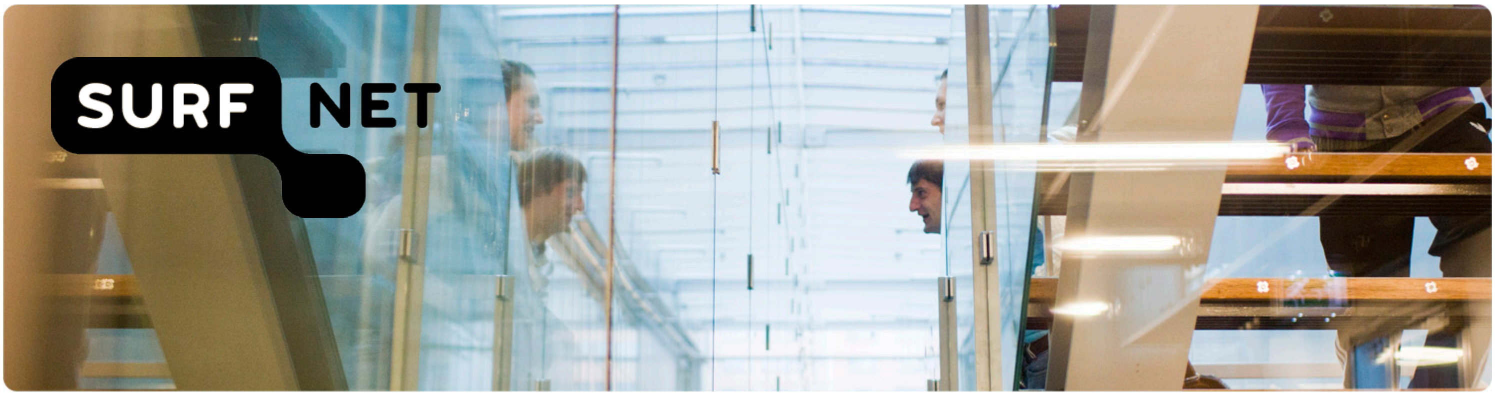

Sustainability in networks

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Contents

1 Introduction

With the growing connectedness of people and things, ICT networks are an important part of our daily lives. This pervasiveness of ICT leads to an increasingly significant footprint. To offer ways to reduce energy consumption, this document describes current and future energy efficient solutions for information and communication networks. Starting with a general section on sustainability and ICT followed by a taxonomy of solutions (section 3), the bulk of this document consists of solutions that can be applied to core and access networks (section 4). Finally, these solutions are mapped on possible ways of reducing energy consumption in NREN and campus networks in section 5.

2 On Sustainability and ICT

Creating a low carbon sustainable society is one of the great challenges of the 21st century. Current climate change is caused by human behaviour [1] and to keep our planet from heating up too much, we need to drastically cut Green House Gas (GHG) emissions (i.e. climate mitigation). The basic strategy for doing so is to electrify our activities, minimize the energy consumption and power these activities through the use of renewable energy. In addition, it might also make sense to be prepared for the impact current and future climate change have on our activities (also called climate adaptation or climate preparedness). In this document, the focus is on the role of ICT in climate mitigation, specifically information and communication networks. So far there has been very little research on the role of ICT in climate adaptation, but that is expected to change in the coming years.

The scientific advances in computer technologies and the widespread use of telecommunication have made information exchange virtually free and independent of geographical distance. Being able to exchange information freely and perhaps more importantly, automatically are currently important drivers for efficiency gains (time, money). It is therefore no surprise that many innovations in products, services, processes, etcetera, have an important ICT component. In other words, ICT is everywhere and everything is becoming connected. While it is true that ICT solutions are generally viewed as environmental friendly solutions – mainly because ICT can substitute for more physical based solutions that have a larger environmental impact; think videoconference instead of travel, e-commerce, etc. – we must not forget the impact ICT itself has.

Currently, the global impact of ICT on GHG emissions is roughly considered to be 2% of total emissions [2], while it consumes more than 8% of total electricity [3]. ICT's piece of the pie is expected to grow, since ICT emissions will grow faster than total global emissions. While this cannot be directly translated into GHG emissions, Greentouch predicts that ICT energy consumption is going to double in the next decade [4].

In the past years work on Green ICT has mainly focused on reducing the energy consumption of datacentres. Since datacentres are highly concentrated ICT sites, consuming lots of energy not only for ICT equipment itself but also for keeping a stable environment through cooling and UPS equipment. However, datacentres are responsible for only roughly 20% of the total impact of ICT, whereas the rest of the impact is mainly caused by end users devices (60%) and networks (20%) [5]. It is also likely that this division will change in the near future, since more devices are expected to be connected all the time (Internet of Things) and given a shift to cloud services. These two trends combined will result in a massive increase in the use of wireless and mobile access networks and especially the mobile access networks are currently critically energy inefficient.

In a recent report by the Centre for Energy-Efficient Communications, at the University of Melbourne-based research centre claimed that by 2015, the energy used to run data centres will be a "drop in the ocean", compared to the that of networks used to access cloud services. The report predicts that by 2015 energy consumption associated with networks will reach 43 terawatt-hours, compared to 9.2 terawatt-hours in 2012. This is an increase in carbon footprint from 6 megatonnes of CO2 in 2012, up to 30 megatonnes of CO2 in 2015, which is the equivalent of an additional 4.9 million cars on the road, the report states [6].

Looking at the general energy consumption of ICT networks, we should consider three factors that impact change in absolute consumption: increased number of devices, increased demand for bandwidth and increased energy efficiency. Key metrics here are total consumption, energy use per device and energy use per bit. Given the last metric, we need to determine whether the general push towards faster networks is enough to compensate the ever-increasing demand from more devices.

Based on projections on the shift to cloud services and data-intensive services such as high quality video, traffic is expected to grow more than 40% annually, doubling roughly every two years [7]. So far this has not been matched by technological advances in network equipment: the efficiency of network equipment is projected to improve by 10-20% annually, doubling every 4-7 years [8]. This means that we need more and more powerful network equipment to handle the increased traffic demand, leading to more energy consumption. Indeed, whereas energy consumption of devices is currently not a high priority for most network operators, it is expected that this will change in the near future, mirroring the path of datacentre operators.

Current networks are designed to optimize capacity and speed. They are not designed for energy efficiency on multiple levels: from components and hardware to network architecture and management – energy efficiency is not part of the mind-set. This results in an environment in which devices are always on and where they consume energy regardless of the load. However, given the growth described above, the mind-set will need to change with the application of a variety of techniques to change networks from ‘always on’ to ‘always available’.

3 Taxonomy of green network solutions

The basic (IP) network infrastructure can be divided into three mayor components: the access network, the metropolitan and edge networks and the core network. The access network can be further divided into wireline, local wireless and mobile wireless access networks.

A core (or backbone) network usually refers to the central part of a telecommunication network. The core network connects primary nodes, typically connecting large cities in a nationwide network to allow for long distance communication and is connected to other core networks. They usually have a mesh typology, carrying large amounts of traffic. Traffic is collected (and distributed) in the metro and access networks.

Metropolitan and edge networks are regional networks, typically covering cities. Their main purpose is to aggregate outgoing traffic from and disperse incoming traffic to organizations and users. They are either directly connected to large organizations or connected to access networks that are responsible for individual consumer traffic. Different networking technologies are deployed across the world with SONET (Synchronous Optical Networking), Optical WDM ring, and Metro Ethernet as the three dominant technologies.

Access networks are also referred to as the “last mile”. They usually connect end users to a central office, which in turn is connected to a metro or core network. Access networks comprise the larger part of the telecommunication network and are responsible for a large part of global network consumption due to the presence of a huge number of active elements. There are different kinds of access networks, each with different technologies: wireline (xDSL, Cable Modem, FTTx), local wireless (WiFi/WiMAX, WOBAN), mobile (Radio Access Networks or RAN – 3G, LTE, 5G).

Most green network solutions are developed for either core networks, wireline/wireless access networks and mobile access networks. Metro networks are hardly mentioned in green networking solutions, probably because solutions in core and access networks can also be applied to metro networks. In this document we will focus on core networks and wireline/wireless access networks (henceforth access networks).

We further divide the solutions into the categories: Equipment, Routing, Architecture, Application and User Behaviour. The first category Equipment refers to solutions that optimize energy efficiency for individual devices. The second category Routing refers to algorithms and protocols that make use of knowledge of energy consumption of individual devices. Architecture, thirdly, is made up out of solutions considering network design, topology and deployment of devices. The final category of applies to solutions that combine network energy efficiency with something outside of the network domain, mainly applications and users. Mapping these categories upon the core and access network results in a matrix of solutions that will be described in the next section.

4 Examples of green network solutions

This section describes a matrix of green solutions that can be applied to telecommunication networks in general. In the next section we will map these solutions onto NREN and campus networks to see how these apply to those specific network types.

This is not an exhaustive list of solutions but it is our hope that we provide enough examples to inspire our readers to apply similar techniques to their own networks. Do note that it cannot be assumed that all solutions lead to energy efficiency per se. These gains depend on the context in which they are applied: different equipment, different network designs will lead to different gains.

All examples presented here are solutions, which can reasonably be applied by network operators. This means that physical changes in network devices (e.g. type of material used, component design) are excluded.

Core network	
Equipment	- Optical switching - Line card / chassis configuration
Routing	- Energy-aware routing - Green routing - Cross-network energy-aware routing - Multipath routing
Architecture	- Pipeline forwarding - Mixed line rates - Redundancy and sleep mode - Maximum path length
Application and user behaviour	- Follow-the-sun/follow-the-wind
Access network (wireline & wireless)	
Equipment	- Adaptive link rate - Low power idle & Energy Efficient Ethernet - Sleep mode - Network connectivity proxy
Routing	- Bit interleaving PON - Burst mode operation
Architecture	- Passive optical networks - Virtual home gateway - Long reach access - Dynamic bandwidth allocation
Application and user behaviour	- Green BitTorrent - Datacenter networking

4.1 Core Network

4.1.1 Equipment

Optical switching [9] [10]

Current network traffic is in principle either directed by optical equipment or electronic equipment. In general, optical equipment offers higher speed; electronic equipment offers more flexibility. Especially at higher bandwidths, optical equipment becomes more energy efficient in terms of energy per bit. In addition switching between these types of equipment consumes energy as well. Eliminating the need of electronics at intermediate nodes and thus optical-electrical-optical (O/E/O)-conversions can significantly reduce power consumption. Pure optical switching can be fairly easy done at the circuit level by directing wavelengths to their destination (also known as optical bypass). However, dedicating a full lightpath to individual nodes suffers from scalability and efficiency since these nodes usually do not require as much bandwidth as offered by wavelength channel capacity. Aggregation is then needed to avoid dedicating a wavelength to a single source-target pair leading to severe bandwidth waste.

Optical Packet Switching (OPS) allows a network to switch at packet level instead, offering much higher granularity and flexibility (similar to electronic switching). This is not yet a commercialized technology however, since OPS faces a number of challenges. An important challenge is optical buffering, which is of too small size to prevent congestion and significant packet loss.

An intermediate solution is Optical Burst Switching (OBS) where IP packets are aggregated into larger optical bursts. This essentially pushes buffers to the edges of the network, reducing the need for larger buffers at central locations. The offset of OBS is that edge routers are more complex and thus require more power (although core routers might become less complex).

Line card / chassis configuration [11]
Line cards, large Ethernet switches and chassis of core routers are the heavier users of energy in core networks compared to other network equipment. Different fill levels of the chassis result in different energy consumption. Mostly empty chassis (i.e. without line cards) still consume large amounts of energy so the higher the fill levels the more energy efficient the network equipment will be (as a general principle). However, careful consideration of bandwidth capacity offered by line cards and actual bandwidth demand is also required. While higher speeds offer more energy efficiency per bit, this might not necessarily be true in the absolute sense.

4.1.2 Routing

Energy-aware routing [12]
When network equipment is energy aware, it becomes possible to adjust routing schemes to optimize the energy efficiency of traffic. Energy-aware routing can be used to minimize the number of nodes or active devices required in the network and turning the unused nodes off or to optimize energy efficiency per node (while avoiding local optima), making use of different modes of operation in the network equipment (e.g. adaptive line rate or low power idle).

Energy-aware routing can for example be achieved by making use of the multilayer traffic engineering (MLTE) technique, originally used for optimizing topologies for costs or quality of service. MLTE allows for optimized routing and logical topology adaptation by creating a virtual full mesh IP layer and calculating the most energy-efficient path. Traffic is groomed and rerouted, after which the topology can be adapted to remove unused edges and switching those off.

Energy-aware routing techniques create the possibility to switch off idle network elements when traffic load decreases, while maintaining quality of service. There are a number of approaches to switch off nodes, for example:

- when a node is not used at all;
- when traffic through the node drops below a certain threshold;
- after proactively rerouting traffic (e.g. because total network traffic is low).

Each approach has consequences for network management so one should always be aware of the trade-off between energy savings and extra management efforts.

Green routing [11]
An extra dimension to energy-aware routing can be added if network nodes are aware of the source of their energy: be they renewable or not. Routing schemes can then be optimized to use as much renewable energy as possible, while keeping energy consumption as low as possible. Note that the balance of priority here may lead to lower GHG emissions but not necessarily lower energy consumption compared to other routing schemes.

Cross-network energy-aware routing [13]
While energy-aware routing is focused on routing within one network, there has not been attention for cross-network optimization. Usually, Internet traffic crosses multiple networks, each having their own routing strategies. Or, because of global collaboration, large amounts of research data is also often transported over multiple research and education networks. In order to truly optimize energy efficiency of these networks, routing techniques should be able to handle reasoning across networks.

One possible way to do so is to use the perfSONAR framework, used for other multi-domain monitoring, to monitor and communicate energy consumption indicators of network nodes (aka GreenSONAR).

Multipath routing [14]
Another design choice in routing schemes concerns the routing of the traffic demands: single-path vs. multipath routing. Adopting multipath routing requires that each traffic demand is split into several sub-demands routed independently, potentially following different paths from the source to the target node. This allows for more effective traffic grooming, resulting in fewer network interfaces and as a consequence in lower network energy consumption. Savings made by multipath routing depend on the combination with other energy saving techniques and are likely significant only for low traffic load.

4.1.3 Architecture

Pipeline forwarding [15]
Pipeline forwarding is a circuit-switching technique to transport predictable Internet traffic in a more energy efficient way on a separate network. Since a lot of the Internet traffic growth comes from predictable services (such as video) one can reduce complexity (e.g., header processing, buffer size, switching fabric speedup and memory access bandwidth speedup) by synchronizing router operation and advanced traffic scheduling.

In Pipeline forwarding IP packet switches are synchronized and use time frames (TF) as a virtual container for IP packets. These TF are forwarded to a predetermined set of destinations and all IP packets in one TF share the same destination. This technique works well in combination with localized content storage of large content providers. The bulk of Internet traffic is predictable and can be transported in TFs over these pipelines on a separate network as “super highways”. This “super highways” network can coexist next to the current Internet and optimizes energy efficiency for these predictable traffic streams.

Mixed Line Rates [16] [17]
Future networks will likely support mixed line rates over its links. Adjusting bandwidth capacity to what is required by individual users/lines can result in significant energy savings compared to single line rate networks. Networks with mixed line rate capacity are also called Elastic Optical Networks (EON).

EON can bring significant advantages in terms of energy efficiency thanks to the variable light path capacity and the adaptive modulation formats. The finer granularity allows a better adjustment of the allocated capacity by expanding or contracting the channel bandwidth according to the actual user demand, whereas the adaptive modulation enables the choice of modulation format according to the demand and distance, thus minimizing the number of regenerations in the network. Furthermore, EON also improves the spectral efficiency which has also an impact on the energy efficiency of the network.

Redundancy & sleep-mode [14]
As network connectivity and the Internet have become indispensable in our daily lives, the fear of losing connection becomes greater. This results in networks that are made redundant, doubling or tripling connectivity paths just to make sure everything and everyone stays connected. Some networks only use the extra equipment in emergency situations and these are thus idling most of the time. These are obvious targets to put into sleep mode. In addition, protection and redundancy strategies and designs can also be optimized to maximize the number of sleeping devices.

Maximum path length [18]
Large networks should design their optical paths in such a way that the number of required regenerations is minimized. For continent-sized core networks, increasing the maximum optical path length in this way can reduce power consumption up to 10%.

4.1.4 Application and User Behaviour

Follow-the-sun/follow-the-wind [19]
Cloud services are in general run on virtual machines in datacentres, which are consumers of enormous amounts of energy. In order to minimize the footprint of their own behaviour, users of these cloud services might prefer datacentres powered by renewable energy. As renewable energy from solar and wind is not always available, single datacentres cannot guarantee green cloud services (although there are of course renewable energy sources, such as geothermal, that are always available). However, when service providers make use of multiple datacentres across the globe, moving these cloud services around to wherever renewable energy is available does enable green cloud services. This technique is called follow-the-sun and is showcased in the GreenStar Network. Some commercial providers are already implementing similar principles.

4.2 Access Network

4.2.1 Equipment

Adaptive Link Rate [12] [18] [20]
Adaptive Link Rate (ALR) is a technology, which makes use of different line rates under the assumption that lower line rates consume less power. ALR allows for temporary reduction of bandwidth during low traffic periods, which can be quickly restored to higher bandwidths when needed. This shows potential in access networks where traffic varies highly as opposed to core networks where there is less variation (due to aggregation).

Ethernet is an example of a communication standard that supports several transmission rates where a significant difference in power consumption can be found in the higher link rates (1 – 10 Gbps) compared to the lower rates (< 1Gbps).

ALR can offer more operating modes than just an idle and a working mode, creating an advantage to reduce energy consumption. However this is partly offset by the need for larger packet buffers to reduce the burstiness of traffic.

Low power idle & Energy Efficient Ethernet [21] [22]
Many of currently used network devices consume power regardless of load. Even when idle they still have an energy consumption of up to 90%. They have no special low power idle mode that reduces this consumption. Low power idle takes advantage of the burstiness of network traffic by quickly shifting to an idle mode between bursts. The idle mode consists of rapidly turning off subcomponents when no activities are performed.

Low power idle is applied in the IEEE 802.3az standard Energy Efficient Ethernet to provide an alternative for continuously active interface at higher data rates. In normal Ethernet devices, when no data is transmitted, an auxiliary signal is sent to keep transmitters and receivers aligned. The Energy Efficient Ethernet standard defines mechanisms to stop transmission when there is no (user) data to send and to resume it quickly when required. This has the potential to reduce energy consumption in idle mode to as low as 10%. Running the standard does require some overhead so it is best applied to devices used in situations with bursty traffic.

The efficiency gains obtained by low power idle and the 802.3az standard can be further improved when they are combined with techniques to increase burstiness of traffic, such as packet coalescence. Packet coalescence simply allows network devices to collect packets within a certain time frame and up to a maximum amount before they are being sent on, creating small bursts of traffic. The combination of packet coalescence and low power idle allows devices to approach an almost ideal energy efficiency proportionality, but at the cost of latency. Depending on the needs of the users, this need not be significant. Since coalescence is already being used at the receiver's end, it may be assumed that some degree of coalescence can be safely used to improve low power idle performance.

On the other hand, low power idle and ALR do not necessarily combine well because ALR spreads out traffic over a longer time period, thereby reducing burstiness of traffic and thus reducing idle time. While the technologies are not mutually exclusive, careful configuration is necessary to take full advantage of both.

Sleep mode [12] [22]
Similar to other ICT equipment, network devices (in the access network) should have the ability to sleep. Especially customer premises equipment is rarely used fulltime and susceptible to fluctuations of use because of day-night cycles, work-home cycles, etc. Devices can take advantage of such user behaviour by automatically entering sleep mode as a next step after an idle state.

Sleep mode can be described as a kind of deep idle state. Compared to idle states, sleep mode is characterized by higher energy savings but larger wake-up time. While more complex designs are imaginable, the basic concept is that as many components as possible are turned off and that the device only listens for specific wake-up messages. Where idle mode does listen to background traffic, devices in sleep mode drop most of this traffic.

Consequently, sleep mode is not compatible with many Internet protocols. They could break because these protocols operate under the assumption that devices are always on instead of always available. When devices do not respond within certain minimal response times, these protocols resend packets under the assumption that previous packets have been dropped while they are actually buffered waiting for a device to wake-up. Using a network connectivity proxy can solve this problem.

Network connectivity proxy [12] [20]
Most current network protocols make a sleeping device (such as a PC) lose its network connectivity. A number of network protocols expect (network) devices to be always on. Losing connectivity therefore could cause problems for example for applications and services that want to remain connected. The solution for this problem can be found in network connectivity proxying (NCP).

NCP basically allows devices to maintain network presence by transferring network presence to a proxy. Such a proxy allows devices to go to sleep and filters incoming traffic, waking them up only when non-trivial packets that need further processing are received. Thus, the main objective of a proxy is to respond to routine traffic while the device sleeps. The internal network interface card or an external device can act as a proxy.

Offloading traffic filtering and processing to an external machine may have several advantages in case of a larger LAN or in access networks. First it allows for economy of scale in NCPs needing less extra devices. Second, such a central NCP can feature more efficient components because overhead is reduced.

In the future, it is likely that more application specific network traffic information can be transferred to proxies to allow for more intelligent proxying behavior.

4.2.2 Routing

Bit interleaving PON [23]
Bit interleaving PON is a new time division multiplexing (TDM) transfer protocol under development in GreenTouch that reduces the power consumption of the Passive Optical Network digital part for the downstream by almost an order of magnitude. In a conventional packet based PON system, every Optical Network Unit processes all downstream data until it is able to extract the incoming packets destined for the local area network and drop the rest of the data. A lot of power is consumed in the processing of this high throughput (e.g. 10 Gbit/s in XG-PON1).

The concept of bit interleaving allows for selecting the relevant bits immediately behind the clock and data recovery. Further processing is done at the user rate instead of the aggregate line rate, which results in significant power savings because these rates are generally much lower and lower rates operate at lower energy consumption. Bit interleaving does not work for upstream.

Burst mode operation [24]
As has been mentioned a number of times, buffering packets and sending them off in bursts instead of continuous transmission, combines well with a number of other energy-saving techniques. Especially in access networks where traffic does not have a continuous character, this can lead to extra optimization of for example idling devices. Stimulating burst traffic can be done at the customer premises, but also at higher order locations in the access network. In general it does require larger packet buffers, which also consume energy so a trade-off point is present.

4.2.3 Architecture

Passive Optical Networks [18]
Fixed access networks come in different shapes and sizes. The most used access networks are xDSL, cable networks and FTTx. While xDSL might be most efficient at lower access rates, it is quickly overtaken by the optical fibre technology FTTx. Although point-to-point fibres could be used in the future, they are currently not feasible because their bandwidth rates are too high for a single subscriber. Instead, passive optical network (PON) architectures offer a way to distribute the fibre capacity over a large number of users and thus offer high energy efficiency in terms of Watt per bit, up to seven times more efficient than traditional xDSL access networks. In addition PONs offer higher bit rates and ranges than other technologies. For all types of access networks, it is generally the customer premises device that consumes the most energy, collectively up to 65%.

Virtual Home Gateway [23]
A Virtual Home Gateway (VHG) takes advantage of economy of scale by virtualizing a number of typical home gateway functions, such as routing, OAM, and security, on a central server in the network instead of on a processor on the customer premises equipment. This simplifies equipment at subscribers, reducing their energy consumption as well as easier operation and maintenance for operators. Thanks to time-sharing by multiple subscribers, the VHG functions more efficiently than the

separate devices. Finally, because equipment at subscribers is simplified, its lifetime is likely extended.

In the future, it might be possible to eliminate energy consumption at the customer premises completely (for wired access) by offering a passive optical connection and transferring all energy consuming network functions to a centralized device such as the VHG.

Long reach access [23]
Long reach access architectures can reduce the number of hops in the access and aggregation network. Such a SuperPON with a high split capacity and a range in the order of 100 km allows for bypassing the local exchange: although functions in the access networks are not necessarily eliminated, they are moved up in the network, allowing for more aggregation and perhaps mergers of access and metro networks. While these higher distances do lead to higher power consumption at the aggregation node, the elimination of lower aggregation nodes should still lead to significant energy consumption reduction.

Dynamic Bandwidth allocation [18]
Subscribers are usually offered a higher access rate than they receive in practice because they have to share line capacity with their neighbours. Operators have to do so in order to keep operational expenses in check because of the burstiness of individual subscriber traffic. By aggregating individual traffic streams, they can increase the utilization of their network equipment. This can be taken one step further with dynamic bandwidth allocation (which is similar to mixed line rates, but on a lower level). The concept here is in principle the same, which is to increase utilization. Operators can use dynamic bandwidth allocation to decrease capacity (e.g. utilizing less ports) during periods of low traffic. This allows elements of centralized network devices to be switched off which in turn lead to reduced power consumption.

4.2.4 Application and User Behavior

Green BitTorrent [25]
Green BitTorrent is a proposed adaptation of the standard BitTorrent protocol that allows the client to sleep when not up- or downloading, potentially reducing the client power consumption by 75%. The majority of previous studies in the area of optimizing file distribution services have mainly focused on minimizing the download time. However, those algorithms, designed to minimize the download time, are not optimal in terms of energy consumption. Green BitTorrent has energy consumption as key optimization figure.

Datacentre networking [26]
A special case of networking happens in datacentres. Recent studies have shown that between 10% and 20% of power in a datacentre is consumed by network devices. Thus, it makes sense to investigate solutions reducing the power consumption of these devices. One solution to optimize network power consumption in a datacentre is called VMPlanner. VMPlanner optimizes two main tasks for energy efficiency: the virtual machines' placement inside the datacentre, and the traffic flow between the virtual machines. Depending on load, this allows datacentres to turn off network devices while guaranteeing Quality of Service (QoS) constraints.

5 Mapping of solutions on NREN and campus networks

This section gives a quick overview of all the solutions described above and indicates whether they are applicable to NREN and campus networks. The comments provided here are based on a practical view using the SURFnet network and the Dutch Higher Education campus networks as cases. The assumption is that these can be generally applied to all NREN and campus networks.

This overview points to solutions that deserve further investigation if interested in energy savings in networks. However, these solutions do differ in maturity and, as mentioned before, their effect strongly depends on the context. In general, core network solutions apply to NREN networks and access network solutions apply to campus networks, however there are some crossover applications as well. This is because the demarcation point can either be at similar locations as with homes (i.e. traffic is aggregated before transmitted to the core network) or it can have direct access to the core network.

If the row indicates a Y(es), it deserves further investigation, if it shows a N(o), we do not think it is applicable or we recommend trying other techniques first.

EE Technology	NREN networks		Campus networks	
Core network solutions				
Optical switching	Y		Y	
Line card / chassis configuration	Y		Y	
Energy-aware routing	Y		Y	
Green routing	Y	NRENs can create green nodes in their network and give preference to those.	N	
Cross-network energy-aware routing	Y	This is especially useful when transporting large amounts of research data.	Y	
Multipath routing	Y		Y	Only for large campus networks.
Pipeline forwarding	Y	The dedicated lightpaths already provide this feature in a sense. These are user-oriented however; might be interesting to consider content-oriented as well.	N	
Mixed line rates	Y		Y	
Redundancy and sleep mode	Y		Y	Only for large campus networks.
Maximum path length	Y	This might have impact on future network design.	Y	
Follow-the-sun	Y	At least for solar, this requires collaboration with other organizations around the world.	Y	

Access network solutions				
Adaptive link rate	Y	This could be applied in smaller rings.	Y	
Low power idle & Energy Efficient Ethernet	N		Y	Interesting for PoE and 802.3az devices (e.g. access points, IP telephony) [27]
Sleep mode	N		Y	
Network connectivity proxy	N		Y	
Bit interleaving PON	N		N	
Burst mode operation	N		Y	
Passive optical networks	Y		Y	
Virtual home gateway	Y	Could be an interesting service for campuses (i.e. expand on firewall-as-a-service, DNS servers).	Y	
Long reach access	Y	This might have impact on future network design.	N	
Dynamic bandwidth allocation	Y		Y	Only for large campus networks.
Green BitTorrent	N		Y	
Datacenter networking	N		Y	

6 Who is working on green networks?

Here are a number of projects and collaborations, mostly from Europe, that provide a good starting point for getting more involved in green networking or learning more about it. These have been used as sources for this document as well. The texts are mostly in their own words:

EARTH

"The goal of the [FP7 IP project EARTH] was to address the global environmental challenge by investigating and proposing effective mechanisms to drastically reduce energy wastage and improve energy efficiency of mobile broadband communication systems, without compromising users perceived "quality" of service and system capacity. … The target of EARTH was to reduce the energy consumption of mobile systems by a factor of at least 50% compared with the current ones." In various simulation projects EARTH claims to have overachieved this ambitious target by providing Integrated Solutions allowing for savings in the range of 70%.
https://www.ict-earth.eu/

ECONET

"ECONET (low Energy COnsumption NETworks) project is a 3-year IP project (running from October 2010 to September 2013) co-funded by the European Commission under the Framework Programme 7 (FP7). … The ECONET project aims at studying and exploiting dynamic adaptive technologies (based on standby and performance scaling capabilities) for wired network devices that allow saving energy when a device (or part of it) is not used. … The overall idea is to introduce novel green network-specific paradigms and concepts enabling the reduction of energy requirements of wired network equipment by 50% in the short to mid-term (and by 80% in the long run)."
https://www.econet-project.eu/

Energy Consumption Rating Initiative

The Energy Consumption Rating (ECR) Initiative is a framework for measuring the energy efficiency of network and telecom devices.
http://www.ecrinitiative.org/

ETSI Technical Committee Environmental Engineering

"ETSI, the European Telecommunications Standards Institute, produces globally-applicable standards for Information and Communications Technologies (ICT), including fixed, mobile, radio, converged, broadcast and internet technologies. … The Technical Committee EE is responsible for defining the environmental and infrastructural aspects for all telecommunication equipment and its environment, including equipment installed in subscriber premises. Wherever possible this will be achieved by references to existing international standards."
http://portal.etsi.org/ee/Summary.asp

GreenStar Network

The GreenStar Network (GSN) is a project that aims to create zero-carbon ICT infrastructure. "Funded by Canadian National Research and Education Network (NREN) CANARIE, the GSN works by creating a network of international nodes within datacentres, powered solely by renewable energy. This means that ICT applications and traffic running across this network do not rely on fossil fuels while still providing the highest levels of performance. … Through a flexible, virtualised international network running between three countries, GreenStar provides a potential future model for the greener operation of commercial networks without impacting performance." GreenStar is quite novel in that rather than focusing on energy efficiency, it uses new network concepts such as follow-the-sun/follow-the-wind to provide always available networking powered by renewable energy.
http://www.greenstarnetwork.com/

http://www.geant.net/Media_Centre/Media_Library/Media%20Library/GEANT_and_the_GreenStar_Network.pdf

GreenTouch
"GreenTouch is a consortium of leading Information and Communications Technology (ICT) industry, academic and non-governmental research experts dedicated to fundamentally transforming communications and data networks, including the Internet, and significantly reducing the carbon footprint of ICT devices, platforms and networks. … By 2015, our goal is to deliver the architecture, specifications and technologies – and demonstrate key components – needed to increase network energy efficiency by a factor of 1000 compared to 2010 levels. We'll accomplish this by designing fundamentally new network architectures and creating the enabling technologies on which they are based."
http://www.greentouch.org/index.php?page=home

IEEE
IEEE has several working groups and task forces working on environmental sustainability issues. A dedicated task force was the Energy Efficient Ethernet Task Force that delivered the 802.3az standard:
http://www.ieee802.org/3/az/index.html

IETF
Aside from a number of individual drafts, IETF has a working group dedicated to energy management for network management systems. They define "the basic objective of energy management as operating communication networks and other equipment with a minimal amount of energy while still providing sufficient performance to meet service level objectives." Its main purpose is to develop a framework for energy management.
https://datatracker.ietf.org/wg/eman/charter/

ITU-T Study Group 5 – Environment and Climate Change
"ITU-T Study Group 5 (SG5) is responsible for studies on methodologies for evaluating ICT effects on climate change and publishing guidelines for using ICTs in an eco-friendly way. Under its environmental mandate SG5 is also responsible for studying design methodologies to reduce ICTs and e-waste's adverse environmental effects, for example, through recycling of ICT facilities and equipment." In addition, ITU-T is regularly organizing events on ICT and sustainability issues.
http://www.itu.int/en/ITU-T/studygroups/2013-2016/05/Pages/default.aspx

TREND
"TREND is a Network of Excellence, coordinated by Politecnico di Torino, funded by the European Commission within the Seventh Framework Programme. … The NoE will integrate and drive towards commonly agreed technical goals [combining] the many recent research efforts in energy-efficient networking, laying down the bases for a new holistic approach to energy-efficient networking, investigating effective strategies and mechanisms to reduce energy consumption in current and future networks in general, and the future Internet in particular. … The aim of TREND is to establish the integration of the EU research community in green networking with a long term perspective to consolidate the European leadership in the field."
http://www.fp7-trend.eu/

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