Energy Efficiency in the Future Internet: A Survey of Existing Approaches and Trends in Energy-Aware Fixed Network Infrastructures

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***Abstract*— The concept of energy-efficient networking has begun to spread in the past few years, gaining increasing popularity. Besides the widespread sensitivity to ecological issues, such interest also stems from economic needs, since both energy costs and electrical requirements of telcos' and Internet Service Providers' infrastructures around the world show a continuously growing trend. In this respect, a common opinion among networking researchers is that the sole introduction of low consumption silicon technologies may not be enough to effectively curb energy requirements. Thus, for disruptively boosting the network energy efficiency, these hardware enhancements must be integrated with ad-hoc mechanisms that explicitly manage energy saving, by exploiting network-specific features. This paper aims at providing a twofold contribution to green networking. At first, we explore current perspectives in power consumption for next generation networks. Secondly, we provide a detailed survey on emerging technologies, projects, and work-in-progress standards, which can be adopted in networks and related infrastructures in order to reduce their carbon footprint. The considered approaches range from energy saving techniques for networked hosts, to technologies and mechanisms for designing next-generation and energy-aware networks and networking equipment.**

***Index Terms*— green networking; wired networks' energy efficiency; energy efficient network devices.**

I. INTRODUCTION

AS the Future Internet is taking shape, it appears that some basic concepts and key aspects should pervade the network infrastructure as a whole, to such extent as to become part of the network design criteria, and to carry across multiple networking domains for the achievement of a general target. One such aspect is that of energy efficiency.

The field of Information and Communication Technology (ICT) has been historically and fairly considered as a key factor for developing innovative control systems and services, which can help in reducing and monitoring third-party energy wastes and in achieving high levels of efficiency [1]. In such context, different projects considered and/or developed networked technologies in order to build smart environments (e.g., houses, buildings) that are also energy-aware. At present, the role of ICT is becoming of paramount importance in addressing better energy efficiency in the energy production and distribution sector, as well as in fostering energy-awareness in all aspects of production and services. It would be odd that ICT would not apply the same concepts to itself [2].

Only recently, triggered by the increase in energy price, the continuous growth of costumer population, the spreading of broadband access, and the expanding number of services being offered by telcos and Internet Service Providers (ISPs), the energy efficiency issue has become a high-priority objective also for wired networks and service infrastructures. These continuously rising trends in network energy consumption essentially depend on new services being offered, as well as on data traffic volume increase, which follows Moore's law, by doubling every 18 months [3].

To support new generation network infrastructures and related services for a rapidly growing customer population, telcos and ISPs need an ever larger number of devices, with sophisticated architectures able to perform increasingly complex operations in a scalable way. For instance, high-end IP routers are even more based on complex multi-rack

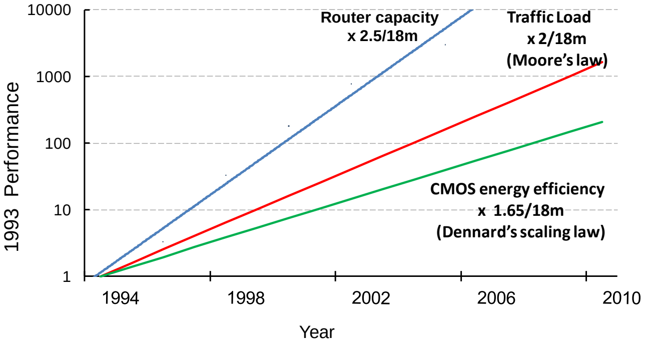

Figure 1. Evolution from 1993 to 2010 of high-end IP routers' capacity (per rack) vs. traffic volumes (Moore's law) and energy efficiency in silicon technologies [28].

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architectures, which provide more and more network functionalities and continue to increase their capacities with an increase factor of 2.5 every 18 months [28]. At the same time, as shown in Figure 1 and as suggested by Dennard's scaling law [29], silicon technologies (e.g., CMOS) improve their energy efficiency with a lower rate with respect to routers' capacities and traffic volumes, by increasing of a factor 1.65 every 18 months.

The sole introduction of novel low consumption silicon technologies cannot clearly cope with such trends, and be enough for drawing ahead current network equipment towards a greener Future Internet.

Thus, much likely as in other areas where energy efficiency is a concern, there are two main motivations that drive the quest for "green" networking:

i) the environmental one, which is related to the reduction of wastes, in order to impact on CO_2 emission (Figure 2);
ii) the economic one, which stems from the reduction of costs sustained by the operators to keep the network up and running at the desired service level and their need to counterbalance ever-increasing cost of energy (Figures 3 and 4).

To this purpose, telcos and ISPs have begun heavily requiring disruptive architectural solutions, protocols and innovative equipment that will allow achieve a better ratio of performance to energy consumption. This has inspired major ICT companies and research bodies to undertake different private initiatives towards the development of more energy-sustainable data centres and network infrastructures.

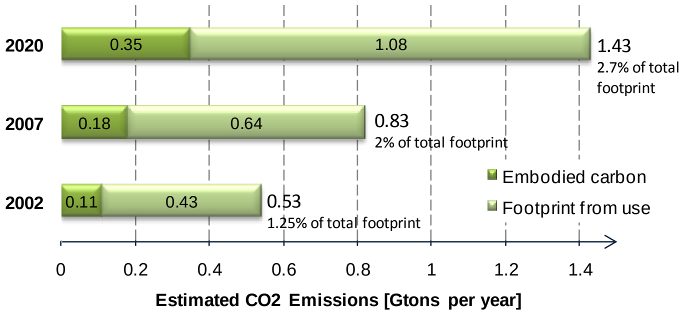

Figure 2. Estimate of the global carbon footprint of ICTs (including PCs, telco's networks and devices, printers and datacenters). Source: Smart 2020 report by GeSI [14].

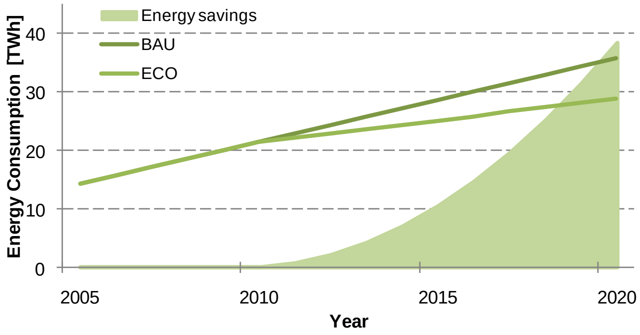

Figure 3. Energy consumption estimation for the European telcos' network infrastructures in the "Business-As-Usual" (BAU) and in the Eco sustainable (ECO) scenarios, and cumulative energy savings between the two scenarios. Source: European Commission DG INFSO report in [12].

The first main objective of this paper is to provide a complete and detailed survey on the main reasons and causes that recently set off so much attention on green networking from research and industrial communities.

Starting from this analysis, we will move our focus on energy efficient network technologies, protocols and standards that have been emerging during the last few years. In this regard, and in addition to a detailed survey of "green" papers from international journals and conference proceedings, we decided to include a further review of the most representative projects and standardization activities that are ongoing in this area.

Moreover, given the heterogeneity and the complexity of energy-aware technologies, we decided to limit our survey to the ones strictly related to the fixed network infrastructure. In this sense, this paper does not deal with energy efficiency approaches and technologies in network-related fields, such as green data centres. For the same reason, also energy efficiency in wireless networking scenarios (including ad hoc and sensor networks) will not be taken into account. Indeed, within the context of mobile devices and wireless networks, energy efficiency has quite different objectives (e.g., to increase the battery lifetime of devices), and considerable specific research has already been performed [30][31]. We will occasionally touch upon the energy-related aspects of the fixed access part of cellular networks and infrastructure WLANs.

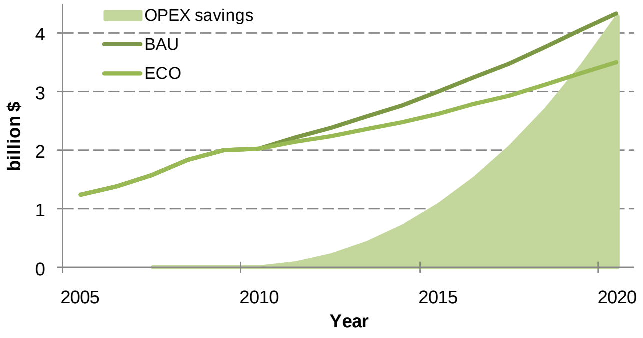

Figure 4. OPEX estimation related to energy costs for the European telcos' network infrastructures in the "Business-As-Usual" (BAU) and in the Eco sustainable (ECO) scenarios, and cumulative savings between the two scenarios. Source: European Commission DG INFSO report in [12] and the U.S. EIA estimation on energy costs [13].

The paper is organized as follows.

Section II includes an analysis of power consumption in today's network infrastructures of telcos and ISPs, and a survey of perspective studies on how energy requirements will evolve in the future years.

Section III is devoted to introduce the most representative approaches, which have been undertaken by networking researchers in the last years, in order to boost the energy efficiency of networks, specific equipment, and terminal hosts.

Section IV gives an overview of state-of-the-art contributions to the scientific literature. To this purpose, section IV will introduce and organize scientific contributions related to energy-efficiency on a per network scenario basis.

Starting from the main concepts and the contributions in sections III and IV, section V will discuss the main open and future issues for an energy efficient future Internet.

Section VI provides a survey on ongoing research projects and industrial private initiatives that have been activated in order to explore novel green network technologies, while section VII describes the main standardization activities regarding network energy efficiency. Finally, the conclusions are drawn in section VIII.

II. PERSPECTIVE AND CHARACTERIZATION OF NETWORK ENERGY WASTES

In the last few years, a large set of telcos, ISPs and public organizations around the world reported statistics of network energy requirements and the related carbon footprint, showing an alarming and growing trend. For example, the overall energy consumption of Telecom Italia in 2006 has reached more than 2 TWh (about 1% of the total Italian energy demand), increasing by 7.95% with respect to 2005, and by 12.08% to 2004 ([4], [5], [6]). This energy consumption especially rose from network infrastructures, which contributed 70% of the total energy requirements. Data-centres weighted for 10%, while the remaining 20% is due to other spurious sources (e.g., offices, shops, etc.). Note that similar breakdowns of energy wasting can be certainly generalized for the largest part of telecom operators.

Another representative example comes from British Telecom, which reported energy requirements similar to the Telecom Italia ones: the overall power consumption for its network and estate during the 2008 financial year was 2.6 TWh [6]. Moreover, it absorbed about 0.7% of the total UK's energy consumption in the winter of 2007, making it the biggest single power consumer in the nation [7]. About 10% of the UK's entire power consumption in 2007 was related to operating IT equipment [8].

In Germany, Deutsche Telekom reported an overall amount of power consumption of about 3 TWh in 2007 [9], which increased of about 2% with respect to 2006 data. Deutsche Telekom justified this energy consumption increase as the result of technology developments (DSL), increasing transmission volumes and network expansion; though the figure also includes a small amount of spurious data, they outlined that almost 20% of such energy waste is due to cooling systems. Moreover, the power consumption of Verizon during 2006 was 8.9 TWh (about 0.26% of USA energy requirements), while the requirements of Telecom France were about 2 TWh [10]. The NTT group reports that the amount of electric power in fiscal year 2004 needed for telecommunications in Japan was 4.2 TWh [11].

The figures above refer to the whole corporate consumption. As such, they account for numerous sources, other than the operational absorption of the networking equipment (e.g., offices' heating and lights). Nevertheless, we have included them to give an idea of the general trend.

Similar trends can be generalized to a large part of the other telcos and service providers. The European Commission DG INFSO report in [12] estimated European telcos and operators to have an overall network energy requirement equal to 14.2 TWh in 2005, which will rise to 21.4 TWh in 2010, and to 35.8 TWh in 2020 if no green network technologies will be adopted (Figure 3).

The Global e-Sustainability Initiative (GeSI) reported a similar estimation [14], and weighted the carbon footprint of networks and related infrastructures at about 320 Mtons of CO_2 emissions in 2020. As shown in Figure 5, GeSI reported that, during 2002, network infrastructures for mobile communication and for wired narrowband access caused the most considerable greenhouse contributions, since each of them weighs for more than 40% upon the overall network carbon footprint. The 2020 estimation suggests that mobile communication infrastructures will represent more than 50% of network CO_2 emissions, while, as far as wired networks are concerned, both telcos' devices (e.g., routers, switches, etc.), and broadband access equipment will cause ever growing and non-negligible contributions, equal to 22% and to 15%, respectively.

Researchers at Carnegie-Mellon University investigated during 2003 the electricity consumption of the telecommunications network in the United States [15]. The scope of the study covered the 'voice' network, including equipment used by both the Public Switched Telephone Network (PSTN) - used by traditional 'wired' telephone companies - and the cellular network - used by wireless companies. Building on results from a previous study, the estimated total electricity consumption of the telecommunications network in the US was found to be 29-34 TWh/year, or about 0.8% or 0.9% of the US total electricity consumption. The paper analyzed the breakdown of the electricity consumption between the PSTN and the cellular network, and found the cellular network to be about 2 times more energy efficient in terms of energy used per subscriber connection; the PSTN is more energy efficient in terms of electricity consumed per call-minute.

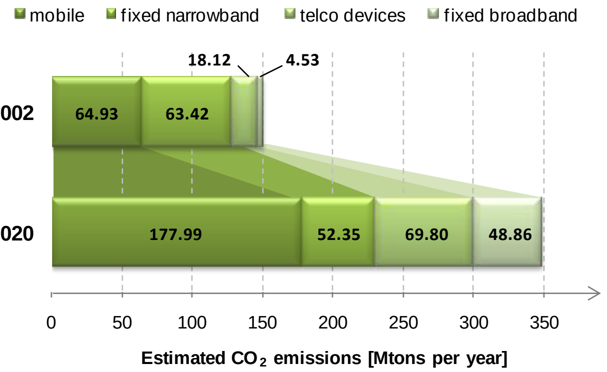

Figure 5. Greenhouse gas emission estimation according to GeSI [14].

Regarding wireless cellular networks, in 2008, researchers at NTT DoCoMo surveyed current mobile network energy consumption issues taking a Japanese mobile operator's network as an example [16]. The authors reported that the dominant part is due to radio access networks, and during 2006, each single user in NTT DoCoMo networks consumed, on average, 120 Wh per day for the network side and 0.83 Wh for the terminal side. The results of the investigation confirmed that current consumption can be reduced by introducing further IP-based Base Transceiver Stations (BTSs) and Radio-over-Fiber (RoF) technologies.

A deeper focus on energy consumption in today's and tomorrow's wired networks can be found in [17] and in [18], where Tucker *et al.* present a stimulating perspective on network design by focusing on cost and energy aspects. This perspective is based on a simple model for network technologies' evolution in the next years, and it uses the datasheets of state-of-the-art commercial devices, as well as projections of future broadband technologies.

By stating that today's network relies very strongly on electronics, despite the great progresses of optics in transmission and switching, the authors outlined how energy consumption of the network equipment is a key factor of growing importance. In this sense, they suggested that the ultimate capacity of the Internet might eventually be constrained by energy density limitations and associated heat dissipation considerations, rather than by the bandwidth of the physical components [19]. The authors pointed out that the data presented in their paper are based on a number of simplifications and approximations. Nevertheless, we believe that the results indicate some important trends.

The model aims at representing devices working at IP core, metro and access levels in order to evaluate the impact of different traffic grooming techniques both on scalability and costs, and on energy consumption of the overall network. To determine the energy consumption of the network, they have used information about the quantity of various types of networking equipment and the power consumption of these pieces of equipment, as minutely described in [20]. As outlined in Figure 6, the model exploitation highlighted that, not surprisingly, the overall energy consumption will increase as the capacity of the network expands. In this respect, it is worth noting that today's average access rates are about 2 Mbps. Thus, starting from the data in Figure 6, today energy requirements of access networks account twice with respect to the core.

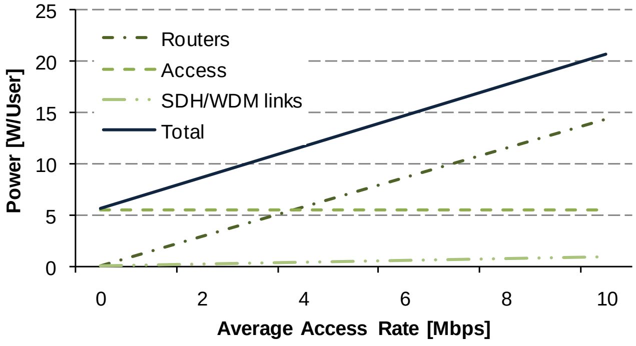

Figure 6. Average power consumption per user with respect to the increase in network access rate according to the results in [21]

The estimate in Figure 6 is also confirmed by an internal report from Alcatel-Lucent, which estimates that, in a typical ISP/telco network configuration, the power consumption of transport and core network represents about 30% of the overall network requirement, and access devices weigh for 70% (Figure 8).

In today's Broadband access network, the energy consumption is dominated by the energy in the user modem. The Passive Optical Network (PON) provides the lowest energy solution for broadband access with respect to point-to-point Ethernet, Fiber-To-The-Node (FTTN) and Wi-Max technologies. This feature of PON could become a driver of future PON deployment in response to concerns about the greenhouse impact of the Internet. Moreover, the authors have shown elsewhere [21] that at low access rates the power consumption in DSL networks is similar to that of PONs.

Tucker *et al.* finally demonstrated that the energy consumption in the routers — particularly in the core — will become more significant, as user access rates increase. The energy consumed in WDM links is relatively small. There is little evidence that optical burst switching or optical packet switching will significantly reduce the cost or energy consumption in future high capacity networks.

In this respect, Tucker's conclusions are confirmed by the trends shown in Figure 7, which reports that capacities and power consumptions of high-end routers grow in an exponential way, by a factor of 2.5 and 1.65 every 18 months on a per rack basis. In more detail, the data in Figure 7 has been obtained by [28] and completed with the datasheets of recent commercial top routers (e.g., Cisco CRS-1 [22], Juniper T1600 [23], Huawei Quidway 5000E [24], Brocade NetIron XMR 160000 and 320000 [25], etc.).

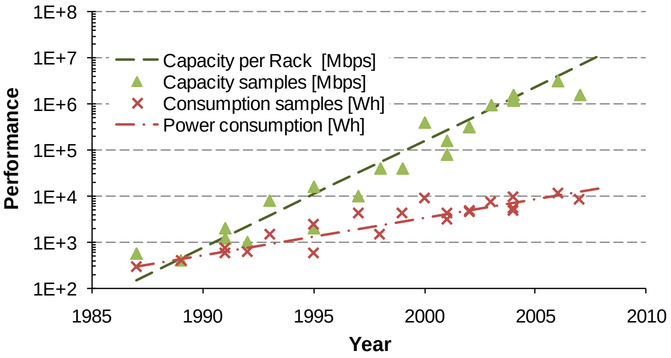

Figure 7. Evolution of capacities and energy requirements of high-end routers from 1985 to 2010. The estimation is on a per-rack basis [22] [23] [24] [25] [28].

III. CURRENT APPROACHES AND CONCEPTS FOR LOW-ENERGY NETWORKING

This section aims at introducing the most significant concepts and approaches that are currently undertaken by research and industrial communities in order to reduce network energy requirements. To this purpose, the section is organized as follows. The rationale of energy efficiency in ICT and the way existing approaches can be applied to wired networks are discussed in sub-section III.A. Sub-section III.B tries to characterize the most significant sources of energy consumption inside today's network devices. Finally, sub-

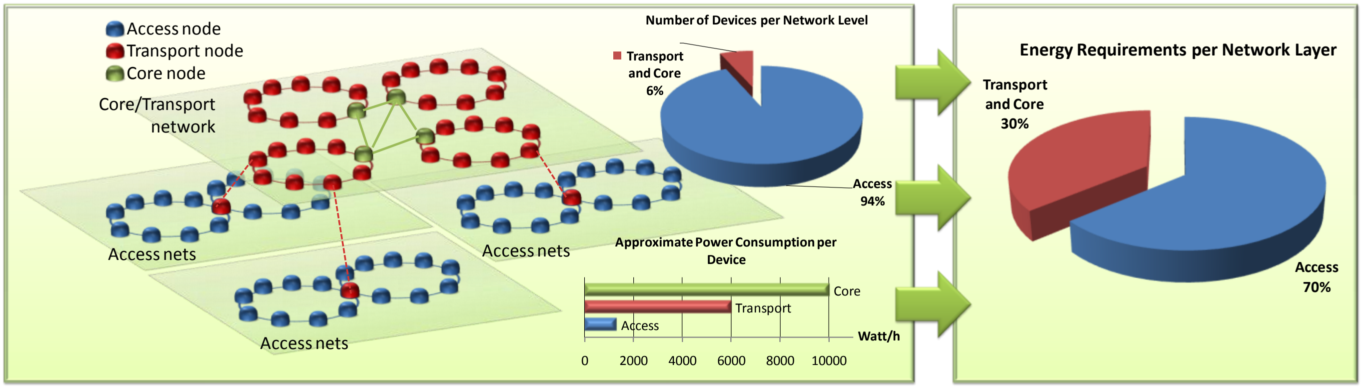

Figure 8. Typical access, metro and core device density and energy requirements in today's typical networks deployed by telcos, and ensuing overall energy requirements of access and metro/core networks.

section III.C introduces the taxonomy of approaches to green networking, which have been recently undertaken in order to reduce the energy wastes in telecommunication devices.

A. Rationale

The energy efficiency concept is far from being new in general-purpose silicon for computing systems. The first support of power management was introduced with the Intel 486-DX processor, and the first official version of the Advanced Configuration & Power Interface (ACPI) standard [27] was published in 1996. With time, however, more energy-saving mechanisms were introduced and HW enhancements were made, so that general purpose CPUs could consume less power and be more efficient.

Concerning network specific solutions, a large part of modern (packet) network devices is derived from computer technologies; here, the evolution has proceeded by including each time new ad-hoc HW engines and customized silicon elements for offloading the most complex and time-critical traffic processing operations.

As a consequence, the introduction of network-specific energy-saving technologies and criteria requires to pave new paths in research and industrial development in order to overcome the limitations due to the fact that network device internal elements have very different features and requirements with respect to general-purpose HW.

Groundbreaking work on energy consumption in the Internet was conducted by Gupta *et al.* [59] already in 2003, and by Christensen *et al*. in 2004 [91], showing that this is a mandatory issue to improve the energy efficiency of the whole Internet. However, only recently (2008-2009) researchers, operators, and device manufacturers started to massively invest their effort in this direction.

So far all these first efforts mainly resulted in patchy technologies and solutions, which refer to specific environments and/or protocols, and do not permit a fast and effective development and large-scale spreading of energy-awareness in telecommunication devices and infrastructures. Moreover, the lack of a standardized approach and of support of legacy technologies for network energy efficiency makes related industrial initiatives extremely costly and economically not viable (i.e., diverse development activities are needed to reduce the energy requirements of different devices, and of their parts).

B. Device-internal sources of energy wastes

In order to face the energy efficiency issue in today's and tomorrow's wire-line networks, we have to firstly understand and accurately characterize the real sources of power wastes. As outlined in section II (see Figures 5, 6 and 8), network devices working in the different network portions play a central role, since the overall energy consumption in networks arises from their operational power requirements and their density.

In more detail, operational power requirements arise from all the HW elements realizing network-specific functionalities, like the ones related to data- and control-planes, as well as from elements devoted to auxiliary functionalities (e.g., air cooling, power supply, etc.). In this respect, the data-plane certainly represents the most energy-starving and critical element in the largest part of network device architectures, since it is generally composed by special purpose HW elements (packet processing engines, network interfaces, etc.) that have to perform per-packet forwarding operations at very high speeds.

Tucker *et al.* [17] and Neilson [28] focused on high-end IP routers, and estimated that the data-plane weighs for 54% on the overall device architectures, vs. 11% for the control plane and 35% for power and heat management (see Figure 9). The same authors further broke out energy consumption sources at the data-plane on a per-functionality basis. Internal packet processing engines require about 60% of the power consumption at the data-plane of a high-end router, network interfaces weigh for 13%, switching fabric for 18.5% and buffer management for 8.5%.

Notwithstanding that this study specifically refers to high-end router platforms, and the same internal distribution of power-wastes cannot be obviously maintained for all the typologies and the architectures of network devices, the resulting estimations provide a relevant and clear indication on how and where future research efforts need to be focused in order to build next-generation green devices.

High-end IP routers based on multi-chassis platforms can be certainly considered as the network node typology with the

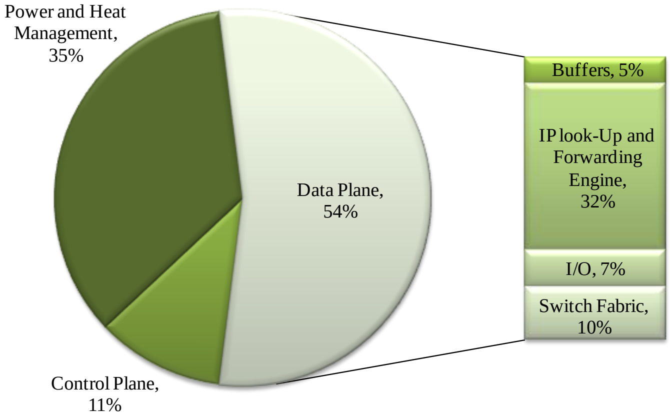

Figure 9. Estimate of power consumption sources in a generic platform of high-end IP router. Source: Tucker et al. [125].

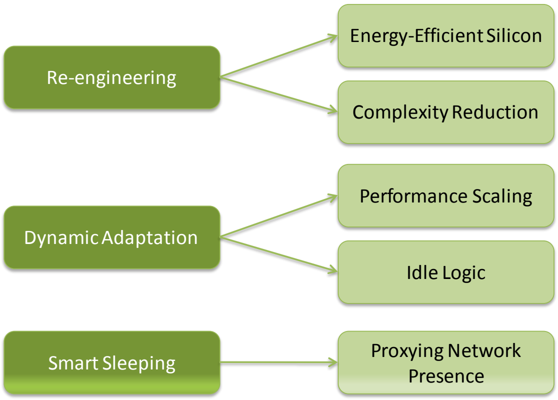

Figure 10. Taxonomy of undertaken approaches for the energy efficiency of the Future Internet.

highest complexity level. Traffic processing engines have generally to support complex forwarding and lookup functionalities, and internal HW elements are generally dimensioned for processing enormous traffic volumes. So, green technologies will have to mainly address the energy-efficiency in packet processing engines in order to effectively reduce the carbon footprint of such kind of devices.

On the other hand, Digital Subscriber Line Access Multiplexers (DSLAMs) generally include less and simpler packet processing functionalities with respect to routers, but also present a much larger number of network interfaces. The current energy requirements of today's DSLAMs mainly spring from link interfaces (I/O with respect to Figure 9). Therefore, future green technologies and solutions for access networks will have especially to focus on energy-efficiency at the link/network interface layer.

Following these basic ideas, the largest part of current research contributions generally focused on introducing novel extensions and solutions for reducing the carbon footprint of particular devices, by working at the level of internal processing engines for core and transport network nodes, and that of at network interfaces and/or link protocols for access and home equipment.

C. Taxonomy for current approaches to low energy networking

From a general point of view, the largest part of undertaken approaches is funded on few base concepts, which have been generally inspired by energy-saving mechanisms and power management criteria that are already partially available in computing systems. These base concepts can be classified as follows:

i) Re-engineering;
ii) Dynamic adaptation;
iii) Sleeping/standby.

Re-engineering approaches aim at introducing and designing more energy-efficient elements for network device architectures, at suitably dimensioning and optimizing internal organization devices, as well as at reducing their intrinsic complexity levels.

The dynamic adaptation of network/device resources is designed to modulate capacities of packet processing engines and of network interfaces, to meet actual traffic loads and requirements. This can be performed by using two power-aware capabilities, namely, dynamic voltage scaling and idle logic, which both allow the dynamic trade-off between packet service performance and power consumption.

Finally, sleeping/standby approaches are used to smartly and selectively drive unused network/device portions to low standby modes, and to wake them up only if necessary. However, since today's networks and related services and applications are designed to be continuously and always available, standby modes have to be explicitly supported with special proxying techniques able to maintain the "network presence" of sleeping nodes/components.

It is worth noting that all these approaches are not exclusive among themselves, and, in the opinion of current authors, research efforts will be needed in all such directions in order to effectively develop new-generation green devices.

The taxonomy of these base concepts for energy efficiency in wire-line networks is reported in Figure 10, while a more detailed analysis of these approaches is discussed in the following.

1) Re-engineering

As previously sketched, re-engineering approaches are devoted to introduce more energy-efficient technologies, and to optimally exploit them inside network equipment architectures, Novel energy-efficient technologies mainly consist of new silicon (e.g., for ASICs, FPGAs, network/packet processors, etc.) and memory technologies (Ternary Content-Addressable Memory (TCAM), etc.) for packet processing engines, and novel media/interface technologies for network links (energy efficient lasers for fiber channels, etc.).

In this respect, the most challenging solution consists in the adoption of pure optical switching architectures [19], which have long been considered the primary candidate for replacing the current electronic based devices. They can potentially provide terabits of bandwidth at much lower power dissipation than current network devices, but their adoption is still far from reality. Current technological problems mainly regard the limited number of ports (less than 100), and the feasibility of suitable buffering schemes.

Focusing on packet processing engines, decreasing feature sizes in semiconductor technology have contributed to performance gains, by allowing higher clock frequencies and design improvements such as increased parallelism. The same technology trends have also allowed for a decrease in voltage that has reduced the power per byte transmitted by half every two years, as suggested by Dennard's scaling law [29].

Fixed the silicon technology, energy consumption largely depends on the number of gates in the forwarding hardware. In general, every cell, block and gate requires power, making a strong case for structural optimization within the forwarding engine. The number of gates is generally directly proportional to the flexibility and programmability levels of HW engines. Simpler and faster packet forwarding silicon achieves the best energy cost per gigabit, but extreme hardware specialization can lead to limitations in feature sets and updatability of network device functionalities [64].

In this respect, general purpose CPUs typically present the worst case with respect to power efficiency, and the best one to flexibility. Recent multi-core CPUs are designed with 45 to 65 nm CMOS technology and can feature over two billion transistors. They are fully programmable and can perform any packet lookup operation in existence, but this comes at a cost of relatively high power consumption. They can forward several gigabits per second within a power budget of 100-150 W for a high-end CPU.

On the other extreme, fully customized silicon for packet forwarding provides the best energy-efficiency, but very low programmability or flexibility levels. However, the high development cost can be ultimately offset with superior scaling and higher energy efficiency. Custom silicon can currently achieve an energy efficiency level equal to about 100 W. This is almost an order of magnitude better than CPU-based platforms.

Between off-the shelf CPUs and fully custom silicon, there are many intermediate solutions featuring a broad array of price/performance ratios and ranging from packet-optimized network processors to fully configurable CPU arrays, where features and instructions can be added or removed at will.

Starting from these considerations, different researchers [32] [85] recently faced the issue of complexity in network device architectures (and in particular in IP routers) by proposing novel clean state solutions and network architectures for the future Internet. Here, the main idea consists of significantly reducing the functionalities of devices that work at core and transport networks, so that high-end routers and switches may be manufactured with a lower number of HW gates.

In this respect, one of the most promising approaches was suggested by Roberts [32]. He proposed a radical new concept for traffic lookup, which allows next-generation routers forwarding traffic at the flow levels. This approach certainly leads to a more scalable and simple network device architecture with respect to the current ones, which forward traffic at the packet level.

With a similar aim, Baldi and Ofek [85] suggest a synchronous time-based IP switching approach, which allows synchronizing the operation of routers and scheduling traffic in advance. Such approach is based on pipeline forwarding concepts, and specifically time-driven switching and fractional lambda switching. This will allow reducing equipment complexity in terms of header processing, buffer size, switching fabric speedup and memory access bandwidth speedup. They additionally propose to adopt different global time sources, freely available on earth and in space, for driving synchronous operations.

2) Dynamic adaptation

Dynamic adaptation approaches are aimed at modulating capacities of network device resources (e.g., link bandwidths, computational capacities of packet processing engines, etc.) according to current traffic loads and service requirements. Such approaches are generally founded on two main kinds of power management capabilities provided by the HW level, namely power scaling and idle logic.

Nowadays, the largest part of current network equipment does not include such HW capabilities, but power management is a key feature in today's processors across all market segments, and it is rapidly evolving also in other HW technologies [33] [34]. In detail, power scaling capabilities allow dynamically reducing the working rate of processing engines or of link interfaces. This is usually accomplished by tuning the clock frequency and/or the voltage of processors, or by throttling the CPU clock (i.e., the clock signal is gated or disabled for some number of cycles at regular intervals). For instance, the power consumption of a CMOS based silicon can be roughly characterized as follows:

$$P = CV^2 f \tag{1}$$

where P is the active power wasted, C the capacitance of CMOS, and V and f are the operating voltage and frequency values, respectively. It is worth noting that V and f are needed to be directly proportional for a correct working of the CMOS silicon. Decreasing the operating frequency and the voltage of a processor, or throttling its clock, obviously allows the reduction of the power consumption and of heat dissipation at the price of slower performance.

On the other hand, idle logic allows reducing power consumption by rapidly turning off sub-components when no activities are performed, and by re-waking them up when the system receives new activities. In detail, wake-up instants may be triggered by external events in a pre-emptive mode (e.g., "wake-on-packet"), and/or by a system internal scheduling process (e.g., the system wakes itself up every certain time periods, and controls if there are new activities to process).

As in general purpose computing systems (see the appendix section), the HW implementation of both idle logic and performance scaling solutions is generally performed by pre-

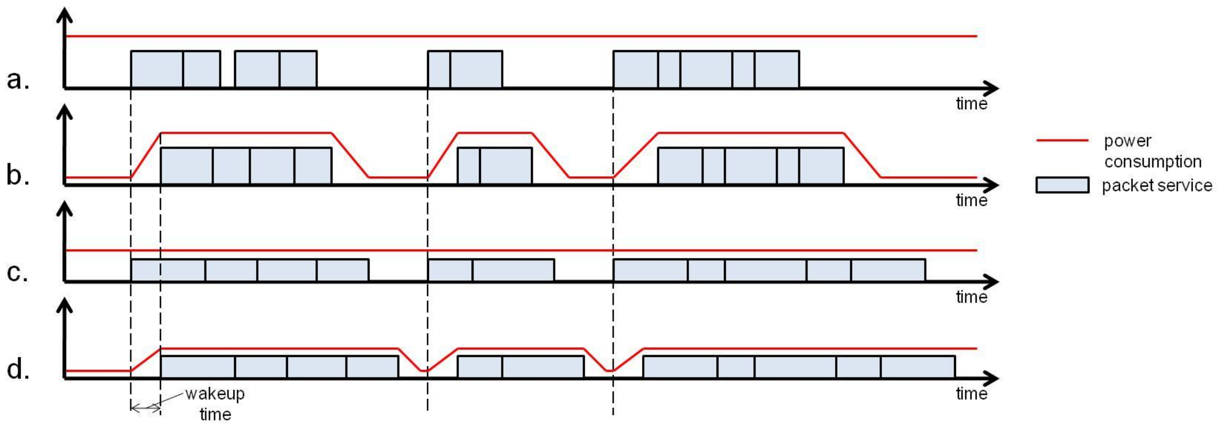

Figure 11. Packet service times and power consumptions in the following cases: (a) no power-aware optimizations, (b) only idle logic, (c) only performance scaling, (d) performance scaling and idle logic.

selecting a set of feasible and stable HW configurations, which provide different trade-offs between energy consumption and performance states. For example, different idle states are usually designed by selectively turning off an increasing number of HW sub-elements. On one hand, this lead to reduce the energy consumption during idle times; on the other hand, larger times are needed to wake up all the HW sub-elements.

In a similar way, performance scaling HW support is designed by pre-selecting a set of operating clock frequencies, whose values are sub-multiple of the maximum one and that provide silicon stability.

Both these energy-aware capabilities can be jointly adopted in order to adapt system performance to current workload requirements, and lead to different trade-off between energy consumption and network performance.

As shown in Figure 11, performance scaling (Fig. 11-c) obviously causes a stretching of packet service times (i.e., header processing time in a processing engine, or packet transmission time in a link interface), while the sole adoption of idle logic (Fig. 11-b) introduces an additional delay in packet service, due to the wake-up times.

Moreover, preliminary studies [69] [111] in this field showed how performance scaling and idle logic work like traffic shaping mechanisms, by causing opposite effects on the traffic burstiness level. The wake-up times in idle logic favour packet grouping, and then an increase in traffic burstiness. On the contrary, service time expansion in performance scaling favours burst untying, and consequently traffic profile smoothing [73].

Finally, as outlined in Fig. 11-d, the joint adoption of both energy-aware capabilities may not lead to outstanding energy gains, since performance scaling causes larger packet service times, and consequently shorter idle periods.

However, the energy- and network-aware effectiveness of idle logic and performance scaling (and their possible joint adoption) must be accurately evaluated by taking HW and traffic features and requirements into account. In this respect, it is worth noting that the overall energy saving and the network performance strictly depend on incoming traffic volumes and statistical features (i.e., interarrival times, burstiness levels, etc.). For instance, idle logic provides top energy- and network- performance when incoming traffic has a high burstiness level. This is because less active-idle transitions (and wake-up times) are needed, and HW can remain longer periods in low consumption state.

Starting from these considerations, Nedevschi [73] firstly proposed to support such energy-aware capabilities (with a special reference to the idle logic) with I/O traffic handling mechanisms, able to shape traffic profiles in order to optimally exploit idle logic and performance scaling. For example, an I/O traffic handling mechanism based on a simple polling policy well suits an optimal use of idle logic.

An optimization policy is generally needed to configure and control the usage of energy-aware capabilities and states with respect to the estimated workload and service requirements. In off-the-shelf computing systems, such optimization policy is usually developed as a SW application, called “governor”.

Regarding the optimization policy, several methods have been proposed in order to estimate the current workload and to optimally control the trade-off between performance and energy consumption in the computing system field. These methods range among predictive techniques [35] and dynamic schemes [36] [37] [38] [39], which were studied for disk drives [40], processors [41] [42] [43], and other components. However, these methods require significant computation to derive the optimal policy and to estimate the current workload, which might not be feasible in all cases.

3) *Sleeping/Standby*

Sleeping and standby approaches are founded on power management primitives, which allow devices or part of them turning themselves almost completely off, and entering very low energy states, while all their functionalities are frozen. Thus, sleeping/standby states can be thought as deeper idle states, characterized by higher energy savings and much larger wake-up times.

The widespread adoption of such kind of energy-aware capabilities is generally hindered by the common aim and design of today’s networking applications and services, which are commonly thought to be fully available all time. In more detail, when a device (or a part of it) goes sleeping, its applications and services stop working and lose their network connectivity. As a result, the sleeping device loses its network “presence,” since it cannot maintain network connectivity, and answer to application/service-specific messages. Moreover, when the device wakes up, it has to re-initialize its applications and services by sending a non-negligible amount of signalling traffic.

In this respect, notwithstanding that PC architectures already include such power management features (allowing desktops and servers to quickly enter sleep and low consumption modes), networking functionalities and applications have often interfered with their effectiveness. This is because of the inability of today's PCs to enter their sleep mode without losing their TCP connections, LAN service broadcasting, etc. This is the main reason why a growing number of networked desktop PCs and servers are continuously left fully powered, even though there is no user demand for their resources most of the time. This is largely because such resources are increasingly shared and must thus be accessible by remote users and other computers 24/7. Moreover, this trend is certainly strengthened by a large part of consumer electronic devices, which are and will be even more “networked” than their PC “relatives”.

Christensen and Nordman directly faced energy efficient enhancements in such kind of scenario [100] [101]. In more detail, their solution to maintain continuous network presence consists of having a network host transfer network presence to a “proxy”, namely Network Connectivity Proxy (NCP), when entering sleep mode [102] [103].

As shown in Figure 11, an NCP is thought to handle ARP, ICMP, DHCP, and other low-level network presence tasks for a network host. An NCP must also be able to maintain TCP connections and UDP data flows and to respond to application messages. Thus, the main objective of such proxy is to respond to “routine” network traffic as the device sleeps, and to wake the device when and only when it is truly necessary.

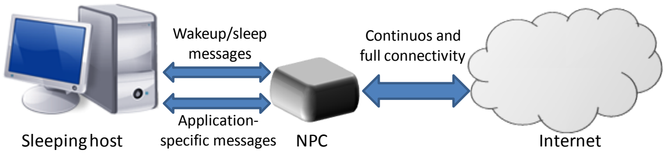

Figure 12. Example of Network Connection Proxy.

In more detail, an NPC and the sleeping device have to exchange two kinds of messages:

- Application-specific: these messages are needed to register sleeping host’s applications and services to the NPC. These messages contain the description of application connections, and of application “routine” messages.
- Wakeup/sleep: these messages are needed to trigger the NPC when the host goes sleeping, or to wake-up the host when the NPC receives a message, whose processing directly requires the host.

As described in section IV.G in more detail, an NPC can be realized as additional functional block of a network interface, of an Ethernet switch, of a third-party server, or of any kind of device near sleeping hosts.

IV. GREEN TECHNOLOGIES AND CONCEPTS FOR NEXT GENERATION NETWORKS

Starting from the high-level research approaches identified in the previous section, the main objective of this section is to show how they can be effectively applied in various real-world network scenarios and technologies.

All current approaches to green networking, partially excepting re-engineering based ones, promise high energy savings at the cost of reducing the network performance. Since network performance indexes have been so far the only yardstick for operators and manufacturers, the proposal of such trade-off may appear odd and hard to accept.

Thus, the current challenge of a large part of researchers involved in this area is to find specific solutions/mechanisms, working with a negligible impact on the network level performance.

Given the high heterogeneity of features, architectures, and operational constraints of protocols and devices working at different architectural layers, the way to develop novel energy saving mechanisms has been, is, and will probably be strictly dependent on the reference network scenario. Consequently, and in order to better discuss the main issues in each field, we decided to organize the description of the most representative research contributions in different sub-sections, each related to a different network type or part.

In more detail, sub-section A reports some representative works regarding the reduction of power requirements in wired access networks and related technologies. Sub-section B introduces green enhancements for the fixed access infrastructures (e.g., access points, base stations, etc.) of wireless and cellular networks. Sub-section C presents a survey related to energy efficient architectures and mechanisms for next-generation routers and switches. Sub-section D reports some interesting network control and traffic engineering criteria that can be adopted to switch off a suitable set of network links and nodes, when the network is lightly utilized. Sub-section E is devoted to the energy-aware extensions proposed for the Ethernet data link protocols. Sub-section F introduces some preliminary works regarding the use of SNMP interfaces for managing energy profiles in network hosts. Finally, Sub-section G explores advanced power saving techniques that can be used for networked terminal hosts.

A. Wired Access Networks

Wired access networks are a very critical scenario for reducing the overall carbon footprint of telcos’ infrastructures, since they represent a large share of network energy requirements (see Figures 5 and 8). Current green networking approaches in this area include the re-engineering of current technologies (e.g., by replacing copper-based technologies with fiber ones to the maximum possible extent), as well as the design of power scaling mechanisms (mainly devoted to design low power idle modes to save energy when the network access is not used).

1) *Re-engineering Approaches*

Recently, Telecom Italia showed in [1] an analysis of the trend in energy consumption for next generation wired access networks, taking into account VDSL2 deployment in FTTx architectures. The paper also focuses on further aspects, such as the need of new standardized environmental classes for active equipment to be hosted in outdoor cabinets, and of possible back-up sources for availability of service.

Based on a model of a typical operator network, [45] and [46] compared the power consumption of different broadband access technologies and architectures, especially DSL, FTTN+ VDSL and FTTH. Even though VDSL power management improves performance, the authors stated that there is still a clear advantage of FTTH with respect to energy efficiency.

Researchers at Aalborg University [44] explored the energy-aware path planning in access networks, in terms of selection of trenches that should be dug up in order to cable-connect the customers with the access nodes. In more detail, they evaluated the potential for using the Cable Trench Problem (CTP) in planning ICT access networks, with particular focus on the FTTH technology. The contribution has been twofold; firstly the authors analyzed the possible cost savings in a large-scale case study, and secondly they looked at the feasibility of solving the CTP exactly. The authors concluded that the concrete savings depend on the costs of cables and trenches; from the results obtained and a realistic ratio between these two costs being in the range of 100, CTP can save around 7% and 20% with respect to the Shortest Path Spanning Tree and Steiner Minimal Tree, respectively.

2) *Power Scaling Approaches*

Alcatel-Lucent researchers [48] faced the power optimization problem in DSL systems. With this aim, they reconsidered the trade-off between dynamic spectrum management and the rate maximization of digital subscriber lines according to a given transmit power constraint of modems. The proposed problem reformulation allows minimizing energy consumption with respect to a minimum rate target. Application of this optimization framework potentially leads to reduce the total power consumed by a DSLAM by a figure between 10% and 20% in ADSL2+.

Shing-Wa *et al.* presented possible implementations of low power idle modes in Optical Network Units (ONUs) for saving energy in Passive Optical Networks (PONs) [49]. Two novel ONU architectures are proposed that can significantly reduce the clock recovery overhead versus current ONU architectures when waking up from sleep mode. Results obtained from analytical models show that current ONUs fail to achieve an effective energy saving under realistic TDM-PON traffic. On the other hand, significant energy savings - namely, more than 50% - are observed when using the two proposed architectures.

ETRI researchers [47] in Korea proposed a novel scheme to reduce the power consumed by a Home Gateway (HG) and the related architecture. The proposed scheme uses sleep and wake-up mechanisms triggered by the presence of real user service traffic on the interface. In more details, the authors proposed a hardware component, namely, the Network Protocol Agent (NPA), with low power consumption. The NPA has to continuously work by controlling the sleep and wake-up instant on the basis of user service traffic detection.

B. *Wireless/Cellular Network infrastructures*

Similarly to the wired access area, also research approaches in wireless/cellular network infrastructures are mainly devoted to re-engineer current device platforms (e.g., access points, base stations, etc.), and to include support for the dynamic adaptation of network resources (and then of power requirements) to the actual traffic loads.

1) *Re-engineering Approaches*

In the last years, specific research activities have been performed in order to reduce the energy wastes of fixed infrastructures of cellular networks (e.g., base stations [50] [51]) and WLAN access points [52] [53]). In more detail, in [50] and in [54], Ericsson proposes innovative methodologies for energy saving from an environmental perspective, and describes specific ideas in improving radio base station efficiency and reducing site-cooling costs.

2) *Dynamic Adaptation Approaches*

For dynamic power management, solutions for wired networks' interoperability with legacy protocols and devices are essential. Widespread adoption of new solutions cannot be expected otherwise. Another factor to consider is that wireless networks mostly operate at significantly lower data rates than wired networks. Correspondingly, the need for buffer capacity can be lower and acceptable latencies can be higher.

Jardosh *et al.* [52] [53] suggest the adoption of resource on-demand strategies for WLANs. Such strategies allow powering on or off WLAN access points dynamically, based on the volume and location of user demand. In more detail, the authors investigated and implemented a specific strategy for high-density WLANs, named SEAR. The obtained results showed that SEAR can reduce power consumption to 46%.

Ajmone Marsan *et al.* [55] [56] investigated energy-aware dynamic planning in the context of UMTS access networks; the main idea is to switch off some access devices during low traffic periods (such as nights), the devices that remain on being in charge of the whole traffic [57].

Louhi [58] suggests that energy consumption of cellular networks can be reduced by improving the efficiency of base station sites and equipment. In more detail, he proposes to shut down parts of the base station during low traffic periods.

C. *Network Routers and Switches*

As far as energy-efficient router and switch architectures are concerned, re-engineering approaches mainly focus on how reducing the complexity of internal architectures, and using more efficient hardware technologies. Here, the main technological issue consists of maintaining the same flexibility and performance levels as today's network devices.

Studies on dynamic adaptation mechanisms propose different solutions (based on both performance scaling and idle logic techniques) for reducing the energy requirements of various internal elements, spanning from network interfaces to packet processing engines.

1) Re-engineering Approaches

An investigation of the potential savings achievable through power-aware network design and routing can be found in [63]. The authors conducted a measurement study of the power consumption of various configurations of widely used core and edge routers. Then, they used these results to create a general model for router power consumption to explore the potential impact of power-awareness in a set of example networks. The achieved results indicate that power consumption can vary by as much as an order of magnitude, and that there may be substantial opportunities for reducing it in the short term.

In a similar way, Juniper researchers identified and characterized some possible green enhancements for next generation routers in [64].

2) Dynamic Adaptation Approaches

Gupta and Singh [59] identified the problem of excessive energy consumption in the Internet, by showing that the energy efficiency of the wired Internet is less than that of a typical 802.11 wireless LAN. Starting from these considerations, they first propose idle logic as the approach to save energy, by examining the impact of selectively putting interfaces to sleep in the implementation of switch protocols and of OSPF and BGP routing protocols.

The same authors [60] proposed to set network interfaces of LAN switches in standby modes during packet inter-arrival times. The next packet arrival time is predicted and, if the time interval is greater than a predetermined value, the interface is powered down. Reductions in power consumption of more than 50% are shown; however, the effect on packet delay is not discussed. Gupta and Singh [61] [62] refined their idea by designing and evaluating a Dynamic Ethernet Link Shutdown (DELS) algorithm that utilizes current technology. DELS leads to significant benefits in energy savings with little noticeable impact on packet loss or delay. The algorithm uses buffer occupancy, the behaviour of previous packet arrival times and a configurable maximum bounded delay to make sleeping decisions. The scheme was evaluated using simulations with inputs generated by a synthetic traffic generator for smooth and bursty traffic.

The results in [62] show that the percentage of total time that a link can be shut down ranges from 40% to 80% for typical LAN traffic conditions. Moreover, the authors also found that the additional packet delay is small enough to be ineffective for the higher-layer protocols.

Researchers at Berkeley [65] propose schemes for power reduction in network switches, namely, Time Window Prediction, Power Save Mode and Lightweight Alternative. These schemes are adaptive to changing traffic patterns and automatically tune their parameters to guarantee a bounded and specified increase in latency. The authors explored the feasibility and the impact on the performance of these schemes in novel switch architectures for buffering ingress packets using “shadow” ports. The proposed mechanisms produced power savings of up to 32% with minimal increase in latency or packet-loss. Moreover, the authors outlined that, in the presence of support of Wake-on-Packet features, shadow ports, and fast transitioning of the ports between their high and low power states, these savings reach 90% of the maximum theoretical savings.

Focusing on network equipment, some of the authors of the present paper [66] [67] [68] proposed a detailed evaluation of the impact of ACPI power management on a SW router data plane, trying to understand and to characterize the trade-off between power consumption and forwarding performance. The same authors [69] extended their approach by exploring the possibilities of using power management techniques in distributed network equipment (including multi-core SW routers and crossbar-based commercial devices), and proposed an analytical framework that can effectively be adopted to optimize power consumption of a network device with respect to its expected forwarding performance [70] [71].

In [72] Mandviwalla and Tzeng addressed the power consumption issue in today’s routers’ linecards, which are generally based on multiprocessor architectures to divide and conquer the network traffic load. In more detail, the authors proposed a simple and yet effective Dynamic Voltage Scaling (DVS)-oriented scheme for energy-efficient operations in such kind of linecards. The achieved results show that, for a given task and a timing constraint, processors in a linecard consume less energy when operating at the same voltage than operating at different voltages. Additionally, the authors derived the optimal configuration for minimal energy consumption in multiprocessor-based linecards and also showed how it can be extended for general-purpose multiprocessor systems.

Nedevschi *et al.* [73] explored the design and evaluation of two forms of power management schemes that reduce the energy consumption of networks. The first one is based on putting network components to sleep during idle times, reducing energy consumed in the absence of packets. The second one is based on adapting the rate of network operation to the offered workload, reducing the energy consumed when actively processing packets. Moreover, they propose the use of smart buffering mechanisms at the interface level, in order to better exploit idle/low power states at the network devices. Nedevschi *et al.* showed that these savings approach the maximum achievable by any algorithms using the same power management primitives. This energy can be saved without noticeably increasing loss and with a small and controlled increase in latency, e.g., 1 ms.

Yamada *et al.* proposed in [74] to reduce the carbon footprint of network equipment by following two main approaches, namely power efficient design and power saving design, respectively. The former is an approach to create a high performance router at low power consumption and the latter is an approach to save wasted power. As far as power efficient design is concerned, the authors worked in multiple directions, like, among others: i) integrating the ASICs/FPGAs and memories of routers; ii) creating a router adopting a scalable central architecture. As a result, the authors claimed to be successful in developing a router with a throughput over 1 Tbps, and with a redoubled efficiency in energy consumption. Regarding power saving design, the authors worked on static performance control, which allows turning off unused ports and modules. Furthermore, they proposed a technology that lowers the frequency of lightly utilized modules to save the wasted power. Running under the low frequency mode, the power efficiency improved by 10-20%.

Other power saving techniques for network devices are also explored in [75] and in [76], where energy efficient architectures for high-speed packet classification are investigated, as well as in [77], which focuses on the energy-aware optimization in network processors.

D. Network and Topology Control

Power saving mechanisms based on network and topology control are currently founded on the extension of traffic engineering and routing criteria to use (see [78] for a recent survey in this field) . In this area, the basic idea is to adapt the network capacity in terms of links and nodes to the actual traffic volumes. Researchers propose to reduce the network energy requirements by switching off unused links and nodes. Thus, the main objective of these studies is to move traffic flows among network nodes in order to find the minimum number of network resources (i.e., links and nodes), guaranteeing the best trade-off between end-to-end network performance and overall power consumption.

1) Dynamic Adaptation Approaches

Neri *et al.* [79] proposed a novel approach to switch off some portions of the UMTS core network, while still guaranteeing full connectivity and maximum link utilization.

The same authors extended their approach in [80] to backbone networks, and faced the problem of defining which is the minimum set of routers and links that have to be used in order to support a given traffic demand. Their main idea is to power off links and even full routers while guaranteeing QoS constraints, such as maximum link utilization. Simple algorithms have been presented to select which elements have to be powered off, and simple scenarios have been considered to assess the proposed heuristics and the achieved energy savings. The approach adopted is to minimize cost or maximize performance, by considering as objective function the total power consumed by the network, while connectivity and maximum link utilization are taken as constraints. After showing that the problem falls in the class of capacitated multi-commodity flow problems, and therefore it is NP-complete, they proposed some heuristic algorithms to solve it.

Neri *et al.* [81] applied their approach to an actual ISP network topology, similar to the one adopted by one of the largest ISPs in Italy, by estimating the power consumption of nodes and links with realistic figures that have been derived from available products. Simulation results in a realistic scenario show that it is possible to reduce the number of links and nodes currently used by up to 30% and 50%, respectively, during off-peak hours, while offering the same service quality.

Tucker *et al.* [82] faced the energy consumption optimization at the network layer, by dynamically shutting off portions of the network, and re-routing traffic in order to meet the expected performance level.

Cardona Restrepo *et al.* [83] proposed a novel energy reduction approach at the network level that takes load dependent energy consumption information of communication equipment into account. With this aim, the authors extended the energy-aware concepts originally proposed by Neri *et al.*, by considering green network nodes capable of adapting their performance to actual traffic load. Provided results show that a reduction in energy consumption – and consequently operational cost – of over 35% can be achieved by applying energy profile aware routing.

Soteriou and Peh [84] face the power consumption issue in interconnection network fabrics, which have been deployed and proposed for a broad range of communication systems – multiprocessor systems, terabit Internet routers, clusters, server blades, and on-chip networks. Interconnection network fabrics have many similarities with wired telecommunication networks. The proposed approach consists in a dynamic power management policy, where network links are turned off and switched back on, depending on network utilization, in a distributed fashion. The authors devised a systematic approach based on the derivation of a connectivity graph, able to balance power and performance in a 2D mesh topology. This coupled with an adaptive routing algorithm guarantees packet delivery. The achieved results show that this approach realizes up to 37.5% reduction in overall network link power with a moderate network latency increase.

E. The Green Ethernet

Ethernet is a well-known dominating technology at the link layer, and it is highly widespread through various standard versions, at both customer and network sides. For example, today a large part of consumer electronic devices include Ethernet interfaces. Such diffusion has attracted the attention of several researchers, since even a marginal reduction in the power requirements of Ethernet interfaces may potentially lead to save a huge amount of energy.

Current approaches in this field include the re-engineering of Ethernet encodings, as well as the development of dynamic adaptation mechanisms, which are currently discussed in the 802.3az task force.

1) Re-engineering Approaches

In [98], some researchers at Berkeley looked at the canonical Ethernet encoded communication problem from a perspective that prioritizes energy. They demonstrated that the encoding circuit energy is much larger than the transmission energy for wired Ethernet. Moreover, the same authors outlined that, in the near future, the encoding circuit energy will likely take an even larger share of the total energy for operating with lower transmission voltage over UTP and for the need of more complex encodings at 10 Gbps and beyond.

The authors found that simpler encodings are more energy efficient, with power savings of around 20% for the best one (i.e., Ethernet MLT-3).

2) Dynamic Adaptation Approaches

The U.S. Lawrence Berkeley National Laboratory is working alongside industrial and academic partners to develop energy efficient solutions for networks in the "Energy-Efficient Digital Networks" project [86] [87] [88]. These activities are strictly related with the ones of the "Energy Efficient Internet" project [89] at the University of South Florida. In such context, as introduced in [90], Christensen and Nordman jointly addressed two efforts, which are specifically targeted to Ethernet networks [91]. The first effort regards the introduction of "Adaptive Link Rate" (ALR) mechanisms [92] [93] [94] in Ethernet data links, while the latter mainly concerns energy efficiency in end-hosts (e.g., networked PCs), and it is discussed in more detail in sub-section IV.G.

As far as ALR is concerned, it is well known that link data rates for wired desktop computers have increased from 10 Mbps to 1 Gbps, which further strains computing system resources. Moreover, within a few years, 10 Gbps Network Interface Cards (NICs) may become standard in desktop PCs.

In this respect, Christensen and Nordman stated that higher data rates require dramatically more power, as increasing energy is being used to transmit small amounts of data most of the time. For instance, a 100 Mbps Ethernet NIC consumes in the order of 1 W, while a 10 Gbps NIC consumes tens of Watts. Thus, ALR is fundamentally conceived in order to adjust NIC speed (and hence power) to effective traffic levels. Moreover, reducing the network link data rate for PCs in low-power states would not affect user productivity. The Ethernet standard already includes auto-negotiation mechanisms, which allow the link data rate to change, but their behavior in today's HW is far too slow to be used for energy efficiency purposes. Therefore, new methods are needed in the Ethernet standard to effectively support ALR, and to quickly modulate link data rates with traffic levels to scale energy consumption with actual service demand. For this reason, Christensen and Nordman worked within the Ethernet Alliance and the IEEE 802 standards committee, to develop this into a standard (the Energy Efficient Ethernet, or IEEE 802.3az [95]). The ALR is already part of the Tier 2 requirements for the Energy Star computer specification [96]. However, the realization of ALR would entail an Ethernet interface having two physical layer implementations and switching between them. The time to switch between different physical layer implementations was deemed to be a major issue resulting in an alternative low power idle approach [97] to be proposed by Intel. Low power idle is the approach specified in the emerging 802.3az standard, and currently allows a 10 Gbps link waking up in less than 3 microseconds.

F. SNMP Green Extensions

In [99], Blanquicet and Christensen proposed, prototyped, and evaluated a new SNMP Power State MIB and its agent to expose equipment power state to the network.

The power state includes all supported power management capabilities, current settings, total and current active, inactive, and sleep times, and statistics on wakeup and sleep events. With knowledge of the power state of network devices, a network manager could remotely audit the energy consumption of IT equipment and make changes to power management settings.

G. End-users and Applications

As outlined in sub-section III.C.3, many end-user devices (e.g., PCs, laptops, etc.) already support power management primitives, like the ACPI. In a large part of cases, these primitives are left disabled, since their adoption collides with applications and services using the network. Here, the basic problem consists in the fact that a device entering standby mode usually loses all its network connections, and it is not able to maintain its network presence (e.g., by replying to heart-beating messages).

Thus, the main objective in this area consists of studying novel paradigms to overcome such limitations, and to support standby states with smart mechanisms for maintaining the network presence of sleeping devices.

1) Smart Sleeping Approaches

As mentioned in section III.C.3), Christensen *et al.* introduced the NPC to maintain the network presence of sleeping hosts. Recently, they evolved the NCP architecture in order to handle P2P traffic of common file-sharing applications [104] [105] [106]. In more detail, while [104] focuses on greening the behavior of BitTorrent clients, in [105] and in [106], the authors proposed a prototype Gnutella-like P2P power management proxy sub-system that handles query messages. This can allow desktop PCs acting as P2P hosts to enter a low-power sleep state for most of the time and be waken-up by the proxy only when needed to serve files. TCP connections with neighbors are maintained by the host when it is awake and by the proxy when the host is sleeping. Christensen *et al.* explored the feasibility and the performance of placing the NCP functionalities both in the PC's built-in network interface, as well as in an external device such as the local network switch, as shown in the prototypic development in [101]. A built-in network interface with NCP capabilities on board is referred to as a "SmartNIC", and it is widely described by Sabhanatarajan and Gordon-Ross [107] [108].

Starting from similar concepts, Agarwal *et al.* [109] proposed and prototyped an architecture, named Somniloquy, that augments network interfaces to allow sleeping PCs to be responsive to network traffic. In this sense, Somniloquy can be thought of as an evolution of SmartNIC architectures, since it allows maintaining the connectivity of a large set of applications (e.g., remote desktop, VoIP, instant messaging and peer-to-peer file sharing) with modest processing and memory resources in the network interface. Moreover, the proposed architecture does not require any modifications to the network and to remote application servers, it can be incrementally deployed on legacy network interfaces, and it does not rely on changes to the CPU scheduler or the memory manager to implement this functionality; thus, it is compatible with a wide class of machines and operating systems. Experiments using the prototype Somniloquy implementation, a USB-based network interface, demonstrate energy savings of 60% to 80% in most commonly occurring scenarios.

Nedevschi *et al.* [110] explored how an energy aware proxy should handle the user idle-time. In this paper, the authors demonstrated that a complex tradeoff exists between balancing the complexity of the proxy, the amount of energy saved, and the sophistication of idle-time functionality. This was achieved through the benchmarking of four different energy-aware proxies, characterized by a growing architectural complexity, in the presence of real traffic traces. Finally, the authors presented a general and flexible proxy architecture, and built an extensible proxy, based on the Click modular Router, that exemplifies one way in which this architecture can be implemented.

Wierman *et al.* suggested in [111] dynamic speed scaling for reducing energy consumption in network end-hosts. In more detail, the authors studied how to optimally scale speed to balance mean response time and mean energy consumption under processor sharing scheduling. The achieved results show that idle/standby optimizations provide nearly the same performance as the optimal dynamic speed scaling. The only key benefit of dynamic speed scaling consists in significantly improved robustness to bursty traffic and mis-estimation of workload parameters.

To conclude and summarize this section, Table I synthesizes all the reported contributions with respect to network segment addressed and undertaken approach.

V. FUTURE RESEARCH TOPICS

Green networking is a relatively new research field, and technologies, approaches and solutions will certainly evolve in the next years. However, thanks to the affinity with other ICT areas that already faced the energy-efficiency issue (e.g., mainly general-purpose computing systems), in the last few years network researchers succeeded in laying the foundations of a greener Future Internet by outlining major research issues and approaches.

Up to now, many topics are still open and will require considerable and widespread efforts from industrial and academic communities.

The following sub-sections try to summarize and to introduce the main future issues on which, in the opinion of current authors, researchers' focus need to be centered.

A. Green Metrics and standard benchmarking methodologies

As a first objective, network researchers and engineers certainly need standard performance metrics, reference benchmarking scenarios and methodologies in order to effectively evaluate and compare different green solutions and mechanisms.

TABLE I – SUMMARY OF UNDERTAKEN RESEARCH EFFORTS PER APPROACH TYPOLOGY AND PER TARGET NETWORK LEVEL

		Wired Access Networks	Wireless/ Cellular Networks	Network Routers and Switches	Network Topology Control	Green Ethernet	SNMP Green Extensions	End-users and Applications
Re-Engineering	Energy-Efficient Silicon	[1][44][45] [46]	[50] [54]	[19] [33] [34] [63] [64] [74] [77]				
	Complexity Reduction			[32] [85] [64]		[98]		
Dynamic Adaptation	Dynamic Voltage Scaling	[48] [49]		[66] [67] [69] [72] [73] [74]	[83]	[92] [93] [94]	[99]	[111]
	Idle Logic	[47]	[52] [53] [55] [56] [58]	[59] [60] [61] [62] [64] [65] [66] [67] [69] [73]	[79] [80] [81] [82] [84]		[99]	[111]
Smart Sleeping	Proxing Network Presence							[100] [101] [102] [103] [104] [105] [106] [107] [108] [109] [110]

Preliminary studies in this respect were carried out by Telecom Italia [26] and Juniper [113], which defined eco-efficiency indicators for evaluating entire telco's networks and single IP routers, respectively. Such indexes generally take into account the long-term ratio between the service delivered (e.g., in terms of bits) and the total energy used by the system under test (e.g., a network, a device, etc.).

Nonetheless, current proposals lack of reference scenarios and methodologies, which would allow evaluating energy-saving with dynamic adaptation and sleeping primitives that certainly will play a central role in the next future.

Focusing on dynamic adaptation approaches, testing methodologies and performance metrics considering different traffic profiles (e.g., traffic burstiness levels) are certainly needed. In this respect, a viable approach may consists in extending existing methodologies, like "back-to-back" tests in the RFC 2544 [112], with green metrics extensions.

B. Green Data/Control planes Abstraction Layer

Significant research efforts have to be devoted to the development of a standard interface (or "abstraction layer") for exposing and controlling the novel green capabilities and functionalities, realized with different typologies of network equipment and of HW technologies, towards "general purpose" control-plane frameworks.

In a similar way with respect to the ACPI standard (see the Appendix) for general purpose computing systems, the main idea consists of creating a kind of middleware, which will hide the implementation details of energy-saving approaches at the data-plane, as well as to provide standard interfaces and methodologies for interactions between heterogeneous green capabilities and HW technologies, on one hand, and energy-aware control applications, on the other hand.

This will be the key for the fast integration and the development of fully capable energy-aware device platforms, including both data-plane green capabilities (i.e., including idle logic, performance scaling and smart sleeping) and control strategies.

In more detail, the realization of a green abstraction layer will require the accurate definition of a synthetic set of energy- aware and performance-aware profiles (i.e., states) and parameters, able to logically represent the different approaches and requirements of such green capabilities. Here, the specific goal is to extend and re-engineer the ACPI standard for computing systems, and adapt it to network equipment architectures, functionalities and paradigms.

C. Green Support for Network Redundancy

A further open issue is related to the energy efficient support of redundant devices, links and internal components, which certainly contribute to the overall carbon footprint of core and metro networks.

Different undertaken approaches [79] [80] [81] simply suggest turning off unused parts of a network. The straightforward adoption of this approach would lead to clear network performance inefficiencies and instabilities. Firstly, the device switching on and off generally requires recovery times that are not compatible with common network resilience requirements [114]. Secondly, switching on and off a device causes network topology changes, and consequent storms of signaling traffic all over the network.

Thus, in the near future, researchers will need to face smarter schemes and solutions able to save energy in redundant HW without causing network inefficiencies. Viable approaches in this specific field may be related to the adoption and the extension of the proxy paradigm (sub-section IV.G): redundant devices, boards and/or link interfaces may be equipped with low-consumption "co-processors", able to maintain the logical state while the device is sleeping. In more detail, such co-processors will have to perform only some basic functionalities (e.g., heart-beating message reply), which are necessary for maintaining device/link presence, and to rapidly wake up the entire device only when really needed.

D. Network/Device Virtualization

Virtualization is one of the primitives that are widely adopted in computing systems and data-centers for reducing the carbon footprint. Today's network equipment already include virtualization primitives, which allow different logical routers from a single physical platform. However, they are generally conceived for being used in VPN-like applications, and do not really permit a complete de-coupling between logical nodes and physical platforms (i.e., a logical router can usually work on a single physical platform, and it cannot be migrated elsewhere).

However, recent studies on router virtualization [115] give the chance of realizing novel virtualization paradigms, which allow logical instances to move among different physical platforms without losing any packets.

In perspective, such kind of primitives can be adopted for adapting the number of switched-on physical platforms with respect to traffic volumes and network requirements. Logical instances, able to migrate among different HW platforms, represent somehow an alternative chance, with respect to the proxy approach, of turning off HW platforms without causing network inefficiencies and instabilities (i.e., since the network presence is usually maintained by logical instances).

In this respect, virtualization primitives, especially if coupled with MPLS and/or WDM traffic engineering capabilities, can be thought of as foundations for novel network-wide and energy-aware control criteria to dynamically re-configure networks and related equipment.

VI. ONGOING RESEARCH PROJECTS

This section provides a survey on ongoing academic and industrial projects that address energy efficiency in network infrastructures. In this regard, sub-section A introduces academic/industrial research projects, while sub-section B describes the most representative industrial initiatives.

A. National and International Projects

In the USA, besides the previously mentioned green projects of Berkeley Labs and of the University of South

Florida, the NeTS-FIND project [118], funded by NSF, explores a style of networking that is termed "selectively-connected". In this paradigm, an end system can knowingly manage the extent of its network connectivity in response to internal or exterior events, as it anticipates changes in connectivity. In this project the researchers undertake initial designs of new architectural components for better supporting selectively-connected networking, by which sleeping hosts can retain their standing in the network or delegate agents to act on their behalf during their absence.

Recently, the authors of the present paper established a partnership with a group of primary device manufacturers and Telcos - Alcatel-Lucent, Ericsson, Lantiq, Mellanox and Telecom Italia, among others – to launch the ECONET initiative [119], an integrated project (IP) funded by the European Commission. The main aim of ECONET is to design and develop innovative solutions and device prototypes for wired network infrastructures (from customer-premises equipment to backbone switches and routers) within 2013. The resulting network platforms will adopt different green network technologies, mainly based on dynamic adaptation and standby primitives, for aggressively modulating power consumption according to actual workloads and service requirements.

The "Design and Analysis of High-Performance, Energy-Efficient, and Secure Clusters" [120] project attempts to address three issues in bottom fashion, starting from the basic cluster components and then proceeding to the entire system. It is planned to design all components to be plugged into the simulation test-bed to assess their impacts on performance.

In Japan, the Ministry of Economic Trade and Industry funded the Green-IT project [121], to develop energy-consumption metrics and energy efficiency standards for networking equipment sold to households and small- to mid-size businesses. Moreover, as shown in [122], the New Energy and Industrial Technology Development Organization (NEDO) has launched several projects in the field of electronics and IT. One example is the project "Development of Next-generation High-efficiency Network Device Technology", which is running from 2007 to 2011 and aiming at developing optical/electronic device technology and related technologies for the purpose of establishing fundamental next-generation high-efficiency networks.

In addition, some other projects funded by the European Union 7th Framework Program (EU FP7), facing research topics related to all photonic equipment, address minor activities towards energy efficiency. Among these projects, we can cite ICT-BOOM [123] and ICT-APACHE [124], which both focus on fully photonic network equipment and components, able to disruptively boost the performance-energy consumption ratio of tomorrow's network devices. However, it is well known that such platforms cannot be rapidly deployed for technical problems in traffic buffering/memory speeds [125].

Regarding low consumption network devices, the EMUCO project [126] addresses a multi-core architecture for mobile devices of tomorrow, in order to get the best ratio of performance and power consumption, while maintaining a high flexibility and scalability in the system through variations in number of cores, cache sizes, clock speeds, etc.

Multi-core platforms are also studied in the MOSART project [127], whose main mission is to define and develop an efficient SW/HW design environment encompassing a flexible, modular, multi-core, on-chip platform, and associated exploration methods and tools, to allow the scaling and optimization of various applications in multimedia and wireless communication.

The AIM project [128] is based on the idea of providing a generalized mechanism of managing power consumption of devices that are either powered on or in stand-by state, by conceiving self-configurable, autonomous mechanisms of achieving this goal. AIM will apply this technology to various home appliances, including communication devices.

B. Industrial Projects

As far as wired network equipment and infrastructures are concerned, many internal initiatives and projects have been undertaken in the last three years in a large part of major ICT companies, triggered by telcos' and service operators' requirements in reducing the energy-related operating costs.

For instance, Cisco launched an innovative energy management architecture, called "EnergyWise" [129], which allows IT operations and facilities measure and fine-tune power usage to realize significant cost savings. EnergyWise focuses on reducing power utilization of all devices connected to a network, ranging from Power over Ethernet devices, such as IP phones and wireless access points, to IP-enabled controllers of building facilities.

Cisco focused also on reducing the power consumption in data centres [130], through the creation of a virtualized community of computing and storage resources, linked with an intelligent network.

The GreenTouch [131] initiative has been promoted by Alcatel-Lucent with the goal to master the technology for future green networks. This initiative has the goal to setup long-term and perspective technologies to achieve a reduction of a factor 1000 with respect to current network power. The ECONET project is addressing similar objectives, even if with narrower scope and shorter-term goals (the ECONET achievements are expected to be deployed in commercial devices in 3-5 years). A further difference between these two initiatives consists in the fact that GreenTouch will focus on all-optical networking systems, while the ECONET project will directly face the reduction of energy consumption also in silicon elements of network devices, as well as in copper-based access technologies (namely, VDSL), which both are expected to be used and deployed in telco networks up to the next 20 years.

The ICT4EE forum [132] was promoted by GeSI, DigitalEurope, JBCE, and Europe TechAmerica to foster a smarter use of technologies that could help other industries and the citizens to cut 15% of global emissions by 2020. Specific objectives of this forum will be both the enhancement of energy efficiency in ICT systems, and the use of such systems to reduce the carbon footprint of other sectors.

IBM launched the Big-Green project in 2007 [133]; this project aims to reduce data centres' energy consumption and transform clients' technology infrastructure into "green" data centres, with energy savings of approximately 42% for an average data centre. Similar projects have been launched by Google and Sun-microsystems.

DLink already produces Ethernet switches with green technologies [134], which allow automatically detecting link status and reduce power usage of ports that are idle, as well as analyzing the length of any Ethernet copper cable connected to them for adjustment of power usage accordingly. Shorter lengths require less power.

In [64] [113] [136] [137], Juniper Networks unveiled its main efforts towards next generation green networks and equipment. On one hand, Juniper suggests novel energy-aware metrics and benchmarking methodologies for evaluating the carbon footprint of network devices. On the other hand, it shows efforts – which are divided in "organic" and "engineered" energy related improvements – in the reduction of the energy requirements of its products. Organic efficiency improvements take energy-aware evolution of silicon circuits and technologies into account, and are commensurate with Dennard's scaling law. Engineered improvements refer to active energy management including, but not limited to, idle state logic, gate count optimization, memory access algorithms, I/O buffer reduction, etc.

VII. STANDARDIZATION ACTIVITIES FOR ENERGY-EFFICIENCY

Different activities towards green technologies standardization have been undertaken by the main standardization bodies (e.g., ETSI, ITU-T, and the IEEE, among others). The following sub-sections describe the most interesting set of green network standards.

A. ETSI activities

A number of documents are still under discussion or revision within the ETSI standardization body [138] [139] [140]. Different interesting issues are under consideration by the Environmental Engineering Technical Body in ETSI:

- The ETSI EN 300 019 series addresses different topics dealing with environmental conditions and environmental tests. A number of documents are under revision, with the possibility of contributing to specifications related to data centres and networking equipment;
- ETSI EN 300 119-3 is dealing with engineering requirements for cabinets;
- ETSI EN 132-3 is exploring novel techniques for power supply interfaces at the input to telecommunications equipment;

Other interesting activities in ETSI regard the following topics:

- o ETSI TR 102 489 is related to thermal management of cabinets and discusses how to increase the efficiency of the cooling system in data centres and telecommunication centres;
- o ETSI TR 102 530 covers various methods of increasing the efficiency of telco systems by controlling/reducing the energy consumption in the TLC network equipment and its related infrastructure
- o ETSI TR 102 532 is devoted to the feasible usage of alternative energy sources in telecommunication installations;
- o ETSI TR 102 533 defines the power consumption limits, the methodology and the test conditions to measure the power consumption of broadband fixed telecommunication networks equipment.
- o ETSI TR 102 614 is discussing aspects related to reverse powering in fixed access networks.

In addition to the previous activities, ETSI ATTM also launched at the end of 2008 a Special Task Force on Efficient Broadband [141] with the objective of producing a number of specifications for the energy efficiency of all segments of the networks (e.g., access networks' equipment, data centres, home gateways and network terminations, etc.).

B. Home Gateway Initiative activities

The Home Gateway Initiative (HGI) launched an internal task force called "Energy Saving" [142] with the objective of setting up requirements and specifications for energy efficiency in the home gateways, starting from a reference architecture depicted in the HGI home gateway residential Profile v1.0. The analysis could also be extended to the Network Termination (NT) used in case of the "2box" solution (NT + service router, possible scenario mainly for FTTH) and to other home network infrastructure devices, and it is well linked with the EU Code of Conduct discussions.

C. ETNO Energy Task Force activities

The ETNO (European Telecommunication Network Operators) Energy Task Force was established in 2004 and is aimed at sharing knowledge and Best Practices, performing benchmarking analysis, and ensuring efficient energy utilization and the reduction of environmental impacts through improved energy management [143].

D. Energy Star activities

As previously introduced in sub-section IV.C, Tier 2 requirements for the Energy Star computer specification [96] already include the ALR mechanism proposed by Christensen and Nordman. Further activities at Energy Star may concern the introduction of mechanisms to support hosts entering energy efficient sleep modes, without losing their network connectivity.

E. EU Code of Conduct and EuP activities

The European Union already published a number of Codes of Conduct covering different categories of equipment, including broadband equipment, data centres, power supplies, UPS. Similarly, the EU "Broadband Communication Code of Conduct" [144] [145] [146] defines and fixes interesting thresholds for the maximum allowed power consumption values of different typologies of broadband access devices in active and standby power modes.

The elaboration of Codes of Conduct is a first step to prepare and stimulate industry in the sense of being compliant to the incoming Directive 2005/32/EC on "Energy using

Products (EuP)" [147], for which a number of additional documents per product category should be produced by the EU in the next years.

The first working plan of "Eco-Design for Energy-Using Products (EuP)" [147], adopted on October 21, 2008, establishes some interesting directives for developing and implementing measures related to stand-by power for network equipment and external power supplies.

F. *IEEE activities:*

Regarding the IEEE standardization bodies, one of the most interesting initiatives is performed by the IEEE 802.3az task force [93], which is studying and standardizing an energy efficient version of the Ethernet protocol [148] [149], based on link rate adaptation mechanisms and power consumption optimization during idle periods.

G. *ITU-T activities:*

ADSL2 and ADSL2+ (ITU-T Recommendations G.992.3 [150] and G.992.5 [151]) already support multiple link rates and power states [152]. ADSL2+ is the recommended technology for home broadband access in the EU. Although VDSL2 [153], the next generation broadband access technology, has less power management capabilities than ADSL2+, the EU Stand-by Initiative [145] [146] has the goal to "trigger action on energy efficiency within standardization" for VDSL2 with the goal of having VDSL2 include the same power management capabilities as ADLS2+ [145].

In addition to these initiatives, ITU-T created in September 2008 a new Focus Group, namely, FG ICT & Climate Change, with the objective of analysing the positive impacts of ICT on other industry sectors and evaluating actions for optimising the power consumption in the ICT world, as well. Four deliverables have been finalized by March 2009: "Definitions", "Gap Analysis", "Methodologies" and "Direct and indirect impact of ITU Standards". The Focus Group has recognized a number of potential gaps in standards which were acknowledged in the various contributions and recapped in the four Deliverables. Therefore, it has identified a number of activities, which – if followed through as a team effort across the ITU and strongly supported and coordinated by ITU management – could lead to greenhouse gas emission savings in line with existing or emerging targets and timescales.

H. *Other standards:*

- CENELEC TC215 launched some activities on energy efficiency of Data Centres and analysis of possible Smart Grid/Smart Metering scenarios;
- ATIS-NIPP-TEE, in the USA, is also working on documents related to energy efficiency for telecommunication equipment, including methodologies for measurement.

VIII. CONCLUSIONS

This paper aimed at providing an up-to-date survey on the current state-of-the-art in energy efficiency for fixed telecommunication networks, both as regards improvements that can be introduced in today's networking equipment and perspectives for the Future Internet.

To this aim, we have explored current data and perspective studies on power consumption for next generation networks. In doing this, we have attempted to identify the main lines of intervention that can be traced from the literature, together with the portions of the network where they can find the most appropriate application. Three base concepts clearly emerge in this sense: i) re-engineering architectural elements of networking equipment; ii) dynamic adaptation of network device resources and network connectivity to traffic load and service requirements; iii) exploitation of sleeping/standby states. These have been correlated with the various levels of application (wired access network, wireless/cellular networks fixed infrastructure, network routers and switches, network topology/connectivity control, green Ethernet networks, green network management, end-user devices), to produce a taxonomy framework were the current approaches in the literature can be classified.

Then, we surveyed in some detail emerging technologies, projects, as well as work-in-progress standards, which can be adopted in networks and related infrastructures in order to reduce their carbon footprint. Our conclusions indicate that future research should mainly address the following aspects: i) green metrics and standard benchmarking technologies; ii) the definition of green data and control plain abstraction layers; iii) green support and management of redundant devices; iv) virtualization of networks and networking equipment.

APPENDIX: THE ACPI STANDARD

In general purpose computing systems, today ACPI provides a standardized interface between the hardware (i.e., the power management capabilities) and software layers (i.e., the governor), which completely hides the different processors' internal techniques to reduce power consumption to the operating systems and SW applications.

The ACPI standard introduces two main different power saving mechanisms, namely performance and power states (P-states and C-States), respectively, which can be individually employed and tuned for each core in the largest part of today's processors.

Regarding the C-states, the C_0 power state is an active power state where the CPU executes instructions, while C_1 through C_n power states are processor sleeping or idle states[1], where the processor consumes less power and dissipates less heat. On the other hand, as the sleeping power state (C_1, …, C_n) becomes deeper, the transition between the active and the sleeping state (and vice versa) requires longer time. For example, as outlined in Table I, the transition between the C_0 and the C_1 states needs just only few nano-seconds, while 50 μs are required for entering the C_4 state.

While in the C_0 state, ACPI allows the performance of the

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[1] Current COTS processors generally include up to 6 C-states. Depending on the processor implementation, each C-state can include further low-energy CPU sub-states.

processor's core to be tuned through P-state transitions. P-states allow modifying the operating energy point of a core by altering the working frequency and/or voltage, or throttling its clock. Thus, using P states, a core can consume different amounts of power while providing different performance at the C_0 (running) state. At a given P state, the core can transit to higher C states in idle conditions. In general, the higher the index of P and C states is, the less will be the power consumed, and the heat dissipated.

TABLE II – INDICATIVE ENERGY SAVINGS AND TRANSITION TIMES FOR COTS PROCESSORS' C-STATES

C-State	*Energy Saving with respect to the C_0 state*	*Transition Times*
C_0	0%	-
C_1	70%	10 ns
C_2	75%	100 ns
C_3	80%	50 µs
C_4	98%	160 µs
C_5	99%	200 µs
C_6	99.9%	unknown

Current multi-core processors generally provide a certain number of feasible C and P states depending on the processor's technology and implementation. Each processor's core can be individually configured for using a pair of C and P states independently of the other cores in the same processor.

Unfortunately, due to issues in silicon electrical stability, the transition time between different P-states is generally very slow (especially if compared with usual time scales in network dynamics): a large part of current CPUs can switch their operating P-state in about 100 ms. Given such large P-state transition times, it is worth noting that any closed-loop policies with tight time constraints (where operating frequencies are throttled at packet- or flow-levels' time scale) are not feasible and cannot be adopted for optimizing power consumption inside network device architectures.

Moreover, the ACPI standard requires specific control applications, namely governors, which are needed to dynamically configure power profiles in terms of C- and P-states through the ACPI standard interfaces. In more detail, the specific objective of such SW governors is to periodically optimize the configuration of ACPI devices with respect to their expected performance and computational load.

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