Energieverbruik en besparingsstrategieën in telecommunicatienetwerken

Energy Consumption and Energy-Saving Strategies in Telecommunication Networks

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Preface

I've decided to write this part of my book in English so that my non-Dutch-speaking colleagues and friends can read along. The academic world is an incredibly diverse work environment. It's been an enriching experience for me to get to know many different cultures first-hand, and I feel lucky to have met interesting people from all over the world.

Many of these people have contributed to one degree or another to my research, and I would like to take this opportunity to thank them.

But first, I have a confession to make. When I started my doctoral research in early 2012 I was not too bothered by sustainability. It seemed like something other people (mostly hippies) could concern themselves with while I was doing my share by sorting my waste correctly for recycling and not taking a separate plastic bag for every apple I bought at the supermarket.

At the time I was looking for a PhD position, it was partly by coincidence (and thanks to a tip from Marlies who was already working at IBCN) that I ended up talking to Mario, Bart and Didier about green ICT research. They suggested linking my background in photonics to the research track on sustainable networking they had launched a few years earlier. I liked the approach they proposed, and so I decided to start working on this topic at the IBCN research group.

From day one, I was welcomed into the group by Willem and Ward, the other PhD students working on this topic at the time. Their enthusiasm and genuine interest in sustainability were positively contagious. This enthusiasm was channeled into a useful direction thanks to the excellent supervision by Mario and Bart.

Mario, as head of the green ICT research cluster, is in charge of steering his PhD students towards relevant topics of research, and does so excellently. At regular intervals he followed up on my research by giving valid criticism where needed, but also regularly showing his appreciation for my work and the obtained results.

Bart brought his experience as a postdoctoral researcher to the table to help me look for solutions to the questions and problems I ran into — especially in the initial stages of my research, there were many, and Bart always made time for meetings when I had yet another list of questions or remarks to dig through. He was the first in line when I needed advice about my research planning and direction, and it was often Bart who introduced me to the right people to talk to when I wanted to explore new areas of research and start up collaborations, something I am very grateful for.

Throughout my PhD, the fellow PhD student I've collaborated with most closely is Ward. He provided me with invaluable PhD life hacks: from the online time convertor tool to plan international meetings; over mind-mapping software to organize your thoughts (admittedly, that one I didn't use for long); to handy LaTeX tips and tricks (the formatting template I used to create this very book is actually based on his book). I still remember vividly the day of the submission deadline of my first journal paper, Ward and I were in Greece for a project meeting, enjoying a lovely dinner by the seaside with the other research partners, when around 10 pm I suddenly realized I was supposed to submit my paper by midnight. Instead of enjoying the late summer night outside, Ward ended up spending the last two hours of the day helping me struggle through the journal submission process, converting the LaTeX code and figures to the right format needed for the journal web portal (because of course, every self-respecting journal must have its own obscure formatting rules). The journal paper was submitted on time, accepted for publication and is included in Chapter 2 of this dissertation.[1] Obviously Ward didn't just help me with the formatting of my PhD research, we also had countless conversations that were mutually beneficial in improving the quality of our research, as well as discussions on the broader implications of our work and sustainability in general (if you need good book recommendations, Ward is your man).

The work presented in the other chapters of this dissertation is also the result of close collaborations. Through my involvement in the European project TREND, I got in touch with Julio from Telefónica Madrid. During my visit at the research department there in early 2013, he provided the initial inputs and ideas for the work presented in Chapter 3. The two weeks I spent in Madrid were fun as well as extremely productive, and Julio proved to be a very pleasant and active collaborator when we continued to work on the paper from a distance with regular phone calls to discuss details in the following months. Abhishek, who was working towards a PhD in our department at the time, and who is probably one of the most productive researchers I have ever met, also contributed some of his insights to this part of my work.

From the start of my PhD, I was also involved in the GreenTouch consortium, that brought together research partners from all corners of the world. I was mostly active in the Fixed Access focus group, where I contributed to the Green Meter power consumption model. The group was led by Peter in the first year of my research; later on Prasanth took over. The project meetings were always intensive with complex technical discussions, but also extremely useful, and it is mostly thanks to Peter and Prasanth's tireless ef-

[1] Besides helping me submit the paper on time, Ward also provided some of the content of the paper: the section on office networks was mostly his work.

forts that we were able to compile the inputs from all project partners. Even once we had the inputs it took us uncountable hour-long phone meetings before we were able to finalize the structured version of the Green Meter presented in Chapter 4, long after the GreenTouch project had ended, but Prasanth always made time and helped where he could to get the job done.

At the GreenTouch meetings, through Alan who was involved in the Fixed Access focus group, I also met Kerry from the Centre for Energy-Efficient Telecommunications (CEET), or, as some of the other GreenTouch researchers might refer to him, "the professor in flip-flops". We arranged an exchange in which I joined CEET in Melbourne for three months in 2014, to program sleep modes on an Internet of things gateway.[2] It was a joy to work with Kerry (except maybe that one time when he accidentally gave away a huge spoiler from the Game of Thrones season finale before I had a chance to watch it) and the other members of the group there: Rob was tirelessly helping me look for solutions when the programming of the gateway just wasn't coming along; while Leith cheered up the group meetings with his dry wit and "gossip" from the conferences he attended. And then of course there were Marco and Álvaro, two other European students who happened to be on an exchange at CEET at the same time I was, and who helped make my time in Melbourne unforgettable (together with Fatemeh, Chris, and the others).

Meanwhile back in Belgium we had started working on the new "post-peak ICT" topic, and like all the work presented in this dissertation, the research included in Chapter 5 is the result of a joint effort: the premise was initially brought forward by Ward during a brainstorming session of the green ICT research cluster; he later also provided inputs for the sections on core networks and data centers. Margot from the Wireless and Cable (WiCa) research group made a big contribution to this work by performing the wireless network simulations for the case study that we included in the paper.

Of course, throughout the years, there were many other colleagues that helped me out with technical questions here and there, and many, many other nice colleagues with whom I could spend my lunch and coffee breaks when I needed to clear my head — a special thanks goes out to my swimming buddies Bram and Sander who helped me get moving again on a more or less regular basis (weekly, in theory) after spending the whole day sitting behind a desk; and to Fre who came up with the crazy idea of organizing an office party earlier this year (the number of registrations quickly got out of hand, but together with Bram and Marlies it was an incredibly fun side project to work on, with a memorable party as a result).

Finally, and perhaps most importantly, I think it's fair to say that the work I realized on a professional level in the past years has been partly

[2] An Internet of things gateway is a kind of modem designed to connect various sensors and smart devices in a home to the Internet.

made possible by the support of my close friends and family. They know who they are, so I won't start listing names (knowing myself I would forget at least one of them and that would be a grave injustice). The assurance that these people have faith in me, support my decisions and appreciate my work almost unconditionally, really makes all the difference in having not just a productive, but also a happy half-decade to look back on.

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List of Acronyms

A

AC	alternating current
ADSL	asymmetric digital subscriber line
AON	active optical network
AP	access point
APD	avalanche photodiode
AS	aggregation switch
ASIC	application-specific integrated circuit
avg	average

B

BAU	business-as-usual
BI	bit-interleaving
Bi-PON	bit-interleaved PON
BM	burst-mode
BRAS	broadband remote access server
BS	base station
BW	bandwidth

C

CAGR	compound annual growth rate
CBI	cascaded bit-interleaving

CDR	clock and data recovery
CO	central office
Co UDWDM	coherent ultra dense wavelength division multiplexing
CPE	customer premises equipment
CRT	cathode ray tube
CW	continuous wave

D

dB	decibel
DBA	dynamic bandwidth allocation
DC	direct current
DFB	distributed feedback
DML	directly modulated laser
DS	downstream
DSL	digital subscriber line
DSP	digital signal processing

E

EB	exabyte
EDC	electronic dispersion compensation
EE	energy efficiency
EML	externally modulated laser
eONT	end-optical network terminal
EPON	Ethernet passive optical network
ER	edge router

F

FSAN	full service access network working group
FTTB	fiber to the building
FTTC	fiber to the cabinet

FTTH fiber to the home

G

GbE gigabit Ethernet
Gbps gigabit per second
GEM GPON encapsulation method
GHG greenhouse gas
GPON gigabit-capable passive optical network
GSM global system for mobile communications
GT GreenTouch

H

HD high definition
HGW home gateway
HW hardware

I

ICT information and communications technology
IO input/output
IP Internet protocol
IPCC Intergovernmental Panel on Climate Change
IPTV Internet protocol television
ISP Internet service provider
ITU-T International Telecommunication Union - Telecommunication Standardization Sector

L

L2 layer 2
L3 layer 3

LA	limiting amplifier
LAN	local area network
LCD	liquid-crystal display
LED	light-emitting diode
LPOE	low-power optics and electronics
LTE	long-term evolution

M

MAC	media access control
MEC	mobile-edge computing
MPLS	multiprotocol label switching

N

NG-PON	next-generation passive optical network
NG-PON2	next-generation passive optical network 2
NLOS	non-line-of-sight

O

ODN	optical distribution network
OE	optoelectronic
OFDM	orthogonal frequency division multiplexing
OLT	optical line terminal
ONU	optical network unit
OSI	Open Systems Interconnection
OTT	over-the-top content

P

PC	personal computer

PON	passive optical network
PtMP	point-to-multipoint
PtP	point-to-point
PUE	power usage effectiveness
PV	photovoltaic

Q

QoS	quality of service

R

REP	repeater
RN	remote node

S

SerDes	serializer/deserializer
SLA	service level agreement
SLIC	subscriber line interface circuit
SOA	semiconductor optical amplifier
SoC	system-on-chip
SPS	Services, Policies and Standards
subs	subscribers

T

TCP	transmission control protocol
TDM	time-division multiplexing
TIA	transimpedance amplifier
TREND	Towards Real Energy-efficient Network Design
TRx	transceiver

TWDM time-shared wavelength division multiplexing
Tx transmitter

U

UMTS universal mobile telecommunications system
US upstream

V

VDSL very-high-bitrate digital subscriber line
vHGW virtual home gateway
VLAN virtual local area network
VoIP voice over Internet protocol

W

WDM wavelength-division multiplexing
WLAN wireless local area network

X

XG-PON1 10 Gb/s capable passive optical network
XLG PON 40 Gb/s capable time division multiplexing based passive optical network
XLG:BI XLG PON using bit-interleaving
XLG:GEM XLG PON using GPON encapsulation method

Samenvatting – Summary in Dutch –

De menselijke consumptie van fossiele brandstoffen en het effect hiervan op het klimaat zijn een bron van groeiende ongerustheid. Er is ondertussen onweerlegbaar bewijs voor de opwarming van de aarde, en klimaatwetenschappers zijn het erover eens dat deze opwarming het gevolg is van uitstoot van broeikasgassen door menselijke activiteiten. Een belangrijk deel van deze uitstoot ontstaat door het verbranden van fossiele brandstoffen om elektriciteit op te wekken. De wereldwijde elektriciteitsproductie groeide de voorbije decennia ongeveer 3% per jaar, wat overeenkomt met een verdubbeling elke 23 jaar. Als we onze uitstoot van broeikasgassen willen verminderen, kan deze groei uiteraard niet op deze manier doorgezet worden, en zullen we nog veel meer moeten inzetten op hernieuwbare energiebronnen of bronnen met een kleinere CO_2-uitstoot, en op energie-efficiëntieverbeteringen in de afnemende sectoren om de vraag te verminderen. Met energie-efficiëntieverbeteringen (of kortweg energiebesparing) wordt bedoeld dat we méér trachten te realiseren met eenzelfde hoeveelheid of minder energie.

Informatie- en communicatietechnologie (ICT) is wellicht niet de eerste sector waaraan we denken wanneer we stilstaan bij onze ecologische voetafdruk, maar deze sector speelt wel degelijk een belangrijke rol: het aandeel van ICT in de globale menselijke emissies van broeikasgassen is ongeveer even groot als dat van de luchtvaartindustrie, en groeit sneller. Aangezien ICT voor steeds meer toepassingen gebruikt wordt in elk aspect van ons leven, kunnen we verwachten dat deze groei van de ICT-voetafdruk zich zal doorzetten als we geen actie ondernemen om energie te besparen in deze sector.

De rode draad doorheen dit proefschrift is "groene ICT" (in het Engels: green ICT), en specifieker het verduurzamen van netwerken (Engels: green networking), waarmee verwezen wordt naar onderzoek dat de uitstoot van ICT en communicatienetwerken tracht te verminderen, een onderwerp dat veel aandacht kreeg in de onderzoekswereld de voorbije tien jaar. De algemene strategieën om de menselijke uitstoot van broeikasgassen door elektriciteitsconsumptie te verminderen zijn ook hier van toepassing: ICT en netwerken kunnen duurzaam gemaakt worden door (hernieuwbare) ener-

giebronnen met een kleinere CO_2-uitstoot te combineren met initiatieven die ICT en netwerken zélf efficiënter maken, zodat er minder energie verspild wordt. In dit werk wordt de nadruk gelegd op elektriciteitsverbruik in de gebruiksfase van ICT en netwerken. De productie en afvalverwerking worden buiten beschouwing gelaten omdat deze verhoudingsgewijs minder bijdragen tot de uitstoot van ICT.

Wereldwijd elektriciteitsverbruik van communicatienetwerken De eerste bijdrage van dit proefschrift is een gedetailleerde schatting van het aandeel van communicatienetwerken in het wereldwijde elektriciteitsverbruik. Een actuele inschatting van dit verbruik is nodig om te zien wat het besparingspotentieel is wanneer nieuwe, energie-efficiënte technologieën worden ingevoerd.

De gepresenteerde methodologie werd ontwikkeld om de wereldwijde elektriciteitsconsumptie in de gebruiksfase van telecomnetwerken (uitgebaat door netwerkoperatoren), kantoornetwerken en bij klanten aanwezige apparatuur in te schatten. Het model wordt in detail beschreven, met bijzondere aandacht voor de modellering van telecomnetwerken, omdat deze het grootste aandeel van het verbruik voor hun rekening nemen. De inschatting is gebaseerd op het gerapporteerd totaal elektriciteitsverbruik van een aantal telecomoperatoren. Een groot voordeel van deze aanpak is dat de resultaten een allesomvattend beeld schetsen van het verbruik, waarin overheads en diversiteit in het netwerk in rekening genomen worden, die moeilijker te bevatten zijn wanneer een meer theoretische analyse gemaakt zou worden vertrekkend van netwerkmodellen.

De methodologie wordt vervolgens toegepast op een dataset voor de periode 2007-2012. De analyse van de resultaten levert enkele interessante inzichten op: de impact van netwerken op het milieu groeit snel, met een gemiddelde jaarlijkse toename van 10% in het verbruik, een groei die voornamelijk het gevolg is van groeiende gebruikersaantallen en stijgende vraag naar hogere bandbreedtes ("snellere" verbindingen). Aangezien deze groei aanzienlijk sneller is dan die van het globale elektriciteitsverbruik, groeit het aandeel van netwerken in het globale verbruik. Tegen het einde van de bestudeerde periode, in 2012, werd al bijna 2% van de wereldwijde elektriciteit opgesoupeerd door netwerken. In totaal komt dit neer op een verbruik van 350 TWh (350 *miljard* kilowattuur), dat is meer dan vier keer het elektriciteitsverbruik van gans België in datzelfde jaar.

Uit deze resultaten blijkt duidelijk dat het verduurzamen van netwerken een belangrijke rol zal moeten spelen als het energieverbruik van communicatienetwerken gestabiliseerd of ingekrompen moet worden.

Vergelijking van de volgende generatie optische toegangsnetwerken In dit werk is het onderzoek naar de verduurzaming van netwerken toegespitst op optische toegangsnetwerken. Een toegangsnetwerk is dat deel van het netwerk dat de fysieke verbinding legt waarmee de eindgebruiker verbinding kan maken met het Internet. Een optisch toegangsnetwerk maakt hiertoe gebruik van een optische glasvezel, waarover informatie wordt verstuurd in de vorm van optische signalen (licht). Meer specifiek gaat dit werk over Passieve Optische Netwerken (PONs), dit zijn netwerken die enkel passieve componenten (zonder energietoevoer) gebruiken op het terrein tussen de eindgebruiker en de centrale. De keuze voor PONs werd gemaakt op basis van hun populariteit voor commercialisering: sommige types PON werden reeds uitgerold door operatoren in verschillende landen, terwijl andere, nieuwere types op het moment van mijn onderzoek in aanmerking kwamen voor standaardisatie om in toekomstige netwerken gebruikt te worden.

Bij elke nieuwe generatie van PONs is er een evolutie naar hogere bandbreedtes om aan hogere vraag van de gebruikers tegemoet te komen, en naar een groter bereik om uitgestrektere netwerken mogelijk te maken. Om te vermijden dat deze evolutie ten koste van een hoger energieverbruik zou gaan, ontwikkelden we een model dat de verschillende kandidaten voor de standaardisatie vergelijkt, met als doel een aanbeveling te kunnen maken over welke technologie de meest energie-efficiënte is. Het model houdt rekening met de specifieke eigenschappen van elk PON-type, de gemodelleerde gebruikersvraag (met bandbreedtes per gebruiker tot 1 Gb/s), de optimalisatie van de split ratio (aangepaste fysieke verdeling van het signaal om de gewenste diensten met minimale energie aan te bieden), de dynamische toewijzing van bandbreedte (rekening houdend met de ogenblikkelijke vraag van gebruikers), en wordt toegepast op een realistisch geografisch scenario in een grootstad (zodat de implicaties van beperkt bereik op de vereiste hoeveelheid apparatuur ook worden meegenomen).

Wanneer de bovenstaande parameters allemaal in beschouwing genomen worden, is een eerlijke vergelijking mogelijk tussen de PON-types op basis van het vermogen per eindgebruiker, berekend voor verschillende scenario's.

Dit resulteert in een aanbeveling voor netwerkoperatoren die de meest energie-efficiënte technologie — aangepast aan hun noden — willen kiezen, niet alleen om hun uitstoot van broeikasgassen te verminderen, maar ook om de kosten te drukken gezien de stijgende energieprijzen. De aanbeveling kan ook gebruikt worden door bedrijven die netwerkapparatuur op de markt brengen, en door standaardisatie-organen in de telecomsector.

Anderzijds tonen de resultaten ook aan dat de introductie van een nieuwe generatie van snellere PONs zal leiden tot een toename van het energieverbruik als er geen bijkomende maatregelen genomen worden om hun verbruik te verminderen.

De GreenTouch-architectuur voor optische toegangsnetwerken Een tweede model dat in dit proefschrift aan bod komt, werd ontwikkeld in het kader van het onderzoeksproject GreenTouch. Het toepassingsgebied van dit model is uitgebreid in vergelijking met dat van het vorige model: hier wordt ook de metro/aggregatie in beschouwing genomen (een centraler deel van het netwerk) zodat technologieën met een groter bereik geëvalueerd kunnen worden. Bovendien integreert het model verschillende energiebesparende maatregelen zoals het gebruik van slaapstanden, virtualisatie en hardware-innovaties. Aan de hand van dit model worden drie scenario's geëvalueerd: (1) een referentie-architectuur van een toegangsnetwerk en metro/aggregatie netwerk, gebruik makend van technologieën die in het jaar 2010 beschikbaar waren; (2) een "business-as-usual" architectuur voor 2020: als de huidige trends worden verdergezet zonder bijzondere aandacht voor energie-efficiëntie, verwachten we dat de energie-efficiëntie al 29 keer zal verbeteren ten opzichte van de referentie; en (3) de GreenTouch architectuur voor 2020: als het voornaamste doel bij het ontwerp van een toekomstig netwerk energie-efficiëntie is, en alle oplossingen die hiertoe bijdragen en die commercieel beschikbaar kunnen zijn tegen 2020 effectief ingezet worden, kan de energie-efficiëntie met een factor 257 verbeterd worden ten opzichte van de referentie. De resultaten tonen aan dat er inderdaad nog heel wat potentieel is om de voetafdruk van netwerken te verkleinen, aangezien het vermogen per verbruiker kan gereduceerd worden van een aantal watt naar de orde van een paar honderd milliwatt.

Post-peak ICT Daar waar het hierboven gepresenteerde onderzoek de nadruk legde op het reduceren van het energieverbruik van netwerken terwijl een optimale dienstverlening gegarandeerd blijft, bekijkt "post-peak" ICT — een onderwerp dat ook uitvoerig aan bod komt in dit werk — het verbruik van netwerken uit een andere invalshoek. We beschouwen hier een scenario waarin fossiele brandstoffen de facto niet meer gebruikt worden (de term "post-peak" verwijst naar het feit dat fossiele brandstoffen voorbij hun piek zullen zijn), en vervangen moeten worden door alternatieve energiebronnen.

Een dergelijk post-peak scenario was tot nu toe een onderbelicht onderwerp in de studie van communicatienetwerken. Eén van de belangrijke bijdragen van dit werk is dan ook een uitgebreide motivatie die aantoont waarom we denken dat een post-peak scenario zich in de nabije toekomst kan afspelen, en waarom er dus meer onderzoek naar zou moeten gebeuren. De voornaamste redenen die we aanhalen om af te stappen van het gebruik van fossiele brandstoffen zijn de mogelijke uitputting van de voorraad fossiele brandstoffen, de instabiele internationale energiemarkt, en de opwarming van het klimaat.

Naast de hierboven beschreven motivatie, bekijken we ook de impact van post-peak op de beschikbaarheid van energie, en hoe dit kan leiden tot een minder constante energiebeschikbaarheid dan we vandaag kennen, met tijdelijke energietekorten als gevolg.

Zoals reeds vermeld, is dit nog een relatief nieuw onderzoeksdomein. De effecten van dergelijke energietekorten op communicatienetwerken zijn dan ook nog niet bestudeerd, en worden in dit werk aangeraakt door het formuleren van een aantal nieuwe onderzoeksvragen, waaronder: "Als we slechts een fractie van het gebruikelijke vermogen ter beschikking hebben in een netwerk, welke dienstverlening kunnen we dan nog aanbieden?"

We passen dit ook toe op het concreet voorbeeld van een bestaand draadloos toegangsnetwerk in een stad, waarin we een strategie simuleren die optimaal gebruik maakt van een sterk gereduceerde hoeveelheid energie door onderdelen van het netwerk in een energiespaarstand te plaatsen.

Tot slot geven we ook nog een kader mee voor toekomstig onderzoek in dit domein, enerzijds door een eerste evaluatie te maken van het potentieel voor post-peak aanpassingen in toegangsnetwerken, kernnetwerken en data centers; anderzijds door de nieuwe onderzoeksrichtingen aan te wijzen die verder bewandeld moeten worden als we ICT-infrastructuren willen die voldoende voorbereid zijn op de toekomst "na de piek".

Summary

There is an increasing awareness and concern about human consumption of fossil fuels, and how its consequences are affecting the climate. Global warming has been proven beyond doubt, and there is a broad consensus among climate scientists that greenhouse gas (GHG) emissions from human activity are causing it. A significant share of these emissions originates in the burning of fossil fuels to generate electricity. Global electricity production has grown about 3% annually in the past, corresponding to a doubling every 23 years on average. Clearly such growth cannot be sustainable if we are to reduce our emissions. In order to counter this trend, we will not only need to change the way we generate electricity by switching to renewable or other low-carbon energy sources, but also reduce the need for production by making the consuming sectors more energy efficient: we should strive to achieve more results with less energy.

Information and communications technology (ICT) may not be the first sector that comes to mind when we think about our carbon footprint, but with a share in global GHG emissions that is about the same size as that of the global airline industry, and more potential for growth, it is far from negligible. Indeed, the ICT sector is growing fast, finding its way to many aspects of our everyday lives, and if no efforts are made to improve its energy efficiency, we can expect its share in our footprint to increase further.

The general topic of this dissertation is green ICT, and more specifically, green networking. This research direction, which has become increasingly popular over the past decade, is aimed at reducing the GHG emissions from ICT and networking. The general recommendation above about reducing emissions remains applicable here: greening of communication networks can be achieved by combining low-carbon (renewable) energy sources with techniques to make networks more energy efficient, so that less energy is wasted. This work only looks at the use phase electricity consumption (excluding manufacturing and end-of-life disposal), as this makes up the largest portion of the overall carbon footprint of ICT.

Worldwide electricity consumption of communication networks A first contribution of this dissertation is that it provides a detailed estimate of the contribution of networks to worldwide electricity consumption. Having up-to-date estimates for the overall consumption of networks is an important

first step towards assessing the impact of introducing new energy-efficient technologies that may reduce this consumption.

We present a methodology that was developed to estimate the worldwide use phase electricity consumption of telecom operator networks, office networks and customer premises equipment. The model is described in detail, with particular attention to the modeling of telecom operator networks, as they take up the biggest share. To estimate this part, we use reports on the electricity consumption of telecom operators. The advantage of this approach is that it takes into account overheads and complexities that are hard to capture in a theoretical analysis based on network models.

The methodology is subsequently applied to a data set for the years 2007-2012. The results show that the impact of networks on the environment is growing rapidly, at a rate of 10% per year, a growth that is mainly driven by growing numbers of subscribers and increasing bandwidth demands. The growth rate for networks is faster than that of the overall electricity consumption, so the share of networks in global electricity consumption is increasing. By 2012, almost two percent of all worldwide electricity was consumed by communication networks. This corresponds to 350 TWh (350 *billion* kilowatt hours), which is more than four times the electricity consumption of the whole of Belgium in that same year.

These results emphasize the importance of green networking to stabilize or reduce the energy needs of communication networks.

Comparing next-generation optical access technologies The green networking research that is presented in this dissertation focuses mostly on optical access. The access network is the part of the network that provides a physical connection to the end users through which they can connect to the Internet. In the case of optical access, this physical connection is an optical fiber that transports information by means of light. We look at passive optical network (PON) architectures (which require no active equipment in the field), because they are the most likely candidates for commercialization, with some types already deployed in the field. Several PON implementations exist and were being developed at the time we published this study, with subsequent generations each time offering higher data rates (in response to growing user demands) and longer reach.

To avoid these innovations coming at the cost of increased energy consumption, we developed a model to compare candidates for future optical access, and to be able to make a recommendation on which technology is most energy efficient. The model takes into account the properties of each technology, user demands (with access rates up to 1 Gb/s), split ratio optimization (changing the network layout to achieve the required quality of service in the most energy-efficient way possible), dynamic bandwidth allocation (dividing network capacity among users dynamically taking into account their instantaneous needs), and considers a realistic geographical deployment for a major city (to take into account the implications of reach when determining the required amount of equipment).

With all these parameters factored in, we can make a fair comparison between technologies by comparing the power per subscriber under various conditions.

As such, we can make a recommendation towards network providers, vendors and standardization bodies that wish to offer the most energy-efficient technology adapted to the network needs. Choosing the most energy-efficient technology can not only help them to reduce their GHG emissions, but also to reduce their operational expenditures, as energy prices are on the rise.

On the other hand, the results also reveal that energy consumption will rise with the introduction of newer, faster next-generation PONs, unless additional measures are taken to reduce their power consumption.

Energy-efficient GreenTouch architecture for optical access This dissertation also presents a second model to evaluate the power consumption of optical access. The GreenTouch model[3] takes into account the metro/aggregation portion of the network as well as the access (to evaluate long reach technologies), and integrates various energy-saving approaches such as sleep modes, virtualization and hardware innovations in a single framework.

The model is used to evaluate three scenarios: (1) a baseline optical access & metro architecture for 2010, using the most energy-efficient technologies that were available at that time; (2) a business-as-usual architecture for 2020 in which current trends are projected to continue without special efforts to improve energy efficiency, resulting in a 29-fold energy efficiency improvement compared to the baseline; and (3) a GreenTouch scenario for 2020, integrating energy efficiency improvement techniques that can be ready for commercial deployment by 2020 if energy efficiency is made a primary target for network design. Thanks to this energy-aware design a 257-fold improvement in energy efficiency can be achieved relative to the baseline scenario. Evidently, the footprint of optical access networks can be reduced greatly compared to current levels — from the order of watts per subscriber to the order of a couple of hundred milliwatts.

Post-peak ICT Reducing the energy requirements of networks while maintaining their original quality of service is of essential importance, but another scenario may also become relevant in the future. This dissertation introduces a so-called “post-peak” future scenario, in which we can no longer rely on fossil fuels as our main resource for electricity production (fossil fuels are “past their peak”), but instead are replaced by alternative energy sources.

[3]The outcome of a joint research effort by the partners in the GreenTouch consortium.

This is a relatively new research direction in the field of communication networks, therefore our first contribution on the topic is to give an extensive motivation, showing why we expect such a scenario may occur in the near future. We refer to fossil fuel depletion, insecure energy supply and climate change as the main reasons to push a withdrawal from fossil fuels.

Secondly, we also assess the impact this will have on energy availability, showing how this may result in a less reliable and constant energy supply than the one we know today, and how temporary energy shortages may result from this.

Since this is a relatively new research domain, the effects of such shortages on communication network infrastructures are not yet clearly defined. We therefore formulated a number of research questions, such as: "If we only have a small fraction of the normal operational energy available, what fraction of the network service can we still offer?"

A wireless case study for an existing mobile network in a city is included to show one possible practical solution that can make optimal use of limited available energy: in the simulated network, well-chosen network equipment is switched from an active to an energy-saving state to offer the maximal possible service under the given energy constraint.

We also describe a framework for future research in this domain, including a basic assessment of the post-peak potential of technologies in access, core, and data centers; and we also propose new research directions that must be explored into if we want ICT infrastructures to be able to cope with post-peak energy limitations.

1 Introduction

This chapter starts with a description of the context in which this research was performed in Section 1.1 , providing background information on global warming and the ecological footprint of networks, and explaining the key concepts and terminology that are needed to understand the work presented in the following chapters. Section 1.2 summarizes the main contributions and outlines the structure of this dissertation. Section 1.3 provides a complete overview of the publications that were authored during this research period.

1.1 Research context

1.1.1 Global warming

Scientific evidence for warming of the climate system is unequivocal. Figure 1.1 shows the evolution of global surface temperature, averaged over land and oceans. There is a clear trend: the earth's surface is getting warmer, and since the 1970s this temperature rise has been happening faster than in the beginning of the 20th century. Nine out of ten of the warmest years in the 134-year record (as far back as we have measurements) have all occurred since 2000. The year 2015 ranks as the warmest year on record, and based on the preliminary data it looks like 2016 is set to break that record.

According to most climate scientists, human emissions of so-called greenhouse gases (GHG) are causing the current global warming trend.

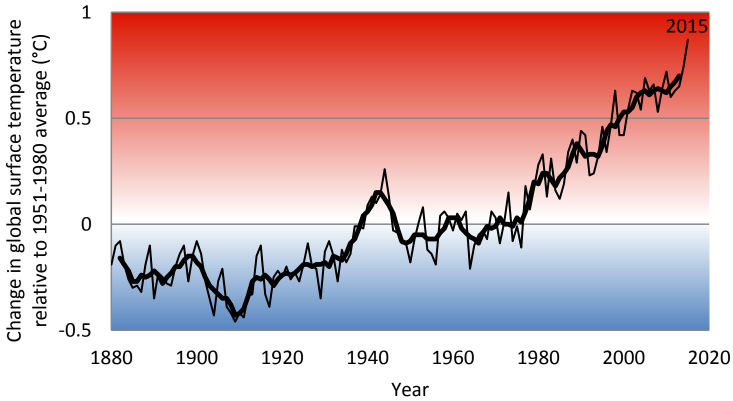


Figure 1.1: *Annual (thin line) and five-year average (thick line) variation of global surface temperatures from 1880 to 2015. Years in the blue zone were cooler than average. Years in the red zone were warmer than average. Data source: [1]*

Certain gases, such as carbon dioxide (CO_2), when released in the atmosphere, block heat from radiating from the Earth towards space. When the amount of greenhouse gases in the atmosphere increases, more heat gets trapped and the Earth gets warmer.

Several gases have the potential to create this effect, but CO_2 is currently the most important one, for two reasons: first, it's a long-lived gas that remains semi-permanently in the atmosphere and does not respond physically or chemically to changes in temperature, also described as *forcing* climate change; second, humans have increased atmospheric CO_2 concentration by a third since the beginning of the Industrial Revolution [2].

The burning of fossil fuels like coal and oil is one of the main sources of CO_2 emissions. To a lesser extent, the clearing of land for agriculture, industry and other human activities have increased concentrations of greenhouse gases. According to the Intergovernmental Panel on Climate Change (IPCC), total emissions from human activities have continued to increase from 1970 to 2010, with larger absolute increases decade after decade despite policies aimed at reducing these emissions [3]. Unless measures are taken to stop this trend, it will continue, driven by growth of the global population and economy.

The consequences of climate change are difficult to predict, but it clearly poses serious risks for human and natural systems [4]. Our vulnerability to climate variability became painfully clear in recent years as we witnessed heat waves, droughts, floods, cyclones and wildfires having a devastating impact on ecosystems, disrupting food production and water supply, damaging infrastructure and costing human lives. Without mitigation (actions to reduce emissions and to stop or slow down global warming), global mean surface temperature increases in 2100 from 3.7°C to 4.8°C are expected relative to pre-industrial levels, and we will likely face even more dramatic consequences such as substantial species extinction and compromised global food security [3, 4].

The overall risks of climate change impacts can be reduced by limiting human emissions of GHGs. Scenarios that offer a likely chance of keeping temperature change by 2100 below 2°C relative to pre-industrial levels include substantial cuts in human GHG emissions: globally they should be 40% to 70% lower in 2050 compared to 2010, and near zero or even negative (using carbon capture and storage techniques) in 2100 [3].

But where are these emissions coming from? Fig. 1.2, showing a breakdown of the carbon footprint[1] by economic sector (following the classification the IPCC makes in [3]), gives us an idea: electricity and heat production takes up the biggest share. These emissions come from burning coal, natural gas, and oil to generate electricity and heat. Furthermore, electricity generation is also responsible for part of the Industry emissions (which primarily involve burning fossil fuels on-site for energy), and Other Energy (indirect emissions from electricity and heat production resulting from extraction, refining, processing and transportation of fuel) [5]. Energy supply sector emissions are expected to continue to be the major source of GHG emissions, ultimately accounting for the significant increases in indirect emissions from electricity use in the buildings and industry sectors. Indeed, Fig. 1.3 illustrates the ever-increasing electricity production (following increasing electricity demand), and how it is mostly using fossil fuels to source its energy.

How can we reduce the emissions from the energy sector? According to the IPCC [3], "*efficiency enhancements* and behavioural changes, in order to reduce energy demand compared to baseline scenarios without compromising development, are a key mitigation strategy". This is exactly the aim of the *green information and communications technology (ICT)* research track, which I pursued in my research, as I will explain in the following sections.

1.1.2 The ecological footprint of ICT

ICT: what's in a name? The term information and communications technology (ICT) has no universal definition, but in general it refers to electronic

[1] Carbon footprint calculated as carbon dioxide equivalent (CO_2eq) using the relevant 100-year global warming potential of the total amount of carbon dioxide and methane emitted by an activity.

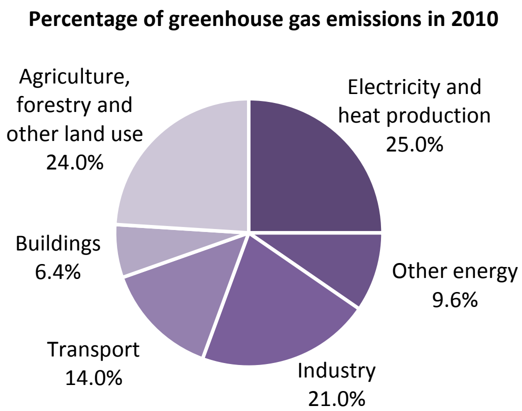


Figure 1.2: *Relative share of economic sectors in total anthropogenic greenhouse gas emissions (CO_2eq/yr for 2010). The energy supply sector is, and is expected to remain, the main source of emissions. Data source: [3]*

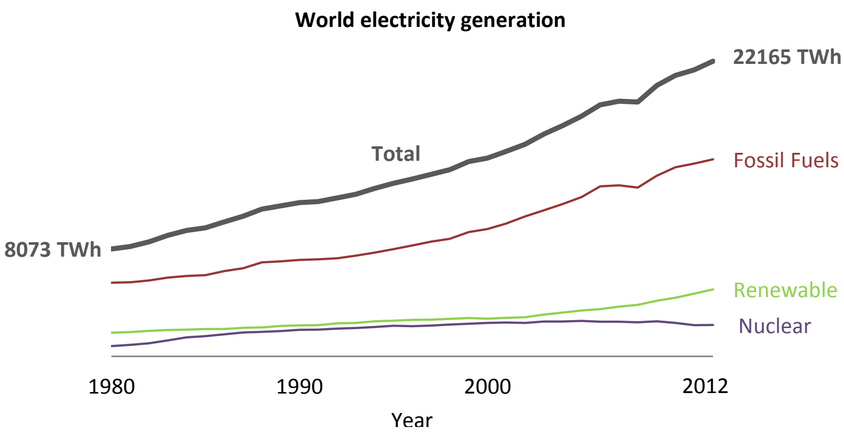


Figure 1.3: *World electricity generation from 1980 to 2012, broken down by energy source (1 TWh = 1 billion kilowatt hours). Most electricity is generated by burning fossil fuels. Data source: [6]*

devices and infrastructures used primarily to exchange information. Using this definition, it's clear that ICT has penetrated many aspects of our lives in the past years: more and more people's jobs involve at least some amount of computer work, often requiring an Internet connection, cars are equipped with navigation systems that receive signals from satellites circling the Earth and, in some cases, real-time traffic updates, video games have become an important segment of the entertainment industry, Facebook has more than one billion daily active users, and more than 4.5 billion people have a mobile phone.

The carbon footprint of ICT When people think about their energy consumption, large household appliances like refrigerators and washing machines often come to mind. However, if you consider the fact that many home gateways (the "modems" installed by Proximus or Telenet in your home) consume 10 watts or more, the same as a small refrigerator, it quickly becomes clear that ICT has an impact too. The worldwide ICT sector has been estimated to be responsible for around 2% of man-made CO_2 emissions each year[2] — similar to the figure for the global airline industry, with ICT growing at a faster pace [7, 8].

The ICT sector impacts the environment in various ways: there is the carbon footprint associated with the energy needed to manufacture the equipment, the electricity used to operate it and the cost of maintenance, pollution associated with mining for rare earth metals, and waste through improper disposal of broken or old equipment. While all of these aspects merit their own study, in this work we focus on the *use phase electricity consumption*, since it makes up the biggest fraction of the total carbon footprint of ICT [9, 10]. We only report on electricity consumption, as the use phase carbon emissions can be directly calculated from the emission intensity (amount of CO_2 emitted per produced kWh) of the electricity. Part of the work conducted in this PhD consisted of estimating the worldwide electricity consumption in communication networks.

To give an idea of the order of magnitude of ICT electricity consumption, Fig. 1.4 summarizes the results of a study from our research group [11]. It incorporates the results of the network study, reported in detail in Chapter 2, supplemented with an estimate of the electricity consumption of personal computers (PCs) and data centers. The relative share of these ICT products and services in the total worldwide electricity consumption has increased from about 3.9% in 2007 to 4.6% in 2012. Fig. 1.4 also highlights the importance of *networks* in ICT electricity consumption: they are the

[2] The 2% estimate is actually on the low end, as the authors of [7] employed a more strict definition of ICT, which did not include certain end devices such as television sets.

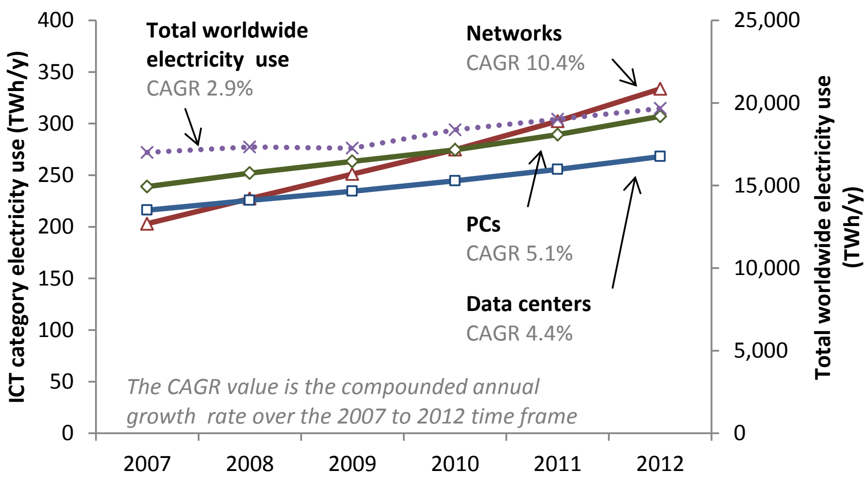


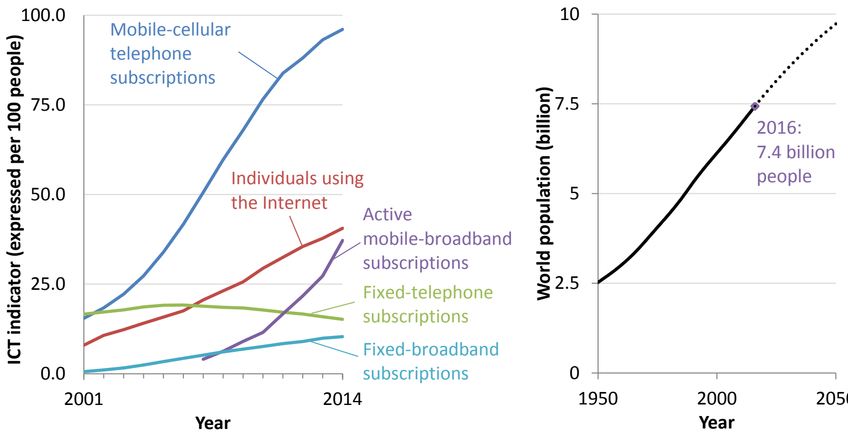
***Figure 1.4:** Electricity consumption in ICT is growing faster than total worldwide electricity use. Networks is the fastest growing category. Figure from: [11]*

fastest growing category, with a compound annual growth rate (CAGR) of 10.4%, corresponding to a doubling every 7 years.[3] We can expect this growth to continue as more and more devices are being connected (not just mobile phones and personal computers, but also machines and household appliances), larger areas are being equipped with ever faster network infrastructures (e.g. recent deployment of 3G and 4G mobile Internet in Belgium), developing countries are catching up with more mature markets in terms of Internet use, and population growth continues, as illustrated by the trends in Fig. 1.5. To counter this trend of growing electricity consumption, we need to take action. This is where green ICT comes into the picture.

1.1.3 Green ICT and green networking

Green ICT: what's in a name? Green ICT and green networking are two terms that are used when we try to minimize GHG emissions from these activities. A first logical step to achieve this is to enforce the use of renewable energy, for example by powering mobile antennas with solar panels instead of diesel generators. The second, complementary step, is to reduce unnecessary energy expenditure by greening of the networking technologies and protocols themselves. Put simply, the goal of green networking is

[3] In the same period, worldwide electricity consumption (for all sectors combined) knew a CAGR of 3%, corresponding to a doubling every 23 years.



(a) Global ICT developments, 2001-2014. Data source: [12]

(b) World population prospects. Data source: [13] (medium fertility variant for 2015-2050)

Figure 1.5: *Drivers for continued growth of electricity consumption in communication networks: (a) increasing connectivity and (b) population growth.*

this: reducing the energy required to carry out a given task while maintaining the same level of performance. This is also called improving/increasing the *energy efficiency*, and it is the goal of the work reported in Chapters 3 and 4.

ICT can also be used in other ways to reduce human GHG emissions. *ICT for green* (also called the *enabling effect* of ICT) leverages communication technology to make other sectors more energy efficient. For example, smart grids can be introduced, using electronic systems to optimize the distribution of electricity (for an overview of other such applications, see, for example, [14]). This is however outside the scope of this research. In any case, if ICT is to be a part of the solution, it will have to have a limited footprint.

Why is there a research interest in green ICT Obviously, reducing electricity consumption and the corresponding GHG emissions linked to global warming (as described in Section 1.1.1 and 1.1.2) is a valid reason in and of itself to invest in green ICT research. On top of this ecological motivation, there are a number of other reasons why telecom network operators might want to invest in green ICT.

From an economical perspective, increasing energy prices are becoming an important cost factor for telecom network operators, especially in energy intensive infrastructures such as data centers and radio access networks. Investing in green ICT can help cut these costs. As an added benefit, such investments can be used for marketing reasons by companies that want to show social responsibility in fighting climate change.

There are also technical reasons for wanting to limit the amount of energy dissipation in electronics. Miniaturization in the past years has been accompanied by an increasing heat dissipation per surface area, making the cooling of this equipment more technically challenging and expensive. This problem could be alleviated by making the equipment less power-hungry.

Besides these immediate economical and technical considerations, green ICT research is also motivated by the observation that energy consumption could become a barrier to network growth if nothing is done to address it [15]; and the fact that energy-efficient technologies make it easier to bring communications infrastructure to developing nations where energy is more scarce.

These various incentives have spurred the creation of a large number of green research initiatives over the past years; a list is included in Section 1.1.4.7, after the discussion of communication networks basics, to be able to specify which portions of the network the initiatives focus on.

1.1.4 Communication networks primer

1.1.4.1 Network sections

Communication networks provide private users and businesses electronic access to information and connections with other users and businesses. The people and organizations who pay the *network provider* or *telecom operator* to get access to the network are called *subscribers*. The general architecture of a communication network uses various layers of aggregation, as shown in Fig. 1.6.

Local area network (LAN) *End devices* such as computers, smartphones and tablets can connect to the Internet through a LAN, which is a network that covers a small geographical area such as a home or a building.[4] A LAN can for example consist of a router and/or wireless access point (AP) installed at the customer premises (a router and a WiFi AP are often integrated in a single device provided by the telecom operator); or a company network using switches and routers. A *switch* receives information (bits) through network links and can determine where this information has to be sent to reach its destination, defined by a hardware address (code) attached

[4] Alternatively, end devices may also connect directly to the mobile access network, discussed in the following paragraph.

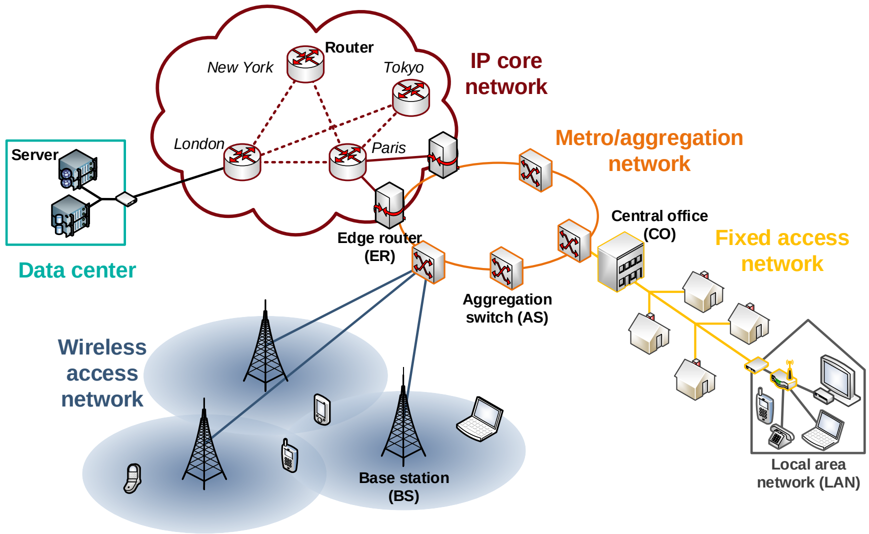


Figure 1.6: *Schematic of a communications network showing the access, metro/aggregation and core networks, and a data center.*

to this information — you can compare it to someone sending traffic in the right direction at an intersection, only the roads are network cables. A *router* is a networking device that forwards data packets between two separate computer networks, for example between your home network and the access network (modem).

Access network This network section provides a physical connection to the end users through which they can connect to the Internet. In *fixed access* networks, a physical wire runs to the end users premises, connecting it to a *central office (CO)* where a first aggregation of information takes place, usually from a couple of thousand subscribers. The physical wire can be a twisted pair telephone line (narrowband dial-up, broadband asymmetric digital subscriber line (ADSL) or its successor very-high-bitrate digital subscriber line (VDSL) as offered by Proximus in Belgium), a coaxial cable (as offered by Telenet in Belgium), or optical fiber (fiber to the home).

In *wireless access* networks, subscribers use standardized radio signals (e.g. 2G, 3G, or 4G technology) to connect to the nearest base station (BS), from where the signal is forwarded through a dedicated backhaul link to an aggregation point.

Metro aggregation The traffic from a CO is sent through an uplink to an *aggregation switch (AS)*, where it is grouped (aggregated) with traffic from other COs to forward it from a large number of relatively low-capacity links to a smaller number of high-capacity optical links. Multiple ASs are connected in a circular topology for resiliency — if one of the optical links breaks, all switches are still connected. A single aggregation switch can serve several tens of thousands of users. Each aggregation ring also contains one or more *edge routers (ERs)*, that form the interface between aggregation and core.

Internet protocol (IP) core In the backbone of the network, data packets are forwarded from one *core router* to the next until they reach their destination node. At this level, traffic from hundreds of thousands or even millions of users is handled by a single core router — there are usually only a handful of routers in a country. The core routers are connected through high-capacity, low-latency optical links that can span large geographical distances.

Data centers These are facilities that house large numbers of computer and storage systems to host a wide range of applications, from websites over search engines to cloud computing. They are not exactly part of the network, but provide a significant portion of the traffic that is routed through the network.

1.1.4.2 Network parameters

In the following chapters, the quantitative comparison of networks will require the definition of a number of parameters. The most important ones are:

Bandwidth, throughput or capacity of a link In network dimensioning, we use these terms to refer to the line rate, the total number of physically transferred bits per second over a communication link.[5] Note that the line rate is usually not the rate of useful information that can be received by the users, because of overhead frames, added to the data to route it through the network; and the need to allow spacing between consequent data frames. So when a user sends or receives information, the upload or download speed will be slightly lower than the line rate. In network dimensioning, we

[5]In communication networks, the term *bandwidth* can also be used to refer to a range or band of electromagnetic frequencies. Throughout this work however, we use it to refer to throughput as defined here.

also distinguish between downstream (DS) and upstream (US) bandwidth, where data going from the network side to the user is called DS traffic, and data going in the opposite direction is called US traffic.

Access rate or user rate The speed at which data can be sent to or from the user. Depending on the context, this can be interpreted as a physical line rate or the useful information rate.

Packet loss Data streams are typically packaged in smaller, structured "frames", also called packets, with headers and trailers — bits that precede and follow the payload, which is the slice of data contained in the packet. These headers and trailers indicate source and destination, the type of data that is contained in the frame, the order in which packets should be put back together, etc. In each stage where packets are handled, there is a buffer to store them for a short time when too many packets are arriving at the same time. When the network has insufficient capacity, these buffers can overflow and packets are lost. The packet loss is then defined as the ratio of packets discarded (lost in the network) over packets offered (leaving from the source with the purpose of reaching a destination). Some degree of packet loss due to statistical fluctuations in traffic is inevitable, and is acceptable, as it can be compensated by retransmitting the missing packets. There is however a maximum allowable fraction. How strict this fraction is, depends on the type of service and the service level agreements (SLAs) between the network provider and his customers.

Availability This is the overall "uptime" of the network: what percentage of the time can the network offer connectivity to the users? Availability can be reduced when insufficient capacity is provisioned, or when components of the network fail and need to be replaced, leaving some parts of the network temporarily disconnected.

Reach When a signal travels over a long distance, its strength is reduced; something we call loss. If the transmission distance is too long, the signal becomes too weak to be detected by a receiver. The *attenuation* quantifies this reduction in signal strength, and can be expressed in decibel (dB) by calculating $10 \times \log_{10}(P_{IN}/P_{OUT})$ where P_{IN} is the power or intensity of the signal entering the link, and P_{OUT} that of the signal arriving at the other end of the link. Fiber optic cables experience less signal loss (lower attenuation) than copper cabling (such as telephone lines or coaxial cable), and wireless transmissions typically experience the biggest losses per distance traveled.

Besides the transmission medium, reach can also be influenced by interference from other (external) signals, quality of transmitters and receivers, components that interact with the signal such as splitters, or amplifiers or regenerators that can be placed throughout the network to increase reach.

Quality of service (QoS) The ultimate goal of a network provider is to provide a connection to the users, so the quality of this connection and of the user experience is of the utmost importance. QoS is a general term to refer to a metric/metrics that is/are meant to capture the quality of the network. Depending on the type of network and user requirements, it can be influenced by any of the parameters introduced above, or other parameters such as the bit error ratio (fraction of bits of a data stream over a communication channel that have been altered due to noise, interference, distortion, or bit synchronization errors), or user coverage (e.g. what percentage of mobile phone subscribers in a certain area can receive a signal on their phone). Given the importance of QoS, when network greening strategies are devised, we must always strive not to let energy gains come at the price of a network performance loss.

1.1.4.3 Factors contributing to network power consumption

All of the nodes and connections introduced in the previous section require power to handle and process the data passing through the network. On top of this *useful* power consumption, there are several other factors contributing to the overall power consumption of networks:

- Power conversion inefficiency: most electronics require direct current (DC), while the grid delivers alternating current (AC). Many devices also require further DC/DC voltage conversion (e.g. from 230 V to 12 V). Some energy is always lost in the conversion from one form of power to the other.
- Ventilation and air conditioning, especially in large facilities.
- Auxiliary power units and batteries to keep equipment running when the power supply is disrupted.
- Backup capacity which is sometimes active for quick recovery and resiliency. This equipment is redundant under normal operation conditions, but is occasionally needed when another device fails.
- Many parts of the network are overprovisioned: they are dimensioned to sustain peak hour traffic, with extra capacity to allow for

unexpected events; and corresponding over-consumption in comparison with the actual traffic load [16].

- Legacy equipment that is still in place but that is only partially or not being used.

This indirect power consumption can be captured in a power *overhead* factor, which you need to multiply the useful power by to get the actual power draw.

An example of such a factor, that is commonly applied to equipment in data centers and large telecommunication facilities, is the *power usage effectiveness (PUE)*, which captures all the building overheads:

$$PUE = \frac{\text{total facility energy}}{\text{ICT equipment energy}} \tag{1.1}$$

The most efficient datacenters have a PUE of around 1.07–1.2, while the industry average is around 2.0 [17], meaning that for every watt of ICT power, an additional watt is consumed by overheads such as cooling and power distribution.

1.1.4.4 Network power consumption metrics

There are several ways to express the power consumption of networks.

The *power per node* (common units: W/node, kW/node) is obtained when looking at a specific network element or a group of network elements (for example, all the equipment in a CO or all components of a router).

Combined with the equipment count (number of nodes of each type) it can be used to calculate the *total network power* (common units: W, GW, TWh/year) for a nation, region or the world. This is a widely used metric, as it allows a comparison of the importance of networks relative to other sectors (like aviation, industry, homes), it can show the evolution of overall power consumption over time (cf. Fig. 1.4), and to see what would be the absolute impact (in terms of GHG emissions) of replacing certain devices by less power-hungry varieties. It is however difficult to measure and/or determine this power directly, as many factors need to be taken into account (a large number of devices with various power models, redundancy of the architecture, overheads, etc.).

A metric that is often used to describe power consumption in the access network is the average power per user or *power per subscriber* (common unit: W/user, W/subscriber). This can be obtained by summing the contributions of all components required to connect a subscriber, or by dividing the estimated total network consumption by the number of subscribers. This metric has several advantages: it provides an intuitive idea of the amount of power needed to provide connectivity, which can easily be compared to the footprint of other human activity; and it allows straightforward comparison across technologies. The disadvantage is that it doesn't capture how much information is passing through the network.

Metrics that do consider the amount of information being exchanged, can either be expressed as energy per bit or power per bit rate[6] (common units: J/bit, W/Gbps), or as their inverse: *energy efficiency* (bits/J or kilobits/J). When a device is more energy efficient, it means it can transmit more bits using the same amount of energy, or can process data faster using the same (average) power. The disadvantage of this metric is that it may create the impression that we are heading in the right direction when we are not (if energy efficiency does not improve enough to compensate for fast traffic growth). Moreover, by boosting traffic estimates the energy efficiency can be artificially increased.[7] Ideally, when using this metric we should distinguish between throughput and "good"put [15]: if a lot of bits are being exchanged in the network unnecessarily (due to inefficient routing paths, retransmissions or large frame overheads), only the useful bits should be counted in the energy efficiency calculation.

In summary, there are many different metrics to express power consumption in networks, each with their own merits. It's important to keep in mind that different metrics provide different optimal solutions to energy efficiency.

1.1.4.5 Power-saving factors

The ultimate goal of green ICT is to improve energy efficiency. Throughout this work, a number of terms that express power savings (or equivalently, when a given time period is considered, energy savings) are used interchangeably. For clarity, we illustrate their meaning with a simple example.

Suppose we have a device that consumes 100 W to perform a certain task. This is called the baseline power. A new device is developed, that only requires 33.3 W to perform the same task. Then the following expressions are synonymous:

- We have reduced power/energy consumption to a fraction 0.333 of the original power;

[6] Note that, since *power* (expressed in watts) is the amount of *energy* (expressed in joules) consumed per unit time (expressed in seconds), J/bit and W/(bit/s) have the same dimension (1 W = 1 J/s).

[7] Suppose for example you have a device that consumes 1000 W, no matter how much traffic passes through it. If you say it will need to handle twice as much traffic as today in a couple of years, it will automatically become twice as energy efficient, without any real efforts being made.

- We have cut or reduced power/energy consumption by 66.7%;
- This is a 66.7% power reduction;
- We are using 33.3% of the original power/energy;
- We have reduced power/energy consumption by a factor 3×;
- We have improved energy efficiency by a factor 3×;
- We have achieved a power/energy-saving factor 0.333× (saving factors can be multiplied to obtain cumulative savings when combining several energy-saving techniques, see Chapter 4).

Note that other works may define these terms differently.

1.1.4.6 Green networking solutions

There are many ways in which the energy consumption of networks can be reduced. We list a few of them below, grouped by the categories introduced in [15]: green technologies, protocols, architectures, and cloud computing. Note that some solutions may cross the lines between these categories; sleep modes for example require both adapted protocols and technologies, and on top of that they can be used to alter the network architecture.

Technologies This first category covers the design of new, more energy-efficient hardware. Examples include the introduction of disruptive new technologies (e.g. replacement of copper links by fiber links), innovations in optical and electronic components (e.g. improved integration and miniaturization, or designing chips that allow switching off some sections when they are not needed), or improved cooling techniques (e.g. optimizing the air flow for cooling in a data center).

Protocols Changing protocols means changing the rules that entities in the network follow to set up connections and transmit information.

For example, designing new packet formats can help reduce the energy consumption per useful bit of information transmitted, if the overhead from headers and frames can be reduced.

Operating systems and applications can also be modified to participate in the reduction of the energy budget: for example, Green BitTorrent [18] is a variation on the bittorrent protocol, in which peers avoid waking up idle peers, preferring to download the chunks from active ones while letting the other ones sleep to save power.

Interfaces that support dynamic rate adaptation (also called adaptive link rate) can switch between different operating modes, depending on the traffic load. For example, the line rate could be switched between 1 and 10 Gb/s, changing the clock frequency and processor voltage in response to traffic demands, making power consumption more proportional with the actual load.

One of the most promising (and most often studied) protocol changes in green networking is the use of *sleep* and *standby states*. These can apply to complete systems or sub-systems. For instance, they can be used to help reduce the power overhead of backup systems, by placing them in a standby mode — similar to that of a computer that will switch to a low-power mode when it is not used for a while, but that can be woken up (switched to the active state) quickly when needed. Depending on the implementation, multiple low energy states may be defined. For example, the gigabit-capable passive optical network (GPON)[8] standard (ITU-T G. Sup45) proposes three types of power conservation methods for the optical network unit (the "modem" in optical access): (1) power shedding: switching off certain user interfaces when the user is not actively using the device for a long time; (2) dozing: the transmitter is powered off but not the receiver (so the device can immediately switch back to the active state when it is contacted by a remote entity); (3) sleeping: turning off all functions, only keeping activity detection or a timer operational.

It should be noted that hardware supporting several operation modes is a necessary condition to apply most of these mechanisms. Practical implementations will also need to account for the energy and time that is needed for transitions between modes.

Architectures Architectural changes impact the path information will follow through the network. We can distinguish between *greenfield* and *brownfield* approaches. In a greenfield approach, the best possible conceivable architecture is designed from the ground up, assuming no network infrastructure is present yet. In a brownfield approach on the other hand, the existing equipment and infrastructure (e.g. ducts for cables or towers for mobile antennas) are taken into consideration, providing less flexibility in the architectural design, but decreasing the cost of deploying the proposed architecture. Intermediate scenarios with partial re-use of existing equipment are also possible.

Examples of architectural power saving approaches include: reducing the number of network hops, using optical bypass to avoid conversion of signals from the optical to electronic domain and back at every router, or

[8]GPON is one of the optical access technologies that will be introduced in Section 1.1.5.

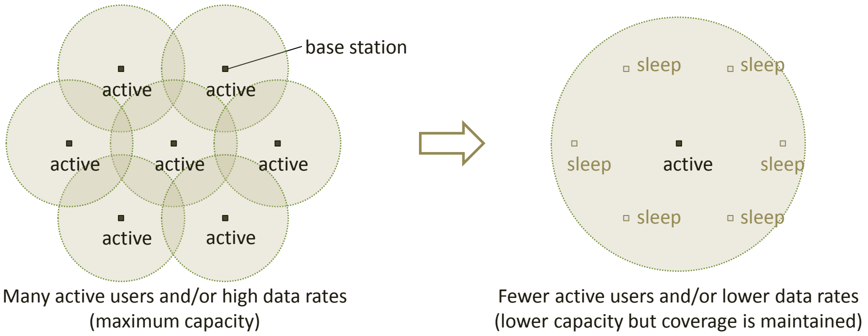


Figure 1.7: *Principle of dynamic adaptation of network capacity to traffic load in a wireless access network, using sleep modes for base stations.*

adapting the level of active over-provisioning to instantaneous network conditions following daily or weekly traffic cycles.

One particular type of network adaptation to the load, is the use of sleep modes in wireless access.[9] The principle is illustrated in Fig. 1.7. In periods of low load (for example at night), unused or underutilized base stations are partly or completely switched off to save power. The remaining active base stations may increase their coverage area, possibly with some small increase in the emitted power, to take over the areas from the inactive base stations and maintain complete coverage. Which base stations are switched off under a particular traffic condition, depends on the chosen algorithm. The survey in [19] provides an extensive overview of such algorithms and techniques.

Cloud and virtualization *Cloud computing* means storing and accessing data and programs over the Internet instead of using local storage and computation power on your computer. For example, if you access your e-mails through a web browser, these e-mails are stored and managed at a remote server location (usually in a data center), but not on your local hard drive. Cloud computing can be more energy-efficient than local computing, especially when data centers leverage clever techniques such as virtualization. *Virtualization* is the use of software to allow a piece of hardware to run multiple tasks at the same time, and to divide tasks into smaller sub-tasks that can be run on multiple pieces of hardware. This technique can be used to improve hardware utilization: all tasks can be moved onto a limited number of servers while the other servers can be removed or placed in a standby mode until they are needed. As such, a more optimal hardware

[9]The case study in Chapter 5 uses sleep modes in wireless access.

utilization and energy efficiency can be achieved than would be possible using local storage.

On the other hand, it should be noted that cloud computing comes at the cost of increased network traffic, with an associated energy cost. Therefore every cloud computing solution should be evaluated individually to see if the total net result is a decrease in energy consumption [15, 20].

1.1.4.7 Green (research) initiatives

A large number of research projects and initiatives in this field were carried out in recent years, partly because energy efficiency in networks was strongly advised by standardization authorities and received support from the European Union.

Many European research projects were directed at energy-efficient wireless communications; examples include EARTH [21] and OPERA-Net [22]. For fixed (optical) networks, fewer projects with the sole purpose of energy efficiency were initiated, but energy efficiency was often one of the main requirements when innovative technologies were being examined, see, for example, the ECONET project [23] that studied dynamic adaptive technologies for both fixed access and core, STRONGEST [24] that wanted to redesign the network core, and ACCORDANCE [25] and OASE [26], two projects that were set up to develop novel optical access architectures.

In addition to these research efforts, energy efficiency in fixed access networks was also promoted by the release of a “Code of Conduct on Energy Consumption of Broadband Equipment” by the European Commission [27]. Service providers, network operators, equipment and component manufacturers were invited to sign this Code of Conduct, in which forthcoming year power consumption targets for both customer premises equipment and network equipment are provided.

The research projects TREND and GreenTouch took a more holistic approach to green networking, considering the network as a whole and taking into account the interactions between network sections. In concrete terms, Towards Real Energy-efficient Network Design (TREND) [28] was a Network of Excellence on energy-efficient networking funded by the European Commission to collect power consumption data and assess the energy-saving potential of green solutions on all network levels. GreenTouch [29], a consortium of industrial and academic partners founded in 2010, set the ambitious goal to deliver the architecture, specifications and roadmap to increase end-to-end network energy efficiency by a factor of 1000 compared to 2010 levels.[10]

[10] The GreenTouch results for optical access are discussed at length in Chapter 4.

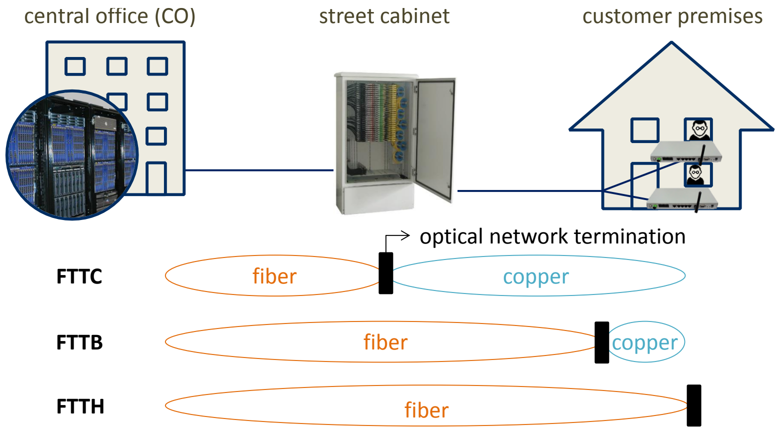


Figure 1.8: Three degrees of fiber penetration: fiber to the cabinet (FTTC), fiber to the building (FTTB), and fiber to the home (FTTH).

1.1.5 Optical access primer

1.1.5.1 Optical access: leading fiber to the home

In fiber-based optical networks, instead of transmitting electrons over a copper cable or telephone line, optical signals are transmitted over a thin, transparent fiber made of glass or plastic. Fiber offers higher bandwidths, lower losses, and better energy efficiency than its traditional copper counterparts, which is why it has been used for many years in core and metro/aggregation networks, and is currently being deployed in the access by operators in several countries.

The penetration of optical fiber can take place in several stages from the CO to subscribers' homes, as shown in Fig. 1.8. In traditional architectures, users have a copper link all the way from their premises to the CO, and data is encoded on that line using for example ADSL technology. When the network operator wants to offer higher bandwidths, it can opt for the introduction of fiber to the cabinet (FTTC), replacing the links between the CO and street cabinets with fiber, and using faster VDSL on the shorter links from the street cabinets to the home. In order to push bandwidths even further, fiber to the building (FTTB) can be introduced, with fiber links leading all the way to (apartment) buildings where only the copper Ethernet links inside the building remain. Finally, the best signal quality and highest capacity can be reached in a fiber to the home (FTTH) scenario, leading the optical fiber all the way to the customer premises. We consider FTTH here as it is the most future-proof and energy efficient solution.

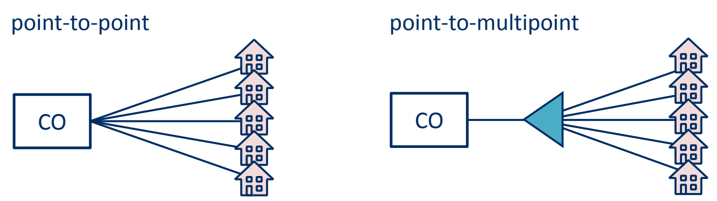


Figure 1.9: *Two optical distribution network (ODN) topologies to connect homes to the central office (CO).*

A fiber to the home topology consists of three main sections: the *CO*, where an optical line terminal (OLT) provides the interface between the access and the aggregation/core network; the *customer premises*, where the optical network is terminated by an optical network unit (ONU) that converts the optical signal into a format understandable to the customer's devices, and the *optical distribution network (ODN)*, which forms the connection between the two ends (for an illustration, see Fig. 1.11 further on).

1.1.5.2 Physical network topologies

The ODN can be designed in two ways (see Fig. 1.9):

1. In a point-to-point (PtP) topology, each fiber leaving the CO goes to exactly one customer. This offers excellent, guaranteed bandwidth to the customer, but comes at a high cost due to the amount of fiber and CO interfaces it requires.

2. In point-to-multipoint (PtMP) topologies, each fiber leaving the CO is shared by many customers. It is split into individual customer-specific fibers relatively close to the customers. Since this solution requires less fibers and only one optical port at the CO for many users, the cost per subscriber is lower, and it is more commonly used in the access than PtP. It also allows flexible and scalable bandwidth assignment, leading to better use of the available capacity.

Given the advantages PtMP offers over PtP and the fact that it is a more likely candidate for commercialization, we will only consider PtMP solutions in more detail.

In such a PtMP topology, there are two ways of splitting a single fiber into multiple fibers:

1. Active optical networks (AONs) rely on electrically powered equipment (e.g. switch, router, multiplexer) to distribute the signal. Each signal leaving the CO is directed only to the customer for which it is

intended, and US traffic is buffered by the active component before transmission on the shared fiber.

2. Passive optical networks (PONs) do not use electrically powered components in the ODN. Instead the signal is distributed using *passive* wavelength-selective components or power splitters. A power splitter splits a fiber into 8, 16, 32, 64 ... fibers (powers of two). PONs are typically deployed in a tree topology, in which several levels of splitters can also be combined (split ratios of the stages are multiplied to obtain the total split ratio, e.g. 1:4 $\times$ 1:32 = 1:128).

AONs hold some advantages over PONs, three of which are listed here: (1) they offer switching and buffering capabilities; (2) PONs require stronger transmitters in the OLT than AONs, because each signal is split among many users in a PON, and the optical signal power is also divided by this value; (3) because signal losses in a splitter are symmetrical, the same is true for US transmission and the reach of a PON is lower than that of an AON [30].

Nevertheless, PONs are being researched, standardized and deployed more widely than AONs, as they have two big operational advantages: (1) having electronic equipment in street cabinets outside the CO is a costly affair for the network operator. Passive equipment does not need a power supply and is easier to maintain; (2) passive components tend to fail less often than active components, improving the availability of the network and reducing the number of required interventions [30].

1.1.5.3 Signal multiplexing

In a PON, signals destined to and coming from different ONUs are transmitted over a shared physical medium. These signals must be somehow "separated" to avoid collisions when signals from several ONUs are joined together on a single fiber, and to allow ONUs to select the relevant information from the broadcast coming from the CO. In optical access networks, there are three main methods to perform this so-called signal *multiplexing*. The principle of each of these three techniques is described in the following paragraphs, and is illustrated by the examples in Fig. 1.10.

Time-division multiplexing (TDM) When this method is used, subscribers take turns transmitting information. The OLT assigns time slots to the ONUs in which they can transmit upstream information; each ONU has its own time slot during which the other ONUs are not allowed to transmit any signals. In the downstream direction, the ONU selects the relevant packets based on their header, which contains the address of the ONU for which the data is meant. Encryption is used to prevent eavesdropping on downstream traffic, as it is seen by all ONUs.

A big advantage of TDM is its simplicity: no wavelength-selective components or complex processing are required (whereas they are required for other techniques, introduced next). It also allows for *dynamic bandwidth allocation (DBA)* in response to changing user demands. The most basic method of allocating bandwidth is to distribute it equally among all ONUs by assigning them equal-size time slots (fixed bandwidth allocation). This is however very inefficient, since the bandwidth needs of the ONUs are not equal at any given time. Bandwidth utilization gains can be made if the bandwidth is allocated dynamically according to the current needs of the ONUs [31] with varying time slot assignments (DBA).

Wavelength-division multiplexing (WDM) Customers can also be assigned a unique wavelength on which they can transmit their signals simultaneously. Wavelength selective components or *filters* in the ODN can separate the signals and only forward the relevant downstream signal to each ONU, or tunable transceivers (transmitters and receivers working on an adjustable wavelength) in the OLT and ONU can be used in combination with simple power splitters in the ODN.

WDM provides less flexibility than TDM, as wavelengths are assigned to ONUs in a fixed manner.[11] Upgrades in network topology are difficult as they require manual reconfiguration of the customer premises equipment (CPE) when the wavelength is changed. This can be resolved by using colorless ONUs (that can change the wavelength they are tuned to), but this comes at an added cost. Wavelength selective equipment in general is relatively expensive. In an attempt to make WDM PONs more cost effecive, the number of customers can be increased. For example, coherent ultra dense wavelength division multiplexing (Co UDWDM) uses coherent detection to be able to assign very closely spaced wavelengths to the ONUs.

Orthogonal frequency division multiplexing (OFDM) This modulation technique that is already being used in commercial broadband wired and wireless communication systems[12], has been adapted for optical communications as well [32]. Like in WDM, information is transmitted on a number of different frequencies simultaneously. However in OFDM the subcarrier

[11] Sometimes different wavelengths can be assigned by tuning ONUs, but not on the timescale needed for DBA.

[12] Examples of commercial use of OFDM include digital subscriber line (DSL) over twisted pair, radio broadcasting, and 4G mobile communications.

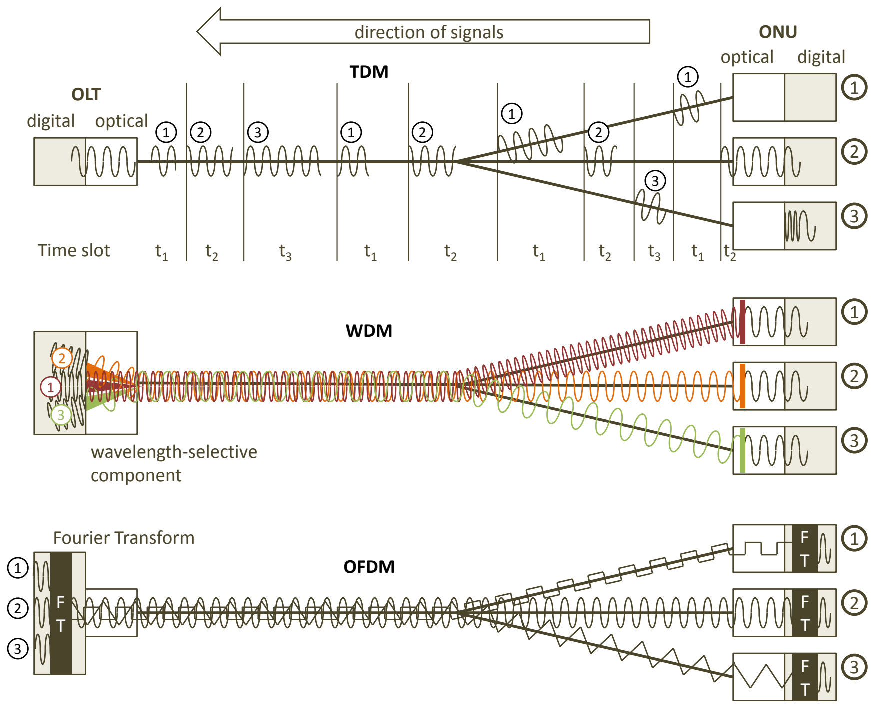


Figure 1.10: *Illustration of three multiplexing techniques: time-division multiplexing (TDM), wavelength-division multiplexing (WDM), and orthogonal frequency division multiplexing (OFDM). In the example, signal multiplexing is used to let several ONUs transmit signals to a single OLT through a shared fiber.*

frequencies are chosen so that the signals are mathematically orthogonal. Where separation of the signals was achieved in the physical domain by filters for WDM, this type of multiplexing is realized in the digital domain using Fourier transforms. The advantage of this technique is that it makes very efficient use of optical bandwidth. The disadvantage is that in current implementations for optical access, the required signal processing for transmission and reception of signals is very power-consuming.

Combined multiplexing techniques The aforementioned multiplexing techniques can also be combined. TDM-PONs usually take advantage of WDM to separate downstream and upstream traffic (using one wavelength for downstream traffic and another for upstream traffic). Time-shared wavelength division multiplexing (TWDM) is a technique that combines WDM and TDM: the spectrum is divided into a number of wavelength bands, and each of these bands is shared by several users through TDM.

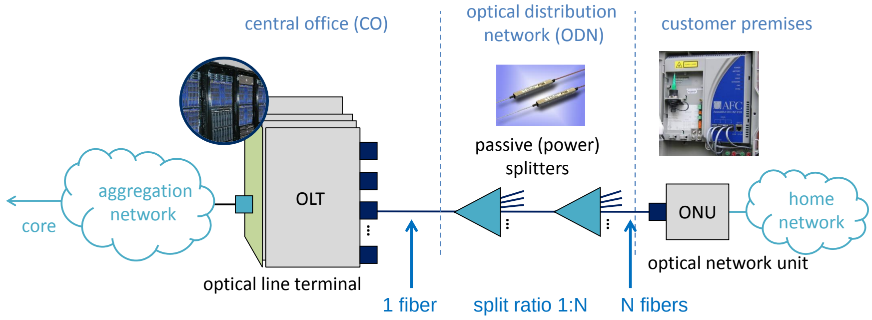


Figure 1.11: *Example of an optical access network consisting of three network sections: central office (CO), optical distribution network (ODN) and customer premises.*

1.1.5.4 Power splitter-based PON: components

Depending on the chosen signal multiplexing method, the signal distribution from the shared medium to individual users in a PON can be performed using power splitters (that distribute an identical signal to all users and combine all incoming signals from connected users) and/or wavelength selective components (that only distribute and accept specific wavelengths of the signal spectrum to and from specific users). In my research, only power splitter-based PONs are studied, a choice that is motivated by a number of factors, including the disadvantages of WDM mentioned above: expensive components; less flexibility and the fact that it does not allow for DBA. Moreover, power splitters ensure full coexistence between several PON generations. In this type of architecture, shown in Fig. 1.11, the ONU and OLT require a specific set of functionalities.

Optical network unit (ONU) The ONU was introduced previously as the device that terminates the PON at the customer premises. Typically, an ONU consists of a transceiver (laser, detector, filters, amplifiers and driving circuitry to transmit and receive the optical signals; and electronics to convert serial signals to parallel signals and vice versa) and of electronic circuitry that implements the media access control (MAC) layer functions, the so-called system-on-chip (SoC) [33].

Optical line terminal (OLT) The OLT provides the interface between the PON and the aggregation network. It consists of a rack with several shelves in which line cards can be installed (the number depends on the required capacity), with each line card carrying a number of optical PON ports from which PON fibers depart. The PON ports perform the electro/optical conversion of signals to the PON, and WDM between downstream and upstream wavelengths. The OLT is also responsible for layer 2 (L2)[13] switching, that is, forwarding frames based on their destination MAC address[14]. Downstream traffic management involves traffic policing and scheduling of flows (also determining their length) based on their service specification, bandwidth and memory resource availability, and dynamic traffic conditions. In the upstream direction, the OLT is responsible for assigning bandwidth to ONUs based on service specifications of the flows that need to be sent from the ONUs, as well as upstream bandwidth availability [31]. It is also responsible for control signal generation, to notify the ONUs in which timeslots they are allowed to transmit upstream signals. Each rack is connected to an AS through the so-called *uplink*.

1.1.5.5 PON flavors

Many PON technologies have been proposed using various combinations of multiplexing methods. In this section we list the PON technologies that have been standardized for commercial use.

- Ethernet passive optical network (EPON) (standard: IEEE 802.32008 section 5) offers symmetric 1 Gb/s capacity and is deployed mostly in Asia. Later, a faster variety was also standardized: XEPON or 10G-EPON (IEEE 802.3av-2009) offering 10 Gb/s.

- GPON (standard: ITU-T Rec. G.984.x) is the technology that is most commonly deployed in Europe and the Americas. The GPON encapsulation method allows very efficient packaging of user traffic, with larger, variable-length frames, and frame segmentation to allow for higher QoS for delay-sensitive traffic (voice & video communications). It delivers 2.5 Gb/s downstream and 1.25 Gb/s upstream

- Next-generation passive optical network (NG-PON) is the term used to refer to PON protocols beyond GPON, designed to increase per-subscriber bandwidth capabilities while minimizing cost by increasing the number of subscribers served by each PON.

[13]The "Layer" numbers in this context refer to layers of the Open Systems Interconnection (OSI) model, a conceptual model that splits communication networks into abstraction layers from the lowest, physical link layer ("Layer 1") to the highest-level application layer ("Layer 7"), where each layer serves the layer above it. *layer 2 (L2)* is the *data link layer*, referring to the functions needed to ensure reliable transmission of data between nodes that are directly connected by a physical link (this includes MAC). *layer 3 (L3)*, a term that will be used in Chapter 4, is the so-called *network layer*, responsible for addressing, routing and traffic control in a multi-node network.

[14]The MAC address is a unique machine address given to each networked device.

– 10 Gb/s capable passive optical network (XG-PON1) was standardized in 2010 (standard: ITU-T Rec. G.987.x) and allows downstream and upstream data rates up to 10 Gb/s and 2.4 Gb/s respectively.
– Next-generation passive optical network 2 (NG-PON2) can be seen as an improved version of XG-PON1, offering a further bandwidth increase up to 40 Gb/s downstream and potential for node consolidation. At the time when the paper in Chapter 3 was written, no decision had been made yet as to which specific technology would be used to reach this goal, but TWDM was the most likely candidate. In 2015 the decision was made to indeed standardize this variety (standard: ITU-T Rec. G.989.x).

1.2 Outline and research contributions

This dissertation is composed of a selection of publications that were realized within the scope of this PhD. A high-level overview of the topics on which I published during my PhD is shown in Fig. 1.12 (numbers refer to the complete list of publications in Section 1.3). The four selected publications (highlighted in Fig. 1.12) provide an integral and consistent overview of the work performed. They are included in the form in which they were submitted to international journals.[15] This section gives an overview of the remainder of this dissertation, explaining how the different chapters are linked together; what the main research challenges leading to this work were; and what the main contributions of this dissertation are.

1.2.1 Worldwide electricity consumption of communication networks

One of the motivations that is often given for research into green networking is that it can help reduce GHG emissions. At the time I started my research in 2012, it was however not exactly clear how significant the contribution of networks to worldwide GHG emissions really was. Some studies on the topic had been published previously, but most of them were hopelessly outdated in a field that evolves as rapidly as ICT, or were focusing on specific parts of the network rather than the network as a whole.

In an attempt to fill this hiatus, we set out to determine the carbon footprint of communication networks. However, it quickly became clear that given the diversity of networks and network equipment deployed in

[15] The papers in Chapters 2, 3 and 5 have already been published; the work in Chapter 4 is currently under review for publication.

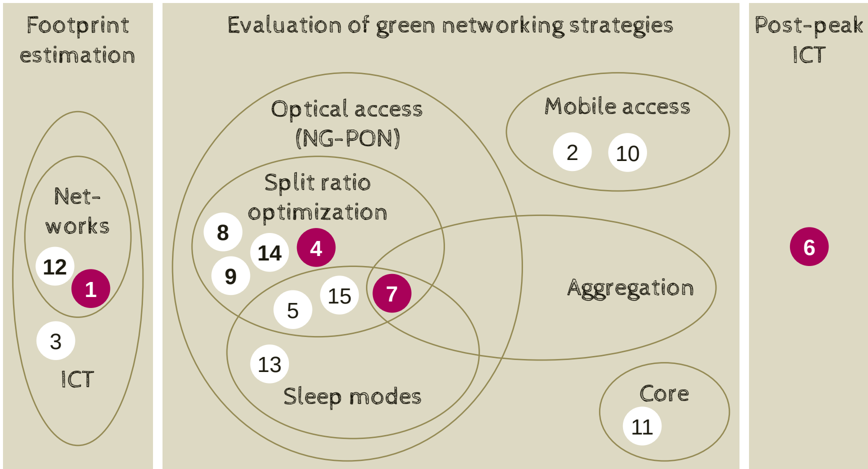


Figure 1.12: *Overview of international publications I authored (bold) and co-authored (non-bold) during this PhD. The numbers refer to the list of publications in Section 1.3. The numbers highlighted in color refer to publications that are included in this dissertation.*

the world, and the limited available data, it is near impossible to perform a full life-cycle analysis of networks — taking into account the emissions from manufacturing, transport, operation and disposal. Luckily, there is another relevant question that is slightly easier to answer: "how much do networks contribute to worldwide electricity consumption?" The answer should provide us with a good approximation of the answer to the initial problem statement, since electricity is an important source of GHG emissions (see Section 1.1.1), and use phase electricity consumption makes up a large fraction of the total carbon footprint of networks (see Section 1.1.2).

Chapter 2 presents the methodology which we developed to estimate the worldwide electricity consumption in communication networks. The results of applying this model for the period 2007-2012 show that the impact of networks on the environment is growing rapidly, and that actions need to be taken if we are to prevent this sector from becoming one of the biggest sources of GHG emissions.

1.2.2 Energy efficiency of next-generation PONs

Chapters 3 and 4 are aimed at comparing, designing, and evaluating energy-efficient optical access solutions.

We focus on access networks because they are the major contributors to current communication network energy consumption, mostly due to the huge number of distributed network elements in the field [34]. Though wireless access networks are the biggest contributors to access energy consumption and would perhaps seem to be a more logical target, we choose to narrow the scope down to fixed (wired) access networks, for two reasons. First, energy-awareness in wireless access has been a primary concern since the advent of mobile devices, and many research initiatives were already initiated to make them even more energy efficient, so there is less low-hanging fruit for mobile networks in terms of energy savings. Second, when green wireless research initiatives deliver results and wireless network consumption is reduced, we can't afford to let wired access networks lag behind and become the biggest energy consumers. Within fixed access, we concentrate on fiber-based access, as this is the most future-proof technology, and it is inherently more energy efficient than access over copper wires. We looked at PONs in particular as these are the most likely candidates for standardization and deployment.

At the time of writing Chapter 3, the new NG-PON2 standard was underway, with the goal of bringing more capacity to the end users in response to telecom market competition and increasing demand for content-rich services. This however also entailed new challenges on reducing power consumption in the optical access — we want to avoid the increased capacity coming at a high energy cost for years to come (given the high cost of infrastructure, once a choice is made to deploy a given technology, it is there to stay for a long time). Since various candidate technologies were being considered for standardization, our work aimed at making a recommendation on which of these was the most energy efficient option. In order to make a fair power consumption comparison, we developed a model that took into account not only the qualities of each technology, but also user demands, and a realistic deployment map for a major city. The model is presented along with the results produced by it in Chapter 3. The conclusions of this work were meant to serve as a guideline for fixed network operators interested in selecting green technologies for future deployments.

1.2.3 GreenTouch final results for optical access

The model that is introduced in Chapter 4, developed in collaboration between the partners of the GreenTouch consortium, extends the optical access model from Chapter 3 by including the metro/aggregation section of the network all the way up to the edge router. This allows us to evaluate technologies that extend the reach of the access network, resulting in more flexibility and further power savings. Furthermore, the model integrates the evaluation of various energy-saving approaches — such as sleep modes, virtualization, and hardware innovations — in a single framework, thus providing a better view on the combined savings that are possible when these approaches are combined.

The model is used to determine the power consumption of the GreenTouch architecture for optical access (which was designed with the goal of creating the most energy efficient-network that can realistically be achieved by 2020), and to compare it with that of a baseline architecture for 2010 and a business-as-usual architecture for 2020 (business-as-usual refers to a future evolution in which no particular focus is placed on energy efficiency). The results show that the power per subscriber can be reduced 37-fold with respect to the baseline, thus proving that energy-aware design can make a huge difference in reducing the energy consumption of the network.

1.2.4 Post-peak ICT

As the broader energy context changed during the course of my PhD and in 2014 we were confronted with the immediate threat of shortages in Belgian electricity provisioning, the relevance of a “post-peak” scenario, in which energy availability is no longer guaranteed, became clear. This was a topic that had, until then, received very little attention in Green networking research. In the publication included in Chapter 5, we provide a definition of the term “post-peak”, an extensive motivation for the relevance of this new topic, and we describe a framework that can serve as a guideline for future research in this domain.

The theory is also applied to a first use case, in which the effects of temporary energy shortages on a wireless access network are evaluated. The wireless use case was selected because of the inherent flexibility in the assignment of users to base stations, which is not present in optical access networks where users have a fixed connection to an OLT. Since this flexibility helps make QoS more scalable with the available energy, we decided to consider wireless networks as a first use case that could be evaluated without fundamental changes to the existing network equipment.

1.3 Publications

The research results obtained during this PhD research have been published in scientific journals and presented at a series of international conferences. The following list provides an overview of the publications during my PhD research.

1.3.1 Publications in international journals (listed in the Science Citation Index[16])

1. **Sofie Lambert**, Ward Van Heddeghem, Willem Vereecken, Bart Lannoo, Didier Colle, and Mario Pickavet, *Worldwide Electricity Consumption of Communication Networks*, In Optics Express, 20(26):B513–B524, Dec. 2012. doi:10.1364/OE.20.00B513

2. Łukasz Budzisz, Fatemeh Ganji, Gianluca Rizzo, Marco Ajmone Marsan, Michela Meo, Yi Zhang, George Koutitas, Leandros Tassiulas, **Sofie Lambert**, Bart Lannoo, Mario Pickavet, Alberto Conte, Ivaylo Haratcherev, and Adam Wolisz, *Dynamic Resource Provisioning for Energy Efficiency in Wireless Access Networks: A Survey and an Outlook*, In Communications Surveys & Tutorials, 16(4):2259–2285, June 2014 doi:10.1109/COMST.2014.2329505

3. Ward Van Heddeghem, **Sofie Lambert**, Bart Lannoo, Didier Colle, Mario Pickavet, and Piet Demeester, *Trends in Worldwide ICT Electricity Consumption from 2007 to 2012*, In Computer Communications, 50:64–76, Sept. 2014. doi:10.1016/j.comcom.2014.02.008

4. **Sofie Lambert**, Bart Lannoo, Abhishek Dixit, Didier Colle, Mario Pickavet, Julio Montalvo, José A. Torrijos, and Peter Vetter, *Energy efficiency analysis of high speed triple-play services in next-generation PON deployments*, In Computer Networks, 78:68–82, Feb. 2015. doi:10.1016/j.comnet.2014.10.037

5. Bart Lannoo, Abhishek Dixit, **Sofie Lambert**, Didier Colle, and Mario Pickavet, *How sleep modes and traffic demands affect the energy efficiency in optical access networks*, In Photonic Network Communications, 30(1):85–95, Aug. 2015. doi:10.1007/s11107-015-0504-4

6. **Sofie Lambert**, Margot Deruyck, Ward Van Heddeghem, Bart Lannoo, Wout Joseph, Didier Colle, Mario Pickavet, and Piet Demeester, *Post-peak ICT: graceful degradation for communication networks in an energy constrained future*, In IEEE Communications Magazine, 53(11):166–174, Nov. 2015. doi:10.1109/MCOM.2015.7321987

7. **Sofie Lambert**, Prasanth Ananth, Peter Vetter, Ka-Lun Lee, Jie Li, Xin Yin, Hungkei Chow, Jean-Patrick Gelas, Laurent Lefevre, Do-

[16] The publications listed are recognized as "A1 publications", according to the following definition used by Ghent University: A1 publications are articles listed in the Science Citation Index Expanded, the Social Science Citation Index or the Arts and Humanities Citation Index of the ISI Web of Science, restricted to contributions listed as article, review, letter, note or proceedings paper.

minique Chiaroni, Bart Lannoo, and Mario Pickavet, *The road to energy-efficient optical access: GreenTouch final results*, Accepted for publication in Journal of Optical Communications and Networking (accepted in Sept. 2016, to be published).

1.3.2 Publications in international conferences (listed in the Science Citation Index[17])

8. **Sofie Lambert**, Julio Montalvo, José A. Torrijos, Bart Lannoo, Didier Colle, and Mario Pickavet, *Energy efficiency analysis of next-generation passive optical network (NG-PON) technologies in a major city network*, In Transparent Optical Networks (ICTON), 2013 15th International Conference on, paper Tu.D1.4, Cartagena, Spain, June 2013. doi:10.1109/ICTON.2013.6602846

9. **Sofie Lambert**, Bart Lannoo, Didier Colle, Mario Pickavet, Julio Montalvo, José A. Torrijos, and Peter Vetter, *Power consumption evaluation for next-generation passive optical networks*, In Digital Communications - Green ICT (TIWDC), 2013 24th Tyrrhenian International Workshop on, pages 1–4, Genoa, Italy, Sept. 2013. doi:10.1109/TIWDC.2013.6664199

10. Yi Zhang, Łukasz Budzisz, Michela Meo, Alberto Conte, Ivaylo Haratcherev, George Koutitas, Leandros Tassiulas, Marco Ajmone Marsan, **Sofie Lambert**, *An Overview of Energy-efficient Base Station Management Techniques*, In Digital Communications - Green ICT (TIWDC), 2013 24th Tyrrhenian International Workshop on, pages 1–6, Genoa, Italy, Sept. 2013. doi:10.1109/TIWDC.2013.6664210

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11. Ward Van Heddeghem, Michael C. Parker, **Sofie Lambert**, Willem Vereecken, Bart Lannoo, Didier Colle, Mario Pickavet, and Piet Demeester, *Using an Analytical Power Model to Survey Power Saving Approaches in Backbone Networks*, In Networks and Optical Communications (NOC), 2012 17th European Conference on, pages 1–6, Vilanova i la Geltru, Spain, June 2012. doi:10.1109/NOC.2012.6249942

[17] The publications listed are recognized as "P1 publications", according to the following definition used by Ghent University: P1 publications are proceedings listed in the Conference Proceedings Citation Index - Science or Conference Proceedings Citation Index - Social Science and Humanities of the ISI Web of Science, restricted to contributions listed as article, review, letter, note or proceedings paper, except for publications that are classified as A1.

12. **Sofie Lambert**, Ward Van Heddeghem, Willem Vereecken, Bart Lannoo, Didier Colle, and Mario Pickavet, *Estimating the Global Power Consumption in Communication Networks*, In Optical Communication (ECOC), 38th European Conference and Exhibition on, OSA Technical Digest (online) (Optical Society of America, 2012), paper We.1.G.1. , Amsterdam, Netherlands, Sept. 2012. doi:10.1364/ECEOC.2012.We.1.G.1

13. Abhishek Dixit, Bart Lannoo, **Sofie Lambert**, Didier Colle, Mario Pickavet, and Piet Demeester, *Evaluation of ONU Power Saving Modes in Next Generation Optical Access Networks*, In Optical Communication (ECOC), 38th European Conference and Exhibition on, OSA Technical Digest (online) (Optical Society of America, 2012), paper Mo.2.B.5. , Amsterdam, Netherlands, Sept. 2012. doi:10.1364/ECEOC.2012.Mo.2.B.5

14. **Sofie Lambert**, Julio Montalvo, José A. Torrijos, Bart Lannoo, Didier Colle, and Mario Pickavet, *Energy demand of high-speed connectivity services in NG-PON massive deployments*, In Optical Communication (ECOC), 39th European Conference and Exhibition on, pages 1164–1166, London, United Kingdom, Sept. 2013. doi:10.1049/cp.2013.1661

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1.3.4 Other publications

16. **Sofie Lambert**, Mario Pickavet, and Bart Lannoo, *Energy efficiency strategies in telecommunication access networks*, In 14th FEA PhD symposium, Ghent, Belgium, Dec. 2013.

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2

Worldwide electricity consumption of communication networks

This chapter presents our study on the power consumption of communication networks. The results show that this consumption is rapidly increasing, confirming the relevance of green networking research.

⋆ ⋆ ⋆

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Abstract There is a growing research interest in improving the energy efficiency of communication networks. In order to assess the impact of introducing new energy-efficient technologies, an up-to-date estimate for the global electricity consumption in communication networks is needed. In this paper we consider the use phase electricity consumption of telecom operator networks, office networks and customer premises equipment. Our results show that the network electricity consumption is growing fast, at a rate of 10% per year, and its relative contribution to the total worldwide electricity consumption has increased from 1.3% in 2007 to 1.8% in 2012. We estimate the worldwide electricity consumption of communication networks will exceed 350 TWh in 2012.

2.1 Introduction

In recent years the energy efficiency of communication networks has received a lot of research attention. Various strategies have been proposed to reduce the power consumption of both mobile and fixed networks on all levels, from the access network to the core [1–4]. In most studies, potential energy savings of proposed innovations are expressed relative to the power consumption of current technologies, e.g. in [5], energy efficiency improvements from applying different techniques are stated as reduction factors (expressed in dB) compared to a baseline consumption. In order to assess the global impact of these savings in absolute numbers, an estimate is required for how much electricity present-day networks consume as a whole.

Most studies on the energy consumption in networks focus on specific network scenarios (particular technologies, bit rates, etc.) rather than worldwide averages. Kilper et al. [6], for example, determine the power per bit rate by adding up the power of all the equipment in the network that is used to deliver a given service on a mean transaction basis. The access equipment considered is that of a Passive Optical Network (PON). This provides state-of-the-art estimates, which are useful for future projections, but which are probably not realistic for present-day networks. Baliga et al. [7] use a similar bottom-up approach to estimate the electricity consumption per user for different access technologies. Although this approach is very useful when comparing different technologies, it is less suitable to get an idea of the global energy consumption in the network, since it is nearly impossible to consider every technology in use, every user profile and every topology.

Often-cited values for the footprint of communication networks and ICT in general date from five to ten years ago or are extrapolations based on these values. Our previous report [8] on the worldwide energy needs for ICT was based on data from 2007. In the Smart2020 report [9], which studied both the footprint of ICT and its enabling effect to reduce emissions, the network section of the analysis was based on reported energy consumption values of telecom providers in 2002. These values were then extrapolated based on the expected increase in subscriptions in 2002-2020. Another extensive study on greenhouse gas emissions and operational electricity use in ICT by Malmodin et al. [10] also provided estimates for 2007. In the past five years, the electricity consumption in networks was likely transformed by fiber rollout, smart devices requiring mobile Internet access and rapid customer base growth in emerging markets.

The contribution of this paper is twofold: (a) we present a top-down analysis of the total global electricity consumption in communication networks, and (b) we base our results on recent data (2007-2011) to get an updated estimate for the network share of worldwide electricity consumption in 2012. We consider three components of communication networks: telecom operator networks, office networks and customer premises equipment. Note that we consider electricity consumption in the use phase only, we do not consider the electricity used to manufacture or dispose of equipment. Our calculation method for telecom operator networks is similar to the approach used by Malmodin et al. in [10]. We extend their approach by adding a representative sample selection, where we try to match the relative subscription ratios for different services in our sample to the worldwide ratios. We discuss the methodology used for operator networks in detail in Section 2.2, along with the results of our calculations. In Section 2.3 we consider the electricity consumption of office network equipment. The numbers in this section are mainly based on previous research by Lanzisera et al. [11], but we change the scope to avoid overlap with telecom operator equipment. We also exclude data centers since we consider these as end devices rather than network equipment. Finally, customer premises equipment used to access the network is discussed in Section 2.4. The equipment considered includes modems and WiFi routers, but excludes end-user equipment such as set-top boxes, TVs and PCs.

2.2 Telecom operator networks

2.2.1 Scope and methodology

Many studies on the electricity consumption in communication networks use a bottom-up approach, where the electricity consumption of individual components of the network is summed to estimate the total consumption (e.g. [6, 7]). The approach we propose is top-down: we start from the total electricity consumption of a number of telecom providers and based on these numbers we estimate the worldwide electricity consumption in communication networks.

A similar approach was used by Malmodin et al. in [10]. Based on data from a number of telecom operators, they determined the average electricity consumption per mobile subscriber and per fixed subscriber. Multiplying these values with the worldwide subscription numbers and summing the results provided them with an estimate for the worldwide electricity consumption in telecom operator networks.

Assigning electricity consumption to specific services Unfortunately, it is very difficult to assign the power consumption of an operator to different services. Sometimes a distinction between the electricity use of mobile and fixed network equipment is made, but then it is still unclear which part of the fixed network is used to transport data for mobile end-users (this problem was also recognized in [10]). Additionally, we want to make a distinction between fixed broadband and fixed telephony in our study, since we believe the power consumption per user for these services can differ significantly. Attributing the power consumption of the fixed network to broadband and telephone services is even more difficult than for the mobile-fixed case since these two services often share a physical medium. We could try to determine the average per-subscriber electricity consumption for each service (mobile access, fixed broadband and fixed telephone) by fitting the calculated power consumption $p_i = \sum_{services} subscribers_{service} \times p_{avg,service}$ for each operator i to their reported power consumption and subscription numbers. This approach is however complicated by the fact that incumbent operators often lease parts of their networks to other operators. This means that the number of customers connected to a network is not necessarily the same as the number of subscribers reported by the operator. Consequently, $p_{avg,service}$ will differ significantly among operators. In the approach we propose, we aggregate the subscriptions and electricity consumption of different operators to cancel the effect of leased lines as much as possible.

Introduction of a representative sample In order to avoid having to assign the power consumption of the operators to different services, we use a subscription-based representative sample. The number of mobile, fixed broadband and fixed telephone subscriptions in this sample have the same relative ratios as the worldwide subscription numbers. This allows us to extrapolate the power consumption of the sample to a worldwide value using a single scaling factor, since the percentage of worldwide subscriptions covered is the same for each type of service. Due to the nature of our sample, we are still taking into account the differences in power consumption for different services. The drawback of our approach is that we cannot determine the relative contributions of different services to the total network electricity consumption, since we aggregate the electricity consumption for all services.

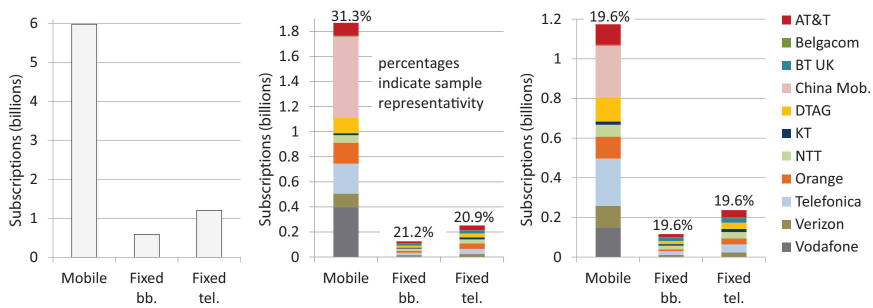
Selection of a sample of telecom operators We select the telecom providers in this study based on their size and on the availability of data. We start by listing some of the world's biggest telecom operators in terms of fixed broadband and mobile customer base. For each of these operators, we try to gather the following information: (a) total annual electricity consumption, (b) breakdown of electricity consumption by activity (offices & retail, data centers, network), (c) number of fixed telephone subscriptions, (d) number of fixed broadband subscriptions and (e) number of mobile subscriptions.

Some of these numbers can be found in publicly available financial and sustainability reports on company websites. We contacted operators and consulted various websites (such as the Carbon Disclosure Project [12]) to obtain additional data. Not all of the operators in our initial list disclosed their electricity consumption. Since this information is essential to our calculation we excluded these operators from our sample.

Scope We are interested in the electricity consumption of operator networks, so we exclude the portion of their electricity consumption that is used in data centers, offices and retail from our calculations (office networks are covered in Section 2.3). For some operators, we found a total electricity consumption but were unable to find a breakdown by activity. In these cases we used a value based on the breakdown for other operators. We found that on average, about 13% of electric power is used in offices and retail, 11% is used in data centers and the remaining 76% is used in the network. Off-grid electricity generation (e.g. by diesel generators for remote mobile base stations) is not included in our results.

Extrapolation to worldwide numbers Once we have determined the network electricity consumption and subscription numbers for each operator, we need to extrapolate these numbers to obtain an estimate of the worldwide network electricity consumption. As mentioned above, we create a representative sample of operators based on subscription numbers in order to do this. The worldwide subscription numbers for 2011 are given in Fig. 2.1a; the numbers for other years can be found in Table 2.1. Our sample of 11 operators for 2011 is represented in Fig. 2.1b (electricity consumption values for individual operators are not shown as some of these numbers are confidential). When we compare the number of subscriptions in the sample to worldwide numbers, we see that mobile subscriptions are overrepresented in the sample: 31.3% of worldwide mobile subscriptions are covered, while only 21.2% and 20.9% of fixed broadband and fixed telephone subscriptions are covered respectively.

In order to create the representative sample — while keeping the number of subscriptions covered as large as possible — we determine a weight factor for each of the n operators ($n = 11$) by solving the following optimiza-



(a) Worldwide **(b)** Unscaled sample **(c)** Representative sample

Figure 2.1: *Operator sample selection for 2011: (a) number of subscriptions worlwide, (b) in the unscaled sample and (c) in the representative sample. The percentages are obtained by dividing the number of subscriptions per service in both samples by the worldwide number of subscriptions.*

Table 2.1: *Worldwide subscriptions (in millions). Sources: [13, 14]. Numbers for 2012 are extrapolations.*

	2007	2008	2009	2010	2011	2012
Mobile subscriptions	3 372	4 034	4 650	5 315	5 975	6 615
Fixed broadband subscriptions	346	409	465	528	590	650
Fixed telephone subscriptions	1 255	1 250	1 249	1 228	1 205	1 182

tion problem:

$$\text{Maximize} \quad M_S(w) = \sum_{i=1}^{n} (w_i \times m_i) \tag{2.1}$$

$$\text{subject to} \quad \frac{M_S(w)}{M_W} = \frac{B_S(w)}{B_W} = \frac{T_S(w)}{T_W} \tag{2.2}$$

$$0 \leq w_i \leq 1 \quad (i = 1 \ldots n) \tag{2.3}$$

where w = vector containing operator weight factors $w_i \quad (i = 1 \ldots n)$

$m_i/b_i/t_i =$ number of mobile/broadband/telephone subscriptions for operator i

$M_S/B_S/T_S =$ number of mobile/broadband/telephone subscriptions in sample

$M_W/B_W/T_W =$ worldwide mobile/broadband/telephone subscriptions (Table 2.1)

Note that the problem stated above, where we maximize the number of mobile subscriptions in the sample, is equivalent to a problem where we maximize the number of broadband or telephone subscriptions (this follows from the first constraint). We solve the optimization problem for five different years, based on the worldwide and operator subscription numbers for 2007-2011, thus creating a representative sample for each of these years. The representative sample for 2011 is depicted in Fig. 2.1c.

Once we have solved the maximization problem, we estimate the worldwide network electricity consumption P_W (this includes the consumption of both fixed and mobile networks) by extrapolating the electricity consumption of the representative sample $P_S(w)$ as follows:

$$P_W = \frac{M_W}{M_S(w)} \times P_S(w) = \frac{M_W}{M_S(w)} \times \sum_{i=1}^{n} (w_i \times p_i) \tag{2.4}$$

where p_i is the network electricity consumption of operator i. From constraint (2.2) it follows that an extrapolation based on the number of broadband or telephone subscriptions would deliver the same result. The calculation of P_W is performed for each year in 2007-2011. For 2012, we estimate the worldwide electricity consumption by extrapolating the values of the previous years.

2.2.2 Results

The estimates for the worldwide electricity consumption in telecom operator networks are given in Fig. 2.2. In 2007, these networks consumed almost 160 TWh. By the end of 2012, at an annual growth rate of 10.2%, their consumption will increase to about 260 TWh per year.

Reliability As mentioned above, the approach we used for our calculations is based on aggregated numbers rather than individual operators' electricity consumption to minimize the effect of leased and rented lines. This effect may have an influence nonetheless, even though our sample covers at least 19.6% of the worldwide customer base for each year in the considered range (markers in Fig. 2.2). Another factor that may influence the reliability of our study is the fact that it is based — for the most part — on publicly available electricity consumption values. This may lead to overly optimistic results, since companies that publish these values are typically those that have already made efforts to improve their energy efficiency.

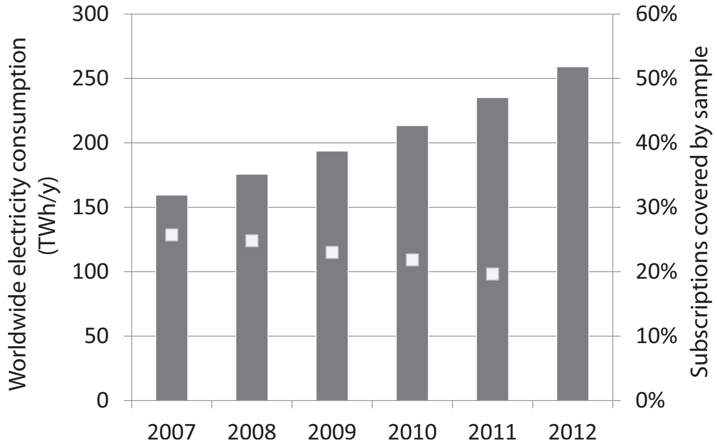


Figure 2.2: *Worldwide electricity consumption in telecom operator networks (columns, left axis) and sample representativity (markers, right axis).*

2.3 Office networks

2.3.1 Scope and methodology

The scope of this section is the electricity used by network equipment in offices, excluding network equipment in data centers. This includes network equipment in network operator offices but excludes equipment in the telecom network they operate (this was already handled in Section 2.2). We do not consider custom enterprise transport networks, such as those between Google or Amazon data centers. There seems to be a growing trend for such companies to roll out their own fiber networks. While it is hard to map these networks, the total power consumption will very likely be negligible, as optical transport networks consume very little compared to other network equipment such as modems, IP routers or base stations. For example, the pan-European Géant network and the US NSFNET network consume each in the order of only a few tens of GWh/y [15]. Nonetheless, with the rise of cloud computing, this might become a relevant component to consider in the future.

We base our estimate on a study by Lanzisera et al. [11], which estimates the USA and worldwide electricity consumption of data network equipment in both residential buildings and offices. Their study focuses on IP-based network equipment only, and does not include the electricity used by power or cooling infrastructure. Their annual electricity consumption estimate is based on an average power consumption per device, and uses values for 2008 with forecasts up to 2012, which we have adopted.

Table 2.2: *Office networks: cooling overhead factors and worldwide electricity use per type of equipment (electricity use estimates are adaptations of the values in [11]).*

	Cooling overhead	Electricity use, 2007 (TWh)	Electricity use, 2012 (TWh)
switching - 10/100	1.38	12.7	10.7
switching - 10/100/1000	1.38	5.4	17.5
routers - small & medium	1.75	3.5	4.2
enterprise WLAN	1.00	1.0	2.3
security - small and medium	1.75	5.3	7.7
Total		27.8	42.4

We consider only the equipment relevant in office use (based on a selection of the classification in [11]), and in addition we add an estimated overhead for cooling. To estimate this overhead, we start from the approach used for data centers, where the cooling equipment and power provisioning equipment combined typically consume as much as the IT equipment itself. Power provisioning equipment includes uninterruptible power supplies and power conversion devices. The cooling and power provisioning overhead is commonly captured by the so-called power usage effectiveness (PUE) factor being equal to 2, i.e. the IT power consumption needs to be multiplied by 2 to estimate the total power consumption. Since the power provisioning in data centers typically makes up about 1/3 to 1/5 of this overhead, but is in general not applicable to office network equipment, the correction factor to account for cooling only is about 1.75. Since not all switches are installed in cooled locations, we have accounted only half of the cooling factor, which gives an overhead factor of 1.375 for switches.

2.3.2 Results

The results are shown in Table 2.2. As can be seen, the worldwide office network equipment is estimated to consume 42 TWh in 2012.

Reliability There is some uncertainty in the considered cooling overhead factors (which are based on discussions with industrial experts), and whether our selection of Lanzisera's network equipment classification correctly covers office network equipment. Concerning the latter, the power consumption in Table 2.2 may include some network equipment located in data centers, which are out of our scope. However, based on [16] we estimate the power consumption of network equipment for data center volume servers (without cooling and power provisioning overhead) at 1.48 TWh in

Table 2.3: Calculation of the office network power consumption per computer based on our results, compared with values from [17].

	Kawamoto 2002 [17] (USA only)	2007 (worldwide)	2012 (worldwide)
Number of computers (desktop + laptop)	60 million [a]	429 million	594 million
Office network equipment power consumption	228.7 MW [b]	3.17 GW	4.84 GW
Office network equipment power consumption per computer	3.8 W/unit	7.4 W/unit	8.1 W/unit

[a] Includes servers, in addition to desktop and laptop computers
[b] LAN routers and switches only; not including cooling and power provisioning overhead

2012.[1] This means that the inclusion of (some) data center network equipment can lead to a maximum deviation of 5% on the total uncooled power consumption.

To get an indication of the reliability of our result, it is instructive to estimate the electricity use of office network equipment per office computer, similar to what was done by Kawamoto et al. in [17]. These values are reported in Table 2.3. As can be seen, our estimate for 2012 is 8.1 W/unit and thus about twice as high as Kawamoto et al.'s value in 2002. Three important factors are responsible for this considerable deviation: (a) Kawamoto et al. do not consider the power consumed by network cooling equipment, (b) they include servers in their computer count, however the influence of this inclusion will be minor since servers account for only about 5% of their total number of computers, and (c) they only consider LAN routers and switches; wireless local area network (WLAN) and security equipment make up 20-25% of the total office network equipment power consumption. If we would not consider cooling overhead and drop the enterprise WLAN and security equipment, our values for 2007 and 2012 would drop to 4.0 and 4.4 respectively, which is in line with Kawamoto et al.'s reported 3.8 W/unit for the USA.

[1]This value was later corrected. The 1.48 TWh for data center volume servers should in fact be 1.48 GW, or almost 13 TWh. As a consequence the double accounting for data center network equipment was underestimated. After updating our estimate accordingly, the final office network equipment estimate for 2007 was lowered to 12.2 TWh, and that for 2012 was lowered to 22.2 Twh. This change does not alter the conclusions of the paper significantly: with these new values, the overall annual growth rate of power consumption in communication networks is 10.4%, only slightly higher than the value we arrive at here. The updated estimates can be found in our later publication [Van Heddeghem et al., Comput. Commun. 50, pp. 64–76, September 2014].

Table 2.4: *Customer premises equipment: average power consumption per user, numbers of users and worldwide annual electricity use.*

	Power per user (W)	Subscribers, 2007 (million)	Electricity use, 2007 (TWh)	Subscribers, 2012 (million)	Electricity use, 2012 (TWh)
Cable	9.5	74	6.2	123	10.2
DSL	7.1	228	14.2	388	24.1
FTTH	13.0	38	4.3	115	13.1
Other broadband	8.3	6	0.4	24	1.8
Narrowband (dial-up)	2.5	283	6.3	142	3.1
Total		629	31.4	792	52.4

2.4 Customer premises equipment

2.4.1 Scope and methodology

In this section, we consider the electricity consumption of residential network access equipment. In order to access the network, every Internet subscriber requires a modem. Most users also have a WiFi router installed, often with integrated wired switching and routing capabilities. The modem and WiFi router may also come in a single box. We estimate the worldwide power consumption by multiplying average power consumption values of these residential devices per access technology category with the number of subscriptions per category.

Number of subscriptions Based on the average number of broadband subscriptions per 100 inhabitants [14] (5.19-8.46 for 2007-2011) and worldwide population data [13] ("Medium variant" for population prospects), we estimate the worldwide number of broadband subscriptions. We distribute these subscriptions over the different technologies using percentages from [18, 19]. Based on the percentage of broadband subscriptions (compared to total Internet) in [20] we derive the number of narrowband subscriptions. The subscription numbers are given in Table 2.4. Values for 2012 are extrapolations based on data from previous years.

Power consumption per user The power per user values for *cable, digital subscriber line (DSL) and fiber to the home (FTTH)* were adopted from a study by Lanzisera et al. [11]. They assume that few users use a modem without a WiFi router and that this number is comparable to those with multiple WiFi routers (or WiFi repeaters). This assertion is confirmed by data in [21] on the installed base of home network equipment: in 2010, there were 46.4 million modem-only devices and 46.2 million wireless routers installed in USA households. For end-users accessing the Internet through *other broadband* technologies such as satellite and fixed wireless access, we assumed a power consumption comparable to that of the more common broadband technologies. The end result is not very sensitive to this value due to the small user base. For *narrowband* users we assumed the average power consumption of a dial-up modem from [22]. This value is significantly lower due to the limited time in which the device is active, compared to always-on broadband modems.

2.4.2 Results

The results are included in Table 2.4. The power consumption by customer premises equipment totalled 31.4 TWh in 2007 and will total 52.4 TWh in 2012. This corresponds to an annual growth rate of 10.8%.

Reliability The reliability of our results depends strongly on the accuracy of our power per user estimates. Most of our power consumption values are based on averages for the USA, which we extrapolate based on worldwide subscription data per technology category (cable, DSL, etc.). However, within these categories there are several subtechnologies (e.g. ADSL2, VDSL, etc. for DSL). If the relative share of these subtechnologies is different in other parts of the world, the average power consumption per user will also be different. Additionally, we were unable to determine the evolution of the average power consumption per device from 2007 to 2012. Consequently we do not account for shifts between different subtechnologies over time. The shifts between different technology categories — the decrease in narrowband and increase in FTTH being the most notable — were however taken into account, which leads us to believe the general trend in our results provides a good estimate of the evolution in power consumption of customer premises equipment.

2.5 Total electricity consumption of communication networks

Our results are summarized in Fig. 2.3. Telecom operator networks make up almost three quarters of the network electricity consumption, the remaining quarter is used by customer premises equipment and office networks. Though our calculation method does not allow us to estimate the

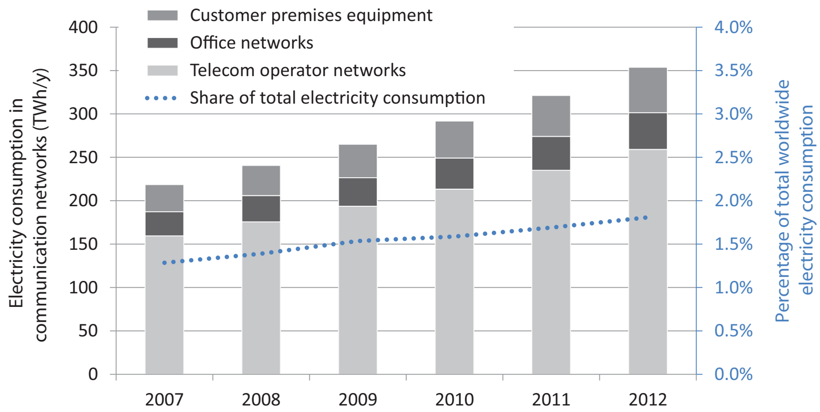


Figure 2.3: *Worldwide use phase electricity consumption of communication networks (columns, left axis) and share of networks in total worldwide electricity consumption (dotted line, right axis).*

relative importance of mobile and fixed infrastructure in telecom operator networks, based on the breakdown provided by a number of operators we expect the contribution of the mobile network to be between 40% and 60%.

The total worldwide electricity consumption in communication networks has increased from 219 TWh per year in 2007 to 354 TWh per year in 2012. This corresponds to an annual growth rate of 10.1%. When we compare this to the total worldwide electricity consumption [23], we see that the share of networks is becoming increasingly important (dotted line in Fig. 2.3). Where communication networks only consumed about 1.3% of worldwide electricity in 2007, their relative contribution has increased to 1.8% in 2012.

2.6 Comparison with previous studies

To validate our results we list a number of power consumption values from related studies in Table 2.5. The Smart 2020 report [9] estimate for the use phase carbon footprint of telecoms infrastructure and broadband modems is converted to an electricity consumption value assuming an average worldwide conversion factor of 500 gCO2/kWh [24]. Considering our value for 2012 and the growth rate for 2007-2012, 414 TWh in 2020 seems to be a rather conservative estimate. The calculation in the Smart 2020 report is based on the assumption that the number of mobile, fixed and broadband accounts will reach 7 billion in 2020, whereas our subscription data suggest that the aggregated number of subscriptions has already exceeded 8 billion

Table 2.5: *Estimates of network power consumption from previous studies [6, 7, 9, 10, 25]. Values between brackets are converted: for the Smart 2020 report the use phase CO2 values are converted assuming 500 gCO2/kWh, Kilper and Baliga's power per user values are multiplied with our worldwide subscription numbers.*

Source	Year	Power per user (W)	Worldwide power (TWh/y)	Scope
Smart2020 2008	2020	-	(414)	Telecoms infrastructure and broadband modems
Malmodin 2010	2007	-	139	Operator networks (mobile + fixed + transport), including overhead for offices and stores
Malmodin 2010	2007	-	35	Broadband modems and routers
Malmodin 2010	2007	-	29	Enterprise networks, including cooling and power systems
Kilper 2011	2007	6	(177)	Mobile networks
Kilper 2011	2007	14	(42)	Fixed networks, including CPE
Kilper 2011	2012	14	(812)	Mobile networks
Kilper 2011	2012	19	(108)	Fixed networks, including CPE
Baliga 2011	2012	3.3 - 7.6	(27)	Broadband fixed access, including modems
Fehske 2011	2007	-	49	Radio access network
Fehske 2011	2012	-	77	Radio access network

in 2012 (see Table 2.1). In the Smart 2020 report itself, the authors note there is a high degree of uncertainty in the telecoms figures.

The 2007 value from Malmodin et al. [10] for operator networks is about 25% lower than our value (assuming offices and retail make up 13% of the value they provide). This difference can probably be attributed to the fact that they used a different sample and did not distinguish between fixed broadband and fixed telephony users in their calculation method. Their value for office networks is similar to our value. For broadband modems their value is significantly higher than our result (which is 25.1 TWh/y). This is due to the fact that they assume relatively high per-user power consumption values (9 W per modem plus an additional 9 W per router, with one router for every two modems).

In a 2011 study by Kilper et al. [6], an estimate is given for the average power per user for mobile and fixed access, core and metro networks (Fig. 5 in [6]). When we add up these per-user values and multiply them by our global subscription numbers (mobile and fixed broadband, see Table 2.1), we obtain very high values for the mobile network power consumption in 2007 and 2012. Since we do not know the breakdown of the electricity consumption among different services, we do not know the power consumption per mobile user in our results, but we can make a rough estimate based on the electricity consumption and subscription numbers of the two operators in our sample that offer (almost) exclusively mobile services: China Mobile and Vodafone. The electricity consumption for these mobile operators is between 0.75 and 2 W per user, much lower than the values provided by Kilper et al. This discrepancy can be explained by the fact that the mobile network considered in the study by Kilper et al. is a high-bandwidth long-term evolution (LTE) network, which is currently only deployed in a relatively small part of the world. Further adoption of wireless broadband access by mobile users can increase the electricity consumption of communication networks significantly in the future. For fixed access Kilper et al. consider state-of-the-art passive optical network equipment that is continuously upgraded each year, which — like their value for mobile networks — provides a good view on the power consumption of possible future deployments but which is not representative for present-day networks. This illustrates the importance of using a top-down approach to obtain reliable estimates for the worldwide electricity consumption, since it is very difficult to assess a worldwide average network deployment scenario.

The per-user power consumption of latest generation broadband access technologies is estimated in a 2011 paper by Baliga et al. [7]. Combining these values for fixed access technologies with our subscription numbers from Table 2.4 gives us an estimate for the worldwide power consumption in fixed access networks. We would expect this value to be higher than 27 TWh since it covers both customer premises equipment (modems) and part of the telecom operator network (fixed access). This can be explained in part by the fact that Baliga et al. assume lower CPE power consumption values, presumably because they do not include WiFi and routing functionality. Furthermore, they only consider state-of-the-art equipment. Legacy equipment, which is typically less energy efficient, has a significant impact on the energy consumption of operator networks (for example, see [26]).

A recent study by Fehske et al. [25] provides another estimate for the electricity consumption in radio access networks (RANs). Diesel generated power is included in their values and accounts for about 10% of the RAN electricity consumption. Their estimate amounts to about 30% of our value for operator networks, which is somewhat lower than our estimate for mobile networks (40-60%), this is due to the fact that they do not include data transport in the RAN electricity consumption.

In [27] Baliga et al. estimate the power consumption of the Internet at about 0.4% of electricity consumption in broadband-enabled countries in 2009. This includes the power consumption of core, metro and edge IP networks and modems, but does not include mobile access or fixed (non-IP-based) telephony. This corresponds to about one quarter of our value for the total electricity consumption of the network (including mobile access and fixed telephony) in 2009. For higher access rates Baliga et al. estimate the electricity share of the Internet can increase to 0.8-1.5%.

Overall there is a large spread on the power consumption values we found in literature, which are in some cases higher and in other cases lower than our values. Notably our estimate is higher than the one in the often-cited Smart 2020 report.

2.7 Conclusion

We have studied the use phase electricity consumption in communication networks, consisting of telecom operator networks, customer premises equipment and office networks. For telecom operator networks, which make up three quarters of the total consumption, we used a top-down approach based on a representative operator sample to obtain a high degree of confidence in our results. According to our calculations, the total worldwide electricity consumption in communication networks will exceed 350 TWh in 2012. This corresponds to 1.8% of the total worldwide electricity consumption. Since the electricity consumption in communication networks is growing at a faster pace (annual growth rate $\approx$ 10% in the interval 2007-2011) than the overall electricity consumption (annual growth rate $\approx$ 3% in the interval 2007-2011), the relative share of communication networks is increasing. These results and the fact that data rates and subscription numbers will most likely continue to grow in the following years confirm the need to invest in more energy-efficient network technologies.

Acknowledgments

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3

Energy efficiency analysis of high speed triple-play services in next-generation PON deployments

Where the previous chapter provided an overview of the footprint of communication networks in general, this chapter looks at the energy consumption of optical networks specifically. We focus on optical access networks, as they are the largest contributors to wired optical communication network energy consumption. A model to compare optical access architectures is introduced, and results for a selection of technologies are discussed.

⋆ ⋆ ⋆

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Abstract In this paper, the energy consumption of high speed access services up to 1 Gb/s per customer is estimated for different passive optical network (PON) technologies. While other studies on PON power consumption typically assume a fixed split ratio, we also consider a greenfield approach, where the split ratio can be optimized for each technology, taking

full advantage of its capacity and reach. The split ratio optimization takes into account Quality of Service (QoS) in terms of bandwidth availability and packet loss for triple-play services (voice, television and Internet). This paper includes an in-depth discussion of our split ratio dimensioning approach and our power consumption model for an optical access network in a major city. The obtained results show that statistical gain provided by dynamic bandwidth allocation as well as power splitting ratio optimization in PONs are key factors for achieving energy efficiency. For access rates up to 900 Mb/s, XG-PON1 turns out to be the most energy-efficient option. For higher access rates up to 1 Gb/s, the optimal technology depends on split ratio restrictions. If an existing optical distribution network (ODN) with split ratio 1:64 is used, XG-PON1 remains the most energy-efficient technology. If higher split ratios up to 1:256 can be achieved, TWDM PON becomes the most energy-efficient solution for access rates up to 1 Gb/s.

3.1 Introduction

Fiber-based passive optical networks (PONs) are currently being deployed by operators in several countries, offering much higher bandwidths than traditional copper-based access networks. Deployments of 2.5 Gb/s capable PONs (gigabit-capable PON or GPON) are currently the most common, while 10 Gb/s capable PONs (next-generation PON or NG-PON) are expected in the next couple of years. In the long term, increasing bandwidth demands associated with mobile backhauling, low-latency cloud services and the convergence of residential and business access will necessitate the deployment of even faster next-generation PONs beyond 10 Gb/s, referred to as NG-PON2s by the Telecommunication Standardization Sector of the International Telecommunication Union (ITU-T) and full service access network (FSAN) working group [1].

At the same time, there is a growing interest in reducing the energy consumption and the associated cost of the access network. Due to rising energy prices and the growing awareness of climate change, energy efficiency is becoming an important factor when analyzing the operational expenditures and carbon footprint of communication networks such as NG-PON(2) systems.

Estimations of energy consumption of NG-PON(2) technologies have already been reported, providing the total energy consumption per customer considering both network operator and customer premises contributions [2, 3]. Some proposals have recently shown the potential for reduction of the energy consumption in customer premises equipment (CPE), for example using a bit-interleaving protocol at the optical networking unit (ONU) in time-division multiplexing PONs [4] or a network-enhanced residential gateway approach [5]. Regarding the energy consumption associated with the network operator, energy efficiency scenarios for long-reach GPON technologies with an optimized number of central offices (COs), have been reported in [6].

Nevertheless, previous works have paid little attention to the provided services, the statistical gain of dynamic bandwidth allocation and the quality of service (QoS) achieved by each PON technology, and only considered the maximum speed capacities of both optical line terminal (OLT) and ONU. The contribution of this work is a network dimensioning approach that can be adapted to the specific qualities of various PON technologies. The split ratio (number of homes passed by fiber from a single OLT PON interface) is optimized to use the PON capacity of each technology as effectively as possible, taking into account user demands. Moreover, we model the optimal deployment of COs in a major city, taking into account technology-dependent reach constraints, as the geographic spread of the locations may impact the filling ratio of OLT racks. Our user demand model considers triple-play services, consisting of (1) fixed voice, (2) high definition Internet protocol television (IPTV), and (3) best-effort Internet and over the top (OTT) media access with up to 1 Gb/s download speed per customer. The model presented in this paper builds on our earlier work [7, 8]; the main differences are the inclusion of IPTV services, general OLT functions now include packet processing and traffic management, updated estimates for OLT and ONU power consumption and an in-depth sensitivity analysis.

Concretely, the energy efficiency analysis is implemented as follows (Fig. 3.1). We start by choosing a number of interesting cases to study. Each case consists of a specific user demand (access speed, number of subscribers, etc.), deployment strategy (one of two options: fixed or optimized split ratio) and PON technology (one of seven options introduced in Section 3.3). Next, a three-stage power consumption analysis is performed for each case. In the first stage, the PON is dimensioned, based on the technology-dependent reach and capacity, user demands and QoS requirements. The PON dimensioning approach is described in Section 3.4. It produces the requirements for uplink and general OLT functions (switching, packet processing, traffic management), which are used further on for the power consumption calculation. It also produces the split ratio, which is used as an input for the second stage: the city deployment algorithm, which is covered in Section 3.5. The algorithm contains a model of the geographical distribution of homes in a major European city, and calculates how much equipment needs to be installed, given the takerate (i.e., the number of fiber subscriptions divided by the number of homes passed by fiber), the

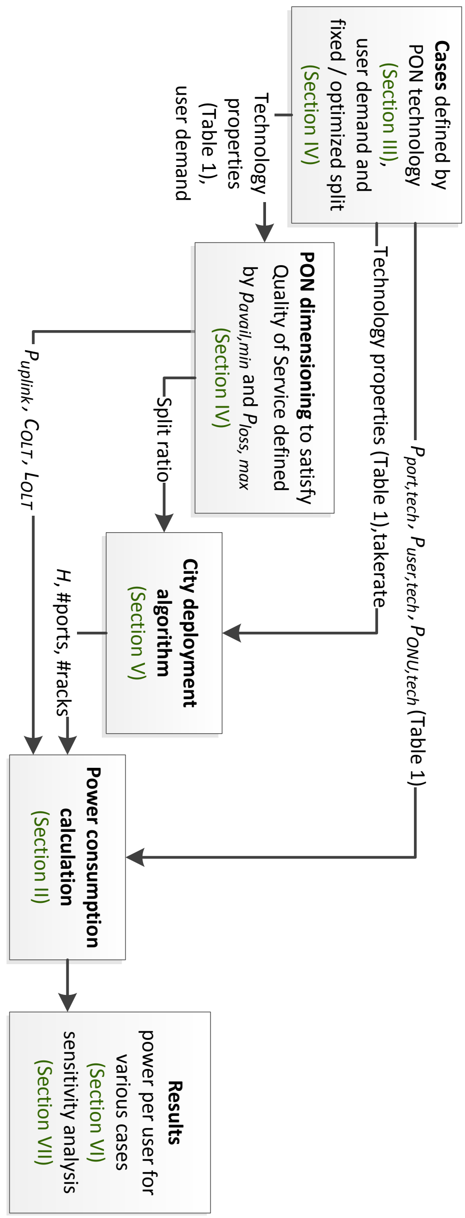


Figure 3.1: *Overview of methodology and paper contents (symbols introduced in Section 3.2).*

technology-dependent reach and the split ratio (depending on the case under study). This stage returns the equipment count (number of ports, racks, etc.), which is an input for the third and last stage: the power consumption calculation. The power consumption calculation is introduced first in this paper, in Section 3.2, because it provides a good overview of the access network and its components, and it drives the calculations in the previous stages.

Section 3.6 presents the results for a number of selected cases and compares the energy efficiency of the various PON technologies. Section 3.7 contains a sensitivity analysis, to determine which parameters are most critical to the energy efficiency model. Finally, a summary of the results and the conclusions of the work are reported in Section 3.8.

3.2 Power consumption model for the access network

Figure 3.2 gives a schematic overview of the considered optical access network. It comprises the optical network unit (ONU) at the customer premises, the optical line terminal (OLT) and uplink to the aggregation network at the network operator's CO and the fibers and splitters between them (optical distribution network or ODN). Since we evaluate *passive* optical networks in this paper, no active equipment is needed in the ODN. Moreover, only technologies over an ODN with optical power splitters will be considered (no wavelength-selective components), thus ensuring full coexistence between several PON generations using the same passive technology, without the need for modifying or replacing the already existing components in the outside plant.

Our power consumption model is mostly based on models and values that are (were) available within the projects GreenTouch and Trend, combined with values reported by Skubic et al. in [2].

3.2.1 Power per user

We consider a deployment in a city where H homes are subscribing to the PON. The total power consumption of the city-wide access network is the sum of the consumption of all ONUs and all OLTs, P_{ONUs} and P_{OLTs} respectively. To obtain the power per user, we simply divide the total power by the number of subscribers.

$$\text{Total power } [W/user] = \frac{P_{ONUs} + P_{OLTs}}{H} \tag{3.1}$$

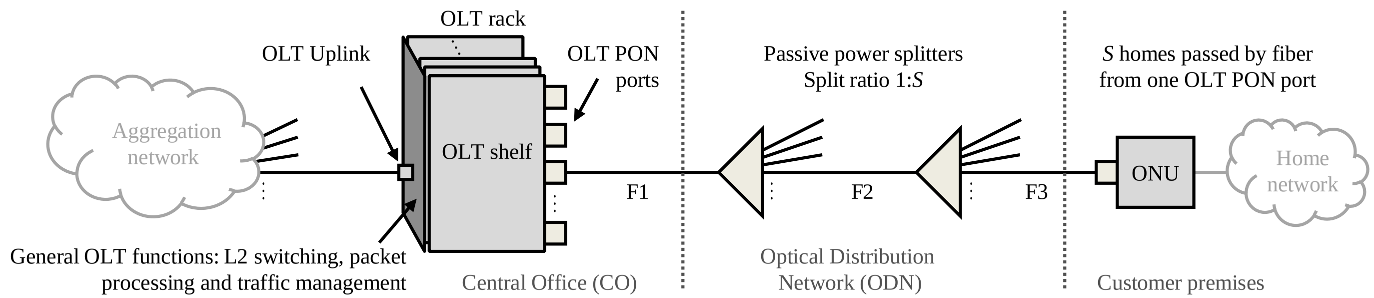


Figure 3.2: *Schematic overview of the access network and its power consumption components. F1, F2, F3 = optical fiber sections.*

3.2.2 City-wide power consumption by ONUs

Because we consider a fiber to the home (FTTH) scenario, each subscribing home has its dedicated ONU. All ONUs have a common baseline power dissipation $P_{baseline}$ of 3.65 W. This baseline power consists of contributions from the embedded processor, gigabit Ethernet interface, dual subscriber line interface circuit (SLIC), memory, and other miscellaneous components [2]. The technology-dependent ONU transceiver power $P_{ONU,\,tech}$ (see Table 3.1) is added to this baseline, and the total is multiplied by a factor 1.25 to account for AC/DC (alternating current/direct current) rectifier and DC/DC (direct current/direct current) voltage conversion efficiencies ($\eta_{AC/DC} = \eta_{DC/DC} = 90\%$).

$$P_{ONUs} = H \times (P_{baseline} + P_{ONU,\,tech}) \times \frac{1}{\eta_{AC/DC}} \times \frac{1}{\eta_{DC/DC}} \tag{3.2}$$

3.2.3 City-wide power consumption by OLTs

On the OLT side, the power consumption is the sum of the contributions from OLT PON ports, general OLT functions (switching, packet processing and traffic management), and the uplinks to the aggregation network. On top of a factor 1.11 for DC/DC conversion inefficiency, we multiply by a site factor 1.6 at the CO to account for auxiliary equipment such as AC/DC rectifiers ($\eta_{AC/DC} = 90\%$), ventilation and air conditioning, auxiliary power units and batteries [2].

$$P_{OLTs} = \left[P_{ports} + P_{gen.\,func.} + P_{uplinks}\right] \times \frac{1}{\eta_{DC/DC}} \times \text{CO site factor} \tag{3.3}$$

The power consumption of the OLT PON ports is technology-dependent and consists of a power per PON port $P_{port,\,tech}$ and, for some technologies, an added power per user $P_{user,\,tech}$ (see Table 3.1). The power per port is multiplied by the number of ports in the city-wide deployment (obtained in Section 3.5), and the power per user is multiplied by the number of subscribers.

$$P_{ports} = \#\text{ports} \times P_{port,\,tech} + H \times P_{user,\,tech} \tag{3.4}$$

The city-wide power consumption of the general OLT functions and uplinks is obtained by multiplying the total number of racks in the city (obtained in the city deployment model, Section 3.5) by the power per rack, which depends on the capacity and traffic load per rack. The average traffic load L_{OLT} and the required capacity C_{OLT} (Gb/s) are dimensioned for a single rack in Section 3.4.3.

For the general OLT functions, a unidirectional power of 1 W/Gb/s is assumed, consisting of 0.5 W/Gb/s for Layer 2 switching [9] and 0.5 W/Gb/s for packet processing and traffic management. 30% of this power scales with the required capacity, the other 70% scales with the actual traffic load (for details, see Section 3.4.3.2).

$$P_{gen.\,func.} = \#\text{racks} \times (0.3 \times C_{OLT} + 0.7 \times L_{OLT}) \times 1\ W/Gb/s \quad (3.5)$$

The uplink of a rack is formed by a combination of Ethernet ports (with corresponding power consumption values given in Section 3.4.3.1), dimensioned such that for a given user traffic, the packet loss in the uplink remains acceptable.

$$P_{uplinks} = \#\text{racks} \times P_{uplink} = \#\text{racks} \times \sum P_{Ethernet\ port,\,i} \quad (3.6)$$

In the following section, we will take a closer look at the PON technologies and their specific parameters. Further on we will discuss the PON dimensioning approach that produces the split ratio and OLT requirements, and the city deployment model that produces the equipment inventory.

3.3 Overview of the considered PON technologies

In this section, we start by giving a brief description of the seven technologies included in our power consumption comparison. Next, we expand on the technology-specific physical limitations (optical budget and bandwidth) and power consumption values.

3.3.1 Technologies considered in this paper

The commercially available Gigabit PON (**GPON**) system with **B+** optics is used as reference technology in this work. Next-generation PON technologies are considered, including 10 Gb/s PON (**XG-PON1 E2** class) as well as several candidates of the second generation systems (NG-PON2) with at least 40 Gb/s capacity per PON. The technological framework of NG-PON2 systems has been described by the FSAN (Full Services Access Network) group [1]. In this paper, we focus on the following NG-PON2 technologies:

- 40 Gbit/s capable (XLG) PON, which consists of a time division multiplexed (TDM) PON using a single wavelength in downstream (DS) with 40 Gb/s line rate and a single wavelength in upstream (US) for all ONUs with 10 Gb/s line rate. O-band DS transmission is assumed to avoid dispersion compensation. We consider two varieties of this technology, with different protocols for DS transmission. **XLG:GEM** uses the GPON encapsulation method (GEM) to package user traffic. The payload is grouped into frames, which are filtered at the ONU based upon the GEM header. This requires electronic processing of the incoming traffic bursts in the ONU at 40 Gb/s. **XLG:BI** uses an alternative bit-interleaving protocol to transmit DS traffic. By interleaving the bits for different ONUs, the electronic processing speed of the ONU receiver can be reduced, resulting in a lower ONU energy consumption [10].

- Time-shared Wavelength Division Multiplexing (**TWDM**) PON consists of four overlaid TDM-PONs in a single physical ODN, using different wavelengths both in DS and US directions, each TDM-PON with a 10 Gb/s line rate in DS and 2.5 Gb/s in US. Tunable ONU transmitters and receivers are assumed, to distribute the subscribers evenly among the four wavelengths (in this work, tunability is not used for dynamic bandwidth allocation in response to variations in user activity).

- Orthogonal Frequency Division Multiplexing (**OFDM**) PON, where multiple orthogonal electrical carriers are multiplexed. The ONU can flexibly filter and down-convert a band of N_s subcarriers in the analogue domain[1], so that subsequent digital signal processing (DSP) and media access control (MAC) functions can be performed at a lower rate.

- Coherent Ultra Dense WDM-PON (**Co UDWDM**), consisting of a logical point-to-point dense WDM-PON system with tunable ONUs and coherent detection [11], which achieves the highest optical power budget. Though systems supporting over a thousand wavelengths in the same PON have been reported, a maximum of 256 wavelengths is considered in this paper. In any case, the impact on the power/user of adding more wavelengths would be limited, since the main contribution to the OLT power for Co UDWDM comes from the added power per user (cf. Section 3.3.3).

FSAN selected TWDM-PON as the main technology for NG-PON2, with an expected practical availability by 2015-2016. The other next-generation technologies that we consider in this paper should be considered for future evolution beyond NG-PON2.

[1] One orthogonal subcarrier for each of the N_s subscribers in the PON.

Table 3.1: *Technology-dependent system and power consumption parameters.*

PON technology	DS capacity (Gb/s)[a]	US capacity (Gb/s)[a]	PON ports per rack	Max. optical budget (dB)	Attenuation α (dB/km)	Power per OLT PON port (W)[a,b] $P_{port,tech} + P_{user,tech} \times N_s$	Power per ONU (W)[b]
GPON B+	2.5	1.25	256	28.0	0.6	3.0	2.6
XG-PON1	10	2.5	128	35.0	0.6	22.8	4.5
XLG:GEM	40	10	64	31.0	0.6	36.1	6.1
XLG:BI	40	10	64	31.0	0.6	36.1	4.6
TWDM	4×10	4×2.5	64	35.0	0.4	54.8	5.0
OFDM	40	10	64	34.5	0.6	$42.8 + 0.7 \times N_s$	9.3
Co UDWDM	$1.25 \times N_s$	$1.25 \times N_s$	64	43.0	0.4	$9.3 + 3.5 \times N_s$	5.7

[a] N_s = number of subscribers per OLT PON port. N_s scales with the split ratio and takerate.
[b] Power consumption values are system-specific contributions, excluding common baseline for ONUs and not yet taking into account conversion inefficiencies and site factor.

3.3.2 System parameters

Table 3.1 shows the aggregated bandwidth capacity per PON interface in DS and US directions, the number of PON ports per OLT rack, the maximum optical power budget, and attenuation for each PON technology. In order to calculate the maximum reach for each technology, 0.6 dB/km propagation losses are assumed for the O band and 0.4 dB/km for the C and L bands, comprising the typical average losses of splices and other penalties in the fiber outside plant.

3.3.3 Power consumption parameters

Estimates of the power consumption for system-specific electro-optical components per OLT PON port (consisting of a per-PON and an optional per-user component) and per ONU, are reported for each technology in the last two columns of Table 3.1. The power values reflect how much a practical application-specific integrated circuit (ASIC) implementation of the PON system would consume if it were made today. Future improvements in electronic and optical design will likely result in reduced power consumption, but these overall improvements will not impact the comparison between technologies. For NG-PON2 technologies, which are not yet commercially available, the power consumption values are best-effort estimates based on internal data and values from literature [2, 12, 13]. The impact of uncertainty in these estimates is discussed in the sensitivity analysis (Section 3.7).

The power consumption per OLT PON port increases as the PON bandwidth increases. For OFDM and Co UDWDM PON technologies, a variable part of the OLT port power consumption scales with the number of users, considering the additional power contribution of digital processing and transceiver groups required when more users are connected to the PON.[2] Except for GPON systems, amplified solutions have been considered for long reach capabilities. A semiconductor optical amplifier (SOA) for both DS and US direction is included in the OLT numbers for XG, TWDM, OFDM and Co UDWDM PON. For XLG-PON, we consider DS amplification by means of an SOA, and electronic dispersion compensation for the US signal (XLG:GEM and XLG:BI use identical equipment on the OLT side).

Significant differences can be observed for the power consumption of the ONU. The technology-specific component typically increases proportionately with the line rate. However, the ONU of a XLG:BI PON can consume about the same power as XG-PON1, despite a four times higher

[2]For Co UDWDM, we assume a pay-as-you-grow concept, where the network operator installs additional capacity as needed.

line rate, by using an energy-efficient bit-interleaving protocol in the DS direction [10]. The TWDM PON ONU consumes slightly more power than XG-PON1 because it is based on the same standard MAC protocol and offers the same line rate, but consumes additional power for the tuning of the laser and receive filter. OFDM PON is highly inefficient due to the need for DSP and optical amplification to meet the stringent signal to noise ratio across a standard ODN. Even though we assumed the possibility to select a subset of carriers and as such reduce the power consumption of the DSP and MAC processing, the ONU power consumption remains high. The optical front-end of the ONU in a coherent UDWDM PON consumes more power due to the coherent receiver requiring two balanced receiver pairs and the optical field modulator for US transmission. On the other hand, the protocol processing is simplified to a 1 Gb/s Ethernet functionality, which consumes less power than in an XLG PON or TWDM PON. The total power of a Co UDWDM ONU is thus only slightly higher than that of an XLG PON or TWDM PON ONU.

3.4 PON dimensioning based on user demand

In this section, we explain how the PON is dimensioned based on a statistical analysis of the aggregated user demands. This statistical analysis takes into account the potential for dynamic bandwidth allocation. The extent to which bandwidth can be shared among users, depends on the chosen PON technology. Therefore, we introduce the concept of a *virtual PON*, in which bandwidth can be divided arbitrarily between the active users. For GPON, XG-PON, XLG:GEM, XLG:BI and OFDM PON, the virtual PON corresponds to the physical PON. In the case of TWDM PON, each physical PON consists of four virtual PONs on separate wavelengths. In a Co UDWDM PON, users have their own dedicated wavelength channel, resulting in as many virtual PONs as there are users, so there is no dynamic bandwidth allocation between users in this case. We consider line rates for the definition of the access speed per subscriber, assuming a similar level of overhead for all PON technologies.

When dimensioning the PON, there are three types of user demands we considered: voice traffic, multicast IPTV traffic and best-effort Internet traffic (including OTT Internet video). The dimensioning for IPTV multicast demands and the statistical flow analysis for best-effort Internet traffic will be performed per virtual PON. In our traffic analysis, we only model DS bandwidth, assuming US traffic is less than or equal to 25% of DS traffic.

3.4.1 User demand model for triple play services

Voice traffic is the highest priority traffic in case of congestion, so the consumed bandwidth by voice should be subtracted from the total bandwidth available for best-effort Internet and IPTV services. The speed rate of voice over Internet protocol (VoIP) codecs ranges from 22 Kb/s to 113 Kb/s [14], which is less than 0.1% of the total access bandwidth values considered in this work, and the average minutes of use per user of fixed voice is 10 minutes per day [15], thus the contribution of voice to the traffic load is negligible and has not been included in the simulations. Nevertheless, in real implementations, this VoIP traffic will need to have the highest priority.

Multicast IPTV traffic also has priority over best-effort Internet traffic. Note that we focus on IPTV in the context of traditional broadcast live TV, as opposed to Video on Demand, which is considered part of the (OTT) best-effort Internet traffic. To estimate the number of channels being watched, we base ourselves on IPTV channel popularities from measured weekly viewing times for a commercial IPTV service in the United Kingdom. We assume high definition (HD) channels with MPEG4 encoding (12 Mb/s per channel). All IPTV channels (127 in total) are broadcast from the aggregation network to the OLTs through the uplinks, but only the channels that are being watched by users within a (virtual) PON are forwarded via multicast within that PON. To guarantee IPTV transmission, we estimate the bandwidth that is required for multicast within a virtual PON during primetime, and reserve it, making it unavailable for best-effort Internet services. We assume 25% of Internet subscribers have an IPTV subscription, and each TV subscriber has 1.85 TVs on average[3], of which 60% are switched on during primetime. We use a Monte Carlo approach to assess the number of TV channels that need to be distributed per virtual PON, similar to the approach used by van Veen et al. in [17]; we however use the measured channel popularities, whereas van Veen et al. modeled channel popularity with a Zipf function. We reserve enough bandwidth in each PON to ensure IPTV multicast is uninterrupted 99.9% of the time.[4] In our results, IPTV multicast bandwidth per PON is always below 15% of the total PON bandwidth.

The bulk of the traffic is *best-effort Internet traffic*. In our Internet service model, a maximum target bandwidth, namely B_{target}, is offered to each customer with a minimum percentage of time of availability, namely $p_{avail,min}$. We adopt the user behavior model from Segarra et al. [19], where each user

[3]40% of TV subscribers have one TV set, 35% have two, and 25% have three [16].

[4]We assume the operator does not allow fast channel surfing (mean time between channel changes $<$ 4 seconds) as this would result in a much higher load during commercial breaks, up to twice the steady state level [18].

has the same probability p_{act} to be active and users are independent.[5] In our simulations, p_{act} is fixed at 10% [20]. We extend the model from Segarra et al. by assuming that users request a fixed target bandwidth B_{target} when they are active. Fastest average connections offered by operators already reached 1 Gb/s in 2012 [21], thus we consider three possible regular access speeds for the majority of users in future broadband scenarios: B_{target} = 100 Mb/s, 600 Mb/s and 1 Gb/s.

The service models for IPTV and best-effort Internet described above, will be used in the next subsections for the split ratio and OLT dimensioning.

3.4.2 Split ratio dimensioning

Two different deployment strategies are used in this work to compare the seven PON technologies. The first is a *fixed split ratio* strategy, in which an existing GPON deployment with split ratio 1:64 is re-used by upgrading the ONUs and OLTs, without any changes in the ODN. For each technology, we calculate p_{avail} using the method described in subsection 3.4.2.2 below, to check if the QoS requirement is satisfied. The second strategy assumes a fully flexible deployment, in which an *optimized split ratio* is chosen. We determine the maximal split ratio at which $p_{avail,\,min}$ can be guaranteed. Note that this optimized split ratio may be higher or lower than the legacy value of 1:64, depending on takerate, user demand, offered bandwidth and PON technology. There is a trade-off between availability (QoS) and power consumption: increasing the split ratio reduces availability, but it also reduces power consumption as the OLT equipment is shared by more users. We assume a maximum split ratio 1:256, with additional restrictions imposed by the technology-dependent reach.

3.4.2.1 Reach restrictions

The reach of a technology for a given physical split ratio 1:S is

$$d_{max} = \frac{(\text{max. optical budget} - L_m - L_c - 3.5 \times log_2 S)}{\alpha} \tag{3.7}$$

where L_m is a 3 dB margin for fiber patching (based on practical experience) and L_c is a 1 dB penalty for a coexistence element in the COs, used for compatibility with existing GPON deployments (based on ITU-T Rec. G.984.5

[5] Users are not perfectly independent in real networks, as some periods of the day will be more busy than others. The assumptions made here are to be interpreted as estimates for peak hours.

Amd. 1). Note that L_c is zero when calculating the reach for GPON. Splitter losses scale with the chosen split ratio: the signal incurs a 3.5 dB loss for each doubling of the split ratio (assumption adopted from OASE [9], consistent with ITU-T Rec. G.671). The maximum optical budget and attenuation factor α for each technology are listed in Table 3.1. In our calculations, we limit ourselves to those subsets of split ratios that allow a reach d_{max} that is greater than 5 km, to ensure all homes in the city can be connected to the COs.

3.4.2.2 Quality of Service (QoS) restrictions

After subtracting the IPTV multicast bandwidth (calculated in Section 3.4.1) from the total PON bandwidth, the remaining best-effort Internet bandwidth is to be shared by all subscribers in the (virtual) PON. We assume ideal dynamic bandwidth allocation without packet loss in the ODN in both US and DS direction. All users within a virtual PON are treated equally. When k active users from N total independent users are demanding or delivering traffic from/to an OLT interface, the maximum bandwidth that can be offered to each user is

$$B_{max} = \frac{\text{PON bandwidth}}{k}, \quad 1 \leq k \leq N \tag{3.8}$$

When B_{max} is greater than B_{target}, all active users get the requested B_{target}. However, when there are too many active users, B_{max} may be smaller than B_{target}, so the offered bandwidth may be lower than the requested bandwidth. The probability p_{avail} that B_{target} is available ($B_{max} \geq B_{target}$), equals the probability that the number of active users k is smaller than or equal to k_{max}, given by the cumulative binomial probability [19]

$$p_{avail} = \sum_{k=0}^{k_{max}} \frac{N!}{(N-k)!k!} \left(1 - p_{act}\right)^{N-k} p_{act}^{k} \tag{3.9}$$

$$k_{max} = \left\lfloor \frac{\text{PON bandwidth}}{B_{target}} \right\rfloor \tag{3.10}$$

This availability is compared to $p_{avail,\,min}$, the minimum percentage of time that the target bandwidth should be available for each connected user ($p_{avail,\,min} = 90\%$ in our simulations, based on the current average for residential fiber services [22]). In case of the fixed split ratio approach, this may eliminate technologies that cannot meet QoS requirements. In case of split ratio optimization, the split ratio is lowered until QoS requirements are met.

3.4.3 OLT dimensioning for a single rack

Once the split ratio has been determined, we can dimension the general OLT functions and the uplink between the OLT and the aggregation network. The traffic passing through an OLT[6] consists of three contributions: (1) Voice traffic: requires negligible bandwidth, (2) IPTV broadcast of all TV channels, for which a combined downstream capacity of 127 × 12 Mb/s = 1.5 Gb/s is reserved, and (3) best-effort Internet traffic: the dimensioning for this traffic is derived from the user demands as follows.

In our model, the number of active users in a single PON follows a binomial distribution (see Section 3.4.2.2). By multiplying the numbers of active users in this distribution by B_{target}, and capping the values at the available PON capacity for best-effort Internet services, we obtain the demand distribution (D_{PON}, P_{PON}) for a single (virtual) PON. This distribution is used in a Monte Carlo simulation, where for each PON in the rack, a random number is generated and mapped onto a demand $D_{PON}(j)$ with probability $P_{PON}(j)$, and the demands of the PONs in the rack are added up. After running the simulation one million times, we can estimate the combined best-effort Internet traffic load of the PONs connected to a rack (D_{OLT}, P_{OLT}) with sufficient precision. Based on this distribution, we dimension the uplink and general OLT functions requirements per rack for best-effort Internet services as described in the following sections.

3.4.3.1 Uplink

The uplink capacity should be sufficiently high so as to keep the packet loss in the uplink (P_{loss}) unnoticeable for users. Average packet loss in present-day residential fiber access networks is in the range 0.13% - 0.34% [22], so we decide to keep the packet loss in the uplink below $P_{loss,max} = 0.1\%$ for the reference scenario. Transmission Control Protocol (TCP) connections with high sustainable rates up to 1 Gb/s may require a lower packet loss rate, in which case a more strict value can be chosen without impacting the conclusions of this work, as the sensitivity analysis shows that overall power consumption is not impacted significantly by varying $P_{loss,max}$ from 10^{-3} to 10^{-8}.

We calculate the minimal uplink capacity C_U for which $P_{loss} < P_{loss,max}$ as follows. In the uplink interface of an OLT rack, the packet loss is the ratio of packets discarded over packets offered. We use the flow model from [23] to estimate packet loss: instead of considering individual packets, we look

[6]Here, "OLT" refers to a single rack, connecting a number of PONs as listed in Table 3.1.

at traffic flows. The packet loss is then

$$P_{loss} = 1 - \frac{m}{m^*} \tag{3.11}$$

where m^* is the average combined traffic load from all PONs connected to the rack (traffic offered), and m is the mean traffic load passing through the uplink (traffic passed). For a given uplink capacity C_U for best-effort Internet services, m^* and m are easily derived from the OLT load distribution as follows

$$m^* = \sum_i D_{OLT}(i) \times P_{OLT}(i) \tag{3.12}$$

$$m = \sum_i min\left(D_{OLT}(i), C_U\right) \times P_{OLT}(i) \tag{3.13}$$

The minimal uplink capacity C_U for which the packet loss calculated in (3.11) is below $P_{loss,max}$, is chosen. This capacity C_U is then added to the IPTV broadcast bandwidth (1.5 Gb/s) to obtain the total required uplink capacity.

The uplink is realized using a combination of Ethernet ports with capacities and corresponding power consumption values adopted from [24]: 1 Gb/s, 10 Gb/s, 40 Gb/s, 100 Gb/s, 400 Gb/s and 1 Tb/s ports consume 7 W, 38 W, 105 W, 205 W, 560 W and 1100 W respectively. The port combination with minimal energy consumption is chosen to realize the uplink. Note that only downstream traffic is considered in this calculation, since the uplink ports are symmetrical and there is typically more traffic load downstream than upstream.

3.4.3.2 General OLT functions

The last contribution to the OLT power consumption comes from the general OLT functions, which include (1) Layer 2 (Ethernet) switching, and (2) packet processing and traffic management. About 30% of this power consumption is static, due to leakage in transistors, and scales with capacity; the other 70% is dynamic and scales with the actual traffic load.

Half of the *static power consumption* is used for switching, for which the installed capacity is symmetrical and thus scales with the highest traffic capacity direction (downstream); the other half is used for packet processing and traffic management, for which different upstream and downstream capacity can be installed. So the OLT capacity C_{OLT} in equation (3.5) should be interpreted as $0.5 \times (2 \times C_{DS}) + 0.5 \times (C_{DS} + C_{US})$ to differentiate between these symmetrical and asymmetrical contributions. The required downstream capacity C_{DS} of the general OLT functions is the sum of IPTV broadcast capacity (1.5 Gb/s) and DS best-effort Internet capacity of the OLT. The upstream OLT capacity C_{US} is 25% of the DS best-effort Internet capacity. The DS best-effort Internet capacity is estimated using a similar method as for the uplink capacity, but with a stricter limitation on the allowable packet loss (10^{-9}). Moreover, this capacity is multiplied by a factor four to over-dimension the equipment to accommodate traffic growth and traffic peaks (an average factor which we obtained as a rule of thumb from providers). The assumptions for OLT capacity dimensioning are more strict than those for the uplink because it is more difficult to upgrade OLT capacity: for the uplink, capacity can be increased by simply plugging in additional transceivers and adding capacity in the aggregation switches in the metro aggregation net, whereas an OLT upgrade will likely involve a replacement of the OLT switch and packet processors.

The *dynamic power consumption* is proportional to the traffic load, and consumes 0.70 W/Gb/s (unidirectional, consisting of 0.35 W/Gb/s for switching and 0.35 W/Gb for packet processing and traffic management). This value is multiplied by the average OLT traffic load L_{OLT}, which is the sum of the average downstream best-effort Internet traffic load, 25% of this value for upstream traffic, and the IPTV broadcast bandwidth.

3.5 City deployment model

A real city scenario is considered in the PON deployment algorithm which — based on the technology-dependent optical budget, attenuation, split ratio and number of PON ports per rack — finds the required inventory of active equipment for providing high speed triple play services with the required QoS.[7] A greenfield approach is followed for fiber network construction, assuming that no other optical access infrastructure has been deployed before and if there are existing ducts, they are not necessarily used. This allows to evaluate the impact of the different PON deployment parameters with total flexibility. In case of a fixed split ratio approach, we assume the existing deployment has been optimized in the past using the same algorithm to obtain the equipment count.

3.5.1 City description

Public source real data from the Spanish National Institute of Statistics [25] have been employed to create the city topology model. This work focused on a major city area in Spain with an aggregate distribution of 1.5 million home units. A classification of the 73 population centers of the city was

[7] City deployment algorithm developed in the framework of FP7 project Accordance.

Table 3.2: Summary of city topology.

	Central zone	Ring 1	Ring 2	Ring 3
Population centers	1	13	19	40
Home units	564,730	434,376	276,217	165,903
Density threshold (homes/km^2)	4,000	4,000	2,000	500
Fiber length F1, F2, F3[a]	40%, 20%, 50m	40%, 20%, 50m	42%, 23%, 75m	44%, 26%, 100m
Surface (km^2)	67.27	91.80	113.03	178.81
Distance to central zone (km)	0	15.55	23.11	29.21

[a] Values for F1, F2 and F3 are based on a typical real GPON deployment. F1 and F2 are reported as percentages of *min(population center radius, physical reach of the PON technology)* to account for reach differences between PON technologies.

established using three geotypes depending on population density: (1) Dense urban geotype with $\geq$ 4,000 home units per km^2, (2) Urban geotype with 2,000 - 4,000 home units per km^2, and (3) Sub-urban geotype with 500 - 2,000 home units per km^2. A simplified model of the city area was built considering three concentric rings with a common central zone. Both the central zone and Ring 1 correspond to the dense urban geotype, while Ring 2 and 3 correspond to urban and sub-urban geotypes, respectively (see Table 3.2).

3.5.2 Optical Access Network Deployment

For a given service definition, the number of OLT racks depends on the filling ratio of each OLT PON interface, which is based on two factors: (1) the coverage area of a PON, which depends on its maximum physical reach, determined by the split ratio, optical budget and attenuation; and (2) the population density, determined by its location in the city. As a consequence, the first step for the PON inventory calculation is locating the COs. Initially, one CO is associated to each of the 73 population centers. For simplicity, each of the rings' surfaces is evenly assigned to each of the identified population centers, and all of the COs of each ring are considered to be at the average distance with regards to the central area. Next, a concentric CO consolidation algorithm is used as PON deployment optimization criterium, because it allows minimum real estate investment for the network operator, as well as lower operational cost. Considering two levels of power splitting in the PON fiber outside plant, the rules for fiber network construction to provide FTTH coverage depending on each type of population center are

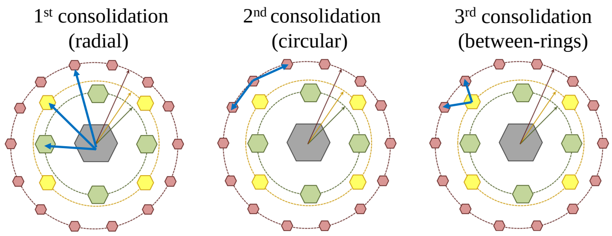


Figure 3.3: *Graphical representation of the CO consolidation steps.*

shown in Table 3.2 (fiber sections F1, F2 and F3 as indicated in Fig. 3.2). For a given PON technology, the algorithm used to calculate the number of COs and the ring location of each CO consists of the following three steps (see Fig. 3.3):

1. *Radial consolidation.* For each of the three rings, the algorithm verifies if an extended feeder fiber from the central zone to the average ring distance is supported, depending on the reach of the PON technology. If the verification is positive, then all the home units of the verified ring are served from the central zone.

2. *Circular consolidation.* When radial consolidation is not possible for a ring, then consolidation of neighboring COs into a single CO within the same ring zone is verified. An average distance between COs is calculated from the ring area and the number of centers in the ring. Increasing multiples of this average distance are added to the length of fiber section F1 for the corresponding ring and the maximum circular consolidation is obtained considering the reach of the PON technology.

3. *Inter-ring consolidation.* After the circular consolidation, the algorithm verifies if the remaining COs in a ring, that cannot be served from the previously consolidated COs (isolated centers), can serve centers of an outer ring.

Thus, depending on the technology performance and the service requirements, the number of serving COs in each of the rings is calculated and the corresponding equipment inventory for the COs (number of OLT racks and OLT PON ports) is returned. The rack filling rate — the actual number of PON ports per rack divided by the theoretical number of PON ports per rack — will depend on the location of the COs, and has an impact on the total power consumption of the access network.

The number of ONUs is also calculated in this stage, based on the number of homes in the city, the percentage of real estate units passed by fiber

(60%) and the percentage of those real estate units passed that are connected, referred to as *takerate* (we take 50% as a reference, and vary this value between 10% and 100% in our sensitivity analysis).

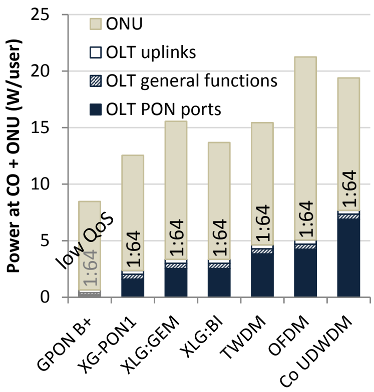
3.6 Results for a reference scenario

All power consumption calculations were implemented in Matlab; except for the city deployment model, which was implemented in Visual Basic (Excel). In our analysis of the results, we focus on the power consumption per user to compare different *cases*. Each *case* consists of a PON technology, a split ratio strategy (fixed or optimized, cf. Section 3.4.2), and a specific combination of the service profile parameters listed in the Appendix (3.9), quantifying user demands (numbers of users, user activity and bandwidth requirements per user) and QoS requirements (availability, packet loss). It must be noted that when the deployment has been optimized for a specific case, the switchover to another case with higher demands or stricter QoS requirements could mandate expensive changes in the ODN (e.g. lowering the split ratio). Therefore, when choosing the input parameters for our model, the cases are defined including a sufficiently large buffer to enable future growth.

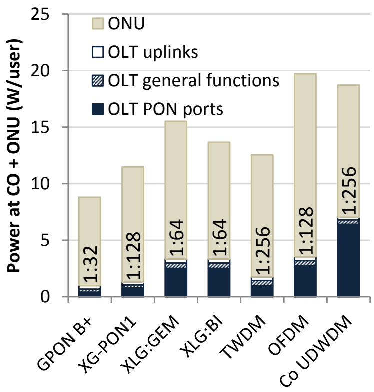
This section will discuss the results for two reference cases: the fixed split and optimized split version of an average user demand scenario. The results for other cases will be discussed in the sensitivity analysis. All results include power conversion inefficiencies and site overhead where applicable (cf. equation 3.2-3.3).

3.6.1 Total power consumption

The stacked bars in Fig. 3.4 indicate the joint power consumption at the CO and ONU for an average user demand scenario (600 Mb/s). The values range from about 8 W/user for GPON to more than 20 W/user for OFDM PON. In general, the ONU is the most important contributor (for a discussion of the technology-dependent ONU power consumption values we refer to Section 3.3.3). The share of the CO becomes even smaller when the split ratio is optimized (Fig. 3.4b, split ratios indicated inside the bars), due to a more optimal use of the OLT equipment. OFDM has the highest overall power consumption, because of the heavy digital signal processing in the ONU. Co UDWDM has the second highest total power consumption, partly due to the need for an increased number of transceivers at the CO, but this also has a number of advantages, which will be discussed below in the detailed evaluation of the CO power consumption.



(a) fixed split



(b) optimized split

Figure 3.4: *Power consumption at CO (OLT) and customer premises (ONU) for a reference scenario (B_{target} = 600 Mb/s). Split ratios are indicated inside the bars. Split ratio optimization decreases OLT power consumption for TWDM and OFDM PON the most. GPON B+ must be deployed with a lowered split ratio to meet QoS requirements. Overall, XG-PON1 is the most energy-efficient technology that can be deployed with a split ratio $\geq$ 1:64.*

Which technology is the most energy-efficient option overall – For the user demands in the reference scenario, GPON B+ is the most energy-efficient solution, but in case of a fixed split ratio (Fig. 3.4a), its capacity does not suffice to serve users in an existing ODN: the probability that an active user gets the requested bandwidth drops to 60%, which is below the QoS requirement of 90% ($p_{avail} < p_{av,min}$). GPON B+ could be deployed with a split ratio 1:32 to meet the requirements, but this would not be an attractive option for network operators, due to the increased costs associated to a higher number of OLT ports and an ODN with a higher number of fibers and ducts. In practice, XG-PON1 would therefore be a more attractive option for the near future (depending on the split ratio flexibility, it can be split 1:64 or 1:128). TWDM is an interesting option for network operators who want to increase split ratios further to achieve node consolidation, in a network that is future-proof for demands up to and beyond 1 Gb/s (see also sensitivity analysis in the next section).

3.6.2 OLT power consumption

The lower three parts of the bars in Fig. 3.4 show the power consumption of the OLT PON ports, general OLT functions and OLT uplinks at the CO. Note that this power consumption is charged to the network provider.

Breakdown of the OLT contributions — The power consumption at the CO is mostly dominated by the contribution of the PON ports, while power consumption of the general OLT functions and uplinks is much lower. For GPON B+ however, general functions and uplinks are the dominant contributors, due to its relatively low power per OLT PON port (see also Table 3.1). Similarly, in case of TWDM with an optimized split ratio, where the power/user for PON ports is low due to a large number of users sharing each port, the contribution of general OLT functions and uplinks is relatively important. As user demands increase (not shown in the graph), the contribution of the general OLT functions and uplinks will grow for all technologies, since they scale with the capacity and traffic load. If the bandwidth per user B_{target} goes up to 1 Gb/s, general OLT functions and uplinks for NG-PON2 technologies will consume about 1.3 W/user in a fixed split scenario, and about 1 W/user in an optimized split scenario.

Impact of split ratio optimization — When the split ratio is fixed, NG-PON2 technologies have a much higher energy demand at the CO compared to the existing technologies, due to the high line rates. Evidently, sharing a 40 Gb/s PON capacity among 32 connected users (split ratio 1:64, takerate 50%) is a substantial overprovisioning, which comes at a high energy cost. Optimizing the split ratio reduces power consumption at the CO for TWDM and OFDM PON the most. Thanks to their high optical budgets and capacities, many users can be connected to a single OLT port, thus equipment sharing can make these technologies more energy efficient. XLG PON[8] has a lower optical budget, so even though it offers the same per-PON capacity as TWDM and OFDM, its maximum split ratio is 1:64, resulting in a high energy consumption per subscriber regardless of split ratio flexibility. Co UDWDM is clearly the most power-hungry technology in every scenario. However, it must be noted that this solution offers the advantage of 100% bandwidth availability on the first mile and lowest traffic latency, which may be useful for specific applications such as business services or mobile backhauling and fronthauling. Moreover, the link budget is very high, and user demands can always be met thanks to the dedicated wavelength channels, therefore this technology can always be deployed with split ratio 1:256 (or even higher), even for very high user demands.

Which technology is the most energy sparing for network operators – As mentioned before, though GPON B+ has the lowest power consumption, it does not have sufficient capacity to offer user rates up to 600 Mb/s with 90% availability when the split ratio is 1:64. Among the other options, XG-PON1 is not only the most energy-efficient solution overall, but also the

[8]We do not distinguish between XLG:GEM and XLG:BI on the OLT side, as they require identical OLT equipment.

most energy-efficient solution at the CO for user demands up to 600 Mb/s.

Effects of statistical multiplexing – It is interesting to note that for XG-PON1, even though the total PON bandwidth divided by the number of connected users is below the target bandwidth, statistical multiplexing allows for an availability of more than 90%, since not all users are active at the same time. The same is true for TWDM PON in case of an optimized split ratio. As demands increase, XLG and OFDM PON could also take advantage of this statistical multiplexing effect, but in this reference scenario, their split ratios are limited by reach restrictions, so their capacity is not fully exploited.

3.7 Impact of parameter variations on results (sensitivity analysis)

Since most of our input parameters are estimates based on literature rather than experimentally verified values, they come with some uncertainty. In order to know the impact of this uncertainty on our results, we perform a sensitivity analysis. We vary fourteen input parameters along the distributions given in the Appendix (3.9), and study the variations in the CO power consumption as a result of these input variations. We only focus on power consumption at the CO, since the ONU power consumption is assumed constant and therefore a sensitivity analysis for the ONU is straightforward: if there is 10% deviation in the input for ONU power consumption, this results in 10% deviation in the ONU result. The results we show do however include ONU power consumption, as we want to compare the overall energy efficiency between technologies.

For each of the fourteen varying input parameters, we calculate the first-order *sensitivity index* per technology for both fixed and optimized split ratios. The first-order sensitivity index [26] quantifies the contribution of a given input parameter to the variance of the output — in this case, the CO power consumption. A qualitative indication of the sensitivity indices is presented in Fig. 3.5. Note that icons are to be compared within columns, since the sensitivity analysis is performed separately for each technology. As an example of how to interpret the symbols in Fig. 3.5, consider GPON with a fixed split ratio. The three-quarter-full disc in the first row indicates that most of the variation in the power consumption for GPON comes from variations in Internet takerate. The half-full disc for active user probability indicates that this parameter variation also causes significant output changes. The impact of the other parameter variations is relatively minor for GPON with a fixed split ratio.

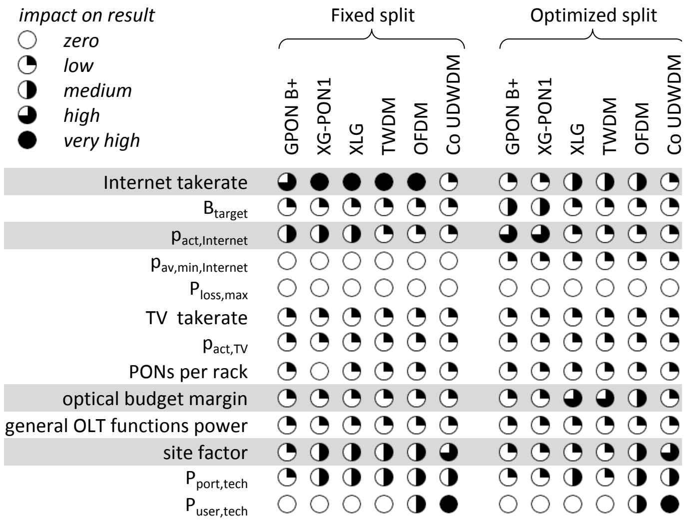


Figure 3.5: *Relative importance of the input parameter variations for each technology. The effect of varying some of the most impacting parameters (highlighted in gray) is shown in Fig. 3.6.*

The four most impacting parameters overall are highlighted in gray in Fig. 3.5. We will discuss the effect of varying each of these parameters individually. But first, we will look into the effect of varying the bandwidth per user between 100 Mb/s (current demands) and 1 Gb/s (future demands).

3.7.1 Impact of varying bandwidth per user

For current user demands (B_{target} = 100 Mb/s), GPON B+ is by far the most energy-efficient option, both for fixed and optimized split ratios. If future users require target bandwidths up to 1 Gb/s and the split ratio is fixed (not shown in graphs), the effect on power per user is similar for all technologies: an increase of about 0.5 W/user compared to the 600 Mb/s reference scenario. Consequently, XG-PON1 remains the most energy-efficient technology for future demands up to 1 Gb/s in case of a fixed split ratio. When the split ratio is optimized, the added degree of freedom leads to a less predictable effect of the target bandwidth changes, shown in Fig. 3.6a. For target bandwidths up to 900 Mb/s, XG-PON1 can be deployed with a split ratio of 1:128, consuming less power per user than TWDM PON. For demands going up to 1 Gb/s however, the capacity limitation of XG-PON1 mandates a split ratio reduction to 1:64, bringing its energy efficiency at the same level as that of TWDM PON. The latter might be a more attractive option in this case, due to its higher split ratio (1:256) and potential for node consolidation.

3.7.2 Impact of varying other input parameters

The *Internet takerate* is the most impacting input parameter for all technologies in case of fixed split ratios, because as the takerate increases, the number of users sharing PON equipment increases, resulting in a lower power per user. Takerates below 30% result in much higher power per user compared to the reference scenario with 50% takerate (e.g. for 30% takerate, TWDM power per user is 2.6 W higher than for the reference case). For optimized split ratios (Fig. 3.6b), the effect is less pronounced, but still significant. For takerates below 20%, there is a notable deterioration in energy efficiency for all technologies. Note that the impact for Co UDWDM is limited for both fixed and optimized split ratios, since the installed capacity for this technology scales better with the number of connected users.

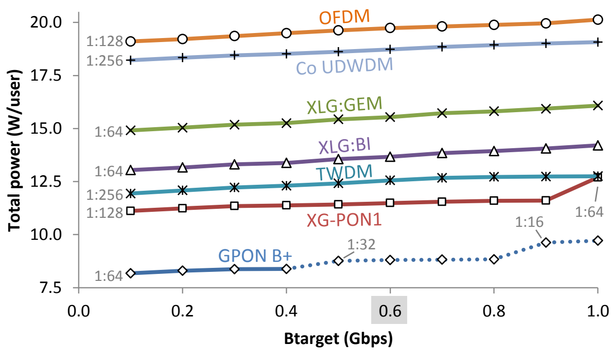
The results for varying *active user probability* show similar trends as for varying B_{target} (cf. Section 3.7.1), as they ultimately have the same effect: an increase in the PON traffic load and in the required OLT capacity.

The *site factor* is applied to all power consumption values at the CO, so it directly impacts power consumption: varying the site factor with 10% scales the total CO power consumption with 10%, this is the case for both fixed and optimized split ratio scenarios.

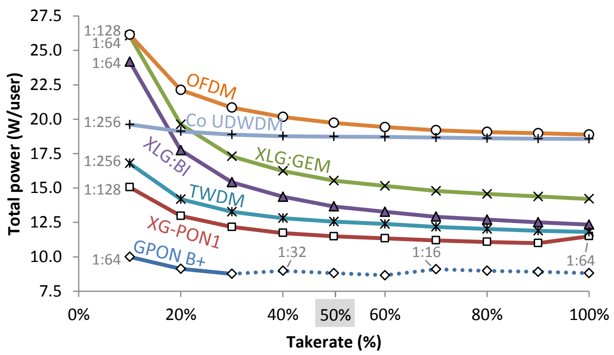
Variations in the *optical budget margin* generally have a limited effect when the split ratio is fixed (not shown in graphs), though a shorter range could result in slightly less equipment sharing due to less centralized COs. In case of optimized split ratios, the optical budget margin is an important parameter for XLG PON, TWDM PON and OFDM PON, as it can be a limiting factor for the split ratio optimization. Due to their high capacities, reach is typically the limiting factor for these technologies. Figure 3.6c shows that XLG:BI could achieve the same power/user if the link budget was improved by 1 dB (for example by making the margin for fiber patching more strict). But in any case, TWDM keeps the advantage of the highest split ratio potential.

3.7.3 Conclusion of the sensitivity analysis

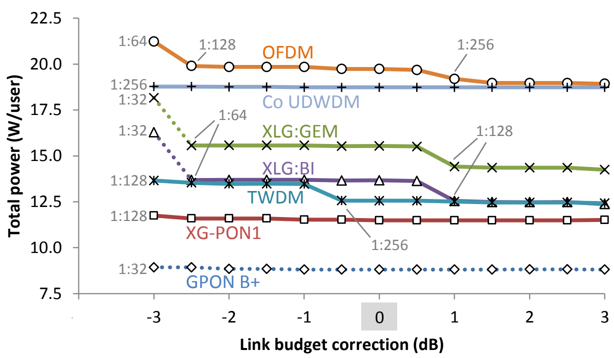
Though changes in the input parameters can result in significant variations in the CO power consumption for individual technologies, the relative proportions between the technologies are preserved in most cases, so the comparison between the technologies still holds. Although our sensitivity analysis focused mainly on the CO, note that changes in the ONU will most



(a) For user rates up to 1 Gb/s, TWDM reaches the same energy efficiency as XG-PON1.



(b) Low takerates worsen energy efficiency, except for Co UDWDM.



(c) With an improved link budget, XLG:BI reaches the same energy efficiency as TWDM.

Figure 3.6: *Sensitivity of the result (total power = CO + ONU) to changes in the most impacting input parameters, in case of optimized split ratios. The shaded value on the horizontal axis is that of the reference scenario. Split ratio changes are indicated in gray. Dotted lines indicate data points with split ratios $<$ 1:64, these cases would result in unacceptable QoS in a fixed split ratio scenario. The results for varying active user probability are not shown, as they show the same trends as for varying B_{target}.*

likely have a bigger impact, due to its bigger contribution to the overall power per user.

3.8 Conclusion

We studied the power consumption of various next-generation PON technologies for a massive residential deployment. The choice for a fixed split ratio or optimized split ratio strategy will impact which technology is the most energy-efficient option for future deployments with access bandwidths up to 1 Gb/s: XG-PON1 (with split ratio 1:64) or TWDM PON (with split ratio 1:256). TWDM PON can take advantage of its high optical power budget, resulting in a long reach that allows node consolidation (reducing the number of central offices and OLT ports), which can help reduce both capital expenditures and operational costs for network operators.

We also analyzed the sensitivity of our results to the input parameters of our model. As it turns out, variations in takerate, active user probability, optical budget margin and site factor have the biggest impact on our result for the power consumption at the central office. Reducing the site factor, for example by using energy-efficient cooling systems, can significantly reduce power consumption. Further, a high takerate significantly reduces power consumption per user due to improved equipment sharing, which brings the actual traffic load closer to the provisioned capacity. This shows that a scenario where multiple operators each have their own optical access network, is not desirable from an energy efficiency point of view. An open access scenario, where multiple operators share the passive optical network infrastructure [27], could be a more energy-efficient solution from network operators' perspective. But the biggest impact on the overall power consumption can be made by improving the energy efficiency of ONUs, as they still consume the bulk of optical access network energy. The inclusion of energy-saving strategies such as sleep modes or energy-efficient protocols in the comparison can have a big impact on the results, as illustrated by the improved energy efficiency of XLG:BI compared to XLG:GEM.

To conclude, we would like to remark that in the current work, our focus has been on energy efficiency with current technology maturity and system performance estimations, and without taking into account cost aspects. TWDM PON, which was selected by FSAN as the main solution for NG-PON2 for its lower expected cost than other candidates and commercial viability by 2015, also turns out to be an energy-efficient solution for residential services. For other services with specific requirements, other characteristics (such as system capacity, bandwidth availability and latency) may be prioritized over energy efficiency or cost.

3.9 Appendix: Input parameters for the sensitivity analysis

Table 3.3 contains an overview of the input parameters that are varied between simulations in the sensitivity analysis. The first column shows the default values of the reference scenario. The other columns show the restrictions for the random variation of the parameters in the sensitivity analysis. The distribution of the parameters for the sensitivity analysis is Gaussian, except when specified otherwise.

Acknowledgments

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We would like to thank L. Guan and M. Ruffini from The Telecommunications Research Center (CTVR), Dublin, Ireland, for providing the IPTV channel popularity information.

Table 3.3: Overview of input parameter variations for the sensitivity analysis.

parameter name	reference scenario (mean)	standard deviation	lower bound	upper bound	description / remarks
User demand: Internet service profile					
Internet takerate	50%	10%	0%	100%	Percentage of homes passed by fiber that are connected.
B_{target}	600 Mb/s	200 Mb/s	0 Mb/s	1 Gb/s	The sustainable bandwidth requested by users when they are active.
$p_{act,Internet}$	10%	5%	0%	100%	Probability that a user is active, requesting B_{target}.
$p_{av,min,Internet}$	90%	10%	0%	100%	QoS parameter: minimum probability that a user will get B_{target} when requested.
$\log_{10}(P_{loss,max})$	-5.5	-	-8	-3	QoS parameter: exponent for maximum allowable packet loss in the uplink. Distribution is flat, not Gaussian.
User demand: TV service profile					
TV takerate	25%	10%	0%	100%	Percentage of Internet subscribers that have IPTV.
$p_{act,TV}$	60%	10%	0%	100%	Percentage of TV sets switched on during peak hour.
Physical characteristics of technologies					
PONs per rack	cf. Table 3.1	10% of mean	50% of mean	2× mean	Number of PONs per rack, rounded to the nearest integer.
L_m	3 dB	1.5 dB	0 dB	(none)	Margin for fiber patching, subtracted from the optical link budget to calculate reach, see equation (3.7).
Power consumption calculation					
general OLT functions power	1 W/Gbps	0.1 W/Gbps	0 W/Gbps	(none)	Power consumption factor for switching, traffic management and packet processing. Unidirectional, excluding overhead factors.
site factor	1.6	0.16	1	2	CO power consumption is multiplied by the site factor (defined in Section 3.2).
$P_{port,tech}$	cf. Table 3.1	10% of mean	0 W	(none)	OLT power per port for opto-electronic components, excluding overhead factors.
$P_{user,tech}$	cf. Table 3.1	10% of mean	0 W	(none)	OLT power per user for opto-electronic components, excluding overhead factors.
uplink Ethernet ports power	cf. page 73	10% of mean	0 W	(none)	Power consumption of the uplink Ethernet ports from [24].

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4

The road to energy-efficient optical access: GreenTouch final results

The model presented in this chapter is more extended than the one in the previous chapter, as it incorporates several energy-saving strategies and includes the metro section of the network as well as the access. It is applied to the architecture developed by the GreenTouch Optical Access working group, which had the goal of finding the most energy-efficient optical access architecture that can be realized by the year 2020. The work contains a detailed description of the chosen architecture, the energy-saving strategies that are applied, and the expected savings.

⋆ ⋆ ⋆

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Abstract The growing energy footprint of communication networks has raised concern about the sustainability of future network development.

The GreenTouch consortium was founded to help counter this trend by developing and integrating green network technologies from the access to the core. In order to evaluate these technologies, an end-to-end network power model was developed in the form of the Green Meter, a tool to assess the overall impact and overall energy efficiency benefits from an entire portfolio of solutions. In this paper, we describe the methodology of the Green Meter for the residential fixed access portion, which was extended to include metro aggregation. A baseline architecture for optical access and metro aggregation networks is defined, and adapted to other scenarios integrating future technologies. The performance is each time evaluated through a mathematical model that captures the energy savings at the component level and has the ability to compute the overall system-level energy savings. We show that energy efficiency can be improved 29-fold over a decade (2010-2020) with business-as-usual trends, and with the added effort of introducing GreenTouch solutions, this could be further improved to achieve a 257-fold increase in energy efficiency. The results confirm that an emphasis on green network design can indeed have a huge impact on reducing the energy consumption of optical access infrastructure.

4.1 Introduction and motivation

Communication networks have grown tremendously over the past decades, becoming more widespread, offering higher rates, and better performance. This has however come at a large energy cost. Worldwide electricity consumption by communication networks grew at an annual rate of 10% from 2007 to 2012 [1]. When this problem became apparent, several large international research projects were initiated to foster a more sustainable growth of communication networks: examples include TREND, EARTH, ECONET, STRONGEST, and GreenTouch.

The GreenTouch consortium was founded in 2010 with the ambitious goal to improve the energy efficiency of communication networks by a factor of 1000$\times$ by 2020. At the conclusion of the project in 2015, the outcome of a comprehensive research study, called the *Green Meter*, was published [2]. The Green Meter assesses the overall impact and overall energy efficiency benefits from an entire portfolio of solutions investigated and developed by GreenTouch. The results are not limited to the energy benefits of a single technology, but instead focus on an end-to-end network perspective including a full range of technologies, and accounting for future traffic growth. It was shown that a 98% reduction of the net energy consumption in end-to-end communications networks can be achieved by 2020 compared to the 2010 reference scenario.

In this paper, we describe the methodology that was used to obtain the residential fixed access portion of the Green Meter results in detail. We quantify the effect of different energy-saving approaches on the main sub-systems such as the optical network unit (ONU) and the optical line terminal (OLT), each time expressing it in a corresponding saving factor. We also include the metro aggregation network containing the aggregation switch (AS) and the edge router (ER) in our model, allowing us to evaluate the effect of technologies bypassing the local exchange, thus extending the reach of the access network. In the rest of this work, when we refer to the access, we always mean the extended version, including the metro aggregation.

The proposed methodology is applied to three scenarios:

1. Baseline 2010: using the most energy-efficient commercially deployed technologies at the start of GreenTouch in 2010;

2. Business-as-usual (BAU) 2020: using similar technologies as in the baseline scenario, assuming energy efficiency is improved following current technological trends until 2020;

3. GreenTouch (GT) 2020: leveraging novel GreenTouch architecture and technologies together with non-BAU techniques that are expected to be available by 2020.

Preliminary results of the Green Meter for fixed access have previously been published in two conference papers [3, 4]. The main updates in the present work are the direct inclusion of cascaded bit-interleaving (CBI) and point-to-point (PtP) in the GT architecture; the extension of the model to include metro aggregation; updates to the saving factors based on demonstrated savings for CBI, PtP, and virtual home gateway (vHGW); updated sleep saving estimates; accounting for managed Internet protocol (IP) traffic in network dimensioning; revised cooling overheads; and further improvements in the way we account for supply transition, Moore's law, and power shedding.

The paper is organized as follows. We start with an overview of the expected traffic growth in fixed access in Section 4.2. Next we introduce the baseline, BAU (Section 4.2) and the GT architecture, including the concepts behind some disruptive technologies that are used in the GT scenario (Section 4.3). A detailed description of the Green Meter model follows in Section 4.4, introducing the saving factors for all energy-saving approaches and how they can be combined. Finally, we apply the model to obtain results for the three aforementioned scenarios in Section 4.5. Conclusions are drawn in Section 4.6.

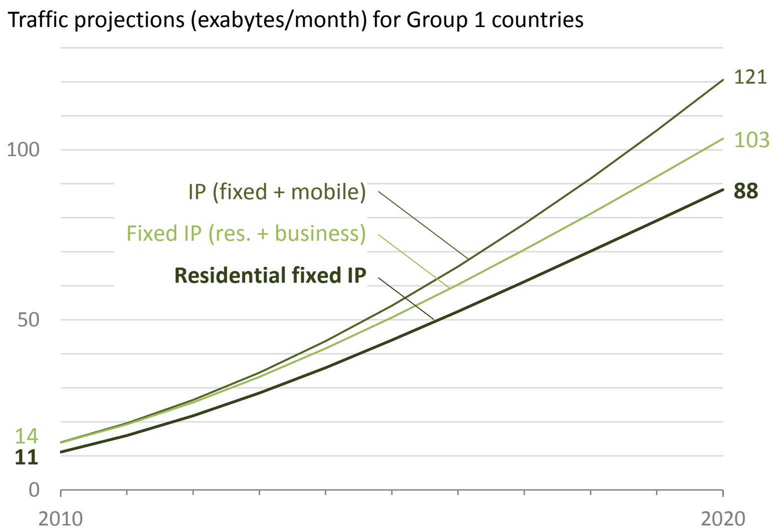

Figure 4.1: Projected traffic (in exabytes/month) until 2020 for Group 1 countries (North America, Western Europe and Japan). A hyperbolically decreasing CAGR was fitted to historical traffic trends to obtain the projections [5].

4.2 Expected evolution of communication networks

4.2.1 Traffic trends

Traffic growth and growing numbers of subscribers are the two main drivers of growing power consumption in communication networks. In order to properly dimension a future-proof network and assess its energy efficiency, we first need to determine how much traffic will be passing through it.

The GreenTouch Services, Policies and Standards (SPS) group developed traffic volume and growth projections from 2010 to 2020 based on regression analysis of historical trends. The projections build on a semi-empirical model in which traffic growth does not follow an exponential trend with a fixed compound annual growth rate (CAGR), but instead exhibits a CAGR that hyperbolically decreases over time (for a detailed description and motivation of the traffic projection model, see [5]). Fitting this model to historical trends and near-term forecasts that were available at the time of the SPS analysis [6, 7] results in the GreenTouch projections shown in Figure 4.1.

The traffic projections and network models are developed for the mature markets of North America, Western Europe and Japan (also called

Group 1 countries) rather than for worldwide markets, because more reliable data is available for Group 1 countries, and to avoid methodological issues from population growth and having to account for limited electricity grid availability in our network design. In this work, when we refer to total traffic volumes and subscriber numbers, we are always considering Group 1 countries.

The three lines in Figure 4.1 show the GreenTouch estimates for overall IP traffic (top), the fixed access contribution (middle), and finally the residential portion of fixed access (bottom).[1] Although the mobile share in overall IP traffic is on the rise, illustrated by the growing distance between the top and middle curve, fixed access will continue to be the main source of IP traffic until 2020 and beyond, and the total traffic volume passing the fixed access network will grow by a factor of 7.5× between 2010 and 2020. Since this work deals with residential access networks, the most relevant trend for our further analysis is that of residential fixed access traffic, which will grow almost 8-fold from an estimated 11 EB/month in 2010 to 88 EB/month in 2020 (1 EB = 1 exabyte = 1 billion gigabytes).

Independent of the traffic analyses, the number of residential fixed subscribers was projected to 2020 by the SPS group based on similar regression analyses for years prior to 2012 [8]. Values for 2010 and 2020 are shown in Table 4.1.

4.2.2 Implications for network design

The dimensioning of the access network depends on the provisioned data rate per subscriber. The traffic and subscriber projections from the previous section are combined to calculate the average total bit rate per subscriber in Table 4.1.

Further, we need to know the downstream (DS) and upstream (US) component of this average bit rate. This requires the DS/US ratio of residential traffic in 2010 and 2020, which is obtained by calculating a weighted average of appropriate DS/US weights for various traffic sub-components based on the type of service[2]. The resulting ratio increases from 79/21 to 83/17 over the years, mainly due to the growing importance of downstream-heavy video traffic. So throughout the period under study, downstream traffic imposes higher bandwidth requirements on the network than upstream. This is not only the case in the network uplinks, which are symmet-

[1] Traffic volumes for fixed access and residential fixed access were estimated by direct fractional interpolation using global and regional subtotals.

[2] We differentiate between Internet traffic (with sub-categories web services, file sharing, gaming, VoIP, and video) and managed IP traffic (mainly video, which is chiefly downstream traffic) to determine the DS/US ratio.

Table 4.1: *Traffic and subscriber projections for residential fixed access in Group 1 countries.*

Year	2010	2020
Total (DS+US) traffic	11.12 EB/month	88.22 EB/month
Number of subscribers	245 million	281 million
Average total (DS+US) bit rate per subscriber	138 kb/s	955 kb/s
Average DS/US ratio	79/21	83/17
Average DS 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

ric, but also in the passive optical network (PON) section of the network, where downstream capacity is twice the upstream capacity. In the following, we therefore limit our analysis to the downstream portion of traffic, since upstream traffic demands will automatically be met if the network can support the downstream traffic.

Starting from the average bit rate per subscriber (Table 4.1), to account for traffic fluctuation, we take the provisioned bit rate per subscriber at busy hour to be 16 times larger: we apply a factor 2× for the peak-to-average ratio in a diurnal cycle, 2× to account any occasional larger volumes, and 4× to ensure an upgrade of aggregation capacity is only needed every couple of years (4× is a factor that is often used in practice by telecom operators to account for this).

4.2.3 Baseline and BAU network

The access network architecture for the baseline and BAU scenario is shown in Figure 4.2. As baseline residential access technology in 2010, we consider gigabit-capable passive optical network (GPON) with 2.5/1.25 Gb/s (DS/US) capacity as this was the most energy-efficient commercially deployed technology at the start of GreenTouch. In the BAU scenario we assume this technology will still be used in 2020, since bit rates per subscriber will not exceed GPON capacity.

The ONUs[3] are connected to the OLT through a 1:64 split PON. We assume a filling rate of 50% in 2010 (32 subscribers per PON on average), which increases to 57.32% in 2020 (36.7 subscribers per PON on average), proportionally with the growth in number of subscribers (Table 4.1). The traffic from twelve OLTs[4] is aggregated on a single connection to an AS, with a second standby link to another AS as backup. Every AS is a layer

[3]Since the ONU power consumption is dominant, we further break it down into the subfunctions shown in the figure. For details, see Section 4.4.1.

[4]We use the term OLT to refer to one OLT rack.

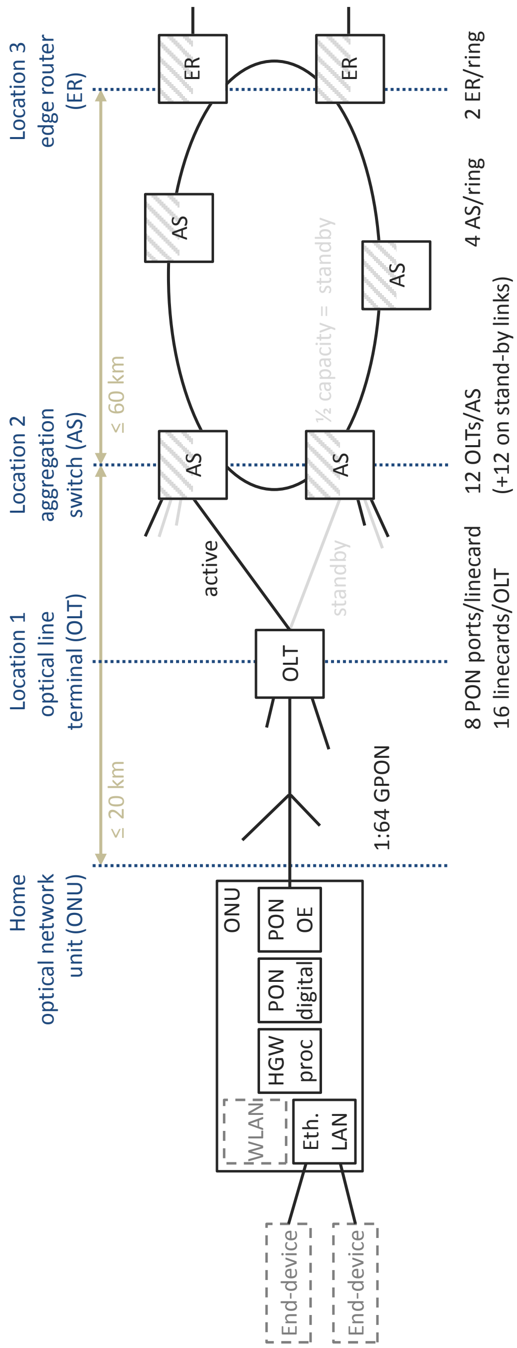

Figure 4.2: Baseline and BAU network architecture

2 (L2) Ethernet switch with virtual local area network (VLAN) and multiprotocol label switching (MPLS) capability. Network resiliency is further improved by use of a ring topology encompassing 4 ASs and 2 ERs with redundant capacity. The ERs are layer 3 (L3) service routers (also broadband remote access server (BRAS) in older architectures) that form the connection to the core network. Under normal operation, the load is shared and 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.

To dimension the network nodes, we start from the provisioned bit rate per subscriber at the ONU (Table 4.1). In each subsequent aggregation stage in the network, the traffic load is multiplied by the total number of subscribers served by that node to obtain the provisioned throughput in Table 4.2. The interfaces are chosen in such a way that they can support this throughput with minimal power consumption.

Table 4.2 also shows how we expect the configuration and interfaces to change by 2020 in a BAU scenario, to accommodate the growing number of subscribers and traffic throughput.

4.3 GreenTouch technologies and architecture

The key technologies that enable drastic energy savings compared to the BAU scenario for 2020 are introduced in this section. Since the focus of this work is on the Green Meter calculation method for energy savings, we will limit our description of the enabling technologies to high-level concepts. The corresponding power-saving factors will be given in Section 4.4. Technical implementation details can be found in the GreenTouch white paper on fixed access [9] and in the references cited below.

4.3.1 Disruptive technologies

4.3.1.1 Cascaded bit-interleaved PON

Though bit rates per subscriber will not exceed GPON capacity by 2020, higher-capacity PONs are still worth considering because they allow OLT equipment to be shared between more subscribers per PON, resulting in power savings at the OLT. On the other hand, when optical access networks start offering higher data rates up to 40 Gb/s DS on a single PON, the fast processing of information in short time-slots at a very high data rate becomes one of the main power consumption drivers in the ONU.
Bit-interleaved PON (Bi-PON) is a new protocol that allows extracting the

Table 4.2: *Node dimensioning for residential access in 2010 baseline network, and expected changes by 2020 in BAU scenario*

		ONU	OLT	Aggregation switch (AS)	Edge router (ER)
Configuration	2010	-	50% filling of 1:64 PON, 8 ports per linecard, 16 linecards. (1+1) uplinks to ASs	12 active and 12 standby OLT uplinks. (1+1) links to ERs	2 ER per 4 ASs in ring, (1+1) capacity
	2020	-	57.32% filling of 1:64 PON (ports, cards, uplinks same as 2010)	(same as 2010)	(same as 2010)
# subscribers (avg)	2010	1	4096	49152	98304
	2020	1	4695.3	56344	112688
Provisioned throughput	2010	1.75 Mb/s	7.2 Gb/s	86 Gb/s	(1+1)×172 Gb/s
	2020	12.73 Mb/s	60 Gb/s	717 Gb/s	(1+1)×1.43 Tb/s
Interfaces	2010	Subscriber side: 2×GbE LAN over copper Network side: GPON (2.5/1.25 Gb/s DS/US)	Subscriber side: GPON ports (2.5/1.25 Gb/s) Network side: (1+1) × 10 Gb/s	Subscriber side: (1+1) × 12 × 10 Gb/s Network side: (1+1) × 100 Gb/s	Subscriber side: (1+1) × 2 × 100 Gb/s Network side: (2+2) × 100 Gb/s
	2020	(same as 2010)	Subscriber side: (same as 2010) Network side: (1+1) × (2×40) Gb/s	Subscriber side: (1+1) × 12 × (2×40) Gb/s Network side: (1+1) × (8×100) Gb/s	Subscriber side: (1+1) × 2 × (8×100) Gb/s Network side: (15+14) × 100 Gb/s

relevant bits for the ONU immediately behind the clock and data recovery [10], so that further processing is done at the lower user rate instead of the aggregate line rate. By arranging the transmitting data streams destined for different ONUs in bitwise interleaving fashion[5], the Bi-PON protocol enables the ONUs to sample data in the physical domain. All subsequent processing at the ONU can then be operated at the lower clock rate, thus resulting in power savings [11].

Moreover, the concept has been extended to multiple cascaded levels, namely a CBI-PON [12], where lower level Bi-PONs are connected to their upper level network through CBI *repeaters*: 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. The lower level Bi-PON supports a variety of DS line rates which can be equal to 1/4, 1/8, 1/16 or 1/32 of its upper level Bi-PON. The introduction of CBI results in a long reach access network and even better sharing of the OLT in comparison with regular Bi-PON.

4.3.1.2 Virtual home gateway

In the baseline network, home gateway (HGW) service functions (forwarding, firewalling, network address translation, dynamic host configuration protocol server, and administration interface) are physically located at dedicated resources at every ONU. In the GT 2020 scenario the HGW at the user premise is replaced by a quasi-passive device without special features. The resource intensive HGW services are pulled to servers that are co-located with the ER. The functions are virtualized into *containers* on the central servers, exploiting scaling and sharing of resources to realize energy savings [13]. GreenTouch demonstrated that a single server can host up to one thousand virtual home gateways [14]. This approach still provides isolation between users, and the provider can take advantage of consolidation for easier future expansion of gateway functionality to advanced services such as video storage or console gaming, while keeping the ONU simple, low-power and reliable.

4.3.1.3 PtP transceiver

In the GreenTouch architecture, in-home copper links are replaced by fiber links. In particular, the traditional gigabit Ethernet (GbE) local area net-

[5]Upstream rates are typically lower (1/2 or 1/4) than downstream, therefore bit-interleaving is only applied downstream; upstream transmission remains a simple time-slot based transfer.

work (LAN) interfaces are replaced by low power PtP optical transceivers. Conventional PtP optical transceivers operate continuously at a high and fixed optical power and the electronic-to-optical signal conversion efficiency is relatively low [15]. GreenTouch researchers have completely redesigned the transceiver and custom-built an application-specific integrated circuit (ASIC) prototype that minimizes the circuit power consumption for a target data rate 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 [16, 17].

4.3.1.4 Low-power optics and electronics (LPOE) — Innovations in optics and electronics

Progress in optical components and electronic circuit technology can reduce power to a fraction 0.75 and 0.33 respectively beyond BAU trends, if special attention is paid to energy efficiency in hardware design. Further, improved PON optoelectronics (OEs) would allow elimination of the limiting amplifier (LA) in the ONU, thereby also eliminating its power consumption. In this work, we group these savings under the term LPOE.

4.3.1.5 Sleep modes

Power consumption can be 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 [18] is used in the access (cf. ITU-T G.987.3) and Ethernet LAN (cf. IEEE802.3az) interfaces. In the PON based access, where a point-to-multipoint topology applies, cyclic sleep mode is applicable mostly 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 Ethernet LAN links, cyclic sleep mode is applicable symmetrically at both ends of the link leading to larger savings. At the ER, we account for turning standby elements (provisioned for redundancy) to a sleep state such that a quick turn on is ensured.

4.3.2 Network architecture integrating all GreenTouch solutions

The GreenTouch residential access network for 2020 is shown in Figure 4.3. As the introduction of CBI allows an extension of PON reach, the OLT is moved to the ER location (along with the virtualized HGW functionality), and the AS is replaced by a remote node (RN) with simple CBI repeaters.

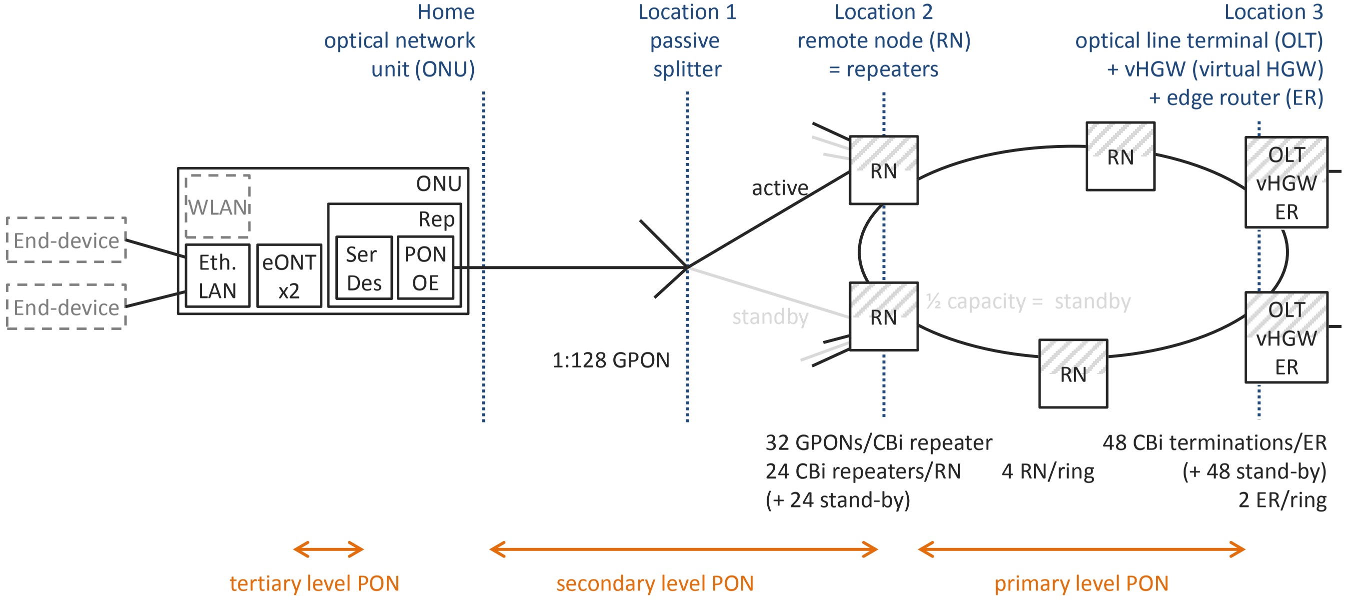

Figure 4.3: *GreenTouch network architecture*

The repeaters in the RN downsample the CBI signal coming from the ER (primary level PON) to divide it between 32 GPONs (secondary level PON). The GPON signal is downsampled a second time in the ONU, where the relevant bits for two LAN interfaces are selected and directed to the appropriate end-optical network terminal (eONT) (tertiary level PON). The node dimensioning for this architecture is detailed in Table 4.3.

The tertiary level PON (in-home) supports 1.25 Gb/s DS and 625 Mb/s US. The eONT functions within the ONU terminate the PON extracting the traffic for the respective LAN interfaces. The repeater function of the ONU eliminates the need for a switching function within the ONU, since the bits are interleaved so that the repeater automatically directs them to the eONT corresponding to the correct LAN interface.

The CBI repeater in the remote node has a standard GPON OLT optical front-end to the subscriber side, so the secondary level PON supports 2.5 Gb/s DS and 1.25 Gb/s US. We assume that 1:128 split in each GPON is possible since this is regular OLT optics state of the art as of 2017 (year of assumed introduction). The power consumption of the GPON OLT remains, but is moved higher up in the network and integrated in the ER. Clock and data recovery (CDR) and serializer/deserializer (SerDes) are shared between 32xGPON.

To the metro ring side, the CBI repeater in the remote node has a 40G transceiver. 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 (BW) allocation by the bit-interleaving scheduler allows to manage all DS subscriber traffic since the sustained user throughput is only about 30 Gb/s.

The load in the metro ring is still shared between two ERs, where each ER supports half the throughput (1.43 Tb/s) under normal operation, but each ER is dimensioned to support the total throughput (2.87 Tb/s) 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 standby state consuming 20% of the active power in order to ensure quick turn on when needed.

The ER chassis features a 40G transceiver into each 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.

Table 4.3: *Node dimensioning for residential access in 2020 GreenTouch network*

	ONU	Remote node (RN)	OLT + vHGW + ER
Configuration (avg)	-	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
# subscribers (avg)	1	56,344.10	112,688
Provisioned throughput	12.73 Mb/s	717 Gb/s	(1+1) × 1.43 Tb/s
Interfaces	2×GbE LAN over fiber GPON (2.5/1.25 Gb/s DS/US)	Subscriber side: GPON ports (2.5/1.25 Gb/s DS/US) Network side: (24+24) × 40 Gb/s	Subscriber side: (48+48) × 40 Gb/s Network side: (15+14) × 100 Gb/s

4.4 The Green Meter model

Implementing green technologies affects different parts of the network to a different extent, hence calculating the overall savings can not be done through a straightforward multiplication of saving factors. The approach we propose in the Green Meter is to break the system down into power consumption components and determine the saving factors for individual components, after which the total power is obtained by calculating the sum of products.

We apply this approach to the optical access network in Table 4.4. In the following, we start by introducing the baseline power consumption values and general calculation method. Next, we explain how we obtain each factor in the table. References are included where available; the other factors are own estimates based on typical values or confidential sources.

4.4.1 Baseline power of system components

The top rows of Table 4.4 show how we break the nodes down into components. The model is most detailed for the dominant contributors to power consumption. All power values include power supply inefficiency for all nodes (90% AC/DC and 90% DC/DC conversion); cooling overhead for OLT, AS, and ER equipment (50% overhead in 2010); and redundant elements for resiliency as indicated by the $(X+X)$ terms in Table 4.2 and Table 4.3 (where X represents a number of devices).

The ONU is broken down into the following sub-functions:

- Optoelectronic (OE) conversion of signals:
  - optics (265.81 mW): accounting for uncooled distributed feedback (DFB) directly modulated laser (DML) at 1.25G (3.3 V supply to laser driver, 15 mA biasing current, and 50 mA modulation current) and PIN diode,
  - electronics (391.19 mW): including transimpedance amplifier (TIA) at 2.5G [19], burst-mode (BM) control and monitor part [20], and LA at 1.25G;
- Digital protocol processing in a system-on-chip (SoC) (1.481 W [21]);
- Integrated HGW processor to handle forwarding, firewalling, network address translation, dynamic host configuration protocol server, and administration interface (1.9 W, estimate derived from [22] and consumption of other ONU parts);
- Two wireline GbE LAN interfaces to connect end devices (1.975 W [22]).

Note that wireless local area network (WLAN) interfaces and end-devices are not relevant in the comparison of fixed access technologies and hence excluded in our analysis.

At the OLT, power estimates are made for one OLT port (serving 32 subscribers in 2010). We consider the following sub-functions:

- OE conversion of the signals from the PON:
  - optics (440.72 mW): accounting for uncooled DFB DML at 2.5G (3.3 V supply to laser driver, 17 mA biasing current, and 55 mA modulation current) and PIN diode,
  - electronics (1117.8 mW): including TIA at 1.25G [23], laser driver continuous wave (CW) power control, and BM LA at 1.25G (scaled down from [24]);
- Digital processing (11 W): estimate derived from [22], subtracting consumption of other OLT parts. 28% of this power is throughput-dependent (dynamic); the remaining 72% is constant under varying traffic loads (static).

We further consider power consumption in the AS (5.9 kW) and ER (7.8 kW): the power per node is estimated by summing values for chassis, fabric, input/output (IO) modules, and blades to support the calculated throughput and interfaces. Since these nodes contribute relatively little to the overall power per subscriber, we do not break them down into components.

All power consumption values above are calculated on a per-node basis. To obtain the power per subscriber (sub) P_{sub}, the power per node P_{node} is divided by the number of subscribers per node $\#subs_{node}$, which can be derived from Table 4.2.

$$P_{sub} = \frac{P_{node}}{\#subs_{node}} \tag{4.1}$$

Note that at the OLT, we consider each termination port of a single PON to be a "node", so $\#subs_{OLT,2010} = 32$ (instead of 4096, the number of subscribers per OLT rack given in Table 4.2).

4.4.2 Future power estimates: calculation method

The *power per node* $P_{K,C}$ of a component C (C = one of the variable names defined in the column headers of Table 4.4) in 2020 when K ($1 \leq K \leq 9$) energy-saving techniques are applied, is obtained by multiplying the baseline power $P_{0,C}$ of that component in 2010 with the appropriate traffic growth factor g_C (see next section) and the appropriate energy-saving factors $f_{k,C}$ for technologies $k = 1..K$.

$$P_{K,C} = P_{0,C} \times g_C \times \prod_{k=1..K} f_{k,C} \tag{4.2}$$

To obtain the 2020 BAU estimates, the four first techniques are taken into account ($K = 4$). For example, substituting the values for OE optics in the OLT (column six in Table 4.4), we get $330.54\ \mathrm{mW} = 440.7\ \mathrm{mW} \times 1.00 \times 1.00 \times 1.00 \times 1.00 \times 0.75$.

The *power per subscriber* $S_{K,C}$ for a component C in 2020 is obtained by applying a similar formula to the baseline power per subscriber $S_{0,C}$ of that component, but including the appropriate "number of subscribers" factors $s_{l,C}$, indicated in grey in Table 4.4, to account for changes in the number of subscribers per node.

$$S_{K,C} = S_{0,C} \times g_C \times \prod_{k=1..K} f_{k,C} \times \prod_{l=1..L} s_{l,C} \tag{4.3}$$

with

$$L = \begin{cases} 1, & \text{if } 1 \leq K \leq 4 \\ 2, & \text{if } K \geq 5 \end{cases} \tag{4.4}$$

For example, there are 36.68 subscribers per PON in the 2020 BAU scenario ($K = 4$) where there used to be 32, so OE optics power per subscriber becomes $9.01\ \mathrm{mW} = 13.77\ \mathrm{mW} \times 1.00 \times \mathbf{0.872} \times 1.00 \times 1.00 \times 1.00 \times 0.75$ (indeed, $9.01\ \mathrm{mW} = 330.54\ \mathrm{mW}/36.68$). Arguably power per subscriber is a more interesting metric than power per node in this context. When the number of subscribers per node changes, the power per node in Table 4.4 does not reflect how many nodes are needed and thus, how much the network as a whole will consume. Nevertheless, we chose to include both, in order to provide more clarity on how the saving factors were obtained.

To obtain 2020 GT estimates, the calculations are performed for $K = 9$. Intermediate scenarios can also be evaluated ($4 \leq K \leq 9$), as long as no technologies are skipped. This condition follows from the fact that the order of introduction of technologies can impact saving factors: for example, introducing CBI first reduces the potential for sleep mode, so the saving factor for sleep mode in the table is only correct in a scenario where CBI is already introduced. Although changing the order of introduction can change the saving factors for individual technologies, the overall savings in the 2020 GT scenario, which incorporates all technologies, will remain the same regardless of the order of introduction.

Table 4.4: *Green Meter power model and power-saving factors*

Node (baseline)	ONU					OLT port (serves 1 PON)				AS	ER
Node components	PON OE optics	PON OE electronics	Digital SoC	HGW processing	2xGbE LAN	OE optics	OE electronics	Digital: dynamic	Digital: static	(all)	(all)
Column labels	*HO*	*HE*	*HD*	*HG*	*HL*	*TO*	*TE*	*TD*	*TS*	*AS*	*ER*
Power: 2010 baseline											
P_0 (mW/node)	265.81	391.19	1481.0	1900.0	1975.3	440.72	1117.8	4183.6	1.076E+04	5.926E+06	7.778E+06
S_0 (mW/subscriber)	265.81	391.19	1481.0	1900.0	1975.3	13.77	34.93	130.74	336.18	120.56	79.12
Power increase due to traffic growth by 2020											
Growth factor g	1.00	1.00	1.00	1.00	1.00	1.00	1.00	7.93	1.00	[in $f_{1,2,3}$]	[in $f_{1,2,3}$]
#subs factor s_1	1.000[b]	1.000[b]	1.000[b]	1.000[b]	1.000[b]	0.872[b]	0.872[b]	0.872[b]	0.872[b]	0.872[b]	0.872[b]
Energy-saving factors[a]: BAU											
f_1 Moore's Law	1.000	0.370	0.261	0.261	0.261	1.000	0.370	0.261	0.261		
f_2 Power shedding	1.000	1.000	1.000	0.475	0.475	1.000	1.000	1.000	1.000	{2.25}	{2.38}
f_3 Efficient HW design	1.000	0.800	0.800	0.800	0.800	1.000	0.800	0.800	0.800		
f_4 Efficient cooling	1.000	1.000	1.000	1.000	1.000	0.750	0.750	0.750	0.750	0.750	0.750
Power: 2020 BAU											
P_4 (mW/node)	265.81	115.79	309.50	188.60	196.08	330.54	248.15	5201.2	1686.1	1.000E+07	1.389E+07
S_4 (mW/subscriber)	265.81	115.79	309.50	188.60	196.08	9.01	6.76	141.79	45.97	177.48	123.25
Energy-saving factors[a]: GT											
f_5 CBI-PON	1.000	1.000	0.281	0.799	1.000	0.889[c]	0.889[c]	2.200[d]	1.100[d]	0.00056[e]	0.533[f]
#subs factor s_2	1.000[b]	1.000[b]	1.000[b]	1.000[b]	1.000[b]	0.500[b]	0.500[b]	0.500[b]	0.500[b]	24.000[b]	1.000[b]

Continued on next page

Table 4.4 — continued from previous page

	HO	*HE*	*HD*	*HG*	*HL*	*TO*	*TE*	*TD*	*TS*	*AS*	*ER*
f_6 vHGW	1.000	1.000	1.000	0.101[g]	1.000	1.000	1.000	1.000	1.000	1.000	1.000
f_7 PtP TRx	1.000	1.000	1.000	1.000	0.269	1.000	1.000	1.000	1.000	1.000	1.000
f_8 LPOE	0.750	0.686	0.330	0.330	0.977	0.750	1.000	0.330	0.330	0.940	0.998
f_9 Sleep mode	0.0761	0.371	0.476	1.000	0.354	1.000	1.000	0.800	0.800	1.000	0.662
Power: 2020 GT											
P_9 (mW/node)	15.18	29.48	13.67	5.00	18.25	220.36	220.57	3020.9	489.6	5244.6	4.891E+06
S_9 (mW/subscriber)	15.18	29.48	13.67	5.00	18.25	3.00	3.01	41.18	6.67	2.23	43.41
Node (GT)	**ONU**			**ER**	**ONU**	**RN**		**ER**		**RN**	**ER**

[a] Note that energy-saving factors only apply when used sequentially: first multiplying the power by g (and s_1 when considering power per subscriber), then multiplying the result by f_1, then by f_2, etc. (multiplying the original power only by f_6, for example, will not return the correct power of a system that uses vHGW without BAU or CBI techniques).

[b] Factor due to change in number of subscribers per node. Only applies to power/subscriber, not to power/node.

[c] OLT OE components are relocated to RN (long reach PON).

[d] OLT digital functions are moved to ER location (long reach PON).

[e] AS functionality is replaced by a simple repeater in the RN.

[f] CBI termination is added to ER functionality.

[g] HGW functionality is moved to ER location.

4.4.3 Power change due to traffic and subscriber growth

The goal of the calculations in Table 4.4 is to obtain power estimates for 2020 in a BAU and GT scenario, taking into account saving factors from various technological advances. But before any saving factors are applied, we need to consider the impact of traffic growth between 2010 and 2020 on power consumption of the baseline scenario. This is done through the *traffic growth factor* g_C in Table 4.4. As we already mentioned in Section 4.2.3, GPON can still be used in the last mile. Since the baseline ONU power is independent of traffic throughput, it will remain constant despite the growth in throughput per subscriber, so $g_{ONU} = 1$. In the OLT, the same is true for all components except for the dynamic portion of digital processing, which increases proportionately with the traffic load per PON. Since the number of PONs does not change between 2010 and 2020 BAU, this is equivalent to the total traffic growth. If we call the power taking into account only traffic growth P_g, for the dynamic part of the terminal (TD) we get:

$$
\begin{aligned}
P_{g,TD} &= P_{0,TD} \times \frac{T_{2020}}{T_{2010}} = P_{0,TD} \times \frac{88.22}{11.12} \\
\Rightarrow g_{TD} &= 7.93
\end{aligned}
\tag{4.5}
$$

where T_y is the total[6] traffic load in year y, taken from the first row in Table 4.1. For the AS and ER a simplified approach is used: there is no separate traffic growth factor for these nodes; instead, we assume that the power consumption stays flat for an evolution to the next generation of technology with 4 times better throughput, thanks to a higher level of ASIC integration and Moore's law (introduced in the next section). This evolution is lumped together in a single factor in Table 4.4 along with the remaining effect of traffic growth on power consumption (for the relevant components), leading to a 2.25-fold increase in power per AS and a 2.38-fold increase in power per RN.

The BAU scenario takes into account a growing take up rate in the PON to serve the growing number of subscribers (from 32 to 36.68 subscribers per PON, cf. Table 4.2). This results in better equipment sharing and, as a consequence, a lower power per subscriber. This is reflected by the first *#subs factor* s_1 in Table 4.4 for OLT, AS and ER:

$$
\begin{aligned}
s_{1,\{OLT,AS,ER\}} &= \frac{\#\text{subs using component } C \text{ in } 2010}{\#\text{subs using component } C \text{ in } 2020} \\
&= \frac{32}{36.68} = 0.872
\end{aligned}
\tag{4.6}
$$

[6]Note that dynamic power consumption scales with total traffic requirements (US + DS), whereas capacity requirements are dimensioned for the most demanding traffic direction (DS).

At the ONU, $s_1 = 1$ (no change), since there is one subscriber per ONU in all scenarios.

4.4.4 BAU saving factors

The first factor we apply follows from *Moore's law*, which is the observation that over the history of computing hardware, circuit integration density has doubled approximately every two years. This miniaturization reduces the driving voltage of electronic circuits, which in turn has an impact on power dissipation. Moore's law is applied to all electronics but not to optics (lasers and photodetectors). The saving factor depends on the type of electronics: digital or analog.

For digital electronics, we distinguish between logic and IO. The scaling of logic has been described in [25] to follow an 8x energy per flop improvement in 10 years, equivalent to dividing the power by a factor 1.22 annually. For IO, the work in [26] indicates that off chip interconnect should scale with technology node size, which scales at about 10 percent per year, dividing power dissipation by 1.1 annually. Combining these two parts, and assuming logic and IO each contribute about half of the digital electronics power, the power $P_{1,dig}$ for digital electronics becomes:

$$\begin{aligned} P_{1,dig} &= P_{g,dig} \times \left(0.5 \times (1/1.22)^{10} + 0.5 \times (1/1.1)^{10}\right) \\ \Rightarrow f_{1,dig} &= 0.261 \end{aligned} \tag{4.7}$$

with

$$dig \in \{HD, HG, HL, TD, TS\} \tag{4.8}$$

For analog electronics, the power scales linearly with the driving voltage. Since digital logic power scales with the square of the driving voltage, we apply the square root of the annual improvement factor from digital logic here:

$$\begin{aligned} P_{1,\{HE,TE\}} &= P_{g,\{HE,TE\}} \times \left(1/\sqrt{1.22}\right)^{10} \\ \Rightarrow f_{1,\{HE,TE\}} &= 0.370 \end{aligned} \tag{4.9}$$

Power shedding is characterized by powering off or reducing power to non-essential functions and services in the ONU while maintaining a fully operational optical link [27]. It is applied to the GbE interface and HGW processing. Power shedding techniques were already available in 2010, but they were only used in the event of a mains power failure [28]. In order to reduce network energy consumption, the feature is extended to power savings during idle periods. If we assume a component uses about one tenth of the active power in power-shed state, and the ONU is used 10 hours a day on average, we can derive the average power consumption $P_{2,ps}$ when power shedding is applied to the relevant components (on top of Moore's law which is already taken into account in P_1):

$$\begin{aligned} P_{2,ps} &= P_{1,ps} \times 10/24 + P_{1,ps} \times 0.1 \times 14/24 \\ \Rightarrow f_{2,ps} &= 0.475 \end{aligned} \tag{4.10}$$

with

$$ps \in \{HG, HL\} \tag{4.11}$$

Further, we predict *energy efficient hardware (HW) design* will cut back power for all electronic components by another twenty percent:

$$f_{3,el} = 0.80 \tag{4.12}$$

with

$$el \in \{HE, HD, HG, HL, TE, TD, TS\} \tag{4.13}$$

Recent years have also shown a trend of more *efficient cooling* techniques being used in data centers and the buildings that house telecommunication equipment (so-called central offices) [29]. We expect the cooling overhead to drop from 50% to 12.5% between 2010 and 2020, so the power P_4 after introducing efficient cooling becomes:

$$\begin{aligned} P_{4,\{OLT,AS,ER\}} &= P_{3,\{OLT,AS,ER\}}/1.50 \times 1.125 \\ \Rightarrow f_{4,\{OLT,AS,ER\}} &= 0.75 \end{aligned} \tag{4.14}$$

4.4.5 GreenTouch saving factors

Starting from the BAU scenario, more radical approaches can be introduced to achieve even better energy efficiency in the GT 2020 scenario.

4.4.5.1 Cascaded Bi-PON

This reduces the energy need for digital processing in the ONU. The 2.5G repeater consumes 188.27 mW, and the two 1G eONTs 2×114.20 mW (values from power estimation tools applied to the chip design for CBI [30]). Because these values are not yet taking into account BAU improvements, the saving factor is obtained by dividing the sum of the aforementioned values by the baseline power for digital processing (1481.0 mW). $P_{5,HD}$, the power for digital processing in the ONU taking into account CBI, is then easily derived from $P_{4,HD}$, the ONU digital power not yet taking into account CBI:

$$P_{5,HD} = P_{4,HD} \times \frac{416.67\,\mathrm{mW}}{1481.0\,\mathrm{mW}}$$
$$\Rightarrow f_{5,HD} = 0.281 \tag{4.15}$$

Secondly, the introduction of CBI makes the switching function in the ONU obsolete. When switching power (381.48 mW in the baseline) is subtracted from HGW processing power, we get the new home gateway processing power $P_{5,HG}$:

$$P_{5,HG} = P_{4,HG} \times \frac{1900.0\,mW - 381.48\,mW}{1900.0\,mW}$$
$$\Rightarrow f_{5,HG} = 0.799 \tag{4.16}$$

As outlined in the architecture description in Section 4.3.2, some of the network equipment is replaced and/or relocated when CBI is introduced. The OLT is replaced by a passive splitter and the OE conversion of the signals from the PON is relocated to the RN which, contrary to the OLT, is uncooled. This means the cooling overhead (12.5 percent in 2020 – we consider the factor for 2020 because energy efficient cooling was already incorporated in the BAU factors) is no longer required once CBI is used:

$$P_{5,\{TO,TE\}} = P_{4,\{TO,TE\}}/1.125$$
$$\Rightarrow f_{5,\{TO,TE\}} = 0.889 \tag{4.17}$$

The OLT digital processing is moved to the ER location (which is cooled, so the savings factor from (4.17) does not apply here) and an overhead factor 1.1x is applied to implement the interleaving function. The number of subscribers per OLT port doubles when CBI is introduced, since the split ratio is doubled with respect to the BAU scenario. Consequently, the dynamic part of the digital processing power P_{TD} is doubled (in terms of power per subscriber, this will be compensated by the #subs factor in equation (4.20)).

$$f_{5,TD} = 1.1 \times 2 = 2.2 \tag{4.18}$$

The factor for the static part $f_{5,TS}$ is independent of throughput so this becomes

$$f_{5,TS} = 1.1 \tag{4.19}$$

The doubling of the number of subscribers per OLT port is taken into account in the power/subscriber calculation by including the #subs factor s_2

for all OLT components:

$$\begin{aligned} s_{2,OLT} &= \frac{\#\text{subs using OLT port before CBI}}{\#\text{subs using OLT port after CBI}} \\ &= \frac{0.5732 \times 64}{0.5732 \times 128} \\ &= 0.500 \end{aligned} \tag{4.20}$$

The AS is replaced by a simple RN containing multiple CBI repeaters. Each repeater consumes: 1349.38 mW in 40G transceiver (TRx) optics (externally modulated laser (EML) [31], avalanche photodiode (APD) and TIA), 968.85 mW in 40G TRx electronics (EML driver + LA [32, 33]; already taking into account Moore's law for analog electronics, cf. (4.9)), and 3263.76 mW for digital processing of 32 GPONs bundled in each repeater (values from power estimation tools applied to the chip design for CBI [30]; already taking into account Moore's law for digital electronics, cf. (4.7)). The power saving factor $f_{5,AS}$ for the components in the former AS location becomes

$$f_{5,AS} = \frac{1349.38 + 968.85 + 3263.76\, mW}{1.000 \times 10^{7}\, mW} = 5.6 \times 10^{-4} \tag{4.21}$$

where it should be noted that the label AS from here on denotes the repeater (REP). Note that the number of subscribers per REP is much smaller than the number of subscribers per former AS, resulting in a high #subs factor $s_{2,AS}$:

$$\begin{aligned} s_{2,AS} &= \frac{\#\text{subs connected to AS before CBI}}{\#\text{subs connected to CBI REP}} \\ &= \frac{56344}{32 \times (0.5732 \times 128)} \\ &= 24 \end{aligned} \tag{4.22}$$

This partly cancels the savings in (4.21), but combined, it still results in a 98.7 percent reduction of this node's power per subscriber (combined factor = 0.013).

The ER is replaced by a more energy-efficient model than the BAU version, now consuming only 7.22 kW to route traffic from the same number of subscribers (#subs factor = 1.000). The power of the CBI termination, which is co-located with the ER, is added. Termination of a single CBI PON requires 3901.42 mW: 1518.06 mW in 40G TRx optics and 1089.96 mW in electronics (identical to the 40G TRx in RN but x1.125 to include cooling), and 1293.41 mW for the SerDes with CDR and electronic dispersion compensation (EDC) (power from [34] scaled up to 40G, taking into account cooling and Moore's law for digital electronics, cf. (4.7)). Since there are 48 CBI terminations in each ER node, the saving factor becomes:

$$f_{5,ER} = \frac{7.22 \times 10^6 + 48 \times 3901.42\,mW}{1.389 \times 10^7\,mW} = 0.533 \tag{4.23}$$

4.4.5.2 Virtual HGW

GreenTouch demonstrated that 1000 virtual home gateways can be hosted on a single server consuming 203.7 W, or 203.7 mW per subscriber. With efficient cooling, this becomes 152.8 mW per subscriber in 2020. Compared to equivalent functions in the baseline network (excluding switching in line with (4.16)), this technology provides a saving factor

$$f_{6,HG} = \frac{152.8\,mW}{1900.0\,mW - 381.48\,mW} = 0.101 \tag{4.24}$$

at the HGW processing sub-component. This factor is applied on top of BAU energy-saving factors, since these factors remain applicable when functionality is moved to the server.

4.4.5.3 Redesigned PtP TRx in LAN

The copper LAN interfaces are replaced by new PtP TRxs. The power consumption of one such interface is the sum of three contributions: 5.1 mW in optics (PIN diode + laser), 3.6 mW in analog electronics (TIA + LA + driver CW), and 46.8 mW in the SerDes. These values from [35] already account for Moore's law, but we still need to include power shedding. Therefore we multiply the total power per transceiver by 0.475, resulting in a power consumption of 26.4 mW per redesigned PtP TRx. The saving factor in Table 4.4 is obtained by dividing the power for two optical interfaces by that of the two copper interfaces in the BAU scenario:

$$f_{7,HL} = \frac{2 \times (5.1 + 3.6 + 46.8) \times 0.475\,mW}{196.06\,mW} = 0.269 \tag{4.25}$$

4.4.5.4 Low power optics and electronics

Progress in optical components and electronic circuit technology beyond BAU trends, and improved PON OE will further reduce power at the applicable sub-components. These savings are grouped under the name LPOE in Table 4.4. The individual factors are obtained as follows.

Progress in optical components beyond BAU trends results in 25% savings, which apply directly to PON and OLT optics:

$$f_{8,\{HO,TO\}} = 0.75 \tag{4.26}$$

The 25 percent savings also apply to the optical part of the two LAN interfaces, which, as shown in (4.25), is (5.1 mW×0.475) per transceiver. Since the total power per transceiver is 26.4 mW, this translates to the saving factor $f_{8,HL}$ for the LAN interfaces:

$$f_{8,HL} = \frac{(26.4 - 0.25 \times 5.1 \times 0.475)\ mW}{26.4\, mW} = 0.977 \tag{4.27}$$

Similarly, applying the 25 percent savings to the optical part of the REP, from (4.21), we get:

$$f_{8,AS} = \frac{(5581.99 - 0.25 \times 1349.38)\ mW}{5581.99\, mW} = 0.940 \tag{4.28}$$

And applying the savings to the optical part of the ER, from (4.23), we get:

$$f_{8,ER} = \frac{7.41 \times 10^6 - 0.25 \times 48 \times 1518.06\, mW}{7.41 \times 10^6\ mW} = 0.998 \tag{4.29}$$

Progress in electronic components beyond BAU trends results in 67% savings in electronics: ONU digital SoC, HGW processing, and OLT digital processing all fully benefit from these improvements, so we apply to all of these components:

$$f_{8,\{HD,HG,TD,TS\}} = 0.330 \tag{4.30}$$

Improved PON OE allows the elimination of the LA from PON OE electronics in the ONU. Extracting the LA power (123 mW×0.37×0.8 = baseline value from Section 4.4.1 with Moore's law and efficient HW design applied) from the PON OE electronics power in the ONU (391.19 mW×0.37×0.8, same reasoning as for LA), we get:

$$f_{8,HE} = \frac{(391.19\, mW - 123\, mW) \times 0.37 \times 0.8}{391.19\, mW \times 0.37 \times 0.8} = 0.686 \tag{4.31}$$

4.4.5.5 Sleep modes

Sleep modes are applied at the ONU, OLT, and ER.

ONU sleep modes An adapted version of the probing-based cyclic sleep mechanism from [36] is applied at the LAN and PON interfaces in the ONU. Different sleep saving factors apply to optics, electronics and SoC; and within these components, different saving factors apply to the transmitter-side and receiver-side power. The sub-components that result from this division are listed in Table 4.5. In this section, we start by deriving the individual saving factors of the sub-components (S_r and S_t for receiver and transmitter, respectively), before combining them to obtain the saving factors per component $f_{9,C}$ in Table 4.4.

To compute the power consumption of the LAN and PON receiver-side components in the ONU with sleep mode, we adapt the analysis in [36] with the following changes. The power consumption in idle and active state for receiver components are assumed to be the same (P_{ra}). The probe state is, by definition, the same as the active state for the receiver. We also consider a wake-up time T_{rw} to turn on the receiver which applies for the transition from the sleep state to the probe (or active) state. The transition time T_u in [36] no longer applies as the probe and active states are the same. We can now adapt [36, Eqn. (8)] as follows. The average receiver-side power $P_{r,\mathit{sleep}}$ at the ONU with cyclic sleep mode is given by

$$\begin{aligned} P_{r,\mathit{sleep}} = \frac{1}{\mathbb{E}[C]} \Bigg(& \left(1 - e^{-\lambda T_t}\right) \left(\frac{1}{\lambda} - \frac{T_t e^{-\lambda T_t}}{1 - e^{-\lambda T_t}} \right) P_{ra} \\ & + e^{-\lambda T_t} T_t P_{ra} \\ & + \mathbb{E}[\zeta] \Bigg((T_s - 2T_{rw}) P_{rs} + T_p P_{ra} \\ & \qquad + 2T_{rw} \left(\frac{P_{rs} + P_{ra}}{2} \right) \Bigg) \\ & + \mathbb{E}[B] P_{ra} \Bigg) \end{aligned} \tag{4.32}$$

where P_{ra} and P_{rs} denote the power consumption of the receiver component in active state and sleep state respectively, T_s and T_p are the time duration in sleep state and probe state for the cyclic sleep mode, and T_t is the trigger time, i.e., the duration of time in idle state after which cyclic sleep mode is initiated. The expressions for $\mathbb{E}[C]$, $\mathbb{E}[\zeta]$, and $\mathbb{E}[B]$ are accordingly calculated as in equations (7), (1), and (6) in [36]. Note that the computation in [36] applies to a standard time-division multiplexing (TDM)-PON. Since we use sleep mode on top of CBI where the traffic is bit-interleaved, the PON receiver needs to be on for a longer duration. We assume a 1.5x overhead on the power consumption applies due to this (this does not apply to the PtP LAN interface).

We take $T_t = 0.1$ ms, $T_s = 10$ ms and, specifically in the PON receiver, $T_p = 250\ \mu$s, which is the time duration for two GPON frames, and in the LAN receiver, $T_p = 24\ \mu s$. The packet sizes are taken as 1500 bytes for simplicity. The average traffic rate is taken as 20 Mbps, from which the packet arrival rate λ in packets per second can be computed. The peak service rate is taken as 1 Gbps (reasoned by gigabit Ethernet), from which the packet service rate μ in packets per second can be computed. The

Table 4.5: ONU sleep mode parameters

	α	S_r	S_t
PON OE optics	0.3%	0.152	0.076
PON OE electronics	52%	0.446	0.292
Digital SoC	50%	0.606	0.345
LAN optics	4%	0.081	0.071
LAN electronics	50%	0.282	0.275

sleep state power P_{rs} is taken as a percentage of the active state power P_{ra} based on the component (5% for optics, 25% for electronics, 30% for digital SoC). As a result, by normalizing $P_{ra} = 1$, we can essentially calculate the savings factor from sleep mode. The wake-up time T_{rw} is also based on the component (1 μs for optics, 100 μs for electronics, 1 ms for digital SoC).

To compute the power consumption of the PON transmitter components with sleep mode, we note that the transmitter is active only for the duration of transmission and is in sleep state otherwise. A small overhead (assumed 1.1x) applies for any control messages e.g., to request bandwidth. The wake-up time for the transmitter to turn on is typically negligible. The corresponding average transmitter-side power $P_{t,\mathit{PON},\mathit{sleep}}$ at the ONU with sleep mode is obtained by adapting [36, Eqn. (9)] as

$$P_{t,\mathit{PON},\mathit{sleep}} = 1.1(\rho P_{ta} + (1-\rho)P_{ts}) \tag{4.33}$$

where $\rho = \lambda/\mu$. The sleep state power P_{ts} is again taken as a percentage of the active state power P_{ta} (same as in the receiver).

Computation of the power consumption of the LAN transmitter components with sleep mode $P_{t,\mathit{LAN},\mathit{sleep}}$ is slightly different because the transmitter (Tx) side on LAN has an additional duty, namely to send the notifications during the probe state, which does not apply for the PON.

$$P_{t,\mathit{LAN},\mathit{sleep}} = \frac{1}{\mathbb{E}[C]}\Bigg(\mathbb{E}[B]P_{ta} + (\mathbb{E}[I] - 2\times T_{tw})P_{ts} + 2\times T_{tw}\left(\frac{P_{ts}+P_{ta}}{2}\right) + e^{-\lambda T_t}\times T_p \times P_{ta}\Bigg) \tag{4.34}$$

$\mathbb{E}[I]$ is calculated from (4) in [36]; P_{ta}, P_{ts}, and T_{tw} take the same values as their receiver counterparts P_{ra}, P_{rs}, and T_{rw} respectively; the other parameters were already introduced above.

Finally, to compute the total savings in the PON interface (considering both receiver and transmitter), we weight the individual savings above according to the power contributions. For OE optics and OE electronics, this is calculated from the detailed split of sub-components. For digital SoC, we assume 50% weight each for transmitter and receiver. The weighted-sum approach holds because of the following: the total PON transceiver power P_8 without sleep can be written as

$$P_8 = P_{r,8} + P_{t,8} = \alpha P_8 + (1-\alpha)P_8 \tag{4.35}$$

where P_r and P_t are power for receiver and transmitter respectively, and α is the weight of the receive power (listed in Table 4.5). If we now apply sleep mode, let us suppose S_r and S_t are the savings factors computed for the receiver and transmitter respectively. Then, the total power with sleep mode $P_{9,hp}$ of the in-home PON components is

$$\begin{aligned} P_{9,hp} &= (\alpha P_{8,hp})\, S_{r,hp} + ((1-\alpha)P_{8,hp})\, S_{t,hp} \\ \Rightarrow f_{9,hp} &= (\alpha S_{r,hp} + (1-\alpha)S_{t,hp}) \end{aligned} \tag{4.36}$$

with

$$hp \in \{HO, HE, HD\} \tag{4.37}$$

In the LAN, we distinguish between optics and electronics (analog electronics + SerDes) to calculate sleep savings in a similar manner. From (4.25), where the first term is the optical power, and taking into account the savings from (4.27), we derive that optics contribute 7 percent to the PtP TRx power, and electronics the remaining 93 percent. Further, we should account for the fact that power shedding was already included in the baseline transceiver power, and the sleep saving factor should only reflect the additional savings from using sleep mode in time periods when power shedding (ps) is not possible. Building on formula (4.10), we can derive the average consumption when sleep and power shedding are combined from that when only power shedding is used as follows:

$$P_{ps+sleep} = P_{ps} \times \frac{P_{sleep}/P_{active} \times 10/24 + 0.1 \times 14/24}{0.475} \tag{4.38}$$

P_{sleep}/P_{active} is replaced by the appropriate factor for optics and electronics derived from Table 4.5 (derivation analogous to (4.36)). Substituting these values in (4.38) and combining with the weights for optics and electronics, this results in

$$\begin{aligned} P_{9,HL} &= P_{8,HL} \times (0.19 \times 0.07 + 0.37 \times 0.93) \\ \Rightarrow f_{9,HL} &= 0.354 \end{aligned} \tag{4.39}$$

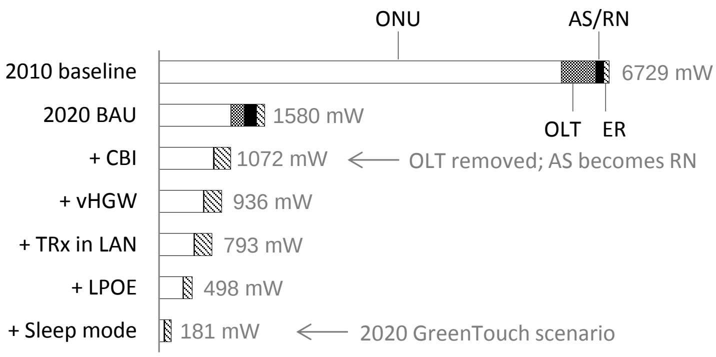

Figure 4.4: *Green Meter results: power per subscriber after sequential introduction of energy-saving technologies. The power per subscriber is 37 times lower in the GreenTouch scenario compared to the baseline scenario.*

OLT sleep modes Sleep savings are less pronounced in the OLT than in the ONU, resulting in an estimated 20 percent savings in digital processing (note that this is co-located with the ER):

$$f_{9,\{TD,TS\}} = 0.80 \tag{4.40}$$

ER sleep modes Sleep savings in the ER apply to the routing functionalities, excluding the contribution from CBI termination (2.5 percent of the power in the numerator of (4.23)). By powering off stand-by elements of the router, 34.6% power savings can be achieved, resulting in the following overall savings in the ER power component:

$$f_{9,ER} = (0.654 \times 0.975 + 1 \times 0.025) = 0.662 \tag{4.41}$$

4.5 Results: power reduction and energy efficiency improvement

When we apply the saving factors in Table 4.4 sequentially, from the top row to the bottom row, we can now easily calculate the *power per subscriber* for a number of access scenarios. Figure 4.4 shows the incremental power consumption reduction resulting from all technologies: first introducing only BAU improvements; then additionally introducing cascaded bit-interleaving (CBI), virtual home gateway (vHGW), the redesigned optical transceiver (TRx), LPOE and finally, introducing sleep mode on top of all the other technologies to reach the GT 2020 scenario.

The results show that the average power consumption per subscriber (considering both the access and metro sections) is already reduced by a factor of 4.3×, cutting 77% of the initial power, when considering only BAU improvements and despite strong traffic growth. This is because standard GPON capacity suffices to serve user requirements up to 2020 in the BAU scenario, and hardware advancements following Moore's law and the use of power shedding strongly reduce ONU power consumption.

Taking energy savings even further by introducing the GreenTouch network architecture and technologies brings together an additional improvement factor 8.7x, resulting in a total power reduction factor 37x, or cutting 97% of the initial power.

While power per subscriber is a good metric to get an idea of the absolute power consumption of the network, it doesn't capture the improvement in network performance that is achieved in the 2020 scenarios. This is why we should also consider the *energy efficiency (EE)* improvement. EE in this context is a measure of the traffic that can be transmitted through the access network per unit of energy consumed:

$$EE = \frac{\text{traffic transmitted (kb)}}{\text{energy consumed (J)}} \tag{4.42}$$

This can be calculated as the total amount of traffic transmitted over a given period (e.g. a year) divided by the total energy consumed in the network in that period, or, equivalently, using the average traffic rates and power consumption values that were given earlier in this work:

$$EE = \frac{\text{average total traffic rate per subscriber (kb/s)}}{\text{power per subscriber (W = J/s)}} \tag{4.43}$$

We make the calculation for the baseline, BAU and GreenTouch scenario in Table 4.6. The factor 257x is the product of three contributions: 4.9x improvement due to traffic increase[7]; 6x business-as-usual improvement; and 8.7x additional improvement from GreenTouch solutions.

4.6 Conclusion

4.6.1 Conclusions of this work

The Green Meter model for fixed access, developed by the GreenTouch consortium, provides an end-to-end framework for the evaluation of various energy-saving approaches in optical access networks, starting from a

[7] If we were to use the 2010 baseline equipment to dimension the network for 2020 traffic load, some components would require more power as shown in line *Power increase due to traffic growth* in Table 4.4, but EE would improve because the nominator in (4.42) increases more than the denominator, so the overall factor is an improvement in EE.

Table 4.6: Energy efficiency improvement in BAU and GreenTouch scenario

	2010 baseline	2020 BAU	2020 GT
Average DS+US traffic rate per subscriber (kb/s)	138	955	955
Power per subscriber (W)	6.73	1.58	0.18
Energy efficiency (kb/J)	21	604	5271
Improvement factor	-	29x	257x

baseline scenario in 2010 and providing estimates for future scenarios in 2020.

In this paper, we described the model in detail, showing how the network power consumption is broken down into components (ONU, OLT, AS, and ER) and sub-components (optics, electronics, and digital processing), to which appropriate saving factors are applied. Estimates for all saving factors were given (Table 4.4) and motivated. We emphasized that the saving factors in Table 4.4 can only be applied sequentially due to complex interactions between the strategies. However, from the detailed description in the text the net effect of individual strategies can be derived.

The main outcome of this model is the evaluation of energy efficiency for two optical access scenarios for 2020: business-as-usual (BAU) and GreenTouch (GT).

In the BAU scenario current trends in energy efficiency are continued until 2020 without specific focus on reducing the energy consumption of access networks. This scenario incorporates Moore's law, power shedding, efficient hardware design, and efficient cooling. As a result, power per subscriber is reduced 4.3-fold with respect to the 2010 baseline power, and energy efficiency (taking into account traffic growth) improves 29-fold.

The ultimate goal of this analysis was to see what savings are possible if more attention is paid to energy efficiency in the future network design. In the GT scenario, on top of BAU improvements we introduce a cascaded bit-interleaving (CBI) architecture, virtual home gateway (vHGW), redesigned point-to-point (PtP) transceiver (TRx), low-power optics and electronics (LPOE) and sleep modes. As such, the power per subscriber is reduced 37-fold with respect to the 2010 baseline, and energy efficiency improves 257-fold, showing that an emphasis on green network design can indeed have a huge impact on network energy consumption.

4.6.2 Future work

Even though this work provides a comprehensive study of the potential for power reductions in the optical access network as we see it today, future expansions of the model will surely be needed as novel technologies and applications are developed and introduced in the rapidly evolving market of telecommunications, and may drastically alter network conditions (examples include 5th generation mobile networks (5G) and the convergence of fixed and mobile access networks, novel media distribution applications, and mobile-edge computing (MEC) bringing cloud-computing capabilities closer to the end user).

Acknowledgments

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5

Post-peak ICT: Graceful degradation for communication networks in an energy constrained future

In this chapter, network energy consumption is approached from a slightly different angle, taking into account the effects of energy supply insecurity in a "post-peak" future. The work sets out guidelines for research in this new domain, and gives a concrete example of a post-peak strategy for wireless access networks.

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Abstract In recent years, rising energy prices and increasing environmental concerns have boosted research in the so-called *green information and communications technology (ICT)* and *green networking* research tracks, aimed at improving the energy efficiency of communications while still offering

maximal functionality. In this paper we explore a future scenario in which low power networking is no longer optional, but instead becomes a necessity due to fluctuating energy availability. The contribution of this work is twofold. First, we argue why a so-called *post-peak* future scenario — in which we can no longer rely on fossil fuels as our main resource for electricity production — is not unlikely, and what it might entail. Second, we explore the consequences of such a scenario for ICT: how well can current and future infrastructures cope with temporary energy limitations? As an illustration, we present a case study showing the impact of reduced energy availability on a wireless access network.

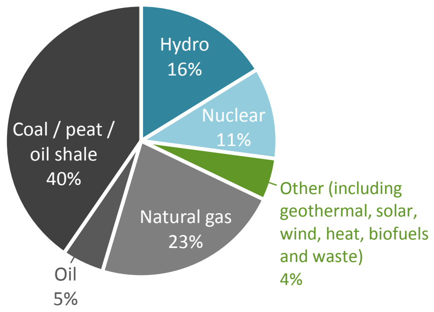
5.1 Introduction

In this paper we consider a *post-peak* future scenario, in which fossil fuels are no longer the main energy source for electricity production (fossil fuels are "past their peak"), but instead are increasingly replaced by alternative energy sources. We start our description below by motivating why a post-peak scenario may be imminent, and how this could result in temporary energy restrictions for ICT networks. Next, we outline a framework to evaluate the post-peak potential of technologies (Section 5.2), and propose new avenues of research to prepare ICT infrastructures for a post-peak situation (Section 5.3). In a specific case study for a wireless access network, we modified a wireless planning tool to make optimal use of energy in a post-peak situation (Section 5.4).

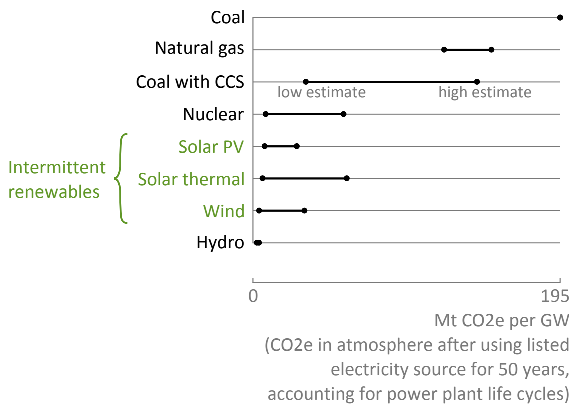
5.1.1 Why should we anticipate a post-peak future?

Present-day societies and economies run mostly on fossil fuels. Oil (petroleum), coal and natural gas made up 82% of the world's primary energy supply in 2012, and 68% of electricity was generated by burning fossil fuels, as shown in Fig. 5.1a.

It is likely that in the coming years, societies will be forced to move from fossil fuels to alternative sources for their energy supply. We see three reasons why this may happen in the near future, in order of increasing importance: fossil fuel depletion, security of energy supply and the impact of fossil fuels on climate change. Some scientists argue that current trends in fossil fuel consumption will result in a peak of conventional oil production before 2030 (referred to as *peak oil*), leading to a global fuel shortage and steep increase in oil prices [1]. Whether this peak oil will indeed occur in the near future is a contested point in scientific literature, but even adversaries of the peak oil theory agree that political instability in oil-producing coun-



(a) Worldwide fuel shares of electricity generation in 2012 (source: Key world energy statistics by the International Energy Agency, published in 2014).



(b) Carbon footprint of various electricity sources (high and low estimates taken from [4]). CCS = carbon capture and storage.

Figure 5.1: *In order to reduce the carbon footprint of electricity generation, the share of fossil fuels must be reduced, and intermittent renewables (solar photovoltaic, solar thermal and wind energy) will need to contribute a bigger share in the energy mix.*

tries can result in severe oil price shocks, which have devastating effects for fossil fuel-based economies [2]. This brings us to the second argument: security of energy supply. Countries that switch to renewable energy sources reduce their vulnerability to the above oil price shocks [3]. Lastly and most importantly, if policy makers take the climate change challenge seriously, renewables offer one of few virtually carbon-neutral alternatives to fossil fuels (see Fig. 5.1b).

Nuclear energy could make an increasing contribution to low-carbon energy supply, but a variety of barriers and risks exist: not only is it costly compared to alternatives, particularly when the high risks involved are factored in; a nuclear power renaissance would also increase the risk of nuclear terrorism and make efforts to control the spread of nuclear weapons much harder.

Due to their intermittent nature, renewables replacing fossil fuels will not be able to offer the same supply continuity as present-day energy provisioning systems. Some of the most mature renewable energy technologies that can be deployed at a large scale and at a relatively low cost, such as wind and solar energy, have varying outputs that depend on fluctuating weather conditions.

Since operation of the electricity grid requires energy production and energy consumption to be in balance at all times, low production periods must either be matched with low consumption, or the production deficit must be compensated with previously stored energy and/or energy imports. In an ideal smart grid scenario, temporary low production can be matched on the demand side by postponing non-urgent energy consumption from homes and industries. The intermittency of renewable sources could also be (partly) compensated for by constructing large energy storage facilities, using e.g. hydro pumped storage or batteries; or by interconnecting production capacities over a large geographical area, taking advantage of weather locality to reduce the chance of an overall low production.

However, upgrading the power provisioning system will take time, as it requires a widespread introduction of smart meters and controllable devices, and the construction of large energy storage facilities and long-distance high-capacity power lines. Meanwhile the consequences of the transition away from carbon-heavy and nuclear sources may already manifest themselves in the very near future: looming electricity shortages have been reported in news outlets of several developed nations in the past year (e.g. Belgium, Germany, the United Kingdom and Japan). Moreover, even once future utility networks are properly dimensioned, there may still be temporary power shortages in rare periods of exceptional weather conditions.

To conclude this motivation, we remark that even though we can't be certain that we are headed for an energy intermittent future, the outlined trends indicate that the possibility is real, and we can only deal with the consequences properly if we are prepared. Even today, this knowledge could already be useful in other energy-constrained situations, such as disaster recovery or off-grid installations in developing countries, to make optimal use of the energy available in emergency generators and backup batteries.

5.1.2 Consequences for ICT

When there is a drop in energy production (lasting from a couple of hours to several days), and the energy gap can't be filled by burning abundant fossil fuels, governments may impose temporary restrictions on power consumption to avoid a collapse of the grid. A number of measures can be taken: cutting off (geographical) clusters of consumers[1], applying dynamic pricing schemes that reflect energy availability[2], or forcing large energy consumers to curb their consumption.

If governments decide to impose energy restrictions on large consumers, ICT service providers and telecom operators will also be targeted, as their extensive infrastructures use considerable amounts of power. For example, Telecom Italia is Italy's second biggest electricity consumer, and British Telecom consumed 0.76% of the U.K.'s national electricity consumption in 2011/12, making it the largest single electricity consumer in the country. Globally, the share of communication networks in total electricity consumption is around 1.7%; data centers contribute another 1.4% [5].

Evidently, pulling the plug on ICT infrastructure altogether is not a desirable option as it supports several critical applications. But some of the services on offer may be more dispensable than others (e.g. omnipresent broadband Internet access vs. lifeline communications). Therefore we introduce the concept of *graceful degradation* under energy constraints: if the available energy for ICT is drastically reduced — falling back to 50%, 25% or a mere 10% of regular power levels — can we still offer a minimal functionality and connectivity? In order to answer this question, we need to determine what part of the functionality is truly indispensable, and how much power is needed to keep it running. This will be the focus in our evaluation of ICT technologies in the post-peak context.

5.1.3 Related work

This is a relatively new research domain as we are only just starting to see the signs of an impending post-peak future. The most notable existing work in the field is by B. Raghavan: his 2011 publication [6] was the first to consider the implications of a permanent energy crisis for ICT, listing a number of post-peak design principles and research questions. The main

[1] For example, the Belgian government installed a "disconnection plan" (Dutch: afschakelplan) after the unforeseen shutdown of two nuclear reactors in 2014. The plan allows the electricity provider to temporarily cut off clusters of consumers when demands exceed supply, for example during peak hours (17h-20h) on a cold winter day.

[2] Throughout this paper, when we talk about energy restrictions or shortages, this does not necessarily mean there is no energy available at all, but rather, that scarcity can make it prohibitively expensive.

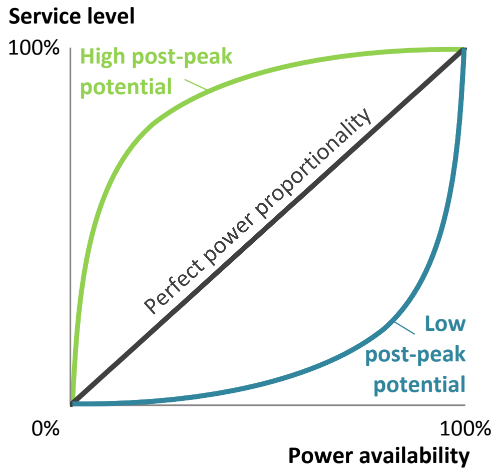


Figure 5.2: *Depending on how their service level scales with power availability, technologies may have* high post-peak potential, *offering relatively good service for a fraction of their normal power, or* low post-peak potential, *losing service level rapidly even for a small power reduction. This relationship is influenced by the choice of service level metric, which can be based on criteria such as speed, reliability, user coverage, etc.*

difference with our work is that Raghavan considered a scenario where energy demands would exceed supply overall and the current Internet architecture could no longer be used, whereas we focus on dealing with short term energy limitations, assuming the current network architecture is still in place and functioning normally most of the time.

5.2 The concept of graceful degradation

In a post-peak context, we want to know how the delivered service level of a network or device scales with the available power. Three generic power profiles are shown in Fig. 5.2. Without graceful degradation, the delivered service level will quickly drop to (almost) zero when the available power decreases, as indicated by the lower line in Fig. 5.2. These infrastructures have *low post-peak potential*, as they are unable to function under energy constraints. The upper two lines in Fig. 5.2 represent devices or networks that do allow graceful degradation: in an infrastructure with perfect power proportionality, the service level decreases at the same rate as the available power; infrastructures with *high post-peak potential* are able to offer a high service level even if the available power is decreased a lot.

As we will discuss in more detail in Section 5.3, a low post-peak potential is typically associated with dedicated devices, whereas a high post-peak potential is typically available when multiple resources can be flexibly shared. The shape of the power profile of the device or network under study depends on the power proportionality that it exhibits, as well as on how its service level metrics are defined, as explained below.

Power proportionality — In Fig. 5.2, 100% power availability corresponds to what the device or network consumes in a normal energy situation to offer maximal service. This maximum power consumption will depend on the specific equipment under study, and whether it uses current (energy-hungry) or future (greener) technologies. The profile is also influenced by the impact on power consumption of a service reduction. Currently deployed networks typically exhibit a power consumption that is relatively constant despite strong diurnal variations in the traffic load or service, corresponding to the lower curve of Fig. 5.2. Reducing the maximum power consumption and improving the power proportionality (making power consumption scale with load, e.g. through load-adaptive network operation) have been important tracks in green ICT research [7], and will become even more important when targeting graceful degradation for post-peak ICT.

Service level metrics — For a given device or network, the power profile will also depend strongly on the metrics used to define the service level. This can be a quantitative assessment, based on a weighted function of data throughput, bandwidth, uptime, error rate, user coverage, computation capacity, etc.; or it can be more qualitative, when certain applications or services are considered critical and thus part of the *minimal service*, while others are dispensable. For an existing example of graceful degradation, consider a smartphone with a battery that is running low. Certain applications, such as the camera functionality, may be temporarily disabled to ensure that the minimal service, texting and making phone calls, is guaranteed for as long as possible. If we define the service level of the smartphone as the number of calculations per second, the service under energy constraints may be quite poor, but if we define the service level as the ability to communicate, it is still relatively high.

5.3 Graceful degradation in ICT infrastructures

In this section we assess the potential for graceful degradation in various ICT infrastructures. We start by introducing some terminology concerning the areas under study; next we look into specific solutions for each of these areas.

5.3.1 Overview of ICT infrastructures

Fig. 5.3 gives an overview of a typical network infrastructure. The access network provides a physical connection to the end users through which they can connect to the Internet. In *fixed access networks*, a physical wire runs to the end user's premises, where the signal is decoded by a modem and distributed further in the local home or enterprise network. In *wireless access networks*, subscribers use standardized radio signals to connect to the nearest base station (BS), from where the signal is forwarded through a dedicated backhaul link to an aggregation point. Traffic from the access networks is aggregated and transmitted further through the backbone or *core network*, which provides high-capacity, low-latency connections across large geographical distances .

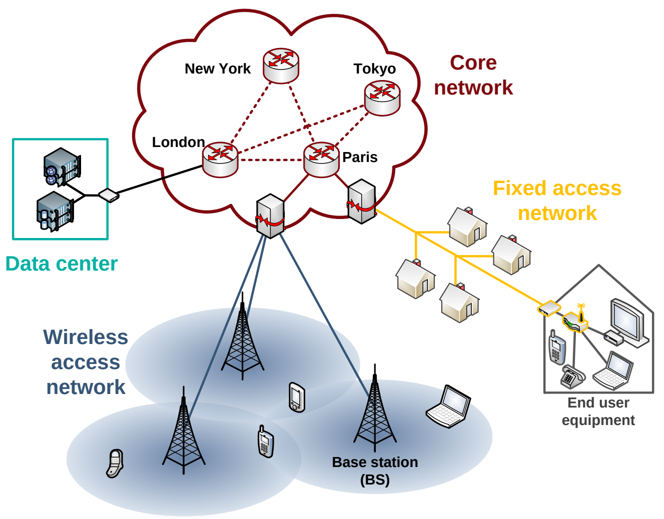
The focus in this paper is on devices that can be controlled centrally by the Internet service provider (ISP). This means that, despite their significant contribution to ICT power consumption, end devices controlled by the consumer such as TVs, personal computers or mobile phones are outside the scope of this work. Modems, routers and wireless access points (APs), installed at the customer premises, may be considered part of the fixed access network, depending on whether they can be controlled remotely by the ISP. *Data centers* can also be controlled centrally, and form the last important contributors to network power consumption. These facilities house large numbers of computer and storage systems to host a wide range of applications, from websites over search engines to cloud computing.

5.3.2 Field-specific solutions and limitations

In the following, we explore the opportunities and limitations for graceful degradation in the four fields introduced above. The list of proposed measures is by no means exhaustive, but rather intended as a starting point for further research. While we discuss the solutions for these fields separately, post-peak strategy design should also keep a holistic overview of the interactions between different fields, and see whether some services can be substituted for others. For example, guaranteeing both wired and wireless connectivity may not be feasible under certain energy constraints, but as long as one of the communication channels remains available, this may be sufficient as a minimal service.

5.3.2.1 Fixed access networks

Since most of the power in fixed access networks is consumed by the customer premises equipment (CPE) [8], this is where we direct our first efforts



Examples of post-peak power reduction measures
Fixed access network
• Improve customer premises equipment (CPE) power proportionality
• Centralized control of CPE power states
Wireless access network
• Selectively switch off some BSs, based on different strategies:
– lowered capacity or reduced covered area
– support fewer wireless technologies
Core network
• Reduce level of resilience or overprovisioning
• Change of virtual topology
• Block specific traffic
Data center
• Reschedule user requests:
– to a later time
– to another location

Figure 5.3: *Schematic of the network showing the areas under study (fixed and wireless access networks, core networks and data centers), along with examples of post-peak solutions for these areas.*

to try and optimize the use of limited power resources. Currently deployed modems, wired and wireless routers typically show bad power proportionality with respect to data rates, corresponding to the low post-peak potential profile in Fig. 5.2.

However, if we define the service level as the number of customers being served, and consider the power consumption of the access network as a whole instead of on a single device level, switching off a selection of CPEs will scale down power consumption as the service level decreases, corresponding to a more power-proportional profile (the straight line in Fig. 5.2).

Depending on how the minimal service is defined, several strategies can be used to power off a well-chosen selection of access equipment. A *time division based strategy* could divide the access network into regions, and assign time slots for each region when connectivity would be available, powering off all access equipment in that region for the remaining time. This would give users periodic, deterministic access to the network. Alternatively, in dense urban networks a *wireless ad hoc strategy* could be applied, taking advantage of the relatively dense deployment of wireless APs. Here, a large fraction of the modems and APs could be powered down, while almost complete wireless coverage of the area (at reduced data rates) could be maintained by connecting users to neighboring hot spots. Note that for these strategies to work, the network provider should be able to power down modems and routers remotely.

In larger office environments, local area networks (LANs) can be structured so that *less critical parts* can be selectively powered off while critical connections are maintained.

5.3.2.2 Wireless access networks

In wireless access networks, BSs are the main power consumers. The power consumption of a single BS does not scale well with the traffic load, corresponding to low post-peak potential in Fig. 5.2. As a consequence, just as in fixed access networks, the only way to reduce power consumption in current networks is by switching off some of the equipment and looking at the service level on the network scale instead of the device scale. We propose two strategies for BS switch-off below, designed to get the maximum possible service out of the limited available energy during a post-peak shortage.

The first is to *cut capacity by reducing network density*. There is a trade-off between the capacity and the range of a single BS: for a given input power, decreasing the capacity (bit rate) results in longer ranges and thus a larger area covered by the BS. In a post-peak situation, the capacity per user can be limited so that the required network capacity would be reduced and, since the range of the BSs in a low-capacity network is bigger, the number of active BSs could be decreased. The achievable savings are calculated for a realistic case in Section 5.4. Depending on what fraction of the normal operating power is available, this strategy may result in reduced coverage. A wireless ad-hoc functionality for emergency communications, where information can be relayed through other end users' devices to reach the access network, may be worth investigating.

The second strategy is to *fall back to single-standard support*. In current mobile networks, overlapping coverage is offered for different standards. The most widespread technology is the second-generation (2G) standard global system for mobile communications (GSM). Third-generation (3G) universal mobile telecommunications system (UMTS) and fourth-generation (4G) long-term evolution (LTE) sites are often built at pre-existing 2G sites to increase peak data rates and the maximum number of user connections. During a post-peak temporary energy shortage, power consumption may for example be decreased by disabling the 3G and 4G BSs, falling back to the GSM network (GSM is currently still the most widely supported technology on handsets). This could result in a drastic reduction in power consumption, since BS consumption is similar across technologies (in the order of 1-2 kW/BS) [9]. For subscribers, this measure would result in a noticeable reduction in quality of experience, as network capacity and peak data rates would be reduced; but coverage would still be guaranteed.

5.3.2.3 Core networks

During a post-peak shortage, the traffic load in the core network will decrease significantly as a consequence of traffic reductions realized in access networks and data centers. Unfortunately, because of the current weak power proportionality in response to changes in the traffic load, the power consumption in the core network will remain almost constant, once again corresponding to a low post-peak potential profile in Fig. 5.2. In future deployments we might see new equipment and techniques that improve power proportionality, such as bit rate variable transponders and power aware routing schemes that increase the potential for sleeping interfaces [10]. In anticipation of these developments, we can think of four other approaches that could keep core networks running under post-peak power reductions.

The first is through *reduced resilience*. Typically, protection mechanisms are in place to almost instantly switch traffic over a secondary path in case of a link or node failure. Turning off backup equipment could reduce power consumption by a factor of two. As a result, recovery would not be instant (within 50 ms) anymore, but would take a couple of seconds when a recovery path is discovered and set-up automatically, or several minutes or hours when links need to be brought back online manually (in case of insufficient capacity). A second, similar approach is to *temporarily reduce the overcapacity* that is installed to handle peak-to-mean traffic variations and unexpected traffic spikes [11]. This could decrease power consumption in the core by another factor of two (or more). However, unexpected traffic spikes would no longer be handled flawlessly and traffic bottlenecks would occur in anticipation of extra capacity being (manually) brought online. Third, we could *change the virtual network topology*. Several works have indicated that, with traffic demands currently being higher than the equipment line rates, fully-meshed virtual (IP) topologies are more energy efficient than ring topologies [12]. Further research is needed to investigate what topology (mesh, ring, etc.) would be most efficient in a post-peak scenario with reduced traffic demands, and how it would affect latency. The fourth and last approach we propose is *blocking service-specific traffic*, where non-critical services are temporarily blocked in the core, insofar as this is not already done at the network edge. This technique could also be used to reduce traffic demand to a level where a topology reconfiguration (introduced above) can bring additional savings.

5.3.2.4 Data centers

In [13], the authors discuss how data center management should be revised to maximize the use of off-grid renewables. These techniques can be adapted for use in a post-peak scenario, taking into account the more restrictive energy limitations. Below we list a number of ways to temporarily reduce the workload in data centers. Note that these measures can only reduce power consumption significantly if the data center manager is able to plan capacity by turning off selected groups of machines when the load is reduced, thus achieving high post-peak potential (cf. Fig. 5.2).

The first logical step is to delay system maintenance tasks such as system updates and backups. Incoming user requests can also be *rescheduled* to a later time or *migrated*, if possible, to another location where energy is more abundant. If workloads cannot be migrated but must be reduced, a *priority label* could be given to the most critical data and services, which would then be placed on machines that are kept on at all times to guarantee the minimal service. This priority label could be assigned manually based on service level agreements (SLAs) with customers, or automatically to the most frequently accessed content. Alternatively, all user requests could be handled with the same priority, but with less resources, keeping all services available, but at the cost of longer response times, including that of

Figure 5.4: *The selected suburban area of 6.85 km^2 in Ghent, Belgium. Users are located on the yellow dots; squares indicate base station (BS) sites. As an illustration of the sleep mode principle, the active and inactive BSs for a simulation with 70% available power and random user distribution are colored green and red, respectively.*

critical services.

5.4 Case study: wireless access network with reduced power

5.4.1 Realistic scenario for a suburban area

As a concrete case study, we evaluate the post-peak potential of a wireless access network by simulating an LTE (4G) network in a suburban area of Ghent, Belgium. Fig. 5.4 shows the selected area together with the locations of the 35 simulated BS sites (based on real BS positions), and Table 5.1 lists the LTE characteristics.

We assume 224 candidate users who want to be simultaneously active, each requesting 64 kb/s, which is more than enough to make a phone call. The location of the users within the selected area is known (a realistic mix of indoor and outdoor users is assumed), but the order in which they connect to the network varies randomly across simulation runs. A heuristic deployment algorithm, based on the one described in [14], chooses which BSs are active and which are in sleep state. The objective of the algorithm is to maximize the number of active users, i.e. users connected to an active BS, by switching BSs on and off in response to the simulated user locations and load, and setting the power level for each BS based on its optimal

Table 5.1: Properties of the considered LTE (4G) radio technology.

Property	Value
Carrier frequency	2600 MHz
Channel bandwidth	5 MHz
Minimum power/active BS (antenna input power 1 dBm)	1204 W
Maximum power/active BS (antenna input power 43 dBm)	1672 W
BS power in sleep state	
- scenario zero sleep power	0 W
- scenario 45% sleep power	752 W
(Coding rates) Modulation schemes	(1/3, 1/2, 2/3) QPSK
	(1/2, 2/3, 4/5) 16-QAM
	(2/3) 64-QAM
Bit rate/BS [1/3 QPSK - 2/3 64-QAM]	2.8 Mb/s - 16.9 Mb/s
Range/BS [1/3 QPSK - 2/3 64-QAM] (NLOS*, @43 dBm)	1090 m - 194 m

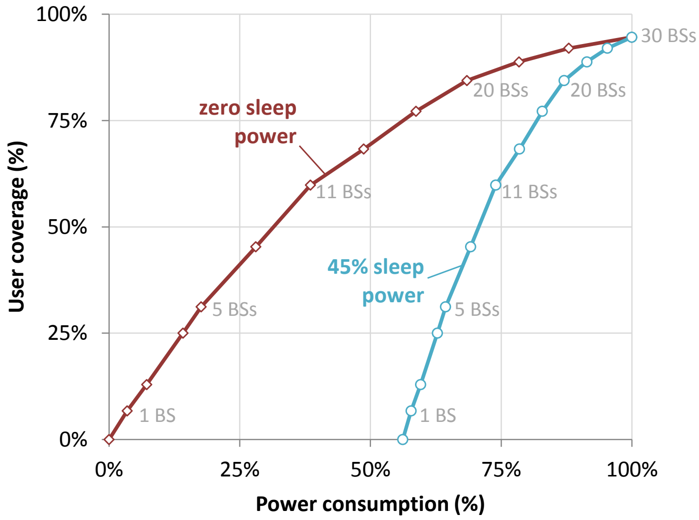
* NLOS: non-line-of-sight.

reach. The original algorithm in [14] was designed to achieve a predefined QoS and coverage with minimal power consumption. In the post-peak version, we introduce an additional constraint: the overall power consumption (summed over all BSs) cannot exceed a pre-defined power budget. This may result in some loss of QoS and coverage.

We consider two scenarios for the power consumption of BSs in sleep mode: perfect sleep, where a sleeping BS consumes no power; and a more realistic sleep power, which would typically be around 45% of the maximum power [15] (see Table 5.1 for values).

5.4.2 Simulation results

The heuristic deployment algorithm is applied to the area under study with varying constraints on the overall power consumption. This results in the power profiles shown in Fig. 5.5, where each simulated point corresponds to the median of 40 simulation runs. The horizontal axis in Fig. 5.5 shows the network power consumption as a percentage of the maximum power consumption (100% = power for a network optimized for maximum coverage). The vertical axis shows the service level, which can be defined using two different metrics. The *user coverage* indicates the percentage of users that can get the minimum bit rate they are requesting from the active BSs (in this case, 64 kb/s). The *geometrical coverage* indicates the percentage of the (outdoor) area that can be reached by signals from the active BSs at the lowest coding rate and modulation scheme (1/3 QPSK), offering a bit rate of 2.8 Mb/s per BS (see Table 5.1). User coverage is a more strict metric, as a geographical location may be within range of a BS while a user in that location may not be covered as such, due to an uncovered indoor position



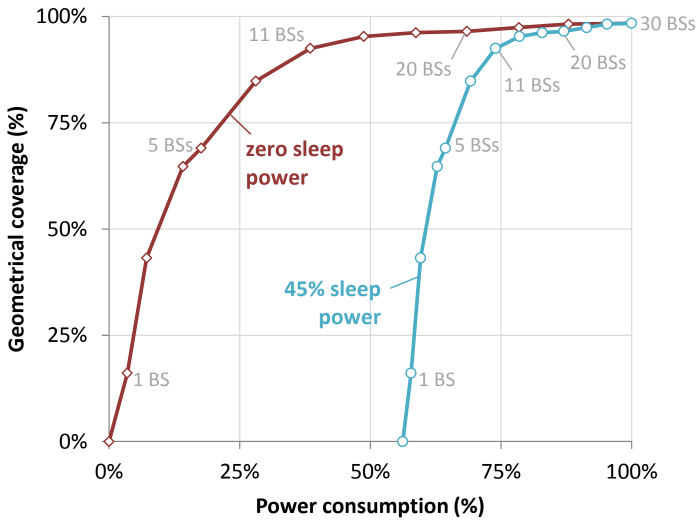


Figure 5.5: *Simulation results of the wireless case study for LTE (4G) technology. When base stations (BSs) consume negligible power in the inactive state (zero sleep power, dark red lines), both user and geometrical coverage have high post-peak potential. When BSs require a significant fraction of their maximum power in sleep state (45% sleep power, light blue lines), most of the post-peak potential is lost.*

or capacity limitations of the BS.

When BSs consume negligible power in the inactive state (zero sleep power, dark red lines in Fig. 5.5), the post-peak potential for user coverage is limited: when 25% of the power is available, user coverage for LTE is only around 30-40%. The power profile for geometrical coverage looks more promising, since about 75% coverage can be guaranteed with only 25% of the power. This is because once most of the area is covered, the energy cost of adding geometrical coverage increases as filling a small coverage gap will still require a complete additional BS to be switched on, and the minimum power per BS is 1204 W (cf. Table 5.1).

The geometrical coverage could be considered the fraction of users that can be served when only outdoor coverage is guaranteed and extremely low data rates are allowed, offering basic communications such as text messaging. Depending on how the minimal service is defined — should it include voice communications and possibly even low-data rate exchange; what about indoor coverage? — one could opt for higher geometrical coverage (avoiding large outdoor coverage gaps) or better user coverage in densely populated areas (leaving large coverage gaps in remote areas, but keeping indoor coverage and higher rates available in urban areas).

When BSs require a significant fraction of their active power in sleep state (45% sleep power, light blue lines in Fig. 5.5), most of the post-peak potential is lost: 56% of the maximum power is still needed even when *all* BSs are in sleep mode (= minimum network power consumption) and thus no service at all is offered. Note that theoretically only 45% of the power would be needed if the network were perfectly dimensioned and all BSs were switched on at maximum load. However, activating 30 out of 35 BSs sufficed to reach the maximum attainable coverage for maximum load; hence the 100% power consumption already corresponds to the consumption of 30 active and 5 sleeping BSs. In any case, the post-peak potential of a deployment with relatively high sleep power is clearly insufficient, as no service at all can be offered when energy availability is temporarily below 50%.

5.5 Conclusion

5.5.1 Conclusions of this work

We studied the effect of post-peak energy shortages on various ICT infrastructures: fixed and wireless access networks, core networks, and data centers. We assessed whether these infrastructures could still offer a basic functionality when the available power was significantly lowered compared to normal operating conditions.

We distinguished between low and high post-peak potential infrastructures and devices (Fig. 5.2). Based on the ICT fields we studied, we conclude that the post-peak potential on a single device level is typically low: most devices are unable to offer half of the normal service (defined as number of calculations, data rate, etc.) when the available power is halved. Therefore, the post-peak potential of dedicated devices to which users are statically assigned, is very limited. In networked environments on the other hand, when users share resources and *flexible* resource assignment is possible, the post-peak potential on a wider scale can be much higher. For example, this is the case in large-scale data centers or wireless access networks, where some of the capacity can be temporarily disabled while still offering a minimal service to all users.

We also considered the concrete case of a suburban wireless access network under varying energy constraints. Simulation results showed that the post-peak potential can only be realized if low power modes are truly low-power and inactive BSs consume negligible power. This is in contrast with present-day sleep modes for BSs which typically consume around 45% of the active power.

5.5.2 Moving forward

This is a relatively new research domain, and though we touched upon a number of strategies already, handling a post-peak situation will no doubt require further research into a broad range of applications and domains. When investigating post-peak features, there are a number of pitfalls that need to be kept in mind.

A first issue is that indirect effects of a post-peak situation on user behavior are hard to predict. For example, offering a slower service could lead to a reduced load if users give up non-urgent activities in response to the reduced quality of experience, but it could also increase the load if users' connection times are increased due to the slower service. Indirect effects on user behavior could also be used to enhance post-peak savings, for example by suppressing TV signals for the indirect effect of having less television sets switched on. Interdisciplinary research is needed to predict these kinds of effects.

A second important issue is that systems will become more vulnerable at the time of energy shortages. While solutions should be chosen carefully to minimize vulnerability, some loss of reliability during a post-peak energy shortage will be inevitable: we should keep in mind that a minimal service level is still preferable to no service at all.

Last but not least, ICT is not only an important power consumer, it can also play a key role in controlling the power consumption of other loads. In a post-peak future, a *smart grid* that gathers information about suppliers and consumers and helps control them, will be an important instrument to balance electricity supplies and demands. This is being studied in a dedicated research track, considering incentives that shape consumer behavior and opportunities for automated power control. Post-peak measures for ICT specifically will need to guarantee the exchange of smart grid control signals. Further research is needed to assess how smart grid control can be set up independently from existing communications infrastructures, or how it can be guaranteed as part of the minimal service.

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6 Conclusion

This chapter summarizes and links together the main conclusions from the previous chapters in Sections 6.1-6.4, and provides pathways for future research on these topics. Section 6.5 puts these conclusions in a broader frame, considering the impact of human society on the environment and the need to bring sustainable development into practice.

6.1 Worldwide electricity consumption of communication networks

In the past decade a great deal of research has been conducted, aimed at improving the energy efficiency in communication networks. This research is motivated by the fact that the manufacturing and operation of communication networks is contributing significantly to human greenhouse gas (GHG) emissions. Just how significant this contribution was, was not clear at the beginning of my PhD.

We developed a methodology to estimate the worldwide electricity consumption in communication networks. It starts from the total energy consumption of telecom providers and attributes this power consumption to different services. By combining these numbers with worldwide numbers of subscriptions, an estimate for the global electricity consumption in communication networks is obtained. This approach avoids problems with overheads and network diversity (the need to consider every technology in use, every user profile, every geography, etc.) that arise when trying to estimate the network consumption by summing the power of individual network components. Our approach does however have a drawback: it is not possible to assign the total power consumption to specific network sections and functions.

The methodology is not only applied to data for the year 2012, but also to historical values for the period 2007-2012. This provides us with valuable insight in the evolution of network electricity consumption, which, fueled by growing numbers of subscribers and ever-increasing bandwidth demands, is growing fast, at a rate of about 10% per year. A comparison with the total worldwide electricity consumption shows that networks took up a share of 1.8% by the end of 2012. In absolute numbers, networks consumed over 350 TWh in 2012, which is more than four times the electricity consumption of the whole of Belgium in that same year.

These results clearly confirm the relevance of green networking research, and provide a baseline that can be used when evaluating the global effect of introducing new green technologies, as estimated savings can now be compared to the overall network consumption.

Comparing our results with previous studies on the topic revealed a large spread on the power consumption values reported in literature. This brings us to one big challenge that remains: while the methods used to make these estimates are exact, the input data often comes with large or unclear error margins — for example, the reported electricity consumption values by telecom operators are not always based on measurements, and their methods to estimate them are rarely disclosed. Nevertheless, the emerging trend is clear enough to state with reasonable confidence that the impact of networks on the environment is growing rapidly, and that actions to reverse this trend should be encouraged.

Future work The study presented here is an update of an earlier study by our research group, which was published in 2008. In a domain that evolves as rapidly as information and communications technology (ICT), regular updates will also be required in the future if we do not want our estimations to become out-dated, and if we want timely feedback on the evolution of growth rates in network consumption. Further, while this study is limited to the use-phase electricity consumption, a full life-cycle approach would definitely add value to the results, although it would be challenging to perform and would require collaboration across scientific disciplines.

6.2 Energy efficiency of next-generation PONs

To reduce the footprint of communication networks, end-to-end solutions are required that bring down power requirements in all sections of the network. In this dissertation, our attention was directed to optical access, as the access is currently the most power-consuming part of optical (fixed) networks. passive optical networks (PONs) are the most popular type of optical access networks, with several types already fully defined in standards and being commercially deployed, while other types were in the pipeline for standardization when we started working on an energy efficiency model for optical access.

There was a need for a redesigned comparison of energy efficiency between PON technologies, since previous studies on the topic, which were typically focusing on component power to estimate power per user values, had their shortcomings. First, it was difficult to compare reported power consumption values per user directly as the technologies offered different maximum speed capacities and reach — there was a need to somehow include quality of service (QoS) metrics in the comparison. Second, it was unclear how well these theoretical estimates would translate to a realistic deployment, as constraints on reach and equipment distribution in the field may result in lower efficiency than the theoretical best-case estimate.

Our proposed model is a network dimensioning and power calculation approach that can be adapted to the specific qualities of various PON technologies. It takes into account user demands (provided services and bandwidth) and simulates statistical gain of dynamic bandwidth allocation in combination with split ratio optimization to make optimal use of the capacity and reach of each technology, while minimizing the power per user. Moreover, the model maps each technology to a realistic city deployment scenario to take into account the implications of technology-dependent physical reach, as the geographic spread of central office (CO) and customer locations may impact the degree of equipment sharing and thus power consumption.

The model is applied to six next-generation PON technologies[1], and a baseline gigabit-capable passive optical network (GPON) deployment. Our results show that there is a threshold (close to 1 Gb/s per user) for access rates beyond which NG-PON2 technologies become the more energy-efficient option. The outcomes also confirm the need for a model such as ours that considers split ratio optimization, as taking this into account alters the conclusions on which technology is more energy efficient.

[1] 10 Gb/s capable passive optical network (XG-PON1) which was already standardized at the time, and five of the next-generation passive optical network 2 (NG-PON2) candidates for standardization in 2012.

Future work Besides allowing a side-by-side comparison of PON technologies, the results also made it painfully clear that the next-generation technologies, as presented in this work, would require a lot more power per user than the baseline GPON to support projected traffic increases. Although these bandwidths are very high indeed — it will be a while still before we reach the 1 Gb/s threshold — this signals the need to not only choose the optimal technology, but also to implement more radical solutions to save energy, if we are to reduce the impact of networks in the future instead of increasing it further. The optical network unit (ONU), installed at the customer premises, is the most power-hungry device, so efforts to save energy will definitely be needed on this front. These issues are addressed in the following chapter, where power saving techniques for the ONU and other network nodes are combined to realize an optical access architecture with optimal energy efficiency.

6.3 GreenTouch final results for optical access

The GreenTouch architecture is designed from the ground up with energy-efficiency in mind. It is able to offer high bandwidths at a lower energy cost by combining various energy-saving approaches developed by partners in the GreenTouch consortium.

In Chapter 4 several approaches are combined to bring the power consumption of the ONU down: traditional home network interfaces are replaced by a novel point-to-point (PtP) optical transceiver (TRx), sleep modes are used during idle periods, home gateway functionality is virtualized at a central location, and the bit-interleaving protocol enables traffic processing at a lower rate.

Bit-interleaving (BI) PON was one of the technologies taken into consideration in Chapter 3, but did not come forward as the most energy-efficient option in the comparison made there. By extending the access reach to the aggregation network, and considering an upgraded version of this protocol, cascaded bit-interleaving (CBI), it can however become part of an optimal solution, by allowing more centralized equipment sharing and letting a simple remote node replace the aggregation switch (AS).

We created a model that integrated business-as-usual (BAU) improvements (expected to occur even if no special attention is paid to energy efficiency) along with more far-reaching improvements (including the ones introduced above, and others applying not just to the ONUs, but also to the rest of the network). The outcome showed that the power per subscriber can be reduced 37-fold with respect to the 2010 baseline, and energy efficiency can be improved 257-fold, thereby proving that drastic energy savings are indeed possible despite strong traffic growth in the optical access, so long as network technologies are chosen wisely.

Future work It should be noted that the results in Chapter 4 are for a different scenario than those in Chapter 3, where we considered higher bandwidth demands in a more distant future and/or operators wishing to offer maximal bandwidth, partly for marketing reasons. In the GreenTouch architecture we only strive to meet the actual demands, which would be much lower, even in the extrapolations for 2020. If we look at the future beyond 2020 another evaluation will be needed to see which technology (or actually, which combination of technologies) is optimal.

6.4 Post-peak ICT

While the conclusions above apply well to a scenario in which we want to save as much energy as possible while offering high QoS, there is another scenario that needs to be considered. Fossil fuel depletion, (in)security of energy supply and climate change may soon force human society to move away from fossil fuels, on to a so-called "post-peak" future. What comes next is hard to predict, but as we motivated extensively in Chapter 5, this may lead to a less constant energy supply, with resulting periods of scarcity. Given their inherent reliance on electrical power for their operation, ICT infrastructures would undoubtedly be affected by this.

We assessed the effect of energy shortages on fixed and wireless access networks, core networks, and data centers. The main question we asked ourselves is whether these infrastructures can still offer a basic functionality when the available power is significantly lowered compared to normal operating conditions. With currently deployed equipment, it seems there is not much potential to keep the network running under such circumstances, except perhaps those parts of the network that allow flexible resource allocation (mostly data centers and wireless access).

In a concrete case study for a wireless access network, we explored the possibility of adapting the network to a low-energy situation by placing some of the base stations in sleep mode. The results showed that while this is a promising approach, it can only be successful if base stations consume very low power in sleep state. Unfortunately this is not yet the case in current deployments.

Future work This new research domain is largely unexplored. Follow-up studies can perform a detailed post-peak analysis for different portions of the network, and try to come up with new strategies to cope with strict energy limitations. At first glance, there are a number of hurdles that need to be taken when devising such strategies.

The design and introduction of more load-adaptive devices (with power that scales better with the tasks being performed) would be an important first step towards a network with better post-peak potential, as a minimal service could then be offered with minimal power.[2] This could be achieved — at least in part — by implementing sleep modes on all new devices; which would require hardware and software optimizations to make sure they reach the lowest power possible when idle, and at the same time guarantee reliable and swift wake-up when needed.

Another challenge that affects both the post-peak potential and the footprint of networks is the presence of legacy equipment. This is hardly ever taken into account in scientific papers which tend to focus on state-of-the-art solutions, but it is still present in the field, often consuming a lot of power. Telecom operators are reluctant to remove equipment so long as it works, irrespective of its power consumption, as their main concern is to offer the best possible QoS to their customers. In future research, upgrades to existing equipment to achieve energy efficiency could be compared with new technologies, and once again, a full life-cycle analysis would help to distinguish which pathway is the most environmentally sustainable.

6.5 Concluding remarks: from theory to practice

The previous conclusions were based on the work presented in this dissertation, which was of a rather specific and technical nature. In these final paragraphs, I'd like to take a step back and take a look at the bigger picture.

The technical work presented in this dissertation has clearly shown two things: (1) The contribution of communication networks to the human footprint is significant. Therefore, if we want to reduce our footprint, the power consumption of communication networks will have to be reduced. (2) There is potential to improve the energy efficiency of communication networks tremendously. In fact, academic research in the area has provided many solutions to achieve this. If these solutions for energy efficiency can be combined with renewable energy sources, we could bring the footprint of networks down to almost zero.

Unfortunately, these optimistic conclusions will not necessarily translate to direct savings in practice, for two main reasons: (1) Energy efficiency

[2]From a green networking perspective aimed at saving power while preserving QoS this would also be a huge improvement, as it would mean power would scale with the actual load rather than with the provisioned capacity, following load variations over time.

improvements do not automatically lead to energy savings. This can be illustrated by a simple example: television sets and computer screens have become much more efficient over the past decades, but today, these screens are using more energy than ever before. Indeed, modern liquid-crystal display (LCD) and light-emitting diode (LED) technologies outperform the former bulky cathode ray tubes (CRTs) by a mile in terms of energy efficiency, if we consider the energy per cm^2. But because the energy and manufacturing cost of these devices decreased, we witnessed a trend of people installing more and more devices (most people in Belgium have several television sets in their home these days) with bigger screens, more than compensating for the savings from efficiency improvements. By making technologies more accessible and cheaper, efficiency improvements may reach the opposite effect of what we were aiming at in the first place. (2) Currently, there are not enough incentives to make green networking technologies the most attractive option to investors. Telecom operators will not carry out expensive infrastructure updates if their benefits (in terms of financial savings) do not outweigh the costs. This is definitely true for optical access, in which operational energy cost is typically much lower than the capital expenditures for infrastructure works associated with digging up roads to install fiber to the home, for instance.

Ultimately it boils down to a problem where companies and customers are acting in their own individual interest with a focus on financial cost — cost reduction is still the most important economic goal for many companies, and most consumers will also look at prices rather than footprints of the products they're buying. But we should be considering the environmental cost instead — a price that we are all paying together. If we want real change to happen, sustainable and green (ICT) practices should have more business value than polluting alternatives. This will only be possible if regulatory organs, particularly governments, incentivize these alternatives, by assigning research funds towards energy efficiency (something that is already happening today), but also by placing higher taxes on GHG emissions (as previous agreements have not succeeded in stopping GHG emissions growth, additional efforts are needed here).

The catch here is that governments cannot act without support of the general population, and a large portion of that population is either not aware of the problem, denying its existence, and/or hoping against all odds that science will come up with a quick and easy fix to patch up the climate. To put it in the words of Steven Levitt & Stephen Dubner: "It's not that we don't *know how* to stop polluting the atmosphere. We don't *want* to stop, or aren't willing to pay the price."[3] Indeed, dramatically reducing our carbon emissions would mean changing the way we communicate, eat, shop, manufacture, and get around, and, ultimately, how we see ourselves. These big changes will be economical, societal, and psychological in nature rather than technical. How do we change consumers' and decision-makers' behavior before it's too late? That may be the biggest challenge of all.

[3]Quote from the book "Superfreakonomics", which was widely criticized for its presentation of geoengineering as a solution to global warming, but may have been right about the (un)willingness of people to change their behavior.