energy efficiency of the various solutions, but also for the interplay among the adopted energy efficiency approaches implemented in different network segments.
- Identification of network contexts that can benefit from the exploitation of renewable energy sources for the network operation. Some work in this area has recently started, but much effort is still necessary both from a theoretical and from and experimentation point of view, having in mind the utilization of renewables both in areas of new networking deployments, where the access to the power grid is typically problematic, and in areas where networks have been in operation for over a century and the power grid is ubiquitous and reliable.

8. Conclusions

The different energy saving schemes proposed by the TREND researchers can realistically claim that a large majority of the energy consumed by networks today can be saved by a clever combination of the proposed schemes described in this paper, say 60–80%. Despite of these very interesting predictions, on which most researchers in the field agree, and of the associated substantial monetary savings in operational expenditures due to the reduction of the operators' energy bills, the adoption of energy-efficient networking approaches is slow in operational networks. The role of the standardization bodies, regulation agencies, academia and industry to accelerate the adoption of the results proposed by the research community in the field of energy-efficient networking is crucial.

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