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White Paper

Roadmap for access and in-building network solutions

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Abstract

This white paper presents the ALPHA roadmaps for next-generation access and in-building network solutions. The different solutions are presented in an integrated network model reaching from the core, over the metro and access to the home/in-building network. Several roadmaps are developed for the access and in-building networks for the short term (1-3 years), medium term (3-5 years), long term (5+ years) and even very long term (10+ years) perspectives. Obviously, the future is hard to predict, but the studies and experiments done in the FP7 ICT-ALPHA project show that fibre-based solutions will inevitably play a crucial role in paving the evolution path of access and in-building networks.

Keyword list – Next generation access and in-building networks, End-to-end QoS provisioning, roadmaps, integrated network model

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1 Introduction

The next generation broadband services are expected to be the main driver for the future access and in-building networks with capacities well above 1 Gb/s to the residential users. The services today include video streaming and medium quality video conferencing, while some others, like remote home monitoring, location based services or Ultra High Definition Video are emerging services of the short or medium term future. Services like Web 3D, robotic assistant and immersive services are long term services. In addition we see services like TV evolve to High Definition TV and further into Ultra High Definition TV. Drawbacks of this development include power consumption in the home and very complex control and management of traffic flows.

The expected traffic evolution and emerging applications will push the next-generation networks to higher bandwidths, higher flexibility in service delivery, and higher quality of service (QoS) demands. The ALPHA project developed an integrated network model and roadmaps for the access/metro network, the in-building network, and the cross domain issues & end-to-end QoS provisioning. The short term (1-3 years), medium term (3-5 years), long term (5+ years) and even very long term (10+ years) perspectives are visualized by these roadmaps.

In section 2, the different next-generation network solutions are put in one general framework by considering an end-to-end network model reaching from the core network, over the metro and access networks, up to the in-building network. This section also describes that the current technical evolution in the access network is a catalyst for a new generation of networks in the building, metro and even core networks. In section 3 and 4, the evolution path from legacy systems to the future network solutions is given for the access and in-building networks, respectively. A high-level roadmap for the respective network evolution trends is presented. For the access network, there is also developed a detailed technology roadmap, and for the in-building network, a generic flowchart is created for selecting the most suitable network solution. Section 5 gives a separate high-level roadmap for the cross domain issues and the control and management functions for end-to-end QoS provisioning. Finally, section 8 formulates some general conclusions.

2 ALPHA framework and integrated network model

The different ALPHA solutions are put in one general framework by considering an end-to-end network model reaching from the core network, over the metro and access networks, up to the in-building network. First, it is indicated that the next generation access networks are a catalyst for a new generation of in-building, metro and even core networks. The different tendencies and relationships between the access and the other three network parts are indicated. Then, the integrated end-to-end network model is presented and the different solutions for the next-generation networks are indicated from a high-level perspective. Finally, we introduce a common network classification which will be used in the remainder of this white paper for classifying the access and in-building networks – i.e. the key research areas of the ALPHA project.

2.1 The access network as the catalyst for a new generation of networks

Up to now, the access network is typically considered as the main bottleneck to offer e.g. 1 Gb/s services to the residential users. However, with the emerging optical access technologies, this paradigm is completely shifted. Optical access network technologies, also indicated as fibre-to-the-home (FTTH), are introduced to overcome the limitation of the copper (using xDSL) and coax cable (using DOCSIS) networks. Although FTTH technologies offer bandwidth fairness to all the subscribers and potential higher bit rates, it is creating new constraints in the entire network. In this way, the next-generation optical access networks are becoming a catalyst for a new generation of networks able to provide flexibility and capacity for a medium (3-5 years) and long term (5+ years) time perspective. Figure 1 illustrates some key tendencies observed.

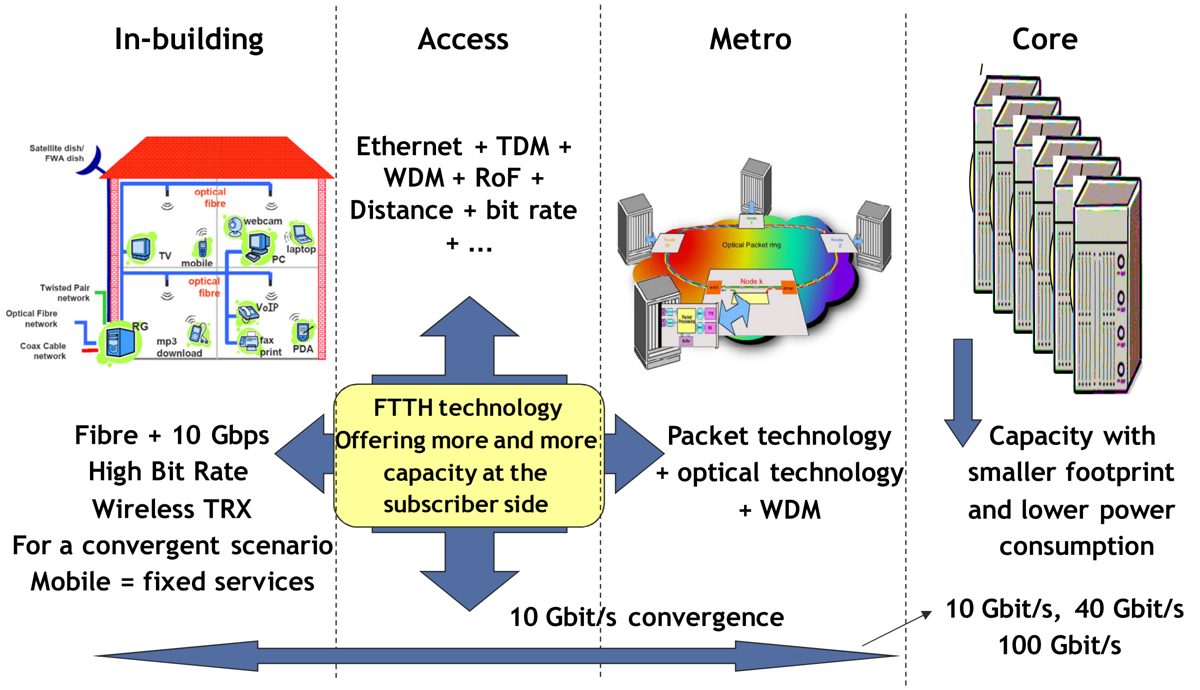

Figure 1: The access network acts as a catalyst for a new generation of networks

Looking at the **in-building network**, there is a large variety of building scenarios, which may be categorised in residential buildings (such as residential homes, multi-dwelling unit buildings a.k.a. apartment buildings) and (semi-)professional buildings (such as office buildings, hospitals, hotels, schools, etc.). As a general trend in all these smaller and larger buildings, there is a need for ever higher data rates following the increasing service demands of the users. A powerful in-building network is mandatory to offer a wide range of (bandwidth-rich and bandwidth-lean) applications to the users. The in-building network must play its role of connecting the end devices (wherever they are) to the access network and it has to be able to manage and transport data flows with the correct QoS (data rate, delay, etc…). When the final link to the user is wireless (for reasons of mobility), such a network enables to put the radio antenna sites close to the user, thus reducing the radio power levels needed and therewith avoiding possible health hazards for the users. Accordingly, optical fibre-based in-building network architectures are investigated, with either active optical-electrical-optical (OEO) nodes which do the signal routing in the electrical domain, or passive optical power splitting/wavelength routing nodes which leave the signals in the optical domain (thus offering signal transparency, allowing arbitrary signal formats and hence upgrading-friendly networks). Within the ALPHA project, several studies were performed in this domain.

To deliver the next-generation broadband services, one of the main tendencies in the **access network** is to propose technologies with higher and more symmetrical bandwidths. In current active optical network (AON) systems this is inherently handled and in passive optical network (PON) systems this means operating at 10 Gb/s for both the upstream and the downstream part. In PONs, in the upstream direction, the data is sent using optical packets. The adoption of this packet format, well adapted to the optical technology in the access part of the network could raise other opportunities, to generalise an optical packet format everywhere in the network and integrate the different core, metro and access networks. Ethernet was initially designed and proposed for local area network (LAN) applications but is today generalised to all the network segments. This tendency could be reinforced to offer an optimised aggregation in the metro side through the use of one packet format everywhere. Different next-generation AON (NG-AON) and next-generation PON (NG-PON) systems were discussed within the ALPHA project.

The main role of the **metro network** is to aggregate efficiently the traffic before going into the core. The aggregation efficiency depends on the traffic profile and on the connectivity requirements of such a network. With the bit rate increase of the access networks (10 Gb/s and 1 Gb/s proposed for the next generation of PON and AON), creating a bit rate convergence in the access – metro area, the aggregation becomes a real problem. One solution explored is to have optical packets combined with optical transparency (packets in transit are not demodulated) in the metro area in order to provide aggregation functions in the edge part of the nodes, and optical statistical time multiplexing (packets generated by different ring nodes and interleaved with transit packets) on the fly to lead to an optimised network in terms of power consumption reductions, footprint of nodes and cost [1].

Finally the **core network** will be impacted too. In addition to a need for a very efficient network, the capacity is a key issue. With the increase of the bit rates at the subscriber sides, the core node capacities could reach 1 Petabit in a time frame of 15 years. Then the key challenge will be to identify a new node architecture able to reach such a capacity in a realistic approach, taking into account in particular the limits of the scheduling part.

2.2 Integrated network model

To offer the next-generation broadband services, an integrated end-to-end network model is proposed, reaching from the core to the home/in-building network. Following a top-down approach, Figure 2 shows an integrated picture with a high-abstract overview. Different technologies, network resources and the general information flows are indicated, without going into detailed physical aspects or protocol details. The topics shown in the picture correspond to the more detailed technical solutions and scenarios covered by the ALPHA project and mapped to the different roadmaps in sections 3, 4 and 5.

For the access network, NG-AON (e.g., using GMPLS, Multi-Layer (ML) Ethernet) and NG-PON (e.g., using increasing bit rates in the time division multiplexing (TDM) domain, using wavelength division multiplexing (WDM) technologies, orthogonal frequency division multiplexing (OFDM) technologies, etc.) are indicated in Figure 1. Also the integration with radio over fibre (RoF) is shown, and was part of the ALPHA project [2]. As the current metro network will be more and more integrated in the NG access network, the use of Generalized Multiprotocol Label Switching (GMPLS), together with Multi-Layer (ML) Ethernet [3], [4], and Packet Optical Add/Drop Multiplexer (P-

OADM) technology [5] are also included. For the home/in-building network, new transport media (like plastic optical fibre, POF [6]) and techniques (like Multi Format Multiplexing [7], [8], UPnP-QoS [9]) are introduced.

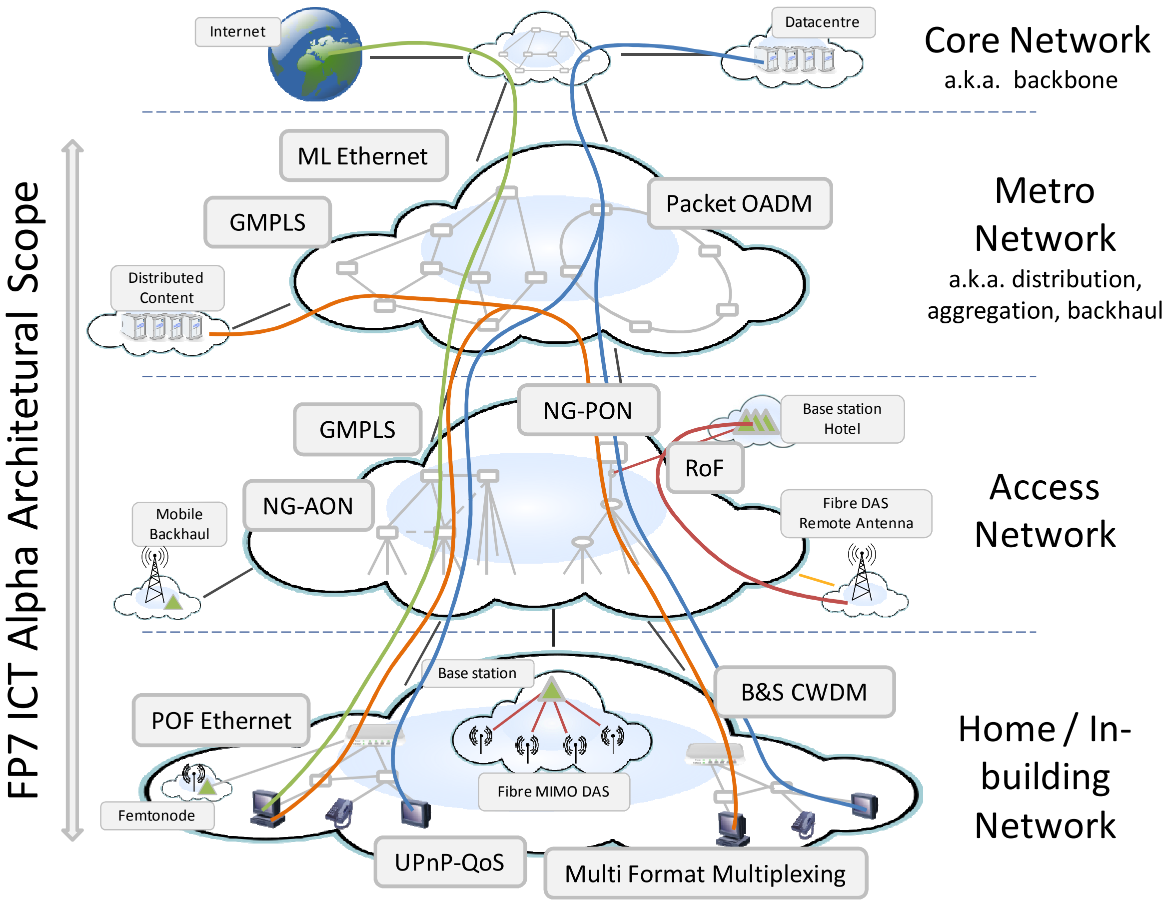

Figure 2: Integrated network model for the next-generation end-to-end network

In addition to the top-down approach from Figure 2, a geographical overview of the end-to-end network from the home to the core is important to have a better understanding of the future technical trends and the possible use or not use of the sites. Figure 3 shows a typical example of the different geographical locations in the access and metro network, with an indication of multiple sites that can contain active network equipment and/or passive optical distribution frames (ODFs). The distances are corresponding to an urban and rural scenario, respectively. Within the ALPHA project, two different trends were denoted: node consolidation and locality of traffic. The ongoing trend of node consolidation, by some large telecom operators[1], will lead to next-generation access networks spanning large distances without any active (switching) equipment in at least the street cabinets and distributed access sites. This trend will lead to NG long-reach PON solutions, probably covering both the access and metro part. If the locality of traffic is becoming more important, e.g. in local community networks, an important amount of traffic can be offloaded from the higher aggregation and core network links (and probably from the metro network) by keeping the local traffic in the access network or lower aggregation levels. This trend will be an important driver for introducing NG-AON solutions, and it balances node consolidation and meets the possible requirements of future traffic patterns.

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[1] France Télécom – Orange targets a reduction by a factor of ten of its central offices in the future, permitted by the longer spans of optical systems compared to copper ones. Many operators worldwide, like DT in Germany, BT in the UK, and Verizon in the US have similar goals.

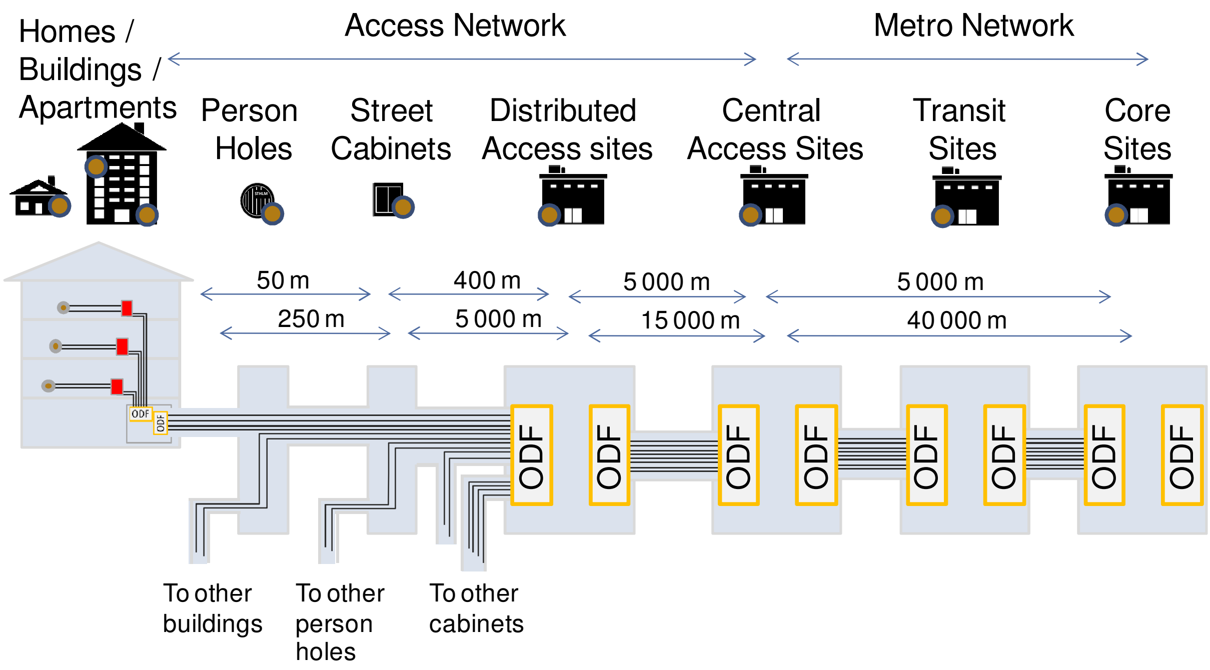

Figure 3: Geographical network model

2.3 Network classification

Based on the capability of the intermediate network nodes installed between the edges of a certain network part, we can classify optical in-building and access network architectures into three main categories according to the use of passive versus active components.

- **Optically passive**: only passive optical components are installed in the intermediate nodes, such as passive power splitters or passive wavelength routers (such as arrayed waveguide gratings, AWGs). Both the data as well as the control remains optically transparent.
- **Optically signal-processed**: active optical components are installed in the intermediate nodes, e.g., optical switches that need power and electronic control. The data transfer remains optically transparent, however, although the control needs OEO conversion in the intermediate node.
- **Opaque**: both the data and control need to be electronically processed e.g. electronic switches or reach extenders based on OEO conversion are installed in the intermediate nodes.

In an in-building network, of the wired network part the edge nodes correspond to the room outlets at the user side, and the residential gateway at the border with the access network, while the intermediate nodes are spread on e.g. each floor. The wireless links to the users' wireless devices are established by radio antenna stations which are hooked up in the edge nodes to the wired network part. In an access network, the edge nodes correspond to the customers premise equipment (CPE) (e.g., combined with an optical network unit, ONU) at the border with the in-building network, and the central access sites (e.g., combined with an optical line terminal, OLT) at the border with the metro network, while the intermediate nodes are the remote nodes in the field installed in e.g. the street cabinets or distributed access sites.

Note that all architectures with an amplification stage for reach extension (RE) become either signal-processed or opaque, as at least some electronic control will be needed. An architecture with optical amplification where the data plane is not touched (e.g. EDFA, SOA), can be classified as optically signal-processed, whilst using an amplification stage with 3R regeneration leads to an opaque architecture. In general, the architectures are classified with the assumption that no RE is needed, since we can assume that every architecture works (at least for a limited distance) without RE.

3 Roadmaps for the access network

This section describes the roadmap figures for the access network, extended with the metro part as a convergence scenario is expected between both network parts in the (very) long term. The section starts with a techno-economic justification in section 3.1, to indicate some important factors for setting up the roadmap from a techno-economic point of view. In section 3.2, the high-level evolution trends for the access and metro networks are discussed. The access part is elaborated in much more detail in section 3.3 by showing all different technology flavours in the expected evolutionary flow.

3.1 Techno-economic justification

When rolling out a (new) optical access network, the civil works always represent the major cost part independent of the technology choice. As the cost of the fibre impacted by the civil works is not negligible, it can be advantageous to exploit the current fibre infrastructure in a more optimal way, e.g. by using the wavelength division multiplexing (WDM) domain, so that an increasing user demand does not immediately require the installation of additional optical fibres in areas that are already served by optical access.

Even if in next-generation optical access (NGOA) architectures, the most expensive optical equipment is the remote node (distributed access site) or the central office (central access site), it can become negligible as it will typically be shared among a large number of customers. Within the ALPHA project, it was shown that these higher sharing ratios (e.g. 256, 512 or 1024) allow the introduction of more advanced concepts to introduce flexibility and dynamic bandwidth allocation in the access network [10].

Then as long as the ONU cost is kept under control (need to identify low cost technologies with possible large volumes of production), it is possible to introduce more advanced technologies in the access network without drastically increasing the cost per user.

Longer reach/distance must also be exploited towards reducing the number of active sites and the resulting OPEX and could be mandatory in some rural cases where the civil works are significantly increasing the cost per user [11]. Also, the use of new technologies to allow higher data rates towards the users while reducing the energy consumption is key in the future access networks.

3.2 Evolution trends in the access and the metro networks

There are two main categories of optical access or FTTH networks, either passive optical networks (PON) or active optical networks (AON) [12]. PONs (mainly deployed as a passive star or tree) are Point-to-Multipoint networks (P2MP), where the access fibre is passively split by a power splitter (TDM PON) or a wavelength router (WDM PON), with current split ratios varying from 1:16 to 1:128. Today, Ethernet PON (EPON) and gigabit-capable PON (GPON) are the two most important standards for TDM PON, while WDM PON is not yet standardized, but already deployed by a few operators [13]. AONs provide a (logical) Point-to-Point (P2P) connection between the central office (central access site) and each user. Active topologies can be divided in two classes: “home run” fibre architectures which offer a dedicated fibre from the central access site to each user and an active star architecture, where a switch or router is installed between the central access site and the user (in the distributed access sites, or even in the street cabinets), and from this point, a dedicated fibre reaches each user.

The FTTH technology is currently discussed in different standardisation bodies to draw an access roadmap for the next decade. Based on the findings in the ALPHA project, we envisage that the evolution of the technologies in the access/metro area will follow the possible technology roadmap shown in Figure 4. Please note that the timescale mentioned is only indicative: “now” means the situation as of today, “short term” the situation in 1-3 years from now, “medium term” the situation in 3-5 years from now, “long term” the situation after 5 years from now, and “very long term” the situation after 10 years from now.

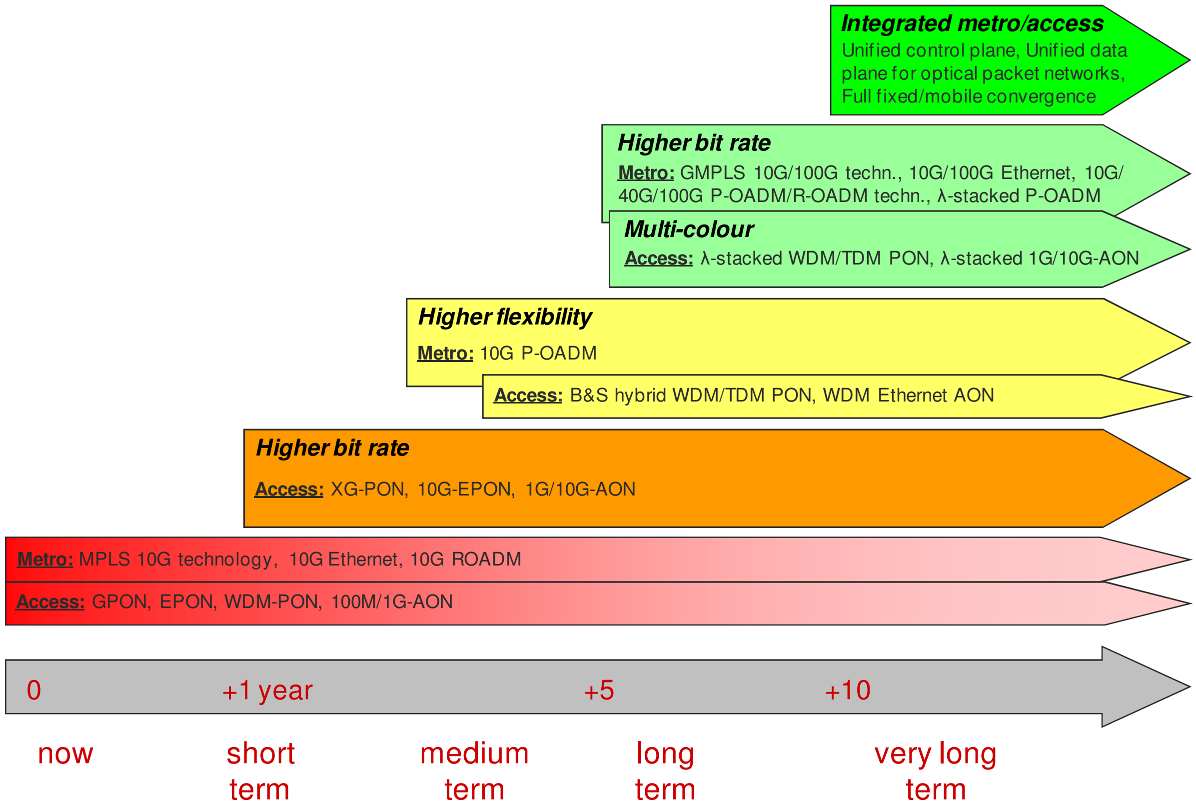

Figure 4: High-level roadmap for the access & metro network evolution

We expect the following phases to occur in access and metro network solutions:

- **Now**: in the access part, a plurality of FTTH solutions is available: GPON, EPON, WDM-PON, Fast Ethernet, Gigabit Ethernet and others with physical bit rates not exceeding 1.25 Gb/s for the upstream part and 2.5 Gb/s for the downstream part. In the metro side three main technologies are competing: MPLS 10G technology, 10G Ethernet and 10G ROADM. The deployment is starting for some of these technologies and we can expect that the deployment varies geographically/nationally, and will cover a time frame of several years. We expect that these technologies will disappear in the long term and will be replaced by the successive generations the future (as indicated by the fading-away of the arrowed line).
- **Short term** (1-3 years from now): the next generation of access networks foreseen is focused on **higher bit rates for the subscriber**, which also leads to higher bit rates in the aggregation network. We will then find 10G EPON and XG-PON (or 10G GPON) for the PON systems generation [14], [15] and 1G/10G AON systems.
- **Medium term** (3-5 years from now): the next big step could then be the evolution in the access and metro area towards WDM concepts to offer **higher flexibility**, a first level of convergence with an overlay approach like radio over fibre (RoF), and higher bit rates (targeting peak rates at 1 Gb/s). Thus for the access part the evolution identified is for broadcast and select WDM TDM PON systems generally called hybrid PONs, and point-to-point Ethernet WDM PONs. The deployment of 10G WDM/TDMA hybrid PON is foreseen to take off after the deployment of GPON systems which is currently taking place in many countries, and therefore it could take some time before a new generation of PONs gains traction. For the metro, a new Packet Optical Add/Drop Multiplexer (P-OADM) technology is currently studied in different laboratories [16], and could replace in a medium term the R-OADM technology. The 10G P-OADM technology, exploiting optical transparency in the optical packet data plane could be a potential technology to optimise the power consumption, reduce the footprint of nodes while offering a performance comparable to full electronic

packet switching technologies. We consider the medium term perspective a fairly aggressive inclusion of 10G P-OADM type technology, but it is considered within this period as nowadays it is included in the solutions portfolio of some companies.

- **Long term** (>5 years from now): the key question is then how to **increase the capacity to ultrahigh bit rates at the user side (average 1 Gb/s per user) leading to physical bit rates at the TX/RX part > 10 Gb/s** of such an access and metro networks at low cost (i.e. it is important to minimize the number of migration steps towards the final goal). We are considering systems where the cost of the network and the power consumption are very important requirements that need to be taken into account. In this roadmap, we propose to exploit a parallel approach called λ-stacked WDM TDM systems for the access and for the metro area even if 10G/40G and 100G technologies could be also envisaged. A multi-colour packet concept is then proposed as a possible evolution of the P-OADM network concept. It consists in the adoption of a new Photonic Integrated Chip (PIC) technology (10 lasers and one optical multiplexer, e.g. an AWG, integrated in one chip for example) to offer a 100G WDM technology. The potential advantages of this approach are: the possibility to keep the frequencies at the level of the 10G technology currently envisaged in the next generation of PON systems, the possibility to decompress the time domain to relax the contention problems accelerating the transmission of DATA in the access + metro area to reduce the end-to-end latency, the possibility to reduce the complexity and the cost of the P-OADM optical interface thanks to a WDM processing of the packets for the transit part. Of course a more classical approach with a bit rate increase can be envisaged also in some network scenarios, to cope with the capacity requirements. Also envisioned is a more evolutionary track which adheres to the ever increasing bandwidth needs and energy efficiency requirements through using next generation version of standard technologies like Ethernet, WDM PON, and dynamic WDM based OTNs under a unified control and in a multi-technology hybrid type of network design. The unified control enables an integrated access and aggregation network with end-to-end QoS enabled auto configuration of the network, efficient use of network bandwidth, and network wide coordination of energy efficiency functions of the network elements.
- **Very long term** (>10 years from now): after 10 years from now, one target could be a **convergence scenario between access and metro** with one unique data protocol and an unified control and management plane to optimise again the resource allocation. This scenario is particularly interesting to have a convergent scenario between fixed and mobile networks. With the recent LTE evolution of mobile networks proposing a convergent view on a MPLS technology, this optical packet vision could be integrated in a mobile + fixed network scenario. The convergence could be at least at two levels: at the optical multiplexing level by interleaving packets transporting data from the fixed network or from the mobile network, or at the electronic multiplexing level through a consideration of a time multiplexing of packets in electronic buffers or an aggregation of client packets coming from fixed or mobile networks into one optical packet frame.

3.3 Technology roadmap for the pure access network

Figure 5 shows the different potential technologies for the pure access part, with some reference points concerning the introduction of new metro technologies. The technology roadmap is split into three categories: optically passive, optically signal-processed and opaque, as defined in section 2.3.

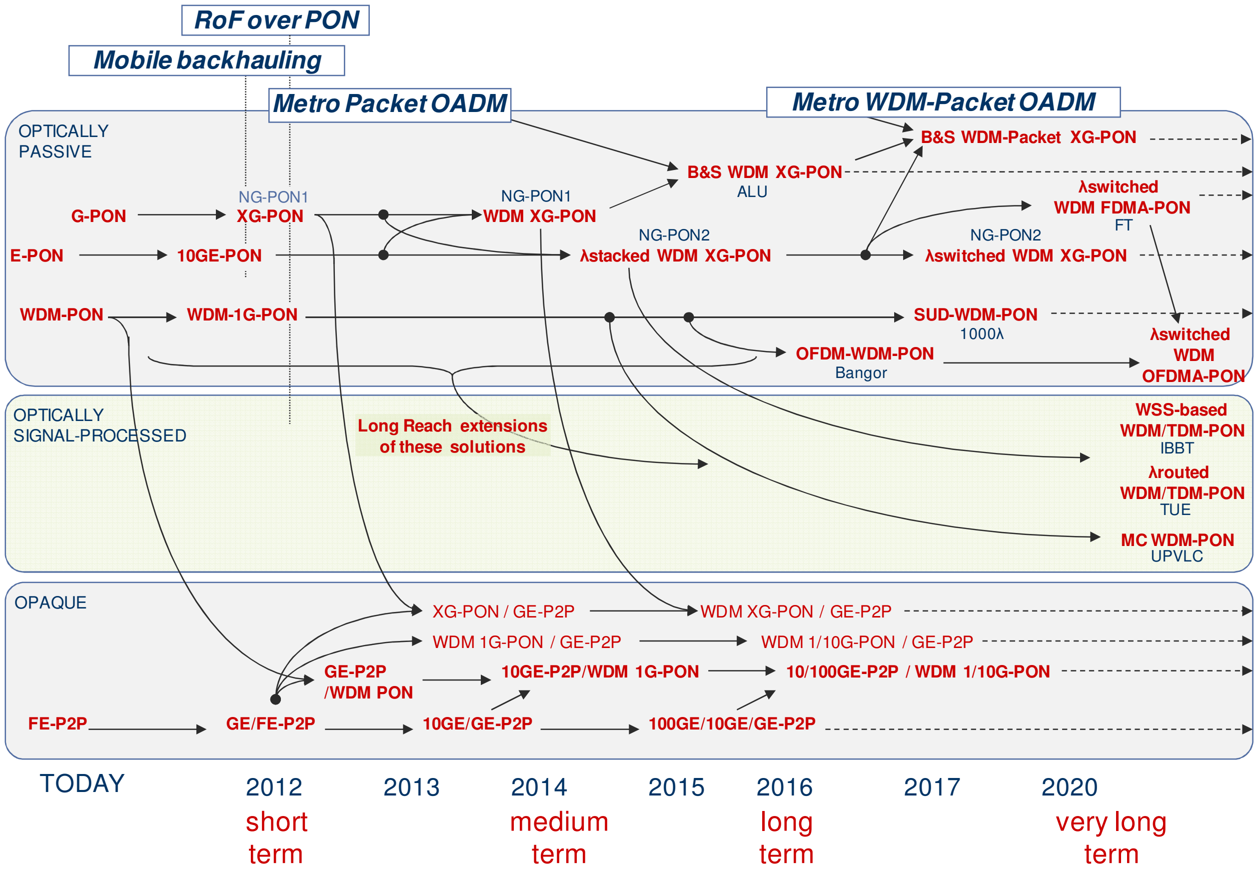

Figure 5: Detailed technology roadmap for the pure access part

Optically passive systems

GPON, EPON and WDM PON systems (hybrid 1G systems) are the technologies that are currently deployed and represent potential alternatives for the access part. The evolution is foreseen towards higher bit rates, mainly 10G per wavelength.

- GPON systems: the evolution identified for 2012, is the XG-PON system, 10G for the downstream and 1G/2.5G/10G for the upstream. Around 2014, the WDM XG-PON is the second evolution in this Next Generation of PONs. The objective of the WDM dimension is to increase the connectivity and to increase the offered bandwidth in a very efficient manner. After 2015, a new PON generation will be standardised know as NG-PON2. The technology of choice is not yet known and a number of candidates are possible. One very interesting candidate, because it allows convergence with future packet based metro networks, is a fully dynamic bandwidth allocation Broadcast-and-select WDM XG-PON system proposed in the ALPHA project. This version could evolve towards a WDM packet B&S WDM packet XG-PON after 2017 if new requirements in term of user bit rate are asked. In this scenario the parallel dimension in the WDM domain is preferred to increase the access bit rate while preserving the cost and the power consumption of the ONUs and technology progresses in integration of optical functions have to be engineered (Photonic Integrated Circuits). Other evolutions are possible (such as the Ultra-Dense WDM PON, OFDMA PON [17] etc…) but represent more innovative approaches, less in line with today evolution of PON but still very interesting because of additional features not provided by the B&S WDM XG-PON scenario.
- EPON systems will follow the same evolution as the GPON systems, and in advance with respect to the GPON technology due to its earlier introduction on the market place. Thus a 10GE-PON system is foreseen around 2012. After this, the EPON and GPON lines follow

similar evolutions and it is not clear anymore whether the ITU and IEEE differences will remain.

- WDM PON systems currently proposed on the market place could follow similar evolutions. The first evolution is a hybrid solution through a WDM 1G-PON also around 2012. This solution is a competitive alternative to the 10G-PON/10GE-PON system. A medium term evolution is an OFDM-WDM-PON system [18], [19], whereas a longer term evolution is a SUD-WDM-PON system offering 1000λ [20]. A wavelength switched WDM OFDMA-PON version is proposed after 2020.

Interdependencies in this category:

The XG-PON system could motivate two technical directions: WDM XG-PON or λ-stacked WDM XG-PON. We see also a similar impact from the 10GE-PON systems that could motivate the same directions.

The λ-stacked WDM XG-PON could be a catalyst for the B&S WDM-Packet XG-PON system or the λ-stacked WDM XG-PON or the λ-stacked FDMA PON. This last proposal could even evolve towards a λ-stacked OFDMA PON solution.

In summary we have first a bit rate evolution in PON systems, then a flexibility evolution in a the WDM concept for a better network performance, and finally a second step of bit rate increase through a new generation of packet formats called WDM packets. The FDM/OFDM technology on the top of xPON systems is foreseen after 2016.

Optically signal-processed systems

Active switches in PON systems were proposed in the middle part of Figure 5. This is an alternative solution to manage wavelengths inside the network. Compared to passive broadcast-and-select architectures, the architectures with active equipment in the remote node result in lower power losses and a higher security (without losing their flexibility). Since the active equipment in the remote node (consisting of e.g. optical switches) is shared among the users the cost is also shared. However solutions are foreseen for the long term perspectives after 2020. Three types of networks have been identified within the ALPHA project: a wavelength selective switch (WSS)-based WDM/TDM PON system [21], a λ-routed WDM/TDM PON system [22] and a multicast (MC) WDM-PON system [23].

Opaque systems

All these solutions are Ethernet based, with point-point links interconnecting Ethernet switches, i.e. both data, control and management plane is electrically processed at all points of the Ethernet level in the network. A pure opaque system is fairly simple and very mature form an optical layer stand point, and the major challenges a steady pace of bit rate increasing standards. For opaque systems the challenge is on the control and management plane, to create higher integration between the different network domains and between different network technologies (i.e. it is likely that the network will consist of both opaque and not opaque systems), in order to be able to coordinate and manage network resources (e.g. bandwidth, energy) in an efficient manner.

At first introduction, there were Fast-Ethernet Point-to-point solutions that can be configured either in an active star or a home run design. This will then further evolve towards a more integrated access and distribution network that relies on a higher degree of mesh topology to create inherent network robustness. Using the same link technology end-to-end makes this integration easier to accomplish, and it leads to a less complex and cost intensive network to run.

Currently there are Gigabit Ethernet/Fast Ethernet P2P installations in the access with 1GE/10GE solutions in the distribution network that can utilize the WDM dimension (i.e. P2P or ROADM based WDM systems) for efficient fibre use. In 2-3 years time, the use of 10GE solutions in the distribution will be even more pronounced, and utilizing 100G solutions at later stages. In parallel, in the access, we also find a mix of FE/GE-P2P/WDM-PON hybrids (i.e., wavelength filtered WDM PONs without an intermediate TDMA layer) with an evolution towards 10GE-P2P/WDM-PON systems.

In summary, it is envisioned that opaque network designs will move towards a hybrid scenario which is Ethernet based at the link layer, but which can utilize P2P WDM-PON in the access and dynamic optical networks in the distribution network. The main focus will be on the auto-configuration of these highly integrated access and distribution networks.

Cross interactions between the three categories

The optically passive technology could offer complementary or disruptive solutions for both optically signal-processed solutions and opaque solutions.

3.4 Conclusion

The roadmap for the access network is considered in parallel with a roadmap for the metro network, as a convergence scenario is eventually expected between both network parts. The following main trends are expected: *presently*, both in the access (FTTH) and metro parts a variety of technologies is available. In the *short term*, the next generation of access networks will be focused on higher bit rates for the subscriber, leading to 10G PON systems and 1G/10G AON systems. In the *medium term*, for both metro and access networks a higher flexibility will be required, which starts at the metro part (to handle the increasing bit rates of the access part in a flexible way) and is followed by the access part where several hybrid technologies are introduced and a higher user count is to be served. In the *long term*, a further increase of the bit rates at the user side is expected, which will lead to a bit rate increase in the metro network, and at the access network the parallel approach delivered by λ–stacked solutions will be exploited. In the *very long term*, a convergence scenario is likely between the access and the metro network with one unique data protocol, a unified control and management plane to optimise the resource allocation and completed with a full fixed/mobile convergence scenario.

Additionally, a more detailed technology roadmap for the pure access network is drawn where all different technology flavours are integrated and shown in the expected evolutionary flow. This roadmap is split in three main categories: optically passive (corresponding to the different PON flavours that remain fully passive in the field), optically signal-processed (corresponding to more advanced PON flavours that need electronic control in the field) and opaque (corresponding to the different AON and P2P flavours) technologies.

For the access networks, a lot of external factors (regulation, operator history, regional differences …) will define the final technology choice, but it seems clear that moving to line rates of 10 Gb/s or higher, to higher numbers of users fed over a longer fibre link from the local exchange or central access site (the 'long-reach PON' architecture), and exploiting the WDM dimension are present in all technology flavours for the next-generation optical access network.

4 Roadmaps for the in-building network

This section describes the roadmaps for the in-building networks. Section 4.1 gives a techno-economic justification to indicate the main trends from a techno-economic point of view, which serves as an input for the different roadmaps in this section. In section 4.2, the high-level evolution for the in-building networks is presented. In section 4.3 a detailed flow chart for choosing the most suitable in-building network is presented.

4.1 Techno-economic justification

Within the ALPHA project, techno-economic studies have been done into wired optical in-building networks [24], [25]. Various basic topologies were investigated: point-to-point (P2P), bus, tree, and hybrid topologies such as star-P2P, star-bus, and star-tree. Also various types of cable media for each topology were considered: Cat-5e, duplex large-core plastic optical fibre (POF), silica multimode fibre (MMF), and single-mode fibre (SMF). And all these topology and media options were applied to typical building scenarios, namely small buildings (e.g. residential family homes), and large buildings (e.g. office buildings and multi-dwelling unit buildings). The fibre-optic networks may come in two flavours: so-called opaque networks (where opto-electronic-optical conversion is done in each node), and transparent or optically passive networks (where the signals stay in the optical domain when crossing a node).

Considering opaque networks, regarding the network installation costs (CAPEX, capital expenditures) per room, we found that for small buildings a P2P topology is the most cost-effective one. For large buildings, where a relatively high amount of cable length is needed, the bus topology is the preferred one. Duplex POF cabling in both cases was cost-competitive with Cat-5e cabling, and even cheaper than that when duct sharing is applied (so putting the POF in the same ducts as the electrical power cabling, which is not allowed for Cat-5e cabling for safety reasons). Regarding the OPEX (operational expenditures), the power consumption per room was lowest for the P2P topologies, followed by the tree topology. Power consumption was the lowest for the Cat-5e solutions, followed by duplex POF.

By taking the CAPEX and OPEX into account together, the total costs over the (economic) lifetime of the in-building network could be estimated. On top of that, estimated price evolutions of the network components [26], of the consumed energy, and of the labour were taken into account. As a major trend, it was concluded that the all-in lifetime costs of POF networks will become lower than those of Cat-5e networks in the near future. They can be even lower already today than those of Cat-5e networks, if duct sharing is applied. The costs of the duplex POF solutions will decrease in the future, due to the growing market size and increasing maturity of POF products, whereas the costs of the Cat-5e solutions will increase due to rising prices of copper (becoming a scarce material).

For optically passive network topologies with passive optical signal power splitting/routing functions in the nodes (so where no OEO signal conversions take place in the nodes and thus the network is capable of transparently transporting multiple signal formats independently), the OPEX will be lower than the OPEX of opaque network topologies, as no electrical power is consumed in the nodes.

4.2 Evolution trends in the in-building networks

Based on the findings reported above, we envisage that the evolution of in-building network architectures and techniques will follow the roadmap shown in Figure 6. Please note that the timescale mentioned is only indicative: “now” means the situation as of today, “short term” the situation in 1-3 years from now, “medium term” the situation in 3-5 years from now, “long term” the situation after 5 years from now, and “very long term” the situation after 10 years from now. The network evolution in our view will follow a number of phases. Please note that each phase is likely to stay after the next one has started, as the installation of in-building networks will involve large capital investments which need to be written off over a long time.

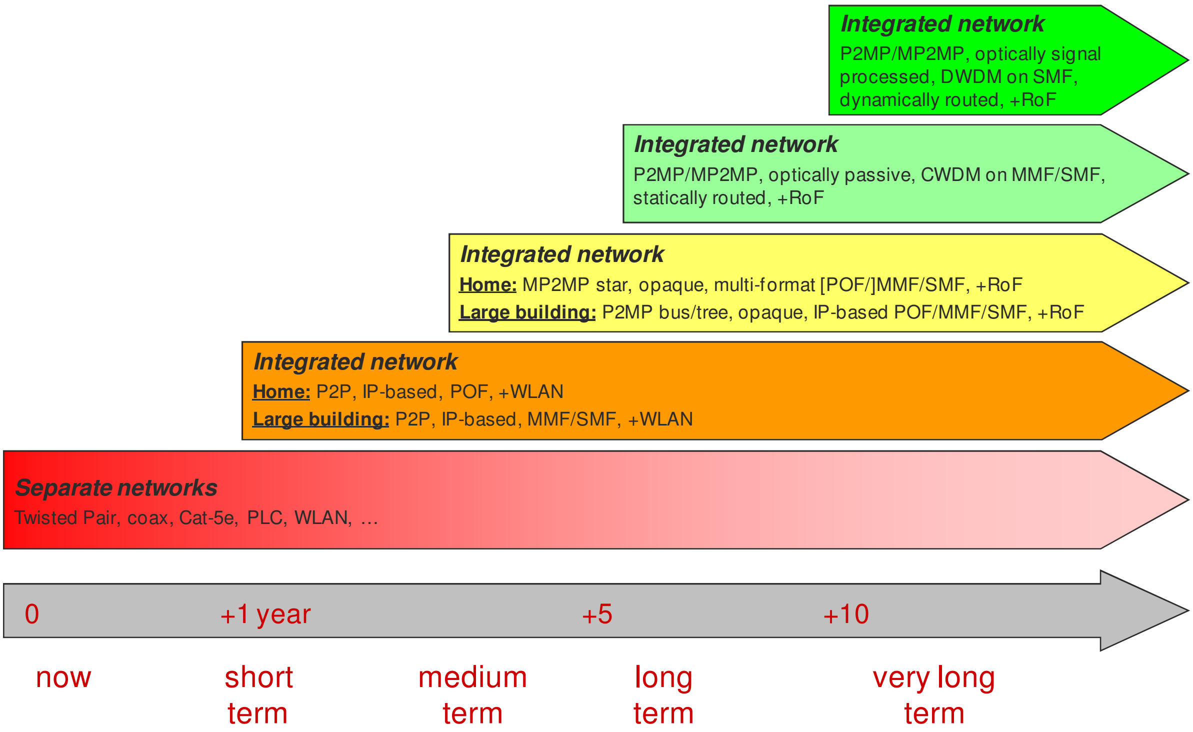

Figure 6: High-level roadmap for the in-building network evolution

As shown in Figure 6, we expect the following phases to occur in in-building network solutions, being installed successively in time:

- **Now**: present in-building networks consist of a **mixture of separate networks**, each optimized for a specific set of services: twisted pair cables basically for telephony, coaxial cables basically for TV and FM radio distribution, and Cat-5e cables, power line communication (PLC) modules and wireless LAN (WLAN) modules for data communication between computers and servers. Such a mixture is not easy to maintain, is not energy-efficient, and is elaborate to upgrade or to introduce new services. We therefore expect that this mixture will disappear and be replaced by integrated network solutions in the future (as indicated by the fading-away of the arrowed line).
- **Short term** (1-3 years from now): **P2P IP-based integrated network** solutions will be introduced, were all services (triple-play, wirebound and wireless) are carried in a single infrastructure. For *smaller buildings*, we expect P2P topologies to be preferred, with large-core duplex POF cabling. For *larger buildings*, we also expect that initially P2P topologies will be preferred for their ease of implementation, but that MMF or SMF cables will be used as the reach of POF cables is limited. For both *smaller and larger buildings*, the integration of all services is expected to take place by carrying these in IP format, including WLAN base stations spread around in the building and connected on IP-basis.
- **Medium term** (3-5 years from now): **P2MP opaque integrated network solutions** will be introduced, with bus or tree topologies for *larger buildings* which at one hand are more complex to install and operate, but on the other hand save duct space and are more economical. As in larger buildings the dominant traffic would be data-based, we expect that all services are carried in IP format, where the network nodes will perform the switching electronically and will do signal restoration. This permits the use of (lossy) duplex POF cables, as well as MMF and SMF cables. For *smaller buildings*, a star topology with a single multi-signal-format electrical switch in the star centre (possibly coinciding with the residential gateway) may be adopted, which allows not only IP-based signals but also other signal formats (such as video and audio streams, domotics control signals, …) to be transported. The

independent transport of multiple signal formats is likely to be done by using multiplexing of several frequency bands; hence the restricted bandwidth of large-core POF makes POF less suited here than MMF and SMF. For both *smaller and larger buildings*, we foresee that the demand for wireless communication capacity will have risen considerably, thus requiring smaller radio cells which can be fed by means of (analogue or digital) radio over fibre (RoF) signals. As these are not IP-based, they have to be transported and regenerated while bypassing the opaque IP-based nodes.

- **Long term** (>5 years from now): **optically passive P2MP integrated network solutions with static signal routing** will be introduced, with bus or tree topologies for *larger buildings*. The optically passive network nodes will route the optical signals transparently by maintaining their signal format deploying passive optical power splitters and/or passive optical wavelength routers (such as arrayed waveguide grating routers). For *smaller buildings*, a MP2MP star topology may be used where in the star centre a passive star coupler distributing optical powers is deployed, or a wavelength router routing the wavelength channels. Several wavelength channels may be deployed, in a coarse wavelength division multiplexed (CWDM) scheme; the wavelength channels are routed statically in the network nodes, and their traffic paths cannot be altered. The RoF signals are carried in separate wavelength channels.
- **Very long term** (>10 years from now): **optically signal-processed P2MP/MP2MP network solutions with dynamically adaptable signal routing** will be introduced, where optical signal processing (such as optical wavelength conversion) is applied in the nodes in order to change the wavelength paths upon external control. This allows to control the traffic flows in the network (the wirebound services, as well as the wireless services embedded in the RoF signals), and thus to provide capacity-on-demand [27] and to better support mobility of the users. Many wavelength channels may be needed, in a dense wavelength division multiplexed (DWDM) scheme, in order to create many individually controllable traffic paths. The network will be based on bend-insensitive SMF, in order to interact with the active optical signal processing devices and to host DWDM transmission and routing schemes.

Overall, we can observe a trend towards higher network capacity and higher network flexibility, which is uniquely supported by fibre-based solutions [28] and their extra features of dynamic traffic routing by means of optical signal processing.

4.3 Choosing the most suitable in-building network

This section presents a detailed flow chart for choosing the most suitable in-building network, consisting of the installation method, the transmission medium, the physical topology and the network protocol. In section 4.3.1, the transmission media are discussed in detail, and in section 4.3.2, the integrated flow chart is shown.

4.3.1 In-building transmission media

A range of signal transport media is available for carrying the in-building communication services. We may coarsely distinguish three groups of transmission media: optical fibre media, copper media, and (hybrid) free-space (radio waves). Each of these three groups contains several media options, which each entail different infrastructure costs and a different capacity which they can offer effectively (i.e. taking into account environmental circumstances, interference effects, …) to a user terminal. Figure 7 intends to give a qualitative representation how the various media impact the effective capacity and the network infrastructure costs. These costs comprise the costs of the cables, the ducts, the connectors, and the network nodes and network terminal ends. The representation is largely based on the cost trends observed within the ALPHA project, plus qualitative information from other market and literature sources.

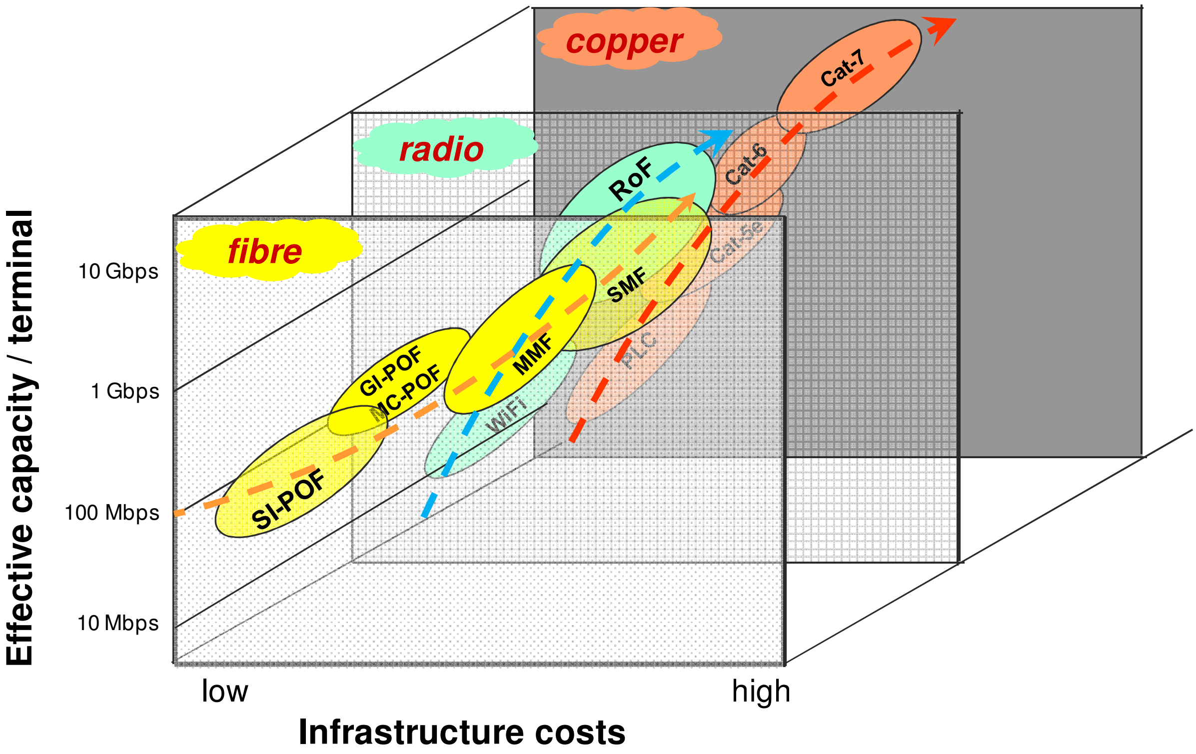

Figure 7: Effective capacity per user terminal versus infrastructure costs, for various transport media

The main trends sketched in Figure 7 are:

- For the **copper-based solutions**, the effective capacity which can be provided increases when moving from PLC to Cat-5e, to Cat-6, and further to Cat-7. However, the infrastructure costs also increase, and do so more than linearly (as indicated by the arrowed trend line). This can be attributed to the increasingly complex signal processing needed to combat signal dispersion and crosstalk, and to the increasing cable costs. It may be noted that the PLC solution is the cheapest of all solutions, as the cable medium (the electricity wiring) is already there; it however also has the lowest effective capacity, due to heavy EMI impact.
- For the **radio-based solutions**, the WiFi solutions are also relatively cheap, but their throughput rarely reaches their theoretical maximum (which may be up to 300 Mb/s) due to external interferences. Going to pico-cells fed by fibre links (RoF solutions, supporting e.g. 60GHz and UWB radio signals) will result in higher effective capacities per terminal, but also in higher network costs as part of the network is to be installed by fibre. Nevertheless, the few last meters to the user terminal are wireless, so do not bring extra costs and thus make RoF solutions slightly cheaper than all-wired (i.e. up to the user) MMF or SMF solutions. Like for the copper-based solutions, the complexity of the radio-based solutions, in particular of the wireless part, increases more than linearly with the required capacity; so the infrastructure costs also increase more than linearly, as indicated by the arrowed trend line.
- For the **fibre-based solutions**, the infrastructure costs have been assessed in considerable detail for a range of topologies within the ALPHA project. As a general trend, visualized in Figure 7, it has been observed that large-core step-index PMMA POF (SI-POF) in an opaque network architecture offers the lowest infrastructure costs; these costs are about equal to the costs of an equivalent Cat-5e architecture, and even lower when the existing ducts of the electricity wiring are used. With the powerful DSP techniques available today, the capacity of a SI-POF link can exceed the capacity of a Cat-5e link for a similar reach. Graded-index large-core POF (GI-POF) and multiple-cores POF (MC-POF) bring higher costs, but also a higher capacity. The (recently introduced) MC-POF is less sensitive for bending, thus easing

installation. Silica graded –index multimode fibre (MMF) and (bend-insensitive) single-mode fibre (SMF) offer significantly lower losses and higher bandwidths, but also require more delicate installation leading to higher costs. However, the costs of MMF and SMF solutions are less dependent on the capacity they can offer, as the fibre's capacity itself is huge and the adaptations to increase the data capacity only involve the transceiver modules. Hence, in contrast to the radio and copper-based solutions, we expect the offered capacity to grow more than linearly with network infrastructure costs, as indicated by the arrowed trend line.

The capacity-vs.-network infrastructure costs trend lines (indicated with arrows in Figure 7) underline our expectation that, with the foreseen growth in capacity demands, fibre-based solutions will outperform the radio and copper-based solutions in the future performance-wise and/or costs-wise.

4.3.2 Flowchart for selecting the most suitable fixed in-building network

Figure 8 depicts a flow chart to indicate the optimal choices for the installation of a new in-building network infrastructure.

The first selection parameter is the **installation method** which will mainly depend on the building status. When installing an in-building network infrastructure, it makes a lot of difference if the installation is done in a new building (green-field) or in an existing one (brown-field). In case of a green-field installation, it is straightforward to work with buried ducts as this is the best protected and most esthetical solution. For existing buildings, however, burying the ducts is very labour intensive and on-the-wall mounted ducts offer a valuable alternative in case a complete new infrastructure is needed. Alternatively, in some buildings an existing network infrastructure can be reused for providing broadband access, either an existing duct infrastructure (e.g., used for the existing electricity network) or an upgradeable network (e.g. PLC (power line communication) using the electricity network, MoCA (multimedia over coax alliance) using the existing coax network). Although these solutions are sometimes less future-proof, they can provide a very cost-effective alternative that meets the current requirements.

The second selection parameter is the choice of the **transmission medium**, which will be related to the bandwidth aimed at, as already shown in Figure 7. For a fixed in-building network, a basic split can be made by copper- and fibre-based solutions. Only when using shared ducts, the choice is limited to the fibre-based media due to the safety regulations and the electromagnetic interference (EMI) sensitivity of copper-based media. In an installation with low constraints and little to no challenging applications the customers can choose for a Cat-5e solution. This will offer the cheapest solution as Ethernet is a well known and on massive scale produced solution. In smaller installations, e.g. residential houses, Cat5-e could even provide the possibility to offer up to 1 Gb/s. More recent copper-based solution like Cat-6 and Cat-7 are very promising as they offer 1 Gb/s or even more. Taking a look at the future and especially when looking at larger installations, e.g. high rise buildings, choosing for either a very easy-to-install POF solution or for a silica optical fibre - easiest with MMF - would provide the best solution. Note that in each case wireless antenna stations can be attached to the wired network, in order to connect the wireless devices of the user. When using an optical fibre-based wired network, the radio signals can be remotely generated and transported over the fibre network to simplified antenna stations (i.e. a RoF solution). This will reduce the installation, operation and maintenance costs of the radio antenna stations in each room (/apartment) of the building. The radio signals can be transported in their radio frequency (RF) format when SMF (or MMF when less than say 5GHz) is used. When using POF (SI-, GI-, or MC-POF), the radio signals may first be down-converted in order to fit in the restricted bandwidth of the POF, and at the antenna end be up-converted again to their original RF format. These down- and up-conversion processes, however, add some complexity (and thus costs) to the system, and also make upgrading less easy.

The third selection parameter is the **physical topology** which will be related to the building size. A distinction can be made between topologies based on Point-to-Point (P2P) links and those based on Point-to-MultiPoint (P2MP) links. We define a P2P link as a direct link between two devices, to which no other devices are hooked up without passing through an active node (i.e. a node in which signal routing or switching is done by active means)[2]. An active node typically is not transparent for the signal format; it is an opaque node[3]. We define a P2MP link as a direct link by which one device connects to multiple devices via a passive device (such as a passive signal splitting element), so without passing through an active node. Such a passive device typically does not affect the signal format; it is transparent. As the copper-based and POF-based network solutions use active (opaque) nodes, they are categorized as P2P. For the silica fibre solutions, a differentiation is made between P2P and P2MP. When passive optical power splitters or wavelength routers are used, the solution is categorized as P2MP. Here, a distinction between high rise buildings (e.g., with more than 4 floors) and lower buildings is useful. Typically, considering the prices for the building lots, a low rise building will also be a smaller building and the distances to the different apartments will be small. In this case, a point-to-point (P2P) installation can be cost-effective and will also provide the highest dedicated bandwidth, most flexibility and the best future proof solution. In the case of a high rise building, it is more cost effective to work with a P2MP bus solution or a hybrid solution in which each floor is connected on a bus and with a P2P from each floor to the access network connection. The selection between both should be made based on the expected bandwidth and the amount of end points to be connected.

The fourth selection parameter is the used **network protocol**. For the copper-based and POF solutions, an IP-based protocol is applied, while for MMF and SMF also a multi-format signal (IP, RF TV, RF wireless) can be carried.

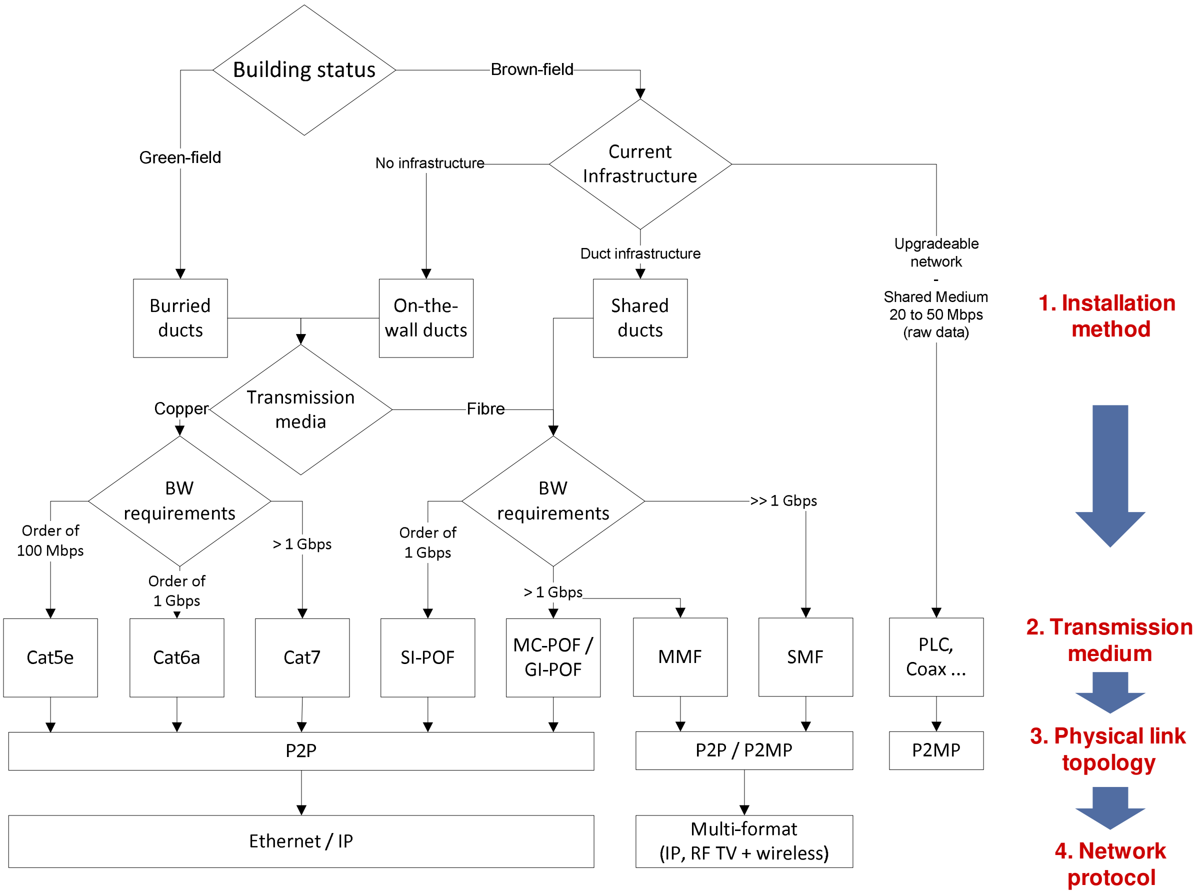

Figure 8: Flowchart for selecting the most suitable in-building network

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[2] For example, a Cat-5e network with multiple routing nodes is still called a P2P topology as each node actively routes the signal, whereas the links between the nodes are P2P links.

[3] The active node typically cannot handle arbitrary signal formats; e.g. an IP packet routing node can only handle IP packets.

4.4 Conclusion

For in-building networks, an overall trend towards higher network capacity and higher network flexibility is observed, plus a trend towards network integration where wired and wireless services are delivered by a single in-building network. This trend is uniquely supported by fibre-based solutions and their extra features of signal format transparency and dynamic capacity allocation by means of optical (and hybrid optical/electrical) signal routing. A number of main trends have been identified for the in-building network. *Presently*, it is a mixture of separate networks, each optimized for a specific set of services. In the *short term*: point-to-point IP-based integrated network solutions will be introduced, where all services (triple-play, wired and wireless) are carried in a single infrastructure using fibre-based solutions like POF (typically for smaller buildings) or MMF/SMF (typically for larger buildings) cables. Other solutions, based on copper, like Cat5/6/7 cables and upgraded versions of PLC, will also be around. WLAN base stations will be spread around in the building for offering wireless services. In the *medium term*, point-to-multipoint opaque integrated network solutions will be introduced using POF, MMF or SMF cables. Next to IP-based signals, multi-format signals are expected, especially in a home scenario with its variety of multimedia and data services plus home automation functions. We foresee that the demand for wireless communication capacity will increase considerably, thus requiring smaller radio cells which can be fed by means of (analogue or digital) radio over fibre (RoF) signals. In the *long term*, optically passive point-to-multipoint integrated network solutions with static signal routing will be introduced. The optically passive network nodes will route the optical signals transparently by maintaining their signal format deploying passive optical power splitters and/or passive optical wavelength routers (such as arrayed waveguide grating routers). Several wavelength channels may be deployed, in a coarse wavelength division multiplexed (CWDM) scheme. In the *very long term*, optically signal-processed point-to-multipoint/multipoint-to-multipoint network solutions with dynamically adaptable signal routing will be introduced, where optical signal processing (such as optical wavelength conversion) is applied in the nodes in order to change the wavelength paths upon external control. Many wavelength channels may be needed, in a dense wavelength division multiplexed (DWDM) scheme, in order to create many individually controllable traffic paths. The network will be based on bend-insensitive SMF.

5 Roadmap for the cross domain issues & end-to-end QoS provisioning

It has become apparent from the produced roadmaps for the access and in-building network, that no single technical solution emerges as a one-size-fits-all solution, but that several solutions will coexist, each adapted to the specific needs of the end-users and also to the legacy and economic situation of the different regions in which the networks will be deployed. End-to-end Quality-of-Service (QoS) delivery integrated over these vastly different networks will be one of the main issues to solve in the coming years where solutions allowing a convergence of the protocols (for instance end-to-end Ethernet or packet based transport mechanisms with distributed intelligence) should facilitate this management. Therefore, the control and management of these heterogeneous solutions has been addressed both for the access and in-building parts and a high-level roadmap for the cross-domain issues and end-to-end QoS provisioning has been elaborated.

5.1 Evolution trends in the cross domain issues & end-to-end QoS provisioning

In Figure 9, a high-level roadmap for the deployment of advanced and integrated cross domain control and management is provided.

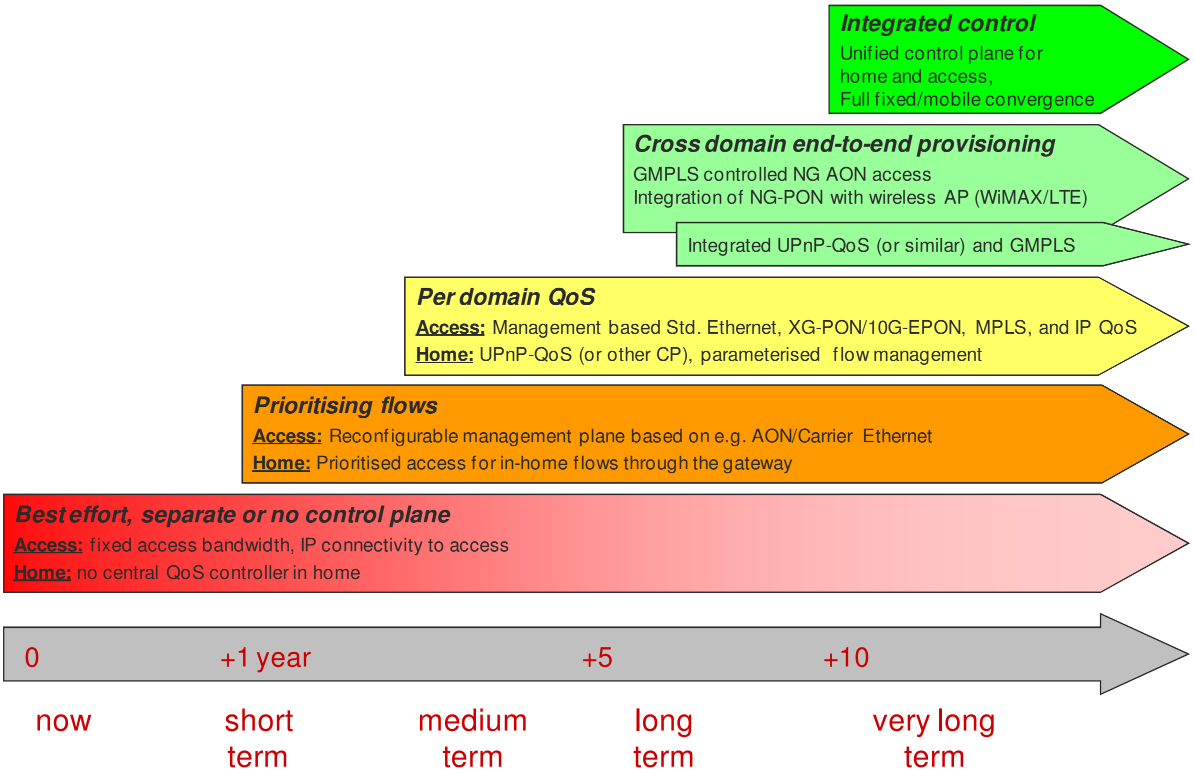

Figure 9: High-level roadmap for cross domain issues and end-to-end QoS provisioning

We expect the following phases to occur:

- **Now**: In the access network, fixed bandwidth is offered through xDSL solutions or GPON (EPON). No control plane related data is passed through the gateway. In the home network, however, no central QoS control is in place and basically the devices in the home compete for the same bandwidth without prioritisation internally or for connections through the gateway.

- **Short term** (1-3 years from now): In the access network, a simple reconfigurable management plane based on e.g. AON/Carrier Ethernet is expected to ease the operation and management of the metro network. The network will only be controlled from the provider's management entity and no switched connections will be enabled. In the home network, the gateway will prioritise specific devices and users based on simple rules enforced locally.
- **Medium term** (3-5 years from now): In the access and metro network, the use of management plane based solutions relying on standard Ethernet, XG-PON/10G-EPON, MPLS, and IP-based QoS schemes are much more pronounced and harmonized in implementation. In the home network, centralised control of the internal flows will be enabled using UPnP-QoS or other similar control plane mechanisms (e.g. OMEGA InterMAC) [29]. Guaranteed bandwidth allocation will be possible using parameterised flow management.
- **Long term** (>5 years from now): In the access and metro network, the GMPLS control plane will be more advanced and the users/ONUs/gateways can request for a specified bandwidth on a shorter or longer timescale. In the first solutions the users can request extra bandwidth or high priority bandwidth using a service provider interface, requiring an explicit request to be sent from the user/gateway. In the later solutions, cross domain end-to-end provisioning will be possible and UPnP-QoS or a similar control plane in the home will automatically and invisible for the user request the necessary resources in the access network through the gateway. A mapping of the internal parameters for traffic specification, e.g. in UPnP-QoS and the RSVP-TE parameters in GMPLS is necessary as demonstrated in ALPHA. In addition, integration of the call admission in wireless technologies as WiMAX/LTE and the available NG-PON technologies is expected to exploit the benefits of integrated wired/wireless end-to-end provisioning [30].
- **Very long term** (>10 years from now): A unified and common control plane like GMPLS will act as glue and mediator between the user and the access network. Hence, next-generation optical access (NGOA) technologies as XG-PON, 10G-EPON, hybrid WDM/TDM PON, NG-AON etc will be controlled and/or managed by a common control plane, which will also be integrated with UPnP-QoS or a similar protocol in the home network. In addition full fixed/mobile convergence will be supported.

5.2 Conclusion

For the cross domain and end-to-end QoS provisioning, the following main trends have been identified. *Presently*, best effort, separate or no control plane is available. In the access, fixed bandwidth is offered; and in the home, devices compete for the same bandwidth without prioritisation. In the *short term*: prioritising flows is expected to be introduced. In the access, a simple reconfigurable control plane will be used; and in the home, the gateway will prioritise specific devices and users. In the *medium term*, per domain QoS is foreseen. In the access, the use of management plane based solutions are much more pronounced and harmonized in implementation; and in the home, centralised control of the internal flows will be enabled using UPnP-QoS or another similar control plane. In the *long term*, cross domain end-to-end provisioning will be possible. In the access, the GMPLS control plane will be more advanced and the users can request for a specified bandwidth. UPnP-QoS or a similar control plane in the home will automatically request the necessary resources in the access network through the gateway. In the *very long term*, a unified and common control plane like GMPLS will act as glue and mediator between the user and the access network, and full fixed/mobile convergence will be supported.

6 Conclusion

In this white paper, we have formulated a view on the integrated network model with emerging technologies and developed a roadmap for the access and metro network, for the in-building network and for the (integrated) control and management plane of these networks for the short (1-3 years), medium (3-5 years), long (5+ years) and even very long term (10+ years) perspectives. In this way, the evolution path from legacy systems to the future network solutions has been given. We could detect some clear trends towards a need for higher data rates per user, higher flexibility in service delivery, and higher QoS demands. However, it is also clear that there does not exist a one-fits-all solution for the different network parts. Nevertheless, different levels of convergence are seen, fixed-mobile convergence, access-metro convergence and protocol convergence to offer cross-domain and end-to-end QoS provisioning.

The different roadmaps are mutually coupled, where in general the technologies positioned in the roadmaps are to support the clear trend in both network parts towards higher data rates per user, higher flexibility in service delivery, and higher QoS demands. Obviously, the future is hard to predict, especially the more distant future, but our studies and experiments done in the ALPHA project show that fibre-based solutions will inevitably play a crucial role in paving the evolution path of access and in-building networks.

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