GreenTouch Final Results from Green Meter Research Study

Reducing the Net Energy Consumption in Communications Networks by up to 98% by 2020

A GreenTouch White Paper

Version 1.0

June 18, 2015

Executive Summary

It goes without saying that information and communication technologies (ICT) are at the heart of the digital economies and play an increasingly important part of all of our personal and professional lives. Their impact spans virtually all industrial sectors, from agriculture, transportation, construction to education and healthcare. Ensuring a sustainable growth, both from an environmental and economic perspective, is vitally important and one of the key challenges for our industry. It is with this goal in mind that the GreenTouch consortium [1] was founded in 2010 with the incredibly ambitious mission to improve the energy efficiency of communication networks by a factor 1000x compared to 2010. It was also a stated objective to provide, by 2015, a roadmap of architectures, specifications and solutions and to demonstrate key technologies to accomplish this goal. A moon shot objective for the research community!

This GreenTouch white paper, issued after the end 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 entire portfolio of technologies, architectures, components, devices, algorithms and protocols being invested, investigated, developed and evaluated 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 these technologies being considered. It also explicitly includes the traffic growth into the calculations of future network energy efficiencies and energy consumption.

GreenTouch publicly announced the results of the Green Meter Research study on June 18, 2015. The study concluded that it is possible through the combination of technologies, architectures, components, algorithms and protocols to reduce the net energy consumption in end-to-end communications networks by up to 98% by 2020 compared to the 2010 reference scenario defined by GreenTouch. 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 predicted between 2010 and 2020, is fueled by significant improvements in the energy efficiencies of the component networks:

- 10,000-fold increase of energy efficiency in mobile access networks
- 254-fold increase in energy efficiency in residential fixed access networks
- 316-fold increase in energy efficiency in core networks

This profound result demonstrates that we can support the predicted traffic growth in future networks while at the same time significantly reducing the total energy consumption of the networks. Increased traffic and increased performance do not have to come at the expense of increased energy consumption. 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. Additional white papers along with scientific publications accompany this white paper with further detailed information on the specific approaches, the evaluation and simulation methodologies and the performance results. More details can be found on the GreenTouch webpage [1]. GreenTouch has also publicly launched an interactive application, called "GWATT for GreenTouch" [2] to visualize the portfolio of technologies and their energy impact.

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. This private sector and academic global research consortium offers the most focused attempt for technology breakthroughs in network energy efficiency.

Initial GreenTouch research had indicated 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 research effort over the 5-year period has then focused on quantifying this energy efficiency improvement opportunity and to pave a real technology roadmap for accomplishing it. GreenTouch is very proud to state that it has been successful in its ambitious mission. 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. An interim report was published in June 2013 following the initial announcement by GreenTouch in May 2013 that its Green Meter Research study showed the potential for reducing the net energy consumption in communication networks by 90% by 2020 [3]. The GreenTouch announcement in June 2015 and the present white paper expands the initial study to now include the entire portfolio of technologies and solutions, some of which had not yet been evaluated in the first phase of the study.

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.

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 the details of the green meter calculations and results for the mobile communications networks. Section 3 provides the corresponding details for the fixed access networks and Section 4 similarly discusses the core backbone network. Finally, we summarize the findings in Section 5 and conclude on the impact that the GreenTouch results will have on the ICT industry and society at large.

2. Mobile Access Networks

The Mobile Working Group concentrated its activities on architectures and technologies that enable the radio access network to provide – in the most energy-efficient way – full coverage and the capacity and performance that will be needed in the year 2020. But, which technologies provide such high energy efficiency and how to calculate the energy efficiency of a mobile network?

Technologies

The Mobile Working Group focused its investigations on the following technologies organized in three umbrella projects:

(i) The ***Beyond Cellular Green Generation (BCG^2)*** project goes beyond the traditional network architecture by using small cells, and by completely separating the signaling and data functions at the wireless interface. With their reduced distance between the network and user terminals, these small cells consume less energy than traditional macro cells, but we need many more of them and at any given time many of them will not be serving active users. By separating the signaling and data functions the small cells can be turned on and off when needed, making the energy consumption proportional to traffic load and the energy efficiency extremely high. A separate lightweight signaling infrastructure provides continuous network accessibility so that communication services can be requested at any time by users.

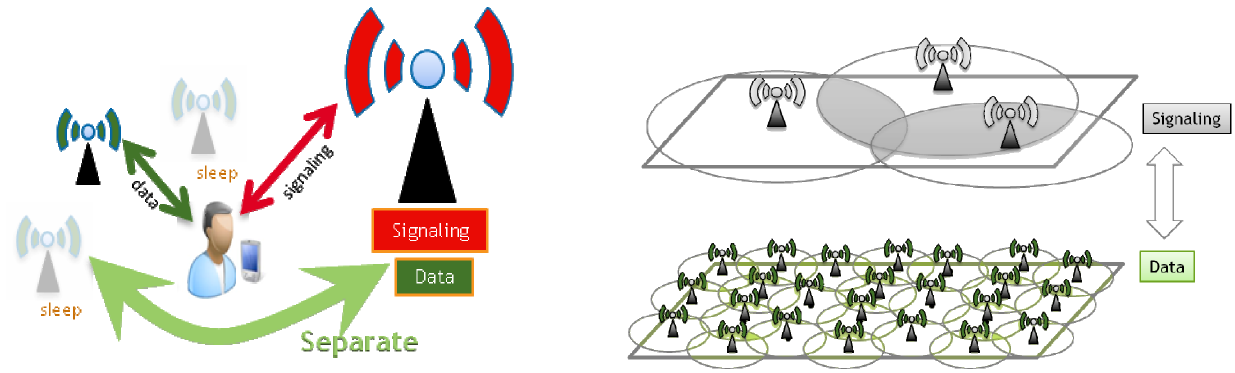


Figure 1: BCG2 architecture with separation of control and data plane functionalities

(ii) The **Large Scale Antenna Systems (LSAS)** approach eliminates sectorization and utilizes a large number of physically small, low-power, individually controlled antennas to create a multiplicity of user-selective beams of data. Doubling the number of service antennas improves the selectivity and permits the total radiated power to be cut in half with no effect on the quality of service. Aggressive multiplexing serves all users over all time/frequency resources, which yields the desired spectral efficiency, and therefore throughput gains. Effective power control ensures uniformly good service for the users, even at the edge of the cell. The energy consumption depends on the emitted power, the inefficiency of generating transmit power and on the power consumption of internal electronics, which is proportional to the number of service antennas as well as the power required for the LSAS-critical signal processing. Optimization algorithms resolve the fundamental tradeoff that more antennas reduce the required radiated power, but increase internal power consumption.

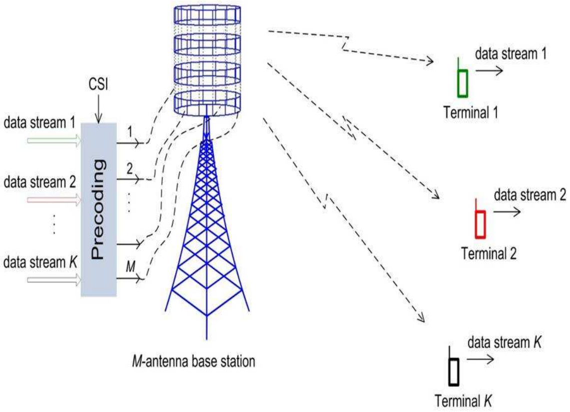


Figure 2: Large Scale Antenna System (LSAS) architecture

(iii) The **Green Transmission Technologies (GTT)** project focused on the fundamental tradeoff between energy efficiency (EE, defined in bits per second per Watt) and spectrum efficiency (SE, defined in bits per second per Hertz). In bandwidth-limited situations, the network EE optimization problem is formulated under the EE-SE tradeoff framework, and various solutions are proposed to best utilize all available resources. These strategies include Dynamic MIMO (Multiple Input Multiple Output) with antenna sleeping, which selects between single-user beamforming and multi-user multiplexing with the optimal number of active antennas. Interference alignment is another technology that is investigated to eliminate the strongest interference produced by a large set of neighboring base stations. The GTT project has developed a methodology to integrate all the different technologies. Dynamically the best performing technology is selected for any given environment and traffic situation.

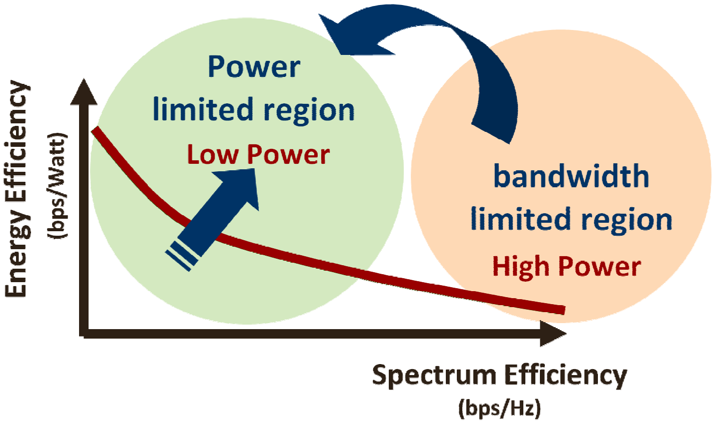
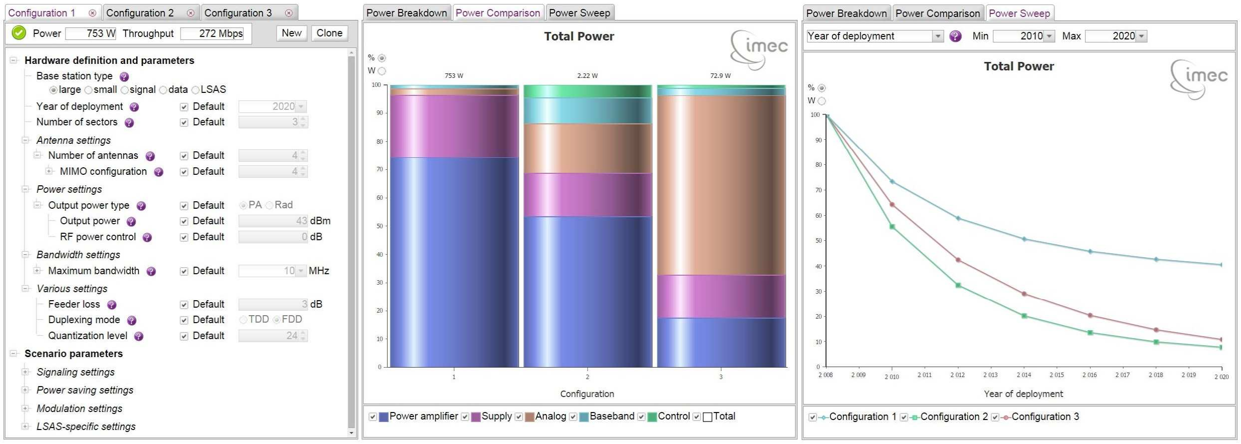


Figure 3: Green Transmission Technologies (GTT) and the tradeoff between energy and spectral efficiency

(iv) An advanced ***power model*** has been developed that provides realistic hardware power consumption values for a diversity of cellular base station types and operation conditions, while incorporating hardware technology trends. The power model has enabled the development of innovative energy-efficient network concepts exploiting the capabilities offered by hardware technology. GreenTouch is convinced that this power model can become a general reference and an industry standard, as it offers a uniform and fair comparison for energy optimization of the mobile network. The clear forecasts of hardware capabilities and power consumption are suitable design guidelines for component and base station manufacturers. Network providers and operators may exploit this knowledge to develop network concepts and deployment strategies for current and future networks. To stimulate the global usage of the advanced power model, a free online web-tool version is available at www.imec.be/powermodel.



Power 753 W Throughput 272 Mbps

Hardware definition and parameters
- Base station type: ● large ○ small ○ signal ○ data ○ LSAS
- Year of deployment ☑ Default 2020
- Number of sectors ☑ Default 3
- Antenna settings
  - Number of antennas ☑ Default 4
    - MIMO configuration ☑ Default 4
- Power settings
  - Output power type ☑ Default ● PA ○ Rad
    - Output power ☑ Default 43 dBm
    - RF power control ☑ Default 0 dB
- Bandwidth settings
  - Maximum bandwidth ☑ Default 10 MHz
- Various settings
  - Feeder loss ☑ Default 3 dB
  - Duplexing mode ☑ Default ○ TDD ● FDD
  - Quantization level ☑ Default 24

Scenario parameters
- Signaling settings
- Power saving settings
- Modulation settings
- LSAS-specific settings

Figure 4: Screenshots of the online power model tool

Network Architecture

The architecture subgroup was in charge to define the most energy efficient mobile architecture build from the technologies developed in the umbrella projects. To evaluate the energy efficiency for a hypothetical nationwide wireless network a methodology was developed and used to benchmark all proposed approaches and technologies. The final mobile architecture is then created by selecting the most energy-efficient technologies separately for each deployment area, such as city centers or country sides.

The energy efficiency of mobile networks depends on the usage pattern and is measured as the electrical energy spent per transmitted data volume averaged over a period of time, i.e., in Joules per bit. The efficiency of a nationwide operator network is then obtained by averaging the energy spent over a wide range of deployment and operational conditions, from busy hours in metropolitan areas down to rural areas at night times with very low traffic demand. Network traffic patterns were analyzed and a representative traffic model was defined for all the use cases, including user densities as well as the anticipated, near-exponential rise in mobile data traffic between 2010 and 2020.

Energy Efficiency Improvement Results

The complementary set of several models is used to predict the overall network behavior, and the energy consumption and energy efficiency for a variety of deployments across technologies and environments: for example, the massive roll-out of small cells or for futuristic base stations with hundreds of antennas or new management schemes with intelligent sleep modes. To calculate the potential energy efficiency gains for the GreenTouch technologies and solutions, a reference scenario using the best available technologies and traffic data from the year 2010 has been defined. This reference energy efficiency is then compared with the efficiency of the GreenTouch mobile architecture assuming the traffic volume and patterns for the year 2020 and the selected most energy-efficient technologies.

By using this methodology, the most energy efficient architecture is comprised of different technologies, each being optimized for a different environment. Table 1 shows the improvement factors that can be achieved separately for each environment. It unveils that the LSAS technology in combination with the separated signaling system from the BCG^2 project outperforms all other technologies in dense urban environments. The BCG^2 signaling system also boosts the performance of the GTT technologies in the urban, sub-urban and rural environment.

Improvement Factor	Dense Urban	Urban	Sub Urban	Rural
BCG^2	8118	9214	2629	3959
GTT	5336	7391	6922	5216
LSAS+BCG^2	14485	10507	2547	1640
GTT+BCG^2	7690	14378	12367	7364

Table 1: Energy efficiency gains for different deployment environments and different mobile architectures and technologies

Our analysis shows that, by combining these technologies in the optimized architecture, it is possible to achieve a nationwide energy efficiency improvement of more than a factor of 10,000 in relation to the 2010 reference scenario. The traffic in the mobile access network is predicted to increase 89-fold between 2010 and 2020. Even with the much higher traffic anticipated in 2020, the network energy consumption can be lowered by a factor of 110 due to the significant improvement in network energy efficiency.

3. Fixed Access Networks

Traffic

GreenTouch traffic projections for Group 1 countries (Northern America, Western Europe, and Japan) indicate that the traffic volume passing the fixed access network is more than 85% of the total IP traffic, where 73% comes from residential traffic and the remaining 12% from business traffic. Compared to the earlier version of our Green Meter analysis [3] [12], we have developed a more complete model taking into account both residential and business traffic, and within each of these categories, accounting for both Internet and managed IP traffic sub-categories. The total residential traffic grows by 8x between 2010 and 2020 as shown in Table 2. Using the number of subscribers and the percentage of downstream versus upstream traffic, we estimate the data rates required per residential broadband subscriber as shown below.

	2010	2020
Residential traffic	11,122 PB/month	88,225 PB/month
Number of residential subscribers	245 million	281 million
Average downstream bit rate per subscriber	109 Kb/s	796 Kb/s
Provisioned bit rate per subscriber at busy hour	1.75 Mb/s	12.73 Mb/s

Table 2: Residential fixed access traffic data for Group 1

For business traffic, we base our analysis on the traffic and subscriber data for USA as data on the number of subscribers was not available for the entire Group 1 countries. We similarly estimate the data rates required per business broadband subscriber as shown in Table 3.

	2010	2020
Business traffic	1,320 PB/month	7,281 PB/month
Number of business subscribers	7.32 million	9.71 million
Average downstream bit rate per subscriber	356 Kb/s	1482 Kb/s
Provisioned bit rate per subscriber at busy hour	11.4 Mb/s	47.43 Mb/s

Table 3: Business fixed access traffic data for USA

We consider fiber-to-the-premise (FTTP) architectures as these are the most energy efficient compared to other access mediums. 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.

Technologies

This section summarizes the different technologies that were considered in the Fixed Access Green Meter analysis. For the baseline residential access technology in 2010, we considered Gigabit Passive Optical Network (GPON) based FTTP solution as this was the most energy-efficient commercially deployed technology at the start of GreenTouch. Similarly, we considered the Gigabit Ethernet (GbE) Point-to-Point (PtP) fiber access as the baseline business access technology in 2010.

We assessed the effect of different energy saving approaches on the main sub-systems such as the optical network unit (ONU) and the optical line termination (OLT). We also included the metro aggregation network containing the aggregation switch (AS) and the edge router (ER) in order to evaluate the effect of technologies that bypass the local exchange thus extending the reach of the access network. The edge router interfaces with the core network described in Section 4. For many of the sub-systems, we broke down the power consumption into sub-components pertaining to the opto-electronic transceiver (OE) and the digital electronics. In the case of the ONU, in addition to the access OE interface, we further broke it down into the access protocol processing, home gateway (HGW) processor and wireline Ethernet interfaces to the local area network (LAN) as sub-components.

Business-as-usual (BAU) improvements to power consumption include the following contributions: Moore's law providing 2.7x savings for the analog sub-components and 3.83x savings for digital sub-components; 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; energy efficient hardware design refers to engineering optimizations (e.g., reduced data transfers across input/output (I/O) of integrated circuits by further integration) that result in an overall power reduction of about 20%; and more efficient cooling techniques in central offices leading to 25% power reduction.

In the GreenTouch network architecture for 2020, we envisage more disruptive concepts some of which we have also shown in physical demonstrators.

(i) ***Cascaded Bi-PON:*** Bit-interleaved PON (Bi-PON) is a new protocol that allows extracting the relevant bits for the ONU immediately behind the clock and data recovery [13]. Further processing is done at the lower user rate instead of the aggregate line rate, which results in more than an order of magnitude power savings as GreenTouch demonstrated in [14], [15]. We recently extended the Bi-PON concept to multiple cascaded levels, namely a Cascaded Bi-PON [16], which results in a long reach access network and thus better sharing of the line termination. In addition, the frame structure is designed such that intermediate *repeater* nodes performing a simple down-sampling function can efficiently extract only the portion of data that is relevant to the nodes subtending that repeater. This leads to 5x savings at the aggregation point and 4.5x savings at the ONU protocol processing and switching functions.

(ii) ***Virtual Home Gateway*****:** In the baseline network, HGW service functions (e.g., forwarding, firewall, network address translation) are physically located at dedicated resources at every ONU and thus energy-consuming. We virtualize these functions into "containers" that are hosted on central servers in the network operator's infrastructure allowing us to exploit scaling and sharing of resources to realize energy savings [17]. We study in particular the energy aspect of this technique and demonstrated that we can host 1000 virtual home gateways on a single server consuming 110W [18]. This results in 165mW power consumption per user accounting also for cooling for the server. Compared to equivalent functions consuming about 1.2W in the baseline network, this technology provides 7.5x savings at the HGW processor sub-component.

(iii) ***Redesigned Point-to-Point Optical Transceiver:*** Conventional point-to-point optical transceivers operate continuously at a high and fixed optical power and the electronic-to-optical signal conversion efficiency is relatively low [19]. We have completely redesigned the transceiver and custom-built an ASIC prototype that minimizes the circuit power consumption for a target data rate up to 1 Gb/s. The savings are enabled by better system integration, optimizing the driving circuitry and signaling, and adapting the transmitter power based on the link distance [20], [21]. A nominal power consumption of 27mW was measured in the lab, which could be further reduced to as little as 12mW with the full benefit of the adaptive power control algorithm. Compared to conventional state-of-the-art optical transceivers, this represents a 17x to 38x improvement [18].

(iv) ***Sleep Mode:*** Power consumption is reduced by switching components from the full power active state to a low power sleep state depending on the traffic load and redundancy requirement. Cyclic sleep mode [22] is used at the access (cf. ITU-T G.987.3) and Ethernet LAN (cf. IEEE802.3az) interfaces and the achieved power savings are estimated based on [23]. In the case of PON based access, where a point-to-multipoint topology applies, cyclic sleep mode is applicable only at the ONU interface; since the OLT interface is shared, the savings at the OLT are smaller. Where a point-to-point topology applies, as is the case in PtP fiber access and Ethernet LAN links, cyclic sleep mode is applicable symmetrically at both ends of the link leading to larger savings. At the AS and ER, we account for turning stand-by elements (provisioned for redundancy) to a sleep state such that a quick turn on is ensured.

(v) Finally, progress in optical components (1.33x) and electronic circuit technology (3x) will further reduce power at the applicable sub-components.

Network Architecture

In this section, we describe how the key technologies are integrated in the GreenTouch network architecture for the 2020 residential and business access networks.

The GreenTouch residential access network (Figure 5) is based on a long reach access architecture enabled by Cascaded Bi-PON where the OLT is co-located with the ER. The network has 3 bit-interleaved levels in cascade with a repeater in the metro ring (replacing the AS) and another repeater built into the ONU eliminating the need for switching functionality. On top of this network, we use virtual home gateways, GbE PtP fiber links using our redesigned optical transceiver for the LAN interfaces, together with sleep mode.

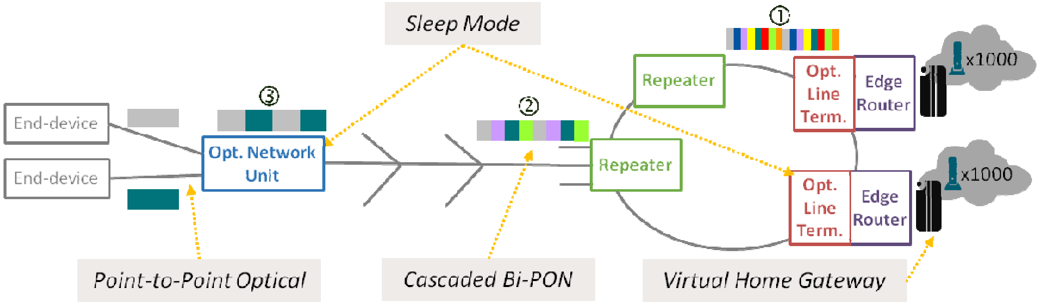


Figure 5: Network architecture of GreenTouch residential access network

In the GreenTouch business access network (Figure 6), we adopt GbE PtP access technology using our redesigned low power optical transceiver. In addition, we also use GbE PtP fiber links for the LAN interface, and the sleep mode capability.

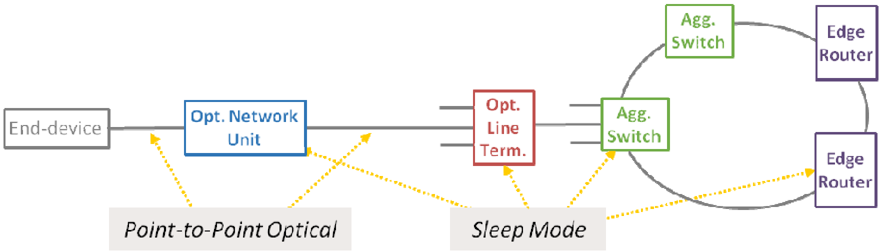


Figure 6: Network architecture of GreenTouch business access network

Based on the estimated bit rates in Tables 2 and 3, we then perform a detailed dimensioning of all the network elements in the architecture which is omitted here for brevity.

Energy Efficiency Improvement Results

The Fixed Access Green Meter methodology brings together this portfolio of technologies and assesses their individual and collective impact on energy savings. In particular, our results shown in Figure 7 demonstrate that, for the residential access network, the average power consumption per subscriber (considering both the access and metro sections) is reduced by 4x using only BAU improvements, whereas the GreenTouch network brings together a power reduction of 37x. Correspondingly, in the business access network, the average power consumption per subscriber is reduced by 2x with only BAU improvements, and by 7x using the GreenTouch network.

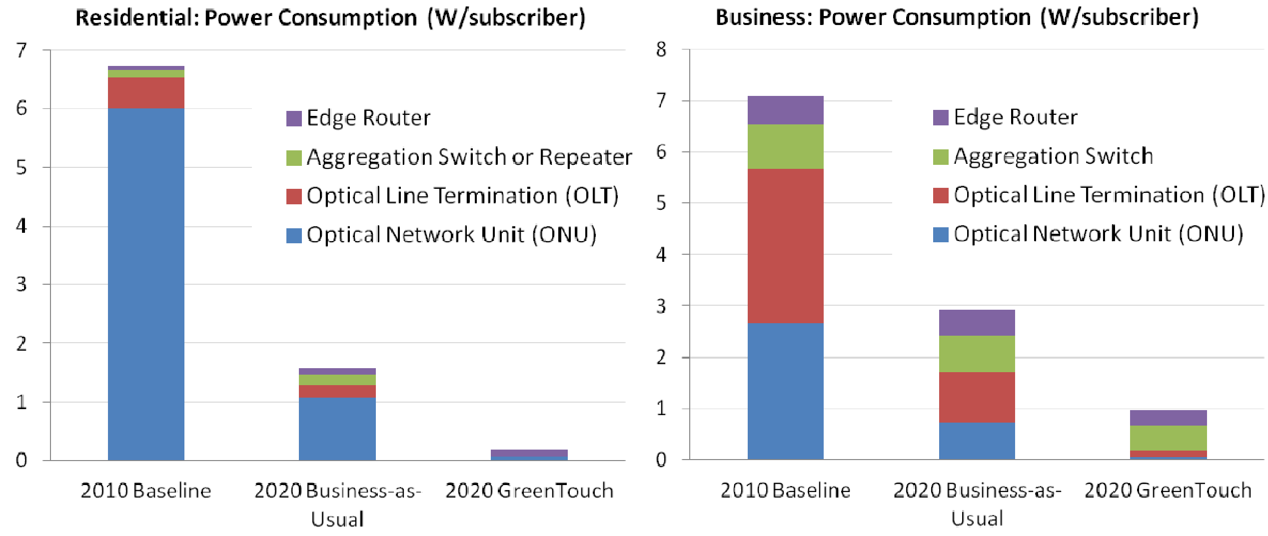


Figure 7: Power consumption improvement in residential and business access networks

In order to calculate the energy efficiency, we divided the total traffic over a year by the total energy consumption for each subscriber integrated over that same period. As given in Table 4, energy efficiency can be improved by 254x for the residential access network and by 30x for the business access network relative to the 2010 reference scenarios.

	Residential Fixed Access		**Business Fixed Access**	
	2010 Baseline	**2020 GreenTouch**	**2010 Baseline**	**2020 GreenTouch**
Energy Efficiency	20.5 Kb/J	5200 Kb/J	77 Kb/J	2343 Kb/J
Energy Efficiency Improvement Factor relative to 2010		254x		30x
Energy Consumption per Year for all Group 1 subscribers	14.47 TWh	0.45 TWh	941 GWh	171 GWh
% Energy Savings per Year versus 2010		97%		82%
Analogies - Annual GHG emissions from cars		2,035,000		112,000

Table 4: Energy consumption and energy efficiency in residential and business access networks

4. Core Networks

In this section, we describe the energy efficiency improvements in core networks obtained as a result of work carried out in GreenTouch over the past 5 years. We again consider the traffic from Group 1 countries and place this traffic on a representative US continental network topology (Figure 8). This topology is then further optimized as part of our research effort.

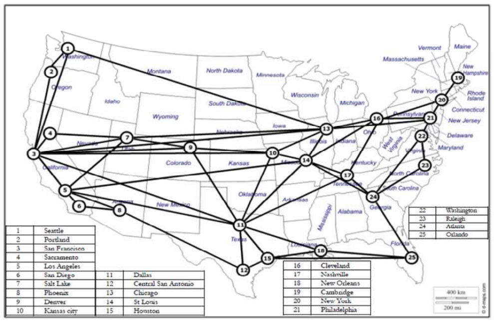


Figure 8: Sample network topology for a continental core network

Technologies

A number of techniques that yield substantial energy savings in core networks were introduced. These techniques include:

(i) Improved network components with lower power consumption. Routers and transponders are the main power consuming components. Power consumption reduction beyond Moore's law was achieved in routers through the introduction of optical interconnects and packet processing adapted to packet sizes. In transponders power savings beyond Moore's law were achieved through optical interconnects and improved Digital Signal Processors with voltage and frequency scaling for lower power consumption.

(ii) Intelligent management of protection resources activated only when required. Traditional protection provides backup routes that are always powered on. We introduced optimum protection routes that are only powered on when needed following a failure.

(iii) Allowing sleep modes in components such that the utilization of these components follows the diurnal traffic pattern. This results in significant savings in all network equipment including routers, transponders, regenerators, amplifiers and optical switches. As routers are the most energy consuming components, we introduced optimized routing strategies that optically bypass intermediate routers [24].

(iv) The use of mixed line rates (MLR) [25] in such a way that an appropriate combination of wavelength rates is chosen for minimal energy consumption. The power consumption of routers and transponders does not grow linearly with data rate and therefore there is an optimum combination of transponders and routers (operating for example at 40, 100, 400 and 1000Gb/s) that result in the minimum power consumption when serving a given traffic demand.

(v) Optimization of the network physical topology through the allocation of direct links between nodes [26]. Direct links between nodes reduce the network average hop count which in turn reduces the network power consumption. Such direct long links may however result in additional power consumption and therefore our optimization identifies the topology that results in minimum power consumption.

(vi) The use of optimized distributed clouds for content distribution [27], content caching [28] and network equipment virtualization [29]. Serving content from a central location in the network results in added journey in the network to access content. We have introduced distributed clouds that bring popular content closer to the users hence saving power and have extended the approach to processing performed on virtual machines where such virtual machines are brought closer to the user. We have also jointly optimized the virtualization of the network functions, processing and storage to minimize the power consumption.

A mixed integer linear programming (MILP) model combining all the aforementioned techniques was built to optimize energy consumption in the core network. IP over WDM was used as the underlying technology.

Table 5 shows the equipment power consumption values of the 2010 network and the 2020 network. The most energy efficient and commercially available core network equipment in 2010 was used for the 2010 network.

Device	Power Consumption in 2010	Power Consumption in 2020
Router Port 40 Gb/s	825 W	21.3 W
Router Port 100 Gb/s	Not widely deployed	39.2 W
Router Port 400 Gb/s	Not widely deployed	46.7 W
Router Port 1000 Gb/s	Not widely deployed	53.9 W
Transponder 40 Gb/s	167 W, reach 2500 km	27.6 W, reach 2500 km
Transponder 100 Gb/s	Not widely deployed	86 W, reach 1200 km
Transponder 400 Gb/s	Not widely deployed	332.6 W, reach 400 km
Transponder 1000 Gb/s	Not widely deployed	801.3 W, reach 350 km
Regenerator 40 Gb/s	334 W, reach 2500 km	55.2 W, reach 2500 km
Regenerator 100 Gb/s	Not widely deployed	172 W, reach 1200 km
Regenerator 400 Gb/s	Not widely deployed	665 W, reach 400 km
Regenerator 1000 Gb/s	Not widely deployed	1602.6 W, reach 350 km
EDFA	55 W	15.3 W
Optical Switch	85 W	8.5 W

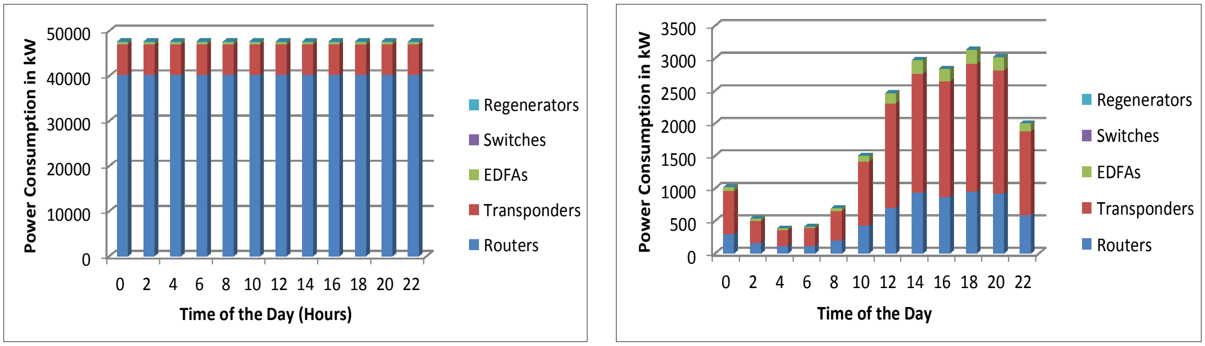
Table 5: Power consumption and reach of network components in 2010 and 2020 networks

The 2020 equipment power consumption is obtained by applying expected Moore's law energy efficiency improvements due to advanced CMOS technologies as well as improvements attributed to GreenTouch initiatives. These improvements affect routers and transponders differently with routers expected to improve more than transponders. Routers are expected to improve by 39x due to the combination of GreenTouch and Business as usual improvements, while transponders and regenerators are expected to improve by 6x. As mentioned the key GreenTouch initiatives in equipment power consumption improvements include the use of optical interconnects, packet size adaptation techniques to minimize packet processing power in routers and the use of dynamic voltage and frequency scaling in transponder DSPs [30], [31]. Erbium Doped Fiber Amplifiers (EDFAs) will only improve according to Moore's law on the part of the control electronics without any significant improvements in the optics power consumption. It should however be noted that at the network level, improvements due to components are much lower than the direct application of ratios for each component. This is due to the fact that these components are used in different proportions and the Power Usage Effectiveness (PUE) values used for 2010 and 2020 are different. The PUE is reduced from PUE=2 in 2010 to PUE=1.5 in 2020. A conservative value of the PUE for 2020 has been used for telecommunications despite data centers having reported PUE values that are approaching one.

Energy Efficiency Improvement Results

The total energy consumption for both the 2010 network and the 2020 network was evaluated. The 2010 network energy consumption is based on the best network design and routing practices of 2010. The 2010 network uses only 40Gb/s router and transponders, without any use of sleep or low energy modes. Protection and working resources are both kept active in 2010 and there is no network optimization or responsiveness to the diurnal traffic cycle. In 2010 the core network is designed to accommodate peak hour traffic and remains static consuming the same amount of power even in off-peak hours. In addition, router processing takes place at each intermediate node as there is no optical bypass. The 2020 network, in addition to the equipment power consumption improvements, uses the techniques presented above to improve the energy efficiency in the network.

Figure 9 shows the 2010 and 2020 network power consumption. In 2010 (Figure 9(a)) the network power consumption is dominated by routers and transponders and it is constant and does not vary with traffic during the day. Figure 9(b) shows the 2020 network power consumption where the traffic has grown by a factor of 12x and all the GreenTouch energy efficiency initiatives are implemented with a PUE factor of 1.5x.



(a) (b)

Figure 9: (a) 2010 Network Power Consumption at Different Times of the Day for Individual Network Components, (b) 2020 Network Power Consumption at Different Times of the Day for Individual Network Components with GreenTouch Initiatives Implemented

The individual energy efficiency contributions of each technique introduced by GreenTouch in the optimized 2020 network are summarized in Table 6.

	Technology	**Improvement Factor**
1	Improvements in Equipment Power Consumption	20x
2	Intelligent Energy Aware Protection	1.9x
3	Optical Bypass and Low Energy State Modes	2.13x
4	Mixed Line Rates	1.21x
5	Physical Topology Optimization	1.43x
6	Distributed Clouds for Content Delivery and Network Equipment Virtualization	2.19x
	Total Improvement in 2020 due to GreenTouch Initiatives	**316x**

Table 6: Energy efficiency gain factors for various GreenTouch techniques in core networks

These techniques have provided a combined 316x improvement in the energy efficiency of core networks compared to the 2010 reference scenario defined by GreenTouch.

5. Summary and GreenTouch Impact

This white paper describes the final results from the Green Meter Research study and the accomplishments achieved by the GreenTouch consortium after its 5-year journey. The research study demonstrates that it is possible to reduce the net energy consumption in end-to-end communications networks by up to 98% by 2020 compared to 2010 while accounting for the traffic growth between 2010 and 2020. Networks of the future support more traffic and consume significantly less energy than today! At the scale of communication networks for North America, Europe and Japan, these energy savings would translate the equivalent greenhouse gas emissions from 5.8 million cars. 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 7.

	Energy Efficiency Improvement Factor (2020 vs. 2010 Reference Scenario)	Traffic Growth (from 2010 to 2020)	Net Energy Reduction of 2020 Relative to 2010
Mobile Access	10,000x	89x	99%
Fixed Access (Residential)	254x	8x	97%
Core Network	316x	12x	96%

Table 7: 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, fixed access and core networks.

The results demonstrated by GreenTouch are truly impressive and show that the potential for energy efficiency improvements across the communication networks are very tangible. From the initial Bell Labs-driven vision and a preliminary set of ideas, GreenTouch has moved to an entire portfolio of architectures, technologies, components and algorithms with specific methodologies to understand the energy performance of all these technologies.

GreenTouch invites all industry stakeholders and interested parties to review the findings from the consortium and to continue to build on these results. Information is made publicly available as follows:

- GWATT – An Interactive Application to Visualize the GreenTouch Results: http://gwatt.greentouch.org
- Power Model for Wireless Base Stations: www.imec.be/powermodel
- A series of white papers, scientific papers, presentations and project video are published and freely available on the GreenTouch webpage: www.greentouch.org

Without a doubt, GreenTouch has been successful in its very ambitious mission set forth in 2010 and the results and accomplishments cement its position as the global thought leader in Green ICT Technologies. Together these technologies pave the road towards ultra energy efficient and sustainable communication networks. The benefits of these networks span beyond the ICT sector and touch all industry sectors across the globe. Communication technologies are vital to bridge the digital divide and connect the unconnected in the world. Energy efficiency and the GreenTouch results are a key contribution and an enabler to a more productive and sustainable future for all of us.

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Contact and Further Information

For further information, please visit the GreenTouch web page at www.greentouch.org

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