



# **GreenTouch Architecture, Technologies and Green Meter Assessment for Fixed Access Networks**

**Improving the energy efficiency of residential  
fixed access networks by more than 250x by 2020**

**A GreenTouch white paper**

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# 1 Introduction

GreenTouch [1] was launched in 2010 to address the ever-increasing energy requirements of communication networks. In a comprehensive research study called the “Green Meter”, the research consortium assessed the overall energy efficiency benefits from an entire portfolio of GreenTouch architectures, technologies, components and algorithms. The results of this study have been published in the GreenTouch white paper [2] in 2015, and can be consulted online in the interactive GWATT tool [3]. In the present white paper, we focus specifically on the technologies and architectures developed for fixed access networks. We show how these solutions enable a 97% reduction in the net energy consumption, and equivalently a 257-fold improvement in energy efficiency, for residential fixed access networks from 2010 to 2020.

## 1.1 Traffic growth

Since traffic growth is one of the main drivers of the growing energy use of communication networks, in the following we first provide our traffic projections for the coming years. GreenTouch traffic projections (Figure 1) indicate that the total traffic volume passing the fixed access network will grow by a factor of 7.5 between 2010 and 2020. Compared to the earlier version of our Green Meter analysis [2] [4], we developed a more complete model distinguishing between **residential** and **business** traffic; and within each of these categories, we account for both Internet and managed IP traffic sub-categories. When dimensioning the access network, we are interested in the data rate required to be provisioned per subscriber in both upstream and downstream directions. This computation is explained in Table 1 below.

Considering **residential** traffic, the total traffic per subscriber is first obtained from the first two rows. Then, we apply appropriate upstream/downstream weights for the various traffic sub-components based on the type of service<sup>1</sup> to compute the average downstream to upstream ratio. We observe that

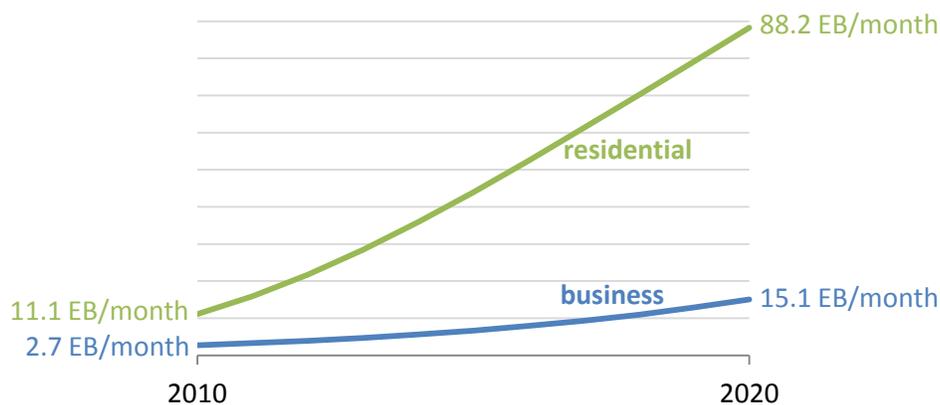


Figure 1: Traffic projections for Group 1 countries (Northern America, Western Europe, and Japan)

<sup>1</sup> We differentiate between Internet traffic (with sub-categories web, file sharing, gaming, VoIP & video) and managed IP traffic (mainly video, which is almost exclusively downstream traffic) to determine the DS/US ratio.

Table 1: Fixed access traffic data used for network dimensioning

	Residential (for Group 1 countries)		Business (for USA)	
	2010	2020	2010	2020
<b>Upstream and downstream traffic</b>	11,122 PB/month	88,225 PB/month	1,320 PB/month	7,281 PB/month
<b>Number of subs</b>	245 million	281 million	7.32 million	9.71 million
<b>Average DS/US ratio</b>	79/21	83/17	65/35	65/35
<b>Average downstream bit rate per sub</b>	109 kb/s	796 kb/s	356 kb/s	1482 kb/s
<b>Provisioned bit rate per sub at busy hour</b>	1.75 Mb/s	12.73 Mb/s	11.4 Mb/s	47.43 Mb/s

downstream traffic imposes higher bandwidth requirements on the network than upstream. Since the network uplinks are typically symmetric, the network dimensioning is primarily dictated by the downstream rates. To account for fluctuating traffic demands, we take the provisioned bit rate per subscriber at busy hour to be 16 times the average bit rate<sup>2</sup>.

We follow the same methodology for **business** traffic (Table 1, last two columns), where we use traffic and subscriber data for the USA as data on the number of subscribers was not available for the entire Group 1 (Northern America, Western Europe, and Japan)<sup>3</sup>. We assume a fixed DS/US ratio of 65/35, which means downstream traffic is again the limiting factor<sup>4</sup>; and we provision 32 times the average bit rate per subscriber in order to ensure business-grade quality of service.

## 1.2 Scope of this work

We consider fiber-to-the-premise (FTTP) architectures as fiber access is more energy-efficient compared to other physical mediums. Since power consumption has little dependence on the fiber distances in the distribution network, we do not differentiate geographical areas with different subscriber densities.

We assess the effect of the proposed architecture and energy saving technologies on the main sub-systems such as the optical network unit (ONU) and the optical line terminal (OLT). We also include the metro aggregation network containing the aggregation switch (AS) and the edge router (ER) in our model. This allows us to evaluate the effect of technologies that bypass the local exchange thus extending the reach of the access network.

<sup>2</sup> 2x for the peak-to-average ratio in a diurnal cycle; 2x to account any occasional larger volumes; 4x to ensure an upgrade of aggregation capacity is only needed every 4 years.

<sup>3</sup> Note that the growth factor for total business traffic in the USA matches that in Group 1 nations closely (both increase about 5.5x from 2010 to 2020).

<sup>4</sup> The DS share is lower for business than for residential primarily because there is lesser video traffic.

In the following sections, we compare three scenarios to evaluate the impact of the proposed GreenTouch architecture and technologies on energy efficiency:

1. **Baseline network in 2010:** using the most energy-efficient commercially available technologies at the start of GreenTouch in 2010 (cf. Section 2);
2. **Business-as-usual (BAU) network in 2020:** assuming energy efficiency is improved following current technological trends until 2020 (cf. Section 3);
3. **GreenTouch network in 2020:** leveraging novel GreenTouch architecture and technologies together with non-BAU techniques that are expected to be available by 2020 (cf. Sections 4 and 5).

We conclude with a summary of the results in Section 6. As a general rule, note that all power values in this document include, where applicable:

- Power supply inefficiency = 81% (90% AC/DC and 90% DC/DC, applies to all nodes)
- Air conditioning overhead for central office (CO) equipment (factor depends on the scenario)
- Redundant elements for resiliency, where present (also depending on the scenario)

## 2 Baseline network in 2010

### 2.1 Overview

For the baseline **residential** access technology in 2010, we consider Gigabit Passive Optical Network (GPON) with 2.5/1.25 Gb/s (downstream/upstream) capacity as this was the most energy-efficient commercially deployed technology at the start of GreenTouch. Similarly, for the baseline **business** access technology in 2010, we consider Gigabit Ethernet (GbE) Point-to-Point (PtP) fiber access with 1 Gb/s symmetric capacity. An overview of the baseline architectures is given in Figure 2 and Figure 3.

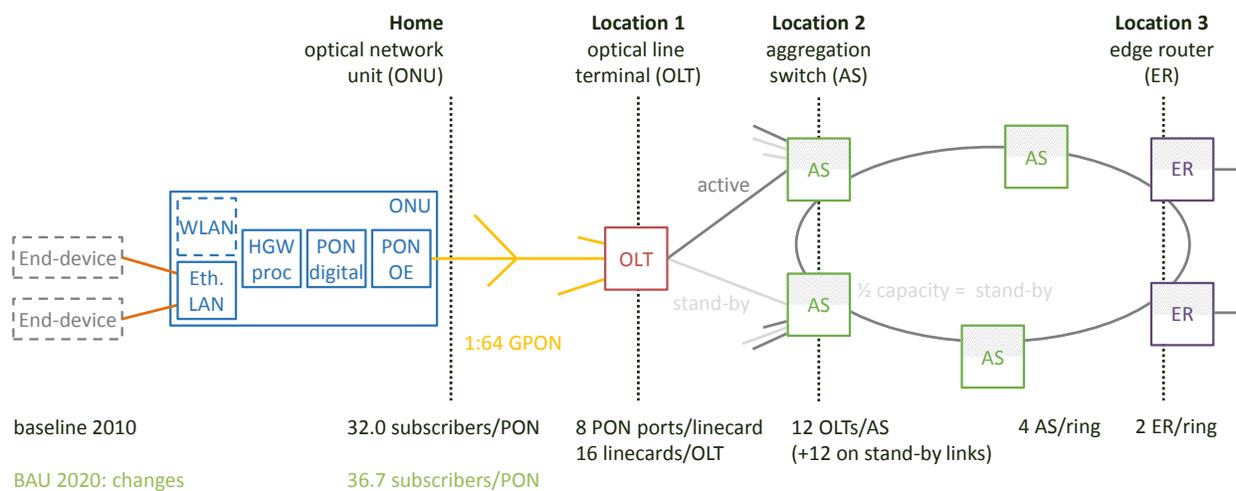
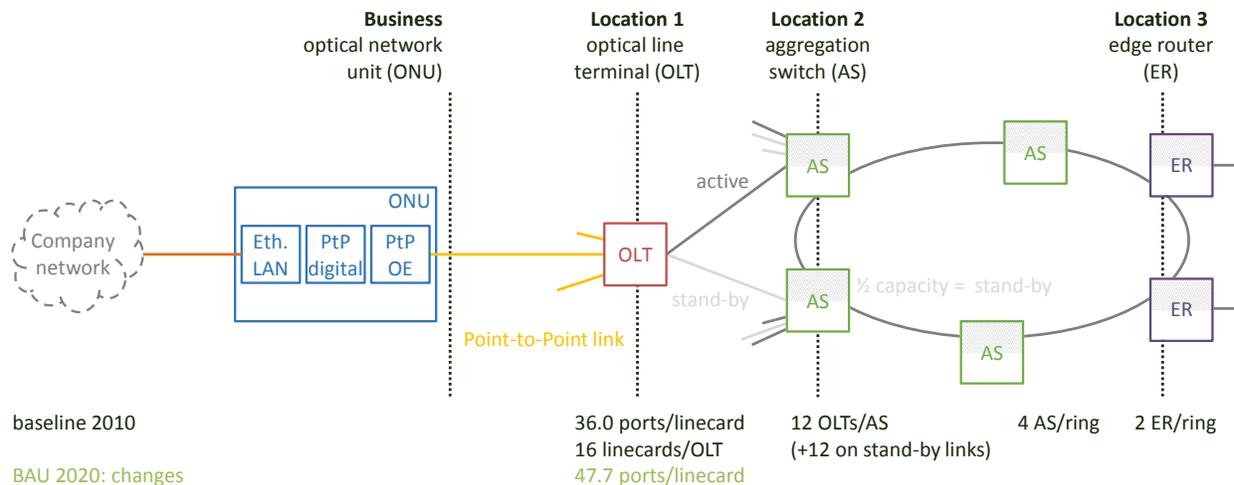


Figure 2: Baseline 2010 and business-as-usual (BAU) 2020 residential network architecture



**Figure 3: Baseline 2010 and business-as-usual (BAU) 2020 business network architecture**

The ONUs are connected via fiber links (either PON for residential or PtP for business) to optical ports on linecards in the OLT. The traffic from the OLT is aggregated on a single connection to an aggregation switch (AS), which is a L2 Ethernet switch with VLAN and MPLS capability. There is also a stand-by link to another AS as back-up. Network resiliency is further improved by use of a ring topology encompassing 4 aggregation switches and 2 edge routers (ERs) with redundant capacity. The ERs are L3 service routers (also BRAS in older architectures) that form the connection to the core network. Under normal operation, the load is shared between the ERs and so, each ER supports half the ring throughput. But each ER is dimensioned such that the total ring throughput can be supported in case the other ER fails.

Since the ONU power consumption is dominant, we further break it down into the following sub-functions in our model:

- Optical-electrical/electrical-optical conversion (OE) of the signals
- Digital protocol processing in a system-on-chip (SoC)
- Only for residential customers: integrated home gateway (HGW) processor to handle forwarding, firewalling, network address translation, dynamic host configuration protocol server, and administration interface
- Wireline Gigabit Ethernet (GbE) local area network (LAN) interfaces: 2 for residential customers, to connect end devices; and 1 for business customers, for signal distribution to the company network

Note that wireless LAN (WLAN) interfaces, end-devices and company networks are *not* relevant in the comparison of fixed access technologies and hence excluded in our analysis.

## 2.2 Dimensioning

To dimension the network nodes, we start from the provisioned bit rate per subscriber (cf. Section 1.1) at the ONU, and in each subsequent aggregation stage in the network, the traffic load is multiplied by the total number of users served by that node. The numbers and configurations are listed in Table 2 for residential access and in Table 3 for business access.

## 2.3 Power estimates

Based on the dimensioning, a power consumption estimate is given for each of the nodes in Table 2 & Table 3. In this scenario, power values include

- Air conditioning overhead for CO equipment = 1.5 x
- Redundancy resulting in doubling of power consumption of the corresponding elements (since the baseline network does not include the ability to switch stand-by elements to a low power state).

In Table 2, the power per node at the ONU is the sum of contributions from the components listed in the previous section: OE (0.657 W), SoC (1.481 W), HGW processor (1.9 W), and LAN interfaces (1.975 W). The power per node at the OLT is calculated from the 11 W per port guideline for OLT power consumption (excl. cooling overhead) in the EU CoC [5]. For the AS and ER, power per node is estimated by summing values for chassis, fabric, IO modules, and blades to support the calculated throughput and interfaces. The power estimates for business access in Table 3 are calculated in a similar manner.

The total power per subscriber is **6.73 W for a residential connection**, and **7.09 W for a business connection**. In terms of energy efficiency<sup>5</sup>, this corresponds to **20.5 kb/J for the residential baseline**, and **77.3 kb/J for the business baseline**.

Table 2: Node dimensioning for residential access in 2010 Baseline network. (1+1) indicates redundancy for protection.

	ONU	OLT	Aggregation switch (AS)	Edge router (ER)
<b>Configuration</b>	-	50% filling of 1:64 PON, 8 ports per linecard, 16 linecards, (1+1) uplink to ASs	12 active and 12 stand-by OLT uplinks, (1+1) links to ERs	2 ER per 4 ASs in ring, (1+1) capacity
<b># subscribers</b>	1	4,096	49,152	98,304
<b>Provisioned throughput</b>	1.75 Mb/s	7.2 Gb/s	86 Gb/s	(1+1)x172 Gb/s
<b>Interfaces</b>	2xGbE LAN over copper, GPON (2.5 Gb/s DS, 1.25 Gb/s US)	GPON ports (2.5 Gb/s DS, 1.25 Gb/s US), Network side: (1+1) x 10 Gb/s	Sub side: (1+1) x 12 x 10 Gb/s Network side: (1+1) x 100 Gb/s	Sub side: (1+1) x 2 x 100 Gb/s Network side: (2+2) x 100 Gb/s
<b>Power per node</b>	6.01 W	2,111 W	5,926 W	7,778 W
<b>Power per sub</b>	6.01 W	516 mW	121 mW	79 mW

<sup>5</sup> Energy efficiency = the ratio of the traffic being carried by the network (for example, measured in kb) to the total energy required to support that traffic over the duration of one year (for example, measured in J), or, equivalently, the average traffic rate per subscriber (DS+US, in kb/s) divided by the average power per subscriber (in W).

Table 3: Node dimensioning for business access in 2010 Baseline network. (1+1) indicates redundancy for protection.

	ONU	OLT	Aggregation switch (AS)	Edge router (ER)
<b>Configuration</b>	-	36 PtP ports per linecard, 16 linecards, (1+1) uplink to ASs	12 active and 12 stand-by OLT uplinks, (1+1) links to ERs	2 ER per 4 ASs in ring, (1+1) capacity
<b># subscribers</b>	1	576	6,912	13,824
<b>Provisioned throughput</b>	11.4 Mb/s	6.6 Gb/s	79 Gb/s	(1+1)x158 Gb/s
<b>Interfaces</b>	1xGbE LAN over copper, 1xPtP optical (1 Gb/s DS=US)	PtP ports (1 Gb/s DS=US), Network side: (1+1) x 10 Gb/s	Sub side: (1+1) x 12 x 10 Gb/s Network side: (1+1) x (2x40) Gb/s	Sub side: (1+1) x 2 x (2x40) Gb/s Network side: (4+4) x 40 Gb/s
<b>Power per node</b>	2.67 W	1,728 W	5,926 W	7,778 W
<b>Power per sub</b>	2.67 W	3 W	857 mW	563 mW

### 3 Business-as-usual network in 2020

#### 3.1 Overview and dimensioning

The dimensioning for the BAU network in 2020 is similar to that for the baseline scenario, while taking into account the increases in number of subscribers and data rates per subscriber from Table 1.

The architecture of the BAU network in 2020 is almost identical to that of the baseline network shown in Figure 2 and Figure 3; the only change is that the residential filling increases to 57.32% or 36.7 subscribers per PON on average instead of 32, and the business OLT can accommodate 47.7 ports/linecard (on average) in 2020 instead of 36. The detailed dimensioning for this increased network load is listed in Table 4 for residential access and in Table 5 for business access.

#### 3.2 Power improvement factors

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 (LAN interface and HGW processing) that are only turned on when a session is established (10 hours per day) and in a power shed state (with 10% power consumption) otherwise
- Energy-efficient hardware design: refers to engineering optimizations (e.g., reduced data transfers across input/output of integrated circuits by further integration) that result in an overall power reduction of about 20% of all electronics (not for optics)

- 25% more efficient cooling techniques for CO equipment reducing the effective air conditioning overhead to 1.125x

In the BAU scenario for 2020, the total power per subscriber is reduced to **1.58 W for a residential connection**, and **2.91 W for a business connection**. This translates into a **30-fold energy efficiency improvement** (to 604 kb/J) for the **residential network**, and a **10-fold improvement** (to 783 kb/J) for the **business network** using BAU technologies in 2020.

**Table 4: Node dimensioning for residential access in 2020 BAU network: changes with respect to 2010 baseline architecture (Table 2)**

	ONU	OLT	Aggregation switch (AS)	Edge router (ER)
<b>Configuration (avg)</b>	-	57.32% filling of 1:64 PON	-	-
<b># subscribers (avg)</b>	1	4,695.3	56,344	112,688
<b>Provisioned throughput</b>	12.73 Mb/s	60 Gb/s	717 Gb/s	(1+1)x1.43 Tb/s
<b>Interfaces</b>	-	Network side: (1+1) x (2x40) Gb/s	Sub side: (1+1) x 12 x (2x40) Gb/s Network side: (1+1) x (8x100) Gb/s	Sub side: (1+1) x 2 x (8x100) Gb/s Network side: (15+14) x 100 Gb/s
<b>Power per node</b>	1.08 W	956 W	10,000 W	13,889 W
<b>Power per sub</b>	1.08 W	203 mW	177 mW	123 mW

**Table 5: Node dimensioning for business access in 2020 BAU network: changes with respect to 2010 baseline architecture (Table 3)**

	ONU	OLT	Aggregation switch (AS)	Edge router (ER)
<b>Configuration (avg)</b>	-	47.7 PtP ports per linecard	-	-
<b># subscribers (avg)</b>	1	763.9	9,167	18,335
<b>Provisioned throughput</b>	47.43 Mb/s	36 Gb/s	435 Gb/s	(1+1)x870 Gb/s
<b>Interfaces</b>	-	Network side: (1+1) x 40 Gb/s	Sub side: (1+1) x 12 x 40 Gb/s Network side: (1+1) x (5x100) Gb/s	Sub side: (1+1) x 2 x (5x100) Gb/s Network side: (9+9) x 100 Gb/s
<b>Power per node</b>	733 mW	745 W	6,528 W	9,028 W
<b>Power per sub</b>	733 mW	975 mW	712 mW	492 mW

## 4 GreenTouch technologies

In the GreenTouch network architecture for 2020, we envisage radically new concepts some of which we have also shown in physical demonstrators. The technical details are explained in the following subsections for cascaded bit-interleaving, home gateway virtualization, point-to-point transceiver design and sleep modes. In addition, progress in optical components and electronic circuit technology beyond BAU trends are estimated to further reduce power by 1.33x and 3x respectively at the applicable sub-components.

### 4.1 Cascaded Bi-PON

Bit-interleaved PON (Bi-PON) is a new downstream protocol that allows extracting the relevant bits for the ONU immediately after the clock and data recovery function [6]. As illustrated in Figure 4, further processing is then done at the lower user rate instead of the aggregate line rate. This results in more than an order of magnitude power savings as GreenTouch demonstrated in [7], [8].

We recently extended the Bi-PON concept to multiple cascaded levels, namely a Cascaded Bi-PON (CBi-PON) [9], which results in a long reach access network and thus better sharing of the OLT. Figure 5 shows a CBi-PON with three stages of bit-interleaving served by a single OLT. Users are connected to the CBi-PON through the end-ONTs (eONTs). Lower level Bi-PONs are connected to their upper level network through *repeaters* (Rep): the frame structure is designed such that these intermediate nodes can perform a simple down-sampling function to efficiently extract only the portion of data that is relevant to the nodes subtending that repeater.

A subtending level Bi-PON supports a variety of DS line rates which is given by  $1/2^p$  (for some positive integer  $p$ ) of the rate of the upper level Bi-PON. Upstream transmission is based on standard time-slot based bursts.

CBi-PON is highly scalable and flexible: in principle, both eONTs and repeaters can be mixed in one stage. Moreover, depending on the traffic loading condition or user demand, an individual Bi-PON may operate at different instantaneous line rates.

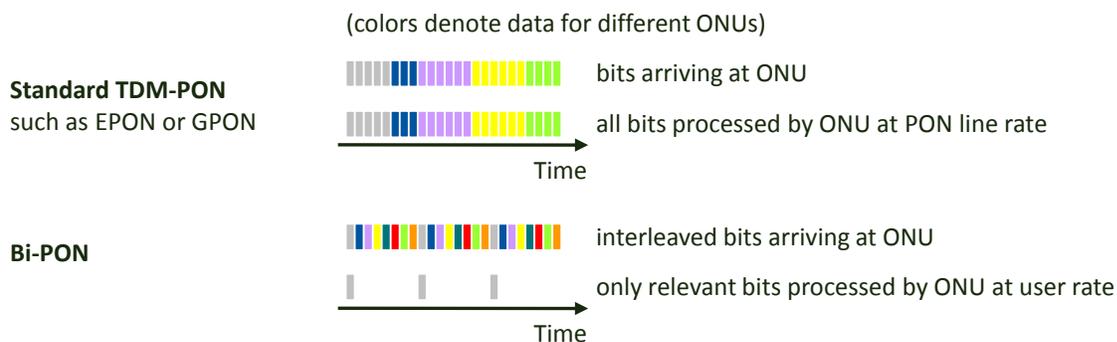


Figure 4: Bit-interleaving allows the ONU to process the incoming bits at a lower rate, thus requiring less energy

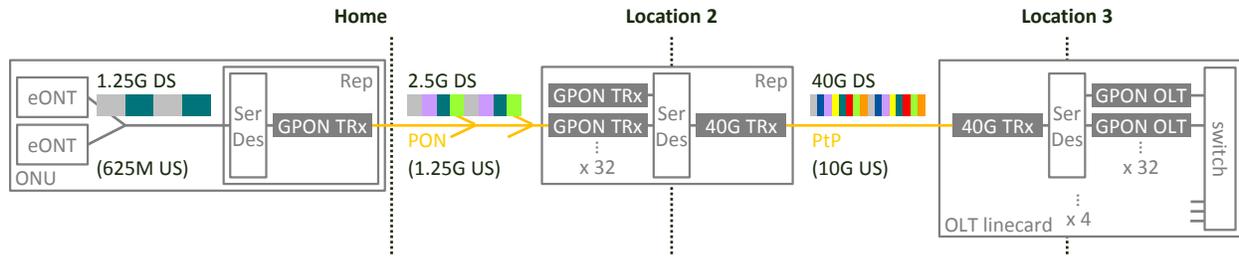


Figure 5: Cascaded bit-interleaving configuration for GreenTouch 2020 residential network

### Comparison to conventional long reach PON

Similar to a long reach high-splitting PON, CBi-PON eliminates the aggregation switch to achieve a net energy efficiency improvement in the network. However, in a conventional long reach PON, the ONU will need to handle the entire aggregate line rate. This, in effect, increases the power consumption of the ONU and defeats the gains in total power consumption. By using CBi-PON, the repeater reduces the data rate from the high speed feeder to a lower rate that is compatible with the PON in the first mile. The power as well as the complexity of the ONU can therefore be kept low.

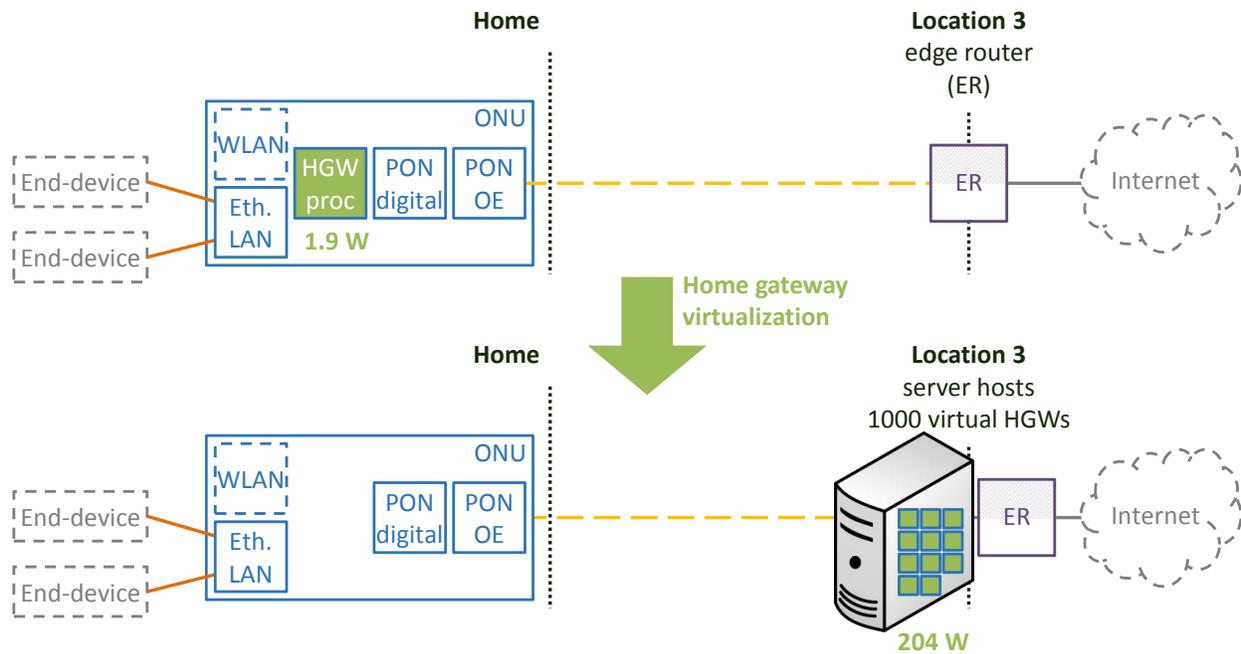
### Demonstrated savings

To experimentally assess the performance of the proposed protocol, a proof of concept 40G CBi-PON platform was designed [10]. Our measurements show that CBi-PON reduces the power consumption of the ONU digital protocol processing from 1.5W to 0.4W. Furthermore, it eliminates the need for a switching function and also contributes energy savings by replacing the Aggregation Switch (121 mW/user in baseline) with a simple Remote Node containing multiple repeaters (24 mW/user). This effectively leads to 4.5x savings at the ONU digital protocol processing and switching functions and 5x savings at the aggregation point.

### 4.2 Virtual home gateway

The principle of home gateway virtualization is shown in Figure 6. In the baseline network, HGW service functions (forwarding, firewall, network address translation, dynamic host configuration protocol server, and administration interface) are physically located at dedicated resources at every ONU and thus energy-consuming – our model includes 1.9 W of the baseline ONU consumption for HGW processing.

In the GreenTouch 2020 network, the resource intensive HGW service functions are moved to central servers that are co-located with the ER, thus simplifying the ONU. The functions are virtualized into “containers” on the central servers, allowing us to exploit scaling and sharing of resources to realize energy savings [11].



**Figure 6: Virtual Home Gateway: resource intensive services are moved to a central server to save energy**

### Server system requirements

In practice, the vHGW scheme requires dynamic consolidation of virtual machines among clustered physical nodes, and dynamic and aggregate live migration of virtual machines among physical nodes to reach the full potential of resource utilization as well as energy consumption optimization by switching physical nodes to standby mode whenever possible. Our approach still provides isolation between users while the provider takes advantage of this consolidation, which, on top of energy savings, also makes it easier to expand gateway functionality in the future to advanced services such as video storage or console gaming, while keeping the ONU simple and reliable.

### Demonstrated savings

We demonstrated that we can host 1000 virtual home gateways on a single server consuming 204 W, or 204 mW per user [12]. Compared to equivalent functions consuming about 1.9 W in the baseline network, this technology provides 9.3x savings for the HGW processing function. This does not include BAU and GreenTouch improvements to the server equipment, which further reduce the share of HGW processing to 5 mW per user.

### 4.3 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 [13]. We redesigned the transceiver from the ground up with power consumption in mind and custom-built an ASIC prototype for data rates up to 1 Gb/s. The savings are enabled by system simplification, better system integration,

optimizing the transmitter circuitry and signaling, and adapting the transmitter power based on the link distance [14], [15].

### **System simplification and integration**

Conventional optical transceivers are often designed for both Point-to-Point (PtP) and point-to-multipoint TDM-based applications, resulting in higher complexity and power consumption. In a dedicated PtP transceiver, the components for each block can be simplified and integrated in a single integrated circuit (IC) design. Some low power optics, such as vertical cavity surface emitting laser (VCSEL) can also be used due to the smaller link loss in PtP.

A proof of concept low-power optical transceiver was developed based on 90nm CMOS technology. The functional blocks of the transmitter and the receiver, e.g. laser driver, reference voltage providers, transimpedance amplifier (TIA), limiting amplifier (LA), decision making circuit and digital control units, are integrated into a single IC and wire-bonded to the optics, i.e., VCSEL and photo-detector (PD). The system integration reduces circuit parasitics, resulting in better circuit performance, and minimizes power consumption by eliminating interconnects between different functional blocks.

### **Transmitter circuitry optimization**

The power consumption of an optical transceiver is dominated by its transmitter power. The conventional optical transmitter topology is based on differential *voltage driving* topology, which has a low current-conversion efficiency (<40%). Alternatively, we use a single-ended *current driving* topology at up to 1GHz operation, which has better conversion efficiency.

In order to further improve energy efficiency, we propose a circuitry that is able to switch the transmitter between current driving and voltage driving topology according to the operating bandwidth. The voltage driving topology has half the impedance of the current driving topology, resulting in a doubled operating frequency. This makes the voltage driving applicable for higher frequency (>1G) with a trade-off on the additional power consumption. In other words, for lower frequency operation, this transceiver is able to operate with current driving topology that consumes less power.

### **Link power adaptation**

Today's optical links are often designed for a fixed optical signal, known as optical modulation amplitude (OMA), considering the maximum reach, the variations in components and couplings, and other penalties. There is a tradeoff between the power consumption of the transmitter and that of the receiver in an optical link, which depends on the transmission distances [14]. Rather than using a fixed OMA, we save energy by adapting the OMA to the link reach, which is logical since different users have different link lengths. An adaptive power control mechanism is proposed to dynamically adjust the laser launch power and the receiver sensitivity to the optimal point. To make this strategy possible, we developed hardware to support these tunable capabilities as well as an algorithm to identify the optimized link power for a given operating condition.

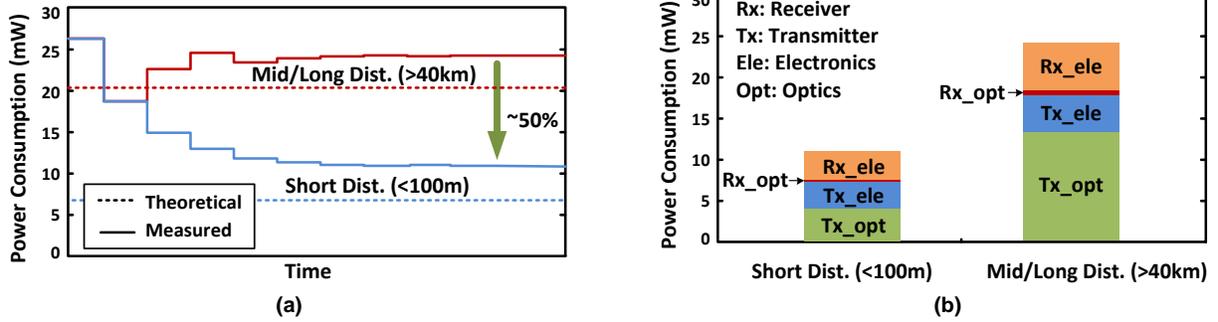


Figure 7: PtP transceiver (a) measured power consumption and (b) power distribution for different transmission distances

### Demonstrated savings

We have successfully demonstrated the benefits of the low power optical transceiver and the adaptive power-control mechanism in an experimental setup. We measured power consumption of 27 mW for nominal operation with longer distance links, which was further reduced to as little as 12 mW for short links using the adaptive power control algorithm as shown in Figure 7. Compared to conventional state-of-the-art optical transceivers, this represents a 17x to 38x improvement [12].

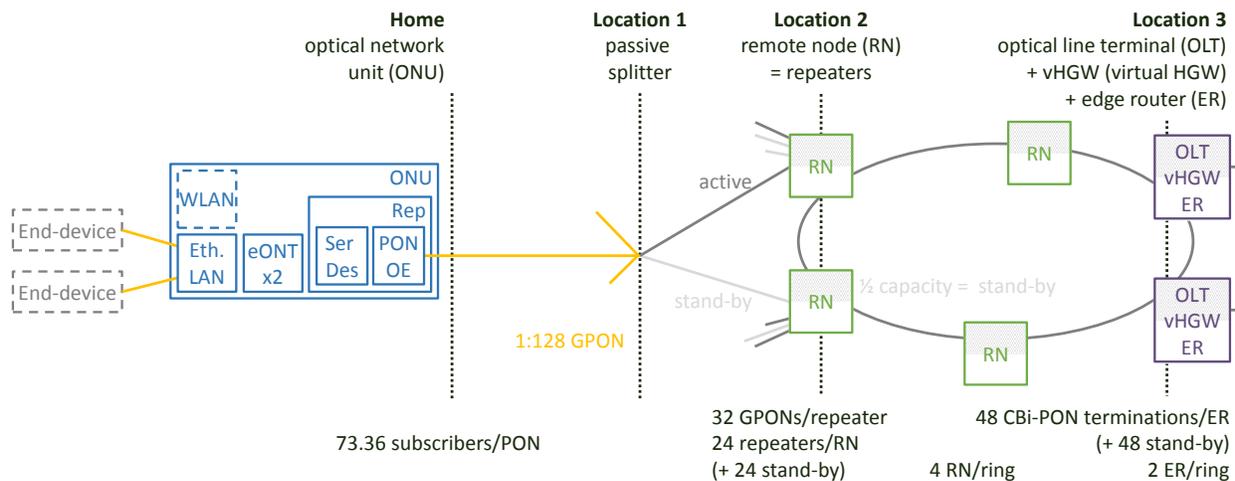
### 4.4 Sleep and stand-by modes

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 [16] 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 [17]. 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. Overall, applying sleep modes on top of the previous technologies in the access would result in an additional 2.3x energy efficiency improvement for residential users, and 1.6x for business users.

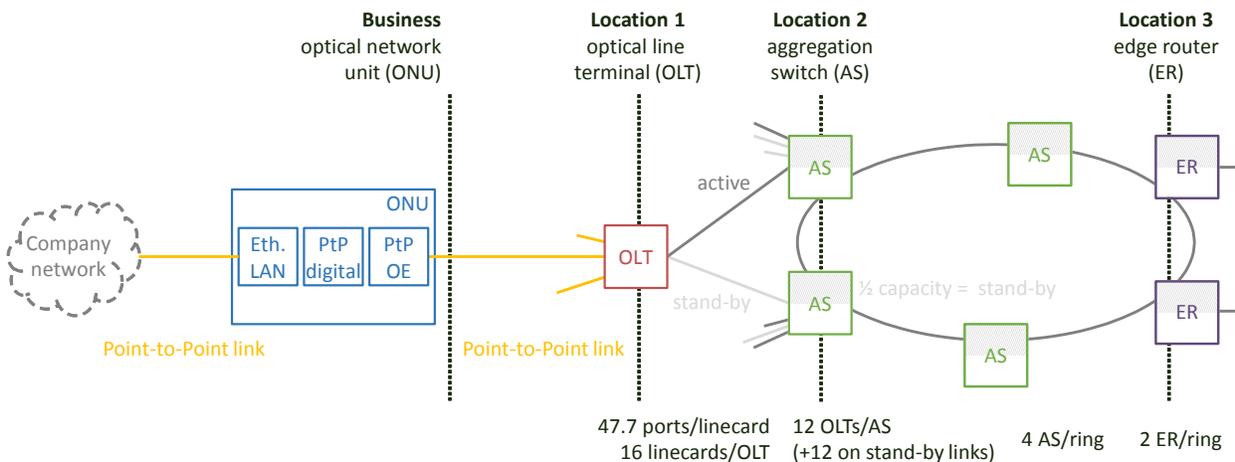
## 5 GreenTouch network in 2020

### 5.1 Overview

The GreenTouch architecture for the 2020 **residential access** network is based on CBi-PON. This leads to an access architecture with extended reach where the OLT is co-located with the ER (Figure 8). The actively-cooled AS in the baseline network is replaced by a passively-cooled remote node (RN) containing many repeaters. The network has 3 bit-interleaved levels in cascade (cf. Figure 5): The bit-interleaved traffic from the OLT is first down-sampled by a repeater (Rep) located in the RN, and again by a repeater built into the ONU, extracting only the relevant bits for the subtending nodes in each case.



**Figure 8: GreenTouch 2020 residential network architecture**



**Figure 9: GreenTouch 2020 business network architecture**

The residential architecture further employs virtual home gateways, GbE PtP fiber links using our redesigned optical transceiver (replacing previously copper links) for the LAN interfaces, and sleep and stand-by modes.

In the GreenTouch **business access** network (Figure 9), we improve upon baseline GbE PtP access technology using our redesigned low power optical transceiver. In addition, the architecture also employs: our redesigned GbE PtP fiber links (replacing copper) for the LAN interface, and sleep and stand-by modes.

## 5.2 Dimensioning

In the metro ring of both the **residential and business** architecture, the load is shared between two ERs, where each ER supports half the throughput (1.43 Tb/s for residential; 0.87 Tb/s for business) under normal operation. However, each ER is dimensioned to support the total throughput (2.87 Tb/s for residential; 1.74 Tb/s for business) in the event that one of them fails. Under normal operation, the power consumed by the redundant network elements is reduced by switching to a low power stand-by state assumed to consume 20% of the active power in order to ensure quick turn on when needed.

The detailed dimensioning is listed in Table 6 for **residential access**. In the residential GT architecture, the OLT is moved higher up in the network and integrated in the ER (see Figure 5 and Figure 8). The ER chassis features a 40G transceiver into a PtP link which connects to the metro ring CBI repeater; the CBI-PON primary level (Metro/Edge PON) supports asymmetrical rates of 40 Gb/s DS and 10 Gb/s US. In addition, the OLT electronics for processing the GPON traffic are included in the ER power calculation. No amplification is needed on <60 km links at 40G (18 dB fiber loss), which should cover most deployments. The ER does not have user side blades because PON OLT blades are directly integrated in the ER chassis.

The repeater in the remote node has a 40G transceiver to the metro ring side and a standard GPON OLT optical front-end to the subscriber side. Consequently the secondary level PON supports 2.5 Gb/s DS and 1.25 Gb/s US. CDR and serializer/deserializer (SerDes) are shared between 32xGPON. The 40G link in the metro ring is oversubscribed by 2x on the downstream side when considering the GPON downstream capacity of 32x2.5G, but a dynamic bandwidth allocation by the bit-interleaving scheduler allows to manage all DS subscriber traffic given that the sustained user throughput is only ~30G.

We take a 1:128 split in each GPON. The tertiary level (Home) PON supports 1.25Gb/s DS and 625Mb/s US. The end-ONT (eONT) functions within the ONU finally terminate the PON extracting the traffic for the respective LAN interfaces. As a result, the repeater function coupled with the eONT functions eliminates the need for a switching function within the ONU.

For **business access**, the configuration and throughput dimensioning are identical to that of BAU, but the use of redesigned optical transceivers and sleep and stand-by modes result in the improved power consumption values listed in Table 7.

Table 6: Node dimensioning for residential access in 2020 GreenTouch network. (1+1) indicates redundancy for protection.

	ONU	Remote node (RN)	OLT + vHGW + ER		
<b>Configuration (avg)</b>	-	57.32% filling of 1:128 PON , 32 ports per repeater, (24+24) repeaters, (24+24) uplinks to ERs	4 CBI-PON terminations per linecard, (12+12) linecards per ER, 2 ER per 4 RNs in ring		
<b># subscribers (avg)</b>	1	56,344.1	112,688		
<b>Provisioned throughput</b>	12.73 Mb/s	717 Gb/s	(1+1) x 1.43 Tb/s		
<b>Interfaces</b>	2xGbE LAN over fiber: new TRx, GPON (2.5 Gb/s DS, 1.25 Gb/s US)	Sub side: GPON ports (2.5 Gb/s DS, 1.25 Gb/s US), Network side: (24+24) x 40 Gb/s	Sub side: (48+48) x 40 Gb/s Network side: (15+14) x 100 Gb/s		
<b>Power per node</b>	77 mW	464.5 W	<b>OLT</b> 5,561 W	<b>vHGW</b> 564 W	<b>ER</b> 4,722 W
<b>Power per sub</b>	77 mW	8.2 mW	<b>OLT</b> 49 mW	<b>vHGW</b> 5 mW	<b>ER</b> 42 mW

Table 7: Node dimensioning for business access in 2020 GreenTouch network. (1+1) indicates redundancy for protection.

	ONU	OLT	Aggregation switch (AS)	Edge router (ER)
<b>Configuration (avg)</b>	-	47.7 PtP ports per linecard	12 active and 12 stand-by OLT uplinks, (1+1) links to ERs	2 ER per 4 ASs in ring, (1+1) capacity
<b># subscribers (avg)</b>	1	763.9	9,167	18,335
<b>Provisioned throughput</b>	47.43 Mb/s	36 Gb/s	435 Gb/s	(1+1)x870 Gb/s
<b>Interfaces</b>	1xGbE LAN over fiber: new TRx, 1xPtP optical: new TRx (1 Gb/s DS=US)	PtP ports: new TRxs (1 Gb/s DS=US), Network side: (1+1) x 40 Gb/s	Sub side: (1+1) x 12 x 40 Gb/s Network side: (1+1) x (5x100) Gb/s	Sub side: (1+1) x 2 x (5x100) Gb/s Network side: (9+9) x 100 Gb/s
<b>Power per node</b>	47 mW	105 W	4,306 W	5,833 W
<b>Power per sub</b>	47 mW	138 mW	470 mW	318 mW

### 5.3 Power improvement factors

Energy savings for GT 2020 include all techniques listed under BAU in Section 2 and, in addition, also include the following:

For the residential architecture

- Cascaded Bit-interleaved PON (CBI-PON): operating at the lower user rate leads to 72% (3.6x) savings in power consumption of digital protocol processing in the ONU; further savings also result from the elimination of the switching function in the ONU. Any overheads introduced due to CBI-PON are also taken into account, e.g., a 10% overhead is estimated at the OLT for the additional interleaving function.
- Virtual home gateway (vHGW): 1000 subscribers are hosted on a 204 W server (including 1.5x air conditioning overhead) leading to 87% (7.5x) savings in HGW service functions.
- Redesigned PtP TRx in the ONU LAN interface: transition from LAN over copper to LAN over fiber with the redesigned PtP TRx effectively reduces power consumption by 80% (5x) per LAN interface.
- Improved PON OE: eliminating the limiting amplifier in the ONU access interface, which is possible since modern CDRs have better sensitivity, saves 19% in the OE transceiver.
- Sleep mode in the ONU access interface: 83% savings for the OE transceiver, 52% savings for the digital electronics<sup>6</sup>.
- Sleep mode in the ONU LAN interface: resulting in 65% savings<sup>6</sup>.
- Doze mode and better load aggregation save 20% in OLT digital components<sup>6</sup>.

For the business architecture

- Redesigned PtP TRx in the access interface: enables 94% (17x) savings at the access OE of both the ONU and OLT.
- Sleep mode in the ONU and OLT access interfaces: 86% savings for the OE transceiver, 58% savings for digital electronics (excl. switching) at OLT<sup>6</sup>.
- Sleep mode in the ONU LAN interface: resulting in 63% savings<sup>6</sup>.

Finally, for both the architectures, we include additional savings from:

- Low power stand-by states at redundant nodes: Redundant stand-by nodes in the AS (for business) and ER now consume 20 percent of active power instead of full active power.
- Low power optics in the ONU, Rep, OLT and ER reducing the power consumption of optical components such as the PIN diode and laser by 25%.
- Low power electronics in the ONU and OLT reducing the power consumption of digital processing components by 67% (3x).

Combining all these power improvement factors, we obtain the new power per node and power per subscriber values listed in Table 6 and Table 7. In the GreenTouch scenario for 2020, the overall power

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<sup>6</sup> Additional savings from sleep (or doze) mode on top of all other energy-efficient technologies (BAU and GT).

per subscriber is reduced to **181 mW for a residential connection**, and **973 mW for a business connection**. This translates into a **257-fold energy efficiency improvement** (to 5271 kb/J) for the **residential** architecture, and a **30-fold improvement** (to 2343 kb/J) for the **business** architecture by 2020 compared to the 2010 baseline scenario.

## 6 Summary

The Fixed Access Green Meter methodology brings together the complete portfolio of GreenTouch technologies and assesses their individual and collective impact on energy savings. In particular, our results shown in Figure 10 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 10 also shows the incremental impact on power consumption reduction of introducing each additional GreenTouch technology on top of the previous ones already in use. The overall savings in the 2020 GT scenario incorporates *all* technologies.

In order to calculate the energy efficiency, we integrate the total energy consumption per subscriber over a year and divide it by the traffic over that same period. As shown in Figure 11, energy efficiency can be improved by 257x for the residential access network<sup>7</sup> and by 30x for the business access network relative to the 2010 reference scenarios.

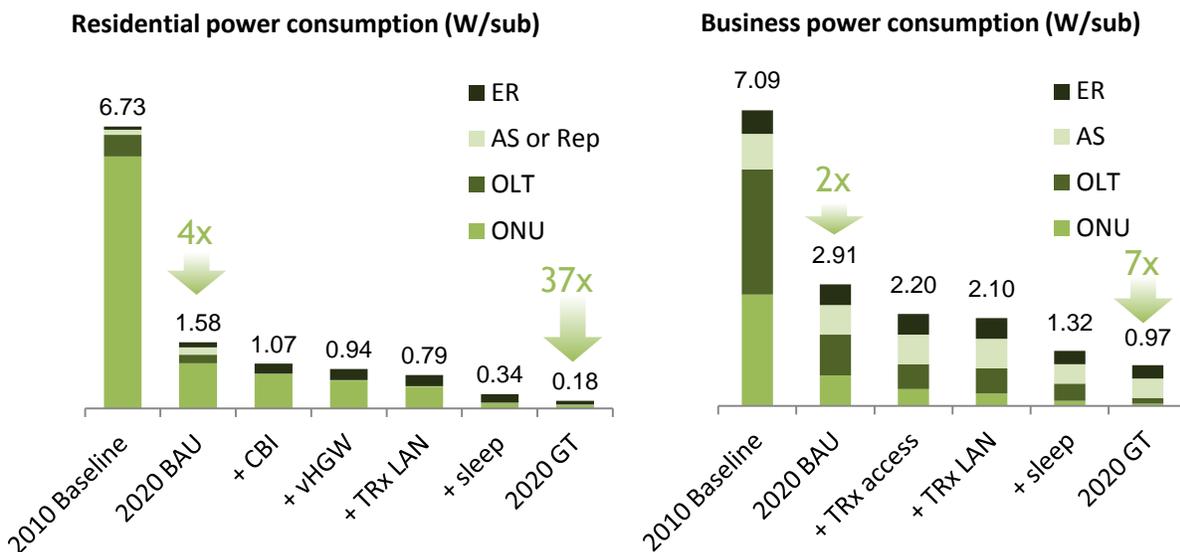


Figure 10: Impact of introducing various energy-saving technologies: incremental power consumption reduction

<sup>7</sup> Minor correction to 254-fold improvement reported in [2].

The factor 257x for residential energy efficiency is roughly the product of three contributions:

- 4.3x business-as-usual improvements described in Section 3 (less Joules per subscriber);
- 8.7x improvement from GreenTouch solutions described in Section 4 & 5 (less Joules per subscriber);
- 6.9x improvement as we support a larger traffic volume (more kilobits per subscriber).

Similarly, for business, there is a 2.4x BAU improvement; 3x improvement from GreenTouch technologies; and a 4.2x improvement by supporting increased traffic.

Overall, this reduction in the fixed access energy consumption is equivalent to the annual greenhouse gas emissions from about 2 million cars (Table 8).

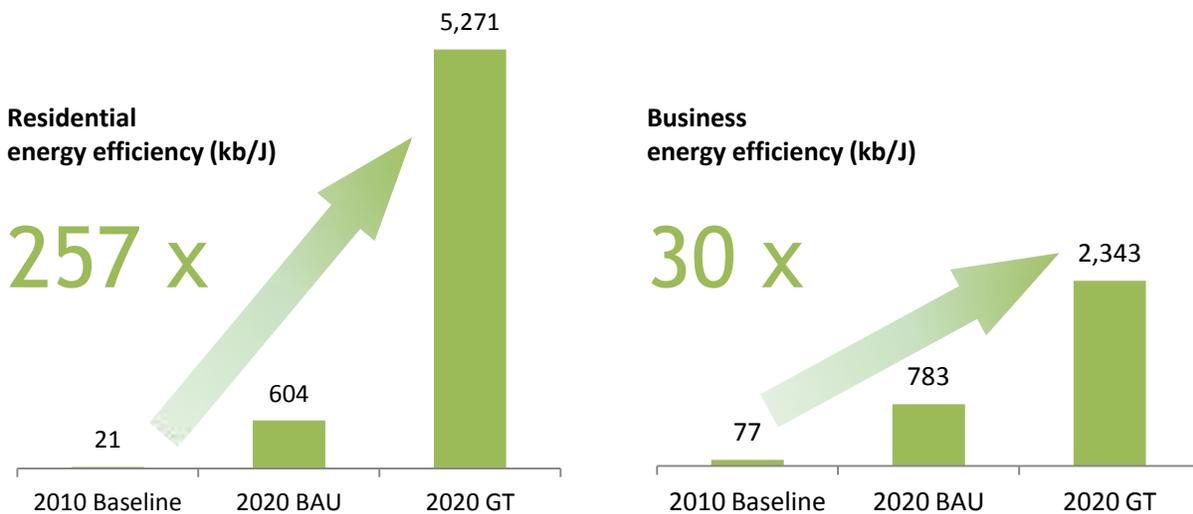


Figure 11: Energy efficiency improvement in residential and business access networks

Table 8: Energy consumption and energy efficiency in residential and business access networks

	Residential Fixed Access		Business Fixed Access	
	2010 Baseline	2020 GreenTouch	2010 Baseline	2020 GreenTouch
<b>Energy Efficiency</b>	20.5 kb/J	5200 kb/J	77 kb/J	2343 kb/J
<b>Annual energy consumption for all Group 1 subscribers</b>	14.47 TWh	0.45 TWh	941 GWh	171 GWh
<b>% Energy Savings per Year versus 2010</b>		97%		82%
<b>Analogy - Annual GHG emissions from cars</b>		2,035,000		112,000



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## 8 List of acronyms and abbreviations

AC	alternating current
AS	aggregation switch
ASIC	application-specific integrated circuit
avg	average
BAU	business-as-usual
Bi-PON	bit-interleaved PON
BRAS	broadband remote access server
BW	bandwidth
CBi-PON	cascaded bit-interleaved PON
CDR	clock and data recovery
CMOS	complementary metal–oxide–semiconductor
CO	central office
CoC	Code of Conduct
DC	direct current
DS	downstream
EB	exabyte ( $10^{18}$ bytes)
eONT	end-ONT
ER	edge router
FTTP	fiber-to-the-premise
GbE	gigabit Ethernet
GHG	greenhouse gas
GPON	gigabit-capable passive optical network
GT	GreenTouch
GWATT	Global 'What if' Analyzer of neTwork energy consumpTion
HGW	home gateway
IC	integrated circuit
IO	input/output
IP	Internet Protocol
ITU-T	ITU Telecommunication Standardization Sector
L2	Layer 2 of the OSI (open systems interconnection) model
LA	limiting amplifier
LAN	local area network
LT	line termination
MPLS	multiprotocol label switching
OE	optoelectronic

OLT	optical line terminal
OMA	optical modulation amplitude
ONU	optical network unit
PB	petabyte
PD	photo-detector
PON	passive optical network
PtP	point-to-point
Rep	repeater
RN	remote node
SerDes	serializer/deserializer
SoC	system-on-chip
sub(s)	subscriber(s)
TDM	time-division multiplexing
TIA	transimpedance amplifier
TRx	transceiver
US	upstream
VCSEL	vertical cavity surface emitting laser
vHGW	virtual home gateway
VLAN	virtual LAN
WLAN	wireless LAN