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SODALES

SOftware-Defined Access using Low-Energy Subsystems

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D1.4 Simulations and physical layer validations

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Abstract

Deliverable 1.4 aims to demonstrate the benefits of deploying the SODALES convergent access infrastructure combining fixed and mobile access, by means of traffic studies and simulations.

The objective of the work is to validate the SODALES architecture and to achieve a solid solution that supports high speed connectivity services in a robust manner, carefully analysing the requirements of present and future transmission services and studying the trends and behaviours of end users.

After this analysis of requirements and trends, and once studied the current solutions offered by network operators to deal with this challenge, the SODALES is compared and validated. The SODALES architecture is validated by means of discrete-event simulations to demonstrate the technical capabilities of the network.

Finally, a roadmap is presented in order to evolve the existing telecommunication infrastructures from a rational and sustainable point of view, so it is energy-sustainable and managed in the most efficient possible way.

The results show that the SODALES architecture is perfectly capable of delivering Gigabit services to the user and offers a scalable roadmap to become a universal access infrastructure for fixed and mobile subscribers.

It is interesting to note the fact that when the bandwidth that is delivered to each user increases, the oversubscription factor is much higher due to the fact that end users cannot take advantage all the bandwidth that they have. This is especially relevant for services higher than +100Mbps.

Document Revision History

Version	Date	Description of change	Authors
1.0	29/12/2014	Final Version	Carlos Bock (i2CAT), Jordi Ferrer Riera (i2CAT), Eduard Escalona (i2CAT), Michael C. Parker (UEssex)

SEVENTH FRAMEWORK PROGRAMME

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List of Acronyms

3GPP	Third Generation Partnership Project
ADSL	Asymmetric Digital Subscriber Line
ADSL2	Asymmetric Digital Subscriber Line and Annex J
APON	ATM-PON
ARN	Active Remote Node
ARPU	Average Revenue Per User
BBU	Baseband Unit
BoF	Broadband over Fibre
BPON	Broadband PON
BS	Base Station
BTS	Base Transceiver Station
CAPEX	Capital Expenditure
CATV	Cable Television
CDMA	Code Division Multiple Access
CO	Central Office
CoS	Class of Service
CPE	Customer Premises Equipment
CPRI	Common Public Radio Interface
C-VLAN	Customer VLAN
DBA	Dynamic Bandwidth Allocation
DSL	Digital Subscriber Line
E2E	End-to-End
EFM	Ethernet First Mile
EoS	Ethernet over SDH
EPON	Ethernet PON
EVC	Ethernet Virtual Channel/Connection
FDD	Frequency Division Duplex
FSAN	Full Service Access Network
FTTB	Fibre-To-The-Building
FTTC	Fibre-To-The-Curb
FTTCab	Fibre-To-The-Cabinet
FTTH	Fibre-To-The-Home
FTTx	Fibre-To-The-x
GEM	GPON Encapsulation Method
GFP	Generic Framing Procedure
GPON	Gigabit-PON
GSM	Global System for Mobile
HDTV	High Definition Television
HO	High Order
HSPA	High Speed Packet Access
HW	Hardware
IEEE	Institute of Electrical & Electronic Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
IPTV	IP Television

ISP	Internet Service Provider
ITU	International Telecommunications Union
LAN	Local Area Network
LCAS	Link Capacity Adjustment Scheme
LO	Low Order
LTE	Long Term Evolution
MAC	Medium Access Control
MEF	Metro Ethernet Forum
MIMO	Multiple-Input Multiple-Output
MPLS	Multi-Protocol Label Switching
NGPON	Next-Generation PON
O&M	Operations and Maintenance
OAM	Operations, Administration and Maintenance
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Termination
OMCI	ONT Management and Control Interface
ONT	Optical Network Termination
ONU	Optical Network Unit
OPEX	Operational Expenditure
P2MP	Point-to-Multi-Point
P2P	Point-to-Point
PDH	Plesiochronous Digital Hierarchy
PHY	Physical layer
PON	Passive Optical Network
POTS	Plain Old Telephone Service
PPB	Parts Per Billion
PTN	Packet Transmission Network
PTP	Precision Time Protocol
QoS	Quality of Service
RAN	Radio Access Network
RBS	Radio Base Station
RF	Radio Frequency
RF	Radio Frontend
RN	Remote Node
ROADM	Reconfigurable Optical Add/Drop Multiplexer
RoF	Radio over Fibre
ROI	Return of Investment
RRH	Remote Radio Head
RSP	Retail Service Provider
RT	Remote Terminal
SME	Small-to Medium-sized Enterprise
SNMP	Simple Network Management Protocol
SoC	System-on-a-Chip
SODALES	SOftware-Defined Access using Low-Energy Subsystems
SOHO	Small Office/Home Office
SONET/SDH	Synchronous Optical Network/Synchronous Digital Hierarchy
SP	Service Provider
SSM	Synchronous State Message

STM	Synchronous Transfer Mode
S-VLAN	Service VLAN
TCO	Total Cost of Ownership
TDD	Time Division Duplex
TDM-PON	Time-Division-Multiplexing PON
TD-SCDMA	Time Division Synchronous Code-Division Multiple-Access
ToP	Time over Packet
TTI	Transmission Time Interval
UDWDM	Ultra-Dense WDM
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UNI	User Network Interface
VCAT	Virtual Concatenation
VDSL	Very-high-data-rate DSL
VLAN	Virtual LAN
VoD	Video on Demand
VoIP	Voice over IP
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplexing
WiMAX	Worldwide Interoperability for Microwave Access
XG-PON	10-Gb/s capable PON

1 Introduction

End user requirements in terms of bandwidth are increasing exponentially. This is due, not just to he increased bandwidth required by video and new applications, but also to the fact that each end user has more and more connected devices.

Service providers and network operators are responding to this challenge with the deployment of new access networks. At present, we are currently experiencing a major technological change, consisting of the deployment, in parallel, of fibre-based fixed access networks and the next generation of wireless networks based on 4G/LTE systems.

Both technologies present significant challenges in terms implementation, deployment, business model and return on investment. Thus, strategies to reduce both the costs of deployment and operation of both infrastructures are of interest of network operators in order to optimize ROI and OPEX.

The trend of deploy all-IP infrastructure is also something to be kept into consideration. This allows deploying all kind of services on the same infrastructure, facilitating the convergence of services and infrastructures. Additionally, CAPEX can also be reduced if instead of several networks, a convergent one is deployed.

Thus, this is the starting point of the FP7-ICT-8 SODALES project, which has developed and is implementing a convergent access infrastructure for 4G and beyond and fixed access transmission services.

On the basis of the SODALES architecture, this work will compare the performance of a current access network with the SODALES architecture, in order to compare existing PON-based access networks with the convergent SODALES architecture in terms of power requirements, bandwidth capabilities and scalability.

1.1 State of the art of access networks

Future access networks will require increased network capacity, not just for specific applications, but also due to the large growth of connected devices. Machine-to-Machine (M2M) communications, mobile devices (phones, tablets, GPS, electronic books), and “wearable” devices and cars connected to the network will require fixed and mobile networks to be able to offer ubiquitous access capacity.

Figure 1.1 shows how these new devices will stress networks in the short and mid term.

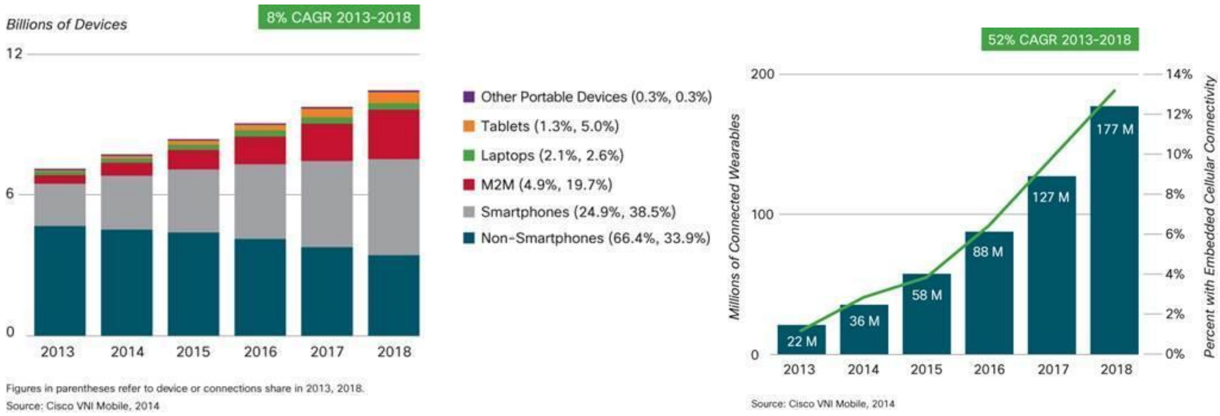

Figure 1.1 Global Connections (left) and Global Connected Wearable Devices

Additionally, the use of the Cloud is increasing every day. Services like Google applications for companies or individuals that provide an office environment and email storage, new services that integrate all the systems in an enterprise cloud, Windows virtualization servers (with its Active Directory, Exchange, IIS webserver Shares, print servers, etc.) that virtualize Microsoft Azure, or even strategies such as of Sony and Microsoft consoles and their OnLive, which are intended to run games on their servers and transmit movement, video and sound through the network with very high quality requirements are the future trend in telecommunications.

Also, digital multimedia content services such as Spotify or Netflix which transmit a huge amount of traffic each day, or free social video services such as YouTube among others have bandwidth requirements that can not be coped with existing access infrastructures.

In the following Figure 1.2 we see how we enter into the "Zettabyte era"

Figure 1.2 Global IP Traffic, Wired and Wireless

"Everything is going mobile," everything is becoming mobile, is the powerful way to begin this report by Ericsson [Ericsson12]. Due to the new mobile devices that are released every year, people are changing their habits and now, the use of smartphones and mobile apps is becoming even more popular than laptops. At present, people tend to access to the Internet through their smartphones anytime and anywhere.

It is expected that by 2017 there will be 5 billion mobile broadband connections, which means that since 2010, mobile traffic has increased by a factor of 15.

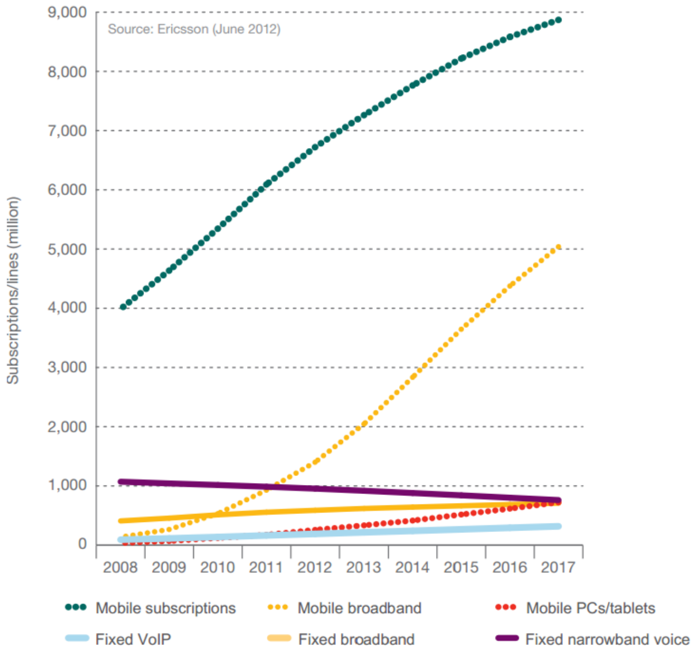

Figure 1.3 Fixed and mobile subscriptions 2008-2017 [Ericsson12]

It is important to note, however, that most of the traffic consumed by mobile devices is not on mobile networks, but using Wi-Fi and fixed broadband connections. This traffic offload it is estimated to be at present of 45% and increasing.

People tend to perform more bandwidth demanding activities using Wi-Fi networks. This helps to keep mobile networks less saturated. In any case, network operators are always studying new technologies to perform traffic offload to fixed networks as close to the terminal as possible, in order to optimize the available spectrum.

The SODALES project proposes a solution for this, which is to offer Wi-Fi access at the CPE and RBS traffic offload to fibre-links, so spectrum utilization is maximized.

The following Figure 1.4 shows this behaviour:

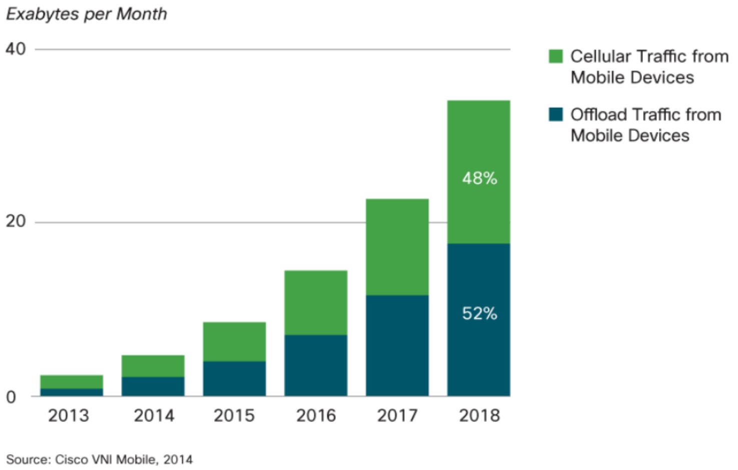

Figure 1.4 Percentage of total mobile data traffic to be offloaded by 2018

This fact, together with the increase of mobile devices reinforces the message of that traffic offload is mandatory to cope with future traffic demands. This means that new base stations with shorter range will be required, in order to increase available bandwidth, leading to atomized deployments, in which the radio infrastructure will allow the end user to have mobility and that will try to reach the wired domain as quickly as possible, in order to guarantee the very high bandwidth that will be required for the services of the future.

All these concepts are perfectly aligned with SODALES architecture and services.

1.2 Current situation

Access networks that are deployed today can be divided in two main types: those which are wired and those which use the radio spectrum to interconnect transmitter and receiver.

At present, wired networks are being migrated to fibre, by means of FTTH technologies. In Europe, this is happening at present, while in other regions, like APAC, most of the connections are already fibre-based.

The key point is that these infrastructures are very expensive, specially the last mille, and this is where SODALES comes into play. The last segment of the network, the drop cable that connects that final user to the infrastructure, tends to be the most expensive part. Thus, solutions to reduce its costs are under study. SODALES proposes several technologies to develop this.

The cost of the access network influences the price of the service, thus it is important to keep it as low as possible in order to boost the competitiveness of the businesses and foster subscriptions to residential users.

In this sense, PON technologies are the ones that tend to be chosen to face these deployments, specially in large countries (France, UK, Spain, Italy, …)

PON technologies offer passive outside plants, which are build using fibre optical cables and power splitters. They are compact in size and offer a good balance between performance and cost. Research is underway in order to integrate PON technologies with radio distribution and mobile backhaul / fronthaul, because there are several challenges that need to be solved, as clock synchronization and cell handover.

The issue that PON networks have when integrating with radio networks is the fact that in any case, powering is required to feed the RBS. Thus, why not take advantage of this to distribute intelligence and perform traffic shaping and QoS as close to the end user as possible?

This is what SODALES specifically proposes, with the development of the ARN.

1.3 Active and passive access networks

As said in the previous section, passive and active networks differ by the presence or absence of active equipment, equipment that requires electricity to operate, between the CO (Optical Header or Central Office) and the customer. PON or Passive Optical Network refers to the passive networks for both networks without active equipment in the outside plant.

PON networks use passive power splitters to distribute the signal among the customers. GPON standard (ITU-T G984) offers 2.5Gbps downstream and 1.25Gbps upstream to be shared among 64 subscribers. However, some vendors have extended the number of connected subscribers to a maximum of 128 using non-standard implementation.

Non-standard implementations are quite common in the PON arena. Interoperability tends to be a critical aspect of PON networks, as those try to keep the solutions closed, so network operators can not use equipment of offer suppliers as ONT devices.

Higher data rate standards have also been developed (like IEEE 802.3av 10Gbps EPON and ITU-T G987 XGPON, standardized in 2009 and 2010 respectively). However, they are not widely used because of the higher cost of the equipment and the fact that the market does not require, at present, such high data rate connections.

PON networks offer a natural multicast domain, which is very interesting for video RF overlay distribution. This technology consists on distributing the RF spectrum in a separate wavelength channel from the data service. This allows reducing the required bandwidth on the data pipes and offers a transient solution for video delivery, as the interactivity that video RF overlay provides is very limited. At present, most network operators and service providers are promoting IPTV and OTT video distribution systems, so this characteristic of PON networks will be no longer required in the mid term.

On the other hand active networks, substitute the power splitter for a manageable switch, in order to interconnect with the end subscribers in a point to point (P2P) approach. This allows extending the reach of the access segments and standardizes the use of equipment, as Ethernet protocols are typically used, which do not have any issue with IOT.

The main drawback of active networks is the fact that powering is required in the field. However, in a convergent network that gives services to fixed and mobile subscribers this is no longer an issue, as RBSs need to be powered anyway.

Electrical components of P2P networks are simpler and potentially lower cost, due to the fact that data rate is dedicated and no busts receivers / transmitters are required. Also, as the channel is unique for each user, no media access protocols are required to share the transmission media.

Thus, in a convergent architecture to provide fixed and mobile services, active networks are a good choice, specially if high data rates want to be offered to end users. In this sense, to deliver Gigabit to the user, if we deploy PON, 10Gbps bursts receivers are required, while in a P2P approach, Gigabit electronics, with are a commodity at present, can be used.

Also, P2P solutions offer a wider range to combine heterogeneous solutions, like the ones we propose in SODALES. The ARN, a key device of the project, acts as an advanced multi-service aggregator, which can connect fixed radio, mobile radio and fixed fibre customers. This is possible thanks to the switched architecture of the device. If PON technologies were used, there is no way to offer agnostic transport solutions, as with the case of P2P networks.

It is important to note, that no matter whether PON or P2P technologies are chosen, at present, thanks to economies of fibre optic components and the cost of fibre optical cables, currently studies [AlcatelEconomicFTTH] indicate that it is less expensive to deploy a fibre network than a new copper-based access solutions. This is especially relevant in Greenfields, where room to deploy fibre infrastructure should not be an issue.

1.4 FTTx Architectures

The telecommunications industry differentiates between several distinct FTTX configurations.

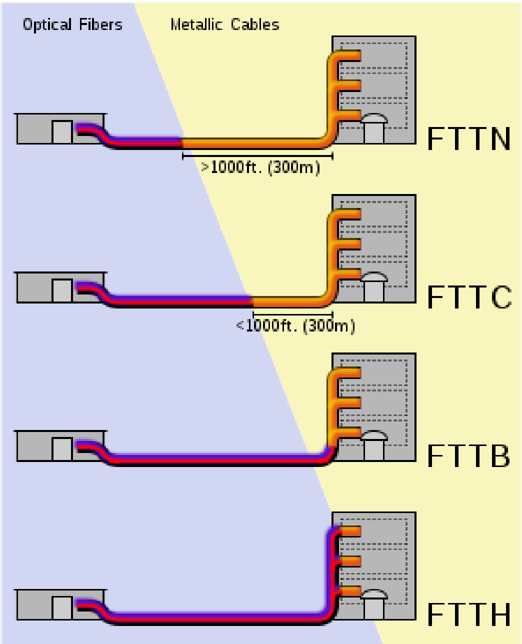

Figure 1.5 FTTx architectures

The terms in most widespread use today are:

- **FTTN / FTTLA** (*fibre-to-the-node, -neighborhood, or -last-amplifier*): Fibre is terminated in a street cabinet, possibly miles away from the customer premises, with the final connections being copper. FTTN is often an interim step toward full FTTH and is typically used to deliver advanced triple-play telecommunications services.
- **FTTC / FTTK** (*fibre-to-the-curb/kerb, -closet, or -cabinet*): This is very similar to FTTN, but the street cabinet or pole is closer to the user's premises, typically within 1,000 feet (300 m), within range for high-bandwidth copper technologies such as wired Ethernet or IEEE 1901 power line networking and wireless Wi-Fi technology. FTTC is occasionally ambiguously called FTTP (fibre-to-the-pole), leading to confusion with the distinct fibre-to-the-premises system.
- **FTTdp** (*Fibre To The Distribution Point*) This is very similar to FTTC / FTTN but is one-step close again moving the end of the fibre to within meters of the boundary of the customers premises in last junction possible junction box know as the 'distribution point' this allows for near-gigabit speeds [Techrep14]
- **FTTP** (*fibre-to-the-premises*): This term is used either as a blanket term for both FTTH and FTTB, or where the fibre network includes both homes and small businesses.
  - **FTTB** (*fibre-to-the-building, -business, or -basement*): Fibre reaches the boundary of the building, such as the basement in a multi-dwelling unit, with the final connection to the individual living space being made via alternative means, similar to the curb or pole technologies.
  - **FTTH** (*fibre-to-the-home*): Fibre reaches the boundary of the living space, such as a box on the outside wall of a home. Passive optical networks and point-to-point Ethernet are architectures that deliver triple-play services over FTTH networks directly from an operator's central office [Telecom10] [NXT13].
- **FTTD** (*fibre-to-the-desktop*): Fibre connection is installed from the main computer room to a terminal or fibre media converter near the user's desk.
- **FTTE** / **FTTZ** (fibre-to-the-telecom-enclosure or fibre-to-the-zone) is a form of structured cabling typically used in enterprise local area networks, where fibre is used to link the main computer equipment room to an enclosure close to the desk or workstation. FTTE and FTTZ are not considered part of the FTTX group of technologies, despite the similarity in name.

To promote consistency, especially when comparing FTTH penetration rates between countries, the three FTTH Councils of Europe, North America, and Asia-Pacific agreed upon definitions for FTTH and FTTB in 2006, with an update in 2009 and another in 2011. The FTTH Councils do not have formal definitions for FTTC and FTTN.

The speeds of fibre-optic and copper cables are both limited by length, but copper is much more sharply limited in this respect. For example, the common form of gigabit Ethernet (1Gbit/s) runs over relatively economical category 5e, category 6, or augmented category 6 unshielded twisted-pair copper cabling but only to 300 ft (91 m). However, 1Gbit/s Ethernet over fibre can easily reach tens of miles.

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Even in the commercial world, most computers have short copper communication cables, typically under 100 ft (30 m). Most metropolitan network links (e.g., those based on telephone or cable television services) are several miles long, in the range where fibre significantly outperforms copper. Replacing at least part of these links with fibre shortens the remaining copper segments and allows them to run much faster.

Fibre configurations that bring fibre directly into the building can offer the highest speeds since the remaining segments can use standard Ethernet or coaxial cable. Fibre configurations that transition to copper in a street cabinet are generally too far from the users for standard Ethernet configurations over existing copper cabling. They generally use very-high-bit-rate digital subscriber line (VDSL) at downstream rates of well over 20Mbit/s. Experimental programs such as Google Fibre plan to offer 1000/1000 Mbit/s symmetrical connections directly to consumer homes.

Fibre is often said to be "future-proof" because the data rate of the connection is usually limited by the terminal equipment rather than the fibre, permitting at least some speed improvements by equipment upgrades before the fibre itself must be upgraded. Still, the type and length of employed fibres chosen, e.g., multimode vs. single-mode, are critical for applicability for future connections over 1Gbit/s. Nevertheless, it offers very high speed compared to DSL.

1.4.1 Ethernet point-to-point

Point-to-point protocol over Ethernet (PPPoE) is a common way of delivering triple- and quad-play (voice, video, data, and mobile) services over both fibre and hybrid fibre-coaxial (HFC) networks. Active PPPoE uses dedicated fibre from an operator's central office all the way to the subscribers' homes, while hybrid networks (often FTTN) use it to transport data via fibre to an intermediate point to ensure sufficiently high throughput speeds over last mile copper connections.

This approach has become increasingly popular in recent years with telecoms service providers in both North America (AT&T, Telus, for example) and Europe's Fastweb, Telecom Italia, Telekom Austria and Deutsche Telekom, for example. Google has also looked into this approach, amongst others, as a way to deliver multiple services over open-access networks in the United States [Ligthwave10].

1.4.2 Fibre to the node

Fibre to the node or neighbourhood (FTTN), sometimes identified with and sometimes distinguished from fibre to the cabinet (FTTC) [daSilva05], is a telecommunication architecture based on fibre-optic cables run to a cabinet serving a neighbourhood. Customers typically connect to this cabinet using traditional coaxial cable or twisted pair wiring. The area served by the cabinet is usually less than one mile in radius and can contain several hundred customers. (If the cabinet serves an area of less than 1,000 ft (300 m) in radius, the architecture is typically called FTTC/FTTK) [McCullough05].

FTTN allows delivery of broadband services such as High Speed Internet. Highs peed communications protocols such as broadband cable access (typically DOCSIS) or some form of digital subscriber line (DSL) are used between the cabinet and the customers. The data rates vary according to the exact protocol used and according to how close the customer is to the cabinet.

Unlike FTTP, FTTN often uses existing coaxial or twisted-pair infrastructure to provide last mile service and is thus less costly to deploy. In the long term, however, its bandwidth potential is limited relative to implementations that bring the fibre still closer to the subscriber.

A variant of this technique for cable television providers is used in a hybrid fibre-coaxial (HFC) system. It is sometimes given the acronym FTTLA (fibre-to-the-last-amplifier) when it replaces analogue amplifiers up to the last one before the customer (or neighbourhood of customers).

1.4.3 Fibre to the curb/cabinet

Fibre to the curb/cabinet (FTTC) is a telecommunications system based on fibre-optic cables run to a platform that serves several customers. Each of these customers has a connection to this platform via coaxial cable or twisted pair. The "curb" is an abstraction and can just as easily mean a pole-mounted device or communications closet or shed. Typically any system terminating fibre within 1,000 ft (300 m) of the customer premises equipment would be described as FTTC.

FTTC allows delivery of broadband services such as High Speed Internet. Usually existing wire is used with communications protocols such as broadband cable access (typically DOCSIS) or some form of DSL connecting the curb/cabinet and the customers. In these protocols, the data rates vary according to the exact protocol used and according to how close the customers are to the cabinet.

Where it is feasible to run new cable, both fibre and copper ethernet are capable of connecting the "curb" with a full 100Mbit/s or 1Gbit/s connection. Even using relatively cheap outdoor category 5 copper over thousands of feet, all ethernet protocols including power over ethernet (PoE) are supported. Most fixed wireless technologies rely on PoE, including Motorola Canopy, which has low-power radios capable of running on a 12VDC power supply fed over several hundred feet of cable.

Power line networking deployments also rely on FTTC. Using the IEEE P1901 protocol (or its predecessor HomePlug AV) existing electric service cables move up to 1Gbit/s from the curb/pole/cabinet into every AC electrical outlet in the home – coverage equivalent to a robust Wi-Fi implementation, with the added advantage of a single cable for power and data.

FTTC is subtly distinct from FTTN or FTTP (all are versions of fibre in the loop). The main difference is the placement of the cabinet. FTTC will be placed near the "curb", which differs from FTTN placed far from the customer, and FTTP placed directly at the serving location.

Unlike FTTP, FTTC can use the existing coaxial, twisted-pair or AC power line infrastructure to provide last-mile service. The G.hn and IEEE P1905 efforts were attempts to unify these existing cables under one management protocol.

By avoiding new cable and its cost and liabilities, FTTC costs less to deploy. However, it also has historically had lower bandwidth potential than FTTP. In practice, the relative advantage of fibre depends on the bandwidth available for backhaul, usage-based billing restrictions that prevent full use of last-mile capabilities, and customer premises equipment and maintenance restrictions, and the cost of running fibre that can vary widely with geography and building type.

In the United States and Canada, BellSouth Telecommunications carried out the largest deployment of FTTC. With the acquisition of BellSouth by AT&T, deployment of FTTC will end. Future deployments will be based on either FTTN or FTTP. Existing FTTC plant may be removed and replaced with FTTP. Verizon, meanwhile, announced in March 2010 they were winding down Verizon FiOS expansion, concentrating on completing their network in areas that already had FiOS franchises but were not deploying to new areas, suggesting that FTTH was uneconomic beyond these areas.

Verizon also announced (at CES 2010) its entry into the smart home and power utility data management arenas, indicating it was considering using P1901-based FTTC or some other existing-wire approach to reach into homes, and access additional revenues from the secure AES-128 bandwidth required for advanced metering infrastructure. However, the largest 1Gbit/s deployment in the United States, in Chattanooga, Tennessee, despite being conducted by power utility EPB, was FTTH rather than FTTC, reaching every subscriber in a 600-square-mile area. Monthly pricing of $350 reflected this generally high cost of deployment. However, Chattanooga EPB has reduced the monthly pricing to $70/month.

Historically, both telephone and cable companies avoided hybrid networks using several different transports from their point of presence into customer premises. The increased competitive cost pressure, availability of three different existing wire solutions, smart grid deployment requirements (as in Chattanooga), and better hybrid networking tools (with major vendors like Alcatel-Lucent and Qualcomm Atheros, and Wi-Fi solutions for edge networks, IEEE 1905 and IEEE 802.21 protocol efforts and SNMP improvements) all make FTTC deployments more likely in areas uneconomic to serve with FTTP/FTTH. In effect FTTC serves as a halfway measure between fixed wireless and FTTH, with special advantages for smart appliances and electric vehicles that rely on PLC use already.

1.4.4 Fibre to the premises

Fibre to the premises (FTTP) is a form of fibre-optic communication delivery, in which an optical fibre is run in an optical distribution network from the central office all the way to the premises occupied by the subscriber. The term "FTTP" has become ambiguous and may also refer to FTTC where the fibre terminates at a utility pole without reaching the premises. Fibre to the premises can be categorized according to where the optical fibre ends:

- FTTH (fibre to the home) is a form of fibre-optic communication delivery that reaches one living or working space. The fibre extends from the central office to the subscriber's living or working space. Once at the subscriber's living or working space, the signal may be conveyed throughout the space using any means, including twisted pair, coaxial cable, wireless, power line communication, or optical fibre.

- FTTB (fibre to the building or basement) is a form of fibre-optic communication delivery that necessarily applies only to those properties that contain multiple living or working spaces. The optical fibre terminates before actually reaching the subscribers living or working space itself, but does extend to the property containing that living or working space. The signal is conveyed the final distance using any non-optical means, including twisted pair, coaxial cable, wireless, or power line communication

An apartment building may provide an example of the distinction between FTTH and FTTB. If a fibre is run to a panel at each subscriber's apartment unit, it is FTTH. If instead the fibre goes only as far as the apartment building's shared electrical room (either only to the first floor or to each floor), it is FTTB.

1.4.5 FTTx by country

1.4.5.1 FTTB

FTTB Rollout in Australia: National broadband companies TPG and iiNet, as well as the competition regulator, have published extensive submissions to the Federal Government supporting the right for commercial telcos to deploy their own Fibre to the Basement (FTTB) infrastructure throughout Australia in competition with the Coalition's Broadband Network (CBN) project, rejecting the idea that such planned investments should be blocked or otherwise regulated to support NBN Co's finances.

1.4.5.2 FTTP

FTTH in Bogotá, Colombia: In December 2013, Colombian operator ETB launched FTTH service in Bogotá D.C. including Internet and IPTV services.

FTTH in Canada: Bell Canada uses the Alcatel-Lucent 7330 ISAM video-ready access device, and provides Internet service via FTTH to 175 Mbit/s.

FTTH in Czech Republic: In December 2013, Czech operator CentroNet, a.s. launched a 1Gbit/s FTTH service in Prague.

FTTH in Italy via Fastweb: Italian operator Fastweb launched the first commercial FTTH service in 2001. Using PPPoE architecture, the service delivered voice, video and data services to thousands of subscribers' homes in Italy over a 100 Mbit/s fibre connection. Fastweb used one of the first residential gateways for both multi-dwelling units as well as residential homes that provided embedded fibre termination, designed and built by Advanced Digital Broadcast, to enable consumers to share services with a range of consumer electronics devices around the home.[18] The deployment of an FTTH network meant Fastweb was the first telecom operator to deliver true triple-play services to its subscribers. This contributed to its ARPU [Average Revenue Per User] being amongst the highest in the industry for a number of years during the early 2000s. Its FTTH network also puts it at the forefront of advanced connected home services. On September 13, 2012 the company announced a national ultra-broadband FTTS/FTTH initiative with the stated goal of offering 100 Mbit/s connections to 5.5 million Italian subscribers by 2014.

Fibre for Italy initiative: The initiative has the stated goal of offering 100 Mbit/s symmetrical connections to 10 million Italian subscribers across 15 cities by 2018 and up to 1Gbit/s for business customers. It involves operators Wind, Tele2, Vodafone and Fastweb. An ongoing pilot project in the Italian capital Rome delivers symmetrical speeds of up to 100 Mbit/s to small businesses. Telecom Italia (the largest Italian operator) is not a participant in the Fibre for Italy program, but has independently committed to provide ultra-highspeed broadband up to 100 Mbit/s symmetrical connections to 50 percent of the country's population (138 cities) by 2018. Both Fibre for Italy participants and Telecom Italia are working with Advanced Digital Broadcast to provide residential gateway technology with embedded fibre termination. Since

2006, Television Sierre SA deploys a FTTH network in most municipalities in the district of Sierre in Switzerland. Triple Play services are offered to the public under the brand Vario.

FTTH in Mexico: In 2011, Mexican operator Telmex launched the FTTH service for its customers in Mexico City, and in other major cities in Mexico.

FTTH in New Zealand: The New Zealand government is funding a GPON FTTH network called Ultra-Fast Broadband. It will cover 75% of the population and cost taxpayers NZ$1.5 billion.

FTTH in Reunion: In June 2013, Zeop launched a 35Mbit/s FTTH service on a first zone on the island. In April 2014, the bandwidth has been upgraded up to 100Mbit/s.

FTTH in Slovakia: Orange in 2007 decided to build FTTH in the country. In 2010 coverage was up to 310,000 households, almost 19% of the country. At the end of 2011 the major operators (Orange, Deutsche Telekom) covered up to 350,000 households. Since 2013 Orange has offered 250/100 Mbit/s. Another ISP, Bonet, offers symmetric 1 Gbit/s for only €25.

FTTH in Spain: Various operators are offering FTTH connections as of 2014, like Movistar, who offer 100/10 connections, or Jazztel, with a 200 Mbit/s symmetrical connection. The user base is rapidly growing. Total installed access to FTTH in February 2014 was around 609,000 homes, while at the end of the year surpassed 1.3M connected homes.

FTTH in Sri Lanka: In April 2014, Sri Lankan operator Sri Lanka Telecom launched a 100Mbit/s FTTH service.

Bournemouth, UK: In October 2012, British operator Gigler UK launched a 1 Gbit/s down and 500 Mbit/s up service in Bournemouth using the CityFibre network.

FTTH in London, UK: In October 2011, British operator Hyperoptic launched a 1Gbit/s FTTH service in London.

North, UK: In North Lancashire Farmers have teamed up to create B4RN, 1GB/s symmetrical FTTP connection to rural farms, offices and schools.

FTTH in U.S: North State in North Carolina is offering ultra-fast internet service to homes in its fibre network in High Point and portions of Greensboro. North State will continue to expand its gigabit offering further.

FTTP in the U.S.: Verizon provides FTTP and FTTN service through its FiOS service.

1.4.5.3 FTTN or FTTC

FTTN is currently used by a number of multiple-service operators to deliver advanced triple-play services to consumers, including AT&T in the United States for its U-Verseservice, Deutsche Telekom in Germany, OTE in Greece, Swisscom, Belgacom in Belgium, and Canadian operators Telus and Bell Canada. It is seen as an interim step towards full FTTH and in many cases triple-play services delivered using this approach have been proven to grow subscriber numbers and ARPU considerably.

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1.4.6 Optical distribution networks

1.4.6.1 Direct fibre

The simplest optical distribution network architecture is direct fibre: each fibre leaving the central office goes to exactly one customer. Such networks can provide excellent bandwidth but are about 10% more costly due to the fibre and central office machinery.

Direct fibre is generally favoured by new entrants and competitive operators. A benefit is that no layer 2 networking technologies are excluded, whether passive optical network (PON), active optical network (AON), or other. Any form of regulatory remedy is possible using this topology.

1.4.6.2 Shared fibre

More commonly, each fibre leaving the central office is actually shared by many customers. It is not until such a fibre gets relatively close to the customers that it is split into individual customer-specific fibres. AONs and PONs both achieve this split.

1.4.6.3 Active optical network

AONs rely on electrically powered network equipment to distribute the signal, such as a switch or router. Normally, signals need optical-electrical-optical transformation in the AON. Each signal leaving the central office is directed only to the customer for whom it is intended.

Incoming signals from the customers avoid colliding at the intersection because the powered equipment there provides buffering. Active Ethernet (a type of Ethernet in the first mile) is a common AON, which uses optical Ethernet switches to distribute the signal, incorporating the customers' premises and the central office into a large switched Ethernet network.

Such networks are identical to Ethernet computer networks used in businesses and academic institutions, except that their purpose is to connect homes and buildings to a central office rather than to connect computers and printers within a location. Each switching cabinet can handle up to 1,000 customers, although 400–500 is more typical.

This neighbourhood equipment performs layer 2 switching or layer 3 switching and routing, offloading full layer 3 routing to the carrier's central office. The IEEE 802.3ah standard enables service providers to deliver up to 100Mbit/s, full-duplex, over one single-mode optical fibre FTTP, depending on the provider. Speeds of 1Gbit/s are becoming commercially available.

SEVENTH FRAMEWORK PROGRAMME

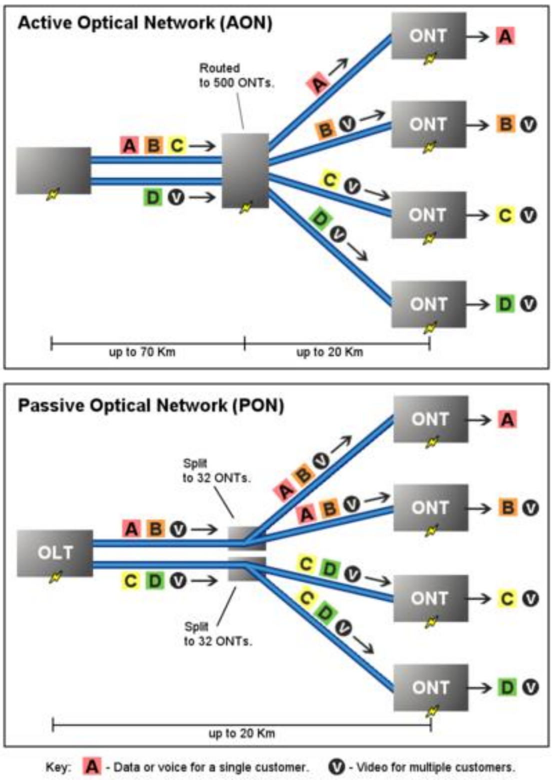

Figure 1.6 PON and P2P comparison

1.4.6.4 Passive optical network

A passive optical network (PON) is a point-to-multipoint FTTP network architecture in which unpowered optical splitters are used to enable a single optical fibre to serve up to 128 customers. A PON reduces the fibre and central office equipment required compared with point-to-point architecture.

Downstream signal coming from the central office is broadcast to each customer premises sharing a fibre. Encryption is used to prevent eavesdropping. Upstream signals are combined using a multiple-access protocol, usually time division multiple access (TDMA).

1.4.6.5 Electrical network

Once on private property, the signal typically travels the final distance to the end-user's equipment using an electrical format.

The optical network terminal (ONT, an ITU-T term) or unit (ONU, an identical IEEE term) converts the optical signal into an electrical signal using thin film filter technology. These units require electrical power for their operation, so some providers connect them to backup batteries in case of power outages to ensure emergency access to telecommunications. The optical line terminations "range" the optical network terminals or units in order to provide TDMA timeslot assignments for upstream communication.

For FTTH and for some forms of FTTB, it is common for the building's existing phone systems, local area networks, and cable TV systems to connect directly to the optical network terminal or unit. If all three systems cannot directly reach the unit, it is possible to combine signals and transport them over a common medium. Once closer to the end-user, equipment such as a router, modem, or network interface controller can separate the signals and convert them into the appropriate protocol.

With VDSL, for example, the combined signal travels through the building over existing telephone wiring until it reaches the end-user's living space, where a VDSL modem converts data and video signals into Ethernet protocol, which is sent over the end-user's category 5 cable. A network interface module converts video signal into radio frequency that is sent over the end-user's coaxial cable. The combined signal can travel over the phone wiring through DSL splitters to separate the video and data signals from the voice signal; over coaxial cable; or to VOIP phones that can plug directly into the local area network.

1.5 4G Technologies

The fourth generation (4G) of mobile telephony is a set of technologies, which have been evaluated and considered for its technical characteristics that exceed pre-set values previous technologies.

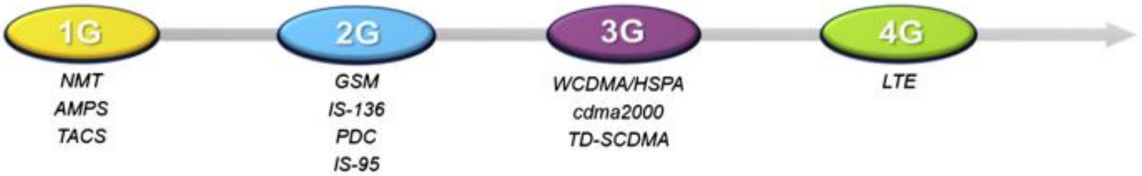

Figure 1.7 Generations of mobile communitacion systems

LTE, an abbreviation for Long-Term Evolution, commonly marketed as 4G LTE, is a standard for wireless communication of high-speed data for mobile phones and data terminals. It is based on the GSM/EDGE and UMTS/HSPA network technologies, increasing the capacity and speed using a different radio interface together with core network improvements. The standard is developed by the 3GPP (3rd Generation Partnership Project) and is specified in its Release 8 document series, with minor enhancements described in Release 9.

LTE is the natural upgrade path for carriers with both GSM/UMTS networks and CDMA2000 networks. The different LTE frequencies and bands used in different countries will mean that only multi-band phones will be able to use LTE in all countries where it is supported.

1.5.1 Overview

LTE is a standard for wireless data communications technology and a development of the GSM/UMTS standards. The goal of LTE was to increase the capacity and speed of wireless data networks using new DSP (digital signal processing) techniques and modulations that were developed around the turn of the millennium. A further goal was the redesign and simplification of the network architecture to an IP-based system with significantly reduced transfer latency compared to the 3G architecture. The LTE wireless interface is incompatible with 2G and 3G networks, so that it must be operated on a separate wireless spectrum.

LTE was first proposed by NTT DoCoMo of Japan in 2004, and studies on the new standard officially commenced in 2005. In May 2007, the LTE/SAE Trial Initiative (LSTI) alliance was founded as a global collaboration between vendors and operators with the goal of verifying and promoting the new standard in order to ensure the global introduction of the technology as quickly as possible. The LTE standard was finalized in December 2008, and the first publicly available LTE service was launched by TeliaSonera in Oslo and Stockholm on December 14, 2009 as a data connection with a USB modem. The LTE services were launched by major North American carriers as well, with the Samsung SCH-r900 being the world's first LTE Mobile phone starting on September 21, 2010 and Samsung Galaxy Indulge being the world's first LTE smartphone starting on February 10, 2011 both offered by MetroPCS and HTC ThunderBolt offered by Verizon starting on March 17 being the second LTE smartphone to be sold commercially. In Canada, Rogers Wireless was the first to launch LTE network on July 7, 2011 offering the Sierra Wireless AirCard® 313U USB mobile broadband modem, known as the "LTE Rocket™ stick" then followed closely by mobile devices from both HTC and Samsung. Initially, CDMA operators planned to upgrade to rival standards called UMB and WiMAX, but all the major CDMA operators (such as Verizon, Sprint and MetroPCS in the United States, Bell and Telus in Canada, au by KDDI in Japan, SK Telecom in South Korea and China Telecom/China Unicom in China) have announced that they intend to migrate to LTE after all. The evolution of LTE is LTE Advanced, which was standardized in March 2011. Services are expected to commence in 2013.

The LTE specification provides downlink peak rates of 300 Mbit/s, uplink peak rates of 75 Mbit/s and QoS provisions permitting a transfer latency of less than 5 ms in the radio access network. LTE has the ability to manage fast-moving mobiles and supports multi-cast and broadcast streams. LTE supports scalable carrier bandwidths, from 1.4 MHz to 20 MHz and supports both frequency division duplexing (FDD) and time-division duplexing (TDD). The IP-based network architecture, called the Evolved Packet Core (EPC) and designed to replace the GPRS Core Network, supports seamless handovers for both voice and data to cell towers with older network technology such as GSM, UMTS and CDMA2000. The simpler architecture results in lower operating costs (for example, each E-UTRA cell will support up to four times the data and voice capacity supported by HSPA).

1.5.2 Features

Much of the LTE standard addresses the upgrading of 3G UMTS to what will eventually be 4G mobile communications technology. A large amount of the work is aimed at simplifying the architecture of the system, as it transits from the existing UMTS circuit + packet switching combined network, to an all-IP flat architecture system. E-UTRA is the air interface of LTE. Its main features are:

- Peak download rates up to 299.6 Mbit/s and upload rates up to 75.4 Mbit/s depending on the user equipment category (with 4×4 antennas using 20 MHz of spectrum). Five different terminal classes have been defined from a voice centric class up to a high end terminal that supports the peak data rates. All terminals will be able to process 20 MHz bandwidth.

- Low data transfer latencies (sub-5 ms latency for small IP packets in optimal conditions), lower latencies for handover and connection setup time than with previous radio access technologies.
- Improved support for mobility, exemplified by support for terminals moving at up to 350 km/h (220 mph) or 500 km/h (310 mph) depending on the frequency band.
- OFDMA for the downlink, SC-FDMA for the uplink to conserve power.
- Support for both FDD and TDD communication systems as well as half-duplex FDD with the same radio access technology.
- Support for all frequency bands currently used by IMT systems by ITU-R.
- Increased spectrum flexibility: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz wide cells are standardized. (W-CDMA has no option for other than 5 MHz slices, leading to some problems rolling-out in countries where 5 MHz is a commonly allocated width of spectrum so would frequently already be in use with legacy standards such as 2G GSM and CDMAOne.)
- Support for cell sizes from tens of metres radius (femto and picocells) up to 100 km (62 miles) radius macrocells. In the lower frequency bands to be used in rural areas, 5 km (3.1 miles) is the optimal cell size, 30 km (19 miles) having reasonable performance, and up to 100 km cell sizes supported with acceptable performance. In city and urban areas, higher frequency bands (such as 2.6 GHz in EU) are used to support high speed mobile broadband. In this case, cell sizes may be 1 km (0.62 miles) or even less.
- Supports at least 200 active data clients in every 5 MHz cell.
- Simplified architecture: The network side of E-UTRAN is composed only of eNode Bs.
- Support for inter-operation and co-existence with legacy standards (e.g., GSM/EDGE, UMTS and CDMA2000). Users can start a call or transfer of data in an area using an LTE standard, and, should coverage be unavailable, continue the operation without any action on their part using GSM/GPRS or W-CDMA-based UMTS or even 3GPP2 networks such as CDMAOne or CDMA2000.
- Packet switched radio interface.
- Support for MBSFN (Multicast-Broadcast Single Frequency Network). This feature can deliver services such as Mobile TV using the LTE infrastructure, and is a competitor for DVB-H-based TV broadcast.

1.5.3 Voice calls

The LTE standard supports only packet switching with its all-IP network. Voice calls in GSM, UMTS and CDMA2000 are circuit switched, so with the adoption of LTE, carriers will have to re-engineer their voice call network.[25] Three different approaches sprang up:

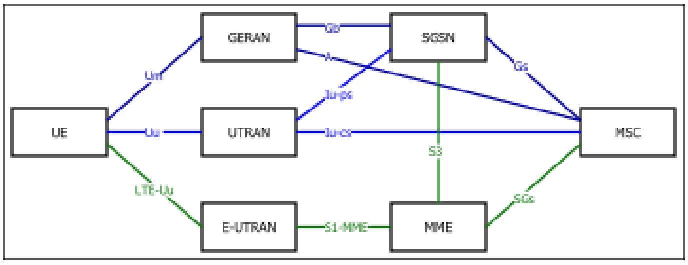

Figure 1.8 Voice implementations in LTE systems

1.5.3.1 Voice over LTE (VoLTE)

VoLTE, an acronym for Voice over LTE, which is based on the IP Multimedia Subsystem (IMS) network, with specific profiles for control and media planes of voice service on LTE defined by GSMA in PRD IR.92. This approach results in the voice service (control and media planes) being delivered as data flows within the LTE data bearer. This means that there is no dependency on (or ultimately, requirement for) the legacy circuit-switched voice network to be maintained. VoLTE has up to three times more voice and data capacity than 3G UMTS and up to six times more than 2G GSM. Furthermore, it frees up bandwidth because VoLTE's packets headers are smaller than those of unoptimized VoIP/LTE.

1.5.3.2 Circuit-switched fallback (CSFB)

In this approach, LTE just provides data services, and when a voice call is to be initiated or received, it will fall back to the circuit-switched domain. When using this solution, operators just need to upgrade the MSC instead of deploying the IMS, and therefore, can provide services quickly. However, the disadvantage is longer call setup delay.

1.5.3.3 Simultaneous voice and LTE (SVLTE)

In this approach, the handset works simultaneously in the LTE and circuit switched modes, with the LTE mode providing data services and the circuit switched mode providing the voice service. This is a solution solely based on the handset, which does not have special requirements on the network and does not require the deployment of IMS either. The disadvantage of this solution is that the phone can become expensive with high power consumption.

One additional approach, which is not initiated by operators, is the usage of over-the-top content (OTT) services, using applications like Skype and Google Talk to provide LTE voice service. However, now and in the foreseeable future, the voice call service is, and will still be, the main revenue source for the mobile operators. So handing the LTE voice service over completely to the OTT providers is thus something which is not expected to receive much support in the telecom industry.

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Most major backers of LTE preferred and promoted VoLTE from the beginning. The lack of software support in initial LTE devices as well as core network devices however led to a number of carriers promoting VoLGA (Voice over LTE Generic Access) as an interim solution. The idea was to use the same principles as GAN (Generic Access Network, also known as UMA or Unlicensed Mobile Access), which defines the protocols through which a mobile handset can perform voice calls over a customer's private Internet connection, usually over wireless LAN. VoLGA however never gained much support, because VoLTE (IMS) promises much more flexible services, albeit at the cost of having to upgrade the entire voice call infrastructure. VoLTE will also require Single Radio Voice Call Continuity (SRVCC) in order to be able to smoothly perform a handover to a 3G network in case of poor LTE signal quality.

While the industry has seemingly standardized on VoLTE for the future, the demand for voice calls today has led LTE carriers to introduce CSFB as a stopgap measure. When placing or receiving a voice call, LTE handsets will fall back to old 2G or 3G networks for the duration of the call.

1.5.3.4 Enhanced voice quality

To ensure compatibility, 3GPP demands at least AMR-NB codec (narrow band), but the recommended speech codec for VoLTE is Adaptive Multi-Rate Wideband, also known as HD Voice.

This codec is mandated in 3GPP networks that support 16 kHz sampling.

Fraunhofer IIS has proposed and demonstrated "Full-HD Voice", an implementation of the AAC-ELD (Advanced Audio Coding – Enhanced Low Delay) codec for LTE handsets. Where previous cell phone voice codecs only supported frequencies up to 3.5 kHz and upcoming wideband audio services branded as HD Voice up to 7 kHz, Full-HD Voice supports the entire bandwidth range from 20 Hz to 20 kHz. For end-to-end Full-HD Voice calls to succeed however, both the caller and recipient's handsets as well as networks have to support the feature.

2 SODALES architecture

The SODALES network is an innovative high-bandwidth access network architecture that offers transparent transport services for fixed (≥1Gbps) and mobile applications (LTE and beyond). The main novelty is the development of a high-functionality, low-energy active remote node (ARN) offering high-speed switching and statistical-multiplexing features for maximal exploitation of available network resources, together with radio and legacy systems compatibility, taking advantage of the required powering at the remote base stations (RBSs).

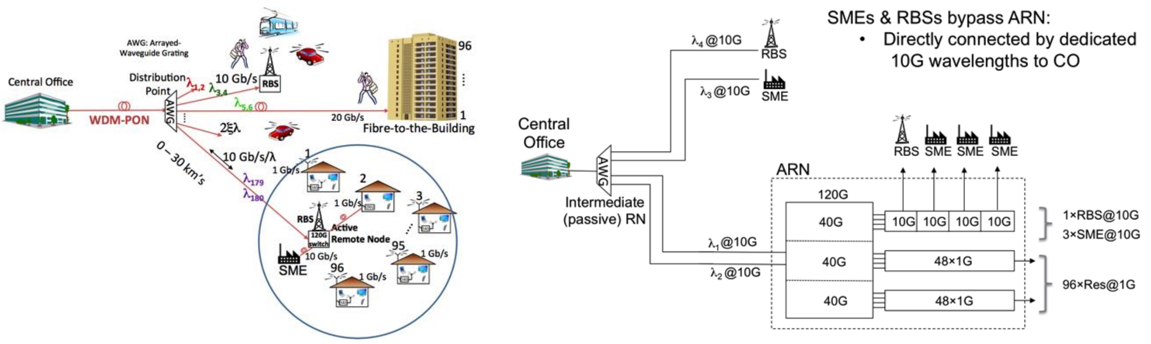

Figure 2.1 Network architecture, featuring a combined RBS/RNA functional Kingdom at the center of a small cell (left) and detail of RNA basic architecture (right)

The proposed architecture enables an optimized and sophisticated management and control plane, allowing service providers to transparently monitor their connections, so simplifying network management and application interoperability with heterogeneous networks. Although inherently future-proofed, the proposed network platform is also intrinsically compatible with existing fibre and wireless access solutions in an open access context. In addition, its low-energy, and low-cost design offers an environmentally sustainable technology solution, whilst acting as a critical enabler for new smart services, e-society initiatives, and intelligent lifestyle management.

2.1 Introduction

End-user access bandwidths of 1 Gb/s will be commonplace by 2016, with 10 Gb/s for domestic applications arriving within the next 10 years [1]. Achieving such bandwidths is a techno-economic challenge, demanding careful deployment (CAPEX & OPEX) of future-proofed technology, whilst balancing green issues (energy-consumption, life-cycle carbon footprint, and environmental impact etc.) and other critical long-term technological trends, such as wireless-wireline convergence.

Up to now, fibre-to-the-home (FTTH) with a passive optical network (PON) between the central office (CO) or local exchange and end-user has been the favoured solution, but the economics remain problematic. The civil-engineering/trench-digging costs are high (variously estimated at 80% of overall costs) and a PON requires a substantial investment in the fibre cabling into the ground because of the intrinsically low utilisation of the available fibre infrastructure. We are proposing a next-generation access (NGA) solution that makes more efficient use of the fibre infrastructure, is scalable and future-proofed, and offers an economically viable deployment trajectory, while offering the flexibility to scale the network and support new wireless transmission technologies together with ultra high speed data services.

Our solution centres on an active remote node (ARN) that, by virtue of being powered takes advantage of the fact that remote base stations (RBSs) require power to operate, and therefore also exploits the substantial operational and economic advantages in combining statistical multiplexing with standard Ethernet switching technology.

We propose a unified form of ARN that combines FTTH to exploit the roll-out of PON infrastructure in certain territories, and acts as a RBS to service mobile wireless signals, whilst also offering 60 GHz mm-wave technology to deliver high bandwidth wireless final-drop. Additionally, this offers legacy, LTE and beyond mobile access services for mobile users, taking advantage of the powering available at the ARN to offer a L2-port interconnection to a RBS in an integrated manner, so enabling central baseband processing for better flexibility in accommodating different technologies. This interface also allows the interconnection of legacy fixed infrastructures to live CATV and DSL technologies by installing a CMTS or a DSLAM at the ARN site, and using already-present (legacy) outside plant to connect to end-users.

2.2 Fixed and radio convergence

Technological with location convergence of fixed (optical and mm-wave) with wireless (mobile) communications is one of the key innovative functionalities that we propose. As part of creating a new access architecture paradigm is the additional realization that the presence of active nodes between end-users and the CO is also likely to become an ever-more essential feature of next-generation access topologies.

This somewhat goes against the PON philosophy of only passive infrastructure between end-user and CO; but since mobile communications require powered base stations at the intermediate street level, the logic of the de facto existence of ARN-type functionality nodes is starting to become inescapable.

Indeed, by dimensioning the ARN appropriately, power/energy saving techniques can also be employed to minimize the carbon footprint. For example, limited statistical multiplexing can be employed so as to exploit the available network resources as optimally as possible. In addition, by designing the ARN to have a maximum power consumption of approximately 1.5 kW, this means that renewable energy sources can be employed to power the ARN; e.g. a solar panel of dimensions 12.5m x 10m will offer, in a worst-case scenario, a dependable output power of about 1.5 kW.

2.3 Network architecture

We aim to develop a unified access platform to interconnect fixed and mobile subscribers. As the number of end-users to be connected to the network will be high, resilience and flexible bandwidth allocation protocols are key to efficiently use the available network resources while providing reliable services.

Thus, as an advance on the basic architecture that is presented in the next section, the platform offers different configuration options in order to grow the basic building block into ring and full mesh topologies that are capable of offering advanced load-balancing and resiliency functionalities.

2.3.1 Basic Architecture

Our basic architecture for an appropriately designed ARN is shown in Figure 1. In this case, the basic architecture has been designed to offer 1 Gb/s statistically-multiplexed bandwidth to each of 96 residential homes, in addition to providing dedicated 10 Gb/s bandwidth pipes to each of three SME companies, and finally an additional 10 Gb/s bandwidth pipe to a cellular RBS site, e.g. for 3G, LTE wireless connectivity etc. In this case, we have designed the ARN to consist of a 120G=3×40G Ethernet switch chassis, where the first 40G rack has 4 output ports of 10G capacity each, connected respectively to the RBS and 3 SMEs.

In this first 40G rack case, there is no contention or statistical multiplexing. The other two 40G racks each have 48 output ports, each offering a maximum 1 Gb/s bandwidth pipe. This allows the 96 residential homes to be offered a final-drop symmetrical upstream and downstream bandwidth of 1 Gb/s, with a statistical multiplexing (over-subscription) ratio of only 1.2 (i.e. 20% over-subscription). The statistical multiplexing ratio at the upstream port of the chassis is much higher (i.e. factor 6) and represents a significantly useful degree of optimal exploitation of network resource. As can be seen from the Figure 1, a total of 20 Gb/s (equal to 2×λ @10 Gb/s/λ) light paths are used between the ARN and the CO. These can be considered as the allocated wavelengths in a XG-WDM-PON backhaul system, such that rather than terminating the ONT at the customer premises as would be conventionally expected, the ONT is actually located at the ARN, and terminates with the 120G Ethernet switch. Apart from this, the XG-PON functions as is conventional, with an intermediate arrayed-waveguide grating (AWG) wavelength-routing lightpaths to other ARNs, or even allowing dedicated wavelengths to be directly routed to a 10G ONT located at a RBS or SME business premises, as indicated.

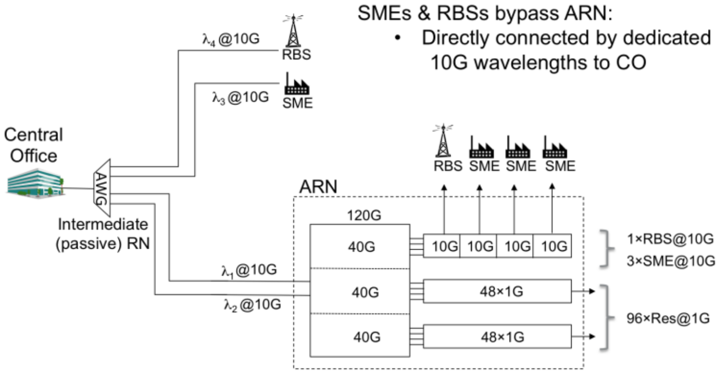

Figure 2.2 Basic architecture, serving 96 homes each with 1 Gb/s, and 3 SMEs with 10 Gb/s each, and one remote base station (RBS) with 10 Gb/s bandwidth pipes.

The XG-PON technology, which is fully passive and uncontested between CO and ONT, is therefore fully taken advantage of; but with the ONT located at the ARN, this enables the flexible final-drop technologies: either wired (fibre-optical, FTTH) or wireless (radio/mm-wave/optical) to the residential home, and likewise convergence with mobile communications. We note that at this stage, the functionality of the ARN is kept to a minimum. Handover functions (e.g. vertical, between macro/femto cells, for example; or horizontal, between femto/femto cells etc.) are not performed at the ARN; neither is any cognitive nor any co-operative function performed locally here. As a means to be fully backwardly compatible with legacy mobile technology, and maintaining a simple (cost inexpensive) ARN solution, any such network intelligence functionality is assumed to be performed at the CO.

Similarly, other intelligent photonic network functionalities, e.g. caching, and/or local routing of local traffic is not expected to be performed at the ARN. That said, given the presence of an actively powered node at the ARN, it is reasonable to expect that such advanced networking functionalities might indeed be performed at the ARN at some point in the future. However, these particular advanced functionalities are not the explicit subject of the current SODALES [5] project focus.

2.3.2 Flexibility and Scalability

The principle of the basic ARN module of Fig. 1 is to be the blueprint to allow multiple configurations. In access networks, deployments are typically heterogeneous and therefore, the existence of a flexible reference module is key to allowing reduced cost due to equipment standardization. At the same time, the design needs to be optimized to maximize port utilization. Therefore, from the basic architecture, one can deploy multiple configurations, like the ones presented in Fig. 2:

– Residential areas: when there are no businesses that require 10G services, the ARN can offer up to 168 GbE services, by reusing the 30Gbps of available bandwidth that is initially reserved for corporate use.
– ARN bypass: in case a corporation requires ultra high capacity, a dedicated wavelength can be allocated.

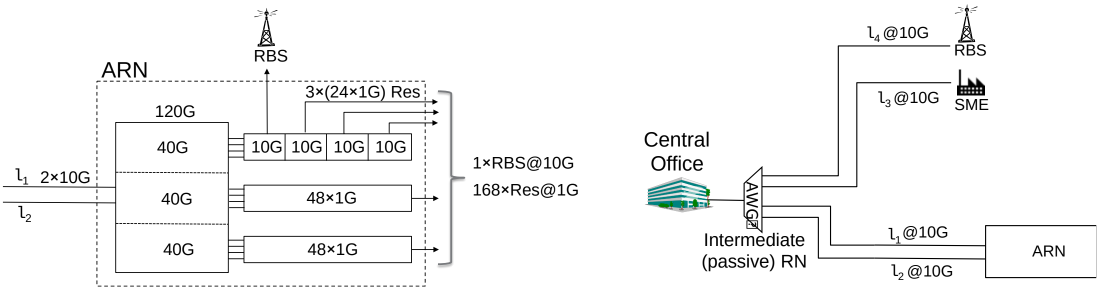

Figure 2.3 ARN variants: residential ARN (left) and network topology with ARN bypass to offer dedicated wavelength to corporations with ultra high bandwidth requirements (right).

These two variants complement the basic architecture and offer an extra degree of flexibility and scalability to the network.

2.3.3 Radio interfacing

Together with flexibility and scalability, integration of radio services is key to optimizing network deployment costs of NGA networks. LTE and beyond services require fibre to reach the RBS ,and therefore to unify fixed and mobile access it is important to reduce both OPEX and CAPEX. To achieve this goal we propose two additional approaches, shown in Figure 3, depending on the capacity required at the RBS.

- Direct IP connectivity (as the native fixed/mobile convergence mode)
- CPRI over SDH/OTN or over Synchronous Ethernet for distributed antennas

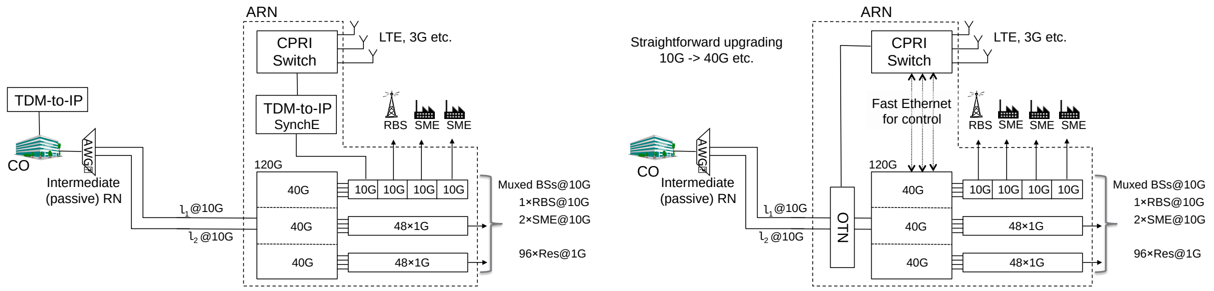

Figure 2.4 ARN variants for radio interfacing: CPRI integration with TDM-to-IP adaptation layer (left) and OTN transport (right)

2.3.4 Interconnection and resiliency

An important aspect to the architecture is the ability to build in resilience and protection, to create a robust converged access network. On the one hand, protection via simple dualling is possible between the CO and ARN (or RBS, and SME etc.) of Figure 1, although this is likely to be an expensive solution. Instead, alternative topologies involving multiple ARNs connected to the same CO can also be considered. There are two main flavours of topology to be considered in this case: ring and mesh.

For the first Ring case topology, shown in Figure 4 (left), multiple ARNs are connected in a ring architecture to the CO and require the presence of 2-degree ROADMs (reconfigurable optical add/drop multiplexers) in the ARN to add/drop the two wavelengths associated with the ARN around the ring. Further to resiliency, the addition of these ROADMs to each ARN allows advanced bandwidth allocation features, which will enhance resource optimization. As can be seen, each ARN is associated with a different pair of 10G wavelengths, which can travel in both directions around the ring. Should there be a cable break somewhere along the ring, then upstream and downstream data can continue to be successfully transmitted between the CO and all the ARNs using the unbroken portion of the ring. Greater resilience to multiple fibre breaks or failures can also be achieved by employing a mesh configuration for the multiple ARNs. As shown in Figure 4 (right), in this case, we depict a fully-meshed topology, with every ARN connected to all other ARNs. For such a mesh topology, multi-degree ROADMs are required at each ARN, so as to allow full flexibility as to which pair of 10G wavelengths to add/drop at each ARN. The mesh architecture is interesting for new mobile concepts such as coordinated multi-point [6].

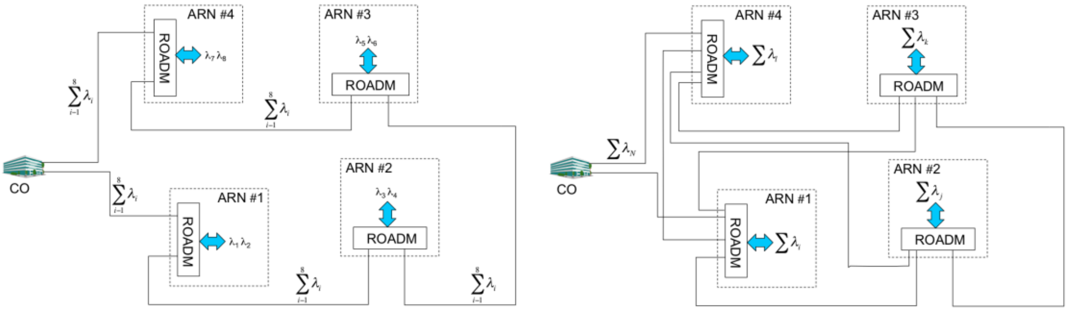

Figure 2.5 Architecture with multiple ARNs in a ring topology (left) and in a mesh topology (right)

Although not explicitly indicated in the diagrams, alternative topological connectivity may also be achieved using the wireless capability associated with each ARN. In such a situation, rather than only relying on the optical fibre ring (or mesh) for data backhaul, it may be possible to use the inherent bandwidth capacity of the RBS to signal to other RBSs located at the other ARNs, to create a wireless mesh network. Such a wireless mesh network can also be achieved either by dedicated high bandwidth wireless links between RBSs (e.g. at 60 GHz, to achieve the required multi-Gb/s throughputs), or by adaptive antennas and beam-shaping etc. (to efficiently exploit the available bandwidth capacity in a RBS). Such an alternative possibility offers a convenient means for robust, redundant protection and resilience in a fully-converged access network at minimum extra cost.

2.4 Simulated architecture

The architecture that will be simulated is intended to be an evolution towards total convergence of fixed and mobile. To do so, the proposal aims to use WDM technology between the CO and the ARNs.

Today's networks are evolving and continue their expansion with more deployments of PON networks, being GPON the main technology used in Europe.

Also, 10Gbps PON systems are starting to be considered by some operators, in order to offer Gigabit to the user. Additionally, 4G and beyond radio systems continue its expansion, offering higher data rates to the users by reducing the size of the cells and optimizing spectrum efficiency.

Thus, it is expected that the two infrastructures will overlap and therefore, strategies to combine services using a single network are desirable. This is actually what SODALES promotes, also taking into consideration the RBS distribution of 4G and future 5G transmission systems.

By deploying ARNs close to the users, where 4G / 5G cells are deployed, the flexibility of the network and its cost is enhanced, optimizing networks efficiency and reducing both, CAPEX and OPEX. Additionally, traffic patters and simulations show that to combine fixed and mobile and residential and corporate users allow to increase oversubscription ratio and maximizes network utilization.

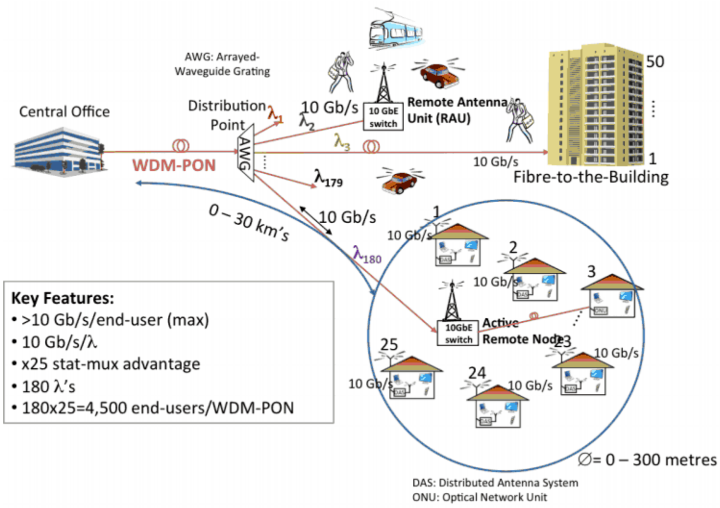

Figure 2.6 basic SODALES architecture and service vision

The ARN is based on a layer-2 aggregation switch. It is a pizza-box modular design, with two controllers and three multi-purpose slots in which several cards can be installed. With this approach, we have the flexibility to deploy different configurations depending on the type of users to be connected.

The traffic aggregator is designed and in this way has been simulated with interfaces of 1 and 10Gbps. 1 Gbps interfaces are designed for residential users, while 10 Gbps interfaces are designed for business users, fibre-to-the-building and RBS.

The cards that can be installed in the ARN are:

- 48-port 1Gbps card
- 4-port 10Gbps card

Also, 100Gbps uplink cards are in the roadmap, but not in the scope of the project, as power consumption is higher than 10Gbps cards and we do not find a short-term necessity to deploy this technology in the access within the next years.

Thus, the most common configuration of the ARN will be:

- Two controllers with two 10 Gb/s uplinks
- Three customer modules, two of them with 48 1-Gbps and interfaces to offer 96 residential endpoints and one with 4x 10Gbps interfaces.

The backplanes of these slots are connected to three 40Gbps switch fabrics, as shown below:

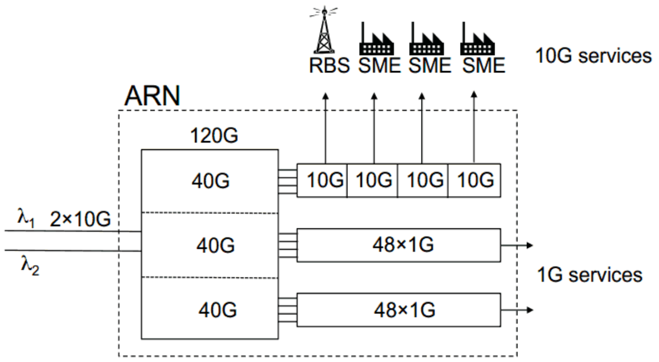

Figure 2.7 ARN architecture

By design, there is oversubscription of 40/48 (83%) in the 1Gbps cards.

10Gbps cards are non-blocking 40/40 (100%).

However, there is a relevant 1:6 oversubscription in the uplink aggregation (2x10Gbps/120Gbps). This leads to a 16% of service guarantee.

However, we will later demonstrate that this is not a limitation, as with Gigabit datarates, oversubscription can be much higher due to the high degree of statistical multiplexing that can be achieved.

Also, oversubscription is a key parameter to make networks cost effective [Ericcson12] [CiscoVNIMobile13-18] [CiscoZettabyteEra14].

The uplinks make use WDM to multiplex two services on the same fibre. These signals routed by means of an AWG allow very high network flexibility, as wavelengths can also be routed to customers with high transmission requirements, which may require +40Gbps transmission services.

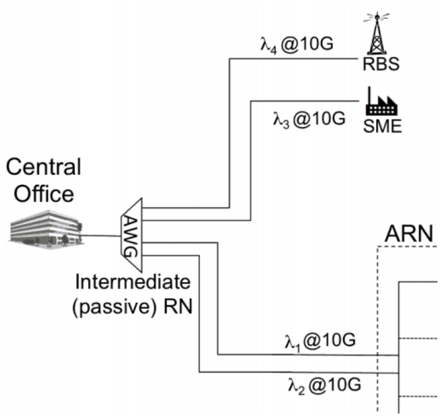

Figure 2.8 Bypass of SODALES ARN architecture for RBS and SME

With respect to power efficiency, it is important to know that 90% of the power consumption of a telecommunications network is in the access. SODALES takes this very seriously and this is the reason why the ARN is configured using 10Gbps links and low-power-consumption subsystems. This has already been described in detail in Deliverable 1.1.

2.4.1 High availability

The ARN is designed to be a carrier-class device.

The aggregator works even though one of the two controllers fails, keeping the system operative.

Another important characteristic of the ARN is the dual power supply to provide continuous operation.

2.4.2 Mobile communications integration

Carrier Ethernet, which is the transport technology chosen to implement the ARN gives a lot of flexibility to integrate different services on the same data stream, by means of queue prioritizing and traffic segmentation.

However, as said before, mobile networks synchronization is an issue that needs to be analysed carefully when implementing convergent access networks. One of the common protocols used for mobile front haul, CPRI, is not compatible with Ethernet aggregation. Thus, in case of CPRI requirements, an extra degree of conversion is required to perform the protocol adaptation. This can be seen in the following Figure:

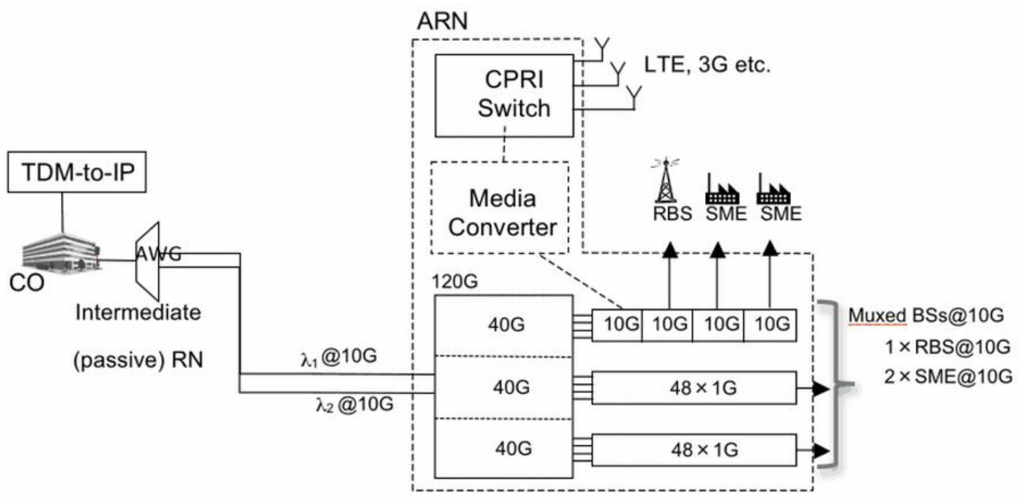

Figure 2.9 Integration of SODALES CPRI over Synchronous Ethernet

2.4.3 Hardware

The ARN is built using carrier-class equipment and with robustness in mind, offering also extended temperature range, in order to be deployed in the field. This is also a very important requirement, as one of the key aspects of the ARN will be the fact that it will be deployed next to the RBS / radio antenna.

Figure 2.10 ARN SODALES backplane with tributary cards

This figure above shows the ARN.

3 Methodology

In order to validate the proposed convergent architecture, we will simulate the performance of the ARN and compare its scalability and throughput with current commercial solutions. It is important to note that traffic parameters have been taken from real FTTH project.

The methodology that has followed has been:

- To select the most appropriate simulation tools based on a benchmark of existing open-source simulation solutions
- To modelling the critical devices on the network
- To characterize common traffic patterns of high-speed access networks
- Perform simulations for various loads and compare them with a reference network

With all this, we want to analyse:

- That our infrastructure is ready to cope with future connectivity demand as per what show the trends of the leading actors in the sector
- To stress it and find the limit of the two-layer switching fabric of the ARN for different load patters without any packet loss in the system
- To determine traffic trends and the system roadmap, as existing PON solutions will not be sufficient to transport future connectivity services and an upgrade will be required
- To simulate and obtain multiplexing factors in convergent fixed / mobile networks, together with acceptable oversubscription factors, which tend to scale when the capacity given to each subscriber increases.

Since SODALES is Ethernet-based, we have taken as reference PON network an IEEE 802.3ah EPON architecture. As has been described in the previous section, EPON provides symmetric 1Gbps, transmitting Ethernet frames directly over the data channel.

The key component that has been modelled in the SODALES architecture has been the Active Remote Node (ARN) located at the RBS. To implement this, the customers have been modelled as computer interfaces and the base stations as aggregators of mobile traffic. Then, two switch fabrics have been modelled to transmit the data traffic to the line card that interfaces with the uplink by means of 2x 10Gbps channels. The size of the queues has been dimensioned to have a non-blocking, zero-packet-loss transmission system, dimensioning the size of the shared memory of each transmission queue.

Real traffic patters of existing FTTH deployments have been used to validate the network. These traffic profiles have been taken from a real deployment in with 100Mbps symmetric services are offered and have been the starting point from with the model has scaled to reach 1Gbps symmetric connectivity services.

Also, traffic from two PoPs in Spain has been considered to model the uplink. Those are Catnix in Barcelona and Espanix in Madrid.

Finally, to model this traffic has also been taken into account two types of services:

- Data traffic
- IPTV traffic

VoIP has not been taken into account, as it does not generate large streams of data. Also, we have differentiated the traffic of residential, corporate and mobile subscribers.

3.1 Benchmark of simulation tools

Several simulation tools have been benchmarked prior to select the one with which the simulations were carried out. Those were:

- NS-2
- NS-3
- OPNET
- OMNET ++

To compare them, first we need to take into consideration that we can differentiate several types of simulators:

Discrete-event simulation (DES) models the operation of a system as a discrete sequence of events in time. Each event occurs at a particular instant in time and marks a change of state in the system.[1] Between consecutive events, no change in the system is assumed to occur; thus the simulation can directly jump in time from one event to the next.

This contrasts with continuous simulation in which the simulation continuously tracks the system dynamics over time. Instead of being event-based, this is called an activity-based simulation; time is broken up into small time slices and the system state is updated according to the set of activities happening in the time slice.[2] Because discrete-event simulations do not have to simulate every time slice, they can typically run much faster than the corresponding continuous simulation.

Another alternative to event-based simulation is process-based simulation. In this approach, each activity in a system corresponds to a separate process, where a process is typically simulated by a thread in the simulation program.[2] In this case, the discrete events, which are generated by threads, would cause other threads to sleep, wake, and update the system state.

A more recent method is the three-phased approach to discrete event simulation (Pidd, 1998). In this approach, the first phase is to jump to the next chronological event. The second phase is to execute all events that unconditionally occur at that time (these are called B-events). The third phase is to execute all events that conditionally occur at that time (these are called C-events). The three-phase approach is a refinement of the event-based approach in which simultaneous events are ordered so as to make the most efficient use of computer resources.

The three-phase approach is used by a number of commercial simulation software packages, but from the user's point of view, the specifics of the underlying simulation method are generally hidden.

3.1.1 NS2

Network Simulator 2 is an open source discrete event simulator, which is mainly used by academia, due to the high number of developed modules. Although it does not have a graphical programming environment and is limitedly precise, it is considered a standard.

It was supported by DARPA but has been discontinued and its latest version dates from year 2009. The main issue is the lack of libraries to simulate PON protocols, as it is mainly focused on packet-based local area networks.

This is based on C++ language and the programming of events and modelling are based on a language called TCL, which is very commont in the networks world due to the fact that it is used in Cisco Systems network equipment.

NS2 offers a graphical environment to plot graphs and traces obtained from the simulators. One of its advantages is the fact that there is vast documentation and examples on the web.

3.1.2 NS3

Network Simulator 3 can be seen a direct evolution of NS2. However, it as a fork, which was built from scratch in 2005 and released its first version in July 2008.

It is not backwards compatible with NS2, but offers the feature to use Python scripts to run the simulations.

Its documentation is based on Doxygen[13].

This provides new libraries to simulate protocols like Wi-Fi, WiMax, LTE and modern routing algorithms. However, it lacks of the vast documentation that NS2 offers.

3.1.3 OMNET ++

OMNeT++ is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators. Network in this case is meant in a broader sense that includes wired and wireless communication networks, on-chip networks, queuing networks,

OMNeT++ provides component architecture for models. Components (modules) are programmed in C++, then assembled into larger components and models using a high-level language (NED)

OMNeT++ is not a simulator in itself but rather a simulation framework. Instead of containing explicit and hardwired support for computer networks or other areas, it provides the infrastructure for writing such simulations. Various simulation models and frameworks cater specific application areas, most of them being open source. These models are developed completely independently of OMNeT++, and follow their own release cycles.

OMNeT++ is released with full source code, and is free to use, modify and distribute in academic and educational institutions under its own license (Academic Public License). Corporate use requires, however, a paid license of OMNEST.

It allows simulating point to point, advanced routing protocols, wireless networks of all types, sensor networks, wireless networks with geographical mobility (even with Google maps), and support the newer EPON standards.

The tool also provides a complete programming environment, which is based on Eclipse. It also provides visualization of the simulation in real time, and allows and allow flexible simulation adapting the variables and queues in real time.

This has been the one chosen to perform the simulation.

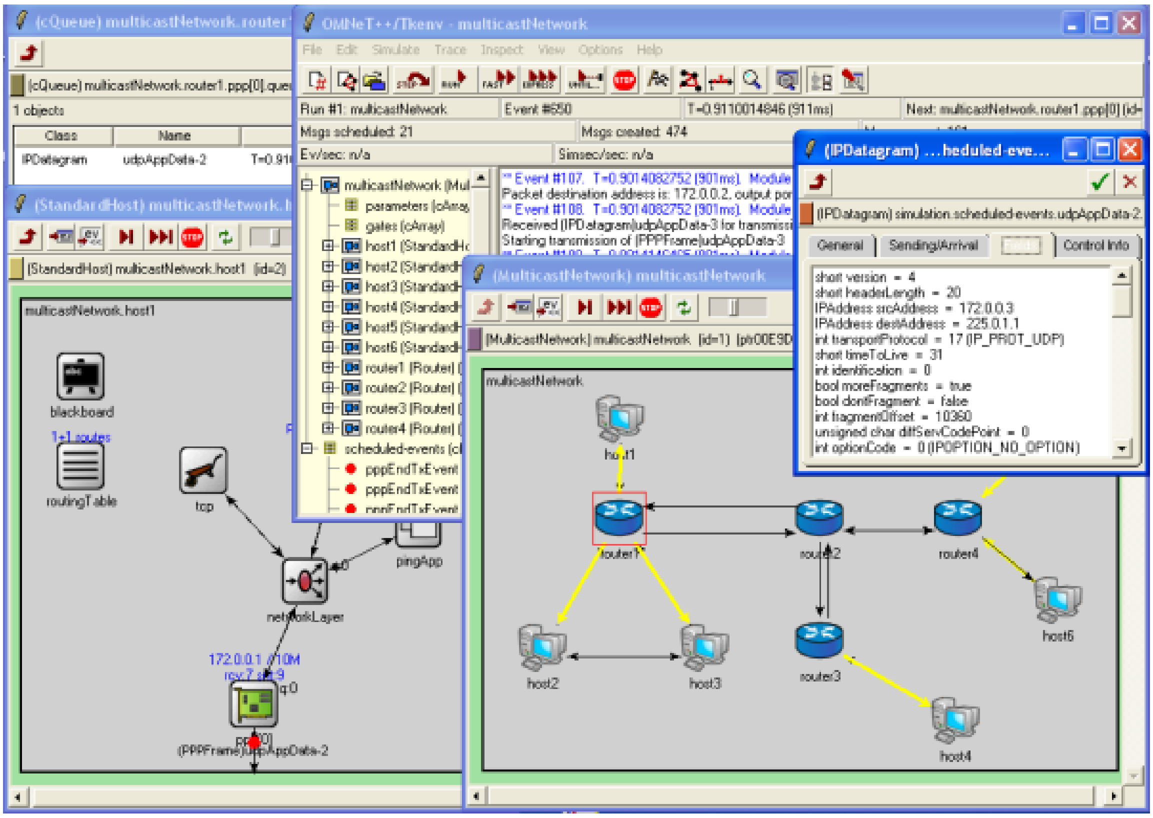

Figure 3.1 OMNET++ Screenshot

3.1.4 OPNET

OPNET Is a commercial object-oriented Simulator similar to OMNET. It is a very mature professional system, and offers many libraries and protocols to model telecom networks. It is more professional than academia oriented.

The internal structure and working procedures are similar to OMNET but OPNET is more oriented to direct simulations. It also allows real-time adjustments of the simulations, but it does not include the programming environment that allows OMNET to develop new starndards and protocols.

3.1.5 Selected Tool

Finally, OMNET was chosen to perform the simulations. It fulfils the requirements; such as being a discrete event Simulator and that can simulate and model access networks. But the greatest advantage is the fact that it is open-source and free for academic use, so it can be completely programed. It is modular and allows the reuse of components, so large simulations can be implemented using a graphical environment.

Use one of the standard environments (IDE) is of great acceptance by programmers. This also happens with Eclipse. It is Linux-based.

By virtue of being object-oriented, is modular and can be customized.

It is a tool very accepted by research environments and adopted year after year with more popularity. This has generated, over time, a powerful community that adds features and refines the code.

Finally, one of the best features is the fact that it offers a vast number of available libraries. It natively supports Ethernet an EPON protocols, simplifying the simulation work and preventing to develop specific libraries to implement the simulations that want to be carried out.

SEVENTH FRAMEWORK PROGRAMME

4 Network Modelling

This section describes how the different components of the SODALES architecture have been modelled on OMNET++ to perform the simulations.

4.1 ARN modelling

The ARN, designed and implemented by PTI, has the following internal architecture:

Port distribution (data plane)

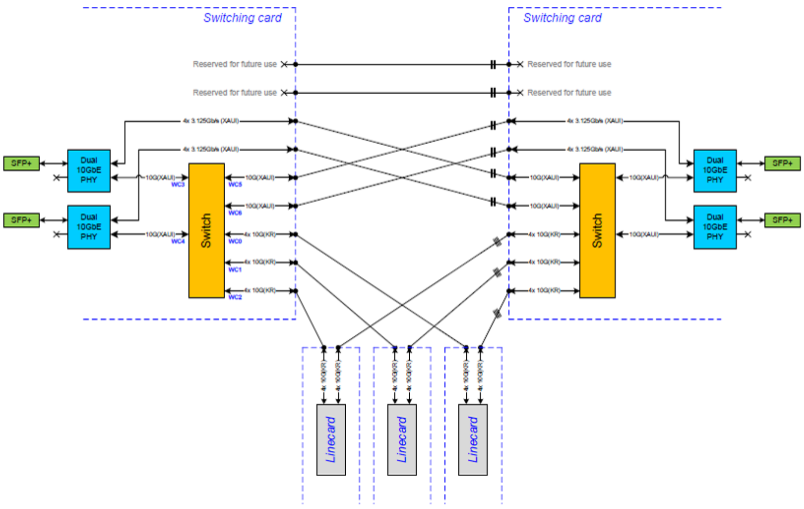

Figure 4.1 Internal architecture and switching

It is designed taking into consideration carrier-class requirements. Thus, resilience and dual links are implemented for every connection to give protection to the interconnection.

The boar also offers two spare links between the two controllers (Switching Card's) reserved for future uses, such as for example to extend the degrees of a possible ROADM system, and two SFP + controller board that would allow to increase the uplinks to the CO.

Also, the platform offers redundancy and if one of the controllers fails, the ARN keeps operating. In the same way, client slots have interfaces to all controllers, being able to balance traffic depending on the available resources.

The aggregator is dimensioned offering a non-blocking architecture, with 32.5GB of memory per controller. This allows multiple queue strategy and an “almost infinite” queuing approach.

4.2 ARN model in OMNET

This section covers how the ARN has been modelled in OMNET in order to perform the simulations and testing of the SODALES architecture.

4.2.1 .NED

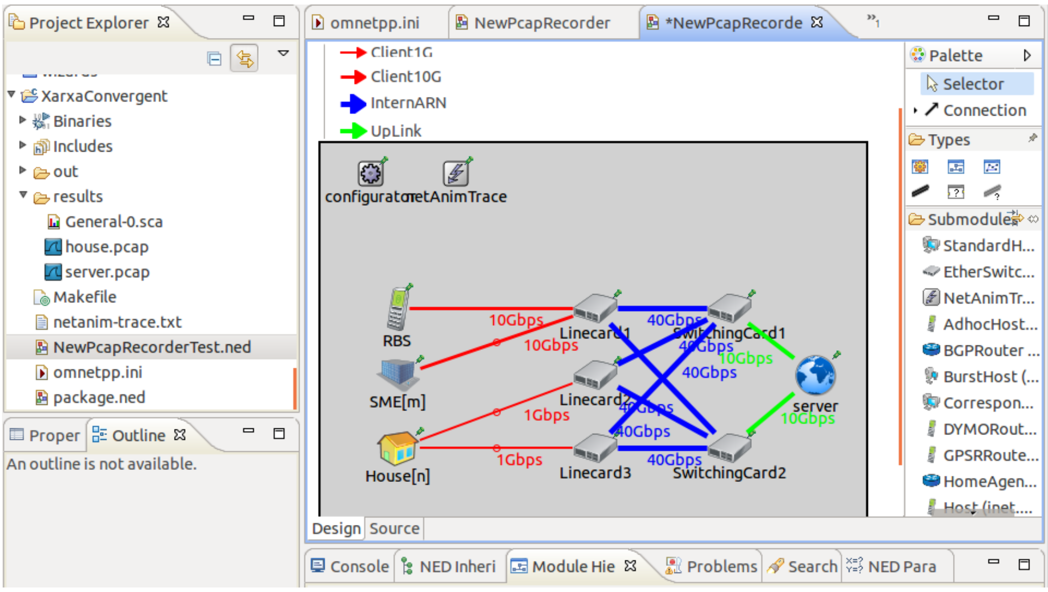

Figure 4.2 OMNET++ ARN Screenshot (.NED/Convergent Architecture Modelling)

On the one hand we have the NewPcapRecorderTest.ned file, which defines the structure of the modelled device.

The ned primarily establishes the physical structure of the modelled network. As we see, the interfaces of each submodule are interconnected by means of 1Gbps to the residential end subscribers. We define one “bucket” per service to be simulated. For SMEs and RBS, 10Gbps links are dimensioned. This is solid with the service definition that has been described in previous sections.

The ARN interconnections are defined in blue, with 40Gbps links. Those links are also low-latency, following the specs provided by PTI for the ARN switching fabric.

The model exactly maps the internal structure of the ARN, with three line cards and two switching cards, one of each offering a 10Gbps uplink.

Uplinks are drawn in green and dimensioned to offer 10Gbps capacity.

The system also is designed to support 802.1Q Q-in-Q VLANs. Typically, in Open Access Networks, each subscriber is mapped on a double-tagged VLAN. The first VLAN tag typically identifies the operators and the second tag the user. However, other configurations are also possible, depending on the Service Provider requirements.

SEVENTH FRAMEWORK PROGRAMME

With all these parameters, the OMNET code was generated in order to be simulated. The .NED file contains the definitions of the variables, the sub modules that are used and the interfaces and VLAN mapping.

Below it is shown a fragment of this code:

```
import inet.util.NetAnimTrace;
import inet.util.ThruputMeteringChannel;

network NewPcapRecorderTest
{
    parameters:
        int n = 96;
        int m = 3;
        @display("bgb=500,392");
    types:
        channel Client1G extends ThruputMeteringChannel
        {
            datarate = 1Gbps;
            delay = 20us;
            @display("ls=red,2,s;t=1Gbps,t,red");
            thruputDisplayFormat = "u";
        }
        channel Client10G extends ThruputMeteringChannel
        {
            datarate = 10Gbps;
            delay = 20us;
```

Figure 4.3 OMNET++ .NED file

4.2.2 .INI

This file includes the simulation parameters. One can also modify the values/attributes of the architecture that has been defined in the .NED file, such as the size of the queues or the quality of service strategy. Also, the simulation time, maximum memory usage, … can also be parameterized.

However, the most important functionality of this file is to define the traffic patterns. This includes:

- Packet intervals
- Size of the packets and generation strategy
- Traffic matrix
- Communication ports

Also, the INI file contains location of the result dump files. This is very important, as with the output results, one can then process them in order to calculate further network parameters (throughput, delay, jitter, …).As an example, output results can be processed using MATLAB to calculate thee delay, showing queue saturation and queue size evolution.

This is an example of the code included in an INI file.

```
[General]
network = NewPcapRecorderTest
tkenv-plugin-path = ../../../etc/plugins
#debug-on-errors = true
record-eventlog = false

**.module-eventlog-recording = false
**.scalar-recording = false
**.vector-recording = false
**.numUdpApps = 24

#0
**.House[*].udpApp[0].typename = "UDPBasicApp"
**.House[*].udpApp[0].localPort = -1
**.House[*].udpApp[0].destAddresses = "server"
**.House[*].udpApp[0].destPort = 1010
**.House[*].udpApp[0].messageLength = 187.5B
**.House[*].udpApp[0].typeOfService = 2

**.SME[*].udpApp[0].typename = "UDPBasicApp"
**.SME[*].udpApp[0].localPort = -1
**.SME[*].udpApp[0].destAddresses = "server"
**.SME[*].udpApp[0].destPort = 1010
**.SME[*].udpApp[0].messageLength = 187.5B
```

Figure 4.4 OMNET++ .INI file

This example indicates how many applications are being run and it later defines the characteristics of each one.

OMNET allows, with the use of packet analysers, like Wireshark, the generation of network statistics, by performing a detailed study of the output PCAP file. Thus, the output will be the same as for a real network, as Wireshark is a tool widely used for network audits and traffic capture.

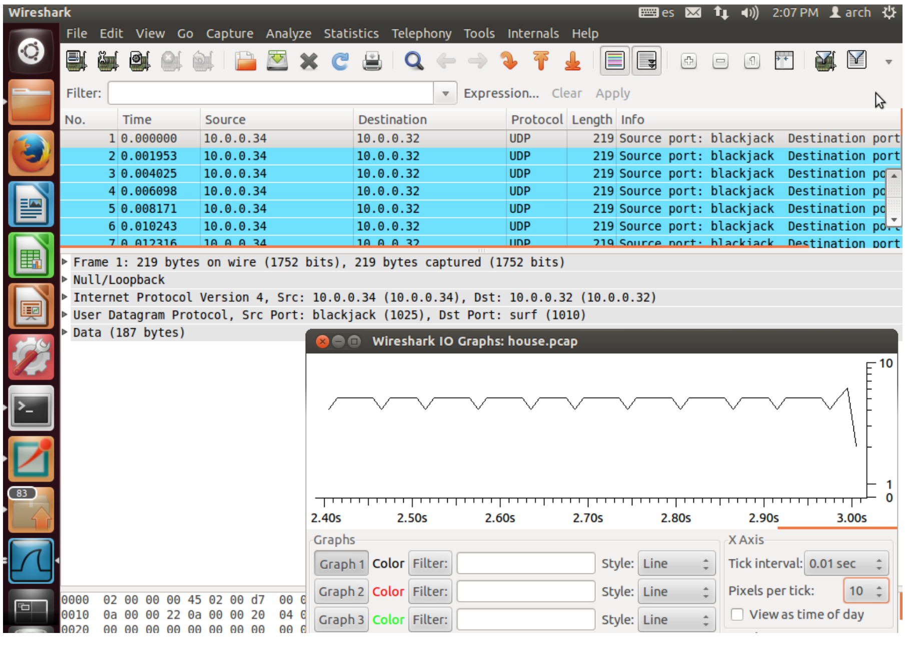

Figure 4.5 Wireshark screenshot

As far as the C++ flies is concerned, we have modified several values of the queues in order to match with the SODALES networks architecture.

These files are the basis of the simulation. We usually find them as libraries or frameworks created by third parties, as OMNET has a wide community of users who have already developed many network protocols.

These C++ files include the algorithms and the intelligence of the simulation. These files always rely on OMNET base to run and there is a library hierarchy that goes from more specific to more generic simulation libraries.

Typically, this code is being downloaded (paid or free) and compiled once to run the simulations. However, due to the flexible nature of the SODALES ARN, we have compiled several network scenarios to run the simulations.

As an example, we have the EtherMACFullDuplex that manages the link queues. This object has a C++ file, together with a .NED that runs on a .INI.

Also, H. files contain the interfaces, where the available methods are declared and a .O and .CC files.

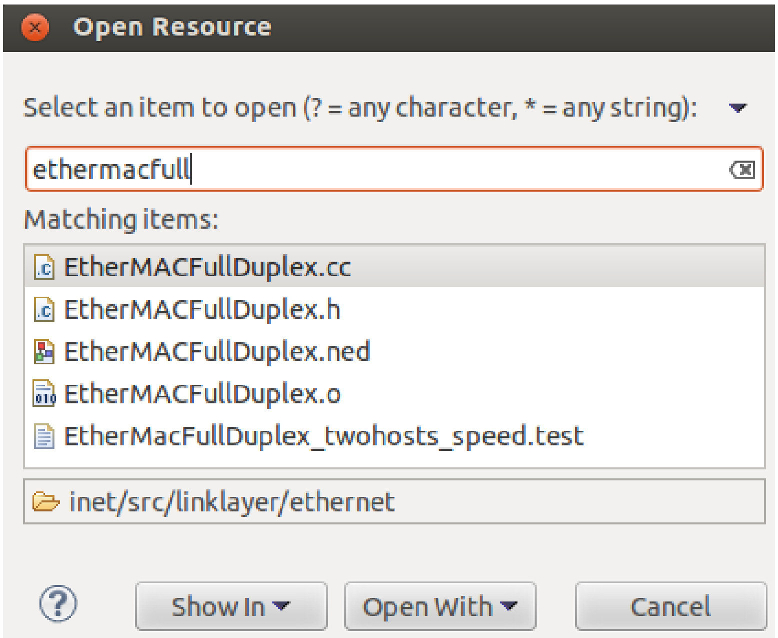

Figure 4.6 EthernetMACFull files

To see a small snippet of C++ code and remember its structure, we can see a part of the EtherMACFullDuplex.cc. One can see also see the interdepencies with other .CC files.

```
#include "NotifierConsts.h"
#include "InterfaceEntry.h"

// TODO: refactor using a statemachine that is present ir
// TODO: this helps understanding what interactions are t

Define_Module(EtherMACFullDuplex);

EtherMACFullDuplex::EtherMACFullDuplex()
{
}

void EtherMACFullDuplex::initialize(int stage)
{
    EtherMACBase::initialize(stage);

    if (stage == 0)
    {
        if (!par("duplexMode").boolValue())
            throw cRuntimeError("Half duplex operation is

        beginSendFrames();
    }
}

void EtherMACFullDuplex::initializeStatistics()
{
```

Figure 4.7 OMNET++ EtherMACFullDuplex.cc file

To run the simulations, the INET Framework has also been required. This Framework includes transport protocols like TCP, UDP, SCTP or network addressing as IPv4 and IPv6, link protocols, like Ethernet or PPP, standards such as 802 .11n, advanced routing protocols, …

The version of the INET Framework that has been used to run the SODALES architecture has been 2.3.0, which includes spanning tree and queue priorization features. Although it was not an stable release, those features were mandatory to effectively simulate SODALES.

4.3 EPON comparative Model

The SODALES network has been compared with IEEE802.3ah EPON standard.

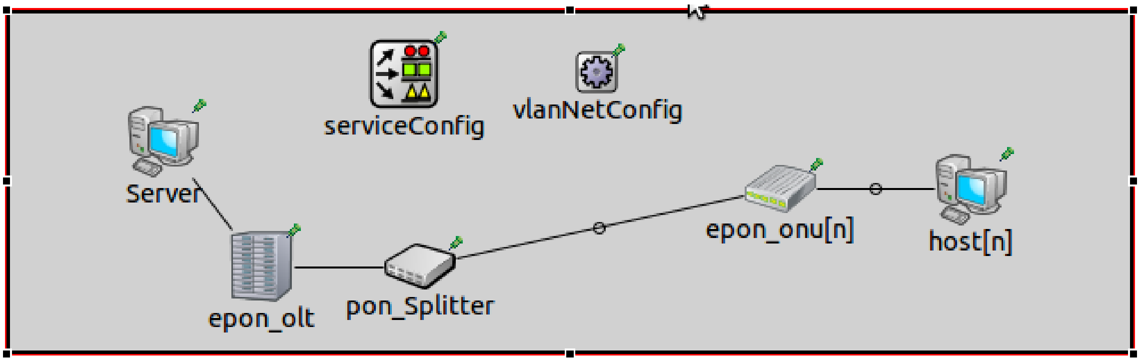

Figure 4.8 OMNET ++ EPON modelling

To model the network, a .NED and .INI files have been generated in order to have a working version of an EPON network.

4.4 Traffic Modelling

One of the key aspects of the simulations have been the use of real traffic profiles. We have used real traffic samples of several FTTH operators, which at present are offering ultra speed broadband services across Catalonia.

Also, these traffic profiles have been compared with two of the more important PoPs in Spain, CATNix in Barcelona and ESpanix in Madrid as they offer good examples of traffic averaging, as the aggregation factor is much higher in the PoPs than in a small FTTH town.

Here we present the three graphs for the same week:

- FTTH network in l'Ametlla de Mar (20Mbps symmetric)
- CATNix
- ESpanix

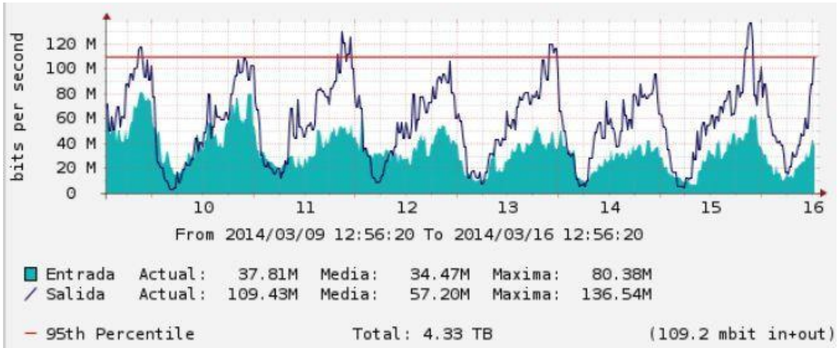

Figure 4.9 FTTH weekly traffic

This network has at present 550 FTTH subscribers. Taking into account peak datarates, one can see that statistical multiplexing factors are very high in this kind of networks. End users can not use all the available bandwidth that they have and this scales when the service is +100Mbps or +1Gbps.

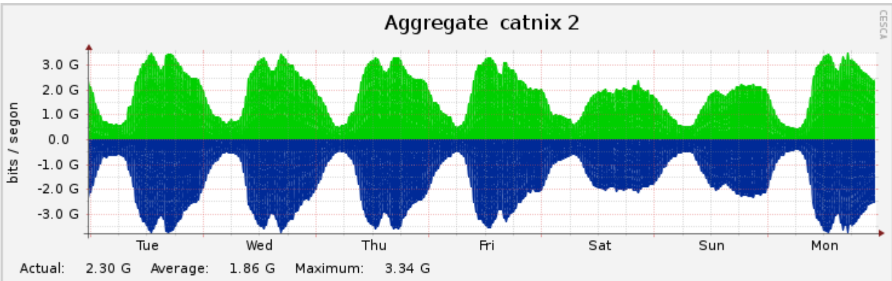

Figure 4.10 CATNIX weekly traffic

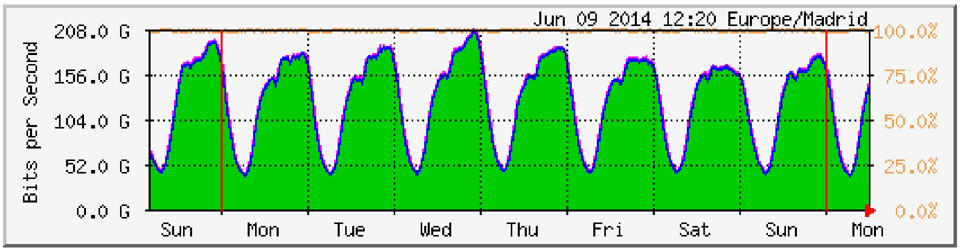

Figure 4.11 ESpanix weekly traffic

We can see that the three graphs are quite similar and represent peaks during the day and valleys during night.

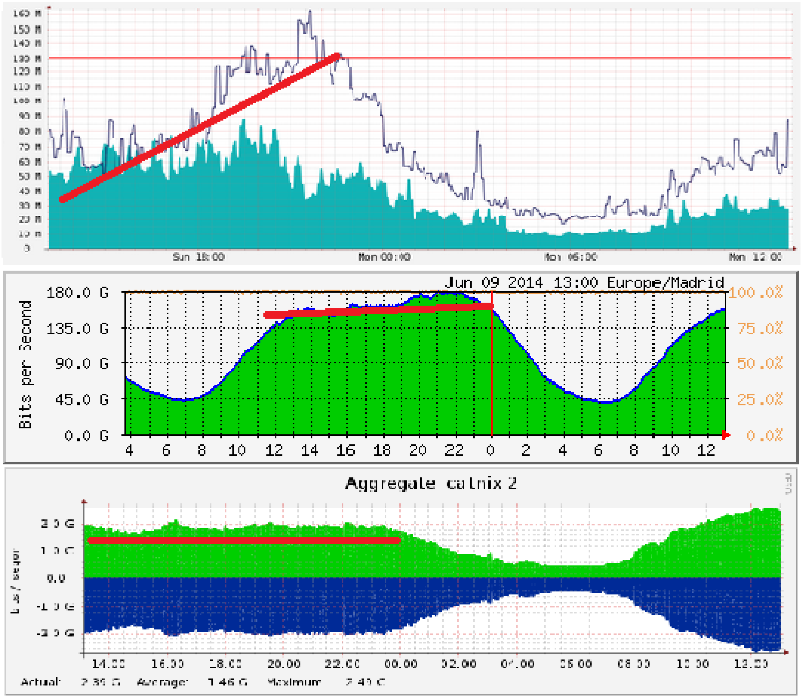

Figure 4.12 Daily traffic comparison

By averaging the three different graphs and considering 100Mbps symmetric services, we have generated the daily traffic baseline, which will be the starting point of the simulations.

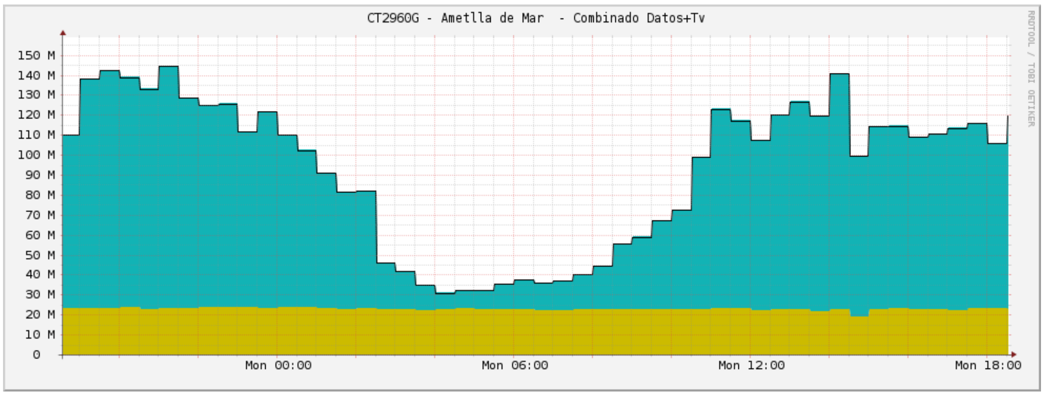

Figure 4.13 FTTH network daily traffic

However, in order to reduce the simulation processing time, we have integrated the results and segmented the periods of time to one hour.

4.5 SODALES traffic modelling

By applying the FTTH traffic profile to the SODALES model, we have obtained the following traffic pattern.

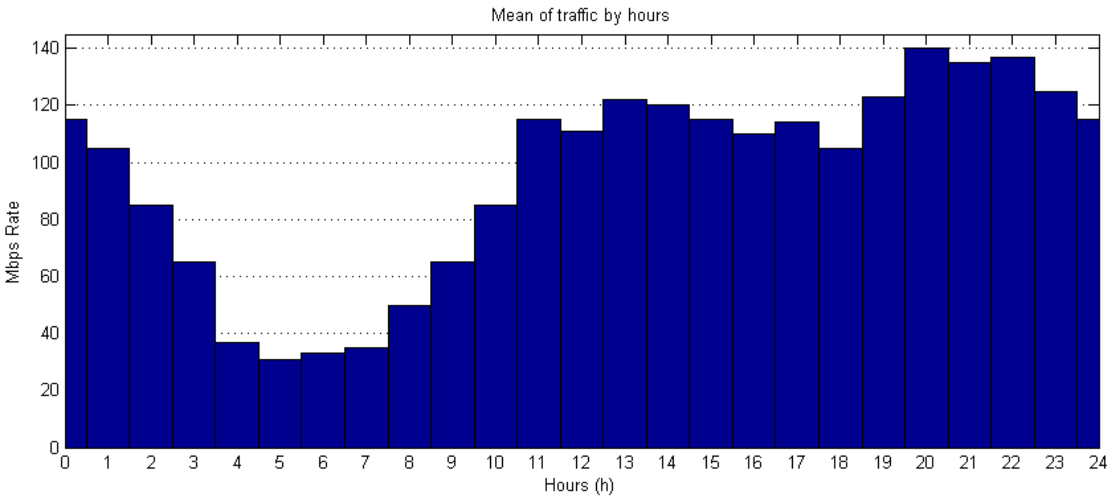

Figure 4.14 Traffic baseline

It is important to segment the different types of users. If we do this, we obtain the following graph, in which

- Residential
- SMEs
- Mobile traffic

Have been characterized.

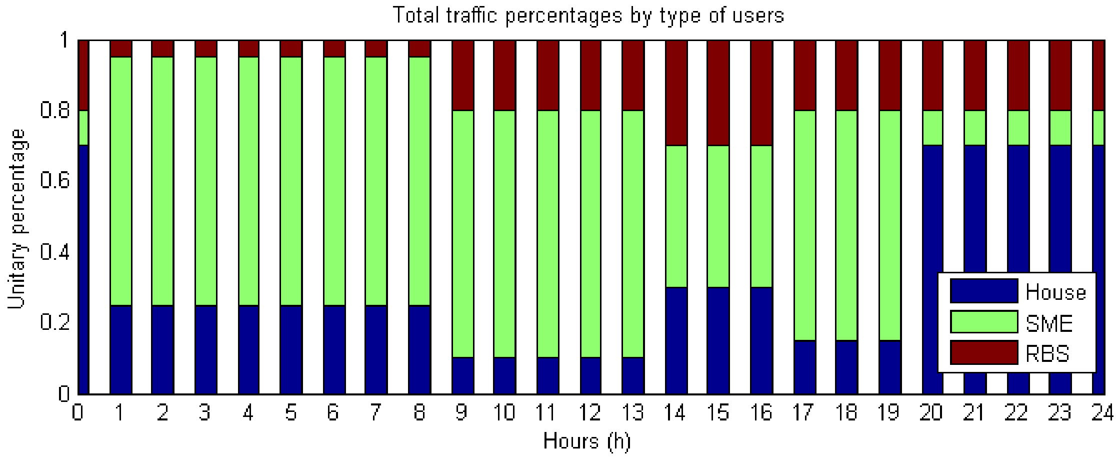

Figure 4.15 Simulation result: Total traffic percentages by type of users

Finally, we have calculated the traffic load per user, considering that an ARN will serve:

- 96 residential users
- 3 SMEs
- 1 RBS

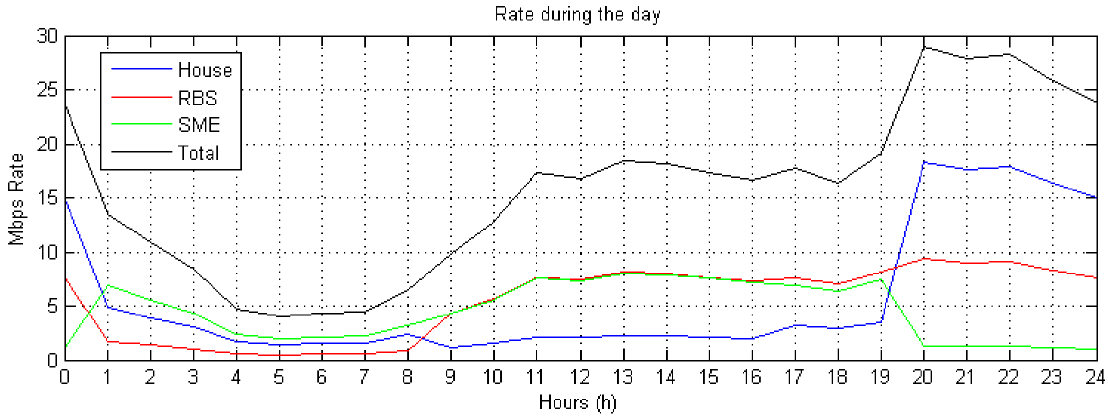

Figure 4.16 Traffic during the day per user (and type of user)

As a final comment, in order to simulate the layer 2 transport model that SODALES promotes, although we have initially simulated data, voice and video using TCP traffic profiles, we have finally chosen UDP traffic segmented by VLAN.

This allows a much better characterization of the traffic load and perfectly matches the Open Access approach that SODALES defines as standard network operation model.

Traffic matrices for each of the simulations have been generated using the data model below:

03:00 - 04:00	messageLength	startTime	stopTime	sendInterval	Rate (Mbps/MBps)	Packets ps	Rate per User	Percentatge	
House	1500,000000	12,000000	18,000000	0,000091575	16,38	10920,000000	0,170625	0,6666666667	Bits
	187,500000	12,000000	18,000000	0,000091575	2,0475	10920,000000	0,021328125	0,6666666667	Bytes
SME	1500,000000	12,000000	18,000000	0,000235479	6,37	4246,666667	2,123333333	0,2592592593	Bits
	187,500000	12,000000	18,000000	0,000235479	0,79625	4246,666667	0,2654166667	0,2592592593	Bytes
RBS	1500,000000	12,000000	18,000000	0,000824176	1,82	1213,333333	1,82	0,07407407407	Bits
	187,500000	12,000000	18,000000	0,000824176	0,2275	1213,333333	0,2275	0,07407407407	Bytes
							1	0,2233636364	Total

Table 4.1 Simulation traffic definitions

This process has been automated in order to generate a simulation batch that could be run for several traffic loads:

fx =(J3*D2)/D1

	A	B	C	D	E	F	G	H	I	J
1	**.House[*].udpApp[0].sendInterval =	0,002072535211	s	142	**.*.udpApp[0].startTime =	0,000	s	72		0,02943
2	**.SME[*].udpApp[0].sendInterval =	0,000045985915	s	10	**.*.udpApp[0].stopTime =	3,000	s	3		0,000653
3	**.RBS.udpApp[0].sendInterval =	0,000060352112	s	Tasa de incremento anual %:	**.*.udpApp[1].startTime =	3,000	s			0,000857
4	**.House[*].udpApp[1].sendInterval =	0,002559859155	s	67	**.*.udpApp[1].stopTime =	6,000	s			0,03635
5	**.SME[*].udpApp[1].sendInterval =	0,000056830985	s	134	**.*.udpApp[2].startTime =	6,000	s			0,000807
6	**.RBS.udpApp[1].sendInterval =	0,000074577464	s	201	**.*.udpApp[2].stopTime =	9,000	s			0,001059
7	**.House[*].udpApp[2].sendInterval =	0,003347887324	s	268	**.*.udpApp[3].startTime =	9,000	s			0,04754
8	**.SME[*].udpApp[2].sendInterval =	0,000074295774	s	335	**.*.udpApp[3].stopTime =	12,000	s			0,001055
9	**.RBS.udpApp[2].sendInterval =	0,000097535211	s	Fins els 5 anys proxims	**.*.udpApp[4].startTime =	12,000	s			0,001385
10	**.House[*].udpApp[3].sendInterval =	0,005880985915	s	Proxims 10 anys	**.*.udpApp[4].stopTime =	15,000	s			0,08351
11	**.SME[*].udpApp[3].sendInterval =	0,0001304929577	s	670	**.*.udpApp[5].startTime =	15,000	s			0,001853
12	**.RBS.udpApp[3].sendInterval =	0,0001712676056	s	Proxims 15 anys	**.*.udpApp[5].stopTime =	18,000	s			0,002432
13	**.House[*].udpApp[4].sendInterval =	0,00701971831	s	1005	**.*.udpApp[6].startTime =	18,000	s			0,09968
14	**.SME[*].udpApp[4].sendInterval =	0,0001557746479	s		**.*.udpApp[6].stopTime =	21,000	s			0,002212
15	**.RBS.udpApp[4].sendInterval =	0,0002044366197	s	1909,5	**.*.udpApp[7].startTime =	21,000	s			0,002903
16	**.House[*].udpApp[5].sendInterval =	0,006594366197	s	Actual*142vegades limit 20Gbps	**.*.udpApp[7].stopTime =	24,000	s			0,09364

Table 4.2 Data simulation parameters

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5 Simulations and results

As we have already defined and developed:

- The network architecture model
- The traffic patters
- Batch processing tools

We can start now with the simulations of the SODALES architecture.

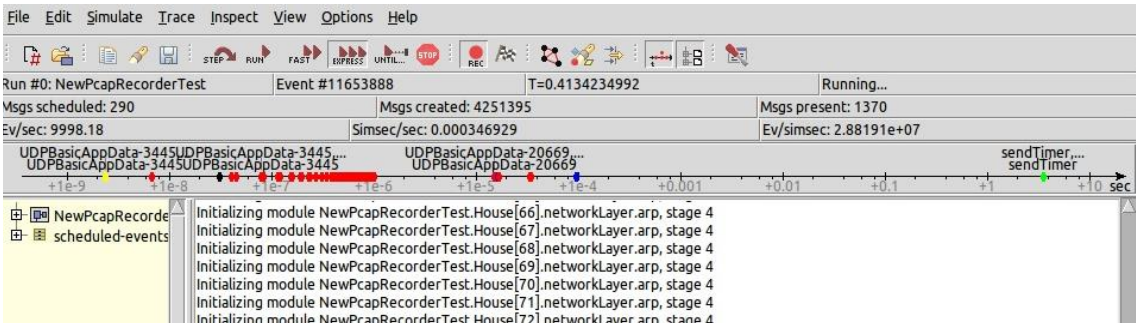

Figure 5.1 Simulation result: OMNET working screen shot

The first thing we see is that the variable that matches simulation time with real time is very small (simsec/sec). For this simulation, for instance, this parameter was 0.000346929.

The initial approach has been that this means that if we want to simulate one complete day, we will need 2860h per simulation. Thus, in order to be able to run several simulations, we have simplified simulation time to 24 seconds and extrapolated to one complete day (1 second = 1 hour equivalence), so 19h per simulation are required.

	Simulation time
Simulated Time (Sec)	24
Time Simsec/sec	0,00034929
Simulation time (Sec)	68710,81336
Simulation time (hours)	***19,08633705***

Table 5.1 Calculation of simulation times (24s)

In any case, we have optimized the simulation environment (deactivated unnecessary logs, …) to reach the final simulation environment, which was to simulate one complete day in 72 seconds. This required 1 hour and 20 minutes of simulation time.

	Simulation time
Simulated Time (Sec)	72
Time Simsec/sec	0,0154
Simulation time (Sec)	4675,324675
Simulation time (hours)	***1,298701299***

Table 5.2 Calculation of simulation times (72s)

With this model, several traffic simulations have been developed, using as an input, real traffic profiles. We have then, validated the SODALES network taking into consideration future traffic increases, as described in the first chapter.

This has lead to a chronological analysis that shows how SODALES will evolve year by year. We will also see that EPON networks will saturate sooner than SODALES, meaning that SODALES is a much more future-proof solution.

Taking into consideration that in a four-year time, traffic growth will be of 67%, we have applied this factor into our model.

5.1 Simulation results

The results of the first simulation are as follows (the first simulation was carried out simulating 24 seconds. All the following graphs are drawn with the Wireshark tool, using OMNeT output PCAP files):

5.1.1 2014

In this graph will show the bits per second generated during a day.

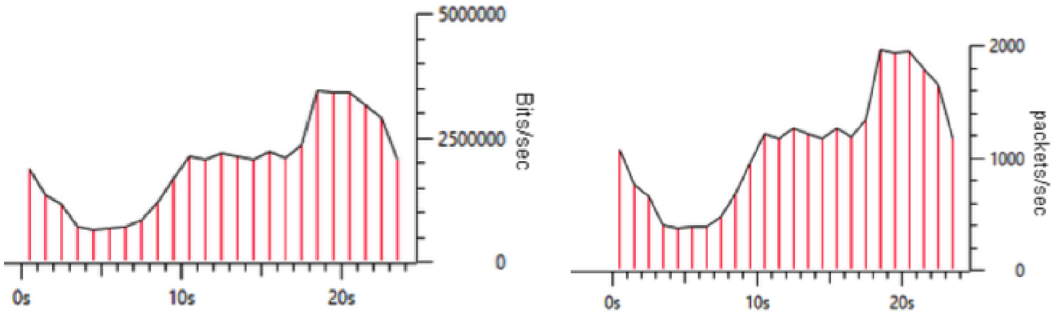

Figure 5.2 a / b 2014 simulation (bitrate and packet rate)

We have also verified no packet loss, as the number of registered packets matches the generated ones (26.287 registered packets)

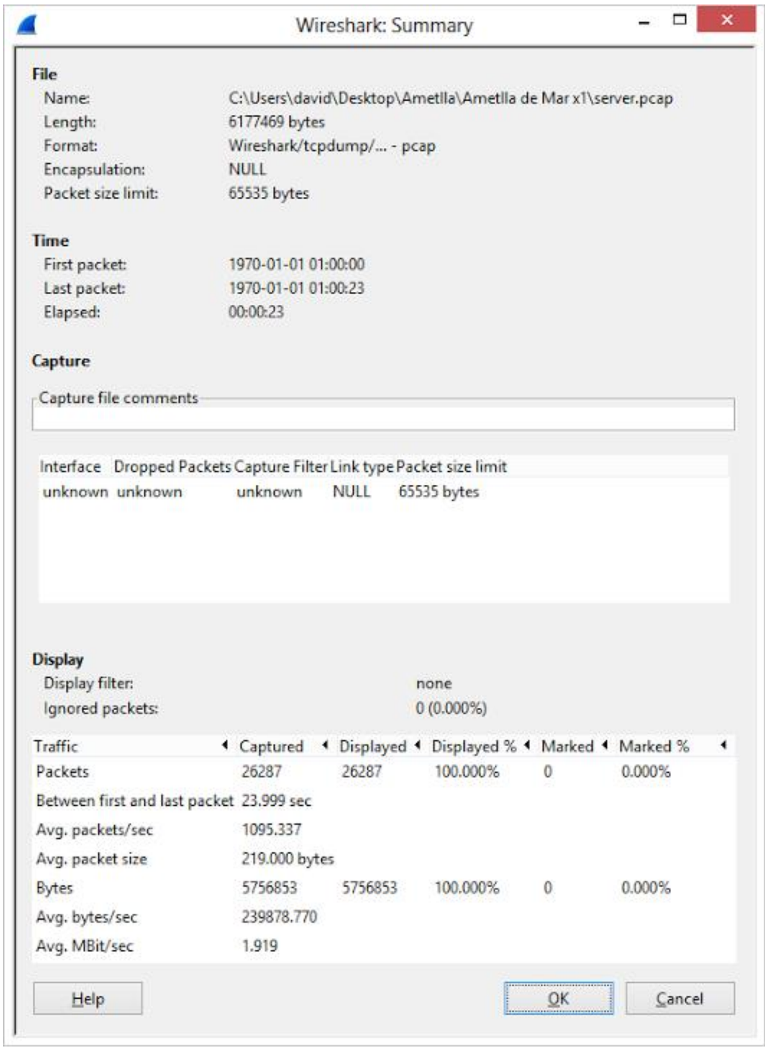

Figure 5.3 2014 simulation summary

This first simulation corresponds to the traffic of 2014. We have then scaled year by year to simulate 2015, 2016, …

5.1.2 2015

The results of the simulation of 2015 are as follows. As fo 2014, the first graph refers to the number of bits per second and the second for packets per second:

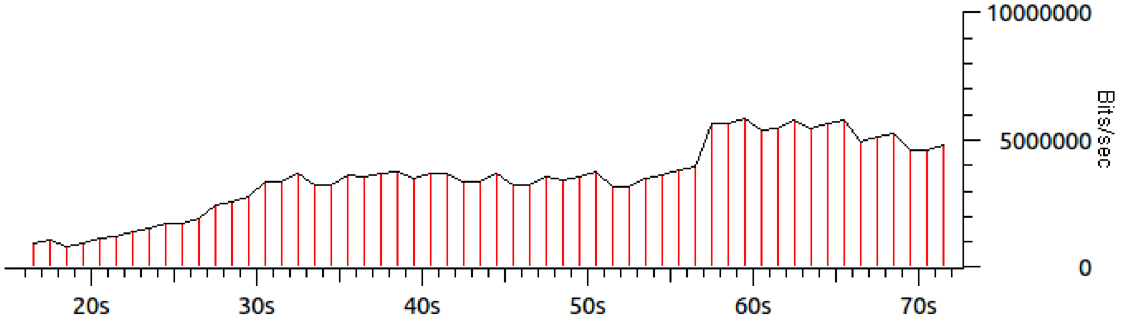

Figure 5.4 a 2015 simulation (bitrate)

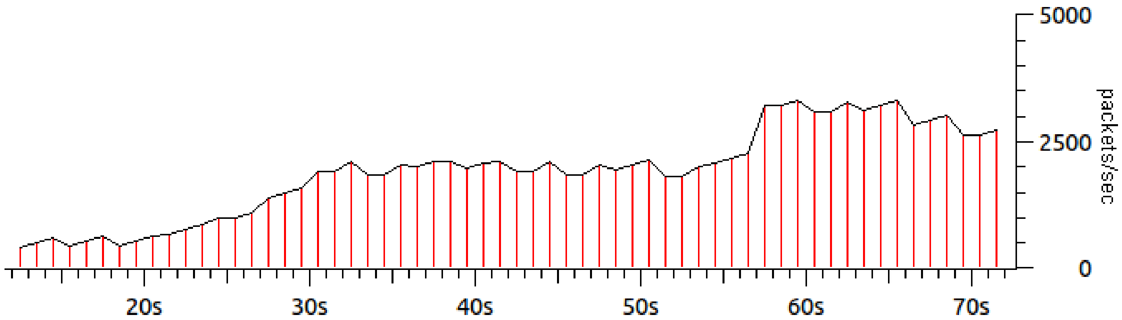

Figure 5.4 b 2015 simulation (packet rate)

Also, there is no packet loss, as shown in the figure below

Traffic	Captured	Displayed	Marked
Packets	125172	125172	0
Between first and last packet	72.000 sec		
Avg. packets/sec	1738.506		
Avg. packet size	219.000 bytes		
Bytes	27412668		
Avg. bytes/sec	380732.843		
Avg. MBit/sec	3.046		

Figure 5.4 c 2015 simulation summary

5.1.3 2016

The results of the simulation for year 2016 (bitrate and packet rate) are the following:

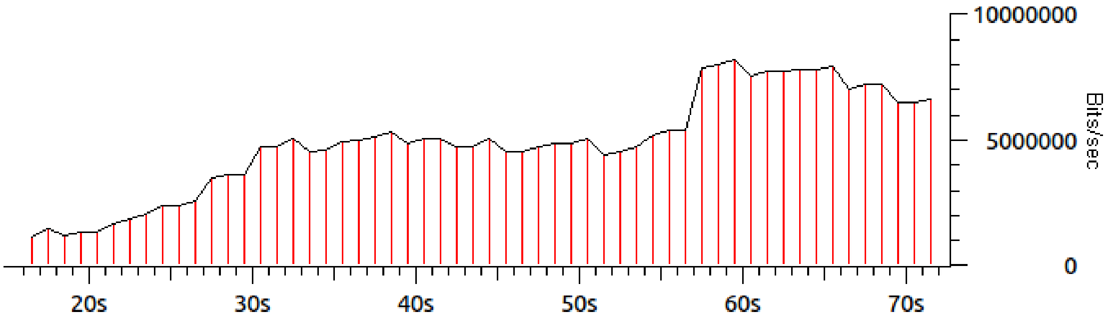

Figure 5.5 a 2016 simulation (bitrate)

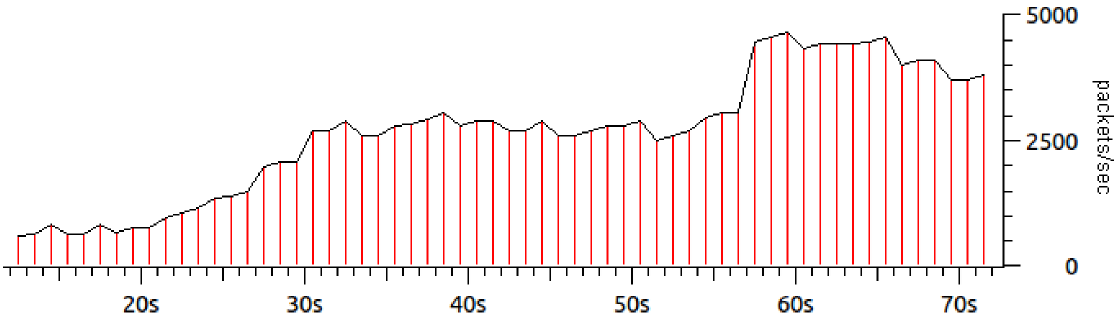

Figure 5.5 b 2016 simulation (packet rate)

There is no packet loss registered.

Traffic	Captured	Displayed	Marked
Packets	174745	174745	0
Between first and last packet	71.999 sec		
Avg. packets/sec	2427.035		
Avg. packet size	219.000 bytes		
Bytes	38269155		
Avg. bytes/sec	531520.766		
Avg. MBit/sec	4.252		

Figure 5.5 c 2016 simulation review

In this simulation, traffic peak has been measured of 327,6 Mbps.

5.1.4 2017

Even though it is difficult to predict traffic growth for year 2017 and beyond, we have lineally scaled traffic predictions to simulate how SODALES will perform in a three years time.

The results of the simulation of the **2017** are the following:

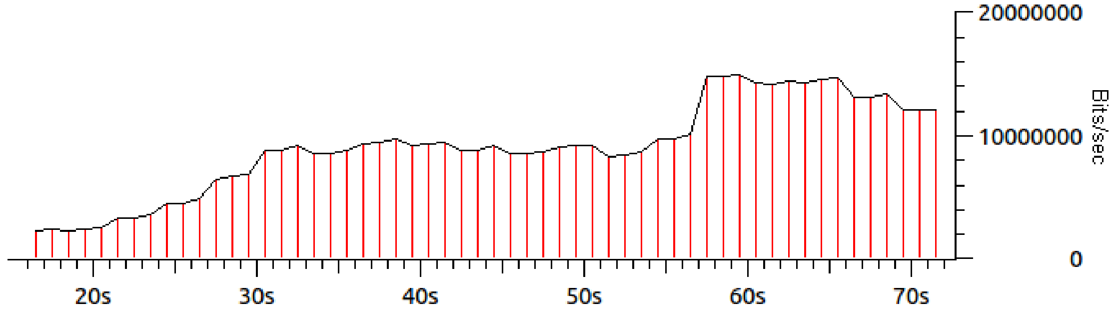

Figure 5.6 a 2017 simulation (bitrate)

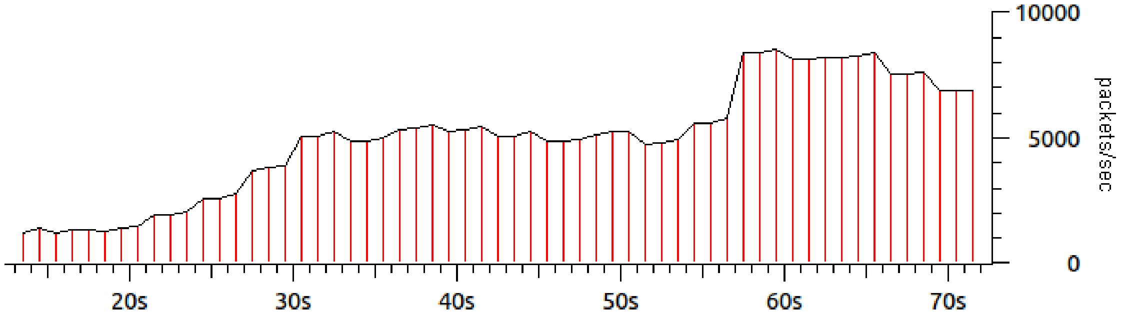

Figure 5.6 b 2017 simulation (packet rate)

Despite the traffic increase, no packet loss have been reported.

Traffic	Captured	Displayed	Marked
Packets	323645	323645	0
Between first and last packet	72.000 sec		
Avg. packets/sec	4495.081		
Avg. packet size	219.000 bytes		
Bytes	70878255		
Avg. bytes/sec	984422.724		
Avg. MBit/sec	7.875		

Figure 5.6 c 2017 simulation summary

We see, that network capacity tends not to be an issue. However, it is relevant to note that latency and jitter is severely affected in the EPON simulations. This affects end user experience.

We find here peaks of 620Mbps.

5.1.5 2019

When we simulate year 2019, we find that EPON saturates and is not capable of handling all the generated traffic. Also, we should take into consideration the fact that traffic offload from mobile networks will increase by 52%.

The following graphs refer to the simulation of the SODALES architecture.

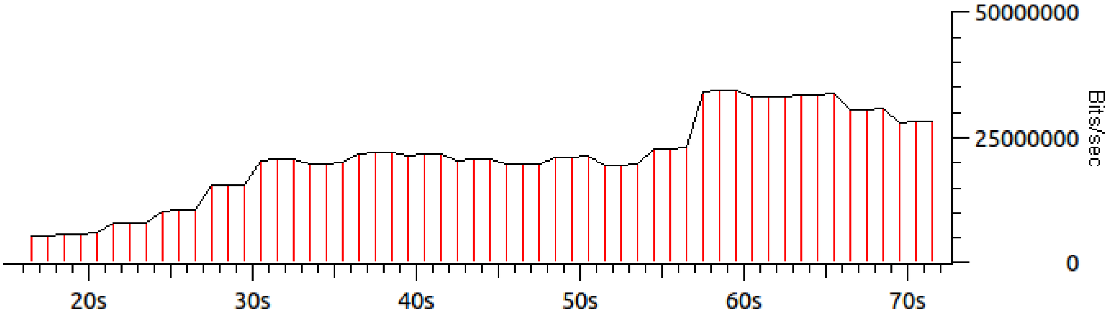

Figure 5.7 a 2019 simulation (bitrate)

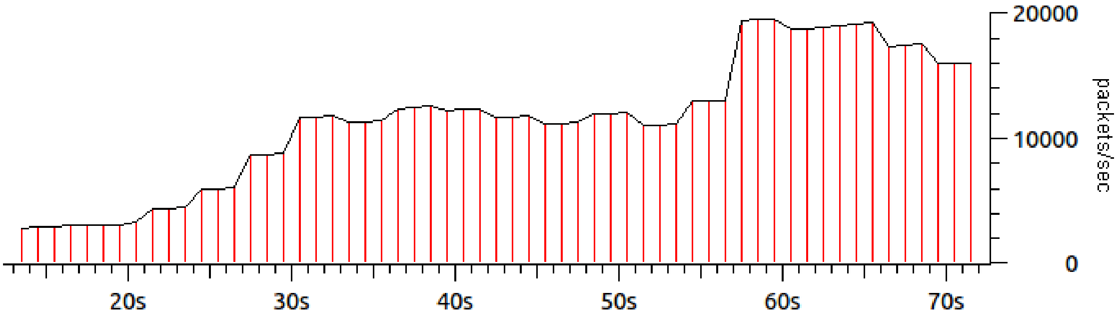

Figure 5.7 b 2019 simulation (packets rate)

EPON saturates when data traffic reaches 0,912Gbps/0,762Gbps (down/up).

To overcome this, there are two strategies: increase queues (this will negatively affect network latency) or to drop packets. In any case, the service quality of experience will be severely affected.

We have detected no packet loss in the simulations of the SODALES architecture.

Traffic	Captured	Displayed	Marked
Packets	746587	746587	0
Between first and last packet	72.000 sec		
Avg. packets/sec	10369.298		
Avg. packet size	219.000 bytes		
Bytes	163502553		
Avg. bytes/sec	2270876.267		
Avg. MBit/sec	18.167		

Figure 5.7 c 2019 simulation summary

Traffic peaks are expected of around 1.5Gbps

5.2 Maximum network throughput

From the simulation results and the traffic predictions, we see that an upgrade will be required on EPON networks to keep with the traffic demands. In GPON networks, this upgrade will be required later, as available bandwidth is higher. However, taking into consideration that in symmetric networks upstream traffic tends to be similar to downstream, GPON just has a 25% upgrade path, compared to EPON. This means that, while EPON will reach its limit in Year 2019-2020, GPON will reach it by years 2021-2022.

This should not be a problem, as XGPON standards have already been developed, but will require a massive investment to substitute all the transmission equipment at the edged.

With the SODALES approach, this does not happen. As the infrastructure is Gigabit-capable, it can cope with this (and the next decade) traffic demands in a robust way.

We forecast that Gigabit connectivity is an upper limit for standard network use. At present, there is no application that requires such a high data rate and even 8k video, which is at present the media contribution that requires more bandwidth, can be transmitted on Gigabit links.

In order to saturate the SODALES network, the initial traffic pattern has been scaled by a factor of x142. This means that end user traffic can scale close to by 150 without any change on the platform.

In these circumstances, we reached peaks of 19880Mbps and an average rate of 260Mbps per user.

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Traffic	Captured	Displayed	Displayed %	Marked	Marked %
Packets	10532127	10532127	100.000%	0	0.000%
Between first and last packet	72.000 sec				
Avg. packets/sec	146279.787				
Avg. packet size	219.000 bytes				
Bytes	2306535813	2306535813	100.000%	0	0.000%
Avg. bytes/sec	32035273.462				
Avg. MBit/sec	256.282				

Figure 5.8 SODALES architecture in saturation mode

When we reach saturation, queue length and latency increases, as expected.

In the figure below, we compare the scalability of both access solutions:

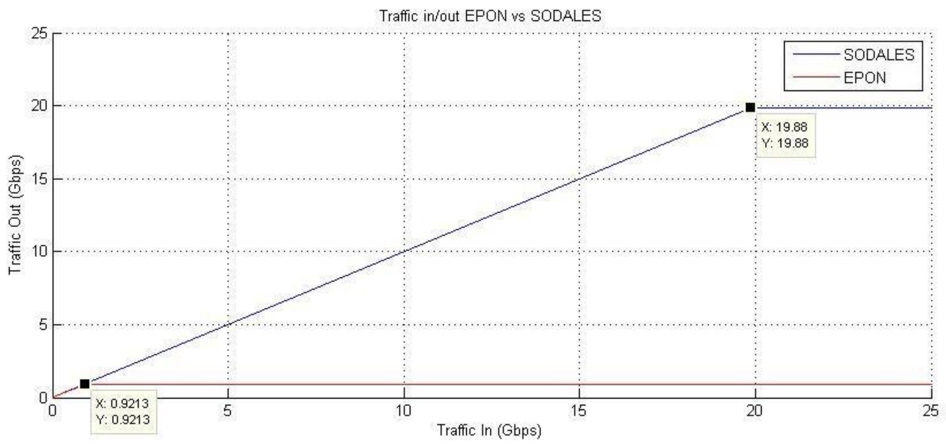

Figure 5.9 Network throughput comparisons between EPON and SODALES

From the figure above, one can see that EPON downstream traffic saturates at 912Mbps, while SODALES reach its limit at 19,88Gbps. This allows much higher scalability and to present SODALES as a much more future proof platform.

However, the most relevant parameter that is being affected by the limited capacity of EPON is network latency.

We have already stated the fact that the parameter that affects quality of experience of access networks is latency, rather than available bandwidth, as end users typically cannot generate enough traffic to saturate their connections.

Thus, the fact that latency degrades much quicker in PON networks than in SODALES is a critical parameter to be considered when benchmarking both network architectures.

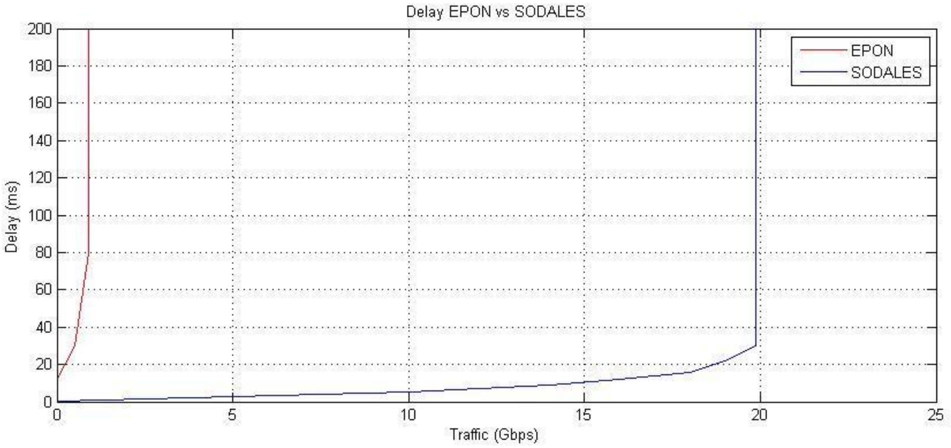

Figure 5.10 Network delay (EPON vs SODALES)

5.3 Gigabit to the user

At present, several operators are offering Gigabit services to end users. However, from the simulations we have seen that end users need to scale their present traffic demands by a factor of 150 to take advantage of this access speed.

Thus, when data rate scales, we have seen that statistical multiplying factors also increase.

We have analysed several access networks that offer Gigabit data rates and we have found that for a universe of 800 connected users, the aggregated traffic was of 1.5Gbps. This leads to a statistical multiplexing factor of over 1:500.

This is solid with the results obtained in the simulations, showing that to increase the data rate of end users affects more their quality of experience in terms of network latency than they maximum transmission capabilities.

6 Conclusions

This deliverable includes the simulation work developed in order to validate the SODALES architecture, and proof its specifications prior to the lab and field validation.

It is important to note that the SODALES architecture has also be compared with existing PON technologies, in order to show the benefits of SODALES compared to existing FTTH deployments.

There are three very important conclusions after this work:

- SODALES offer much more capacity than present PON networks (+10 times more throughput compared to GPON and +20 compared to EPON) and doubles the capacity compared to 10GPON standards. Also, allocating more wavelengths to the ARN can easily scale the SODALES network, thus a clear upgrade path is provided.
- Statistical multiplexing increases when we increase the bandwidth one offers to end subscribers. When available bandwidth per user suspases +100Mbps (and reaches 1Gbps, which is the SODALES reference), the statistical multiplexing factor exponentially scales. We have shown real examples of statistical multiplexing factors close to 1:500 when delivering Gigabit services to end subscribers.
- The most relevant parameter that affects the quality of experience of end users is network latency. End users can not saturate their available sevices, thus, +100Mbps data rates are more a marketing strategy than a practical service upgrade. However, network latency of Gigabit connections is much lower than low speed ones, so the main benefit of increase data rates is to reduce network latency.

On top of this, by mixing corporate, residential and mobile traffic, statistical multiplexing is even increased. This is due to the fact that corporate and residential users have very complementary traffic patters (when corporate users have more activity, residential customers tend to be idle, during working hours). This also happens with mobile traffic.

Finally, SODALES direct traffic offloading of mobile traffic, which allows to optimize spectrum utilization and offer higher data rates to mobile subscribers, thanks to a distributed networks approach, with small cells and a reduced number of users per cell.

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