Chapter 9
Advanced Architectures for PON Supporting Fi-Wi Convergence

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Abstract The phenomenal growth of mobile backhaul capacity required to support the emerging mobile traffic including cellular Long-Term Evolution (LTE), and LTE-Advanced (LTE-A) requires rapid migration from today's legacy circuit-switched T1/E1 wireline and microwave backhaul technologies to a new fiber-supported, all-packet-based mobile backhaul infrastructure. Mobile backhaul is utilized to backhaul traffic from individual base stations (BSs) to the radio network controller (RNC), which then connects to the mobile operator's core network or gateway. Many carriers around the world are considering the potential of utilizing the fiber-based passive optical network (PON) access infrastructure as an all-packet-based converged fixed-mobile optical access networking transport architecture to backhaul both mobile and typical wireline traffic. This chapter details the case for backhauling wireless traffic utilizing an optical access network, the various standards and technology options for passive optical networks (PONs), as well as the design of a novel, fully distributed, ring-based WDM-PON architecture that could be utilized for the support of a converged next-generation mobile infrastructure. Further, as in 4G and 5G the radio access network (RAN) becomes a broad concept that describes network transport systems including mobile backhaul, mobile fronthaul, and wireless connections between radio equipment and user devices, a fiber-wireless integrated system is nowadays not only limited to mobile backhaul, which is mainly composed of fixed wires, but also includes mobile fronthaul. Thus, a discussion is also added at the end of this chapter on mobile fronthaul utilizing PON infrastructures.

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9.1 Introduction

Advances in optical networking technologies over the last two decades have provided tremendous growth in both backbone and MAN communication capacity, and at the same time, enterprise local area networks (LANs) have scaled tributary speeds progressively from 10 to 100 Mb/s toward multi-gigabit speeds (e.g., 1 and 10 Gb/s Ethernet, or GbE/10 GbE). The last front of this evolution is the access technology so as to address the bottleneck in bandwidth and service quality between a high-speed residential/enterprise network and a largely overbuilt core backbone network. This in turn will enable the support of more bandwidth-intensive networking applications, as well as the support of end-to-end QoS for a wide variety of applications, particularly non-elastic applications such as voice, video, and multimedia that cannot tolerate variable or excessive delay or data loss.

Bridging this gap between the capacity provided by the backbone and metro networks on one side, and the actual capacity experienced by end users on the other, is a significant challenge that is currently being addressed by service providers and local carriers. The introduction of optical technologies solutions in the access network is one way to address this acute need for bandwidth. This need is exacerbated, as discussed in detail in Sect. 9.2 that follows, by the additional requirement imposed on the access network to backhaul wireless traffic.

Fiber-to-the-home (FTTH) access systems are considered the ultimate level of access bandwidth. Further, to lower the cost and expedite the implementation of FTTH, passive optical network (PON)-based solutions have been proposed. PONs are point-to-multi-point (P2MP) fiber optical networks with no active elements in the signal's path. Deployment of PONs as architectures for FTTH access networks is viewed as a future-proof last mile technology that has enough flexibility to support new and unforeseen applications. The rest of this chapter details the case for backhauling wireless traffic utilizing an optical access network, the various standards and technology options for passive optical networks (PONs), as well as the design of a novel, fully distributed, ring-based WDM-PON architecture that could be utilized for the support of a converged 4G/5G mobile infrastructure. The chapter ends with a short discussion on fronthauling mobile traffic.

9.2 Backhauling Wireless Traffic

The current standardized mobile telecommunication system, universally recognized as 4G, provides increased capacity and reliable wireless communications. Wireless access architectures such as Mobile WiMAX and LTE are two competing technologies that achieve data rates beyond 100 Mb/s per end user. Unlike WiMAX, LTE uses an evolution of the existing universal mobile telecommunication system (UMTS) infrastructure, used by over 80 % of the mobile operators [1]. Thus, it is not necessary to build a new network infrastructure, making LTE more popular with operators worldwide. In addition, LTE-Advanced, which can be seen as an enhancement to LTE, offers a clear upgrade path to mobile carriers. This makes it more cost effective for vendors to offer LTE and then upgrade to LTE-Advanced. Furthermore, LTE and LTE-Advanced can also make use of additional spectrum and multiplexing to achieve higher data speeds. Coordinated multi-point (CoMP) transmission (as discussed in various other chapters of this book) can also allow for more system capacity to help handle the enhanced data speeds, something that is a necessity for the optical-wireless architecture convergence.

The demand for high-bandwidth access networks is expected to grow continuously, due to the increased expansion of innovative and high-bandwidth applications like Web 2.0, mobile TV, and streaming content, that will be the dominant application in LTE/LTE + networks. Thus, current backbone standards are expected to become less effective for building mobile access networks. Specifically, legacy technologies such as circuit-switched T1/E1 wireline or microwave used for existing 3G network infrastructures cannot scale to the capacity requirements of new 4G (and 5G) access architectures [1]. Thus, mobile operators are investing heavily in upgrading their backhaul infrastructure, with fiber-optic deployments to the LTE base stations ("fiber to the cell"). Due to their compelling advantages, many works have addressed the need for building access architectures for LTE networks, such as [2, 3]. However, LTE/LTE + technologies possess specific requirements, when considering issues like intercommunication of base stations, traffic roaming, and end-to-end service provision across heterogeneous networks. Therefore, it is worth looking into the enhanced base stations called "evolved node Bs (eNBs)," before identifying the needs of the LTE network for backhauling network traffic. The LTE network architecture consists of an all-IP core network, called Enhanced Packet Core or in short EPC. The eNBs are connected by means of the S1 interface to the EPC, whose logical components are the Mobility Management Entity (MME), the Serving Gateway (S-GW), and the Packet Data Network gateway (P-GW), together also known as the Access Gateway (AGW) (see Fig. 9.1). LTE also introduced support for inter-BS connectivity via the X2 interface, to support handover operations. Recent studies have estimated traffic traversing the X2 interface to reach 4–10 % of traffic traversing the S1 interface [3]. Thus, it is important for an efficient converged architecture to support at least partial meshing of eNBs, so that X2 traffic does not flow through the AGW, which would waste resources and significantly increase packet delay. With respect to the eNB architecture, ASIC and/or FPGA are used to implement the PHY, DSPs for lower layer protocols (i.e., MAC and RLC), and CPUs or network processors for the upper layers of the protocol stack. The MAC sublayer is responsible for QoS-aware downstream/upstream packet scheduling. For downlink traffic, the scheduler decides which packets to be sent to the intended user equipment (UE).

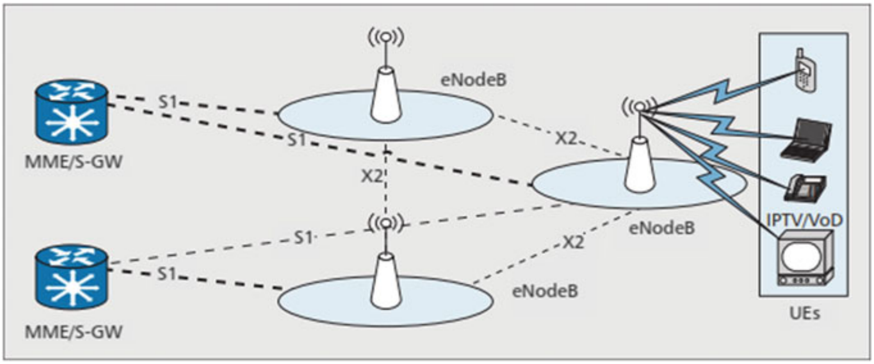

Fig. 9.1 LTE network architecture

Uplink scheduling results in resource grants being sent to UEs. Each UE is responsible for determining, which data to transmit within the granted resources. A QoS-aware MAC Scheduler at the eNB aims to distribute the available air interface resources to the UEs within the cell, supporting QoS guarantees. The Bearer information (QoS mapping) must be carried on all system interfaces and mapped to pre-configured QoS parameters regarding priority, packet delay, and packet loss. This includes RAN elements that might be prone to congestion-related losses or excess packet forwarding delay. QoS mapping (bearer information) and X2 traffic are two key issues that the backhaul network should handle, apart from the general support of high-speed connection.

It is generally accepted that fiber deployment to cell towers ("fiber to the cell") is the only future-proof solution to build mobile backhauls, which will scale to the increased capacity requirements of future NG-WBAN technologies [1]. It will alleviate the need of using expensive RF point-to-point links (i.e., 26 GHz) or even the unlicensed 60-GHz Wi-Fi band. Apart from requiring additional RF circuits and antennas, they lack the high capacity, inherent resilience, and the ubiquity offered by optical fiber networks. Therefore, the implementation of an optical network supporting the fiber-enabled cell towers is the only viable solution. Among the optical network architectures, passive optical networks (PONs) meet the needs for such high-capacity access architecture. PONs have been proposed in the past 10 years as an access technology, bearing (a) low deployment costs, avoiding active components in the field, (b) bandwidth sharing between the end users, (c) scalability in terms of users and points of presence, as well as (d) bandwidth granularity. Different variants of PONs have been proposed, but most were conceived based on the demands and bandwidth prospects of the past. PONs architectures have slightly changed since then and only the technology (i.e., TOSA/ROSA) has changed. These are discussed in detail in the sections that follow.

9.3 Passive Optical Network (PON): Standards and Technology Options

Passive optical network (PON) technology has been widely considered for building mobile access networks. The mobile backhaul portion of 4G telecommunication networks, or radio access network (RAN), interconnects the Enhanced Packet Core (EPC) with the edge section of the wireless domain and transports traffic from individual base stations (BSs) to the access gateway (AGW). However, it must be noted that with peak per-edge cell downlink throughput of 1 Gbit/s and uplink of 500 Mbit/s in the case of LTE-Advanced, 4G base stations are expected to be densely populated to achieve high spectral efficiency and require high bandwidth and cost-effective backhauling.

A PON consists of three parts: (i) an optical line terminal (OLT) that is located at the operator's central office and hosts the active equipment. In particular, it hosts the laser TRx banks depending on the standard deployed. (ii) A set of optical network units (ONUs) that communicate with the OLT either directly with a separate wavelength or over a passive splitter. The number of ONUs deployed determines the splitting ratio and thus the power budget of the system. The ONUs are located near end users, either in multi-tenant buildings, businesses, or individual houses. Further, the ONU provides the required service interface to all operator's customers. (iii) A passive feeder network, also called optical distribution network (ODN) that is utilized to interconnect the OLT and ONUs. The ODN uses simple optical fiber and a power splitter and typically is in the form of a tree network architecture. Depending on how data are multiplexed and transmitted, in downstream (from OLT to ONU) and upstream (from ONUs to OLT) mode, there exist three different technology options. The most popular one is time division multiplexing (TDM) PON, where traffic from/to the OLT to multiple ONUs is TDM multiplexed over a single (or more) wavelength(s). Wavelength division multiplexing (WDM) PON (also called PtP-WDM-PON) uses discrete wavelength channels, one per ONU. In this, capacity is not shared as in TDM-PON and each OLT-ONU link uses a different wavelength. A third option is orthogonal frequency division multiplexing (OFDM) PON, where a number of orthogonal subcarriers are employed to transmit traffic from/to the ONUs. With the WDM and OFDM technology, PONs are capable of providing data rates of up to 40 Gb/s.

9.4 Technology Options

9.4.1 TDM-PON

TDM-PONs (sometimes referred to as *power-splitting* PONs (PS-PONs) since the branching device used in the outside plant is a $1 \times N$ power splitter) utilize a single wavelength containing downstream information that is shared by N users. Upstream

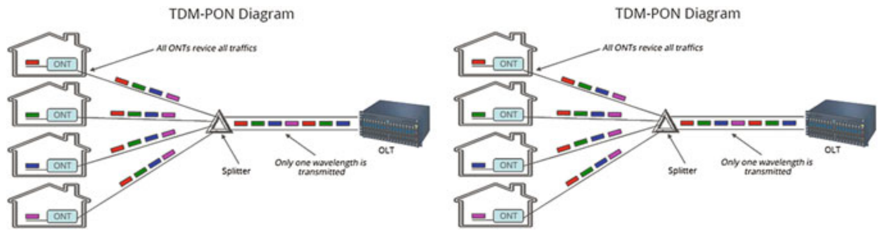

Fig. 9.2 Time-division-multiplexed passive optical network architectures

information is provided by a low-cost transmitter placed in the ONU. Coarse wavelength division multiplexing is used to separate the upstream and downstream transmissions.

Figure 9.2 illustrates a typical tree-based TDM-PON architecture. The ONUs terminate all traffic and constitute the service interface for end users such as DSL or coaxial cable. In contrast, OLT constitutes the gateway interface of the entire PON to the (outside) IP core network and is commissioned to forward IP traffic over standard interfaces, i.e., SDH/SONET or Ethernet. Downstream traffic is forwarded by broadcasts from the OLT to all connected ONUs, while in the upstream direction an arbitration mechanism is employed, so that data packets from the ONUs do not overlap at a given time frame (slot). The start time and length of each transmission time slot for each ONU is scheduled using a bandwidth allocation scheme, which is executed at the OLT. In order to achieve a high degree of bandwidth utilization, with a notion of fairness among the ONUs, a dynamic bandwidth allocation (DBA) technique is employed that can adapt to the current traffic demand if required. To facilitate bandwidth sharing as well as ONU registration and service discovery, a multi-point control protocol (MPCP) has been proposed and designed, consisting of five basic messages: (a) REGISTER REQ, REGISTER, and REGISTER ACK for discovering and registering new ONUs at the network and (b) REPORT and GATE for facilitating centralized medium access control. Upon receiving ONUs buffer sizes, the OLT executes the dynamic bandwidth allocation (DBA) and communicates via a GATE message to all ONUs the granted transmission window (number of slots) as well as the starting time.

Since the OLT and the ONUs can be separated by ~ 10 km and the distance from each ONU to the OLT is not the same, a TDM-PON architecture suffers from switchover shortfalls. Interleaved polling is subsequently used to mitigate the large propagation delays. With interleaved polling, the next ONU to be polled is issued a GATE message giving transmission access, while the previous ONU is still transmitting. Guard band times are used between ONU transmissions to avoid any overlap in data transmission as well as to allow each to switch ON and OFF its lasers, thus preventing CW spurious transmission in the network (upstream traffic). Data from the ONUs arrive at the OLT at different power levels, and thus the OLT must adjust its threshold and decision criteria to receive data without errors.

Therefore, the OLT should keep a record of all ONU transmissions over time (something that is not the case in downstream traffic).

Various bandwidth allocation schemes have been devised for the efficient usage of available bandwidth as well as making allocation decisions computationally light [4]. Grant sizing can be divided into four major categories: *Fixed*, where the grant size is fixed for each ONU every cycle; *Gated*, where the granted size equals the queue size of the ONU; *Limited*, where the grant size is set between the reported buffer size and a maximum one, specified for that ONU; and *Limited with Excess Distribution*, which is based on the *Limited* grant size with the excess bandwidth being distributed to the "overloaded" ONUs. Both the *Limited* and the *Limited with Excess Distribution,* approaches prevent bandwidth monopolization by a certain ONU, which is the case for the *Fixed* granting scheme.

The execution of the DBA algorithm at the OLT, once per cycle, poses computation overhead. Therefore, both the algorithms and the MPCP messages should be kept simple for fast execution to avoid delays in packet transmissions.

TDM-PONs, though cost-effective, have some limitations for future access network demands. TDM-PONs place a lot of stress on the electronic and opto-electronic components in the OLT and ONU, since these components have to operate at the aggregate bit rate. Also, the insertion loss of the power splitter increases with increasing number of subscribers. In addition, privacy is limited in TDM-PONs since all the downstream information is broadcast to all ONUs.

The currently deployed PON systems are mostly TDM-PON systems, which include ATM-PON (APON), Broadband PON (BPON), Ethernet PON (EPON), Gigabit PON (GPON), 10G EPON, and Next-generation PON (NG-PON) [4–16] to provision different data rates up to 10 Gbps. APON/BPON, GPON, and NG-PON architectures were standardized by the Full Service Access Network (FSAN), which is an affiliation of network operators and telecom vendors. Since most telecommunications operators have heavily invested in providing legacy TDM services, these PON architectures are optimized for TDM traffic and rely on framing structures with a very strict timing and synchronization requirements. EPON and 10G-EPON are standardized by the IEEE 802 study group. They focus on preserving the architectural model of Ethernet. No explicit framing structure exists in EPON, and Ethernet frames are transmitted in bursts with a standard inter-frame spacing. The above-mentioned standards are further discussed in the sections that follow.

9.4.2 WDM-PON

Another PON variant is the wavelength division multiplexing PON, or WDM-PON (or Pt-to-Pt WDM-PON). In this architecture, ONUs do not share wavelength capacity, but each ONU possesses its own wavelength, directly routing its traffic to the OLT (as Fig. 9.3 illustrates). The different wavelengths may coexist on the same fiber or may be router over different ones. WDM-PONs offer the advantage of higher speed, as well as scalability in capacity and network size, simply by adding

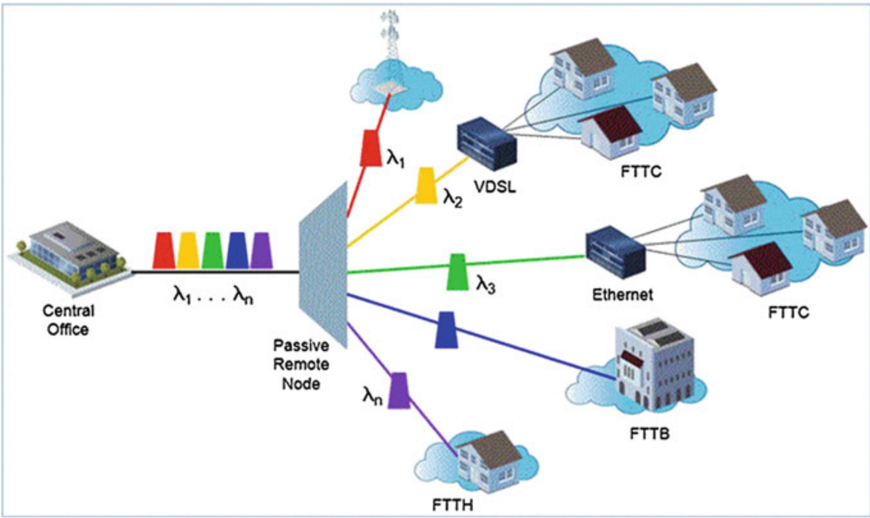

Fig. 9.3 Wavelength-division-multiplexed passive optical network architecture

more wavelengths and more ONUs, respectively. However, this bears the disadvantage of deploying more WDM active components, yielding a higher cost of initial setup. This should not be ignored, having in mind the relative low (<1 Gbps) bit rate service that access networks provide to their end users.

In either case, WDM-PONs have several advantages compared to their TDM counterparts. Apart from their higher bandwidth, WDM-PONs entail protocol, modulation format, and rate transparency. Furthermore, WDM-PONs provide a higher notion of security, since data are not broadcast to all ONUs, but each ONU receives its own dedicated data. In terms of the split ratio that determines the power budget and PON reach in TDM-PONs, this is now not as significant in WDM-PONs, since the employment of more ONUs actually means the addition of extra wavelengths. In addition, no arbitration is required for upstream transmission, and thus the need for the P2MP media access control is no longer required. Finally, system speeds can now be increased in a pay-as-you-grow fashion, whereas in a TDM-PON an upgrade of the OLT would create the need to upgrade the entire set of ONUs. Nevertheless, WDM-PONs also present some disadvantages, such as increased deployment costs due to the WDM components required (AWG, MUX/DMUX, tunable sources, etc.), increased temperature sensitivity, which entails the need for temperature control (temperature control is costly and requires active electronic parts in the optical distribution network or alternatively temperature-insensitive WDM components), as well as increased operational expenditures in terms of maintenance, spare parts, inventory stocks, and production lines since ONUs are now λ-specific (creating the need for “colorless ONUs”).

Therefore, WDM-PON resembles a typical point-to-point optical network, where reach and optical transmission is mainly determined by the type of laser source (WDM sources can achieve >80-km repeater-less transmission). Finally, the control layer and the bandwidth allocation mechanism are much simplified, compared to typical G(E)PON. In essence, there is no need for DBA algorithms, and OLT-ONUs communicate in a point-to-point fashion.

Despite these attractive features, WDM-PON installation is costly, mainly because of the use of active WDM sources. These must be anchored on the ITU grid, with proper thermal management, a fact that also increases power consumption. Many different solutions have been proposed in the literature. Among these are solutions where the ONUs are employed with tunable laser sources, so as to tune each ONU to the proper wavelength. However, tunable sources are relative expensive and thus do not constitute a viable solution. Another solution is to equip each subscriber with a wavelength transparent optical modulator, and the OLT with a bank of all lasers. In such a case, the OLT can send the downstream data with a low modulation index. The signal will be split at each ONU for data reception of the downstream traffic and modulation of the upstream traffic. The technique is known as *reflective modulation*, and either optical modulators or SOAs can be used to implement it. SOAs provide the advantage of optical signal amplification, bearing in mind the extra losses incurred due to the doubling of transmission reach. Alternatively, the ONUs may employ a fixed but different wavelength optical source (ONUs are not colorless in this case), while the OLT will have a bank of fixed-wavelength sources for all ONUs connected to it. Further, the OLT will also employ the same number of fixed-wavelength (or broadband) optical receivers.

Various WDM-PON architectures have been proposed in the research literature over the years, with different variations for the optical sources at the OLT and ONUs, as well as different OLT and ONU architectures [17]. As an example, the Composite PON (CPON) architecture utilized a single-wavelength, burst-mode receiver at the OLT to receive the upstream signal. Even though it avoided the drawbacks of upstream WDM, it was cost prohibitive, as it was limited to the use of a single-frequency laser, such as a distributed feedback (DFB) laser diode (LD) at the ONU. The Local Access Router Network (LARNET) architecture, on the other hand, employed a broad-spectrum source at the ONU, in order to avoid the limitations of CPON, using an inexpensive light-emitting diode (LED) whose spectrum was sliced by the AWG-based router into different optical bands in the upstream direction. However, spectrum slicing with AWG may lead to high-power loss. Therefore, the distance from the OLT to the ONU utilizing this architecture was considerably reduced. For the Remote Interrogation of TErminal NETwork (RITENET) architecture, at the ONU, the light was split by a passive tap, with a portion of the light detected by the receiver, while the remainder was looped back toward the CO through a modulator. The signal from the OLT was shared for downstream and upstream transmission through time sharing. Another type of WDM-PON architectures is the multistage AWG-based WDM-PON architectures that exploit the periodic routing property of the AWG so that the reuse of a given wavelength for more than one subscriber is possible. These architectures provide scalability in bandwidth as well as in the number of users, either by employing additional wavelengths at the CO or by cascading multiple stages of AWGs with increasing AWG coarseness at each stage. Further, architectures such as super-PON (SPON) proposed a solution that covers a range of over 100 km with a splitting ratio reaching 2000 with the usage of optical amplifiers (OAs) placed in the long feeder and after the first splitting stage, while architectures such as SUCCESS-DWA separated the upstream and downstream traffic by a wideband WDM filter residing between the AWG and the PON, aiming to offer scalability by employing dynamic wavelength allocation.

9.4.3 OFDM-PON

Orthogonal frequency division multiplexing (OFDM) PONs or in short OFDM-PONs use a number of orthogonal subcarriers assigned to different ONUs. Figure 9.4 displays sub-carrier allocation to the ONUs for such an OFDM-PON implementation. OFDM-PONs bear all the advantages of OFDM transmission, namely enhanced spectral efficiency and superior transmission performance (extended reach, dispersion, polarization and noise tolerance, power budget requirements, lower nominal repetition rates, etc.). As in xDSL technology, each sub-carrier is modulated with a conventional m-QAM scheme at a lower symbol rate. Thus, bandwidth (as well as transmission) reach can be increased with a negligible effect of chromatic and/or polarization mode dispersion. Albeit OFDM-PON is considered for future deployment (NG-PON2), it possesses some significant advantages. First, transmission reach has been extended to beyond 100 km without the use of specialty fibers, optical amplification, or expensive laser sources. Such an extension can be beneficial, when connecting distant users and/or

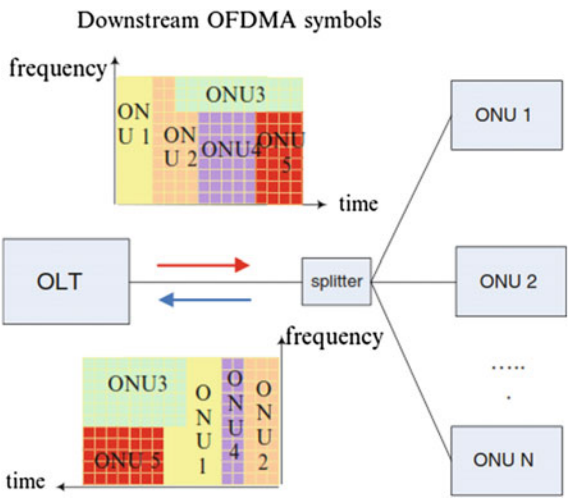

Fig. 9.4 Time-division-multiplexed passive optical network architectures. RE-DRAWN

designing PONs that cover a large geographical scale. Further, OFDM relies on low-cost ASICs for advance signal processing and not on optical components (WDM lasers) that are more expensive and have stringent requirements in terms of packaging, thermal management, etc. Another advantage of OFDM-PON is that bandwidth allocation per user can differ, by simply changing the subcarrier modulation frequency and/or modulation scheme. Thus, different services can be provided with no extra components or complex control plane algorithms.

Even though OFDM-PON has significant advantages, it still is a premature technology, mainly due to the high cost and requirement of high-speed ADC/DACs, and is currently being considered as a research topic for potential future deployment.

9.4.4 Hybrid PONs

Hybrid PONs refer primarily to a TDM-WDM co-design of PONs and secondarily to OFDM-WDM. In the first case, hybrid WDM/TDM-PON bridges the gap between TDM-PON and pure WDM-PON and can be deployed for a smooth migration of the currently deployed TDM-PONs. There are different concepts of hybrid TDM-WDM-PONs. One such concept is illustrated in Fig. 9.5 [18], where the number of available wavelengths to all ONUs/end users is simply increased. Such an approach invests on scheduling bandwidth requests, originating from ONUs, to a larger pool of shared wavelengths, thus increasing PON capacity. Another approach relies on a joint ring/tree architecture [19], where a WDM ring serves distant remote nodes with a separate wavelength, whereas remote nodes serve multiple ONUs over the same wavelength. Such an approach constitutes a

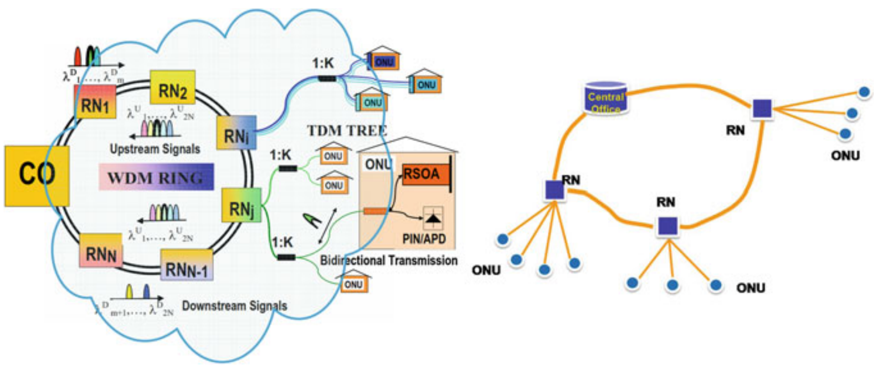

Fig. 9.5 Implementation of hybrid WDM-TDM-PON networks in the ACCORDANCE project [20]

smooth migration from currently deployed PONs (mainly GPON) with increased scalability and backwards compatibility.

Overall, looking at all different types of PON architectures, the major issue of PONs is that they are purely digital systems. They are bandwidth consuming and lack flexibility and scalability as the data rates and system capacity of 4G/5G systems increasing exponentially. To support future multi-tier, carrier aggregated heterogeneous mobile data networks, PONs should be service/format agnostic. Combination of Digital and Analog Radio-over-Fiber RANs can be a future-proof solution, and many research works have been carrying out on this approach as discussed in various chapters of this book.

9.5 PON Standards

9.5.1 GPON/EPON

Most advances on PONs were carried out upon ITU standardization of the older ITU-T G.983 standard based on Asynchronous Transfer Mode (known also as ATM-PON (or simply APON)). Due to the low penetration of the ATM protocol, the ITU developed the final version of ITU-T G.983 widely known as Broadband PON, or simply BPON. BPON was initially designed to offer 622 Mbit/s (OC-12) of downstream bandwidth and 155 Mbit/s (OC-3) of upstream traffic. Soon, ITU finalized G.984 Gigabit-capable passive optical networks (GPONs) representing a smooth upgrade in terms of upstream/downstream speeds (2.488/1.244 Gbit/s). GPON has and still is the most successful implementation in fiber access networks. Among the implementations, the Ethernet PON (or in short EPON or GEPON) has been the successful candidate due to the ease that the Ethernet protocol offers in layer 2 networking, as well as the fact that Ethernet has emerged as the frontrunner technology for transporting data, video, and voice services over a single platform (the great majority of all installed connections of all LANs is Ethernet based).

The initial EPON standard 802.3ah has evolved since 2004 from symmetric 1–10 Gbit/s (10G-EPON standard is IEEE 802.3av). Both standards use separate wavelengths for downstream and upstream traffic (1.5/1.3 μm). The GEPON standard continues to evolve, bearing in mind the advances in GEthernet interfaces. The IEEE 802.3 working group is commissioned with the task of maintaining and extending speeds beyond 10Gbps. To this end, the 802.3ba standard describes 40- and 100-Gbit/s connection speeds for a variety of connection reaches spanning from a few meters to beyond 40 km. Discussions for 400 GbE and 1 TbE are also currently under way.

9.6 10G-PON

As demand for network speed continues to grow, new and faster technologies are spawned from the existing standards. 10G-PON is the next-generation ultra-fast capability for G-PON providers, designed to coexist with installed G-PON user equipment on the same network. To this end, ITU-T in 2010 completed the G.987 standard, also known as 10G-PON or XG-PON, defining shared network access rates up to 10 Gbit/s over existing fiber, specifically for last mile, access networks. Initially, G.987 was designed for multi-tenant buildings, where 10G capacity is shared by all end users. ITU-T defined two variants in the G.987 standard. The first concerns asymmetric 10G-PON (also known as XG-PON1) with 10 Gbit/s downstream and 2.5 Gbit/s upstream line rates and the second concerns symmetric 10G-PON (also known as XG-PON2), where both downstream and upstream speeds are 10 Gb/s (the nominal rates are 9.95328 and 2.48832 Gbit/s, respectively). 10G-PON and G-PON are similar with respect to framing and protocols but differ in the operating wavelengths (10G-PON uses wavelengths of 1577 and 1270 nm for downstream/upstream traffic, while GPON and EPON use wavelengths of 1490 and 1310 nm). This was decided so as to allow coexistence of 10G-PON and GPON over the same access network. It should be noted that symmetric operation of an access networks implies a stringent requirement; the ONUs must employ expensive high-speed burst-mode lasers, while the OLT must employ expensive burst-mode receivers.

ITU is now developing 40/80G PON standards (also noted as NG-PON2), based on a multi-wavelength scheme (similar to 100 GbE). The primary solution that is considered is a hybrid time/wavelength division multiplexing (TWDM) scheme, while an optional evolutional scenario concerns a pure point-to-point wavelength division multiplexing (PtP-WDM) scheme. Both schemes use colorless power splitters in the feeder network and “colorless” ONUs.

9.7 10G-Epon

As mentioned previously, GEPON is a variant of GPON based on Ethernet protocol. As in 10G-PON, 10G-EPON supports both symmetric at 10 Gbit/s and asymmetric 10G/1G downstream/upstream operation (as per the 802.3av standard). Specific attention has been given to the coexistence of 1G and 10G-EPON, again by using different wavelengths but only in the downstream direction. In this case, 1G-EPON uses the 1480–1500 nm band, while 10G-EPON uses the 1575–1580 nm band. In the upstream direction, the 1G-EPON and 10G-EPON upstream bands overlap. 1G-EPON uses the 1260–1360 nm band, while 10G-EPON uses the 1260–1280 nm band. This is feasible since the upstream communication is separated over time and thus GEPON and 10G-PON packets do not overlap in time. The 10G-EPON standard also defined different link classes and power budget for different fiber reach and splitting ratios. The min class "×10" defines a 10-km reach with a 1:16 split ratio and a 20-dB power budget, while the maximum "×40" a 20-km reach with a 1:64 split ratio and a 33-dB power budget.

9.7.1 NG-PON2

To enable cutting-edge standardization of future optical access systems, the Full Service Access Network forum and ITU-T Study Group 15 are currently discussing the specifications of a 40-Gigabit-capable PON, which employs wavelength division multiplexing (WDM) technology, for the purpose of enabling cost-effective 40-Gigabit-capable transmission capacity and multiple service capability. It is worth noting that the term NG-PON1 is used for the evolutionary growth of EPON/GPON, which supports coexistence with EPON/GPON on the same feeder network, while the term NG-PON2 represents the revolutionary change in NG-PON, with disruptive technologies, such as optical code division multiplexing (OCDM), with no requirement of coexistence with EPON/GPON. The NG-PON2 standard, ITU-T G.989, emerged in 2015 and details the architectural and technology features for network throughput of 40 Gbps, corresponding to up to 10-Gbps symmetric upstream/downstream speeds available at each end user.

An example of NG-PON2 system architecture is shown in Fig. 9.6. Although the previous PON systems offer broadband service only for residential users,

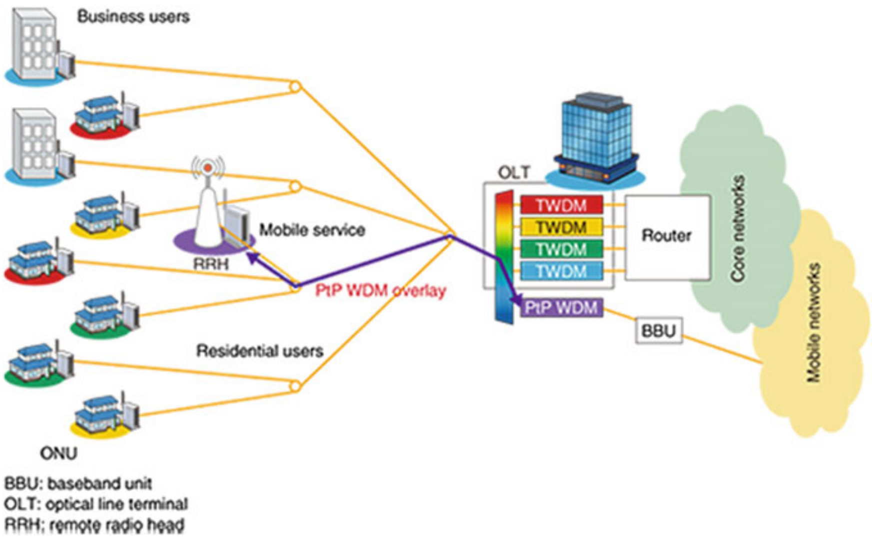

Fig. 9.6 NG-PON2 system architecture. RE-DRAWN

NG-PON2 systems are expected to accommodate business users and mobile users in addition to residential users. The primary NG-PON2 solution is called TWDM (time and wavelength division multiplexing)-PON, which is a hybrid of conventional TDM (time division multiplexing) and WDM technologies. Optionally, NG-PON2 also supports point-to-point (PtP) WDM overlay, which is expected to be suitable for mobile services that require low latency. In NG-PON2, colorless optical network units (ONUs) are mandatory for reducing system operating expenses because they can eliminate the complicated inventory management of ONUs.

In TWDM-PON, there are four (with an option to deploy eight) multiplexed wavelengths for upstream and downstream transmission. In addition, NG-PON2 envisages the use of three line rates for each wavelength, particularly symmetric 2.5 and 10 Gbit/s, as well as 2.5 and 10 Gbit/s for upstream and downstream, respectively. Therefore, the transmission capacities for each line rate are symmetric 10 and 40 and 10/40 Gbit/s for upstream/downstream. The symmetric 40 Gbit/s is expected to be used by business users, while the 10/40 Gbit/s asymmetric one by plain residential users. In TWDM-PON upstream traffic, time division multiplexing is supported through the use of tunable burst-mode lasers at each ONU. Wavelengths are dynamically assigned, through the use of burst lasers at each ONU, and thus it is important that wavelengths do not overlap over time. In the downstream direction, wavelength division multiplexing is supported by combining four fixed-wavelength lasers, hosted at the OLT and combined with a wavelength MUX filter before launching to the feeder network. At each ONU, the MUXed signal (4 or 8 wavelengths) is actively filtered with a tunable filter that forwards only the appropriate wavelength.

The NG-PON2 wavelength assignment plan uses the 1524–1544 nm band for upstream transmission and the 1596–1602 nm band for downstream transmission. The G.989.2 standard also specifies two other options with a reduced spectrum band for upstream traffic: 1528–1540 and 1532–1540 nm. Wavelengths used are anchored on the 50-, 100-, or 200-GHz grid spacing, matched with the corresponding tunable components employed at each ONU. Attention is given to dispersion compensation and polarization maintaining techniques, especially for 40 Gbit/s-capable NG-PON2 access networks.

The case of WDM-PON is simpler, as the wavelengths used cover the expanded spectrum 1524–1625 nm, with no specification on the number of wavelengths and the exact allocation for upstream/downstream traffic. This is because the number of wavelengths specifies the number of supported ONUs and it is a choice of the operators. For supporting backward compatibility with other PON standards, the spectrum band is narrowed to 1603–1625 nm only. Figure 9.7 illustrates the complete wavelength allocation plan for all PON standards.

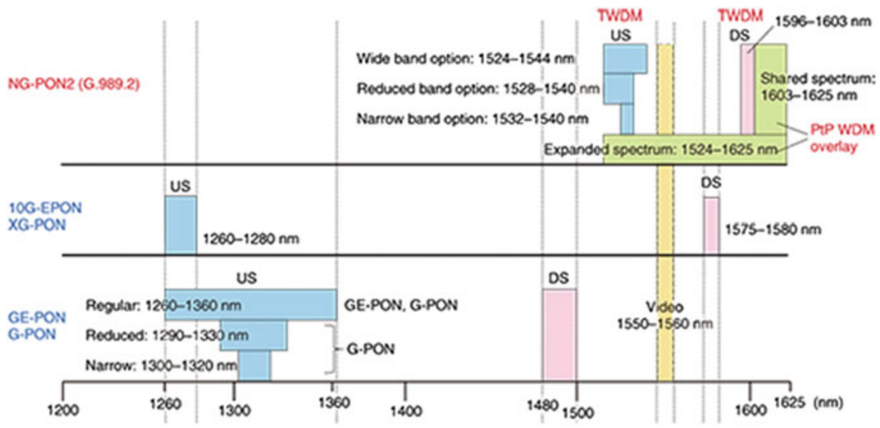

Fig. 9.7 Wavelength allocation plan for PON standards for backwards compatibility

9.7.2 Evolution Scenarios

Market opportunities for 10G-PON rely on the penetration of next-generation multimedia rich applications. These span from typical triple play services (voice, video, and Internet), to interactive ones, and to remote storage cloud services. Examples of bandwidth-hungry applications include IPTV, online gaming, video-conferencing, and interactive video. Further, the rapidly increasing use of advance cloud services for storage and processing (either from typical PCs or handheld devices) has further fueled traffic in the access networks. Soon, the explosive growth of access traffic together with the wide usage of real-time services with strict quality-of-service (QoS) requirements (e.g., low packet delay and jitter, and bandwidth guarantee) will justify the need of Next-generation PON standards, such as NG-PON2 and beyond [21].

The reader should also note that 100G-EPON is currently the up-to-date PON standard and it has attracted significant research attention. The objectives of the standardization work being carried out on 100G-EPON include defining the specifications for physical layers operating over a single fiber strand and supporting symmetric and/or asymmetric data rates of 25, 50, and 100 Gb/s (note that the specified data rate should be supported in the downstream direction and less than or equal to the specified data rate should be supported in the upstream direction), with a BER better than or equal to 10E-12 at the MAC/PLS service interface, and supporting coexistence with 10G-EPON. Due to the several technology, interoperability, and economical issues raised for this technology, 100G-EPON has attracted interest across the entire optical communications field, including network operators, system and device vendors, as well as researchers working on issues such as optical fiber transmission and the application of signal processing techniques.

9.8 Challenges in PON Design

With the emergence of LTE/LTE + networks, PONs have been revisited as viable architectures for also backhauling wireless traffic. Among the most important challenges are the extension of the PON reach and the development of burst-mode receivers. PON operators are mainly interested in increasing the PON reach instead of deploying new feeder networks. Similarly, they prefer to increase the split ratio, which limits reach, for adding new ONUs. Among the options for how to extend reach, Raman amplification has been proposed, especially for the upstream traffic. In order to maintain the feeder network completely passive, a Raman pump can be placed at the OLT for providing distributed gain in the feeder fiber for the upstream signal, while a high-power signal source, EDFA or SOA, can be employed at the OLT for amplifying the downstream signal. Work presented in [22] demonstrated a GPON extension system of 60-km reach and 1:128 split ratio, employing Raman amplification.

Another important challenge is the design and development of high-speed, low-cost burst-mode receivers. As mentioned before, upstream packets from ONUs are asynchronous and may travel different distances before arriving at the OLT. Thus, they may enter the OLT with different optical power, as well as with different amplitude and phase noise. It is therefore essential that the OLT has a burst-mode receiver that can receive such optical burst signals and instantaneously amplify them to a fixed amplitude in the electrical domain. Furthermore, for backward compatibility issues, a burst-mode receiver must support more than one rate. For example, GEPON and 10G-EPON customers are both connected to the same OLT's burst-mode receiver. Therefore, the design of a reliable burst-mode receiver is challenging and requires high-sensitivity, a wide dynamic range, as well as short setting times in order to meet PON specifications. Of particular importance is the response time for clock and data recovery, which must be below 400 ns for GEPON and 10G-EPON.

Currently research focuses on developing 40G burst-mode receivers using discreet IC designs of broadband transimpedance and limited amplifiers (TIA/LA), as well as clock and data recovery CDR circuits.

9.9 Distributed Ring-Based WDM-PON Architecture

As previously described, traditional WDM-PON systems allocate a separate pair of dedicated upstream and downstream wavelength channels to each subscriber, enabling the delivery of a symmetric 1 Gbps or more of dedicated bandwidth per subscriber/ONU in each direction, with bit rate and protocol transparencies, guaranteed quality of service (QoS), and increased security. Despite these numerous crucial advantages, traditional tree-based WDM-PON architectures suffer from several inherent limitations that must be addressed first before WDM-PON evolves as the dominant NG broadband access infrastructure able to efficiently backhaul wireless traffic. These include (i) the inability to efficiently utilize limited available network resources and to cope with the dynamic and bursty traffic patterns of the emerging services [23, 24]. The former limitation is exacerbated when some wavelength channels are heavily loaded, while others are underutilized or are totally idle. Since bandwidth is dedicated on a point-to-point basis, there is no way to dynamically move capacity from a heavily loaded channel to another lightly loaded/idle channel, leading to the waste of scarce network resources. Therefore, to increase the total throughput, it is essential that future WDM-PON access architectures must support dynamic bandwidth allocation (DBA) and sharing; (ii) the inability to support a truly shared LAN capability among end users (end users attached to these PONs cannot directly communicate with each other, and thus the need for meshing of the eNBs as previously described cannot be accommodated). This LAN capability also provides the ability to support a distributed control architecture. Mainstream PON dynamic bandwidth allocation (DBA) schemes have been centralized, relying on a component at the distant OLT to arbitrate upstream transmission. In addition to the typical single point of failure problem, the centralized processes of upstream bandwidth allocation at the distant OLT are lengthy and complex and require many changes at each ONU.

Numerous WDM-PON architectures have been proposed in the literature to address the aforementioned limitations of traditional WDM-PONs [8, 9, 23–29]. To address the former problem, several WDM-PON architectures and protocols that dynamically manage and allocate bandwidth in both time and wavelength dimensions have been proposed [8, 9, 23–29]. Most of these schemes, however, are costly, require many redundant components, and assume complex OLT and ONUs setups, which require tunable transceivers, or an array of fixed transceivers, or both, WDM filters, and wavelength/waveband-selective receivers at both the OLT and ONUs. Furthermore, schemes that support dynamic wavelength sharing, where additional wavelength channels are added to accommodate the fraction of bursty downstream traffic that may exceed the user's dedicated downstream wavelength channel rate, are still falling short of addressing the fundamental problem of the inefficient utilization of network resources [23, 24]. This is because unused capacities of those lightly loaded, or even idle dedicated downstream wavelength channels are being wasted. Overall, each of these complex architectures has only targeted a single limitation and applied specific solutions and workarounds to traditional WDM-PONs, mostly resulting in increased cost and complexity.

The latter problem has received considerable attention due to the rising importance of supporting virtual private connections among end users (for instance, branch sites in a business enterprise). In this regard, several physical layer LAN emulation schemes have been proposed to achieve intercommunication among the ONUs, but only within the context of TDM-PONs. Fewer schemes have also been proposed to achieve intercommunication among the ONUs within a WDM-PON infrastructure. In addition to the added cost and complexity, most of these schemes, however, suffer from poor scalability due to high splitting losses as the redirected LAN signals traverse through the star coupler/AWG once or twice, resulting in lower power budget that limits the number of ONUs that can be attached to a single PON. In general, achieving intercommunication among subscribers within a tree-based WDM-PON setup is a lengthy and complex process that requires much more resources than those needed for a TDM-PON.

In this section, we examine a simple and cost-effective local access WDM-PON architecture that addresses some of the limitations of conventional tree-based WDM-PON architectures including supporting dynamic allocation of network resources as well as a truly shared LAN capability among end users. The proposed architecture combines the salient features of both traditional static WDM-PON (i.e., dedicated connectivity to all subscribers with bit rate and protocol transparencies, guaranteed QoS, and increased security) and dynamic WDM-PON (i.e., efficiently utilizing network resources via dynamic wavelength allocation/sharing among end users).

As 4G is a distributed architecture where, in particular, the 4G LTE standard requires a new distributed mobile backhaul radio access network (RAN) architecture and further creates a requirement for fully meshing the BSs (as previously mentioned the X2 interface for LTE BS-BS handoffs requires a more meshed architecture), a PON-based mobile backhaul RAN must be capable of supporting a distributed architecture as well as distributed network control and management (NCM) operations. The proposed architecture eloquently complies with both requirements via a purposely selected simple ring topology, which enables direct intercommunication/connectivity among the access nodes (ONUs/BSs), allowing for the support of a distributed PON-RAN access architecture as well as for simply meeting the stringent requirement to fully meshing the ONUs/BSs. Thus, the proposed ring-based architecture may provide a simple and cost-effective mobile backhaul RAN solution. Note that the proposed ring-based architecture can also be evolved to an all-packet-based converged fixed-mobile optical access networking transport infrastructure by simply interconnecting (overlaying) the ONUs with the 4G/5G BSs.

9.10 Architecture Design

Unlike a typical WDM metro access ring network, where the feeder fiber of a PON is replaced with a metro fiber ring that interconnects the hub and access nodes, the proposed architecture interconnects WDM ONUs via a short distribution fiber ring in the local loop but allows them to share the feeder fiber for long reach connectivity to the OLT (Fig. 9.8). Specifically, the OLT is connected to the ONUs via a 20-km trunk feeder fiber, a passive three-port optical circulator, and a small fiber ring. To cover the same local access area as in a similar tree-based architecture, the small ring at the end of the trunk is assumed to have a 1–4 km diameter. The ONUs are joined by point-to-point links in a closed loop around the access ring. The links are unidirectional: Both downstream and upstream signals (combined signal) are transmitted in one direction only. Each ONU is assigned a single dedicated

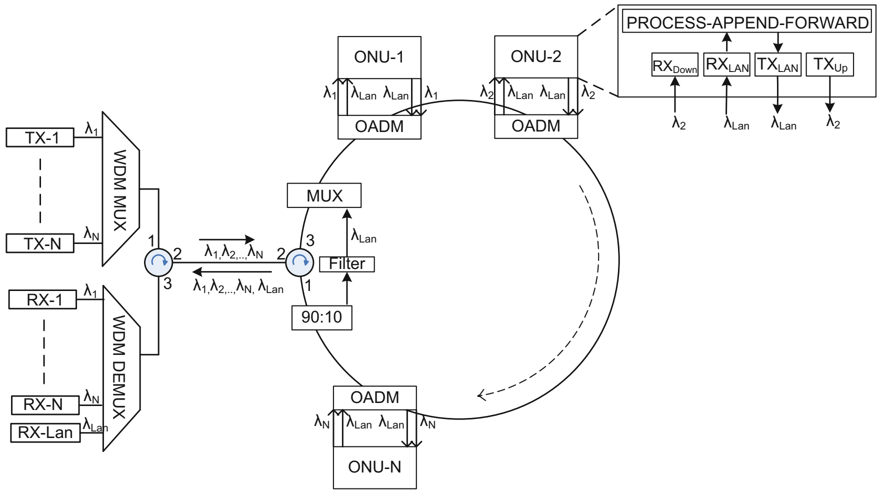

Fig. 9.8 Ring-based C/DWDM-PON architecture [32]

wavelength for both downstream and upstream transmissions. Direct intercommunication among ONUs is achieved via an additional local control/LAN wavelength channel, λ_{LAN}, which is terminated, regenerated, and retransmitted at each ONU [30, 31].

Downstream/upstream wavelengths as well as the LAN wavelength are spaced 200 GHz apart in the 1530–1565 nm standard C-band. For example, for an architecture supporting 16 ONUs, the total number of required wavelength channels would to be 17 (corresponding to 16 downstream/upstream wavelength channels plus an additional local control/LAN wavelength channel) and these channels could also be allocated over the 1270–1610 nm CWDM spectrum that can offer up to 18 available channels with 20-nm spacing, as defined in ITU TG.694.2. Thus, the overall system cost could potentially be reduced via the utilization of low-cost commercially available CWDM components. To scale beyond 16 ONUs, the number of downstream/upstream wavelength channels could be doubled or quadrupled by reducing the channel spacing in the C-band to 100 or 50-GHz, respectively (provided, of course, that the overall system power budget would still be satisfactory).

The OLT houses an array of N fixed transmitters (Tx) and another array of $N + 1$ fixed receivers (Rx), a passive three-port optical circulator, and a commercially available low-cost thin-film-based DWDM multiplexer/demultiplexer. Each Tx/Rx pair corresponds to one ONU and utilizes the same wavelength for transmitting and receiving downstream and upstream traffic, respectively. The extra receiver ($N + 1$) located at the OLT is used to detect the local control/LAN channel. Each ONU has a Tx/Rx pair which is matched to the corresponding pair at the OLT and another Tx/Rx pair for transmitting and receiving the local LAN channel, λ_{LAN}. In addition, each ONU houses a commercially available low-cost four-port thin film filters-based fixed optical add-drop multiplexer (OADM), where two wavelengths (corresponding downstream/upstream and LAN wavelengths) are dropped and added at each node.

The DWDM downstream signal is coupled to the ring via port 3 of the optical circulator. After recombining it with the re-circulated LAN signal via a 2×1 WDM combiner (placed on the ring directly after the optical circulator), the combined signal then circulates around the ring (ONU_1 through ONU_N) in a drop/add and go-through fashion. Finally, at the last node (ONU_N), wavelengths λ_N and λ_{LAN} are dropped/added. Thus, the DWDM downstream signal is terminated at the last node.

The combined DWDM upstream and LAN signals emerging from the last ONU at the end of the ring are split into two components via a (10:90) 1×2 passive splitter placed on the ring directly after the last ONU. The first component (90 %) is directed toward the OLT via circulator ports 1 and 2, while the second component (10 %) passes first through a band rejection filter that terminates the DWDM upstream signal. The second component emerging from the band rejection filter, the LAN signal, is allowed to re-circulate around the ring after recombining with the downstream signal (originating from the OLT) via the 2×1 WDM combiner (multiplexer). The first component of the combined DWDM upstream and LAN signal is received and processed by an array of $N + 1$ fixed optical receivers (housed at the OLT). Specifically, each one of the N upstream optical receivers detects the corresponding upstream signal and recovers the MAN/WAN traffic, while the LAN optical receiver, as will be explained below, processes the control messages and may discard or process the LAN traffic provided that, as will be shown below, it carries upstream traffic as well [32].

9.11 Allocation of Network Resources

The potential of this architecture is further explored below in terms of its capability to support distributed and dynamic allocation/sharing of overall network resources among the access nodes (ONUs). As previously mentioned, direct communication among ONUs is achieved via the LAN/control channel, which is terminated, processed, regenerated, and retransmitted at each ONU. Since control messages are processed and retransmitted at each node, the ONUs can directly communicate their LAN queue status and exchange signaling and control information with one another in a fully distributed fashion. The control plane utilized among the ONUs can thus support a distributed PON architecture, where each access node (ONU) deployed around the ring has now a truly physical connectivity and is capable of directly communicating with all other access nodes. Supported by the distributed control plane, each ONU can now independently provision both upstream and LAN traffic and can further collaborate with the OLT to dynamically provision downstream traffic as well.

9.11.1 Dynamic Bandwidth Allocation

The proposed scheme utilizes a fully distributed time division multiple access (TDMA) arbitration scheme in which the OLT is excluded from the arbitration process. This work utilizes the control and management messages defined by the IEEE 802.3ah multi-point control protocol (MPCP) standard that were previously described in Sect. 9.4.1. It further assumes a cycle-based LAN link, where the cycle size can be either fixed or variable length confined within certain lower and upper bounds to accommodate the dynamic LAN traffic conditions. During each LAN cycle, the ONUs transmit their control (REPORT) messages along with LAN data sequentially in an ascending order within their granted time slots around the ring from one node to the next, where each REPORT message is finally removed by the source ONU after making one trip around the ring. ONUs sequentially and independently run instances of the same LAN-DBA algorithm outputting identical bandwidth allocation results each cycle [33, 34]. The execution of the algorithm at each ONU starts immediately after the collection of all REPORT messages. Thus, all ONUs must execute the DBA algorithm prior to the expiration of the current cycle so that bandwidth allocations scheduled for the next cycle are guaranteed to be ready by the end of the current cycle. An execution of the DBA algorithm produces a unique and identical set of ONU assignments. Once the algorithm is executed, the ONUs sequentially and orderly transmit their data without any collisions, eliminating the OLT's centralized task of processing requests and generating grants for LAN bandwidth allocations. It is important to emphasize that maintaining accurate time synchronization between the ONUs is essential for the appropriate operation of the distributed DBA algorithm. In general, this is always the case, as all ONUs are synchronized to a common reference clock extracted from the OLT downstream traffic.

This architecture can also be utilized for implementing an efficient dynamic wavelength assignment/sharing strategy for upstream and downstream traffic (implemented jointly at both the OLT and ONUs).

9.11.2 Upstream Traffic Flows Rerouting and Sharing

Analogous to traditional WDM-PONs, each ONU in the proposed architecture is assigned a dedicated wavelength for upstream transmission. However, if the incoming user's bursty traffic flows exceed its dedicated upstream wavelength channel rate for some interval, the corresponding upstream queue becomes congested. In this case, the flow scheduler at that ONU may redirect one or more of the user's excess upstream service flows to the local LAN queue, provided that this LAN queue has some available space that can accommodate one or more of the upstream excess flows. More details on the proposed techniques can be found in [32].

9.12 Wavelength Assignment/Sharing for Downstream Traffic

Each OLT downstream queue is assigned to a specific ONU and is connected to a dedicated downstream wavelength. Each ONU houses two queues: One queue is assigned to a dedicated upstream wavelength, while the other queue is assigned to the LAN/control traffic. The process of dynamically assigning/sharing downstream wavelengths is implemented jointly at both the OLT and ONUs as follows: If a dedicated downstream wavelength channel, λ_i, with traffic destined to ONU_i is overloaded (i.e., incoming bursty traffic flows may exceed the dedicated channel rate for some interval, so that its corresponding queue is congested), the following steps are executed [31]: (i) The scheduler at the OLT searches for another underutilized/idle downstream wavelength channel, i.e., a channel λ_j whose corresponding queue has some available space that can accommodate one or more excess flows (i.e., Q_j). (ii) If the search is successful, the available channel is selected if and only if its corresponding LAN queue at the corresponding ONU (ONU_j) is also available. (iii) The scheduler redirects one, some, or all of the excess flows to Q_j, where it is then transmitted, along with ONU_j's native downstream traffic, to ONU_j over its dedicated wavelength channel λ_j. (iv) The λ_j-downstream optical receiver housed at ONU_j terminates all λ_j's downstream traffic, including both native downstream traffic destined to ONU_j and traffic destined to ONU_i. It examines the destination MAC address of each detected Ethernet frame and then performs the following two functions: (a) Native downstream traffic that matches ONU_j's MAC address is copied and delivered to end users; (b) traffic destined to ONU_i (whose MAC address does not match that of ONU_j) is redirected to ONU_j's LAN queue and then retransmitted, along with ONU_j's own local LAN traffic, as LAN traffic around the ring to its final destination (ONU_i), within the proper designated LAN timeslot of ONU_j.

Various resource allocation schemes that efficiently support dynamic and fair allocation of wavelengths and sharing traffic among PON end users have been developed for this architecture and can be found in [32, 35, 36]. Performance results on link throughput and delay as detailed in the aforementioned works demonstrate that the proposed methodologies can meet the capacity requirements of the dynamic and highly fluctuant traffic pattern of the emerging multimedia applications and services.

9.13 Fault Detection and Recovery

While the economics for commercially deploying WDM-PONs in the access arena for backhauling wireless traffic or as a converged fixed-mobile optical networking transport infrastructure are quite compelling, however, several key outstanding technical hurdles must be further addressed. The key stumbling block has been, and certainly remains to be, the inherent lack of simple and efficient resilience capabilities in mainstream tree-based PON topologies, which guarantee the reliable delivery of the massive amount of fixed-mobile traffic, specifically, against failures in the distribution network. Since a single-wavelength channel failure may affect the premium services delivered to thousands of fixed-mobile end users, the reliability offered by such an access networking transport infrastructure to the services and customers it supports is one of the most important considerations in designing and deploying such a PON-based converged architecture. Thus, given the unique advantages provided by the aforementioned ring-based WDM-PON architecture, it was also imperative to introduce efficient resilience mechanisms for such architecture.

Figure 9.9 illustrates the proposed fully distributed self-healing WDM-PON architecture. The solid lines (working fiber) represent the normal state architecture, while the dotted lines (protection fiber) represent the redundant protection components. The protected architecture is identical to that of the normal working architecture (as explained in Sect. 9.10) except for the following additional components (dotted lines): (i) a redundant short distribution fiber ring and a trunk fiber; (ii) two 2×1 optical switches located at the OLT; (iii) an automatic protection switching (APS) module located at each ONU.

The APS module attached to each ONU is the basic building block of the proposed self-healing mechanism that monitors the state of its adjacent distribution fiber paths and its own state and performs both fault detection and automatic switching process. The APS module connects to both incoming and outgoing working and protection fibers. Each APS module houses a commercially available low-loss 4×4 bidirectional optical switch (OS) that is capable of switching from any input port to any output port [37]. It also includes two detection circuits, where each circuit comprises a band splitter (to separate the combined downstream/upstream/LAN signal into its constituents LAN and downstream/upstream signals), control circuit to configure the OS, and a PIN

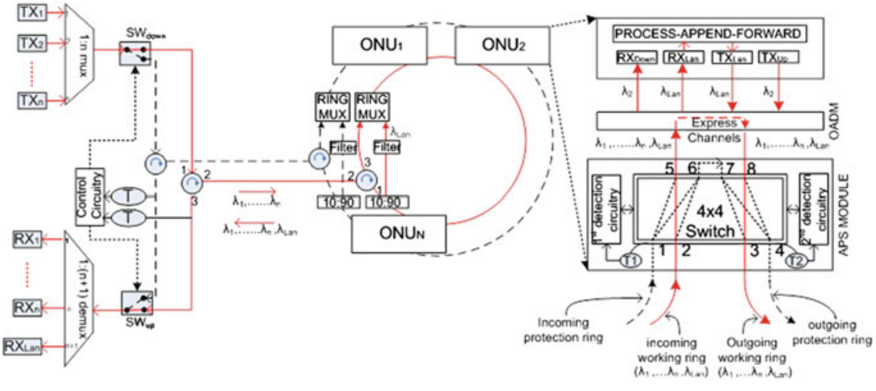

Fig. 9.9 Self-healing ring-based C/DWDM-PON architecture [38]

detector. Under normal operation, as shown in Fig. 9.9, the combined signal traverses the incoming and outgoing working fibers via ports 2–5 and 8–3, respectively.

9.13.1 Fault Detection

If a failure occurs in the network, the REPORT message transmitted by the affected ONU typically contains a failure indication alarm message that includes specific instructions to both the OLT and a remote node that will be involved in the recovery process. Since the LAN signal is always present on the ring and trunk (cyclic control message is always transmitted independent of the presence or absence of LAN data), general failure detection scenarios (general distribution link and node failures) will primarily be based on detecting the absence/presence of the LAN signal only. Thus, all ONUs are continuously monitoring the status of the LAN signal on both incoming and outgoing fibers. If, for example, the first control circuit of a given ONU_n detects the absence of the LAN signal on its incoming working fiber, a general distribution link failure is assumed. This is the link that interconnects ONU_{n-1} with ONU_n. On the other hand, if the first control circuit of a given ONU_n detects presence of the LAN signal on its incoming working fiber, while the second control circuit detects absence of same signal (after being processed, regenerated, and retransmitted by ONU_n) on its outgoing working fiber, a node (ONU_n) failure is assumed. While ONU_n detects its own failure (via an APS module attached to it), however, managing the failure is delegated to the next node on the ring (ONU_{n+1}). Complete details on the detection of all types of failures in this architecture can be found in [38].

9.13.2 Fault Recovery

In general, the recovery process is implemented via the participation of three cooperating network nodes including the affected node (ONU_n), OLT, and either ONU_{n-1} (in the case of a link failure) or ONU_{n+1}(in the case of a node failure). As an example below the general link failure recovery is described. A detailed description of all failure recovery mechanisms for any other type of failure can be found in [38]. These protection schemes are capable of protecting against both node and distribution/trunk fiber failures, and they enable the recovery of all network traffic including upstream, downstream, and LAN data. In addition, these schemes can also protect against any combination of concurrent double failures including trunk/distribution fiber breaks and node failures.

General Link Recovery: The successful completion of the recovery process of a given general link failure scenario involves the following steps: (i) To avoid false failure detection, once the affected node (for instance ONU_n) detects a given link failure (e.g., fiber cut), it must wait for a predetermined timeout. (ii) ONU_n then stops both LAN and upstream transmissions, switches to the incoming protection fiber, and floods the network with a failure indication alarm message (first REPORT message) that includes specific instructions to ONU_{n-1}(to switch its transmission from outgoing working fiber to outgoing protection fiber), each and every other ONU (to stop both LAN and upstream transmissions), and OLT (to stop downstream transmission). (iii) ONU_n keeps flooding the network with the failure message expecting its failure frame to loop back to it via ONU_{n-1}'s outgoing protection fiber. (iv) Upon receiving the failure message, each and every ONU on the ring stops LAN and upstream transmissions; likewise, OLT stops downstream transmission. (v) Once ONU_n receives back its failure frame (assuming ONU_{n-1} has already switched to the outgoing protection fiber), it starts flooding the OLT with a second REPORT message requesting downstream resynchronization frames. (vi) Once the OLT receives a resynchronization request from ONU_n, it resumes all downstream transmissions. (vii) Once ONU_n receives resynchronization frames from the OLT, it initiates a new cycle (recovery process is now complete) by transmitting its normal REPORT control message to all other ONUs. Then, all ONUs sequentially send their REPORTs; once all reports are exchanged for LAN-DBA calculation of the new cycle, new grants are calculated and normal operation resumes.

Performance results as illustrated in [38] demonstrate that the recovery time associated with any and all different distribution network/trunk failures is still within the delay bound limit required for delivering guaranteed triple play services.

9.14 Fronthauling Mobile Traffic

As previously explained in various other chapters of this book, to increase efficiency in LTE and LTE-Advanced systems, an important feature is the distributed radio access network (RAN) architecture that includes remote radio heads (RRHs) (comprising of the radio, amplification, filtering, and the antenna) connected to the baseband unit (BBU) (utilized for the centralized signal processing functions) using the Common Public Radio Interface (CPRI) standard (a digital interface standard for encapsulating radio samples between a radio and a BBU). This CPRI traffic must be fronthauled efficiently, following tight quality constraints (in terms of maximum latency, jitter, and bit error rate) between the RRH and BBU locations. It should be noted here that CPRI requires significantly higher data transmission rates than the payload it is carrying (fronthaul carries uncompressed digital data—the digitally sampled analog radio signal with error correction and encapsulation on top).

There are several options for CPRI fronthaul, including utilizing dedicated fiber links (albeit a costly solution), the OTN (that can potentially add latency into the system), microwave links (only for short distances and a subset of the CPRI bit rate options), as well as PONs. In general, fiber connections are the best choice for this applications, partly because of the long reach and capacity that they can provide, and partly because of their characteristics (weight, ice loading, wind resistance, etc.) that make them ideal for running up the tower.

Fronthauling mobile traffic utilizing PONs is a potentially attractive solution for CPRI transport as the data-rate requirement of CPRI matches the development of PON technologies. Further, the stringent delay requirements of the CPRI protocol are also well supported by using PONs, as the only source of transport-incurred latency is due to signal propagation (allowing the maximization of the distance between the RRH and BBU). Nevertheless, if PONs are utilized to fronthaul mobile traffic, careful engineering is required to accommodate for the power loss budget and prevent additional latency being incurred which would limit the cell radius.

Further, looking at the PON technologies and standards described previously in this chapter, NG-PON2 can easily support the required fronthaul speeds and distances; however, for the TWDM-PON implementation of NG-PON2 it could potentially be very challenging to meet the strict latency and jitter requirements imposed. Other potential techniques to implement fronthaul utilizing PONs include dedicating one of the wavelengths in the TWDM-PON implementation of NG-PON2 for fronthauling mobile traffic or utilizing a WDM-PON (that has a large number of available dedicated 1G/10G wavelengths). There are a number of recent research efforts on utilizing WDM-PONs for mobile fronthauling, including the 5G-XHaul initiative, a project that is part of the EU Horizon 2020 5G Infrastructure Public-Private Partnership (5G PPP).

Finally, the reader should note that as the choice of technology for mobile fronthauling is still an open issue, the Full Service Access Network (FSAN) forum has set up a Mobile Fronthaul Study Group to collect mobile fronthaul requirements from operators, evaluate possible solutions, and present recommendations on the technology best suited to be used for mobile fronthauling.

9.15 Conclusions

This chapter motivates the need for utilizing fiber-based passive optical network (PON) access infrastructure to backhaul mobile traffic and subsequently describes the various standards and technology options for this type of networks. It also describes a novel, fully distributed, ring-based WDM-PON architecture that could be utilized for backhauling wireless traffic, as well as supporting a converged next-generation mobile infrastructure. This architecture can support dynamic allocation of network resources as well as a truly shared LAN capability among end users, combining the salient features of both traditional static and dynamic WDM-PON. Efficient distributed QoS-aware resource allocation schemes were developed for this architecture, guaranteeing the delivery of delay and jitter-sensitive real-time applications. The ring architecture design also provides simple and cost-effective resilience capabilities against any and all kinds of networking failures, enabling the recovery of all network traffic including upstream, downstream, and LAN data.

Finally, as in 4G and 5G the radio access network (RAN) becomes a broad concept that also includes mobile fronthaul, a discussion is also added at the end of this chapter on mobile fronthaul utilizing PON infrastructures.

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