Faculdade de Ciências e Tecnologia
Departamento de Engenharia Electrotécnica e de Computadores

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Power saving techniques in access networks.

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Universidade de Coimbra

Faculdade de Ciências e Tecnologia da Universidade de Coimbra

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i. Abstract

Our modern society interacts with the surrounding through various electronic devices, causing ever growing demand for energy around the world. Energy usage of Information and Communication Technology (ICT) devices in Portugal (based on reports of Portugal Telecom) are examined in this thesis, along with current trends around the world. Various characteristics (components, protocols, software and traffic periodicity) of known access technologies, including wireless, wired optical and copper media, were examined in detail while performing the study of energy consumption in the access networks. Detailed analysis of power saving methods meeting the contracted Service Level Agreements (SLAs) was also carried out. Ways to save power were classified into active (requiring adaptation to the load conditions with the use of algorithms and software), passive (more efficient components) and hybrid (combination of active and passive methods). To study the potential for power saving in various access network architectures, a data trace analysis software was developed in Matlab environment. This program examines user activity profiles based on real data traces, performing necessary aggregation for selected activity profiles, and calculates overall power consumption and power saving potential while taking device characteristics into consideration. Conclusions on the power saving capacity of various access technologies are drawn based on the developed software model. Possible future research topics, including development of a global database with detailed information about power consumption in network devices, studying the effects of various combinations of power saving mechanisms on network performance, were also listed in Chapter 5, "Future studies".

Annex A contains a brief overview of access technologies. Annex B provides a detailed tutorial with examples for the designed data analysis software, providing a starting point for any future user of this software model.

ii. Keywords

Environment, access network, telecommunication, power consumption, power saving, wireless, wired, PON, P2P, periodicity, traffic models.

iii. List of tables

iv. List of figures

v. Acronyms

AC	Alternating Current
ADSL	Asymmetric Digital Subscriber Line
ADSL2	Asymmetric Digital Subscriber Line Second Generation
ADSL2PLUS	Second Generation ADSL With Extended Bandwidth
ADSLAM	ADSL Access Multiplexer
AP	Access Point
ARP	Automatic Routing Protocol
ASIC	Application Specific Integrated Circuits
BCOC	Broadband Code Of Conduct
BS	Base Station
CATV	Cable Television
CDMA	Code Division Multiple Access
CO	Central Office
CPE	Customer Premises Equipment
CPU	Central Processing Unit
DC	Direct Current
DHCP	Dynamic Host Configuration Protocol
DMZ	Demilitarized Zone
DOCSIS	Data Over Cable Service Interface Specification
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DVS	Dynamic Voltage Scaling
ECO	Ecological
EDGE	Enhanced Data Rate GSM Evolution
EE	Energy Efficiency
EEE	Energy Efficient Ethernet
EIRP	Equivalent Isotropically Radiated Power
ENB	Evolved Node B
EPON	Ethernet Passive Optical Network
EU	European Union
FFR	Fractional Frequency Re-Use
FIFO	First In First Out
FPGA	Field–Programmable Array
FTTB	Fibre To The Block
FTTC	Fibre To The Curb
FTTH	Fibre To The Home
FTTP	Fibre To The Premises
GHG	Green House Gasses
GPON	Gigabit Passive Optical Network
GPS	Global Positioning System
GSM	Global System For Mobile Communication
HFC	Hybrid Fibre Coaxial
HNID	Home Network Interface Device
HSPA	High Speed Packet Access
ICMP	Internet Control Message Protocol
ICT	Information And Communication Technology
IEEE	Institute Of Electrical And Electronics Engineers
IP	Internet Protocol

IPTV	Internet Protocol TV
IT	Information Technology
ITE	Information Technology Equipment
ITU	Information Technology Union
LAN	Local Area Network
LBL	Lawrence Berkeley Laboratory
LPI	Low Power Idle
LTE	Line Termination Equipment
MAC	Media Access Control
MAN	Metropolitan Access Network
MDU	Multiple Dwelling Units
MIMO	Multiple Input Multiple Output
MPCP	Multi- Point Control Protocol
MSC	Mobile Switching Centre
MV	Medium Voltage
NB	Node B
NG	Next Generation
NIC	Network Interface Card
OFDM	Orthogonal Frequency- Division Multiplexing
OFDMA	Orthogonal Frequency- Division Multiple Access
OLT	Optical Line Termination
ONT	Optical Network Terminal
ONU	Optical Network Unit
P2P	Point To Point
PA	Power Amplifier
PC	Personal Computer
PCB	Printed Circuit Board
PON	Passive Optical Network
RAC	Radio Access Network
RDSLAM	Remote Digital Subscriber Line Access Multiplexer
RF	Radio Frequency
Rx	Receiver
SFU	Single Family Unit
SIEPON	Standard For Service Interoperability in Ethernet Passive Optical Networks
SIM	Subscriber Identification Module (Pcs)
SISO	Single Input Single Output
SLA	Service Level Agreement
SNS	Social Network Service
Tx	Transmitter
TCP	Transmission Control Protocol (With Internet Protocol [IP], The Main Protocol Of The Internet)
TDT	Televisión Digital Terrestre (Digital Television Type, Spain)
TJ	Tera Joule
TV	Television
TW	Tera Watt
UNI	User Network Interface
USB	Universal Serial Bus
VDSL2	Very High Speed Digital Subscriber Line Second Generation
VOD	Video On Demand
WAN	Wireless Area Network, Wide Area Network

WDM	Wavelength Division Multiplexing
Wi-Fi	Wireless Fidelity (IEEE 802.11b Wireless Networking)
WiMAX	Worldwide Interoperability For Microwave Access
XG-PON	10 Gigabit Passive Optical Network

vi. Index

1 Telecommunication sector and its power consumption around the world and in Portugal

1.1 Overall power consumption in telecommunication networks

In our modern society, we are interacting with the surrounding environment and other people through various types of electronic devices with increased frequency. The very style of our communication has also changed. Nowadays, we have not only voice communication available but also video-conferences, e-mails, variety of blogs, and SNSs (Social Network Services). In recent years, TV services have evolved as well, shifting from pure broadcast towards VOD (Video on Demand), ITV, multicast services and TDT (Televisión Digital Terrestre – Digital Television) integrating many media services into a single distribution platform that can be easily accessed by an end user. A lot of everyday services, like banking, shopping, stock exchange, environment monitoring through various sensor networks with different types of aggregation (river levels, road traffic), telemetering, cloud services, and telemedicine (among the others) are available online.

In 2007, Gartner publication concluded that Information and Communication Technology (ICT) was responsible for approximately 2% (see Figure 1) of the global CO_2 emissions, and the grand majority of the consumed energy was actually lost due to underutilization of the networking resources [1].

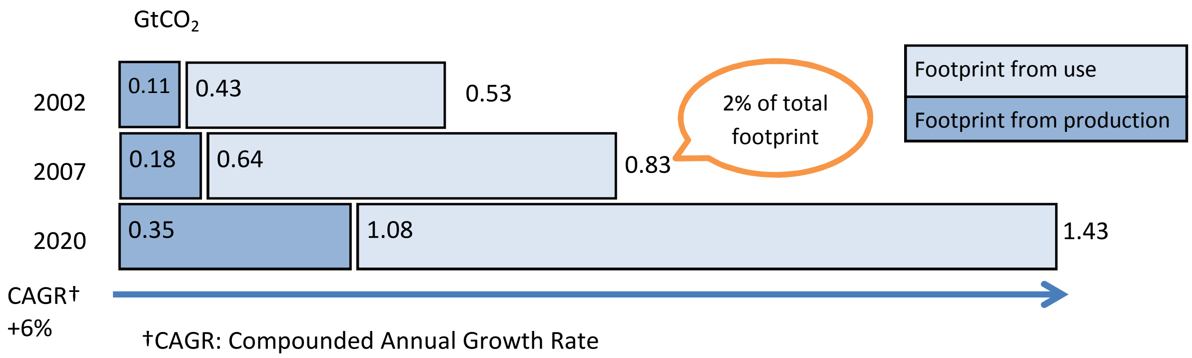


Figure 1: Global ICT footprint [2]

The global CO_2 emissions in 2010 reached 9.2 billion tons and in 2011 increased to 9.5 billion tons, presenting a year-to-year increase in emissions of roughly 3%.

In 2010, Portugal emitted 14.5 million tons of CO_2 and increased its emissions in 2011 by 1% [3]. If we take in consideration data from [1] and [2], combined with the percentage indicated in

[3], the Portuguese ICT sector itself is responsible for about 300 thousand tons of CO_2. Furthermore, in the future, its share in the CO_2 emissions is expected to increase.

It is estimated that in 2015, the ICT equipment deployed in European networks alone will consume around 50 TWh/year (1.5% of the total of 3374 TWh generated in Europe in 2008 [4]), so we can clearly see how big part ICT plays in manmade greenhouse gases emissions. This value depends on penetration level, requirements of the service provider and specifications of deployed equipment [2].

Even in the case of applying the new energy efficient technologies, the ICT is expected to increase the associated CO_2 emissions by 6% each year by 2020 and in the future may reach even higher levels [2].

1.2 Telecommunication infrastructure and devices

Over the past few years, the increased usage of Internet and mobile telephony has driven rapid expansion of the ICT infrastructure. The numbers of fixed line narrow-band and voice clients is expected to maintain their current levels. However, the number of broadband access accounts served by telecom and cable operators (accounts without cable TV) is expected to more than double by 2020 (as compared to 2007 numbers). The number of mobile clients (using both voice and data utilizing range of existing access technologies: GSM, CDMA, EDGE, 3G, etc.) is predicted to almost double by 2020 (again, using 2007 figures as reference) [1].

The use of mobile phones, chargers, internet protocol TV (IPTV) boxes and home broadband routers is expected to increase over the next 12 years, primarily due to rapidly developing countries like China and India, where the middle classes are quickly catching up with the developed countries in terms of the use of ICT equipment and added-value services. The global footprint of ICT equipment was estimated at 18 million tons of CO_2 (Mt CO_2) in 2002 and is expected to increase almost threefold to 51 Mt CO_2 by 2020, driven mainly by the increase in the use of broadband modems/routers and IPTV boxes (see Figure 2)

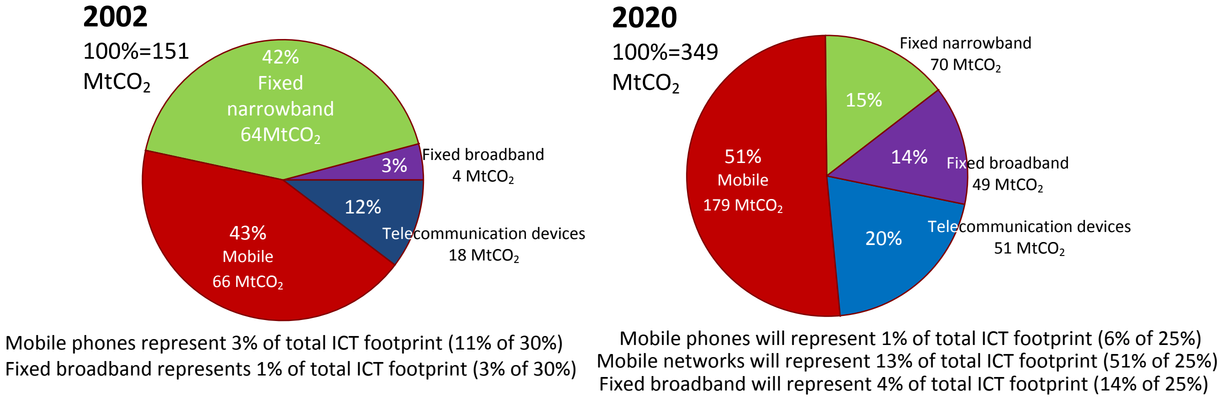


Figure 2: Global telecommunication footprint (devices and infrastructure) [2]

Table 1 exhibits the global CO_2 footprint associated with the use and production process of telecommunication devices in 2002 and predictions for consumer trends for 2020. It can be clearly see that along with the increase in the number of manufactured devices (increase of overall power consumption), there is also associated increase in the volume of emitted CO_2.

This trend of increasing CO_2 emissions can be lowered either by more efficient production technologies, use of recycled or new materials, and by power saving techniques used in operating devices.

Table 1: Global telecommunication devices footprint

	production process	use	total
IPTV boxes [Mt CO_2]			
2002	0	0	0
Growth along current trends	6	14	20
Change in power consumption	-	9	9
2020	6	5	11
Broadband modems[Mt CO_2]			
2002	1	1	2
Growth along current trends	8	13	21
Change in power consumption	5	-	5
2020	9	9	18
Mobile phones[Mt CO_2]			
2002	3	13	16
Growth along current trends	9	41	50
Change in power consumption	-	44	44
2020	12	10	22

Growth trends: Increase in number of mobiles, routers and IPTV equipment causes increase in power consumption and CO_2 emissions.
Change in power consumption: CO_2 emissions related to power consumption decrease due to smart charger technologies and implementation of 1W standby mode for plugged in equipment.

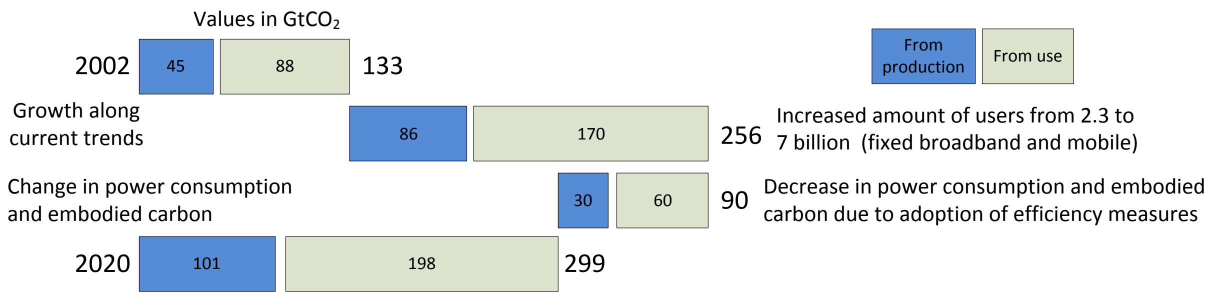


Figure 3: Global telecommunications infrastructure footprint [2]

Figure 3 presents the importance of reducing energy consumption in electronic equipment alongside the predicted continuous growth in their everyday use. In year 2002 telecommunication usage produced 88 $GtCO_2$ and production of devices 45 $GtCO_2$. In case of growth along current trends emissions ay increase by 256 $GtCO_2$. By applying power consumption saving and new production methods bringing 90 $GtCO_2$ of reduction, by year 2020 emissions may reach 299 $GtCO_2$.

Authors of [5] made certain assumptions about numbers of ICT equipment sold, delivered and used and power consumed by them and performed detailed study about global energy consumption and related CO_2 emissions. Table 2 summarizes some of the results of that publication. 3.9% of total global electricity during 2007 was used for operating equipment and networks in the ICT sectors, whereof 17% end-user standby-related, 50% network-related and 32% active use (end-user).

Table 2: Global scope of operational electricity (TWh/year) and total CO2-eq emissions (Mt/year) in 2007 of some ICT branches [5]

ICT type	Operational electricity [TWh/year]	Total CO2 emissions [millions of tones/year]
Mobile networks operation	50	46
Mobile phones operation	9	5
Fixed networks, operation	72	54
Cordless phones, operation	22	13
Broadband modems and routers, operation	35	21
PCs, operation	258	155
Data centres, enterprise networks and transport networks	226	170
Data centres, operation	180	108
Enterprise networks, operation	29	17
Transport networks, operation	17	10

According to [6] just in 2010, all the networked devices created or replicated over a zettabyte (1 ZB = 2^{70} bits) of data. About 25% of this data was generated by sensor and remote monitoring networks and this tendency is expected to increase in the future. Predictions made in [7] indicate that by 2015, the amount of data generated is going to grow to about 8 zettabytes. This will require many new data centres to be built and a high-performance network to be available to general population to access data stored in these “server farms”. The increase in the energy consumption in the ICT sector is therefore an unavoidable consequence of the increased internetworking and digitization of media and services, and can be only combated by introduction of power efficient equipment. Rapid development in the data storage, transmission and virtualization sector is going to force the need for improvement in electrical efficiency of the telecommunication equipment.

Just by applying guidelines on power consumption gathered in [8] we may be able to limit energy usage of the telecommunication devices to about half of the predicted usage that stands at 50 TWh per year (for Europe only). This may bring about €7.5 billion of savings and eliminating equivalence of 5.5 million tons of oil equivalent being burned what will slow down the increase of already high levels of concentration of GHG in the Earth’s atmosphere and benefit better health of all living organisms.

1.3 Situation in Portugal

[9] presents PT’s investment into environment protection and the focus on the use of renewable energy sources. Such an energy policy brings monetary benefits to the company as well, while reducing its carbon footprint. With the CO_2 price in Europe as high as €20 per tonne [10], monetary benefits from reducing energy consumption in ICT industry are substantial.

PT’s CO_2 emissions were higher in the last year due to, as explained in the report, shortage of renewable energy available on the market, caused by below-the-average wind speeds and rainfall that year. However, it is also worth noting that the overall energy consumption in the PT network dropped, primarily thanks to advances in electronics, making networking equipment more power-efficient and environment-friendly.

Table 3: Environmental facts [9]

Type of action	2009	2010	2011	Change 2009/11
Investment in environmental protection (millions €)	1.0	1.2	2.8	190%
Benefits from environment management system (millions €)	0.2	4.4	3.1	~1.3%
Carbon emissions (kilotons)	177	166	217	23%
Energy consumption (TJ)	1688	1816	1780	5%
Energy consumed from renewable sources	40%	42%	26%	-14%

Table 4 presents energy consumption evolution over the last few years. In 2009, the peak consumption was reached, probably due to the rapid growth of provided services and expansion of the ICT infrastructure. The wireless department in 2010 decreased its energy consumption, primarily because of the adoption of more energy-efficient equipment. The decrease in the energy consumption of the wireline department may indicate a migration of a fair share of users from fixed-line access technologies to mobile solutions, which happen to be more convenient for everyday use.

Table 4: Energy consumption of branches [9]

Type and amount of energy consumed (TJ) per branch	2008	2009	2010
Electric: wireline department	1 106	1 193	1 185
Electric: wireless department	339 916	363000	341000
Electric: business support(office consumption)	26 898	26000	25000
Natural gas, petrol fuels	223 684	235000	229000
total	1 687 749	1 816	1 780

Power savings and reduction in CO_2 emissions (see Table 5) was achieved also by consolidating networking equipment. By doing so, the number of active power supplies in the network has been reduced, causing a significant decrease in the energy usage. Redesigning equipment cabinets and central office infrastructure either eliminated in some cases or minimized in the vast majority of COs the use of power-hungry air-conditioning systems. The use of fossil fuels to power wireless base stations in remote regions with no reliable access to the power grid has been replaced by either wind generators or solar panels. Furthermore, by monitoring the use of corporate vehicles with the aid of GPS sensors, the company have managed to achieve measurement savings in terms of CO_2 emissions at the cost of moderate data transfer.

Table 5: Emissions avoided [9]

Type of action	Tons of CO_2
Removing obsolete equipment from network	532
Different air conditioning policies	1268
New lighting systems and equipment	53
Migration of traditional networks to next-generation	1641
Automotive fleet management and monitoring	383

2 Overview of existing access technologies and their power consumption

The access network spans between a CO of the local service provider and individual businesses or homes (groups of homes and offices for fibre networks in Fibre to the Premises (FTTP) architecture or individual homes or offices in Fibre to the Home (FTTH) in some areas as well as Digital Subscriber Line (DSL)). The function of the access network is to collect traffic from customer locations and deliver it into the carrier network through a number of layers of aggregation, e.g., through LAN, MAN and into WAN, or directly in the WAN in case of enterprise customers.

The access network reach is typically a few kilometres and depends on type of access technology used. The aggregation level in the access network is rather small and it is possible to observe long periods of inactivity during off peak hours due to repeatable daily user activity patterns, associated with work hours, leisure hours as well as weekly changing patterns.

Review of existing access technologies is presented in Annex A.

2.1 Periodicity of Internet usage

Figure 4, Figure 5, and Figure 6 present traffic activity profiles for Northern Europe, Southern America and a single operator in Asia, respectively. Data for the day time usage is represented by the symbol ☀ and the night time is represented by the symbol ☾. Each vertical line represents one hour.

All the referenced figures have highly distinguishable features, where there is an easily observable difference in user activity between the day time and night time periods. It is also interesting to note how the main traffic types vary over the 24 hours' period. Video playback and web browsing are good examples of such a traffic pattern variation. Software updates generate considerable traffic at night. Traffic profiles do not undergo major changes during weekends, as presented on Figure 7.

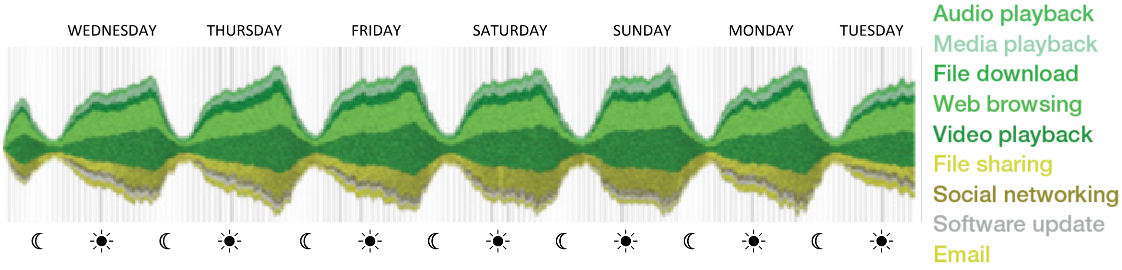


Figure 4: Stacked area chart of weekly day/night traffic consumption profiles of Northern Europe [11]

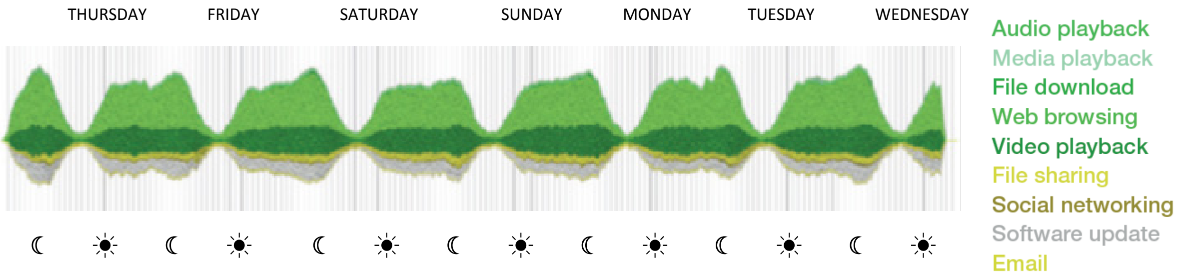


Figure 5: Stacked area chart of weekly day/night traffic consumption profiles of South America [11]

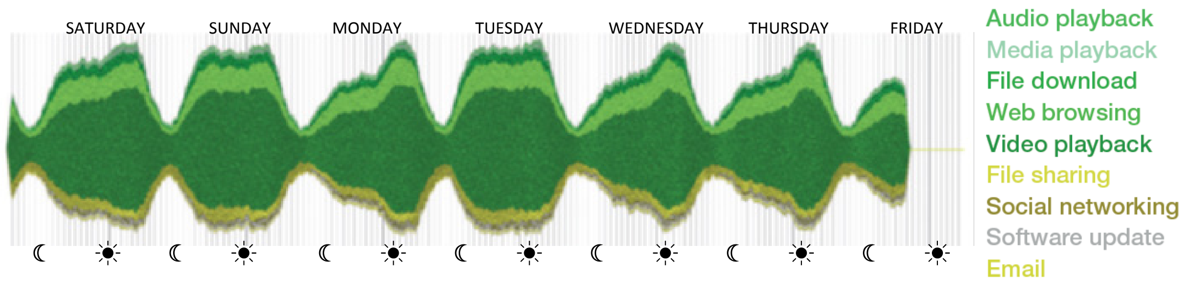


Figure 6: Stacked area chart of weekly day/night traffic consumption profiles of single operator in Asia [11]

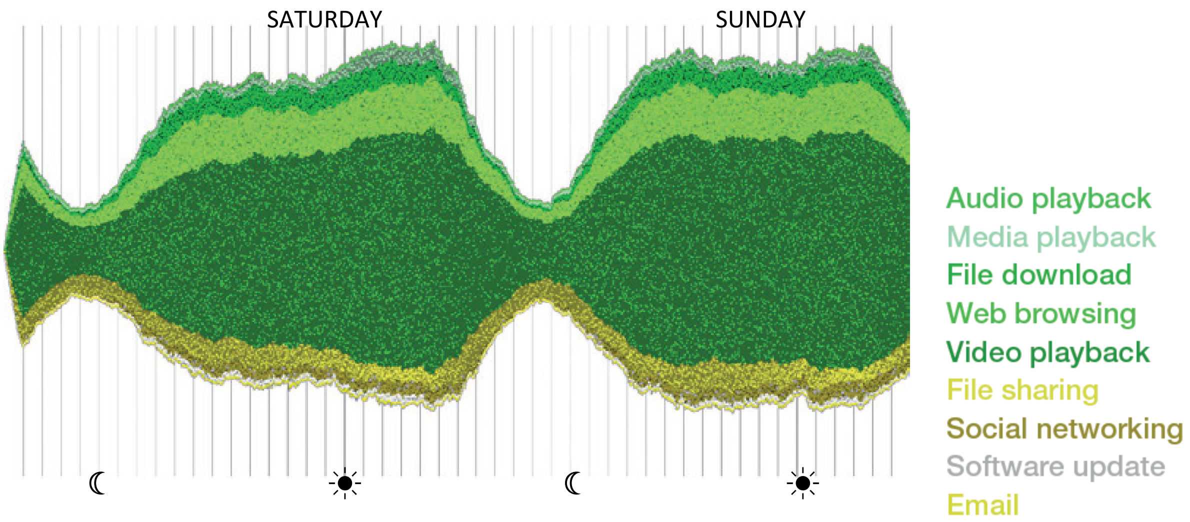


Figure 7: Amplification of the weekend period of Figure 6 [11]

2.2 Network equipment, power consumption, and mechanisms of saving power in networks

2.2.1 Central office – provider side

2.2.1.1 *Central office power consumption*

A typical CO power consumption model presented in [12] is based on a traditional architecture with a voice-switch, DSLAM, some IT and power inverter equipment, and a DC power transformers providing 48 V power supply, cooled by a standard central air conditioning system. A breakdown of power consumption for such a typical CO architecture is presented in Table 6.

Table 6: CO components and their power consumption

Equipment type	Consumption [kW]	% of total
Telecommunication equipment	53	31,7%
IT equipment	5	3%
Broadband equipment	20	12%
Lighting	3	1.8%
DC power and distribution losses	17	10.2%
Cooling power draw	64	38.3%
Switchgear/medium voltage (MV) transformer	5	3%
TOTAL	**167**	

Cooling and telecommunication equipment represents a substantial share of the overall CO power consumption reaching almost 40% of the total energy used. Network elements (telecommunication, broadband, DC power, ITE) are responsible almost for almost 60% total power consumed.

2.2.1.2 Power saving methods

Authors of [12] demonstrate ways of achieving power saving in the CO architecture (Figure 8). They conclude that small savings at the root of the whole system yield substantial power savings at the end of the system chain. For example, just 1 W of power saved at the ICT level results in the total savings of 2.42 W at the overall CO power consumption level. Table 7 summarizes the potential power saving opportunities in the CO.

Table 7: Possible power saving scenarios in CO [12]

Strategy	Description	Saving [kW]	Cascade saving [kW]	%
Modes of power saving in IT equipment	Implementing power saving mode	9.9	24.3	14.6 %
DC powered IT equipment	Elimination of inverters	1.4	2.8	1.7%
Implementing better cooling	>3kW/rack policy, not mixing cold	16.4	16.9	10.2%

practices	with hot air			
Additional high density cooling	Cooling at the load	10.7	11.0	6%
Replacing legacy rectifiers	New rectifiers with higher efficiency 93%	5.2	7.1	4.3%
DC system working in ECO mode		1.6	2.2	1.3%
		Total	**64.3**	**38.6%**

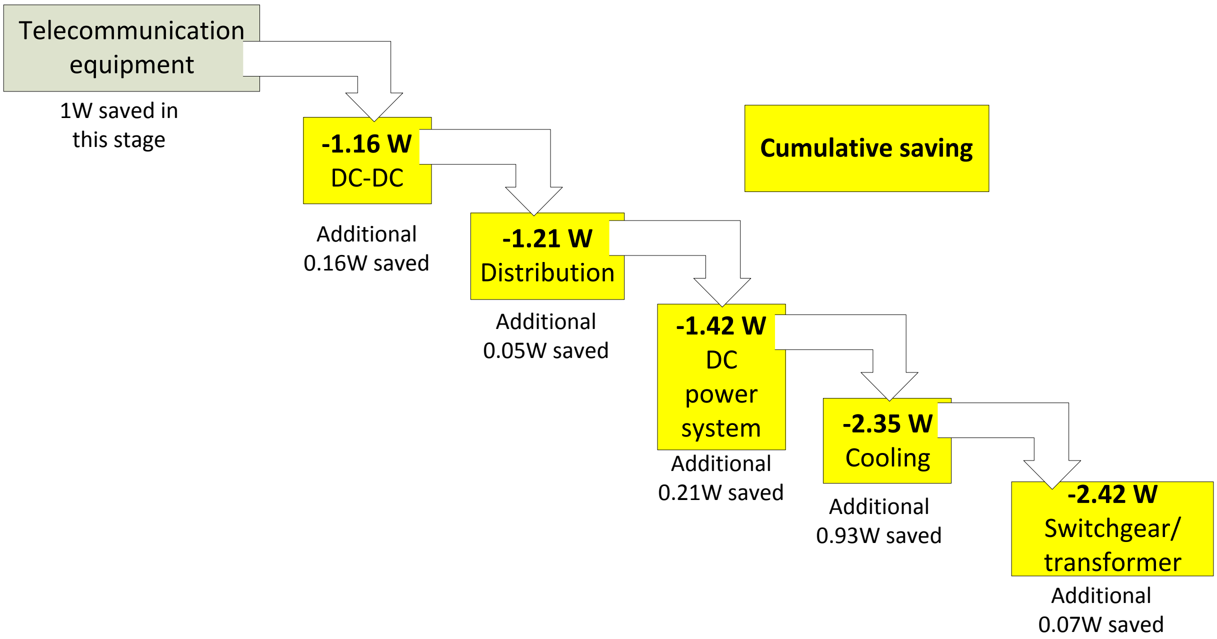


Figure 8: Wireline cascade power saving effect [12]

2.2.1.2.1 Passive power saving methods

Significant power consumption reduction in the CO can be achieved when using IT equipment conforming to the guidelines included in [8]. Even further energy consumption reduction can be achieved by eliminating the power conversion at the inverter and use of traditional -48 V DC power supply architecture. Heat dissipation may be improved by the use of proper air circulation techniques inside the CO building (returning hot air to the cooling unit through hot-aisle/cold-aisle configuration and use of blanking plates, pressurizing the cold aisle or usage of return air ducting for hot air containment).

2.2.1.2.2 Active power saving methods

When using the traditional -48 V DC power supply architecture, it is possible to employ a DC eco mode thanks to the use of a sophisticated software–controlled DC power plant. This allows boosting the efficiency of individual power supplies, which reduces the generation of excess heat caused by the power conversion process, leading to the immediate power savings thanks to reduced need for cooling.

2.2.1.2.3 Hybrid power saving methods

Heat dissipation equipment should follow the stricter ASHRAE standard instead of NEBS guidelines [13]. Great deal of energy is used to humidify or dehumidify and maintain specific temperatures of the surrounding of equipment. Relaxing those requirements by expanding allowable levels, limits or even eliminates the necessity to adjust humidity and use forced cooling systems. If a cooling system is needed, more efficient cooling fluids in combination with higher operation start point of the system equipped with new types of fans may further improve efficiency of cooling systems. In special situations there may be a need for additional high-density supplemental cooling systems that may be installed over the rack or cabinet on the ceiling or in the row to provide the necessary boost in cooling straight at the source.

2.2.2 Provider side equipment

2.2.2.1 Wired provider side equipment

2.2.2.1.1 Copper medium equipment power consumption

Access technologies may use different types of copper medium, including twisted pair (DSL, P2P Ethernet) and HFC.

RDSLAM and DSLAM cabinets have ports at certain specifications to provide interconnection of CPE equipment with CO of the service provider for DSL technology. Depending on transmission type, load state of the given port and ports transmission power the consumption spans from 0.3 W/port (idle state) to 1.7 W/port (full load state).

For CATV access technology operating on HFC copper wires, headend cabinets located in the field closer to users consume 6 W/equipment regardless of transmission technology used and amount of downstream ports.

More detailed information about power consumption and possible configurations of DSL and CATV equipment are located in Table 16 and 17 (page 28) and Table 27 (page 36) in [8].

2.2.2.1.2 Optical fibre based equipment power consumption

Depending on network designer needs, OLTs can be equipped with a number of different access configurations tailored to the specific situations to provide FTTx services to residential and business markets. Each PON port installed can support (for example) 32 ONUs thanks to 1:32 passive splitter ratio. The number of supported (connected) subscribers can be much higher, especially when MDU-type ONUs are used. In some cases ports that support either optical or electrical Gigabit Ethernet connection are installed in OLTs. Depending on configurations and possibilities to support different types of connections, power consumption may significantly vary. Industrial OLTs are represented by BDCOM IEP3000 series device with power consumptions reaching 43.5 W - 48.4 W. Higher power usage is due to different configurations and connection possibilities [14]. Since a lot of components create OLT and a lot of connection protocols may be supported, each of them should be explored for possibilities to cut down individual power consumptions, what in total may yield a significant drop in power required to operate. SUN-GE8100 is an example of an OLT configuration. It is large equipment with rack structure and 8 OLT module cards, supporting 8 PON systems and 256 remote ONU equipment at the splitting ratio of 1:32 with transmission distance of 20km. This kind of configuration consumes 20 W[15]. ZTE ZXA10 C300 is an example of multi-service optical access system, which supports EPON, GPON, 10G-EPON, P2P, and smooth upgrading to NG PON and WDM PON providing various networking solutions, including FTTH, FTTB, FTTC, and FTTCab. Depending on configuration and size of the shelf it may consume anywhere between 680-1250 W [16].

More detailed information about power consumption and possible provider side equipment configurations are located in Table 20 (page 31 – 32) and Table 21 (page 33) in [8].

2.2.2.1.3 Power saving methods

At the provider side equipment most effective are passive power saving methods. Margin value have active power savings due high level of traffic aggregation at network devices translating into small periods of inactivity of devices.

2.2.2.1.3.1 Active power saving methods

Adaptive link rate is a strategy in which different line rates are supported on a single physical link. Typically, when the link operates at a lower line rates, it consumes less power, providing a power saving mode. Such adaptive link data rate provides power saving not only on the operator side, but also for CPEs as well. The downside of this power saving mechanism is twofold: (a) the devices need to be equipped with special link activity monitoring functions, capable of observing and adapting the link data rate in the function of the observed link load, and (b) added latency to data exchange, especially when switching from the low data rate operation mode to the higher data rate [17].

In [18] two possibilities of link rate adaptation are presented. One of them is the sleep mode where data links are turned off during long period of inactivity. Here only two operational states are considered: a sleep mode (when device disables its communication link) and an active mode (when the data link is fully operational). It is obviously difficult to find a desired compromise between power saving and system wake up delays.

Depending on technology used, different types of sleep are possible. Interface may be in deep IDLE state and dropping off packets and returns to normal state by any packet received during sleep intervals. Buffer may be used to store packets received during sleep and later process them after waking up. A shadow port option is available to handle packets on behalf of sleeping ports.

Wake-up mechanisms can be implemented on OLTs without any additional changes to ONUs. In a synchronized wake-up, OLT governs and aligns times for each connected ONU, enforcing instances when such ONUs go to sleep and wake up. This allows better control over bandwidth allocation for multicast and broadcast services providing improved QoS and lowered energy consumption with the same user experience as in case, that no power saving is used [19].

Other form of link rate adaptation is rate switching where link rate is reduced during low periods of utilization with different energy consumption figures for each rate used.

A crossover of sleep modes and adaptive link rates produces even better results.

In addition, rates can be distributed exponentially or uniformly. Uniform distribution provides smaller additional delays and average rate reduction what translates to power saving. Increased number of rate levels increases performance but increased system complexity.

Interface proxying as defined in [18] provides also a chance for save power. In the interface proxying, all or part of the traffic related processing is handed over to more energy efficient network entities. Processing may simply involve filtering, generation of simple response to network queries (e.g., for ARP, ICMP or DHCP), or just forwarding. More complex tasks may be required to process traffic from P2P applications like Bit Torrent.

2.2.2.1.3.2 Passive power saving methods

The passive power saving mechanisms are focused on the improved utilization of the available electrical energy and decrease in the energy required for cooling active elements on the PCBs, which are achieved through:

- improved PCB design:
    - alternative component layout, shorter data traces, decreased Tx loss etc., causing effectively decreased signal loss across the PCB traces;

  - better cooling solutions for individual elements (packages), provided by better heat conducing materials, improved dissipater design, etc.

- innovative cooling solutions:
  - completely passive cooling solutions, which require no active fan inside of the given device (removal of a single cooling fan can save as much as 1-1.5 W and guarantee silent operation of the device);
  - improved air flow through the PCB keeps electronics operating at optimum environmental conditions.
- utilization of higher density electronics:
  - integration of MAC and currently external devices (e.g., memory) saves on power and loss on traces, speeds up execution and simplifies design;
  - migration from generic purpose, reprogrammable devices to application specific devices (ASIC).
- utilization of power saving modes for UNI ports
  - in case of copper Ethernet UNIs, support for IEEE Std 802.3az quickly becomes common-place for consumer electronics.

All of the aforementioned passive power saving mechanisms are employed typically in SFU type ONU devices in combination with active power saving mechanisms defined in the respective standards prescribing the given network protocol. In MDU type ONU devices, typically serving a larger number of subscribers, active power saving mechanisms are of limited importance, while efficient design of individual line cards, utilization of more advanced electronic components and finally common support for various power shedding schemes for inactive UNI ports guarantees achieving power efficiency superior to other access solutions.

In case of EPON devices built around the multi-line card architecture, further power saving is possible, through the utilization of line-card power shedding modes, in which inactive elements are disabled keeping only minimum required functionalities to allow for rapid transition in the active mode. Figure 9 shows an example of an OLT, which may partially or completely disable some of the line cards carrying limited or no live traffic at all.

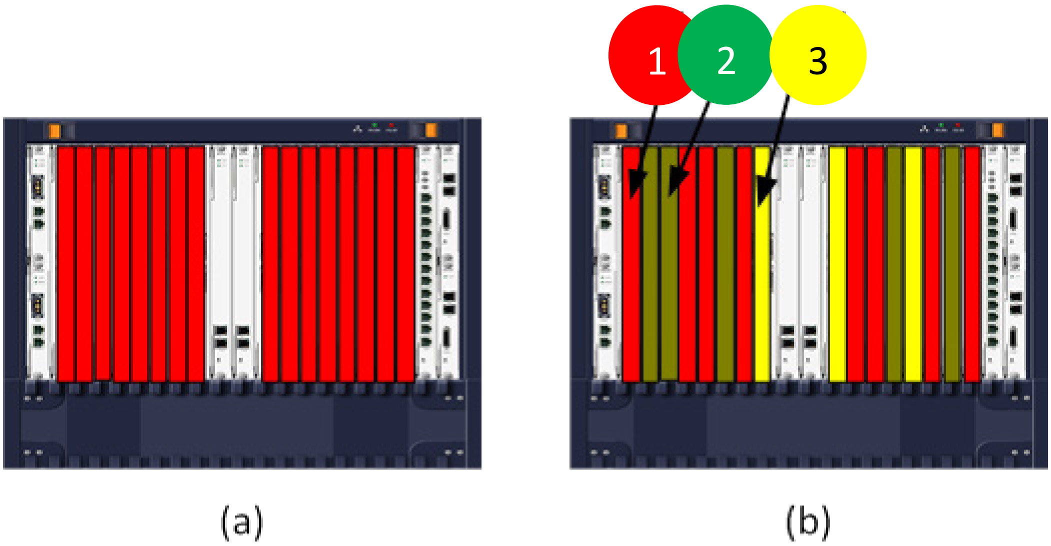


Figure 9: Example of advanced passive power saving mode for OLT: (a) OLT with fully loaded (1), (b) OLT with partially (3) and fully (2) disabled cards

2.2.2.2 Wireless provider side equipment

2.2.2.2.1 Wireless equipment power consumption

This part of the network includes MSC and radio BS. It is estimated that 90% of energy consumed by wireless networks is at operators' side [20]. Typical base station is divided into 3 sectors that combine into a omnidirectional BS. Basic building blocks of a BS are shown on Figure 10. It takes 10.3 kW to produce 120 W of transmitted signals what indicates of only 1.2% of efficiency of the system. Out of that 120 W is delivered to the antenna but additional 120 W has to be feed to the feeder cables that are at the base of the antenna. Radio frequency (RF) power amplifiers consume 4 kW and signal processing 2.1 kW. Air conditioning module consumes 0.34 W for each 1 W of heat produced by electronic components what gives in total 2.5 kW. Division of the total power used by BS is presented on Figure 11. Various technologies require different amounts of energy to provide service for a given area. Since WiMAX technology provides the biggest coverage area, amount of users connected is the biggest, what gives the lowest value of power consumed per user that is 34 W [21]. Values for other technologies are presented in Table 9.

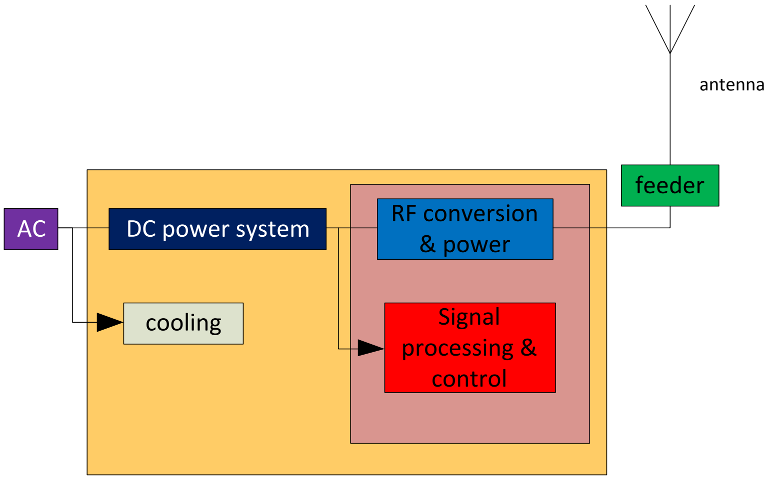


Figure 10: Radio BS schematics [12]

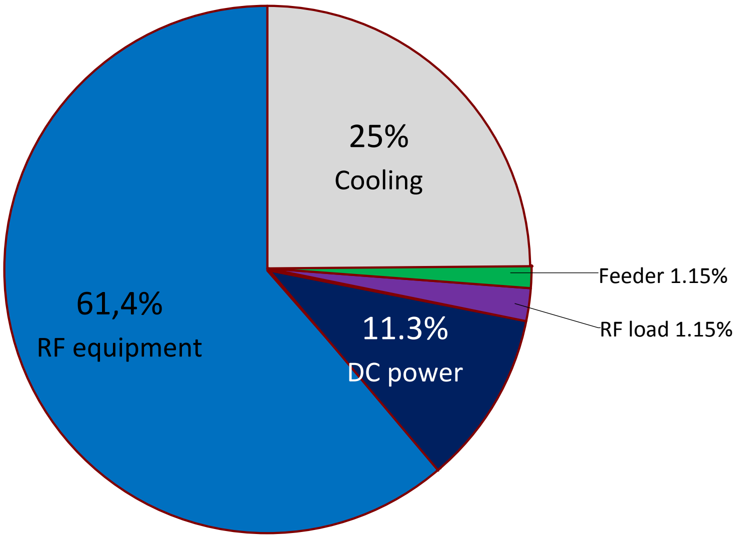


Figure 11: Power consumption of each component of radio BS [12]

More detailed information about technologies and their power consumption is covered in Tables 22, 23, and 24 (page 34) and Tables 25 and 26 (page 35) [8].

2.2.2.2.2 Power saving methods

All of radio BS components are connected together and by saving energy at the top of the system chain (feeder cables- see Figure 12) there is a possibility for a significant reduction of consumption. Just by reducing energy usage at feeder cables by 1 W, 17.3 W is saved at the lower stage of function blocks cascade (see Figure 12) – amplification and modulation. This triggers a drop in consumption at DC rectifiers causing further 7.1 W drop at cooling processes due to lower heat emissions (Figure 12). It is also possible to decrease the total power consumption by 28 times due to cascade effect presented at Figure 12. [12] indicates possible ways to save power in radio BS that are further summarized in Table 8.

Table 8: Power saving strategies for radio BS.

	Strategy	Present	Future	Saving (W)	Cascade saving (W)	Cascade saving %
Telecommunication equipment	1 Remote radio units	RF equipment distant from antenna	Avoiding feeder cable losses by moving RF equipment closer to antenna	120	3429	33.1
	2 Radio standby mode	Transmitting and receiving functions are always ON	Transmitting functions in standby mode in periods of low voice traffic.	416	660	6.4
Power and cooling	3 Passive cooling	Power hungry air conditioning used in some systems	Changes in cooling policies, redesigning the allocation of devices	1179	1179	11.4
	4 Advanced climate control	Thermostats are fixed	Dynamic adjustment of thermostats	315	315	3.0
	5 DC system ECO mode	DC system has 85% efficiency	Better use of rectifiers curve increases efficiency to 90%	272	272	2.6
	6 Higher rectifier efficiency	Rectifiers with 90 % efficiency	New type of rectifiers with 94 % efficiency	188	188	1.8
	TOTAL				6042	58.4%

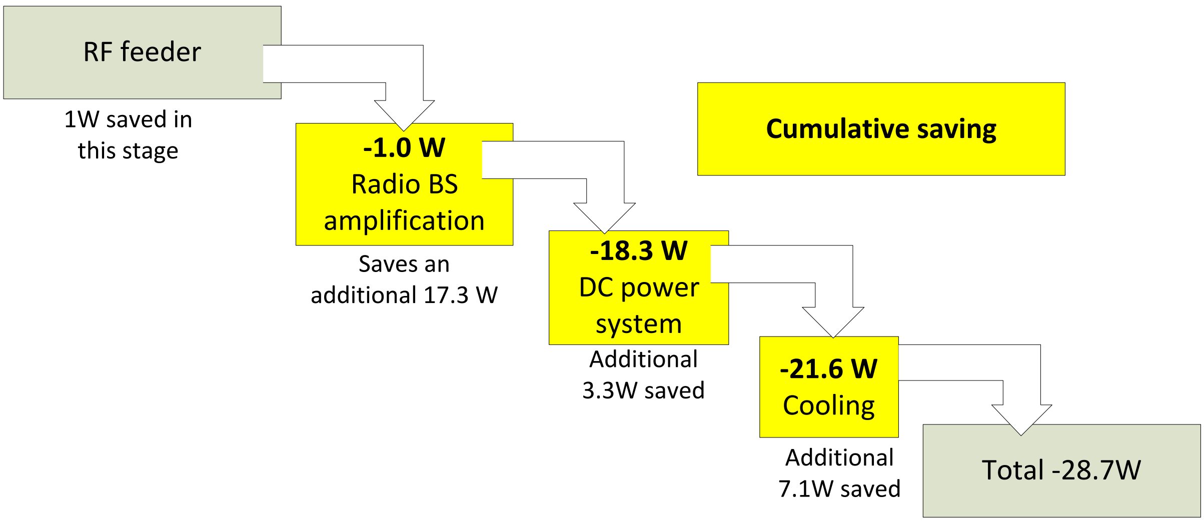


Figure 12: Wireless cascade power saving effect [12]

2.2.2.2.2.1 Active power saving methods

During periods with low call volume, it is possible to provide power saving by putting transmitters and receivers to a low power consumption state called ECO mode. In this mode, immediate 10-20% power savings are achieved, followed by additional benefits in terms of reduction in power conversion and cooling overhead. Mobile network systems are always designed for the worst case operating conditions, which typically means that there are redundant units always in operation. The mobile BSs have redundant rectifier units that are always operational. This causes some of them to work below 40% of their capacity, which significantly lowers their efficiency, causing unnecessary power consumption (shown in Figure 13).

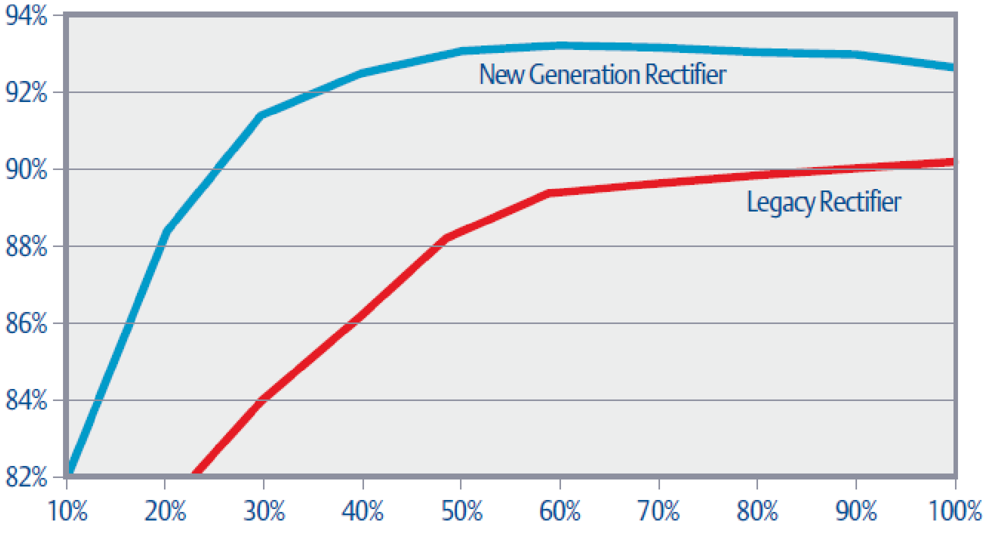


Figure 13: A rectifier efficiency curve [12]

To increase the efficiency of rectifiers, an advanced system controller scheme may be introduced to monitor the load current and allow only rectifiers operating at peak efficiency to supply the power for components, while switching off the other rectifiers. This control scheme makes rectifiers work in turns so they are equally utilized over time [12].

Authors of [21] in their study concluded that use of proper access technology, in this case WiMAX, can substantially lower down power consumption of the base station, while providing a larger coverage area when compared with HSPA and LTE. The comparison is presented in Table 9.

For simple scenarios considered in [22], potential power saving can be obtained just by switching off base stations in periods of low load while still guaranteeing the quality of service. Those periods are caused by diurnal patterns in migration of users. For example, base stations covering office buildings area are experiencing lower loads during late afternoon and night hours, while the ones providing service to housing areas are more active. This may require advanced algorithms searching for the proper base stations that may be switched off from the network. Information exchange between base stations is then required to notify which of them is working at a low load and which users have to be handed over to BS that are going to be still operational. With user density drop from 10^5 to 10^3 for a given test area (in km^2), just by reducing accordingly the number of BS, a 95% power saving compared with peak loads can be achieved. The reduction in the user density by a factor of 10 due to diurnal patterns of user migration is sufficient to save more than 85% on power consumed at peak load thanks to possibility of switching off unnecessary BS while still providing coverage for the given area with an acceptable quality of service (QoS) and service level agreements (SLA).

A study [23] indicates a possibility of power saving through energy aware resource allocation. Soft fractional frequency reuse (soft FFR) divides available spectrum into two distinctive parts, sub-bands for the inner and outer region of the cell. Sub-bands for the inner region are common for each cell where outer ones are different among adjacent cells. Soft FFR uses the outer bands within the cell for low power transmissions allowing for high spectral efficiency. Orthogonal resource allocation splits the frequency band into multiple independent subcarriers that can be modeled as non-interfering flat narrowband channels. This allows multiple users to be served simultaneously by assigning those subcarriers to users in a way that each subcarrier is occupied by at most one user. Fully orthogonal resource allocation, compared with soft FFR for LTE access technology, thanks to even higher spectral efficiency, allows the transmission power of eNBs (evolved NB) to be reduced significantly. Those are the only mandatory nodes in the radio access network (RAC) of LTE (a complex base station) that are designed to handle radio communications with multiple devices in the cell and carry out radio resource management and handover decisions.

[23] presents a possibility of energy-efficient orthogonal frequency-division multiplexing (OFDM) systems, a special case of efficient orthogonal frequency-division multiple access (OFDMA). In contrast to the traditional spectral-efficient scheme that maximizes throughput under a fixed overall transmit power constraint, the new scheme maximizes the overall energy efficiency by adjusting both the total transmit power and its distribution among subcarriers. It is demonstrated that there is at least a 15% reduction in energy consumption when frequency diversity is exploited.

2.2.2.2.2.2 Passive power saving methods

RF equipment consumes about 60% of the total energy consumed by BS, so this area should be prioritized in search for power savings possibilities. As stated in [12], in order to transmit the effective power of 120 W, additional 120 W must be dissipated, leaving the transmission efficiency at the low 50% at best. By moving RF converters and power amplifiers (PA) from the base of the station to the top of the tower (close to the antenna) and connecting them via fibre cables, power loss can be minimized and power needed to push those RF signals to the antenna greatly reduced (see Figure 14). Cutting down on power usage lowers significantly heat emitted by RF components and typical power hungry AC cooling system can be replaced by unassisted air flow, forced fan cooling with hydrophobic filtering or heat exchangers (subjects to a detailed study for each base station due to unique environmental conditions at placement location). To further improve the potential for power saving, high-efficiency rectifiers may be considered but only when the BS is operational for a longer period of time and it reaches planned capacity that it has been designed for at the time of deployment. In other cases, it may cause underutilization of the equipment and costs of installation may overcome the benefits from having high-efficiency rectifiers [12].

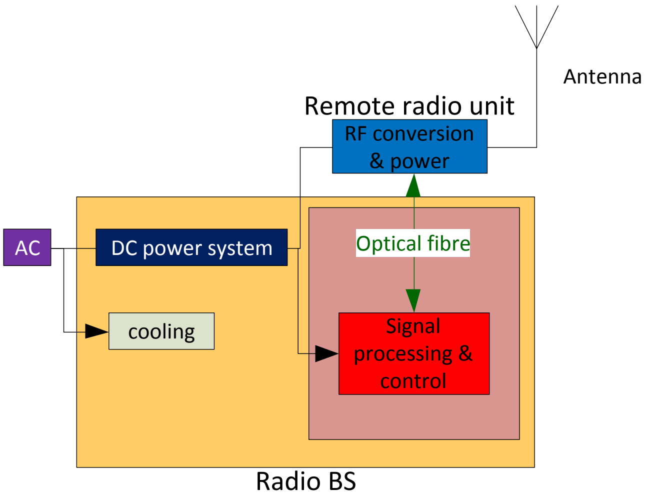


Figure 14: Radio BS with remote radio unit

The use of MIMO antenna system allows to significantly increase the coverage range compared with standard SISO system (40%, 66%, 132% respectively for 2x1, 2x2, 4x4 MIMO system using WiMAX technology with values presented in Table 9) and improve the bitrates at a small cost of increase in the energy consumption (2-4% for 2x1 and 2x2 MIMO system and 8 % for 4 x4 MIMO system). Overall, the use of MIMO technology translates into more power effective operation, while allowing more users to be connected per base station and reducing the amount of BSs necessary to provide coverage for a given area of interest [21].

Base station deployment is designed to provide acceptable user performance at peak traffic loads. Some layouts, Manhattan and hexagonal, are most energy efficient compared with Poison distributed layout due to variability in cell sizes indicating that a careful study of the area has to be performed before the deployment of the actual equipment is carried out [22].

In [23] an example is presented, demonstrating power saving through the use of a combination of various cell sizes. In the scenario examined in the study, an operator wanted to fully cover an area of 4 km^2 with WiMAX BS. Figure 15 a) presents initial situation with 2 types of macrocell BS used with total power consumption 8.9 kW. Blue circles represent BS with a bigger range and higher power consumption than the red ones. Figure 15 b) demonstrates coverage possibility using only macrocell BS to eliminate coverage holes, having total power consumption standing at 16.1 kW. Figure 15 c) presents the scenario where coverage holes were covered with microcell BS represented by green circles. The overall power consumption for this configuration was estimated at 15.6 kW, which is about 460 W less than in case of the solution only with macrocell BS (Figure 15 b). This real life problem solution directs mobile network designers to use mixed types of base stations while designing the coverage for the given area.

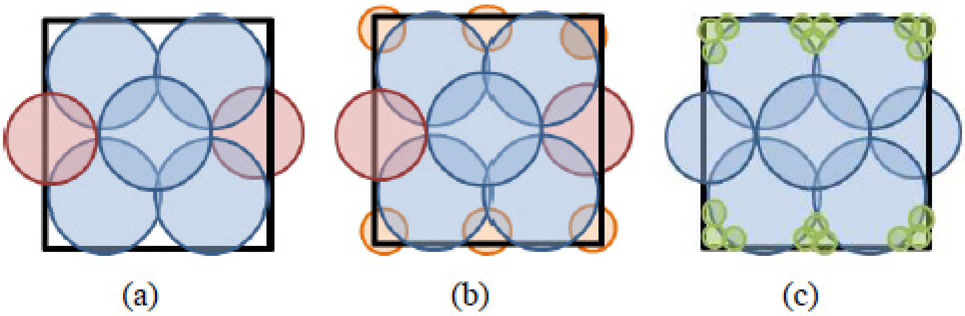


Figure 15: Possible coverage solutions. a) initial situation, b) only macrocell BS used, c) macro- and microcell BS used.

[23] indicates the possibility of use of new types of power amplifiers that achieve 45% efficiency. Next stage in RF power amplifier development that currently is in test phases, may allow up to 70 % efficiency. Prototypes have problems achieving sufficient output levels what is the limitation factor for macrocell consideration. At current development state, output power levels provided, are sufficient to be considered in pico- and femtocells deployment.

According to the Moore's Law, saying that number of transistors per square inch is destined to double approximately every 18 months, transistor geometry decrease in the future will increase power efficiency translating directly into power dissipation reduction per transistor. This will reduce BS energy consumption due to higher efficiency of electronic circuits and reduce or even eliminate the need for powered component cooling systems [23].

Strategic use of repeaters and relays may provide cost efficient and energy efficient coverage thanks to path loss savings that depend on path loss environment, cell size, shadowing conditions. For a cellular multi-hop system, path loss reduction ranges from 21 dB and for a two-hop system about 3-7 dB. Careful planning has to be undertaken due to amount of energy consumed by repeaters and relays in IDLE state and interference effects not to negate any possible power saving achieved [23].

Concept of home- or femto-BS can significantly enhance in-building coverage Avoiding the need for excessive transmission power form conventional outdoor BS. Compared with only macro-BS deployment, this type of cells, may reduce overall network energy consumption by the factor of 7. Same as with repeaters and relays deployment concept, IDLE state power consumption has to be taken into account and additional interference produced, to avoid negation of any achieved power savings [23].

Renewable energy resources play significant role in reduction of energy intake from power grid fed by fossil fuel power plants. Solar panels and wind turbines may also power remote BS sites, where electricity grid is not available replacing diesel generators [23].

2.2.2.2.2.3 Hybrid power saving methods

Unfortunately, some locations have ambient temperatures that require the use of active AC cooling. To make the cooling system more eco-friendly, a higher start point makes the unit to turn on less frequently and higher temperature difference at the air exchange improves operational efficiency. A sophisticated system with complex software has to be used to govern the operation point and monitor the conditions inside the housings and surrounding environment [12].

By combining WiMAX technology with MIMO antenna systems even greater improvements can be achieved in coverage area and available bitrate. Only downside of using MIMO antennas is a small increase in BS power consumption, but in overall a better (smaller value) power consumption for a covered area factor is achieved which indicates that less BS can be used to provide service for a given area. Benefits from using a combination of WiMAX and 4x4 MIMO systems are visible in Table 9.

Table 9: Comparison of available wireless access technologies and antenna configurations according to various factors [21].

HSPA			
Power consumption per user [W]	462.3		
	2x1 MIMO	**2x2 MIMO**	**4x4 MIMO**
Power used [W]	3859.4	3859.4	4896.8
Coverage radius [m]	129.6	153.3	214.7
Bitrate [Mbps]	11.3	22.6	45.2
Power consumed/coverage area [mW/m^2]	73.14	52.27	33.81
LTE			
Power consumption per user [W]	83.5		
	2x1 MIMO	**2x2 MIMO**	**4x4 MIMO**
Power used [W]	3859.4	3859.4	4896.8
Coverage radius [m]	306.4	362.6	507.8
Bitrate [Mbps]	10.20	20.40	40.8
Power consumed/coverage area [mW/m^2]	13.09	9.34	6.05
WiMAX			
Power consumption per user [W]	34		
	2x1 MIMO	2x2 MIMO	4x4 MIMO
Power used [W]	2986.4	2986.4	3150.8
Coverage radius [m]	422.3	499.7	699.8
Bitrate [Mbps]	11.5	23	46
Power consumed/coverage area [mW/m^2]	5.33	3.81	2.05

2.2.3 Client side

Home gateways are built from many components like processor, memory, WAN interface, LAN ports and other. Depending on the purpose of given equipment, different combinations of components may be used. The overall power consumption is being calculated as a sum of all values of individual components. The building blocks of CPEs and their individual characteristics are described in [8] in Table 10 (page 22), Table 11(page 23), Table 13 (page 25), Table 14 (page 26) for wireless CPEs, in Table 10 (page 22), Table 11 (page 23) for CPEs working over copper medium and in Table 10 (page 22), Table 12 (page 24) for optical fibre CPEs.

2.2.3.1 Wireless – client side

2.2.3.1.1 Equipment used to access networks and power consumption

Access to the network is provided through several models of mobile devices like mobile phones, smartphones and tablets with wireless cards or laptops with inbuilt wireless interfaces. In case the device does not have a slot for a SIM card or wireless card, a USB dongle with a SIM card slot or a wireless dongle can be used to overcome those hardware limitations. [8] in Table 13 on page 25, presents power consumption guidelines for different types of USB dongles.

Power consumed by user equipment for WiMAX, HSPA, and LTE is about 2.5 W per user [21].

2.2.3.1.2 Mechanisms of power saving

USB devices are considered as not equipped with additional chipsets implementing applications or complex software stacks that will drastically change the power values so it can be assumed that power consumption only can be lowered by more energy efficient electronics and antenna systems.

Devices powered by batteries with wireless interfaces were under the improvement from the beginning to prolong the battery life as much as possible so the biggest amount of energy saved can be achieved by looking into the provider side of the wireless networks. To increase the dynamic voltage scaling (DVS) can be used to further lower down power consumption of battery powered equipment [18]. In DVS systems, the performance level is reduced during periods of low utilization such that the processor finishes each task "just in time". As the processor frequency is reduced, the supply voltage can be reduced. The reduction in frequency combined with a quadratic reduction from the supply voltage results in an approximately cubic reduction of power consumption. However, with reduced frequency the time to complete a task increases, leading to an overall quadratic reduction in the energy to complete a task [25].

2.2.3.2 Wired optical (PON) and copper – client side

2.2.3.2.1 Equipment used to access networks and power consumption

2.2.3.2.1.1 Copper medium

Amount of power consumed by CPE per user varies depending on technology used. Table 10 presents numbers for power consumed per user for CPEs working over copper medium.

Table 10: Power consumed per user of ADSL2 and VDSL2 technology [21]

Access technology	Power consumed per user [W]
ADSL2	3.8-5.0
VDSL2	6.0-7.5

2.2.3.2.1.2 Based on optical fibre

As presented in Table 11, the values of power consumed per user by CPE are higher than previous technologies described, due to the presence of lasers or other light sources necessary for transmission.

Table 11: Power consumed per user of P2P and GPON technology[21]

Access technology	Power consumed per user [W]
P2P fibre (1 Gbps)	5.6-7.1
GPON	7.7-9.7

Table 12 demonstrate examples of copper and optical fabre based access technologies and associated performance parmeters for maximum available bandwidth for given technology. Table 13 presents analyse . Even with higher power consumption of CPE optical devices, the technology (esspecially PON) allows for more energy efficient data transmission due to higher bitrates per subscriber and associated with bandwidths lower per bit power consumption.

Table 12: Properties of diffrent wired access technologies [17]

Access technology	Range [km]	Bitrate [Mbps]	User/Node	Min sub density [sub/km^2]	Power/subs [W/subs]	Bitrate/subs [Mbps/sub]	Power/bit [W/Mbps]	Bitrate/power [Mbps/W]
ADSL2+	1.5	24	384-768	50-100	2-4	0.03-0.07	57.1-66.7	0.015-0.0175
VDSL2+	0.3	100	16-192	50-700	6-10	0.5-6.25	1.6-12	0.083-0.625
GPON (32)	20	2488/32	(4-72)*32	0.1-2	0.4-1.6	1-19.5	0.08-0.4	2.5-12.2
GPON(64)	10	2488/32	(4-72)*64	0.8-14		0.5-9.7	0.165-0.8	1.25-6.1

Table 13: Energy per bit for various access technologies [26]

			Per user access rate		
			10 Mb/s	75 Mb/s	1Gb/s
Technology	Per user power consumption [W]	Technology limit [Mb/s]	Energy per bit [nJ/b]	Energy per bit [nJ/b]	Energy per bit [nJ/b]
DSL	8	15	816	NA	NA
HFC	9	100	900	120	NA
PON	7	2400	745	99	NA
FTTN	14	50	1416	NA	NA
PtP	12	1000	1201	160	12

2.2.3.2.2 Mechanisms of power saving

2.2.3.2.2.1 Active methods of power saving

For high data rates transmitters, there is a need to send continuously auxiliary signals called IDLE to keep the transmitters and receiver aligned. This causes high power consumption due to continuous activity of most of the elements on the interfaces. The energy needs are destined to grow with the increase of the complexity of interfaces and higher link speeds. Depending on the services used and types of traffic, CPE devices can be made conformant to energy efficient Ethernet standard (EEE) to reduce amounts of power consumed on both client- and provider side due to background transmissions. EEE states, that transmission without any data to be carried, is limited to periodic refresh intervals, what keeps transmitters and receivers alignment. Devices enter into so called low power IDLE (LPI), where large periods of inactivity are interleaved by small bursts keeping alignment needed when new packets arrive to be sent. The standard itself is a guideline and exact power savings, may vary between devices due to different implementations. Energy consumption in a LPI mode can be as low as 10% of the active mode [27].

Already good EEE performance can be improved by packet coalescing (aggregation) in which FIFO queue at the interface is used to collect multiple packets before sending them to a link as a burst. This approach reduces CPU overhead for packet processing automatically saving energy due to shorter periods of CPU utilization [27].

Another way to achieve power saving is putting the ONU into sleep mode while still providing SLA. The OLT and connected ONUs interact before the given ONU goes to sleep mode. When the OLT determines that the given ONU may power down, it notifies the unit by a proper protocol signalling. Various methods are used for detecting ONU's eligibility to enter the sleep mode: observation of ONU activity, tracking user sessions, predictive methods based on time of the day, periodic traffic patterns, etc. [19]. The ONU entering the sleep mode powers down all nonessential functional elements, including optical transceivers for transmission or transmission and reception, memory, chipsets, etc. What components are switched off is left for the vendors to decide as long as QoS requirements are met.

Two modes of power reduction are described in the SIEPON standard (IEEE P1904.1 "Standard for Service Interoperability in Ethernet Passive Optical Networks" [27]): Tx mode where ONU disables only the transmit data path maintaining the ability to receive data from OLT while being asleep, TRx mode having both transmit and receive data paths disabled allowing ONU to save more power. Decision which mode to enter is taken by OLT, ONU or both as an agreement and is depending on ONU complexity, activity detection mechanisms, signalling protocols. Two types of power saving mechanisms are supported by SIEPON standard. One of them is cooperative mechanism where sleep cycles are established as a mutual decision of the OLT and the ONU, allowing the ONU to take decisions of entering into sleep mode based on users activity. Other is the OLT-driven mode, where the ONU is strictly controlled by the OLT using all necessary activity detection mechanisms to control the ONU state at any time.

A single- and multiple-sleep cycle options are available. Single sleep cycle forces the ONU to remain active after the sleep cycle finishes until the OLT sends a signal to enter the sleep mode again. Here active mode is default one when no control signalling is present and the OLT and the ONU need to exchange a control message every time the ONU goes to or leaves the sleep mode. When multiple-sleep cycles are used, the ONU switches between sleep and active modes using the same configured parameters until the OLT decides to adjust those parameters to meet the service level agreements (SLAs). In this cycle type, the ONU can repeat the sleep and active modes by a single control message preserving bandwidth of the control channel. The downside of this power saving mechanism is that the OLT needs to force ONUs to resynchronize their local clocks by exchanging GATE/REPORT control messages. In ONUs designed for multi-dwelling houses (MDUs) serving greater number of subscribers, active power saving methods are of limited value [19].

2.2.3.2.2.2 Passive methods of power saving

One of the possible power saving techniques is to obligate manufacturers to conform to power consumption rules defined in [8].

Improved printed circuit board (PCB) design with new component layout with shorter data traces decreases signal loss on traces through the PCB as well speeding up the execution limiting the usage of CPUs and other components. New design schemes are used to channel air in a specific way to help keep individual components at their optimum operating temperatures without the need for power hungry cooling. As well designers have migrated from field–programmable arrays (FPGAs) to application specific integrated circuits (ASICs) allowing for higher density of components and better power efficiency [19].

2.2.3.2.2.3 Hybrid methods of power saving

On top of conforming to rigorous manufacturing standards, optimization of the power consumption of CPE is important. These individual devices need to be active only during periods when user is active. During the rest of the time they can be in principle switched off, but in reality it rarely happens. Regarding standby power consumption standards of 0.5W are emerging what will lead to significant drop in total power consumption of the CPEs used around the world [17].

2.2.3.2.3 Impact on QoS with power saving ON

Implementation of energy efficiency comes as a trade-off between performance and power consumption. [27] presents a detailed evaluation of trade-offs. Increase in power saved comes with a cost of increased packet latency and increased burstiness of traffic sent by interfaces. For an end to end connection a round trip time would be tens of hundreds of milliseconds and increase of few milliseconds caused by EEE scheme would be negligible [27].

Advanced features of power saving modes are described in SIEPON standard that allow meeting the QoS requirements. Early wake-up functions allows ONUs to leave immediately the sleep mode in the presence of specific triggers, including high priority traffic on any subscriber port, telephone call setup signalling, etc. even before the ONU itself is scheduled to enter into active mode. This function minimizes the delays for high priority traffic allowing to some level of power saving and not impacting QoS and user experience [19].

In TRx mode described in 2.2.3.2.2.1, a long sleep cycle duration may lead to loss of multi-point control protocol (MPCP) synchronization between ONU in the sleep mode and OLT causing MPCP degradation affecting QoS of supported devices [19].

2.3 Ways to save power in the next generation networks

2.3.1 Higher bitrates per user

In wired optical networks, optical burst switching and optical packet switching takes point-to-point wavelength division multiplexing (WDM) networks to the new level. In the optical packet switching, individual packets are optically switched on the correct outgoing interface. Optical buffers with appropriate sizes are not yet commercially available, which makes the optical burst switching be proposed as an intermediate technology. In this approach, for each data burst, a control signal is sent in advance of the packets and allows the burst-switched router to set up a light path for the data that is going to follow the control signal what eliminates the need for infeasible yet optical buffers. Optical packet switching would provide lower power consumption due to eliminating power-hungry optical-electrical-optical conversion stages. For the next decade, a more feasible hybrid approach of still having electronic buffering is considered as a low-power solution [17].

2.3.2 Concentration of equipment

As mentioned in 2.2.2.1.3.1, with the increase in the number of individual network devices, interface proxying can be used to delegate background network traffic processing from internal power hungry CPUs to NIC low-energy processors or to external proxies that may support many interconnected devices. In case of household environment “chatter” traffic processing task may be performed [18].

2.3.3 New applications

One of possibilities to save power indicated in [18] is focused on designing new and redesigning already existing protocols allowing their clients to go to sleep after a specific period of inactivity and recover quickly when needed. This requires, however, modification of already implemented protocols (notification of the client’s idle states to servers that they are connected to, requires additional signalling) and might be rather complex to implement globally.

2.3.4 New semiconductor technologies

New components are manufactured using increasingly power-efficient processes that allow decreasing the supply voltages and leakage currents automatically making PCBs using those integrated circuits less power hungry. Advanced power down modes can be implemented to power down unused chipset subcomponents to save energy [27].

Benefits from advanced PCBs design are described in 2.2.3.2.2.2.

2.3.5 Other factors

[29] states about a possibility of splitting data and signalling of wireless network operation to allow switching off some of the base stations when users are not active in a given BS range. Since not much information is needed to be transmitted to enable “always connected” behaviour, base stations dealing with signalling can be designed for low-rate and long distance transmissions that are more efficient than current mixing between data and signalling transmissions. For BS that provide data connections, at areas that no user is currently active, no signal from any data access point is provided (BS are switched off) to avoid unnecessary waste of radio resources. Since the data BS are designed to provide low data-rate coverage all the time, in case of a user turning to an active state, they may provide service until a proper BS providing data transmissions becomes operational and a handoff can be made.

3 Data analysis software

3.1 Why do we need this tool?

The data analysis tool developed in the scope of this thesis allows for the study of the power profile of the examined device types, demonstrating clearly the potential power saving for such telecommunication devices. Conclusions drawn based on the study of the data traces for different device types are expected to provide guidance for improvements in telecommunication protocols, software, and hardware implementations, aiming at optimizing the power saving potential of such devices.

3.2 Environment used

Data from network traces was pre-processed using Microsoft EXCEL. Trace analysis software was developed in MATLAB.

3.3 Data used and analysis method

3.3.1 Source data and aggregation of activity profiles

Data traces were obtained from the Internet Traffic Archive, representing a moderated repository sponsored by ACM SIGCOMM [31] containing thirty days' worth of wide-area TCP connections established between the Lawrence Berkeley Laboratory (LBL) intranet and the rest of the world. The data set contains trace information starting from midnight, Thursday, the 16th of September 1993 through midnight, Friday, the 15th of October 1993. Newer traces are available, but they are much shorter and do not allow for observation of 24 hours' long activity.

The examined data trace contains activity information for many users connecting to the LBL Ethernet DMZ network (perimeter physical or logical subnetwork that contains and exposes an organization's external-facing services to a larger untrusted network, usually the Internet. Its purpose is to add an additional layer of security to an organization's LAN). In the processing of the data trace, a list of active users (based on their fixed IP address) is generated, together with their activity information (number of activity windows within the examined trace). This list is then sorted in a random fashion, to guarantee most heterogeneous assignment of individual users to individual simulated CPEs possible. The process of selecting individual users and assigning them to individual CPEs is described in more detail later on.

Each CPE was assumed to be connected to three (3) users (average number of habitants per household in Portugal is approximately 3 [32], with the typical number of simultaneously connected networked devices not exceeding five) and the resulting aggregated user activity was observed for the period of 24 hours, producing a day's long activity profile for the access network device.

Next, a number of CPE devices and their activity profiles are aggregated together into a bundle, representing an access port of a DSLAM (in case of xDSL-based access network) or OLT in case of PON-based access network. The resulting activity profile for such a network port is calculated by overlaying activity periods from individual CPEs. The contention caused by simultaneous activity of various CPEs at the same time is disregarded in this study for simplicity.

Finally, a number of access ports are then aggregated into access edge equipment in order to examine its activity profile and study the potential for any power-saving mechanisms.

3.3.2 Input data format

The source data trace data is stored in a Microsoft EXCEL file in columns representing the start time for the activity period (Figure 16 column A) and the duration of the activity period (Figure 16 column B). Column G at Figure 16 indicates the user's unique IP address used to filter out individual users from the large data trace available for processing.

	A	B	G
1	1	2	7
2	748162802.4	1.24383	128.97.154.3
3	748162802.8	3.96513	128.8.142.5
4	748162804.8	1.02839	140.98.2.1
5	748162812.3	138.168	128.49.4.103
6	748162817.5	10.0858	128.32.133.1

Figure 16: Sample of the Microsoft EXCEL initial data file

Information from the original data trace has to be ordered in the descending order according to the column containing the start times of the activity of the users. After this pre-processing, the file can be introduced into MATLAB using the *xlsread* function, which reads data from Microsoft EXCEL cells and stores in MATLAB matrices. The activity periods for individual users can be then plotted with the use of the stairs function in MATLAB, assuming that the active period is represented by a logical "1" and the inactive period – by a logical "0".

The custom-designed data trace analysis software developed in MATLAB examines performs then the analysis on the input data trace, as described in the next section, creating CPE models, aggregating individual CPEs into ports and then creating a model representation of an access device located in the CO.

3.3.3 Input data analysis and network model

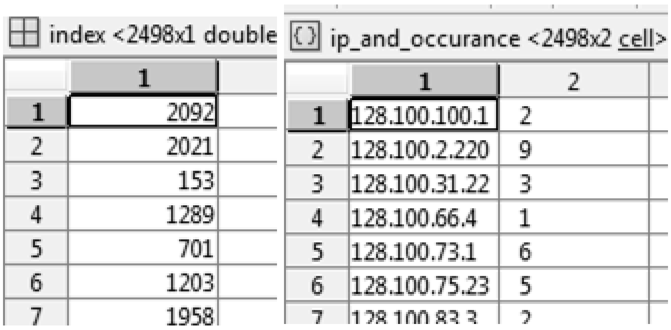
The process of analysis of information included in the data trace features the following stages:

- creation of the randomized user pool; followed by
- creation of the CPE device profile, with connected population of users through aggregation of individual user activity profiles; followed by
- creation of the network port, with connected population of CPEs, through aggregation of individual CPE activity profiles; and finally followed by
- creation of the network device profile, comprising a number of network ports, each with its unique activity profile.

Individual stages are discussed in more detail below.

3.3.3.1 Creation of the randomized user pool

The input data trace contains information about activity periods for a number of individual users. Each IP address and its occurrence in original data file correspond to one user connected to the CPE. Database is built containing IP number and the number of its occurrence in the examined data trace. Data pool is randomized. Figure 17 shows that 1st entry in the index array represents users' IP address stored in 2092 line in *ip_and_occurance* array. Amount of indexes of IP addresses indicated by software user are chosen from the top of the list and erased afterwards to prevent duplicated usage



index <2498x1 double

	1
1	2092
2	2021
3	153
4	1289
5	701
6	1203
7	1958

ip_and_occurance <2498x2 cell>

	1	2
1	128.100.100.1	2
2	128.100.2.220	9
3	128.100.31.22	3
4	128.100.66.4	1
5	128.100.73.1	6
6	128.100.75.23	5
7	128.100.83.3	2

Figure 17: Randomized index list for each IP address and IP addresses list and their occurrence in source file presented in Figure 16

3.3.3.2 User activity profile

Each entry in the index array represents IP address stored in indicated line in *ip_and_occurance* array. The original data trace is scanned for occurrences of the given IP address associated with the specific user and the resulting activity periods are then aggregated into a separate data array, representing the user activity profile, with on and off times (see Figure 18, Figure 19).

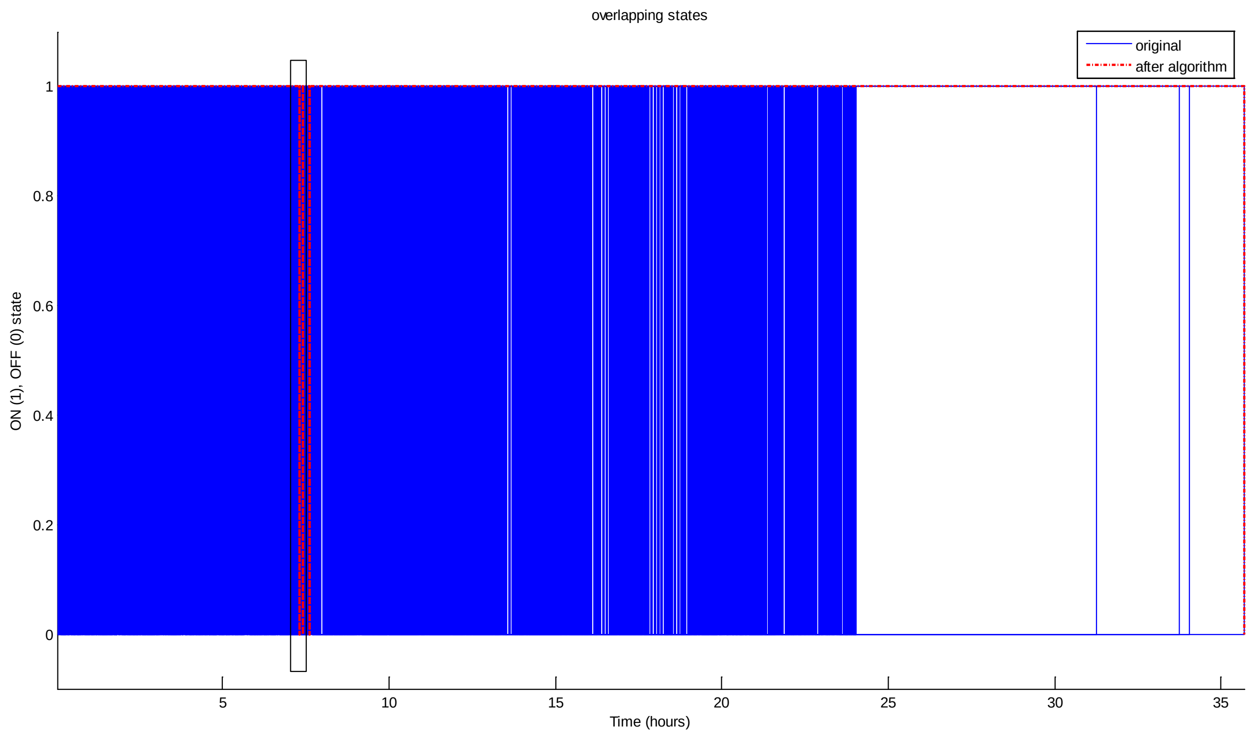


Figure 18: Activity of the user

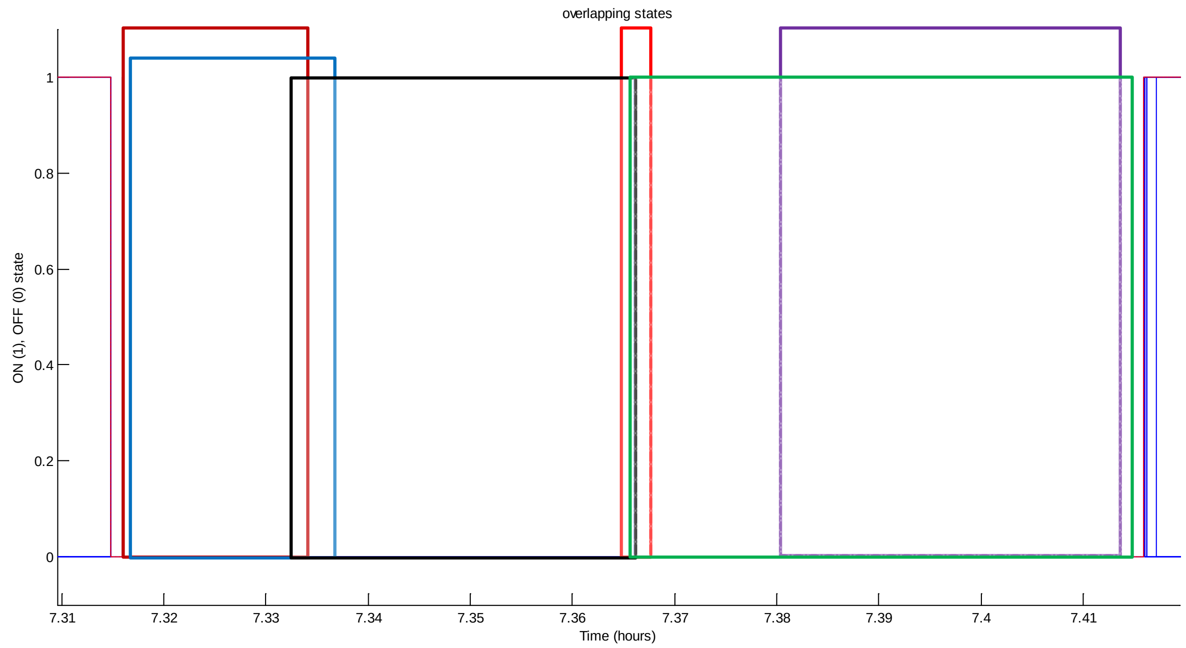


Figure 19: Detailed activity of the user (black rectangle marker on Figure 18). Various colours and diffrent sizes represent multiple ovelaping activity windows.

3.3.3.3 Aggregation algorithm

As seen on Figure 19, the activity of a user is constituted by many overlapping periods what is caused by running various software types accessing the network at different times. The algorithm replaces overlapping windows by one continuous period of activity (see Figure 20).

To allow proper functioning of the algorithm previously mentioned input data pre-processing stage cannot be omitted. Flowchart of the algorithm is presented on Figure 21.

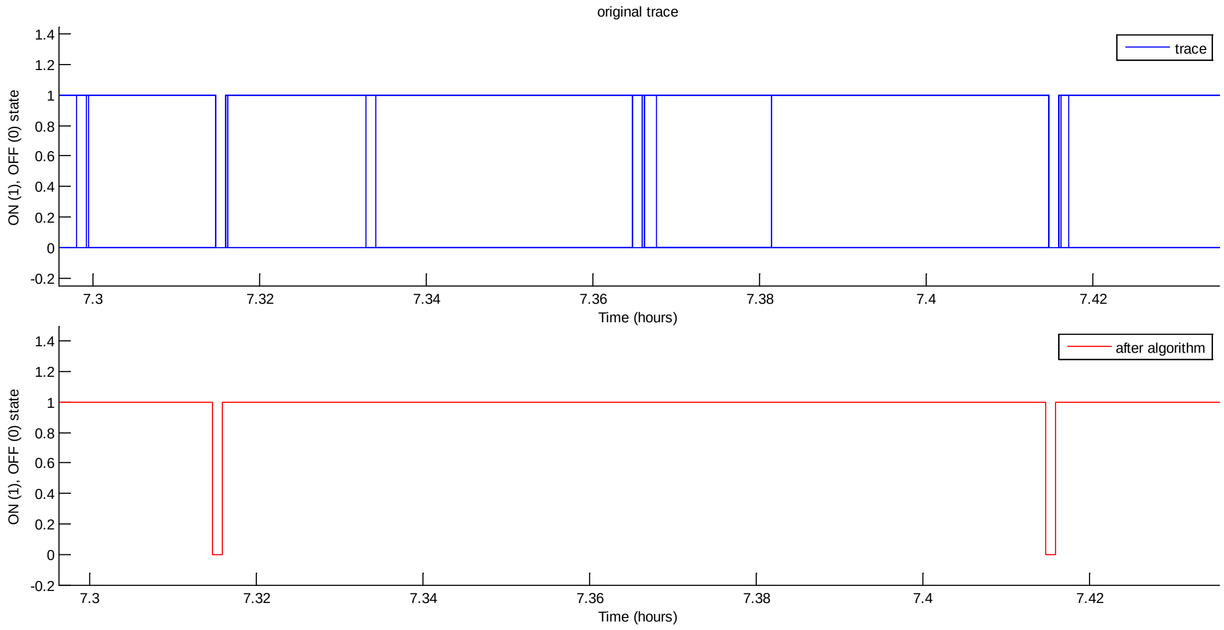


Figure 20: example of algorithm at work

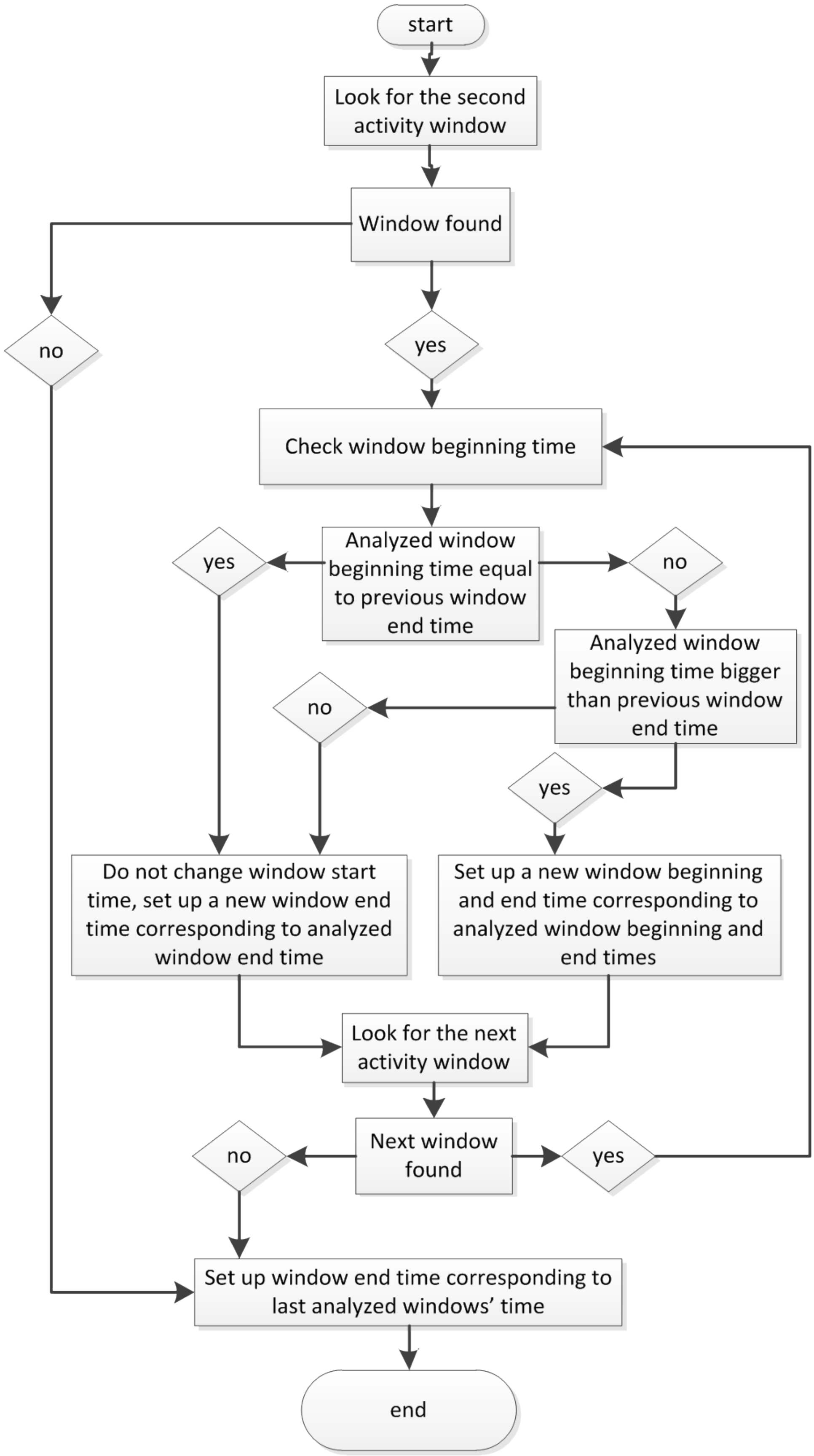


Figure 21: Activity window aggregation algorithm flow chart

3.3.3.3.1 Particular cases

If beginning of the analysed activity window (Figure 22, time point *b*) is starting earlier than the end of the previous activity period represented by block “1” (Figure 22, time point *c*), the initial start time of the window (Figure 22, time point *a*) is not changed. When end time of activity period “1” (Figure 22, time point *c*) is after the beginning time of the analysed activity window (Figure 22, time point *b*) but earlier than the end of the period that is looked into (Figure 22, time point *d*), new end time is saved (Figure 22, time point *d*) and the activity periods are merged (Figure 22, time point *a* and *d*) and new window is chosen to analyse (Figure 22, time points *e* and *f*).

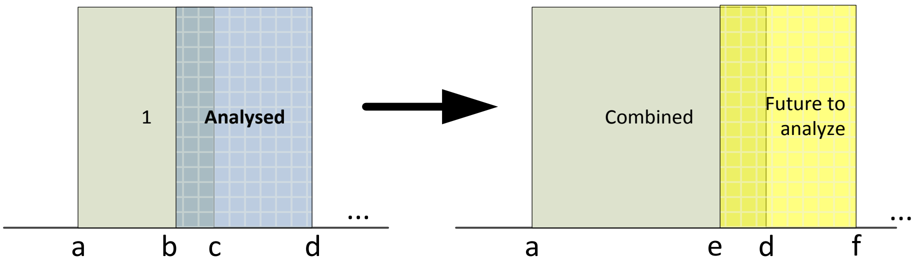


Figure 22: Window overlapping with analysed

When the start of the analysed window (Figure 23, time point *c*) begins after the end of the window “1” (Figure 23, time point *b*), the new start time of the window is set up (Figure 23, time point *c*) and analysed window becomes window “2” with end time designated by point *d* and new window is chosen to analyse with time points *e* and *f* .

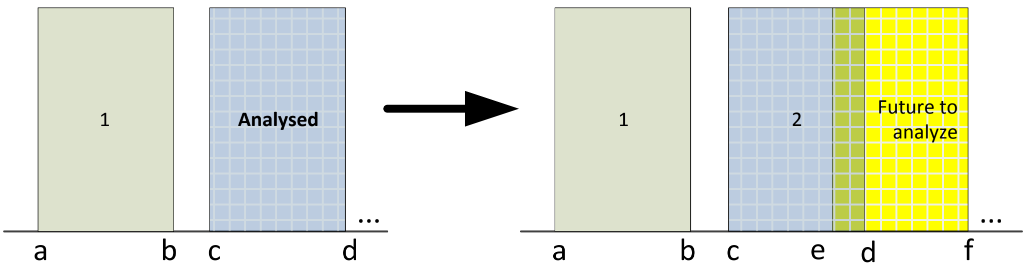


Figure 23: Window not overlapping with analysed

3.3.3.4 Aggregating multiple activity profiles

During the preparation process, connection times are sorted descending to use the algorithm that has been developed for data organized in this way. It is expected that each user is going to connect in isolated time instances, but reality is completely different. In the case of APs, ports or device users connection attempts may occur in same or similar times, creating overlapping activity periods (Figure 24)

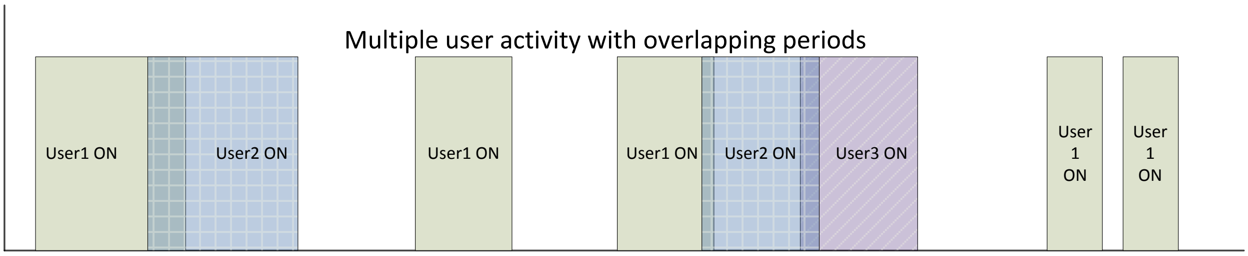


Figure 24: Overlapping activity periods of multiple users connected to a single CPE

Thanks to the algorithm, overlapping periods are converted into a single, longer activity window representing the overall CPE's activity (see Figure 25).

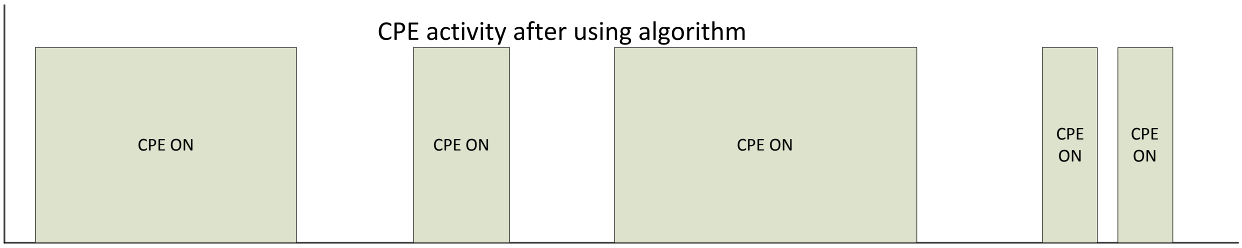


Figure 25: Aggregated by algorithm activity periods of multiple users creating CPE activity

Since post-processing is used for each CPE, port or device, additional delays that are needed for power-up and power-down phase of access point can be applied to the data at this point. After applying power-up delay to the first activity window, situation may appear that its beginning time may take on negative value. In this case the model hast to be rescaled to avoid negative time values. After applying all delays, some periods of activity may overlap (Figure 26)

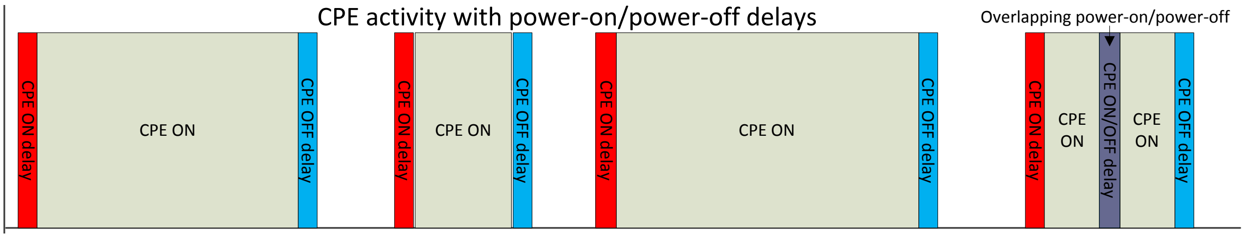


Figure 26: Activity of CPE with power-on/power-off delays

Aggregation algorithm described in section 3.3.3.3 is applied to overlapping periods to create larger, continuous periods of activity (Figure 28).

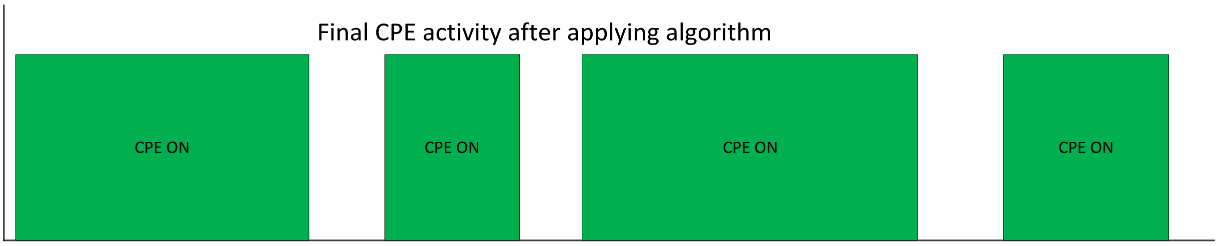
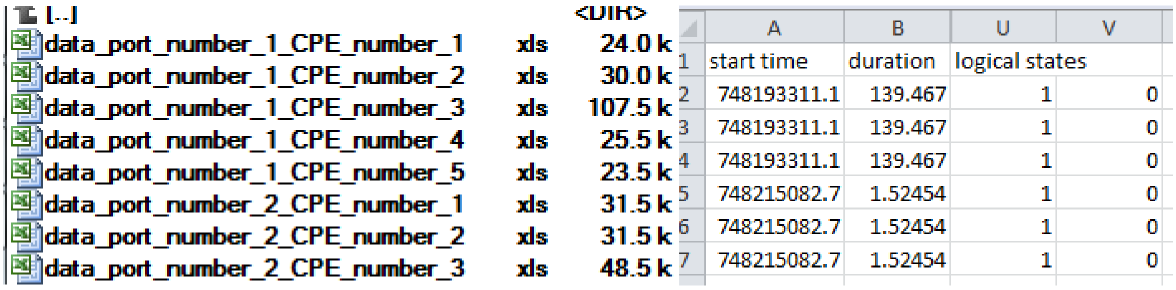


Figure 27: Final CPE activity periods

3.3.3.5 Creation of the CPE device profile

Data analysis software is designed to have an option to input manually the number of users connected to each CPE. This number signifies how many IP addresses from the original data trace are used and erased from the top of the index table as described in section 3.3.3.1. Aggregated data representing combined activity of all users connected to a given CPE is returned to a pre-specified folder to a Microsoft EXCEL file with name "*data_port_number_X_CPE_number_Y*", where "*X*" and "*Y*" correspond to number of network port and CPE respectively (see Figure 28).



	A	B	U	V
1	start time	duration	logical states	
2	748193311.1	139.467	1	0
3	748193311.1	139.467	1	0
4	748193311.1	139.467	1	0
5	748215082.7	1.52454	1	0
6	748215082.7	1.52454	1	0
7	748215082.7	1.52454	1	0

Figure 28: Format of output files for CPE and sample data preview

3.3.3.6 Creation of the network port profile

After introducing amount of CPE connected to a single port, data from number of CPEs indicated is aggregated to create a single port activity and a data is returned to a pre-specified folder to a Microsoft EXCEL file with name "*data_port_X*", where "*X*" corresponds to port number (Figure 29). Data structure corresponds to the one from CPE.

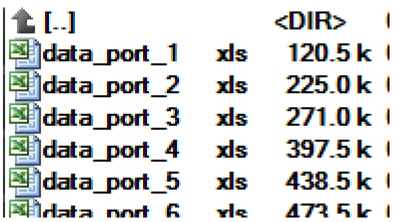


Figure 29: Format of output files for network port

3.3.3.7 Creation of the network device profile

Network device activity is created after introducing the number of ports being active and data from corresponding ports is aggregated and stored in a pre-specified folder to a Microsoft EXCEL file (see Figure 30).

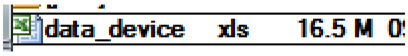


Figure 30: Device data profile output file

Since it is very probable that the amount of data lines needed to be saved in the file is much larger than 65536 (maximum amount of lines that *xlswrite* function in MATLAB allows to write in one go to the file), a safety mechanism has been developed to store each 65535 lines in a new sheet (see Figure 31). The last sheet always contains the outstanding data form division of total amount of lines stored in *provider_device* variable by maximum data length that can be managed by *xlswrite* function (65536).

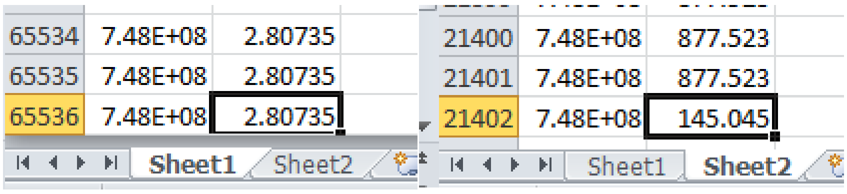


Figure 31: Restrictions of xlswrite MATLAB function and final data sheet

3.3.4 Energy consumption calculations

Once the network model is established and there is an automated mechanism available (see paragraph 3.3.3) to build a network topology based on the input data trace, the energy consumption for the hypothetical network model needs to be established. The process of calculating energy consumption accounts for individual CPE instances, as well as the network device models, and their power consumption in the active and inactive states. Put simply, the developed software calculates the total amount of time the given device (CPE, port, or network device) remains in the active state over the period of 24 hours, and then using the power consumption profile for the given device – calculates its total power consumption. During the process, the on/off times are also accounted, for, required for the given examined device to properly power up / down (respectively) and enter into the alternative activity state.

Thanks to list of options included in the developed software tool, it is possible to customize power consumption as well as on/off times for individual network elements, including CPE, network port, and network device as a whole.

First option is choosing type of the data aggregation followed by the data file saved in previous steps of the software execution (see paragraphs: 3.3.3.5, 3.3.3.6 and 3.3.3.7).

To make calculations as close as possible to reality for a specific device, an option is introduced to choose start-up / power down delays specific for the equipment of choice.

After this stage software returns the total working time, ON time, OFF time and ratios of ON/OFF time to the total time that gives fraction ON/OFF time presented in percents.

Another option is to specify the period of time, for which we would like to have calculations of power consumption done, what can be done thanks to the ratio ON/OFF time to the total time.

In next phase, a type of CPE, port or device can be chosen, each with individual power consumption profiles (see paragraph 3.3.5). Data can be adjusted if needed by editing file "*always_on.m*" (CPE profile), "*always_on_port.m*" (port profile), "*always_on_device.m*" (device profile) for no power saving and "*always_on_off.m*", "*always_on_off_port.m*", "*always_on_off_device.m*" for devices that use energy conservation mechanisms.

Having all data necessary like fraction of ON/OFF time, period of time used for calculation, energy consumption profiles, amount of energy consumed by a given device with/without power saving mechanisms can be calculated to perform further data analysis(see Figure 32, Figure 33).

```
power used while ON with power saving = 96.548 Wh

power used while OFF with power saving= 39.3184 Wh

power used while ON without power saving=  Wh

power used while OFF without power saving=  Wh

total power used for given choice of work type= 135.8664 Wh
```

Figure 32: Example results for a given equipment of choice for 24 hour period with power saving mode ON

```
power used while ON with power saving =  Wh

power used while OFF with power saving=  Wh

power used while ON without power saving= 96.548 Wh

power used while OFF without power saving= 64.252 Wh

total power used for given choice of work type= 160.8 Wh
```

Figure 33: Example results for a given equipment of choice for 24 hour period without power saving mode ON

3.3.5 Power consumption profiles

To perform energy consumption study for a given CPE, port, and network device, it is necessary to have information about equipment configuration and detailed power consumption profiles. Data presented in Table 14, Table 15, Table 16and Table 18 was taken from [8], [16], [33] and [34]. Product specification data sheets provide only the maximum energy consumption. [35] states that the exact data about power consumed by ONU and OLT while working in the power saving mode is inaccurate and needs further investigation. Equipment is bound to conform to IEEE 802.3az standard (EEE – Energy Efficient Ethernet) standard, an assumption can be made that each port of a given device using EEE and in power saving mode uses approximately 10% of port's maximum energy consumption. For ONU network equipment it is safe to say that in low load state, power consumption may drop to 30% of the maximum value. For ADSLAM equipment, only data available for power usage for low load states is for ports. Based on information for DSL devices, power usage has been approximated.

Data from Table 14 through Table 19 presenting power consumption in different states is stored in files *always_on.m*" (CPE profile), "*always_on_port.m*" (port profile), "*always_on_device.m*" (device profile) for no power saving and in "*always_on_off.m*", "*always_on_off_port.m*", "*always_on_off_device.m*" respectively for energy conservation mechanisms.

Equipment states are defined as follows:

ADSL home gateway:

- in idle-state: all Ethernet LAN ports disconnected, no traffic on Wi-Fi

- in on-state: all Ethernet LAN ports active, traffic on Wi-Fi

VDSL2 home gateway:

- in idle-state: all Ethernet LAN ports disconnected, no traffic on Wi-Fi, no active voice call

- in on-state: all Ethernet LAN ports active, traffic on Wi-Fi, 1 active voice call (the second FXS port has no device connected and for this port the idle target needs to be considered)

DOCSIS 3.0 CPE in 8x4 configuration:

- in idle-state: the Ethernet LAN port is disconnected

- in on-state: the Ethernet LAN port is active

Table 14: Examples of home gateway configurations with power consumption targets [8]

Functional clocks of the devices	idle-state for years 2013/2014	on-state for years 2013/2014
ADSL Home Gateway		
Central functions + ADSL WAN interface	2,4 W	3,4 W
4 Fast Ethernet LAN ports	4 × 0,2 = 0,8 W	4 × 0,4 = 1,6 W
single radio IEEE 802.11b/g Wi-Fi interface (23 dBm EIRP)	0,7 W	1,5 W
USB ports	2 × 0,1 = 0,2 W	2 × 0,1 = 0,2 W
Total	4,1W	6,7W
VDSL2 Home Gateway		
Central functions + VDSL2 WAN interface (17a)	3,2 W	4,6 W
4 Gigabit Ethernet LAN ports	4 × 0,2 = 0,8 W	4 × 0,6 = 2,4 W
single IEEE 802.11n radio Wi-Fi interface with 3 RF chains 3x3 MIMO (23 dBm)	0,8+0,1 = 0,9 W	2,0+0,4 = 2,4 W
USB ports	2 × 0,1 = 0,2 W	2 × 0,1 = 0,2 W
FXS ports	2 × 0,3 = 0,6 W	1,2+0,3 = 1,5 W
Total	5,7W	11,1W
Ethernet router with 4 Fast Ethernet LAN ports		
Central functions + Fast Ethernet WAN interface	2,0 W	3,0 W
Fast Ethernet LAN ports	4 × 0,2 = 0,8 W	4 × 0,4 = 1,6 W
Total	2,8W	4,6W
Cable DOCSIS 3.0 CPE		
Central functions + DOCSIS 3.0 basic configuration WAN interface	6,2 W	7,1 W
1 DOCSIS 3.0 Additional power allowance for the additional 4 downstream channels	2,2 W	2,8 W
1 Gigabit Ethernet LAN port	0,2 W	0,6 W
Total	8,6W	10,5W
Complex HNID: dual-band 11n access point with 4 Gigabit Ethernet LAN ports		
Wi-Fi Access Points with single band IEEE 802.11n radio (23 dBm), 2x2 MIMO	2,3 W	3,9 W
single IEEE 802.11n radio Wi-Fi interface (23 dBm), 2x2 MIMO	0,8 W	2,0 W
3 additional Gigabit Ethernet LAN ports	3 × 0,2 = 0,6	3 × 0,6 = 1,8 W
Total	3,7W	7,7W
GPON ONT used in FTTH: ZXA10 F660 [34]		
	1.2 W	< 12 W

Table 15: Power consumption of deployed optical CPEs 1

Deployed optical devices	IDLE - state[W]	ON - state[W]
F401(EPON + 1GE)	2.8W	<5W
F1400(10G-EPON + 4GE)	4.5 W	8 W

[1] Data courtesy of ZTE Company R&D team

Table 16: Examples of different port configuration power consumption [8]

Port configuration	IDLE-state[W]	ON-state[W]
ADSL2plus (including ADSL and ADSL2 and with transmission power of 19,8 dBm)	0.9 W	1.7 W
GPON, >32 ports	0.8 W	8 W
GPON, <=32 ports	0.85 W	8.5 W
XG-GPON, >32 ports	2.2 W	22 W
XG-GPON, <=32 ports	2.3 W	23 W
1G-EPON, >32 ports	0.81 W	8.1 W
1G-EPON, <=32 ports	0.88 W	8.8 W
10/1G-EPON, >32 ports	2.24 W	22.4 W
10/1G-EPON, <=32 ports	2.58 W	25.8 W
10/10G-EPON, >32 ports	2.47 W	24.7 W
10/10G-EPON, <=32 ports	2.7 W	27 W

Table 17: Power consumption per port of deployed network cards[2]

Deployed optical network cards	IDLE - state[W]	ON - state[W]
C300 19 inch Chassis: 16 ports EPON Line card - 56W	0.35 W	3.5 W
C300 19 inch Chassis: 8 ports 10G-EPON line card - 80W	0.8 W	8 W

Table 18: Examples of network device power consumption [16]

Network device configuration	IDLE-state	On-state
ZXA10 C300 Shelf		
full configuration (EPON)	225 W (30% of ON)	< 750 W
full configuration (GPON)	300 W (30% of ON)	< 1000 W
full configuration (10G-EPON)	375 W (30% of ON)	< 1250 W
D-Link DAS-3248 a 48-port IP-based DSL Access Multiplexer [33]		
	126 W	< 150 W

Table 19: Configuration of deployed network devices[3]

Deployed optical network devices	IDLE - state[W]	ON - state[W]
Full C300 19 inch Chassis with 16 ports EPON Line cards configuration (14 line cards)	300 W (30% of ON)	1000 W
Full C300 19 inch Chassis with 8 ports 10G-EPON line cards configuration (14 line cards)	435 W (30% of ON)	1450W

3.4 Results of data analysis

The parameters (Figure 35, Figure 36, Figure 37, type of device) used for the analysis are arbitrary and their purpose is to indicate the necessity of using power saving techniques in designing new network equipment.

[2] Data courtesy of ZTE Company R&D team

[3] Data courtesy of ZTE Company R&D team

```
number of users per CPE:    5
number of CPE per port:    5
number of ports per network device:    12
```

Figure 34: Amount of users per CPE, CPEs per port and ports per network device

```
                                MENU:

          choose type of data you want to process:

  1 to choose data for CPE:
  2 to choose data for port
  3 to choose data for whole equipment
your choice : 1



 CPE
```

Figure 35: CPE chosen to be analysed

```
insert start-up delay for the device in micro seconds:
22
insert shut-down delay for the device in micro seconds:
22
```

Figure 36: Start-up, shut-down delays

```
total_on_time = 47237.3189 seconds
total_off_time = 35897.0215 seconds
total_time = 83134.3404 seconds
fraction_on_time = 56.8 %
fraction_off_time = 43.2 %
```

Figure 37: ON and OFF times and ON and OFF fractions of time obtained for the given CPE data profile by software algorithm.

```
total_on_time = 123704.1007 seconds
total_off_time = 2798.8995 seconds
total_time = 126503.0002 seconds
fraction_on_time = 97.8 %
fraction_off_time = 2.2 %
```

Figure 38: ON and OFF times and ON and OFF fractions of time obtained for the given network device data profile by software algorithm.

After running the algorithm described in section 3.3.3.3 activity profile has been obtained and is presented on Figure 39.

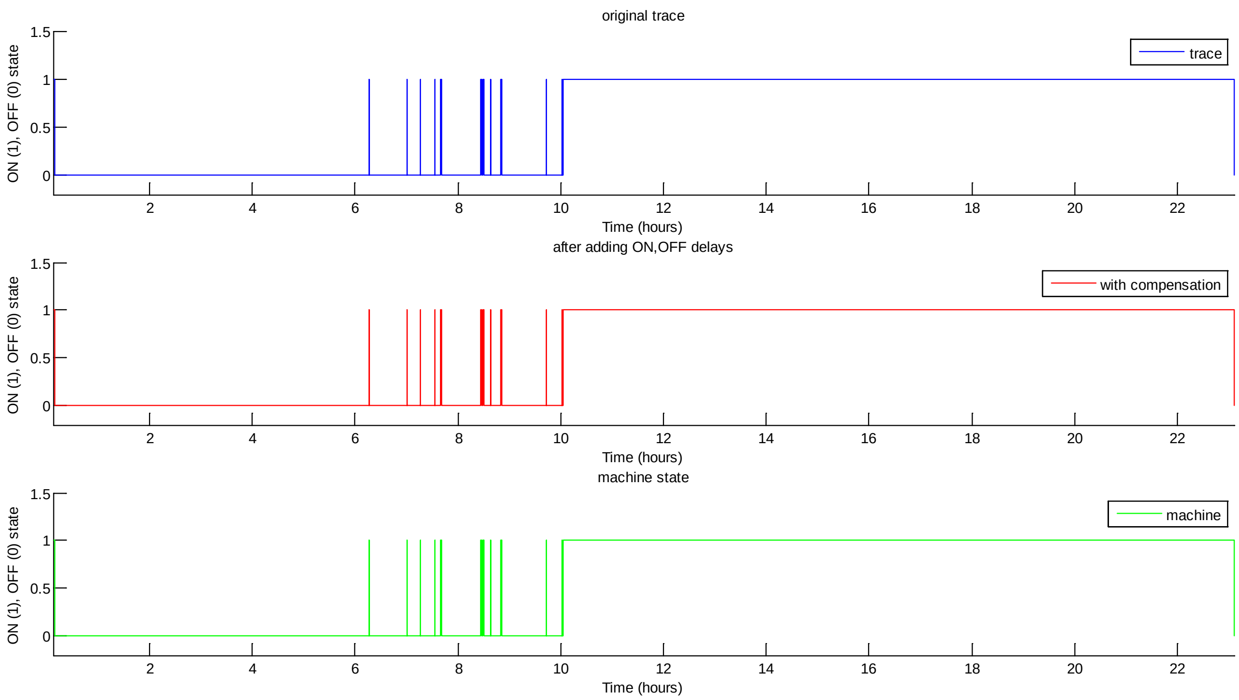


Figure 39: Activity of users and equipment including mentioned start-up and power-down delays

An activity period of 24 hours has been chosen for the given CPE device (Figure 40).

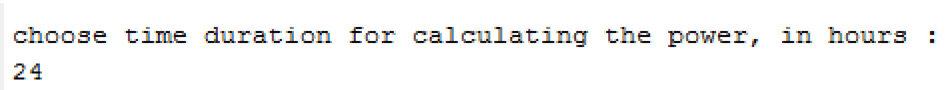


Figure 40: Activity duration for analysys

After executing the algorithm described in 3.3.3.3, the activity profile for the network device was obtained, as shown in Figure 41.

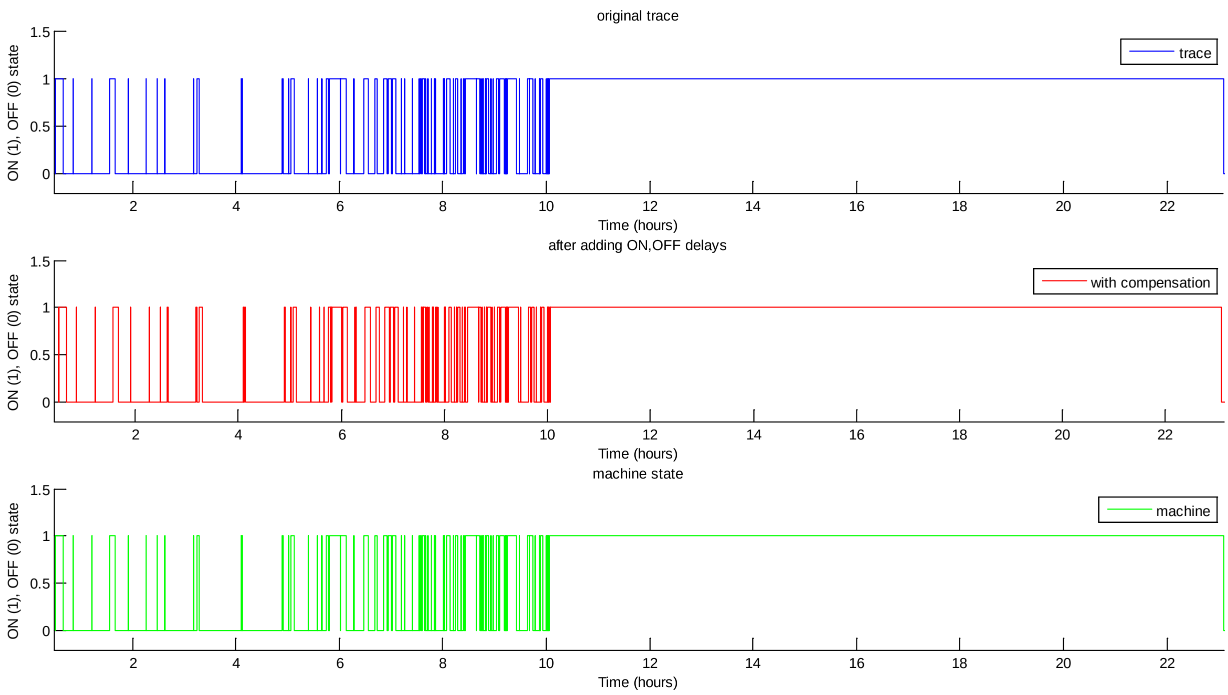


Figure 41: Network equipment activity profile

4 Conclusions from data analysis

Few chosen CPE's and network devices were examined using the developed software model using the data analysis software. Table 20 presents the values of the total energy consumed in normal operation and with power saving modes being applied.

Table 20: Results of data analysis

device		Power used when busy [Wh] [1]	Power used when idle [Wh] [2]		Total power used [Wh]		Gain from power saving [Wh]	Gain from power saving [%]
			Power saving ON	Power saving OFF	Power saving ON	Power saving OFF		
CPE	HNID [3]	105	38	80	143	185	42	23%
	VDSL2	151	59	115	210	266	56	21%
	1G-EPON F401	68	29	52	97	120	23	19%
Network device	DSL DAS-3248	3520	67	80	3587	3600	13	0.36%
	1G-EPON	17601	119	398	17721	18000	279	1.55%
	10G-EPON	29336	199	664	29535	30000	465	1.55%

[1] power used when traffic is present on port
[2] power used when traffic is absent on port
[3] includes dual-band 802.11n access point with 4 GE LAN ports

It is estimated that around the world 60 million EPON ONUs [19] are deployed what gives a potential of saving 1.4 TWh (taking into consideration values from Table 19 for F401 ONU) per day for a network utilization profile used as reference in this thesis. Even more gain can be achieved if more advanced technologies and algorithms are developed and utilized in the CPE equipment.

Around the world there is about 2.34 million OLT ports deployed [19]. The usual cabinet has 14 line cards with 16 ports what gives 224 ports per cabinet translating into about 10500 cabinets. For considered network activity profile a possibility of saving about 2.93 MWh (for values from Table 19) for EPON equipment exists only by implementing active energy conservation methods.

Taking into account that the average household power consumption in US is around 1kW (24kWh) [19], the energy saved through active power saving techniques during utilization of ONU, would be sufficient to power about 58 million households and in case of OLTs – 125 houses. Even greater savings may be achieved by combining active and passive saving methods.

5 Future studies

Developing optical buffers with sufficient storage capabilities can make optical packet switching feasible [17].

Energy consumption of devices like switches and routers are generally not available with a proper level of details. Guidelines for manufacturers are located in [8]. Datasheets of these devices indicate single value of consumed energy which corresponds to a particular operation mode or maximum energy consumption. By knowing the technical specifications of the equipment and combined with data from BCOC [8], approximated values can be obtained. Community still lacks a set of measurement figures and efforts are necessary to gather and publish this type of a database that should have different types of equipment (DSLAMs, switches, set-top-boxes, etc.) and comparing different communication technologies available on the market [18].

In the near future users may run energy aware applications in a home equipped with devices implementing various protocols allowing saving energy while connected to internet service provider using sophisticated routing and adaptive link rate lines. This picture brings number of interesting questions mainly how different combinations may impact on performance from user-perspective and network behaviour since each of the power savings separately may not pose threat to security of transmission or QoS but when joined – then may constitute serious threats [18].

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7 Annexes

A. Types of access networks

See separate file for Annex A

Data analysis software tutorial

B. See separate file for Annex B

Annex A
Types of access networks

Table of Contents

i. Figure list

ii. Table list

iii. Acronyms

ADSL	Asymmetric Digital Subscriber Line
CATV	Cable Television
CPE	Customer Premises Equipment
DOCSIS	Data Over Cable Service Interface Specification
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
EPON	Ethernet Passive Optical Network
HFC	Hybrid Fibre Coaxial
IEEE	Institute Of Electrical And Electronics Engineers
ISDN	Integrated Services Digital Network
ITU	Information Technology Union
LAN	Local Area Network
MSC	Mobile Switching Centre
P2P	Point To Point
PBX	Private Branch Exchange
PON	Passive Optical Network
PSTN	Public Switched Telephone Network
RDSLAM	Remote Digital Subscriber Line Access Multiplexer
SS7	Signalling System No. 7
Wi-Fi	Wireless Fidelity (IEEE 802.11b Wireless Networking)
WiMAX	Worldwide Interoperability For Microwave Access

1 Introduction

An access network is the part of the telecommunications network which connects subscribers to their immediate service provider. The access network may be further divided into (a) feeder plant or distribution network, and (b) drop plant or edge network. The function of the access network is to collect traffic from customer locations and deliver it into the carrier network through a number of layers of aggregation, e.g., through LAN, MAN and into WAN, or directly in the WAN in case of larger enterprise customers.

This annex provides an overview of modern access technologies to allow better understanding of the power saving technologies described in the main document.

2 Wireless networks

2.1 Cellular network [1]

In cellular access networks (see Figure 1), a Mobile Switching Centre (MSC) manages wireless base station (BS) and acts as an interconnection to the core network. Users connect directly to a BS via a wireless link or through a wireless Access Points (AP). An AP may be connected directly to an MSC or may provide relay function for the signal from a BS.

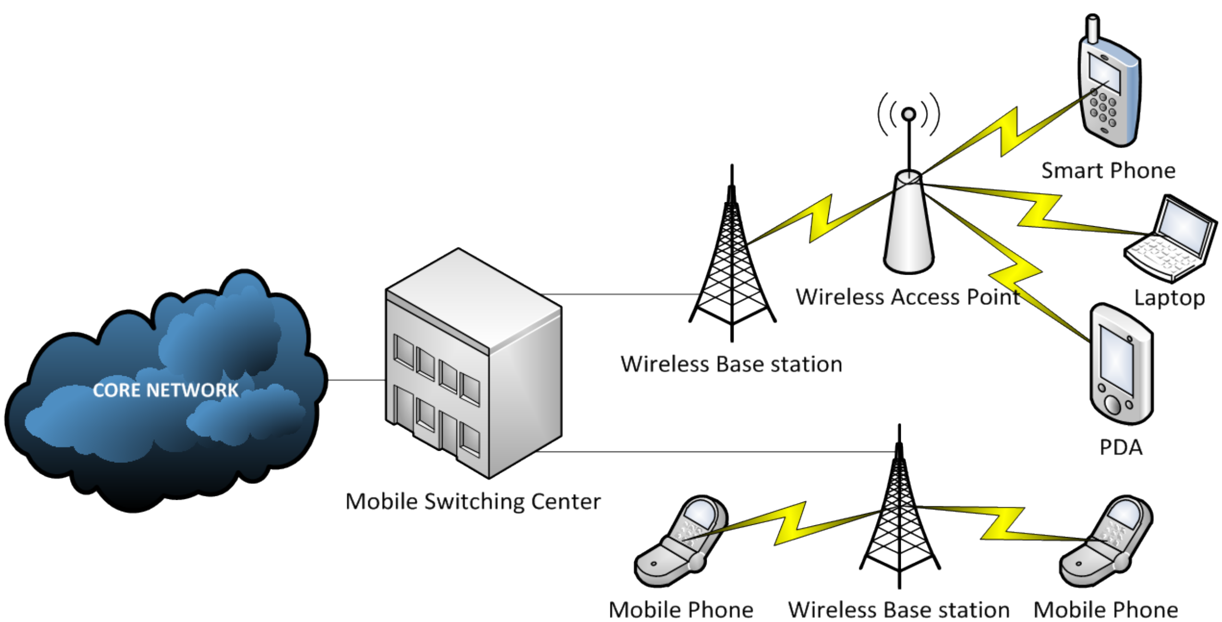

Figure 1: Wireless access network and user equipment

Furthermore, each BS requires a backhaul link in the form of a wired line or a microwave link, providing connectivity to the MSC. The MSC provides connectivity between many BSs and the aggregation / core network to guarantee access to Internet and connection for other available services like voice calls, messaging services, etc.

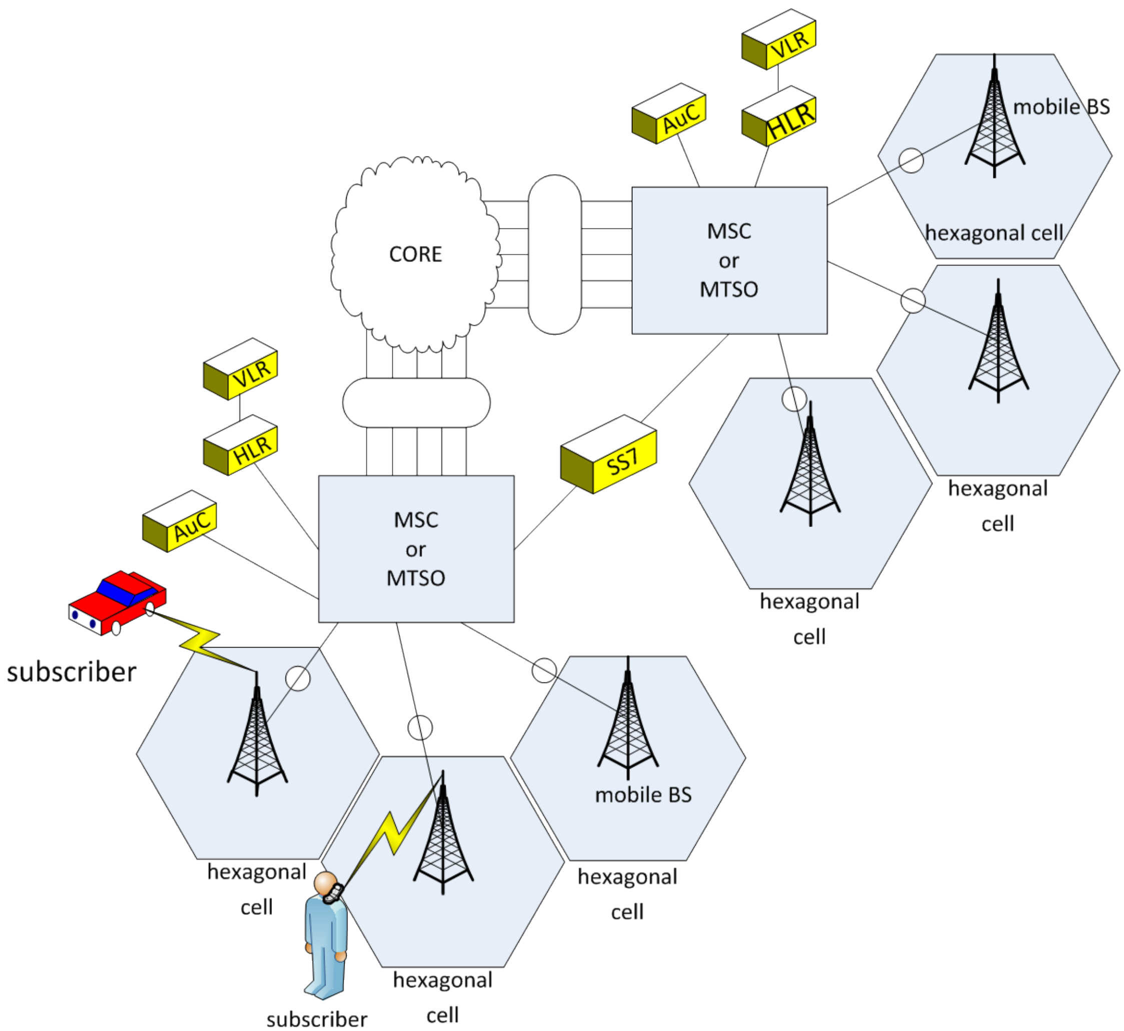

Figure 2 Block diagram of cellular system

2.2 Wi-Fi [1]

Wireless Fidelity (Wi-Fi is a family of IEEE 802.11 standards for wireless networking) has enabled the proliferation of cost-effective, high-speed networking for mobile devices, primarily laptop computers in various locations, including coffee shops, hotels, homes, classrooms. Wi-Fi (see Figure 3) eliminates the need for wired network connection, providing wireless Ethernet connectivity within a geographically constrained area, with the radius of typically a few hundred meters at best. Wi-Fi uses unlicensed portions of the microwave bands (2.45–5.7 GHz). The network radius depends strongly on the presence of any obstacles, primarily walls, trees, landscape elements etc. Wi-Fi networks in general suffer much more from attenuation than cellular networks, and only recent additions to the family of IEEE 802.11 standards provided support for multi-antenna arrangements (MIMO), enabling echo cancellation and improved beam formation.

As shown in Figure 3, a Wi-Fi AP is connected to local area network (LAN) via a wired connection, typically some form of point to point (P2P) Ethernet link, using either copper (most often) or fibre (more common in enterprise-class APs) medium. A number of users within the coverage area of a Wi-Fi AP access the network using their devices equipped with Wi-Fi cards. Nowadays, Wi-Fi cards are embedded into laptop computers, PCs, mobile phones, printers and other computer and general-purpose equipment, providing simple network access, requiring no cables and very little technical knowledge to setup.

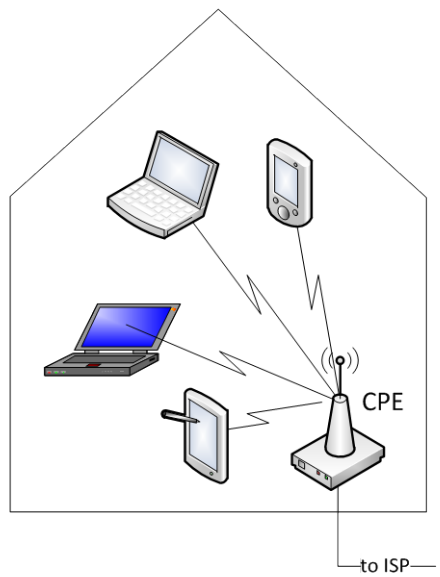

Figure 3: Wi-Fi used within a building

2.3 WiMAX [1]

WiMAX (Worldwide Interoperability for Microwave Access, Inc. – a group promoting IEEE 802.16 wireless broadband standard) provides a wireless alternative to fibre, cable, and even the cellular phone system for broadband access. WiMAX is primarily used for mobile backhauling, linking existing cellular BSes together where wired connectivity is not available, or its deployment cost would be prohibitive. WiMAX has the line-of-sight limitation and is typically quoted to work at distances of up to 50 km. In rural areas, where population density is low and the cost of deploying a complete wired networking architecture makes such business economically-unsound, individual or business clients receive WiMAX signals via rooftop antennas, similar to the way terrestrial television is received. In some cases, it is also possible to receive WiMAX signals directly using dedicated computer cards, in a fashion similar to the Wi-Fi is used in laptops nowadays. In fact, some high-end portable computers are equipped with both Wi-Fi and WiMAX cards to provide a more complete network access solution. In the scenario presented in Figure 4, WiMAX AP supplies signals to computers directly through their WiMAX cards or to Wi-Fi APs, that in turn distribute data connection to individual users connected via Wi-Fi links.

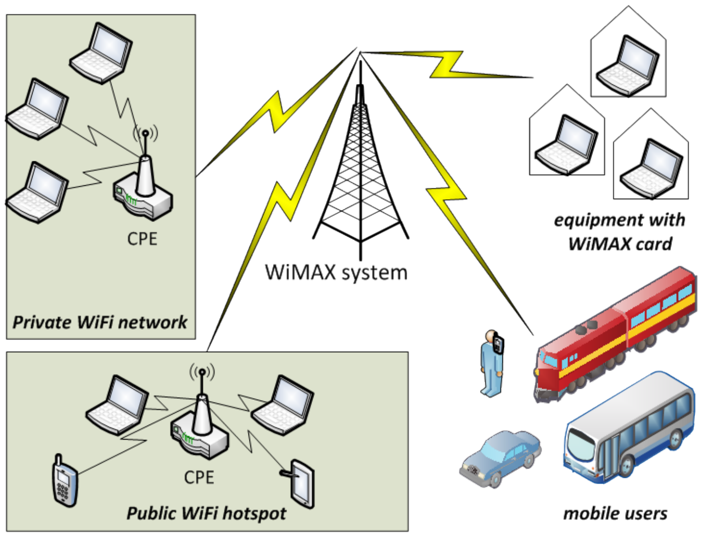

Figure 4: WiMAX applications with mobile and fixed users

3 Wired network

In a wired access network (see Figure 5), a customer premises equipment (CPE) is connected to central office (CO) via a copper cable or an optical fibre or some combination of both. Inside the customer premises, there is a CPE with a number of electrical or optical network-side interfaces. This device may provide only wired or as well wireless connection capabilities for subscribers.

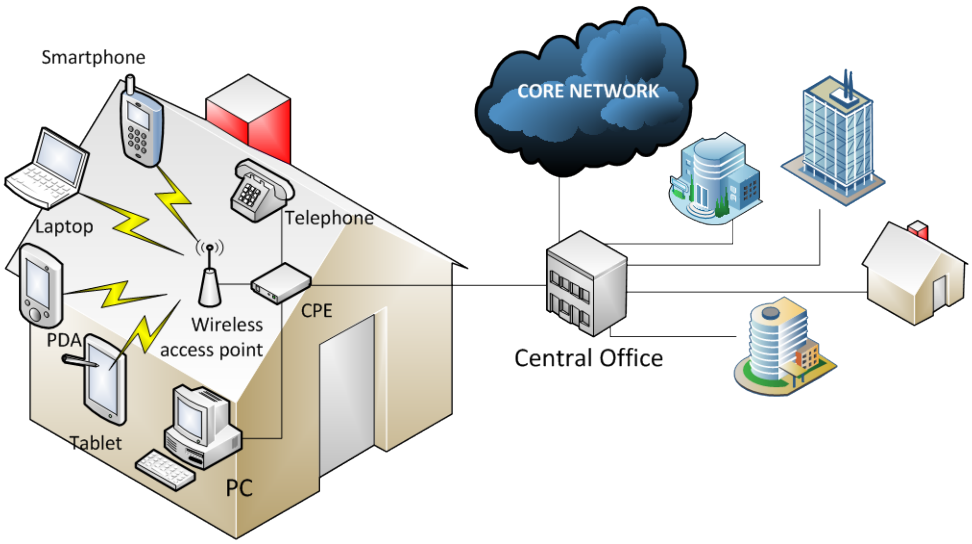

Figure 5: Wired access network and the location of CPE

3.1 Public Switched Telephone Network (PSTN) architecture [3]

The PSTN architecture (see Figure 6) includes a number of transmission links and nodes. There are basically four types of nodes: CPE nodes, switching nodes, transmission nodes, and service nodes.

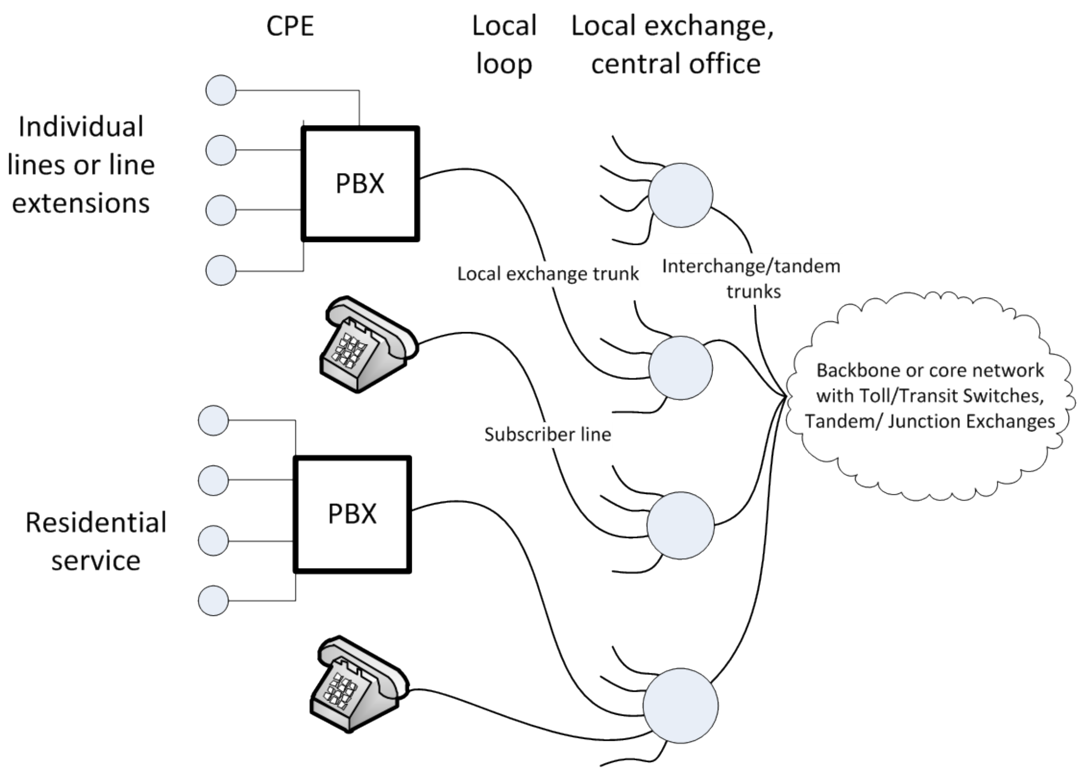

Figure 6: PSTN architecture

CPE nodes generally refer to equipment located at the customer site. The main function of CPE nodes is to transmit and receive user information. The other key functions include exchange of control information with the network management system. CPE equipment includes private branch exchange (PBX), key telephone systems, and single-line telephones.

Switching nodes interconnect transmission facilities at various locations and route traffic through a network. They set up the circuit connections for a signal path, based on the number dialled. To facilitate this type of switching, the ITU specified a worldwide numbering plan (based on ITU E.164) that essentially acts as routing instructions indicting how to forward a call through the PSTN. Switching nodes include local exchanges, tandem exchanges (for routing calls between local exchanges within a city), toll offices (for routing calls to or from other cities), and international gateways (for routing calls to or from other countries). Primary network intelligence is contained in Class 4 switches (i.e., toll offices switches) that provide long-distance switching and network features and in Class 5 switches (i.e., local exchange switches) that serve as local switches and allow specific features that subscribers

Transmission nodes are part of the transport infrastructure and provide communications paths that carry user traffic and network control information between the nodes in a network. The transmission nodes include the transmission media as well as transport equipment, including amplifiers and/or repeaters, multiplexers, digital cross-connect systems, and digital loop carriers.

Service nodes handle signalling, which is the transmission of information to control the setup, holding, charging, and releasing of connections, as well as the transmission of information to control network operations and billing. A very important area related to service nodes is the ITU standard specification Signalling System 7 (SS7), used to set up and tear down calls, handle number translation, assure local number portability, support prepaid billing mechanisms, short message service (SMS), and a variety of other mass market services.

3.2 Digital subscriber line (DSL, originally digital subscriber loop) [4]

DSL (see Figure 7) uses two pieces of equipment to provide customer services. DSL transceiver is located at the customer premises, and provides DSL connectivity, together with regular telephone services through the use of a filter). The other equipment called Digital Subscriber Line Access Multiplexer (DSLAM) or remote DSLAM (RDSLAM) is at the side of the Internet service provider (ISP), telephone company or other provider of DSL services. DSL was widely understood to mean asymmetric digital subscriber line (ADSL) as it was the most commonly installed DSL technology. Nowadays VDSL2 is the most popular deployed technology as per port number basis.

Various kinds of DSL technology have been standardized over the years. Table 1 presents their summary.

Table 1: DSL technologies, sorted in alphabetical order against acronym

Name	Acronym	Description
Etherloop		Ethernet Local Loop
Asymmetric Digital Subscriber Line	ADSL	volume of data flow is greater in one direction than the other
Asymmetric Digital Subscriber Line Plus Plus	ADSL++	technology developed for the Japanese market that extends downstream rates
Asymmetric Digital Subscriber Line 2	ADSL2	improved version of ADSL
Asymmetric Digital Subscriber Line 2 Plus	ADSL2+	version of ADSL2 that doubles the data rates by using twice the spectrum
Bonded DSL Rings	DSL Rings	shared ring topology at 400 Mbit/s
Symmetric High-speed Digital Subscriber Line	G.SHDSL	standardized replacement for early proprietary SDSL
Gigabit Digital Subscriber Line	GDSL	based on binder MIMO technologies
High Data Rate Digital Subscriber Line (	HDSL / HDSL2	the first DSL technology that used a higher frequency spectrum of copper, twisted pair cables
ISDN Digital Subscriber Line	IDSL	uses ISDN based technology to provide data flow that is slightly higher than dual channel ISDN
Rate-Adaptive Digital Subscriber Line	RADSL	increased range and noise tolerance by sacrificing up stream speed
Symmetric Digital Subscriber Line	SDSL / SHDSL	volume of data flow is equal in both directions
Uni-DSL	UDSL	technology developed by Texas Instruments, backwards compatible with all DMT standards
Universal High bit rate Digital Subscriber Line	UHDSL	Converts HDSL-1, 2 or 4 copper service into fibre optic HDSL service
Very High Speed Digital Subscriber Line	VDSL	speeds supporting applications such as high-definition television, as well as telephone services (voice over IP) and general Internet access, over a single connection
Very High Speed Digital Subscriber Line 2	VDSL2	Second-generation systems, newest and most advanced standard, degrades at a much slower rate from VDSL over longer distances,

DSL provides a dedicated connection from between each connected user and the local DSLAM.

DSLAM aggregates connections from many customers onto a single, high-capacity connection to the wider network. DSLAMs are generally flexible and able to support multiple types of DSL in a single central office, and different varieties of protocol and modulation in the same type of DSL.

DSLAMs may provide additional functions, including routing or dynamic IP address assignment for the customers and are fed through various access technologies (P2P Ethernet, PON, etc.) for backhauling purposes.

An RDSLAM is a DSLAM that is not installed in the central office. Instead it is installed in a pole mounted box or a steel cabinet on the ground, somewhere along the phone line between the local central office and the residence. RDSLAMs are used to decrease the distance between your DSLAM and the DLS modem, thereby improving service by boosting the signal quality that reaches CPE. The voice telephone service is still routed to the central office.

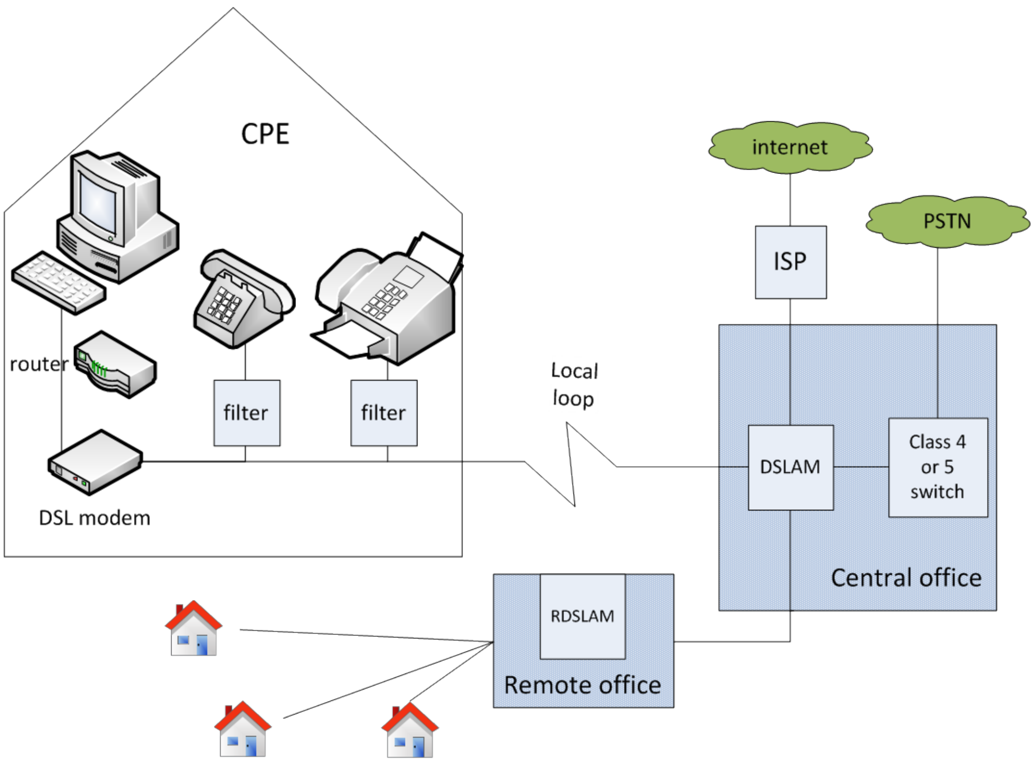

Figure 7: DSL architecture

3.3 Community antenna television (CATV) [3]

In cable TV network for data delivery, a set of frequency channels (frequency range assigned depends on region and service provider) are allocated for downstream traffic to homes and another set of frequency channels is used to carry upstream signals.

Cable operators' network infrastructures are based on the hybrid fibre coaxial (HFC) architecture (see Figure 8), which is in essence a community LAN that uses a bus topology with a shared-access architecture. On the left side are the headends, from which information is broadcast towards customer sites. Those headends are tied together, generally with fibre that may be either digital or analogue, referred to as fibre in the backbone. By moving to a fibre-based backbone, cable operators have also made improvements to operation and maintenance costs of the network and better performance. HFC is a shared infrastructure; this is one of the drawbacks of the HFC architecture.

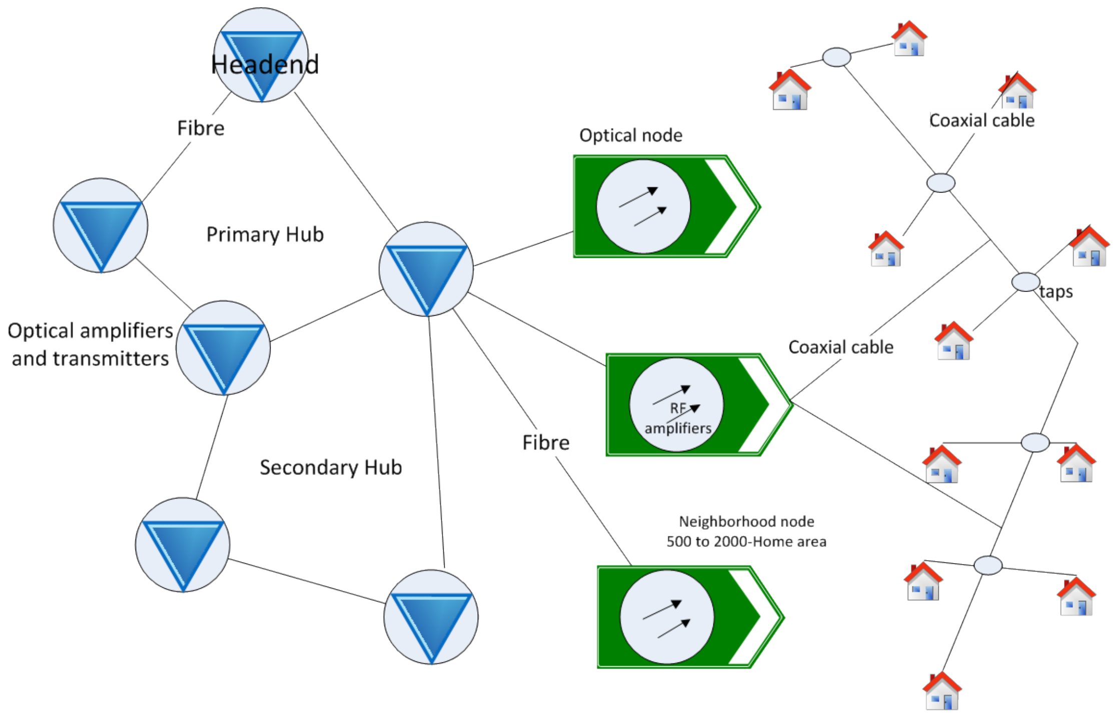

Figure 8: HFC architecture

3.4 Passive multipoint fibre architecture: PON [5]

A passive optical network (PON) (Figure 9) (see ITU-T G.983, ITU-T G.984, ITU-T G.985, ITU-T G.987.1, IEEE 802.3-2012), does not (typically) use any electrically powered switching equipment in the outside plant and instead relies on the use of optical splitters to separate and collect optical signals as they move through the network. PON shares fibre optic strands along a part of the network that spans from OLT to optical splitter/combiners (typically referred to as the trunk fibre). Powered equipment is required only at the CO and customer site ends of the signal.

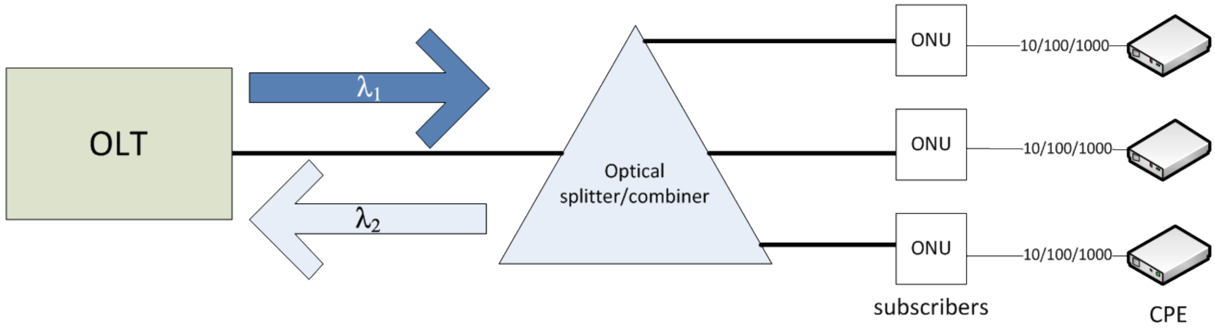

Figure 9: PON architecture

3.5 Access over active fibre [5]

An active optical system (see Figure 10), uses electrically powered switching equipment in the outside plant, such as a router or a switch / aggregator, to manage signal distribution and direct signals to specific customers. Such an active device redirects the incoming and outgoing signals to the proper destination. In such a system, a customer may have a dedicated fibre running to the house. Optical to electrical conversion is performed at CPE.

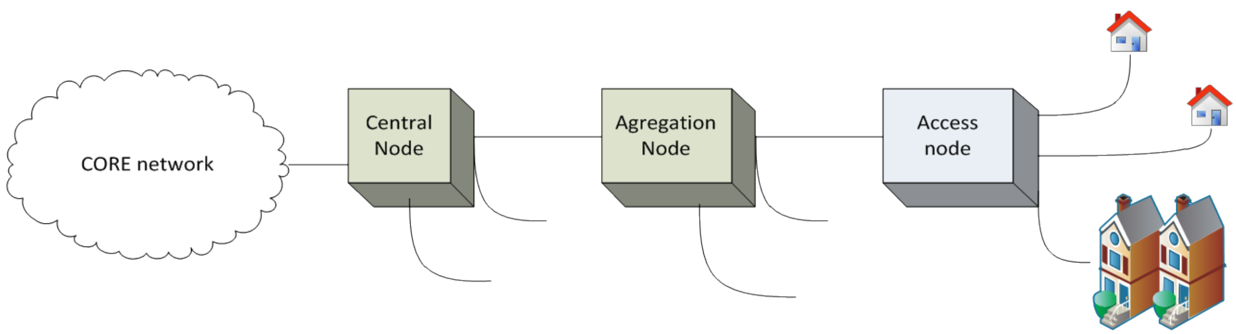

Figure 10: Optical system with active components.

3.6 P2P network [5]

A point-to-point network (see Figure 11) is one of the simplest network architectures, because it involves only two nodes, connected to each other via a dedicated physical link, using either copper or fibre medium. This is one of the cheapest and most effective (in terms of raw data rate) network architectures to interconnect only two points, because it does not involve the cost of redundancies and it does not require several nodes to make a connection work. This causes problems for business customers that require some protection against network failures. To have redundancy a separate dedicated line has to be laid down what brings additional costs connected with extra physical medium and space required to install such a redundant line. The initial investment costs of other architectures are smaller as they do not require dedicated point to point links and already in the design of the network some type of redundancy is provided (star, mesh topology).

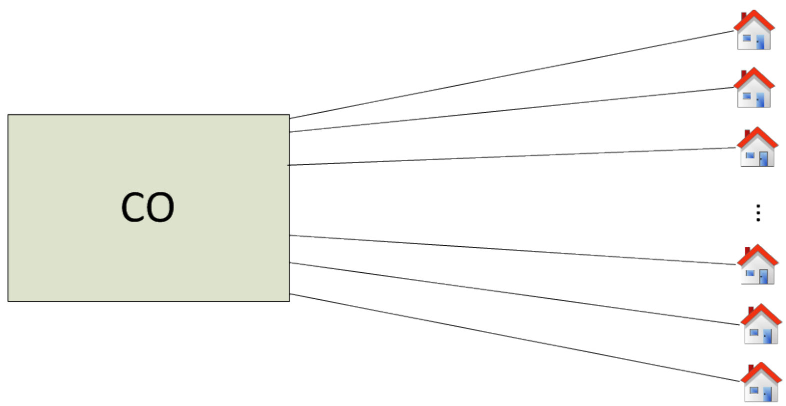

Figure 11: P2P network architecture

More information about P2P links provided over copper can be found in [48] and about optical technologies [49]

3.7 Comparison of P2P with PON [6]

This paragraph contains comparison of two technologies, fibre P2P and PON. Three factors are taken into consideration: technical aspects, investment cost (CAPEX) and operating expenses (OPEX). Each technology has advantages and disadvantages and is up to the customer to decide which network would bring more benefits.

3.7.1 Technical comparison

This paragraph contains comparison of system bandwidth, ease of allocation and increase of bandwidth, fault isolation and recovery, security, redundancy, possibility of tailoring, and standardization issues.

Bandwidth allocation granularity and ease of upgrade is a key factor in deciding the technology choice for the networks. PON technology offers bandwidth determined by the splitting ratio at the passive splitter-combiner. P2P is characterized by a higher flexibility for the bandwidth allocation in kilobit increments that may be governed by the type of interface or traffic shaping on the access node, giving it clear advantage. P2P offers larger maximum bandwidth per user and for business customers is much easier to allocate individually different bandwidths. When offered bandwidth is not enough with P2P thanks to active modular nodes, interface upgrade is done by changing or adding the boards without necessity to modify architecture of the network. To have same results, PON needs to bundle several time division slots at the cost of amount of subscribers per PON branch.

Network reliability is critical for connected customers. A faulty subscriber in P2P can be easily identified and the associated issue – readily fixed. A PON with just one failing ONU may take down the whole PON, causing a service outage for all connected subscribers.

Security and privacy is a big concern while choosing the technology for accessing the network. Wiretapping is not possible in P2P dedicated links. PON tree even with individual encryption for each customer leaves a possibility to obtain confidential information sent by users. After tapping into one subscriber is possible to hack the encryption for others.

Some customers may require protection against network failures. In active networks like P2P, a customer can be connected into various redundant topologies like rings and in case PON no redundancy is provided.

CPEs are devices allowing users to establish connection through various interfaces (wired and wireless). Since Ethernet P2P in electrical domain exists much longer than in optical domain, standardized CPEs with various interfaces gives a possibility to terminate the network according to customers' needs. Standard for Service Interoperability in Ethernet Passive Optical Networks (SIEPON) working group has been engaged to allow full "plug-and-play" standardization of PON equipment in a multi-vendor environment. In the recent years it allowed various connection possibilities for the users to fast optical links.

3.7.2 Investment cost (CAPEX) comparison

The initial investment into CPEs for P2P and PON is comparable. At the beginning of the PON technology development, there was no compatibility between different manufacturers what was forcing the need to buy CPEs and OLTs from same source. This problem disappeared thanks to the recent standardization efforts of projects such as IEEE P1904.1 SIEPON.

Cost of PON active components deployment per customer is much lower in PON when compared to P2P, since each OLT port is shared by several customers through passive splitter-combiner.

While looking into initial investment into network technology P2P is more favourable as only paying customers are connected to active ports and it can be rolled out for single customers. On the other hand to avoid excessive expenses, PON is deployed only when a specific minimum occupation ratio can be guaranteed.

Space required to deploy system technology plays a key role in investment costs. PON requires little space at the central site but needs passive splitter-combiners to be located in the outside plant. The space occupied by P2P deployment in CO is much bigger, given that it is necessary to accommodate various active interfaces. However, along with the development of higher density P2P solutions, the space requirements decrease with each new generation.

In case upgrades of the network equipment, active components of P2P have scalability and customers affected by the exchange of the equipment can be easily separated. When doing upgrades in PON, entire tree is affected and all ONU have to be replaced at the same time increasing the cost of the operation.

3.7.3 Operating expenses (OPEX) comparison

The PON’s greatest advantage is the use of passive splitter-combiners in the outside plant and greater subscriber density on the OLT, what translates to smaller OPEX, where in P2P, each interface contains an active laser increasing deployed infrastructures’ energy consumption increasing overall OPEX values.

Detecting faults in PON cannot be done by network management system and technician is needed to visit each individual customer connected to the service. Since ONTs are not always easily accessible, this may prolong the inactivity period and increase costs associated with fixing the fault. P2Ps’ dedicated optical path it is much easier to detect and deal with faults what brings down the costs of locating and fixing possible faults.

4 Central Office

CO is a dedicated network service provider building with the necessary equipment inside. CO contains separate switching and control system equipment with leading-in lines for connecting data lines to the switching system, power supply installation and auxiliary equipment. End users' lines are connected to aggregation switches providing connectivity between individual subscribers, and connecting them to metro or wide area network. Depending on the access technology and medium used, southbound links (towards CPEs), may contain various connected devices including DSLAM or RDSLAM (DSL), passive splitter-combiners (PON), various BSs (mobile technology), multiplexers/demultiplexers. In case of large business customers, CO and CPE may be directly connected. In the northbound direction (towards backbone network), CO may be connected with other COs that aggregate traffic even further and later connect to the backbone network, or alternatively it may be connected directly to backbone when no further aggregation is needed.

4.1 Backbone network

Backbone networks carry traffic between PoPs of various service providers. Backbone is typically comprised of a number of high-speed links, with national or even inter-continental coverage, and high availability and reliability, employing a number of redundancy schemes at various layers (physical, data, and link layer). Both wired and wireless technologies may be employed in backbone networks, depending on the target coverage, reliability as well as target investment requirements.

5 Bibliography

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Annex B
Data analysis software tutorial

Table of Contents

Figure list

Acronym list

CPE	Customer Premises Equipment
EPON	Ethernet Passive Optical Network
OLT	Optical Line Termination
PON	Passive Optical Network

After executing the *main.m* file, the user is asked to point the Excel file which stores data necessary for all calculations done by this software (see Figure 1).

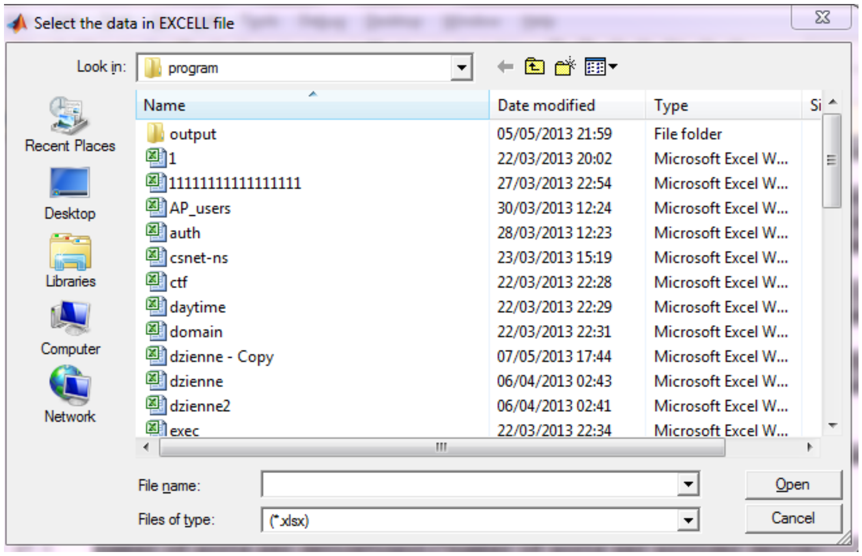

Figure 1: "Pop-up" window to select the initial data file

Next, the user is asked (see Figure 2) to introduce the number of users connected to each customer premises equipment (CPE), the number of CPEs connected to each port on optical line termination (OLT) and the number of ports per OLT.

```
number of users per CPE:    5
number of CPE per port:    32
number of ports per network device:    112
```

Figure 2: Option to introduce number of users per CPE, number of CPEs per port and, ports per OLT

The numbers shown in Figure 2 represent a 1:32 split ratio for a passive optical network (PON) and number of ports on a fully loaded reference OLT platform (ZTE ZXA C300 19 inch chassis) with 8 port 1 gigabit Ethernet passive optical network (1G-EPON) line cards configuration (14 line cards in total).

Next, the program takes into consideration the number of users, CPEs and ports introduced with data introduced at the beginning of the software execution and saves the output data into an Excel file to a pre-defined folder. The default output path can be changed by editing the *main.m* file in line 43 for CPEs, 57 for ports on the OLT and line 70 for OLTs. In the case of a large data set, patience is advised as the data saving process may take several minutes, depending on the processing capabilities of the machine used. If the entry data file does not contain the sufficient amount of user data, the program is going to give an error (see Figure 3).

```
end
??? Index exceeds matrix dimensions.

Error in ==> AP_users at 5
        index_users_of_AP=out1(index(beginning:number_of_users_for_AP));

>> |
```

Figure 3: Possible error message when the entry data file has too little data

When such an error is observed, it is suggested to redefine the number of users, CPEs, and ports per device or alternatively select a different entry data file with more available data.

If the aforementioned error appears, information for individual data ports and CPE is still calculated and stored in the appropriate files (see Figure 4 and Figure 5) and it can be used by the next phases of the program.

↑Name	Ext	Size
[..]		<DIR>
data_port_number_1_CPE_number_1	xls	33.5 k
data_port_number_1_CPE_number_2	xls	66.0 k
data_port_number_1_CPE_number_3	xls	66.0 k
data_port_number_1_CPE_number_4	xls	31.0 k
data_port_number_1_CPE_number_5	xls	63.5 k
data_port_number_2_CPE_number_1	xls	26.0 k
data_port_number_2_CPE_number_2	xls	26.0 k
data_port_number_2_CPE_number_3	xls	27.0 k
data_port_number_2_CPE_number_4	xls	32.5 k

Figure 4: Files with data corresponding to CPEs

↑Name	Ext	Size
[..]		<DIR>
data_port_1	xls	170.0 k
data_port_2	xls	207.0 k
data_port_3	xls	293.5 k
data_port_4	xls	408.5 k
data_port_5	xls	440.5 k
data_port_6	xls	496.0 k
data_port_7	xls	579.0 k

Figure 5: Files with data corresponding to port

To aggregate data for a network device in the case of error (see Figure 3), lines 68 to 91 (see Figure 6) of `main.m` file have to be selected and executed to obtain a *data_device.xls* file (see Figure 7).

```
%% saving device data; since excel has restrictions in amount of lines saved has to be saved into separate sheets in one file
provider_device1=provider_device; % moving necessary data to temporary variable
filename_device=['E:\studia\praca magisterska\glowny katalog do pracy\dokumenty uzyte\100 % uzyte\program\output\data_device'];
 xlRange='A2' ;
 max_data_length_due_to_excel_restrictions=65536;

if length(provider_device)>max_data_length_due_to_excel_restrictions;
    for l=1:fix(length(provider_device)/(max_data_length_due_to_excel_restrictions-1)) % dividing the data into chunks that allow
        % length  of the variable is divided into integer amount of parts each with 65535 lines
        % each 65535 lines are written to a new sheet in EXCEL file
        sheet_final=['sheet',num2str(l)];% new sheets according to the length of the data
              xlswrite(filename_device,provider_device1(1:(max_data_length_due_to_excel_restrictions-1),:),sheet_final,xlRange);
              xlswrite(filename_device,z,sheet_final,'A1');
        provider_device1 = provider_device1(setdiff(1:size(provider_device1,1),[1:(max_data_length_due_to_excel_restrictions-1)])
    end
    % saving leftovers from the data file for provider device
    sheet_final=['sheet',num2str(l+1)];
    xlswrite(filename_device,provider_device1(1:end,:),sheet_final,xlRange);
    xlswrite(filename_device,z,sheet_final,'A1');
else
    sheet_final=['sheet',num2str(1)];
    xlswrite(filename_device,provider_device1(1:end,:),sheet_final,xlRange);
    xlswrite(filename_device,z,sheet_final,'A1');
end
```

Figure 6: Lines to execute in *main.m* file in case of an aggregation error shown in Figure 3

↑Name	Ext	Size
[..]		<DIR>
[AP]		<DIR>
[port]		<DIR>
data_device	xls	6.4 M

Figure 7: File with data corresponding to network device and folders containing data for CPEs and ports

After the completion of the aggregation step, all raw data necessary for further execution of the software is prepared and saved in specific folders providing the necessary hierarchy and easy access.

Next, the user is asked to choose a data aggregation type (see Figure 8).

```
                        MENU:

          choose type of data you want to process:

  1 to choose data for CPE:
  2 to choose data for port
  3 to choose data for whole equipment
your choice :
```

Figure 8: Options to choose aggregation type of data to be analysed

When option 1 is selected, the user is prompted to select the entry data file (see Figure 9) for further analysis.

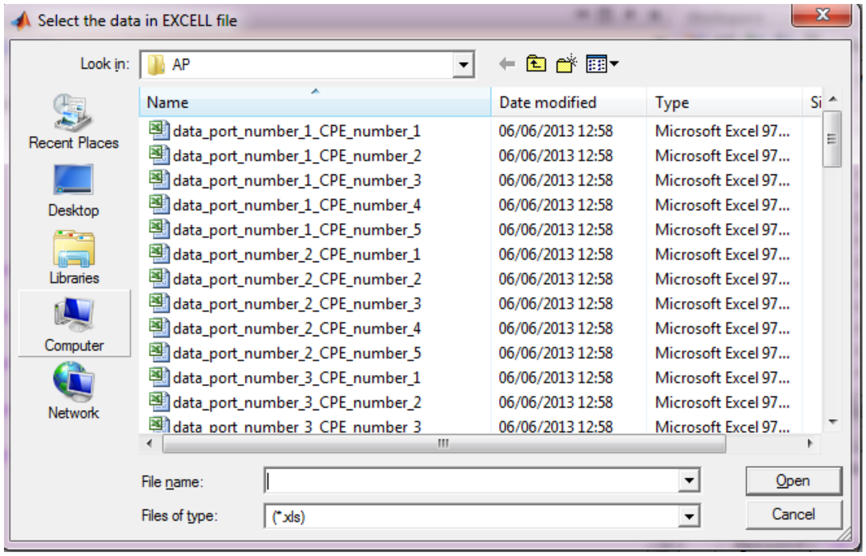

Figure 9: "Pop-up" window to choose data file to be analysed for CPE

When option 2 is selected, the user is prompted to select the entry data file for the port aggregation process (see Figure 10).

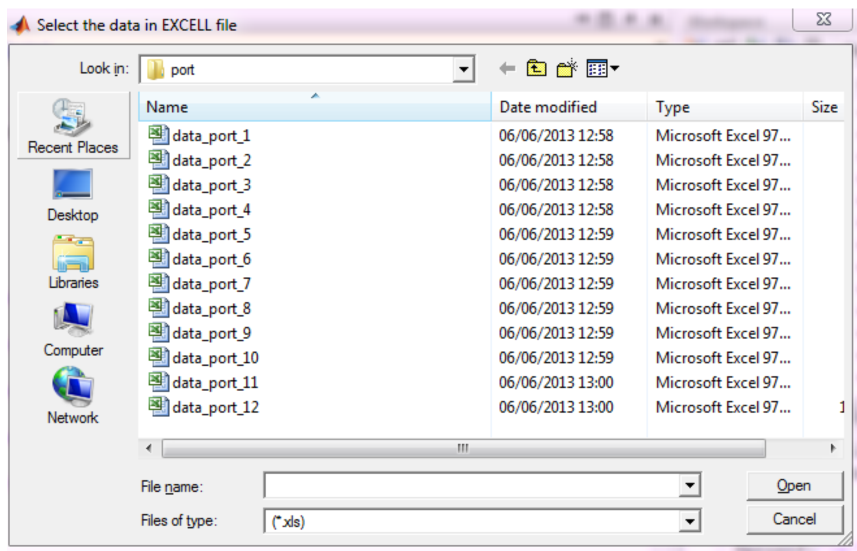

Figure 10: "Pop-up" window to choose data file to be analysed for port

When option 3 is selected, the user is prompted to select the entry data file for the OLT aggregation process (see Figure 11).

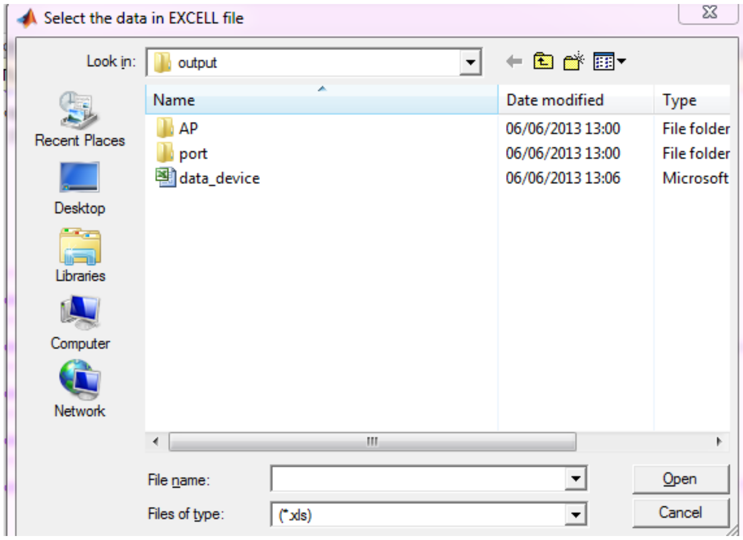

Figure 11: "Pop-up" window to choose data file to be analysed for network device

Once the proper data file is selected for further analysis, the user is asked to introduce start-up and power-down delays (see Figure 12), describing the time needed to wake the device up when in the sleep mode, or bring it out of the sleep mode, accordingly. It is assumed that during those specific periods of time, the device under analysis uses same amount of energy as during the active state.

```
insert start-up delay for the device in micro seconds:
22
insert shut-down delay for the device in micro seconds:
22
```

Figure 12: Option to introduce start-up and shut-down delays (here 22 micro second delays were introduced)

Duration of time that the device remains in active and sleep states, as well as the fraction of the total operation time they represent (see Figure 13) are then calculated. Furthermore, the program prepares a graphical representation of the overall network activity, accounting for previously configured start-up and shut-down delays (see Figure 14).

```
total_on_time = 47237.3189 seconds
total_off_time = 35897.0215 seconds
total_time = 83134.3404 seconds
fraction_on_time = 56.8 %
fraction_off_time = 43.2 %
```

Figure 13: Examples of time calculation and fractions of time for ON and OFF states

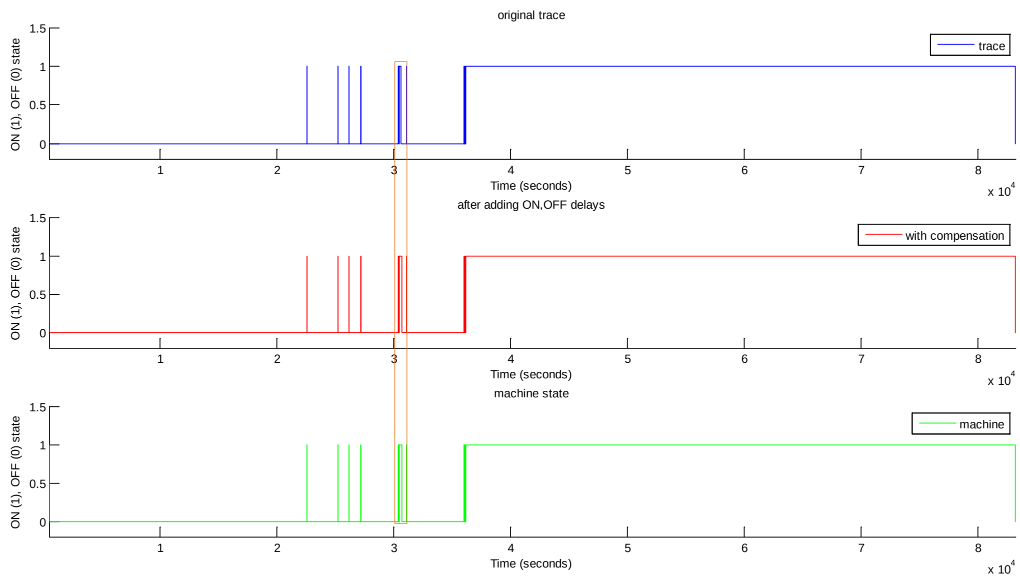

Figure 14: Example of graphical representation of the device activity

Figure 15 represents a stage where only activity from the entry data file is presented, while Figure 16 demonstrates the activity from the entry data file with start-up and shut-down delays and the overlapping windows of activity after applying those delays. Afterwards, the algorithm is applied to aggregate the overlapping windows into one continuous period of activity (see Figure 17) representing the operation period of the CPE, port or network device depending on the options previously chosen.

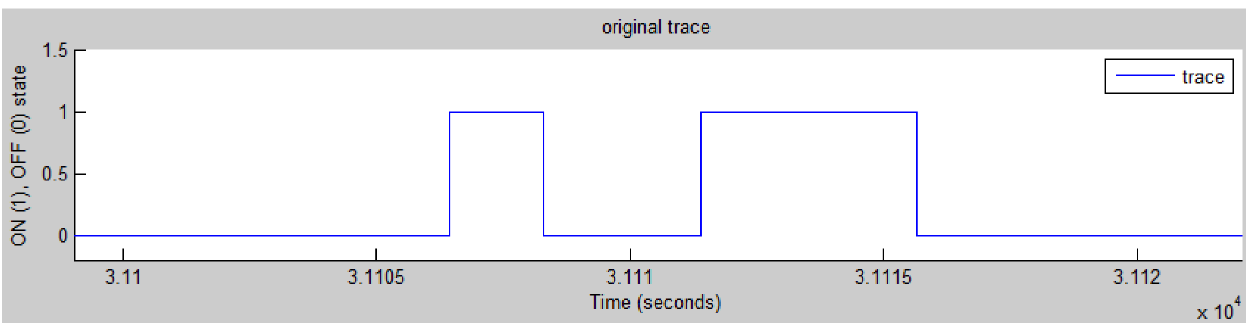

Figure 15: Part of activity from data trace (highlighted part of Figure 14, blue line)

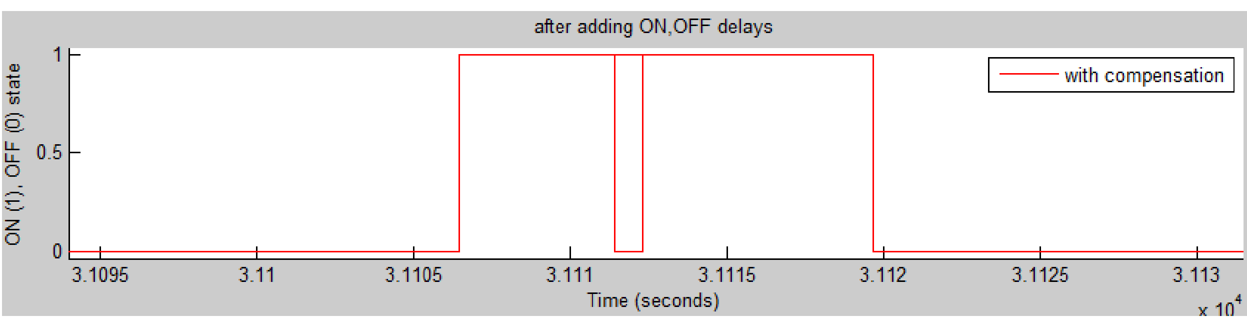

Figure 16: Part of activity from data trace with added delays and visible overlapping (highlighted part of Figure 14, red line)

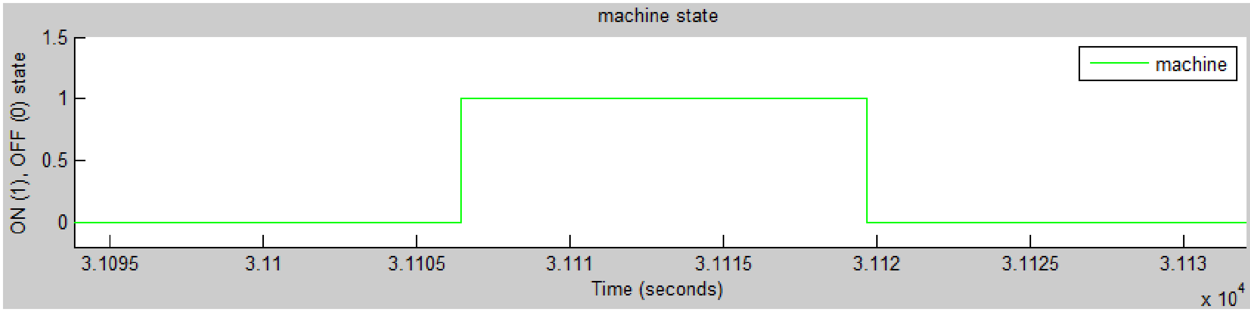

Figure 17: Part of activity that is aggregated to a continuous window (highlighted part of Figure 14, green line)

Next, the user can choose between power saving and normal operation mode through the option menu presented in Figure 18, followed by another option displayed in Figure 19 allowing to introduce a period of time for analysis.

```
          MENU:

  1 for power saving ON:
  2 for power saving OFF, device always ON:

your choice :
```

Figure 18: Option to choose operation type for the device

```
choose time duration for calculating the power, in hours :
```

Figure 19: Option to choose duration in hours used for calculations

Next, the user is given a set of options, allowing to choose the CPE type (see Figure 20), line card configuration on the OLT (see Figure 21), and finally the OLT (see Figure 22) architecture, using ZTE ZXA C300 as a reference platform.

```
 choose a device to test :

number 1 for ADSL Home Gateway :
number 2 for VDSL2 Home Gateway :
number 3 for Ethernet router with 4 Fast Ethernet LAN ports :
number 4 for Cable DOCSIS 3.0 CPE :
number 5 for Complex HNID. :
number 6 for GPON Optical Network Termination unit used in FTTH (ZXA10 F660) :
number 7 for F401(EPON + 1GE) configuration :
number 8 for F1400(10G-EPON + 4GE) configuration :

 choose option?? :
```

Figure 20: Options to choose type of device for CPE power consumption analysis

```
number 1 for ADSL2plus (including ADSL and ADSL2 and with transmission power of 19,8 dBm):
number 2 for GPON, >32 ports:
number 3 for GPON, <=32 ports:
number 4 for XG-GPON, >32 ports:
number 5 for XG-GPON, <=32 ports:
number 6 for 1G-EPON, >32 ports:
number 7 for 1G-EPON, <=32 ports:
number 8 for 10/1G-EPON, >32 ports:
number 9 for 10/1G-EPON, <=32 ports:
number 10 for 10/10G-EPON, >32 ports:
number 11 for 10/10G-EPON, <=32 ports:
number 12 for C300 19 inch Chassis: 16 ports on EPON Line card :
number 13 for C300 19 inch Chassis: 8 ports on 10G-EPON line card :

 choose option?? :
```

Figure 21: Options to choose type of device for port power consumption analysis

```
 choose a device to test :

number 1 for D-Link DAS-3248 ADSL 5,0 W per equipment for each PON (1G-EPON) interface:
number 2 for ZXA10 C300 cabinet with full configuration EPON ports:
number 3 for ZXA10 C300 cabinet with full configuration GPON ports:
number 4 for ZXA10 C300 cabinet with full configuration 10G EPON ports:
number 5 Full C300 19 inch Chassis with 16 ports EPON Line cards configuration (14 line cards):
number 6 Full C300 19 inch Chassis with 8 ports 10G-EPON line cards configuration (14 line cards) :

 choose option?? :
```

Figure 22: Options to choose type of device for network device power consumption analysis

Final results for the selected CPE under consideration, when operating with power saving enabled (see Figure 23) or disabled (see Figure 24) are then displayed depending on configuration choices.

```
power used while ON with power saving = 105.1306 Wh

power used while OFF with power saving= 38.2827 Wh

power used while ON without power saving=  Wh

power used while OFF without power saving=  Wh

total power used for given choice of work type= 143.4133 Wh
>>
```

Figure 23: Example of results with enabled power saving mode

```
power used while ON with power saving =  Wh

power used while OFF with power saving=  Wh

power used while ON without power saving= 105.1306 Wh

power used while OFF without power saving= 79.6694 Wh

total power used for given choice of work type= 184.8 Wh
```

Figure 24: Example of results with disabled power saving mode