Power Consumption in Telecommunication Networks: Overview and Reduction Strategies

Willem Vereecken, Ward Van Heddeghem, Margot Deruyck, Bart Puype, Bart Lannoo, Wout Joseph, Didier Colle, Luc Martens, and Piet Demeester, Ghent University

The work described in this article was carried out with the support of the BONE project ("Building the Future Optical Network in Europe"), a Network of Excellence funded by the European Community's Seventh Framework; the IBBT-project GreenICT and the STRONGEST project, funded by the European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement no. 247674.

ABSTRACT

One of the main challenges for the future of information and communication technologies is reduction of the power consumption in telecommunication networks. The key consumers are the home gateways at the customer premises for fixed line access technologies and the base stations for wireless access technologies. However, with increasing bit rates, the share of the core networks could become significant as well. In this article we characterize the power consumption in the different types of networks and discuss strategies to reduce the power consumption.

INTRODUCTION

In the last decade the attention on environment-friendly solutions has drastically increased. Especially due to the debate concerning climate change, every emerging technology is scrupulously evaluated on its carbon footprint. This is also the case for information and communication technologies (ICT). It is estimated that ICT is accountable for 2–4 percent of worldwide carbon emissions. The power consumption during the use phase of the equipment accounts for roughly 40–60 percent of the carbon emissions. By 2020 these emissions are expected to double if no initiatives are taken to reduce this footprint. A significant part of these emissions, about one sixth, is attributed to telecommunication networks [1].

Worldwide, the growth rate of Internet users is about 20 percent per year. In developing countries this growth rate is closer to 40–50 percent. Thus, the share of greenfield deployments in telecommunication networks will be significant. Consequently, emerging technologies need to be evaluated on their environmental impact. Also, ICT is being regarded as a solution with the potential to eliminate about 15 percent of the global carbon footprint [2]. If the sector wishes to realize its ambitions, it will also need to demonstrate that it can reduce its own footprint. Different research efforts analyze the power consumption of telecommunication equipment [3, 4]. Next to the characterization of the power consumption, we also give an overview of the optimization strategies. In [5] the authors suggest the introduction of sleep modes, and [6] suggests component optimization and power management as power saving strategies. However, currently new approaches or variations on the suggested approaches are emerging. We introduce the different network architectures and the design parameters that define their power consumption. Based on these parameters the power consumption is then quantified. We elaborate on approaches for the reduction of power consumption.

NETWORK ARCHITECTURES

Figure 1 gives an overview of the different types of network architectures we consider. We make a distinction between fixed line and wireless access networks and core networks.

ACCESS NETWORK ARCHITECTURE

The purpose of access networks is to provide a connection to users through which they access the Internet. They are usually organized in tree structures. All users are connected to a central office in which the traffic is aggregated and transferred to a core network. This connection is provided through different branches of the tree. Depending on the used technologies, the tree has different aggregation levels at intermediary nodes. In the access networks we distinguish between wireless and fixed line access networks (Fig. 1).

In *fixed line access networks* the user connects through a physical wire. Three main types of technologies are currently used.

First, there is digital subscriber line (DSL), which uses the twisted pair copper cables from the old telephone lines. Several technology flavours exist, varying in bit rate and maximum range. Asymmetric DSL (ADSL) and very high bit rate DSL (VDSL) flavors are best known.

A second technology is coax cable technology on which the Data Over Cable Service Interface

 0163-6804/11/$25.00

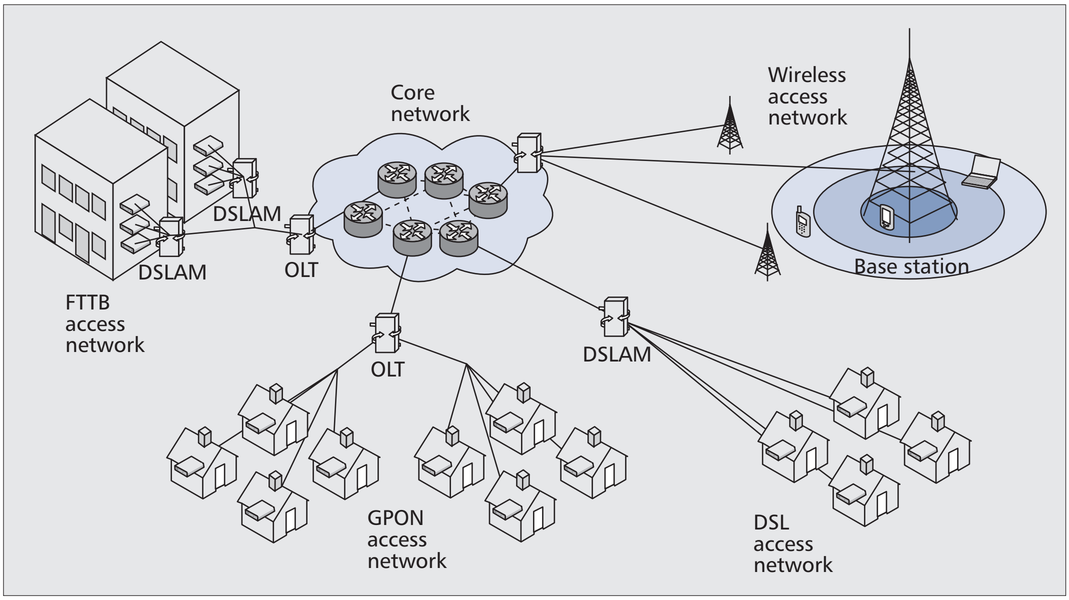

Figure 1. *Network overview.*

In fixed line access technologies the largest power consumer is the home gateway, which can easily be optimized with relatively easy approaches. For wireless access technologies the largest power consumer is the base station.

Specification (DOCSIS) standard is used. These networks are typically built starting from legacy television broadcasting networks.

Presently, optical technologies are emerging. These technologies are already used deeper in the network where higher bit rates are required. At present, optical technologies are starting to appear at the user edge of the network. They are built with either a dedicated connection to the user (point-to-point), an intermediary active splitter (active star), or intermediary passive splitters (passive optical network, PON).

Depending on the offered bit rate and traffic aggregation, the technologies can be used together in an access network. When aggregating the bit rates of VDSL, only optical technologies are able to handle the aggregated traffic load. Therefore, cable access networks are constructed with an optical backhaul and denoted hybrid fiber coax (HFC). Also, optical access networks can be terminated with a VDSL node with limited range and are called fiber to the building (FTTB), fiber to the cabinet (FTTC), or, more generally, fiber to the x (FTTx). Note, however, that FTTx also includes fiber to the home (FTTH), which denotes full optical access networks.

In this analysis we focus on the optical and DSL technologies.

Traffic in the access network is bursty and highly variable. The equipment used in the access network, on the other hand, has a power consumption that is largely constant in time and thus load-independent. Therefore, when evaluating power consumption in the access networks, we consider the power consumption per subscriber as a metric.

ADSL used to be the main access network technology, providing downstream speeds from 8 Mb/s (ADSL) to 24 Mb/s (ADSL2+) and upstream speeds of 1 Mb/s. The maximum range is between 1.5 and 5.5 km. The largest range corresponds with the lowest bit rate capacity. This range allows for large numbers of users to be aggregated in the first node of the access network. Because of this large user aggregation, the power consumption per subscriber of the devices in the backhaul of the access network will be negligible.

VDSL uses an extended frequency spectrum compared to ADSL, resulting in higher bit rates but lower ranges. Consequently, the first aggregation is closer to the user. This also means that a larger backhaul network is necessary, and the power consumption of that backhaul network is more significant.

Optical fiber technologies allow for both higher bit rates and ranges. The bit rate can go up to 10 Gb/s for a single optical fiber with a maximum range between 10 and 20 km. Currently, these bit rates are too high for a single subscriber. Therefore, point-to-point connections are mainly used in the backhaul network to aggregate large amounts of traffic. In active star and PON architectures the bit rate capacity is distributed over large numbers of users. For PONs split ratios of 32 (range = 20 km) and 64 (range = 10 km) are common. The most frequently used standard is GPON (Gigabit PON). Current implementations do not provide large numbers of fiber connections on the optical line terminal (OLT). Usually, between 4 and 72 fibers can be connected.

In *wireless access networks* the user connection is provided through a wireless link. The user's devices use radio signals to connect to a base station, which is then further connected to the central office through a backhaul network. Different technologies are available varying in transmission power, transmission frequency, modulation scheme and multiplexing technique and thus providing different access bit rates to the users.

The three main emerging wireless technologies are mobile Worldwide Interoperability for Microwave Access (WiMAX), high-speed packet access (HSPA), and Long Term Evolution (LTE).

Mobile WiMAX is based on the IEEE 802.16 standard. It operates in the 2–6 GHz band, and

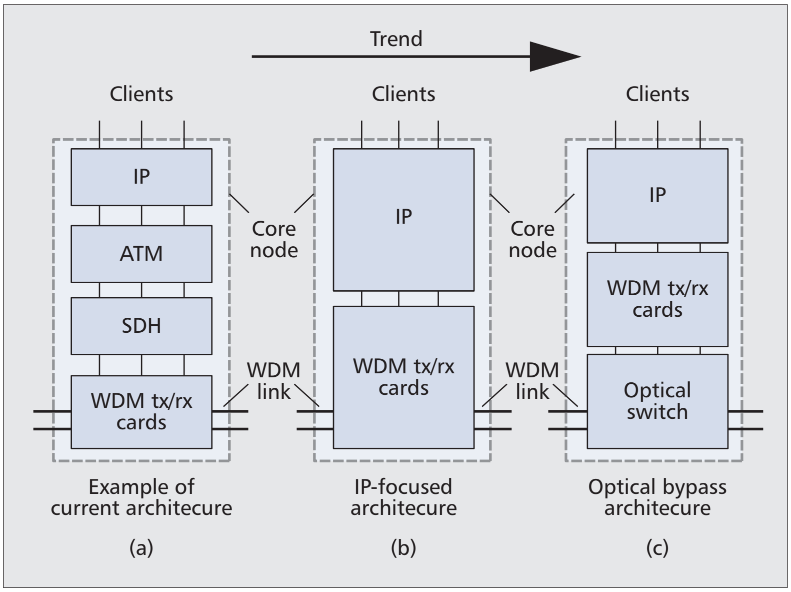

Figure 2. *Core network node architecture.*

is developed for mobile wireless applications and allows people to communicate while they are moving. The highest supported bit rate is approximately 70 Mb/s.

HSPA is the successor of the widely deployed universal mobile telecommunications system (UMTS, also known as third generation [3G]). HSPA provides increased performance by using improved modulation schemes and refining the protocols by which handsets and base stations communicate. The end-user experience is further improved by increasing the peak data rates up to 14 Mb/s in the downlink. HSPA uses the 2.1 GHz band.

LTE is the newest wireless broadband technology. LTE is marketed as the fourth generation (4G) of radio technologies. Targets for the bit rate are to have peak data rates from 10 Mb/s up to 300 Mb/s in the downlink. However, in practical implementations 300 Mb/s rates have not yet been achieved. LTE uses the 2.6 GHz band. However, in the future LTE may use the 800 MHz band.

Contrary to fixed line access networks, the determining factor in wireless access network design is the area covered by the base stations. The covered area is related to the input power of the base station antenna and the bit rate [3]. The input power determines the reach of the signal and thus the area covered by a base station. Current technologies allow different modulation schemes to be used, determined by the signal-to-noise ratio. Therefore, higher bit rates will be achieved at smaller ranges from the base station.

CUSTOMER PREMISES EQUIPMENT

At the customer premises the access networks connect to *customer premises equipment*. For fixed line networks this is usually a home gateway, which then further connects to other equipment such as a notebook or set-top box. For wireless access networks this equipment is more diverse. It can be a mobile phone, a wireless network interface card in a computer, or a home gateway. For wireless technologies we therefore use the more generic term *mobile station.*

CORE NETWORK ARCHITECTURE

Access networks aggregate the users in a certain area. In order to interconnect these areas *core networks* are used. A core network consists of a number of core nodes that are interconnected through wavelength-division multiplexed (WDM) optical fiber links, usually in a mesh or ring topology.

Current core networks are typically a mix of several layers of technologies on top of each other, such as IP-over-ATM-over-SDH (Internet Protocol, asynchronous transfer mode, synchronous digital hierarchy), as illustrated in Fig. 2a. However, there is a trend to move to more homogenous architectures where IP is routed directly over WDM links (Fig. 2b). Given this trend, we focus on the latter architecture only. (Figure 2c will be discussed later).

From a high-level view, core nodes are optical-electrical-optical-based. This means that all optical traffic is converted to the electronic domain and processed by the node, whether the traffic is terminated at this node or not. In general, a node consists of a number of WDM transmit and receive cards, also referred to as transponders or transceivers, which are connected to an IP router. The IP router in turn can be connected to a number of access routers.

WDM fiber links carry a number of wavelengths, each typically having a capacity of 10 or 40 Gb/s. Forty to 80 wavelengths/fiber are common. Optical amplifiers are necessary at intervals of about 80 km to make up for signal attenuation. With the finite range of light paths (depending on the line rate and technology employed, this is on the order of 1000 to 4000 km), long links require regeneration of the optical signal.

QUANTIFICATION OF POWER CONSUMPTION

In this section we quantify the power consumption of the architectures described above. The quantifications in this section are based upon equipment data sheets, own measurements and external literature sources.

FIXED LINE ACCESS NETWORKS

In fixed line access networks each subscriber (Subs) has a dedicated connection. Thus, the power per subscriber is a stable metric. In DSL technologies the last node before the subscriber is the DSL access multiplexer (DSLAM). ADSL equipment consumes 1–2 W/Subs; VDSL equipment roughly consumes 3–5 W/Subs. VDSL equipment power consumption is slightly higher, although trends indicate this technology is being optimized.

Optical network equipment currently consumes 10–20 W/port. However, using GPON technology, this can be further distributed. The OLT consumes 0.2–0.8 W/Subs. Due to the small range of VDSL technology, it is possible that

Technology	Range (km)	Bit rate (Mb/s)	Users/node	Minimal user density (subs/km²)	Power/subs (with PUE) (W/subs)
ADSL ADSL2+	5.5 1.5	8[1] 24[1]	384–768	4–8 50–100	2–4
VDSL VDSL2+	1.0 0.3 0.3	26[1] 55[1] 100	16–192	5–60 50–700 50–700	6–10
GPON (32) GPON (64)	20 10	2488/32 2488/64	(4–72) * 32 (4–72) * 64	0.1–2 0.8–14	0.4–1.6
Mobile WiMAX HSPA LTE	0.340 (3 Mb/s) 0.240 (3 Mb/s) 0.470 (3 Mb/s)	1–70 1–14 1–300	272[2] 225[2] 180[2]	N/A N/A N/A	27[3] 68[3] 18[3]

[1] Downstream [2] Simultaneous Active Users [3] Modelled for 300 subscribers per km^2

Table 1. *Properties of different access network technologies.*

VDSL equipment with a small number of connections are used. For example, for a VDSL DSLAM with 16 connections, the power consumption of the optical backhaul is 0.01–0.05 W/Subs.

When evaluating the power consumption of these devices, one needs to consider that the premises where they are located often need to be cooled. Also, measures are taken in order to prevent power failure. This overhead is expressed in power usage effectiveness (PUE), which denotes the factor by which the equipment power consumption is to be multiplied in order to know the total power consumption (i.e., equipment + overhead). The PUE is typically a factor two. This means that in reality the above mentioned numbers need to be doubled to estimate the full power consumption.

The total power consumptions, including the PUE and delivered bit rates, are summarized for the different technologies in Table 1 and Fig. 3.

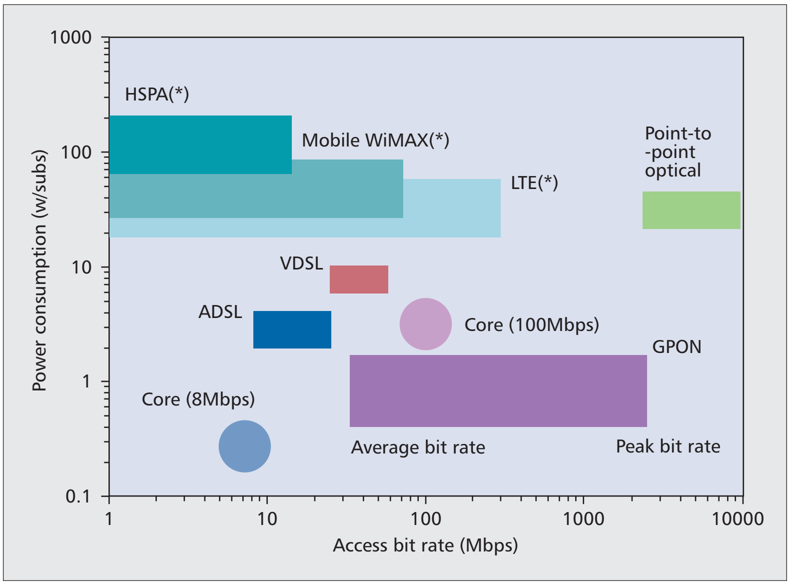

Figure 3. *Power consumption per subscriber of different network technologies.*

Wireless Access Networks

In wireless access networks, the highest power consumer is the base station. The power per subscriber is largely dependent on the subscriber density in the area covered by the base station. Hence, we first evaluate the power consumed per base station and then translate that to the power consumption per user.

A base station is here defined as the equipment needed to communicate with the mobile stations and the backhaul network. For the base stations we assume outdoor placement in a suburban environment at a height of 30 m, covering three sectors, and a mobile station at a height of 1.5 m.

In order to make a fair comparison between the considered technologies, we define a bit rate per active user of approximately 3 Mb/s. We consider the total power consumption of the base station, which includes the PUE overhead.

Mobile WiMAX has the lowest power consumption of approximately 2.9 kW/base station, and a range of 340 m. LTE has the highest power consumption, 3.7 kW/base station, and the largest range, of approximately 470 m. HSPA has the lowest range, 240 m, of all the considered technologies and a power consumption of 3.7 kW/base station, which is comparable to the power consumption of LTE.

In urban and suburban areas it is fair to consider subscriber densities between 100 and 300 users/km^2. When we assume a density of 300 users/km^2 and compare the power consumption per user, we see that LTE performs the best with a power consumption of 18 W/Subs, followed by Mobile WiMAX with a power consumption of 27 W/Subs. The power consumption per user is lower for LTE because of its larger range. HSPA has the highest power consumption per user, 68 W/Subs, caused by its lower range. Note that these numbers are related to the considered subscriber density. When

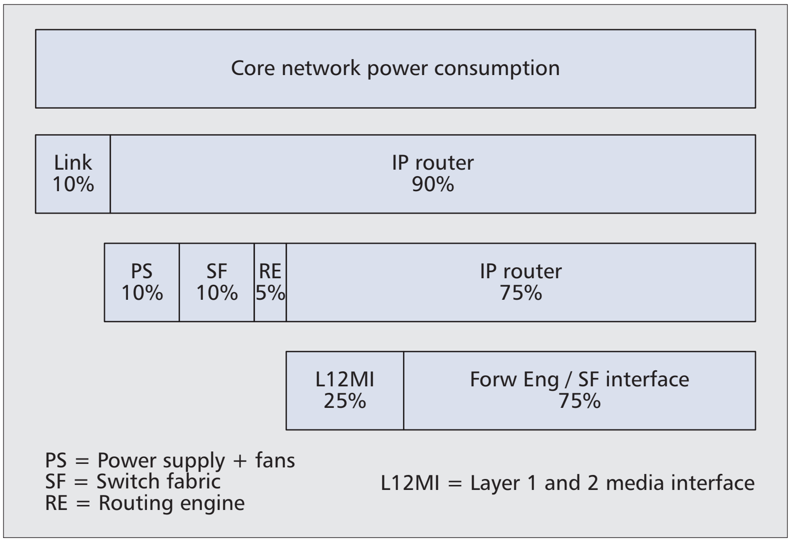

Figure 4. *Generalized core network power consumption distribution.*

we consider half of the subscriber density, the estimated power consumption per subscriber doubles.

For wireless access networks the parameters are also summarized in Table 1 and Fig. 3.

Customer Premises Equipment

Next to the power consumption of the access network, the power consumption of the customer premises equipment is important as well.

At present, for fixed line technologies, the home gateway (e.g., a DSL modem) consumes 5–10 W, which is higher than the power consumption in the access network. Home gateways for optical networks also tend to have higher energy consumption than their DSL counterparts. This is a problem since it can annihilate the potential power reduction benefit of adopting GPON technology. In wireless networks the power consumption of the mobile stations is much lower since these are designed for mobile applications, which require low power consumption for long autonomy times.

Core Networks

As shown in Fig. 4 the major share, about 90 percent, of core network power consumption is concentrated in the nodes. The WDM links, by way of optical amplifiers, make up only around 10 percent or less of the power consumption.

We used datasheets on Juniper T-series core routers to determine the power consumption distribution among the components. The line cards that provide input/output interfaces and apply the packet forwarding logic are the major power consumers. The line cards' layer 1 and 2 media interface provides framing, line speed signaling, and physical connection to a specific network media type such as ATM, synchronous optical network (SONET), SDH, or Ethernet. The purpose of core networks is to transfer traffic streams between different sites. Thus, power consumption in the core network is typically expressed in Watts per transferred bit. Figure 5 plots the maximum power consumption of a number of Juniper routers against their aggregated capacity. As can be seen, high-end routers are more energy-efficient than low-end routers: while consuming more in absolute values, the power required to transfer a bit decreases with increasing router capacity. Current routers consume between 0.1 and 0.01 W/Mb/s. On average, taking into account that near the edge of the core are a higher number of low-end routers, core routers consume about 0.05 W/Mb/s. These values already include a correction for PUE.

In [4] a calculation method is suggested to estimate the power consumption per subscriber of the Internet. Based on this method, we estimate that at ADSL access bit rates (8 Mb/s) the core consumes about 0.24 W/Subs. When accounting for an increase in access bit rate to 100 Mb/s, this will increase to approximately 3 W/Subs. We have indicated these values in Fig. 3. At present, the power consumption in core networks is significantly lower than that in the access network. With increasing bit rates due to the adoption of PON technologies, the absolute power consumption of core networks will increase. However, evaluating the power consumption in Watts per transferred bit, router technologies are expected to become more efficient. This is illustrated, for example, by Cisco's CRS router series, where its most recent member (CRS-3) appears to consume less than half of its six-year-old predecessor (CRS-1). Thus, the figure of 3 W/Subs is an upper bound, which can be lowered by the adoption of power optimized technologies. These technologies are discussed next.

Power Consumption Optimization

Switching Off Components

Presently, telecommunications networks are designed to handle peak loads, and little consideration is given to medium and low load situations. Designing adaptable networks, able to switch off elements when demand is lower, will lead to networks that consume less power.

In core networks this can be achieved with *dynamic topology optimization*. This means from the multiple possible topologies that satisfy the traffic demands, the topologies with lower overall power consumption should be preferred. Dynamic optimization typically exploits the daily or weekly alterations in traffic load, where off-peak volumes are potentially lower than 50 percent of peak volumes. When employing multilayer traffic engineering (MLTE) and changing the MLTE strategy to optimize power consumption, reductions of more than 50 percent during off-peak hours can be achieved [7]. MLTE adapts the topology to optimize power consumption, thereby increasing the number of inactive line cards, which can subsequently be switched off and thus save power.

In fixed line access networks, a similar strategy is possible by using dynamic bandwidth allocation (DBA) in PONs. DBA is currently used as a way to allow users to have increased bit rate while other users on the same medium require lower bit rate. The same strategy could also be used to create dynamically adaptable OLTs, which utilize less ports on which a higher split ratio is applied during periods of low traffic. This allows elements to be switched off in the OLT and leads to reduced power consumption.

In wireless access networks optimization can be achieved by the utilization of *hybrid hierarchical base station deployment*. When using base stations with differentiated cell sizes and wireless network technologies, a basic access network can be created that provides a low bit rate but high coverage to users. In the hierarchical layers above, base stations with smaller cell sizes but higher bit rates can be utilized to provide high-bandwidth connections when these are needed. The advantage is that the higher layers can be put to sleep and only need to be activated with high traffic demand.

For example, LTE-Advanced, the successor of LTE that is under development, will support advanced repeaters. Repeaters are active elements without full base station capabilities. Currently, repeaters are designed as always-on devices. However, in LTE-Advanded the transmission power of these repeaters will be controlled by the network and activated when users are present in the area handled by the repeater.

The WiMAX next-generation standard, 802.16m, includes handover support between femto base stations, which are designed for residential or business environments and may enhance indoor coverage, and macro base stations. They typically have a range on the order of 1 to 10 m.

Finally, it is important to optimize the power consumption of the home gateway. These are individual devices that only need to be active during periods when the user is active. At other times, it can in principle be switched off, although in reality this rarely happens. In legislation concerning standby power consumption standards of 0.5 W are emerging. Implementing this on home gateways will already lead to large optimizations.

Reducing Load

With the idle components in the telecommunication networks switched off, the next step is to reduce the load on the remaining components. This strategy will be especially important in access networks since we already pointed out it is difficult to switch off elements.

Adaptive link rate is a strategy in which different line rates are supported on a link. The lower line rates are assumed to consume less power and thus power can be saved. At the customer premises this can be used to reduce the power consumption of the home gateway. In different access network technologies this strategy is showing potential. However, mainly the higher link rates on the order of 1–10 Gb/s have significantly higher power consumption than lower link rates. Second, the algorithms for adaptive link rate use larger packet buffers. These larger buffers also require hardware that needs to be powered. In core networks it makes less sense to use adaptive link rates since the traffic shows less variation.

In core networks a promising technique to reduce power consumption is *optical bypass*, which is already in use for cost reduction and router capacity offloading (Fig. 2c). Traffic not intended for the intermediate node remains in the optical domain and is not processed by the core router. The light path is switched, using optical add/drop multiplexers (OADMs) or optical cross-connects (OXCs), from an incoming fiber link directly to the appropriate outgoing fiber link. This allows the capacity of the router and the corresponding power consumption to be reduced. Optical bypass is possible at single-wavelength or waveband granularities (requiring less ports in the OXC or OADM since multiple wavelengths are switched simultaniously). Wavelength conversion can be employed to optimize fiber utilization and resolve contention. Depending on light path utilization and network size, the power saving potential of optical bypass is up to 45 percent [8].

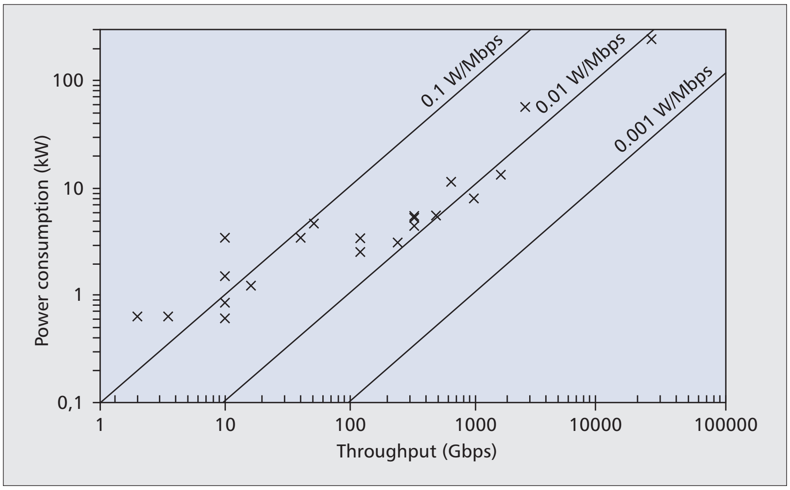

Figure 5. *Power consumption of a set of mid-tier and high-end routers.*

Optimizing Power Consumption of the Remaining Components

When the networks are optimized and the load is minimized, the power consumption of the elements should be reduced.

In next-generation PONs (NG-PONs), OLTs will be designed for higher bit rates (up to 10 Gb/s per port) and higher split ratios (up to 1:128 or even 1:256). Additionally, the range of the signal will be increased, supporting up to 60 to 100 km. In itself, a higher range will lead to higher power consumption per OLT and can require active remote nodes, which add additional power demands. However, in large operator networks there is an ongoing trend of node consolidation, reducing the number of central offices and leading to long-reach access areas. This network consolidation can enable important power consumption reductions.

The energy efficiency of wireless access networks can be improved by increasing the ranges of the base stations. Thus, larger areas can be covered by a single base station, and fewer base stations are necessary. This can be done by the use of multiple transmitting and receiving antennas. This technique is known as multiple-input multiple-output (MIMO). When using, for example, 2 transmitting and 2 receiving antennas (i.e., 2 × 2 MIMO), the range increases by 66 percent, *In wireless access networks many optimizations can still be implemented. At present, in core networks the power consumption is relatively low. Nonetheless, due to the expected increase in traffic volumes, power optimizations are welcomed here as well.*

while the power consumption increases only by 2 to 4 percent, resulting in higher energy efficiency. In the next-generation technologies, LTEAdvanced and WiMAX 802.16m, up to 8 transmitting and 8 receiving antennas can be used.

The technique of optical bypass illustrated an evolution from point-to-point WDM networks to more optical circuit-switched networks. *Optical burst switching* and *optical packet switching* take this technique further and are supposed to provide even finer switching granularity. In optical packet switching, individual packets are switched optically on the correct outgoing fiber. Since optical buffers of an appropriate size are currently infeasible, optical burst switching is proposed as an intermediate technology. A control signal is sent in advance of the packets, allowing the burst-switched router to set up a lightpath for the data, thus eliminating the need for buffering.

While optical packet switching can lead to low power consuming solutions since it eliminates power-hungry opticalel-electrical-optical conversions, it is not yet technically feasible [9]. On the other hand, it is argued that with the line card buffers and switch fabric, the two main candidates for optical implementation, consuming only about 15 percent of the total power consumption of an electronic router, potential energy savings are not as high as commonly expected [10]. A hybrid approach in which optical switches still use electronic buffering seems a more feasible low-power approach for the next decade.

It is not yet clear if the technique of optical burst switching is a viable alternative, the main issue being the relatively low throughput requiring an overbuild.

For continent-sized core networks, increasing the maximum optical path length (i.e., not requiring regeneration of the optical signal) can reduce power consumption. For a pan-European network, savings could be up to 10 percent.

Conclusion

The number of Internet users is fast increasing, and these users demand increasing bit rates. Meanwhile, the carbon footprint of ICT has to be reduced. Saving power in telecommunication networks is becoming an important challenge. Emerging technologies can lead to reduced power consumption, but the design of these technologies needs to be applied with low power consumption in mind. This means switching off components where possible, reducing the loads on the networks, and optimizing the power consumption of the network elements.

Currently, the main share of that power consumption lies near the customer. In fixed line access technologies the largest power consumer is the home gateway, which can easily be optimized with relatively easy approaches. For wireless access technologies the largest power consumer is the base station.

In fixed line access networks power consumption optimization is focused on the technology shift toward full optical networks. In particular, PONs provide low power consumption and are still being optimized. In wireless access networks many optimizations can still be implemented. At present, in core networks the power consumption is relatively low. Nonetheless, due to the expected increase in traffic volumes, power optimizations are welcomed here as well.

References

[1] M. Pickavet *et al.*, "Worldwide Energy Needs for ICT: The Rise of Power-Aware Networking," *2nd Int'l. Symp. ANTS '08*, Dec. 2008, pp. 1–3.

[2] M. Webb *et al.*, "Smart 2020: Enabling the Low Carbon Economy in the Information Age," The Climate Group, tech. rep., 2008.

[3] M. Deruyck *et al.*, "Power Consumption in Wireless Access Networks," *Euro. Wireless Conf.*, Lucca, Italy, Apr. 2010, pp. 924–31.

[4] J. Baliga *et al.*, "Energy Consumption in Optical IP Networks," *J. Lightwave Technology*, vol. 27, no. 13, July 2009, pp. 2391–2403.

[5] M. Gupta and S. Singh, "Greening of the Internet," *SIGCOMM '03: Proc. 2003 Conf. Apps., Technologies, Architectures, and Protocols for Computer Commun.*, New York, NY, USA: ACM, 2003, pp. 19–26.

[6] K. Christensen and B. Nordman, "Reducing the Energy Consumption of Networked Devices," IEEE 802.3 tutorial, 2005.

[7] B. Puype *et al.*, "Power Reduction Techniques in Multilayer Traffic Engineering," *11th Int'l. Conf. Transparent Opt. Net. 2009,* July 2009, pp. 1–4.

[8] W. Van Heddeghem *et al.*, "Energy-Efficiency in Telecommunications Networks: Link-by-Link Versus End-to-End Grooming," *ONDM '10*, Kyoto, Japan, Feb. 2010.

[9] S. Aleksic, "Analysis of Power Consumption in Future High-Capacity Network Nodes," *IEEE/OSA J. Opt. Commun. and Net.*, vol. 1, no. 3, Aug. 2009, pp. 245–58.

[10] R. Tucker *et al.*, "Evolution of WDM Optical IP Networks: A Cost and Energy Perspective," *J. Lightwave Tech.*, vol. 27, no. 3, Feb. 2009, pp. 243–52.

Biographies

WILLEM VEREECKEN (Willem.Vereecken@INTEC.ugent.be) received his M.Sc. degree in electrotechnical engineering from Ghent University, Belgium, in July 2005. He is a Ph.D. student with the INTEC Broadband Communication Networks (IBCN) research group in the Department of Information Technology at Ghent University/Interdisciplinary Institute for Broadband Technology (INTEC UGent/IBBT). His research is funded by a Dehousse Ph.D. grant. His main research interests are the environmental impact of ICT systems and the design of energy-efficient network architectures.

WARD VAN HEDDEGHEM received his Master's degree in applied engineering electromechanics from Hogeschool Gent, Belgium (1999), and his M.Sc. degree in computer science engineering from Vrije Universiteit Brussel, Belgium (2009). He is a Ph.D. student in the IBCN research group at INTEC UGent/IBBT. His research interests are in the environmental impact of ICT and energy-efficient network architectures.

MARGOT DERUYCK received her M.Sc. degree in computer science engineering from Ghent University in July 2009. Since September 2009 she has been a research assistant in the Wireless and Cable (WiCa) research group at INTEC UGent/IBBT. Her scientific work is focused on green wireless access networks with minimal power consumption and minimal exposure of humans.

BART PUYPE received his M.Sc. degree in electrotechnical engineering in 2002 and a Ph.D. degree in 2008 from Ghent University. He is working as a researcher in the IBCN research group at INTEC UGent/IBBT. His main interests are in the field of communication networks, focusing specifically on the design and evaluation of multilayer IP-over-optical networks.

BART LANNOO received his M.Sc. degree in electrotechnical engineering from Ghent University in July 2002. He received his Ph.D. degree in May 2008. Since August 2002 he has been working with the IBCN research group of the Department of Information Technology at INTEC UGent/IBBT, where he is a postdoctoral researcher in the field of fixed and wireless access networks. He is currently active in the European projects ICT-ALPHA and ICT-OASE.

WOUT JOSEPH [M'05] received his M.Sc. degree in electrical engineering from Ghent University in July 2000. In September 2000 he became a research assistant and postdoctoral researcher in the WiCa research group at INTEC UGent/IBBT. Since October 2009 he has been a professor in the experimental characterization of wireless communication systems. His professional interests are electromagnetic field exposure assessment, propagation for wireless communication systems, antennas, and calibration.

DIDIER COLLE [M'01] received his M.Sc. degree in electrotechnical engineering (option: communications) from Ghent University in 1997. Since then, he has been working as a researcher in the IBCN research group at INTEC UGent/IBBT. His research led to a Ph.D. degree in February 2002. His work focuses on optical transport networks to support the next-generation Internet. He has been involved in several European projects like NOBEL, LASAGNE, and TBONES, and COST actions 266 and 291.

LUC MARTENS [M'92] received his M.Sc. degree in electrical engineering and his Ph.D. degree for his research on electromagnetic and thermal modeling and the development of measurement systems for that application from Ghent University in 1986 and 1990, respectively. Since January 199, he has been responsible for research on experimental characterization of the physical layer of telecommunication systems at INTEC UGent. Since April 1993 he has been a professor of electrical applications of electromagnetism.

PIET DEMEESTER [M'89, SM'98, F'09] received an M.Sc. degree in electrical engineering and a Ph.D. degree from Ghent University in 1984 and 1988, respectively. In 1992 he started a new research activity on broadband communication networks resulting in the INTEC IBCN research group. In 1993 he became a professor at Ghent University, where he is responsible for research and education on communication networks. His research focuses on several advanced research topics: network modeling, design, and evaluation; mobile and wireless networking; high-performance multimedia processing; autonomic computing and networking; service engineering; content and search management; and data analysis and machine learning. This research resulted in about 50 Ph.D.s, 1250 publications in international journals and conference proceedings, 30 international awards, and 4 spin-off companies.