GreenTouch Green Meter Research Study: Reducing the Net Energy Consumption in Communications Networks by up to 90% by 2020

A GreenTouch White Paper

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Executive Summary

The GreenTouch consortium [1] was launched in 2010 with the mission and the very ambitious goal to improve the energy efficiency in communications networks by a factor of 1000 compared to 2010 and to provide, by 2015, a roadmap of architectures, specifications and solutions and to demonstrate key technologies to accomplish this goal.

This GreenTouch white paper, issued after three years of the five-year journey, describes the outcome of a comprehensive research study, called the "Green Meter", conducted by GreenTouch to assess the overall impact and the overall energy efficiency benefits from the portfolio of technologies, architectures, components, devices, algorithms and protocols being investigated, developed and considered by GreenTouch. It is in essence an interim assessment of the progress of the consortium toward its goal and an outlook for further opportunities for improving the energy efficiency in communications networks. This is a first-of-its-kind study due to its breadth and depth of technologies being included, from the mobile networks, to the fixed access networks and the core networks. The study does not just quantify the energy benefits of a single technology but rather focuses on the end-to-end network perspective and includes a full range of technologies. As a result the research provides valuable insights into the overall impact as well as the relative impacts of these technologies being considered. It also explicitly includes the traffic growth into the calculations of future network energy efficiencies and energy consumption.

GreenTouch recently publicly announced the results of its Green Meter research study [2], which concluded that it is possible through the combination of technologies, architectures, components, algorithms and protocols to reduce the net energy consumption in communications networks by up to 90% by 2020. This dramatic net energy reduction in the mobile access, the fixed access and the core networks, while taking into account the dramatic increase in traffic, is fueled by significant improvements in the energy efficiencies of the component networks (including a factor of 1043 for mobile networks, a factor of 449 for fixed access networks and a factor of 64 for core networks).

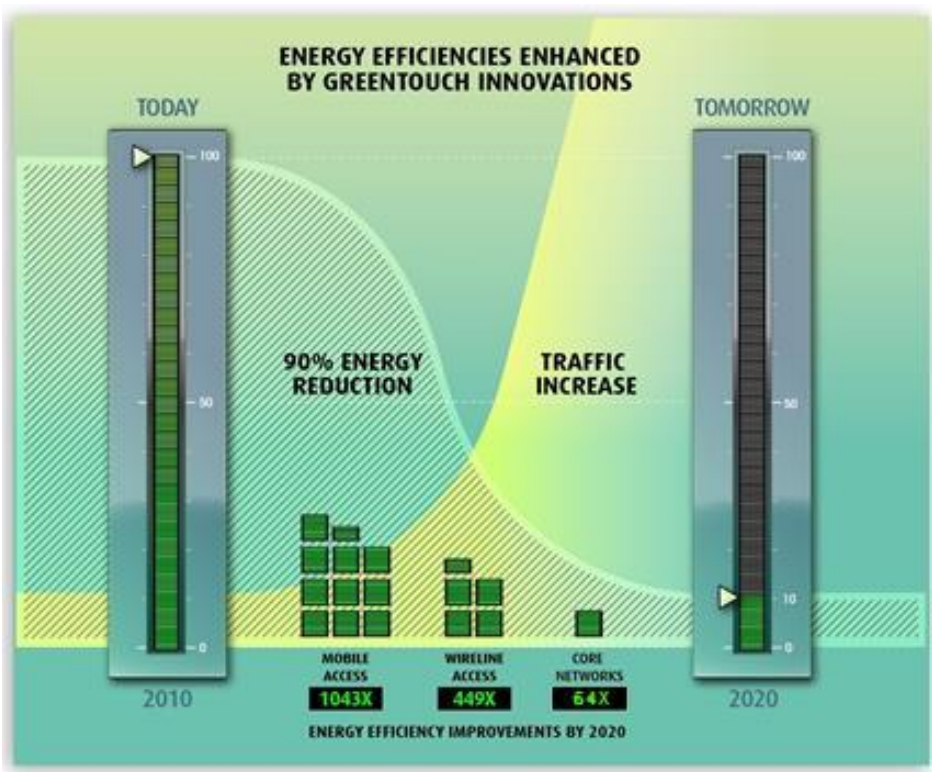


Figure 1: Energy efficiencies enhanced by GreenTouch innovations.

This profound result demonstrates that we can support the predicted traffic growth in future networks while at the same time reducing the total energy consumption of the networks significantly. Deploying these technologies would have a significant economic impact (through reduced operational expenses) and environmental impact (through reduced energy consumption and carbon emissions) for operators and service providers, while at the same time providing value to consumers and businesses as well as revenue-generating opportunities through the delivered applications and services.

This paper provides the technical background, assumptions and methodologies behind the Green Meter calculations and explains how these results are obtained. In the process it also describes a roadmap and a portfolio of technologies for equipment vendors and service providers and quantifies the relative energy efficiency benefits of the individual technologies. GreenTouch is well on its way to accomplish its very ambitious mission, and through the publication of its research results we hope to stimulate further discussions, research and focus within the industry on the topic of energy efficiency of future communications networks. Nevertheless, a lot of challenges remain in front of us, and GreenTouch is continuing its mission to address these challenges, to validate and demonstrate technologies and to seek new ideas to further improve network energy efficiency.

1. Background

With the continued dramatic rise of applications, services, devices and machines all being connected to the network, the total Internet traffic in the next decade is expected to grow exponentially. One of the challenges for next-generation networks is the ability to support the predicted traffic in a sustainable and economically viable way. In addition to the resulting increased energy consumption, the rising energy costs, the environmental impact of networks, and more socially conscious consumers and service providers demand that our future communication and data networks be greener and more sustainable. Recognizing this challenge and the growing gap between traffic growth and network energy efficiency improvements, the GreenTouch initiative [1] was formed in 2010. GreenTouch is a global research consortium of equipment providers, operators, research institutes and academic organizations with the mission to deliver architectures, specifications and solutions, and to demonstrate key technologies, that, if combined in an end-to-end network architecture, improve the network energy efficiency by a factor of 1000 compared to 2010 levels. See the video at the following link for an overview of GreenTouch:

http://www.youtube.com/watch?v=pAyQ-kxPw9o

Initial GreenTouch research indicates that there is a significant opportunity to increase the energy efficiency in today's communication and data networks, to improve the network performance and to support the projected traffic growth. The GreenTouch effort offers a roadmap of technology assets for a sustainable Internet while also enabling efficient solutions to lower the carbon footprint of all other industry sectors touched directly and indirectly by ICT. This private sector and academic global research consortium offers the most focused attempt for technology breakthroughs in network energy efficiency.

Since its launch in 2010, GreenTouch has built an extensive research portfolio around five major themes, including wireline access, mobile communications, switching and routing, optical networking, and services, applications and trends. It published a document on key strategic research directions along with its initial project portfolio [3]. Among the large set of projects, the Large Scale Antenna System (LSAS) and the Bit Interleaved Passive Optical Networks (Bi-PON) technology have recently been showcased in public demonstrations. See videos of these demonstrations at the following link:

http://www.greentouch.org/index.php?page=videos

This white paper describes the outcome of a comprehensive research study, called the “Green Meter,” conducted by GreenTouch to assess the overall impact and the overall energy efficiency benefits from the portfolio of technologies, architectures, components, devices, algorithms and protocols being investigated, developed and projected by GreenTouch. This is a first-of-its-kind study due to its breadth and depth of technologies being included, from the mobile networks, to the fixed access networks and the core networks. The study does not just quantify the energy benefits of a single technology, but rather focuses on the end-to-end network perspective and includes a full range of technologies. As a result the research provides valuable insights into the overall impact, as well as the relative impacts of the technologies being considered. It also explicitly includes the traffic growth into the calculations of future network energy efficiencies and energy consumption.

In order to arrive at the Green Meter results, GreenTouch has developed methodologies and metrics that assess the impact of the new technologies, the traffic growth projections and their relative impacts on the overall power consumption and energy efficiency of communications networks, including mobile, wireline and core networks. Energy efficiency is defined as the ratio of the traffic being carried by the network (for example, measured in Gbytes) to the total energy required to support that traffic over the duration of one year (for example, measured in TWh). The energy efficiencies in different component networks were evaluated through a combination of forecasting and trend projections, theoretical and analytical calculations, semi-analytical optimizations and network simulations. Some components were also demonstrated through lab implementations and prototyping activities.

The Green Meter is then a comparison of the energy efficiency and the energy consumption of communications networks between the baseline year in 2010 and a future reference year in 2020. For the reference year in 2010, we considered the traffic volumes in 2010 along with the most energy-efficient, commercially available technologies, which are assumed to be universally deployed throughout the network to support the traffic. It should be noted that this does not necessarily represent a typically deployed network in 2010, considering all the legacy equipment and different technologies deployed in 2010.

For the 2020 network model, we included the most energy-efficient technologies, components and solutions that are being researched by GreenTouch, and we also included some other “business-as-usual” evolutions, such as Moore’s law for electronics. These technologies will not necessarily be universally deployed by 2020, but we believe that they are realistic and could be commercially available. The target year of 2020 is chosen as a basis for the projected traffic levels and service requirements to serve as the target requirements for the GreenTouch goals. For the purpose of calculating the projected network energy efficiency in 2020, it is assumed that the next-generation energy-efficient network equipment, architectures, and technologies being considered are deployed throughout the network. This is a hypothetical network scenario and does not fully take into account standardization, development time, commercial availability, deployment times, backward compatibility and total cost of ownership. Of course such considerations will be taken into account when the technologies are productized and deployed in real networks, but these aspects are beyond the scope and mission of the GreenTouch consortium. Our mission is to investigate new research directions, to invent, develop, demonstrate and de-risk new technologies and to quantify their impact for future energy-efficient networks.

The main result of the Green Meter research study shows that it is possible through the combination of technologies, architectures, components, algorithms and protocols to reduce net energy consumption in communications networks by up to 90% by 2020 [2]. This is a profound result that demonstrates that we can support the predicted traffic growth in future networks, while at the same time reducing the total energy consumption of the networks significantly. Deploying these technologies would have a significant economic impact (through reduced operational expenses) and environmental impact (through reduced energy consumption and carbon emissions), while at the same time providing value to consumers and businesses as well as revenue-generating opportunities through the delivered applications and services.

In this white paper, GreenTouch provides the necessary information to understand this major result, the assumptions made and the methodologies used to derive the result, as well as the portfolio of technologies that form the basis for these energy efficiency improvements and the reduction in net energy consumption. The white paper is organized as follows. Section 2 provides background information on the projected traffic volumes and the traffic growth rates in the different network domains. Section 3 provides the details of the green meter calculations and results for the mobile communications networks. Section 4 provides the corresponding details for the fixed access networks and Section 5 similarly discusses the core backbone network. Finally, we conclude in Section 6 and provide some directions for current and future activities in GreenTouch.

2. Traffic Growth in Communications Networks

For the purpose of identifying network requirements and assessing network energy consumption, GreenTouch has analyzed historical global Internet traffic volumes and near-term forecasts to prepare longer-term Internet traffic projections [4], [5]. Using a semi-empirical hyperbolic function to model the growth rate, linearized regression analyses of a combination of historical and nearer-term traffic forecasts have been carried out to project macroscopic Internet traffic to 2020 for several geo-economic regions, market segments, and application categories [5].

GreenTouch has defined mature and emerging market segments by dividing the geo-economic regions into two groups based on the growth of the number of Internet video users in the geo-economic regions that is forecast between 2010 and 2015. The Mature Market segment was defined to consist of those geo-economic regions in which the growth of the number of Internet video users over the period is forecast to be less than or equal to 10%, and the Emerging Market segment was defined to consist of the remaining geo-economic regions for which the Internet video growth is forecast to be greater than 10%. Using these definitions, the Mature Market segment consists of Japan, Northern America and Western Europe; and the Emerging Market segment consists of the Asia-Pacific region less Japan, Central and Eastern Europe, Latin America and the Caribbean, and the Middle East and Africa.

In this context, all markets included, the results indicate that, in contrast to the decade of 2000-2010 when global Internet traffic grew more than 100-fold, over the decade 2010-2020 global wireline Internet traffic will grow approximately 16 times larger, to approach 250 exabytes per month, and global mobile Internet traffic will grow approximately 150 times larger, to approach 40 exabytes per month. The projections also indicate that over the present decade the compound annual growth rate of global wireline Internet traffic will decrease from approximately 45% to 25% per year and the growth rate of global mobility Internet traffic will decrease from approximately 170% to 30% per year.

At present the total traffic for the Mature Market segment is larger than for the Emerging Market segment, but near-term forecasts predict the Mature Market segment to be growing more slowly. From the perspective of driving technological improvements to improve energy efficiency, a larger-volume traffic that is growing more slowly is more challenging, as the improvement in energy efficiency must come from new innovative solutions rather than increased utilization of existing solutions. For this reason the traffic volumes used by GreenTouch in its energy modeling are those of the Mature Market segment. GreenTouch has divided the communications network infrastructure and technologies into the categories of Mobile Access, Wireline Access and Core Network. Table 1 gives the traffic projections and the ratios of the projected traffic volumes in 2010 to the volumes in 2010 for the Mobile, Wireline Access and Core categories of the Mature Market segment.

Mature Market Traffic Projections (PB/month)			
YEAR	**Mobile Access**	**Wireline Access**	**Core Network**
2010	161	7,727	10,707
2015	3,858	33,879	45,402
2020	14,266	74,462	103,085
2020/2010	89x	9.6x	9.6x

Table 1: Traffic projections and corresponding multiplicative growth factors between 2010 and 2020 for the mobile access, wireline access and core networks modeled by GreenTouch for the Mature Market segment.

The network and energy consumption models for each of these categories reflect their different characteristics. Therefore, each category constructs an appropriate traffic model based on the traffic projections.

Mobile Access Network

In the case of the mobile access network, the network infrastructure is not differentiated into consumer and business. Nor does the time dependence of the available traffic data differentiate consumer and business. Therefore, for the Mobile Access network the appropriate traffic category is Mobile Data IP, which includes both Consumer and Business Mobile Data Internet traffic. Note that there is no significant managed IP component of mobile traffic.

The total mobile traffic volume in PB/month is proportionally distributed over the geographical area types (i.e., dense urban, urban, suburban and rural) according to the population density. Table 2 shows an expected traffic growth of 89 times between 2010 and 2020 and the monthly traffic growing from approximately 180MB/inhabitant to 16GB/inhabitant (at a stable population of 878 million people for the Mature Market segment).

Traffic volume	PB/month	GB/month/person
2010	161	0.183
2015	3,858	4.40
2020	14,266	16.3

Table 2: Evolution of mobile IP traffic volume.

In addition to the spatial imbalance over area types, the traffic is also unevenly generated over time. As an example, Figure 2 shows the daily profile observed in dense urban areas of a GreenTouch operator network.

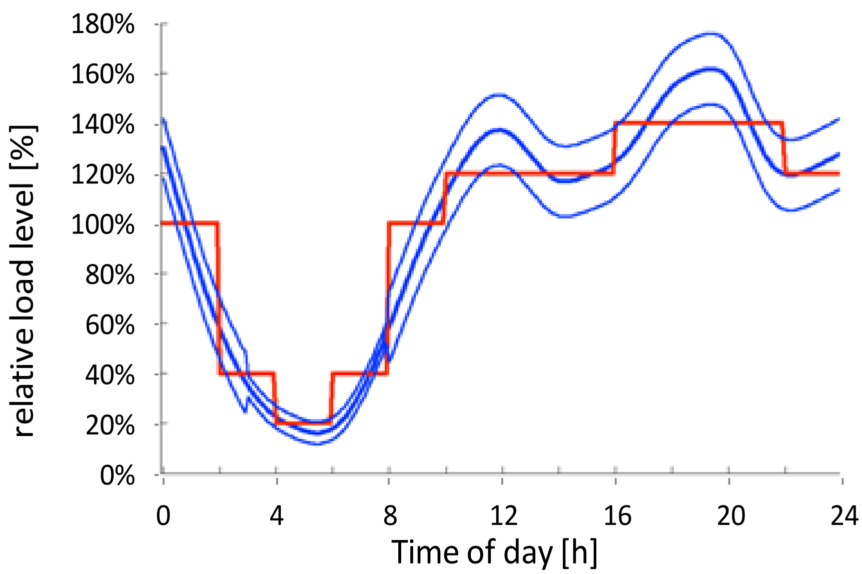


Figure 2: Daily traffic profile, indicating a large saving potential in night times.

The profile is fitted by a step profile of five load levels, associated to 20% to 140% of the average load. We observed that the detailed traffic pattern is slightly shifted between the area types; however, the number of hours in each of the load levels [Table 3] is the same in all area types.

	Night time	Low traffic	Average	High traffic	Busy hour
Load level	20%	40%	100%	120%	140%
Duration [h]	2	4	4	8	6

Table 3: Daily traffic profile, approximated by five levels.

Using the above parameter values, we arrive at busy hour traffic levels of 0.024Mbps/km² (rural areas) to 7.9Mbps/km² (dense urban areas) in 2010 and 2.1Mbps/km² to 702Mbps/km² in 2020, respectively.

Wireline Access Network

Unlike the mobile network, the infrastructure of the wireline access network is differentiated between Fixed Internet and Managed IP and between consumer and business traffic. For example, the ideal consumer broadband network might be considered PON, and the ideal business broadband network might be dedicated optical GigE, 10GigE, or 100GigE. Further, it might be considered that the efficiency of optical XGigE is similar to the backbone infrastructure, and businesses might have direct and relatively short feeds to/from the backbone. For these reasons, and because the total of wireline business traffic is a small fraction of the total wireline Internet traffic, GreenTouch's emphasis for the Wireline Access network is on the category of Consumer Fixed Internet traffic. Table 4 summarizes the traffic volumes and numbers of subscribers considered for the Green Meter calculation. In a wireline access network, power consumptions per access line are evaluated per subscriber (i.e., a living unit) rather than in power consumption per user (or person), as done for the mobile network. Note furthermore that we use fiber-to-the-home as the baseline architecture. Since power consumption is very little dependent on the different distances of fiber access lines, we did not need to consider different geographical areas with different subscriber densities.

Traffic volume	PB/month	GB/month/subscriber	# subscribers (in Millions)
2010	7,727	31.5	245.3
2015	33,879	124.1	273.0
2020	74,462	264.8	281.2
Relative increase	9.6x	8.4x	1.15x

Table 4: Evolution of IP traffic for wireline access network in Mature Markets considered for the Green Meter evaluation.

Core Network

The emphasis of GreenTouch's efforts on the core network is Internet traffic, as Managed IP traffic is relatively small in comparison. Furthermore, based on the traffic volumes in Figure 3, we note that the traffic contribution to the core network coming from the mobile wireless backhaul is small in comparison to the traffic from the wireline network. Like the mobility network, the core network also does not differentiate consumer from business traffic. Consequently, the traffic projections used for the analysis of the core network are those of the category of Fixed Internet traffic.

Traffic data is typically provided as total bytes per month or per year [4], [5] totaled over geographical regions. However, communications networks are designed based upon the link-by-link, peak-hour traffic (in bits/second) that occurs during the daily diurnal traffic cycle. The usual approach is to design the network to accommodate the peak-hour traffic, taking account of the statistical properties of the traffic to minimize the amount of equipment required. Further, the traffic is not uniformly distributed across all the links in the network. Rather, it may be somewhat concentrated on several major links between large nodes in the network. The total energy consumption of a network is strongly dependent upon these temporal and geographical factors. Therefore, to estimate the energy consumption of a network, we need to translate the traffic data from total regional traffic in bytes per month to hourly traffic in bits per second on the various links within the network. Using this data and a set of network design rules, the total network equipment can be determined and, from that, the network energy consumption.

To make the translation from total regional traffic (bytes per month) to link-by-link hourly link capacity (bits per second) we assume the temporal and geographical dependencies are independent. That is, we assume the diurnal cycle dependence is identical for all links. This does not mean the peak hour occurs at the same time for all links, rather it means each hour's traffic in the diurnal cycle, as a percentage of peak-hour traffic, is identical for all links. The geographical dependence is determined using the traditional gravity model for traffic between population centers. This model has been shown to apply to Internet data [5]. The gravity model states that the traffic between two population centers is proportional to the product of the population of those centers and inversely proportional to the distance between them raised to a power. For Internet traffic, indications are that the distance dependence does not apply. In addition to traffic between individuals, the Internet carries a substantial amount of data center traffic. This consists of data center to human traffic and inter-data center traffic. Therefore, traffic to and from a node in the Internet will also depend upon whether or not a data center is serviced by that node. Further, one would expect the traffic would also depend upon the size of the data center. This means that the traditional gravity model needs to be amended to reflect the location and size of data centers that communicate with customers via the Internet. We would expect the traffic generated by a data center will be dependent upon the size of the data center. To include this in the gravity model, we need a measure of data center size. A good measure would be the number of operating servers in the data center. However, this data is difficult to gather. A simpler, although less precise, parameter is the data center floor space. This information is more easily accessed.

Bringing these two factors together, population sizes and data center sizes, a combined gravity model for the magnitude of traffic between network nodes can be constructed. To this geographical model we now add the temporal traffic dependence. Using hourly traffic data collected over large geographical regions, the ratio of peak to average hourly traffic and hourly traffic as a percentage of peak-hour traffic can be readily calculated. The total per-month traffic can be taken as 30 times the average daily traffic. Using this and the ratio of peak to average hourly traffic, we can construct a direct conversion from monthly totals (bytes per month) to hourly capacities (bits per second) [24].

As shown in Figure 3, today the total volume of fixed IP traffic is approximately 25 times larger than the volume of mobile IP traffic, but this ratio is decreasing, as the present growth rate of mobile traffic is approximately three times larger than that of fixed traffic.

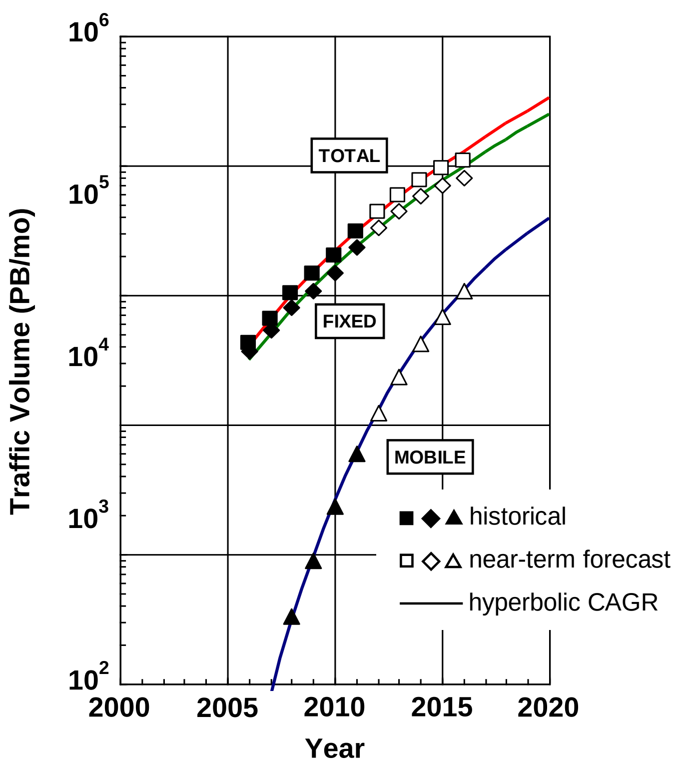


Figure 3: Mobile and wireline Internet traffic volumes versus year. Historical data and near-term forecasts based on [4] and Projections based on Ref. [5].

Additionally, the growth rates of fixed and mobile IP traffic are both decreasing, and, as mobile traffic has been becoming a larger fraction of the total, the growth rate of mobile traffic has been decreasing more quickly.

The projections indicate that the ratio of fixed to mobile IP traffic will decrease from its present value by four-fold to 6:1 by 2020 and change only slowly thereafter as the two growth rates continue to converge. Specifically, between 2010 and 2020 the compound annual growth rate of global wireline Internet traffic is projected to decrease from approximately 45% to 25% per year, and the growth rate of global mobile Internet traffic is projected to decrease from approximately 170% to 30% per year. While these changes in growth rates are significant, the growth rates of 20 to 25% projected for 2020 are still large -- corresponding to a doubling of the global traffic volume roughly every three to four years.

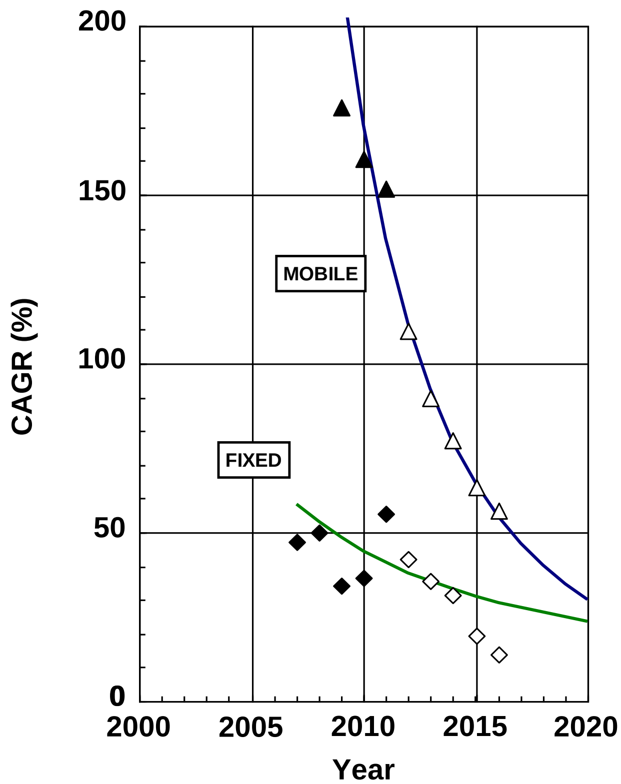


Figure 4: Mobile and wireline Internet traffic growth rates versus year. Historical data and near-term forecasts based on [4] and projections based on [5].

3. Mobile Communications

In this section, we study the effect of mobile IP traffic growth on the energy consumption of LTE networks from 2010 to 2020 for the most developed markets. The model is assuming full coverage of the inhabited areas with broadband LTE data service. We followed the traditional roll-out strategy with a reuse of the available sites from legacy networks. In 2010, cooperation by network sharing between operators was not state-of-the-art, so we modeled four competing operators, each with full coverage and 25% market share. For 2020, however, we expect that standardization and regulation will enable strong cooperation between operators to enable a more effective spectrum usage and avoid the costs for a four-fold deployment. So we assumed in the 2020 scenario that all traffic is served by a single physical infrastructure.

The methodology developed in the Mobile Working Group of GreenTouch [6], [7] extends the framework developed in the EU-funded project EARTH [8], [9] and applied by ETSI [11]. The parameters are defined to compute the complete energy consumption for the most mature markets of North America, Western Europe and Japan (i.e., the Mature Market segment defined in Section 2) for the years 2010 and 2020. Further, several assumptions, such as the power models and the antenna configuration, are refined for 2020 mobile communication systems [7].

The fundamental idea is that network simulations are not possible on a national or even global scale due to limitations of computational power. Rather, the network is divided into five typical deployment areas, representing dense urban (DU) areas in the centers of large cities, urban (U) and suburban (SU) areas, and rural (RU) areas with rather low population densities. Further, large parts of the target market area (e.g., in Canada and Scandinavia) are basically unpopulated and for these regions there is no business case for providing broadband mobile services. Table 5 provides the population distribution and the intersite distances (ISD) of the macro base station (BS) deployments that we assumed in this study. The resulting population numbers per BS site in Table 5 show that RU sites are limited by cell range rather than by capacity. With the five different traffic levels during a day (e.g., busy hour vs. night time) this results in 25 scenarios for which system level simulations are applied individually and their efficiencies are weighted according to their relative contribution, to yield an overall network efficiency.

Area Type	Pop. density [1/km^2]	Relative area [%]	Macro BS ISD [m]	Frequency band [GHz]	Pop. per BS area (3 cells)
DU	10,000	0.1 %	500	2	2,200
U	1,000	0.9 %	1,000	2	870
SU	300	3.0%	1,732	2	780
RU	30	26 %	4,330	0.8	490
Unpop.	1-2	70 %	none	none	NA

Table 5:Network deployment model and distribution of population over the area types.

For the 2010 reference scenario we applied conventional 3-sectorized macro BSs operating with 10MHz bandwidth and 2x43dBm transmit power per sector. For 2020 we anticipated a technical evolution to 20MHz and to 8 MIMO remote radio head (RRH) antennas with 8x40dBm per sector. For 2020 we applied a heterogeneous deployment with additional small cells (HetNet scenario) where required by capacity demand. We used small cells with two omnidirectional MIMO antennas with 2x27dBm transmit power.

The power consumption of the base stations is modeled in a simplified power model with linear load dependency. For 2020 we assumed that momentarily empty BSs can apply a microDTX sleep mode [10]. Table 6 shows the power model parameter.

BS type	Micro sleep	No load	Full load
Macro BS 2010	648 W	712 W	1,394 W
Macro BS 2020	157 W	189 W	665 W
Small cells 2020	2 W	4 W	11 W

Table 6: Base station power model with load dependency.

Each BS site is further consuming power for the backhaul, which is assumed to be independent of the load level. Microwave backhaul is modeled for 2010 with 145W for every BS of the RU scenario and for 50% of the BSs in SU and U scenarios. Optical backhauling is assumed in all other scenarios with 10W for 2010 and 5W for 2020.

We studied each of the 25 scenarios by running event-based system level simulations with non-full buffer traffic according to the traffic demand given in Section 2. Simulation parameters [7] are largely aligned with 3GPP performance simulations [12]; that is, we use the Urban Macro channel model of the HetNet specification and Rural Macro channel model for the rural case.

For the very highly loaded DU scenario in 2020, the macro BS capacity is exhausted and a large part of the traffic is offloaded to two arbitrarily placed small cells per macro sector. This is achieved by assuming that 66.7% of the users are within 40m of the small cell (3GPP case 4b [12]). The small cells operate in the 2 GHz band out of the macro cell frequency. Next to the throughput performance, we computed energy consumption and calculate for each area (A) and load (L) scenario the resulting energy intensity in [J/kbit] as the ratio of consumed energy $E_{A,L}$ over the served traffic volume $T_{A,L}$. The overall energy intensity is computed as a weighted average according to the relative amount of traffic served in each scenario. Finally, we computed the average energy efficiency η of the complete Mature Market LTE network in [kbit/J] as the inverse of the overall energy intensity.

In the results shown in Table 7 [26], we see that the energy efficiency of the scenarios strongly changes with the load of the system. This is due to the offset power that BSs consume even without any traffic. Therefore, in 2010 the value varies between scenarios from 62.7J/kbit in RU at night to 1.7J/kbit in DU during busy hour. With the improvement of the BS hardware (see models in Table 6), 89-fold traffic growth and network sharing of all operators, the energy efficiency is predicted to improve dramatically. Table 7 shows a 733x to 1730x-fold improvement of the energy efficiencies in all scenarios. Averaged over all scenarios, the overall energy efficiency gain is 1043. Assuming an overall 89-fold increase in mobile traffic, the 2020 system simulations predict a reduction of total energy consumption by a factor of 11.5, representing a net reduction of total energy consumption by 90%.

$E_{A,L}/T_{A,L}$	Night	Morning	Average	High	Busy Hour
[J/kbit]	**2010**				
DU	11.8	5.9	2.4	2.0	1.7
U	32.7	16.4	6.5	5.4	4.6
SU	35.2	18.2	7.3	6.0	5.1
RU	62.7	32.1	12.6	10.4	9.0
[J/Mbit]	**2020**				
DU	9.0	4.9	2.4	2.2	1.9
U	20.9	12.1	7.2	6.6	6.3
SU	23.9	13.5	7.7	7.5	7.0
RU	36.2	20.1	10.1	9.1	8.4

Table 7: Energy efficiency of all area type (A) and load scenarios (L). Note the 1000x larger traffic units used for 2020.

Figure 5 presents the breakdown of the overall energy consumption of the Mature Market network by area type, both for 2010 and 2020. This is compared to the relative traffic shares. The figure shows that RU is serving an under-proportional traffic load, indicating the coverage-limited deployment. The opposite holds for DU. Looking at the 2020 scenarios, the efficiency improves most in rural areas, driven by the BS sharing between operators. Also, DU areas improve slightly due to offloading to small cells. However, as the share of DU energy consumption is only 10%, the effect on overall efficiency is limited.

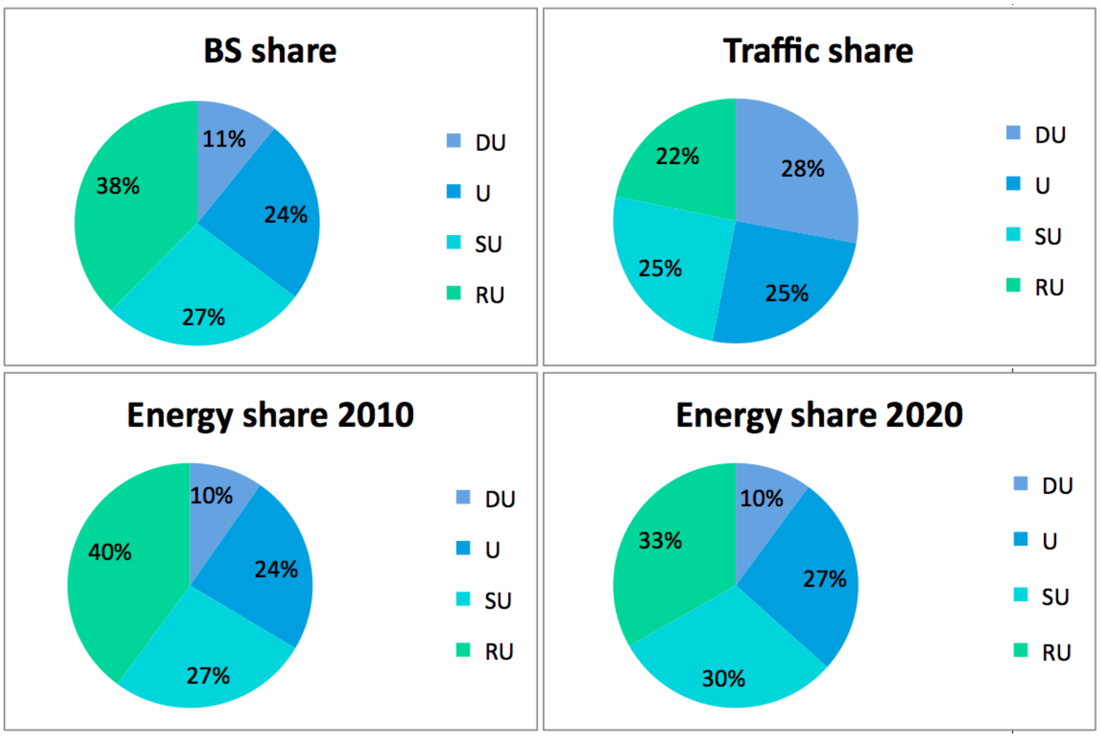


Figure 5: Breakdown of total number of BS, total served traffic and energy consumption in the reference and 2020 scenarios.

The reasoning for the 11.5-times reduction in energy consumption and the breakdown of the saving potential can be summarized by the following observations.

- The LTE system in the 2010 reference scenario is strongly over-dimensioned and provides a capacity that is by far above the demand from the year 2010. Then, the power consumption is only weakly dependent on load, but dominated by the BS offset power.
- Operator network sharing can be applied to avoid redundant coverage by four networks. When all traffic is served by a single physical infrastructure, the typical resource utilization in 2020 is around 25%. This reduces the number of BSs and results in nearly four times less energy consumption.
- Due to improvements in the hardware and hardware management, the BSs in 2020 will operate at 2.3-fold less power per BS even at the higher load of 2020 (308W at 25% load) compared to 2010 (712W at 0.1% load).
- Further savings come from micro sleeps (20% overall saving) and from the use of HetNets in DU (10% overall saving).

Going forward, GreenTouch will continue to investigate additional energy efficiency gains for future mobile communications networks. Ongoing research activities include the massive deployment of small cells, intelligent algorithms for turning small cells on and off and the separation of the control and data plane functionalities. These concepts are being studied and evaluated in the Beyond Cellular Green Generation (BCG2) project in GreenTouch [3], [6], [27]. In addition, the Large Scale Antenna System (LSAS) project investigates the use of a large number of service antennas at the base station for increased spectral efficiency and increased energy efficiency [3], [28]. Beyond the improvements in radiated energy efficiency, we are also evaluating total system energy efficiency including the per-antenna overhead and the computational complexity and resulting energy consumption. The energy efficiency gains achieved from these technologies are part of our ongoing research projects and will be quantified in future updates of the Green Meter research study.

4. Wireline Access Networks

This section summarizes the different approaches that were considered in the Green Meter to improve the energy efficiency of a wireline (also called fixed) access network. Part of this section is also published in [13]. We started from a Gigabit Passive Optical Network (GPON) based fiber-to-the-home (FTTH) solution as the baseline for the year 2010, because this was the most energy-efficient commercially deployed wireline access technology at the start of GreenTouch. In order to assess the effect of different energy saving approaches, we broke down the average power consumption per subsystem in an optical network unit (ONU), as shown in [13]: opto-electronic transceiver (OE) of the PON termination, digital electronics of the PON termination, wireline Ethernet interfaces to the local area network (LAN) and home gateway (HGW) processor. We also included the access aggregation network in order to evaluate the effect of a long-reach access technology that bypasses the local exchange. We treated the optical line termination (OLT), aggregation switch (AS), and edge router (ER) each as a subsystem without further detail, because their contribution is relatively small compared to an ONU. The edge router interfaces with the core network described in Section 5. For completeness, we also show the contribution of wireless LAN (WLAN) in [13], though it is not within the scope of the wireline access activities in GreenTouch and hence not included in the total efficiency improvement numbers reported in this section.

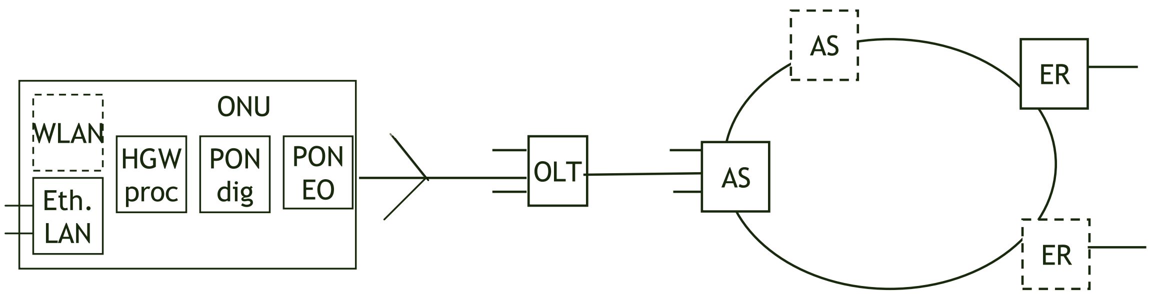


Figure 6: Wireline access and metro aggregation network with main subsystems considered in the Green Meter. At the optical network unit (ONU): Ethernet local area network (LAN), home gateway processor (HGW proc), passive optical network (PON) digital electronics (digital) and electro-optical transceiver (EO). In the network: optical line termination (OLT), aggregation switch (AS) and edge router (ER).

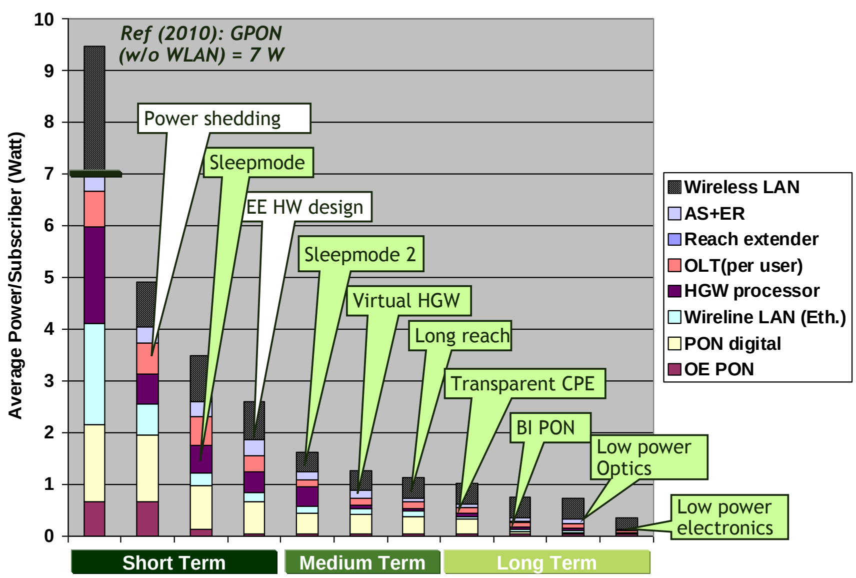


Figure 7: Evolution of average power consumption per subscriber.

Energy-saving approach	Gain factor	Subsystems affected
Power shedding	2.4x	Home gateway (HGW) processor, Ethernet LAN
Sleep mode (1 and 2)	2x	Electro-optics PON, PON digital, Ethernet LAN, OLT
Energy-efficient hardware (HW) design	1.2x	All hardware
Virtual HGW	5x	HGW processor
Long reach	2x	Edge router (ER), aggregation switch (AS) and OLT
Transparent CPE	2x	Ethernet LAN
Bi-PON protocol	10x	PON digital
Low-power optics	1.5x	EO PON, Reach extender
Low-power electronics	3x	All digital electronics
Moore's law for CMOS 2010-2020	2.6x	All digital electronics

Table 8: Energy efficiency gain factors per energy-saving approach and affected subsystems for wireline access.

Figure 7 categorizes the different efficiency improvements in a roadmap according to the time frame for possible deployment. Table 8 summarizes the gain factor for each approach and the subsystems that are affected. In the short term, it is already possible to save energy by power shedding of functional blocks (e.g., a specific LAN interface) that are only turned on when a session is established and powered off otherwise. We assumed an average use of the affected functional block for 10 hours per day, resulting in a 2.4x average energy gain. With periodic sleep mode [14], the average energy consumption of the fiber EO interfaces of an ONU (cf. ITU-T G.987.3) and line drivers of the Ethernet LAN (cf. IEEE802.3az) can be reduced. Energy Efficient Hardware (EE HW) design refers to engineering optimizations that result in an overall power reduction of about 20%. They include, for example, reduced transfers of data across input/output (I/O) of integrated circuits, thanks to further integration, more efficient interconnection techniques, critical review of required memory accesses, and use of clock gating or power switching for parts of an integrated circuit that are not in use. EE HW also includes more efficient cooling techniques in central offices.

In the medium term, we can achieve additional improvements with an advanced sleep mode (labeled "sleep mode 2" in Figure 7) in an ONU, thanks to dedicated hardware designs that feature a lower sleep power and allow for a faster wake-up. We also considered the ability to power off unused functions in the OLT. A virtual home gateway (HGW) runs typical home gateway functions, such as routing, OAM (operations, administration, and maintenance), and security, on a central server in the network instead of a processor on the customer premises equipment (CPE). GreenTouch demonstrated up to a thousand virtual HGW on a single server, which results in a 5x saving of processing power despite a penalty for air-conditioning in the server location [15]. Long-reach PON reduces the power consumption in the provider's network thanks to a better sharing of the line termination, which is moved to the edge router location, and a reach extender, which is simpler than the bypassed aggregation switch (AS). While many reach extension solutions reported in the literature require a higher rate and more demanding optics, which then increase the power consumption in the CPE, GreenTouch follows an approach that does not affect the power consumption of the CPE [16].

In the long term, more disruptive concepts are being investigated by GreenTouch. A transparent, quasi-passive CPE realizes connectivity between the first mile and the home network by a simple repeater, or in its ultimate form, even a fully passive device [17]. The functions of a conventional CPE can be moved to a virtual HGW server as described above.

Bit Interleaving PON (Bi-PON) is a new time division multiplexing transfer protocol that reduces the power consumption of digital electronics for protocol processing by more than an order of magnitude, as GreenTouch demonstrated in [18], [19].

In a conventional packet-based PON system, every ONU 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. Much power is consumed in processing this high throughput, most of which is unnecessary. 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. Progress in optical components and electronic circuit technology will further aid energy efficiency.

We have developed an analytical model for wireline access network energy consumption to combine the described approaches, along with the contribution of Moore's law for improvements in semiconductors by 2020. Based on this model, we demonstrate that it is possible to reduce the average power consumption per subscriber of a wireline access and aggregation network by more than 50x. In order to calculate the energy efficiency, we integrated the total energy consumption per subscriber over a year and divided it by the traffic over that same period. Considering a traffic growth of 8.4x per subscriber (i.e., a single family unit) and 15% growth in the number of subscribers in a mature market between 2010 and 2020, this results in an improvement of energy efficiency per transferred bit of 449x. For the assumed wireline access reference network and traffic growth, its total energy consumption can be reduced by 98%.

5. Core Networks

In this section, we provide technical details for energy efficiency improvements for core networks. Quantifying these potential improvements provides a significant challenge because of the diversity of available network architectures and technologies that can be applied in core networks. The traffic from the Mature Market segment spans the globe and so both terrestrial and inter-continental networks are involved. This fact of itself presents a significant hurdle. Optimizing the architecture of a global network that will include hundreds of nodes is extremely computationally intensive. Therefore, our first approach to model the core network involves a range of simplifications to make the model tractable. Despite this, the model provides an order of magnitude of what may be possible when improving the energy efficiency of core networks.

We have investigated the energy efficiency improvement obtained by implementing a number of techniques in the core network, including GreenTouch developments in:

i. improved components with lower power consumption,

ii. mixed line rates (MLR) [20] by selecting the power optimal combination of 40G, 100G and 400G interfaces for the given traffic distribution,

iii. sleep and low energy state modes [21], and

iv. physical topology optimization with respect to the diurnal cycles [22], [23].

Quantification of the efficiencies provided by these improvements was contributed by GreenTouch projects. A family of Mixed Integer Linear Programming (MILP) models was built to optimize the network when implementing these energy-efficiency techniques. For the purposes of our first model we adopted the well-known continental research network topology of NSFNet. Although this network is not a typical modern day trans-continental network, it is a well-known and understood mesh network. Further, optimizing this network is within the computing resources currently available. In subsequent refinements of the Green Meter, a larger, more representative network will be adopted. However, it is not expected that this will make a significant change to the efficiency improvements estimated using NSFNet.

Device	Power Consumption 2010	Power Consumption 2020
Router Port	440 W	16 W
Transponder 40Gb/s	148 W, 2500 km reach	5.5 W, 2500 km reach
Transponder 100 Gb/s	Not widely deployed in field	6.4 W, 2000 km reach
Transponder 400 Gb/s	Not deployed In field	7.2 W, 150 km reach
Regenerator 40 Gb/s	22.2 W	8.25 W
Regenerator 100 Gb/s	Not widely deployed in field	9.6 W
Regenerator 400 Gb/s	Not deployed in field	10.8 W
EDFA	52 W	12.5 W
Optical switch	85 W	8.5 W

Table 9: Power consumption of network equipment and reach of transponders [25], (Power usage efficiency (PUE) of 2 and 1.5 in 2010 and 2020 respectively).

Table 9 shows the equipment power consumption of the 2010 network and 2020 network [25]. In the 2020 network, the continuation of current energy efficiency improvement trends in the router ports, transponder and regenerators is expected to provide an energy efficiency improvement factor of 3.6 and the Power Usage Effectiveness (PUE) is reduced from PUE=2 in 2010 to PUE=1.5,; that is, reduced by a factor of 1.33. We need to complement these trends with the improvements expected from the GreenTouch initiatives listed above. For 2020 and implementing the GreenTouch technology projections, power consumption by routers, transponders and regenerators is reduced by a factor of 27x compared to the 2010 network. This factor includes the 3.6x Moore's law reduction, power consumption reductions of 1.5x due to the introduction of energy-efficient optical interconnects and a reduction factor of 5x due to improved system design and integration.

Note that the net equipment power consumption reduction is estimated to be about 27.2x, which is smaller than the 35.9x obtained by simply multiplying all the individual contributing factors. This is because (a) the factors of 1.5x, 5x, 3.6x and 1.33x apply to routers and transponders, but not to EDFAs (optical amplifiers) and optical switches. In 2020 the power consumption of routers and transponders becomes low and the EDFAs' power consumption becomes important. From Table 9, in 2020 the router port and transponder power consumption at rates of 40Gb/s to 400Gb/s is 5W-7W. The EDFA is 12.5W. And, (b) EDFAs and regenerators are deployed in the field, so in 2010 and in 2020 a PUE of 1 is used. As a result the PUE reduction factor considered for 2020 does not affect the EDFAs.

We evaluated the total energy consumption of a 2010 network and a 2020 network. The 2010 network energy consumption is based on the best commercially deployed equipment in 2010, and the network design and routing practices of 2010. Referring to the list of energy efficiency technologies, the 2010 network is based on 40Gb/s router ports, without the use of sleep or low energy modes and without any network optimization that may be available due to the diurnal traffic cycle. Rather, the network is static in that it is designed and operated to accommodate the peak-hour traffic load without any adjustments and dynamic resource allocations being implemented during off-peak hours. In addition, optical bypass in the core network is not considered and all the traffic is processed by the IP routers in each hop of the core network. The 2020 network results are based on traffic projections presented above, along with the continuation of the current energy efficiency improvement trends (such as Moore's law) plus the introduction of the energy efficiency improvement measures listed above.

Figure 8 shows the 2010 network power consumption, which is constant independently of the traffic and is dominated by the power consumption of the routers and transponders. Figure 9 shows the 2020 network power consumption, where the traffic grows by a factor of 9.6x, but GreenTouch initiatives listed above have been implemented and a network facility PUE is reduced by a factor of 1.33x.

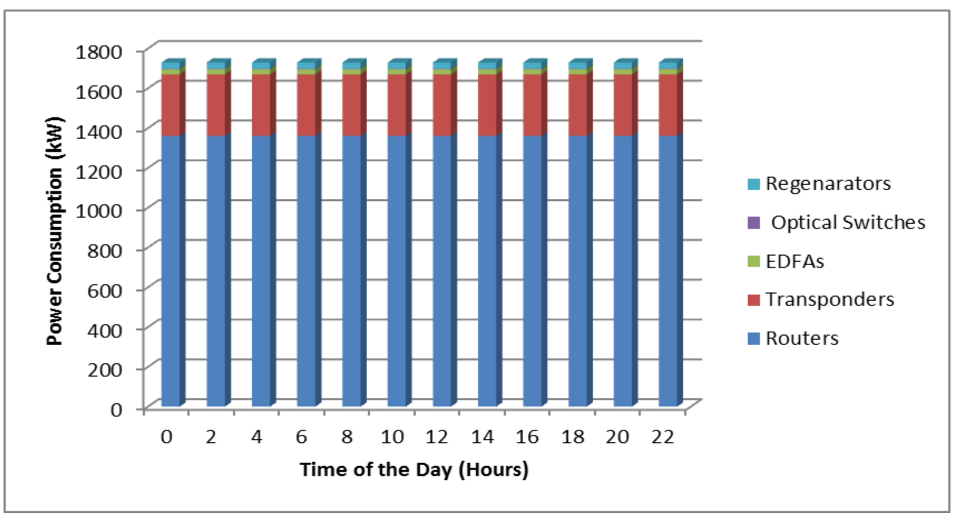


Figure 8: The 2010 network power consumption as a function of the time of day with the detailed breakdown of the component power consumption.

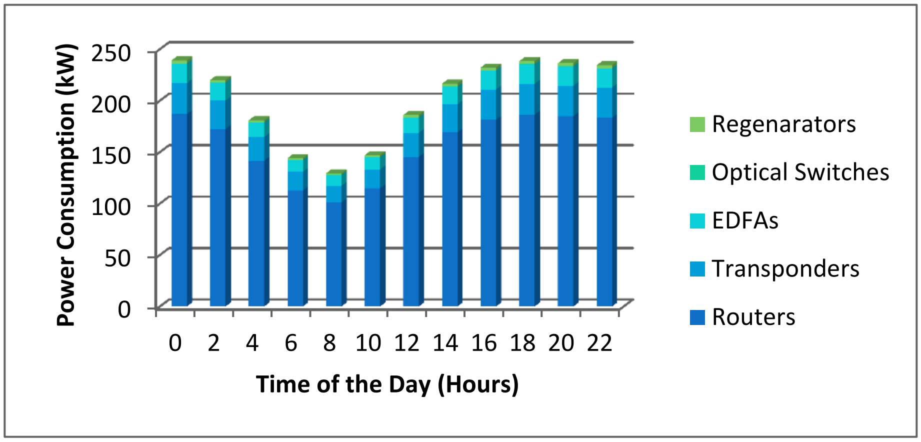
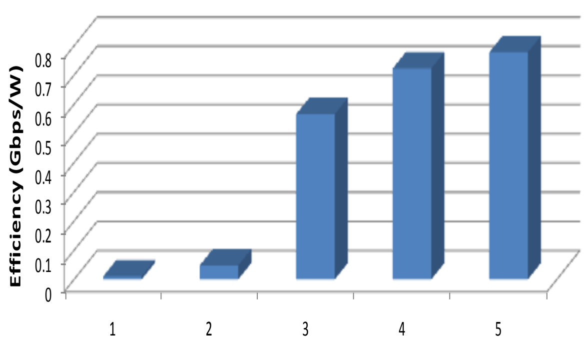


Figure 9: The 2020 network power consumption as a function of the time of day with the detailed breakdown of the component power consumption.

A summary of the GreenTouch initiatives for optimizing the 2020 network is shown in Table 10. Figure 10 shows the improvement in network energy efficiency in the 2020 network relative to the 2010 network. It also shows the relative contributions of the different technologies being considered.

Technology	Energy Efficiency Improvement Factor
Improved components with lower power consumption	27
Mixed line rates (MLR)	1.2
Optical bypass, sleep and low-energy state modes	1.8
Physical topology optimization	1.1
Overall efficiency improvement	64

Table 10: Energy efficiency gain factors per energy-saving approach and considered technologies for the core network.



1. Original NSFNET topology, 2010 components power consumption, 40 Gb/s, non-bypass
2. Original NSFNET topology, 2020 components power consumption, 40 Gb/s, non-bypass
3. Original NSFNET topology, 2020 components power consumption, sleep, 40 Gb/s
4. Original NSFNET topology, 2020 components power consumption, sleep, MLR
5. Optimized NSFNET topology, 2020 components power consumption, sleep, MLR

Figure 10: The energy efficiency of the network with 2020 component power consumption under different energy saving techniques.

As work on the GreenTouch technologies continues, we can expect these values to change with the development and greater understanding of new technologies and their potential applications. For example, an active topic of discussion is the use of data compression. Further evolution in compression algorithms for video and data can be expected to save bandwidth by 2020. A GreenTouch analysis showed that this also aids overall energy network efficiency despite the extra energy required for compression. It is, however, debatable whether better compression by new algorithms can be performed at the application layer and can therefore be assumed for all content before it enters the network, or whether additional compression functions can be embedded in the network to make up for content that is compressed with legacy technology and not with the latest and most efficient algorithms. We have investigated the potential use of compression in the network and it provides an additional efficiency gain that would yield an overall energy efficiency improvement in the core network of up to 95x.

Optimizing the topology may also provide an improvement factor if a full mesh is deployed to serve nodes with symmetric traffic. The traffic considered in this work is attributed to population size in a given node and as a result the nodes (cities) produce varying amounts of traffic. Currently, operators divide a large city into multiple nodes, so that each node in the network serves a comparable population size. Such additional refinements in topology design can lead to further energy saving. In addition with a full mesh and hence a direct route to each destination, the reliance on IP layer routing can be reduced in the core with the potential of significant power saving [23]. Further improvements are possible through a range of additional identified measures including optimum caching and content placement, reducing the protection redundancy, reducing the overprovisioning redundancy and through better topology design. These additional measures are currently being actively pursued within GreenTouch and we expect to report on our research findings in the future and subsequent updates of the Green Meter.

6. Summary and Next Steps

This white paper describes the initial results from the Green Meter research study conducted by GreenTouch. This study demonstrates that it is possible to reduce the net energy consumption in communications networks by up to 90% compared to 2010 while accounting for the traffic growth between 2010 and 2020. The study also highlights a roadmap of technologies that are able to achieve these results and their individual energy efficiency benefits. The results of the Green Meter study are summarized in Table 11.

	Energy Efficiency Improvement Factor (2010 vs. 2020)	Traffic Growth (from 2010 to 2020)	Net Energy Reduction of 2020 Relative to 2010
Mobile Access	1,043x	89x	>90%
Wireline Access	449x	9.6x	98%
Core Network	64x	9.6x	85%

Table 11: Summary of the Green Meter research study with the energy efficiency gains, traffic growth and net energy reductions that can be achieved in the mobile access, wireline access and core networks.

While the Green Meter research study presents a significant advance into our understanding of future energy-efficient communications networks and describes a portfolio of promising technologies, more research work remains and more opportunities for additional gains present themselves. GreenTouch continues on its mission towards improving the energy efficiency of communications networks. Several current research projects and activities underway in GreenTouch have not yet been included in these calculations and the results described in this white paper. Some of these technologies include a massive deployment of small cells and the separation of the control and data planes in mobile networks. We are also investigating intelligent algorithms and control mechanisms for efficiently turning small cells on and off to provide on-demand coverage and capacity. The benefits of large scale antenna systems from an overall system energy efficiency perspective are also being studied. In the core network we are conducting research into energy-optimized content distribution, storage and processing. Significant research activities are ongoing in all of these areas, and we expect to include the results from these activities in future updates of the Green Meter calculations. GreenTouch will also continue to demonstrate key technologies that are contributing to the overall research study and confirming or refining our understanding of the predicted energy efficiency improvements.

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About 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.

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