Chapter 2

Passive optical networks

This chapter starts by introducing PON topologies and standards with particular emphasis on their deployment characteristics in developing access network architectures. Following the evolution of access networks in synchronism with online services, potential solutions for further developing the existing PON standards are reviewed, including increased speed and fibre-span TDM PONs as well as densely penetrated PONs by means of applying dense wavelength division multiplexing (DWDM). Finally, the techno-economical aspects of these developments are discussed and intermediate solutions are presented employing hybrid schemes and coarse WDM (CWDM).

2.1 Passive optical networks topologies and standards

PONs are promising candidates for developing broadband access networks due to their simplicity of implementation and low OPEX [1, 2]. As shown in Figure 2-1, there are a number of possible PON topologies appropriate for the access network [3] including tree, bus and ring configurations. Data transmissions in a PON are carried out between an OLT and ONUs [3], with the former located in the central office, connecting the access network with the metro backbone and the later at either a street cabinet in FTTC architectures, or at the customer premises in FTTH and fibre-to-the-building (FTTB) architectures. The ONUs are connected to the OLT by means of a feeder fibre through passive components in order to be maintained and managed economically [1, 2].

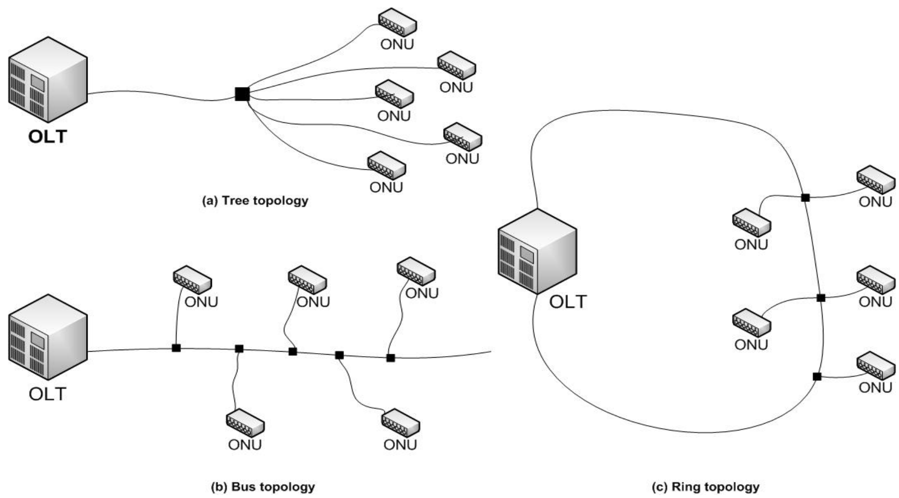

Figure 2-1 PON topologies

Among the various PON topologies the tree infrastructure is mostly deployed as it allows maximum network coverage with minimum splits, consequently reducing optical power loss to avoid the use of amplifiers along the optical link [1]. In downstream, signals communicated from the OLT reach the passive optical splitter and broadcasted to all ONUs in the PON. Although all ONUs receive all downstream data, due to broadcasting, secure channels are established to ensure that each ONU only recovers the data intended for itself [4]. In upstream, as shown in Figure 2-2, the splitter combines all ONU packets in a TDM fashion to avoid collisions in the feeder fibre. Consequently, each ONU has to restrict its transmission only to predefined time-slots administrated by a mandatory access control (MAC) protocol, which can statically or dynamically allocate time-slots among ONUs [4].

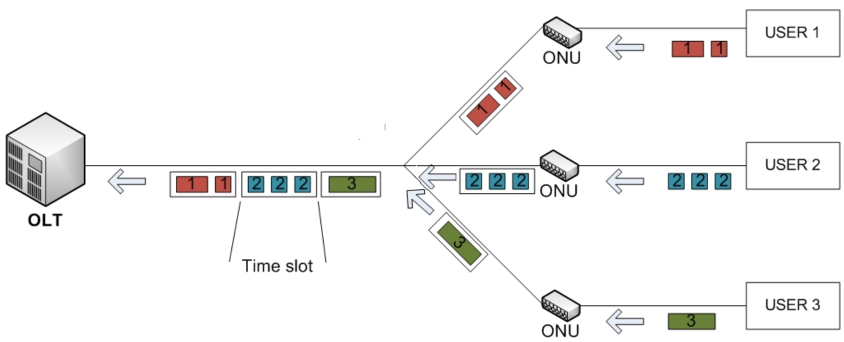

Figure 2-2 Upstream traffic in a TDM-PON

The TDM-PON based tree topology allows for the implementation of typical fibre distances of 20 km between the OLT and ONUs, delivering high bandwidth with considerably less OPEX and CAPEX [5] and also saving in the amount of optical fibre installed [2]. In addition, since downstream transmission is broadcasted, video broadcasting at either analogue or Internet protocol (IP) can be demonstrated using a separate wavelength overlay. Finally, being optically transparent end to end, due to the agnostic nature of the passive splitter, it allows a smooth upgrade to higher data rates and additional wavelengths [6].

TDM-PON standards include the existing EPON [7] and GPON [8-11], the outcome of two different groups of equipment vendors and network operators. EPON was developed and formalised in the IEEE 802.3ah standard [7] to bring Ethernet to residential and business customers in the access network [3] and has been adopted rapidly, primarily due to its ubiquitous and cost-effective technology, allowing for interoperability with a variety of legacy equipment [3, 6]. EPON is capable of providing triple-play services [2] at symmetrical 1.25 Gbit/s data rates using wavelengths at 1490 nm and 1310 nm for downstream and upstream transmissions respectively, with a wavelength at 1550 nm reserved for future extensions or additional services such as analogue video broadcast for a maximum of 32 ONUs at distances of up to 20 km [1, 6, 9]. In upstream, a typical MAC protocol is used, avoiding data collisions in the distribution network. In order to extend the capacity limitation of EPON by means of data rates and splitting ratio, the ITU-T has set standards for the GPON in the G.984 series [8-11].

The GPON is set to accommodate full services and support Gigabit bandwidth for subscribers in the access network. It emerged to remove the bandwidth bottleneck in the first mile [12-14] offering technical advantages over EPON due to higher splitting ratio, data rates and bandwidth efficiency [15]. GPON provides triple-play services at variable bidirectional data rates of up to

2.5 Gbit/s compared to a single data rate of 1.25 Gbit/s in EPON using similar wavelength assignment, allowing network operators to configure transmission rates according to user requirements. Unlike EPON, GPON supports a maximum of 128 ONUs for distances of up to 60 km [8, 15] as well as offering almost double bandwidth efficiency due to less data transmission overheads. To address security issues in downstream, GPON provides an advanced encryption standard [13]. The encryption key associated with each ONU can be sent in the secured upstream data since individual ONUs cannot have access to upstream transmissions of others.

2.2 Next generation access networks

To provide even higher bandwidth, greater coverage and penetration than EPON and GPON, with the aim to support new bandwidth-hungry online services, and to further reduce the cost for delivering existing services, next-generation PONs (NG-PONs) studies have considered several architectural approaches. As shown in Figure 2-3, one approach would be to further increase the speed and reach/split of the existing PON standards, offering economical bandwidth and service upgrade, allowing merging of the access and core networks to grant cost savings for network operators. To that extent, burst-mode transceivers at 10 Gbit/s are under development [16, 17] and long-reach network architectures are investigated [18]. A second approach suggests to employ greater number of wavelengths to allow new services to be transmitted in order to increase network throughput and the number of media-rich services on a shared access network infrastructure [19]. Also, to ensure flexibility and smooth migration compatibility [20] between TDM and next generation densely penetrated PONs. In that direction the ITU-T has recently defined extended bands reserved for extra services to be overlaid via WDM [21]. Another WDM scenario is to assign a single wavelength to each subscriber in a PON to provide virtual point to point links between the OLT and each subscriber, offering dedicated bandwidth, greater security and protocol transparency [22, 23].

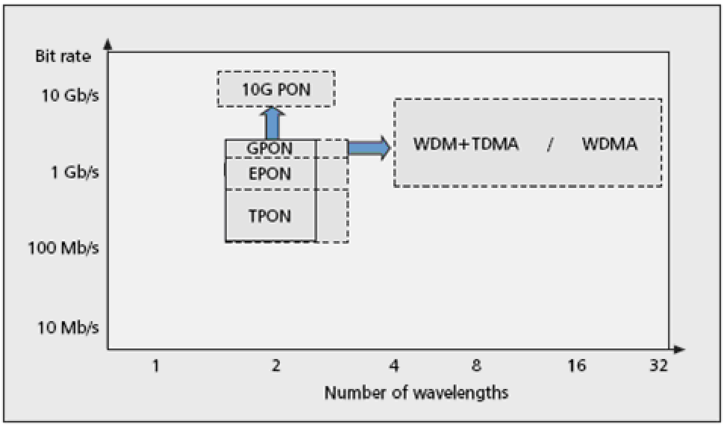

Figure 2-3 Different approaches for next-generation optical access networks [15]

2.2.1 10 Gb/s and long reach TDM PONs

To standardise a symmetrical 10 Gbit/s TDM-PON, a task group has been formed by IEEE [24] and FSAN [25], particularly aiming to achieve cost-effective 10 Gbit/s in the upstream for distances of at least 20 km where chromatic dispersion may become significant over the standard single mode fibre (SSMF) [26]. To allow a smooth upgrade on the standard deployed PONs, a minimum 20 km reach and 1:32 splitting ratio must be supported. For cost purposes PONs eliminate the use of expensive optical components in the ONU, instead they employ higher-performance costly components in the OLT that are shared in cost among all subscribers. Applying these considerations onto the standard PON physical parameters will require the use of signal processing such as forward error correction and optical amplifiers [26]. In addition, the bursty nature of the upstream transmission in a PON will require the development of cost-effective 10 Gbit/s burst-mode transmitters in the ONUs and burst-mode receivers in the OLT.

Extending the physical reach and split of PONs to distances of at least 100 km has recently received much attention [18, 27], offering reduction in the number of deployed central offices managed by the network operator resulting in direct connection of access to core networks [26], in the form of either a tree [18] or ring [27], which in turn leads to large reduction in cost [28]. This solution allows large number of customers, e.g. 8192 [29], located beyond the reach of a standard PON, usually placed in more rural and low-density serving areas, to be connected with a single distant central office by placing low-powered optical amplifiers at intermediate locations, normally 90 km from the central office [18].

Finally, since NG-PONs may employ different or additional wavelengths to traditional PONs, wavelength blocking filters, to be supported by traditional ONUs, are under definition to ensure that next generation and traditional ONUs can operate concurrently in the same PON [30].

2.2.2 WDM-PONs

WDM-PONs have been also extensively researched as a viable solution for next-generation access networks. Different implementations have been reported [22, 31-34], all based on a passive wavelength router in the distribution network utilised to provide each ONU with a dedicated and permanent wavelength, requiring as a result, dedicated transceivers in the OLT to form logical point to point connections to each individual ONU, as shown in Figure 2-4. The passive wavelength router, located in the remote node (RN), is realised by an array waveguide grating (AWG) or set of thin film filters (TFFs), with the advantage of employing the former since it can operate over multiple free spectral ranges (FSRs), allowing for the same device to employ different wavelength bands for downstream and upstream using its reciprocal nature [33]. In addition, AWGs have an optical loss of approximately 5 dB, independent of channel count, being 12 dB less than a typical 1:32 splitter used in standard PONs [8, 35], potentially allowing low-cost WDM sources to be used.

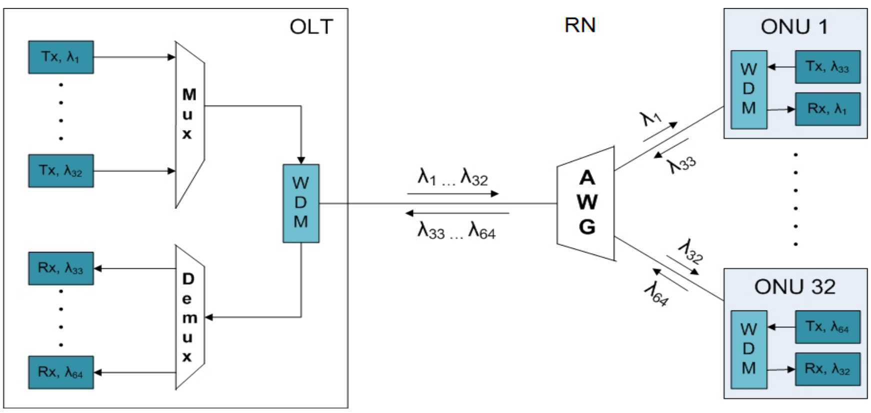

Figure 2-4 Typical logical point to point WDM-PON architecture

Recently reported WDM-PON architectures have focused on a common aim to eliminate the laser source in the customer equipment by establishing a wavelength independent ONU, also known as a colourless ONU. This allows for a universal customer equipment to be used everywhere in the PON and as a result to provide significant reduction in maintenance and cost [6] associated with DWDM devices and deployment of densely penetrated PONs.

At first, a logical point to point architecture supporting 32 ONUs at 155 Mbit/s each for distances of 20 km [22] has been reported and commercialised [2]. As shown in Figure 2-5, it is based on wavelength-locked Febry-Perot (FP) lasers, employing injection of spectrally sliced amplified spontaneous emission (ASE) noise. In upstream, a C-band broadband light source (BLS), generated by an Erbium-doped fibre amplifier (EDFA) in the OLT, is transmitted via a feeder fibre and subsequently spectrally sliced by the AWG in the RN into multiple narrow bands, each of which is injected into identical FP lasers in different ONUs, directing them to operate on a single and dedicated wavelength. In each ONU, the FP laser is modulated to demonstrate upstream transmission and via the feeder fibre and the RN transmitted to the OLT where a demultiplexer communicates the optical signals to the designated receivers. In downstream, another BLS for the L-band is spectrally sliced by the AWG in the OLT, subsequently injected to the FP lasers and modulated to demonstrate downstream transmission following the exact path as upstream, consequently terminated at the optical receivers in the ONUs [22]. Despite the use of low-cost transceivers in both the ONUs and OLT in a densely penetrated PON architecture, the use of the BLS in conjunction with FP lasers limits the architecture to achieve higher transmission rates and distances due to the conversion of excess intensity noise from the seed broadband light to the FP lasers [36].

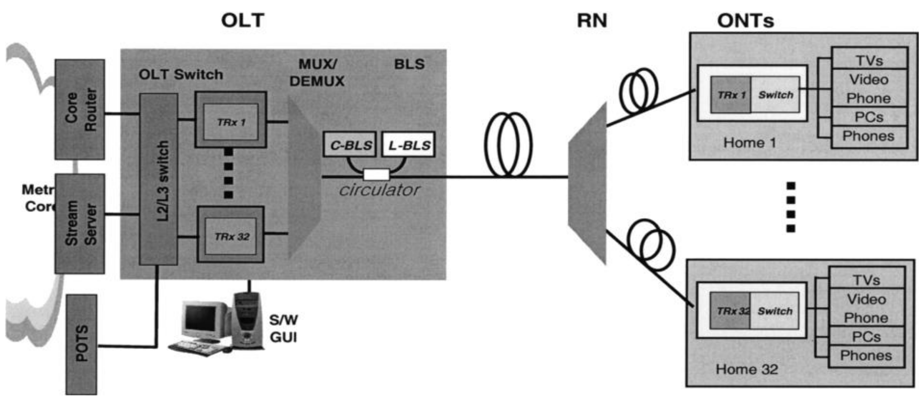

Figure 2-5 WDM-PON architecture based on ASE-injected FP lasers [22]

To that extent, scaling up the number of users will require the use of power-splitting in each distribution fibre, consequently, all ONUs connected to corresponding fibre will have to time-share the limited bandwidth of 155 Mbit/s. A more costly alternative can be obtained by replacing the AWGs in both the RN and OLT with a finer wavelength spacing and increasing the number of transceivers in the OLT.

In a different approach [37, 38], as shown in Figure 2-6, self-seeded reflective semiconductor optical amplifiers (RSOAs) are employed as colourless ONUs by exploiting the broadband ASE noise emitted from each RSOA in conjunction with an AWG and a wide band-pass filter (BPF) in the RN, avoiding the need for decentralised broadband sources [22]. Downstream and upstream wavelength signals are divided into adjacent FSRs of the AWG, subsequently combined and separated by WDM filters in the OLT and ONUs [38]. The BPF in the RN utilises a wide passband similar to a single FSR of the AWG and is centred on the FSR band employed for upstream transmission. In upstream, the broadband ASE spectrum emitted by the RSOA is spectrally sliced by the AWG, while the BPF ensures that, due to multiple FSRs of the AWG, only one spectrally sliced light per output port passes through and reflected back to the RSOA for self-seeding, subsequently modulated at 1.25 Gbit/s to demonstrate upstream transmission via a 20 km SSMF to the OLT [38]. Nevertheless, the broad transmitted spectrum of the upstream signals in the architecture induces increased ASE noise, allowing for limited transmission distances and rates due to chromatic dispersion [36].

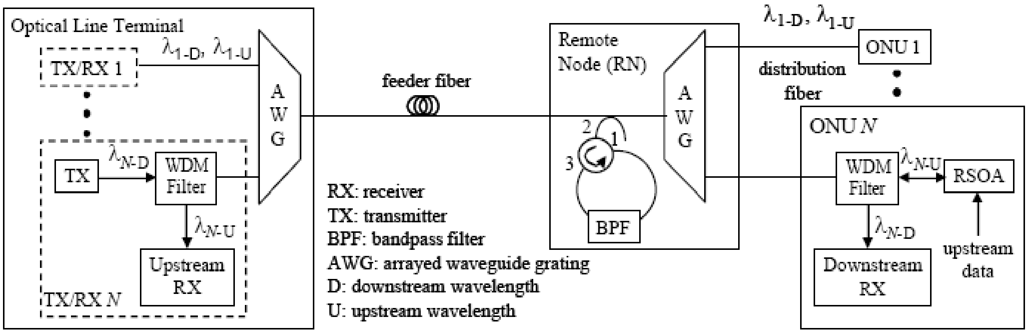

Figure 2-6 WDM-PON with directly modulated self-seeding RSOA [37, 38]

As a result, a recent work [36] proposed a WDM-PON architecture employing FP lasers in the OLT and ONUs, injection-locked by continuous wave (CW) signals to allow lower ASE noise. The architecture not only avoids the use of amplifiers and external modulators in the ONUs, but also employs CW signal sources in the central office that are shared by multiple PONs, consequently reducing the cost of both the ONUs and central office significantly [36]. In similar schemes [31, 39] an optical carrier supply unit in the OLT sends its CW signals to RSOA-based ONUs employed to demonstrate upstream transmission by remodulating each CW at 1.25 Gbit/s. The injection lasers from the optical carrier supply unit in the OLT can be also distributed for several WDM-PONs allowing to share the cost of this unit [39].

Although ASE noise does not impose limitation in these schemes [31, 36, 39], they often suffer from crosstalk associated with Rayleigh backscattering [40] and Brillouin backscattering [41], consequently limiting the supported link budget, regardless of data rate.

As a part of the effort to increase transmission data rate per wavelength and to eliminate additional light sources such as BLSs and carrier supply units, consequently to achieve simpler architectures, additional remodulation schemes have been reported [42-44]. Figure 2-7 displays a bidirectional WDM-PON architecture based on gain-saturated RSOAs in the ONUs [43] operating at 2.5 Gbit/s downstream and 1.25 Gbit/s upstream. The downstream signals are generated by directly modulating single-mode lasers (SMLs).

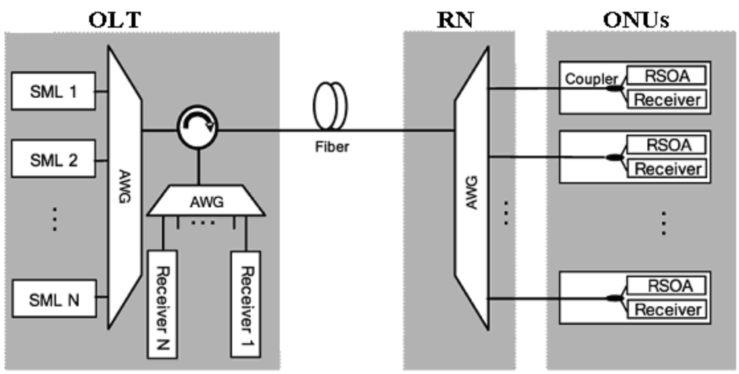

Figure 2-7 Bidirectional WDM-PON Based on gain-saturated RSOAs [43]

Once inside individual ONUs, each downstream signal is injected into an RSOA, operating in gain-saturation regime, consequently compressed, i.e. "erased", and subsequently directly remodulated to demonstrate upstream transmission [43]. The main source of impairment in the architecture though may be an imperfect "erase" operation, as it depends strongly on the amount of residue from the downstream part that is proportional to the extinction ratio of the downstream signal [45].

Similarly, a bidirectional WDM-PON architecture utilises the modulated downstream signal for upstream transmission, by remodulating it with a higher extinction ratio by the RSOA in the ONU at 1.25 Gbit/s [44]. Consequently, the downstream signal is not "erased", instead, the decision threshold of each OLT receiver is adapted in order to select the upstream data [44]. Yet, the residual downstream component included in the upstream signal degrades the upstream transmission of individual ONUs and as a result reducing the total fibre length to below a typical of 20 km. Alternatively, to allow using a typical fibre length, a dual feeder fibre must be used for upstream and downstream independently.

2.2.3 Hybrid TDM/WDM-PON architectures

The economic model for a densely penetrated PON deployment in the access, as presented in the architectures analysed in the previous section, has not been justified yet, mainly due to the high cost of components in the ONU and OLT [46]. Consequently, research efforts have been concentrated in providing enhanced PON architectures combining the merits of time and wavelength multiplexing achieving data rates up to 1.25 Gbit/s per wavelength [32]. These hybrid architectures [32, 34, 47] have the ability to serve increased number of customers by assigning more customers on each wavelength, and to share OLT resources among greater number of PONs, consequently increasing cost efficiencies and revenue from invested resources. At the same time they allow minimum modification in the ONUs and outside plant when upgrading to densely penetrated PONs.

An early proposition for realising a hybrid TDM and WDM architecture is known as SUCCESS-DWA [34]. The scalability of the architecture, shown in Figure 2-8, allows for smooth network upgrade since all routing components such as DWDM AWGs and filters are placed in the OLT and ONUs. This is achieved while the existing field-deployed PONs remain intact [34]. In its initial deployment the network employs a single tunable laser (TL) and a single AWG in the OLT to serve dynamically multiple subscribers across several PONs. When demand grows, more TLs alongside with additional AWGs can be employed as shown by the dotted areas in Figure 2-8. Upstream bandwidth is still shared on a TDM basis though, as the ratio between the number of wavelengths and ONUs in a PON is relatively low and hence end-user practical bandwidth depends critically on network utilisation. In addition, since each ONU employs a dedicated optical filter, the network scalability to increase the number of ONUs in a PON is poor as it requires reconfiguring all ONUs of that PON.

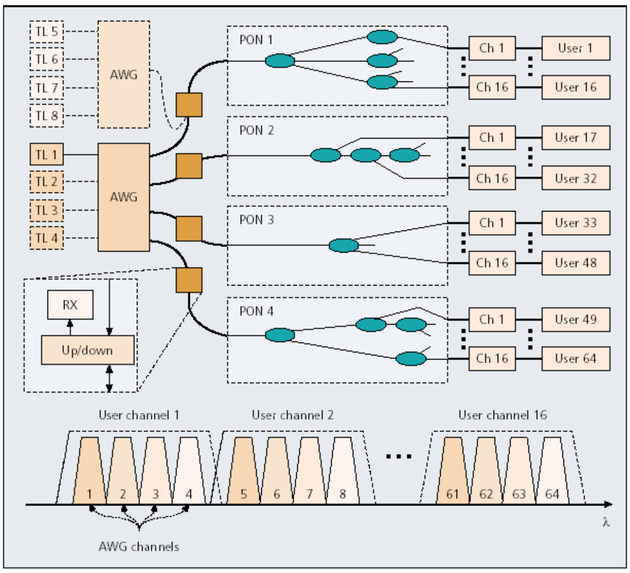

Figure 2-8 Success-DWA network architecture [34]

More recently, a hybrid network architecture was reported [32], exploiting the benefit of power splitting in TDM-PONs and wavelength routing in WDM-PONs, simultaneously realising low cost for each subscriber while maintaining a relatively high bandwidth and scalability for increasing subscribers number. The network architecture [32], displayed in Figure 2-9, demonstrates a hybrid WDM/TDM-PON to serve 128 subscribers at data rates of 1.25 Gbit/s downstream and 622 Mbit/s upstream. It employs 16 DWDM wavelengths, each of which is shared by eight subscribers on a TDM basis. The network operation is similar to the WDM-PON architecture based on ASE-injected FP lasers [22], shown in Figure 2-5, and as a result it is imposed to similar limitations.

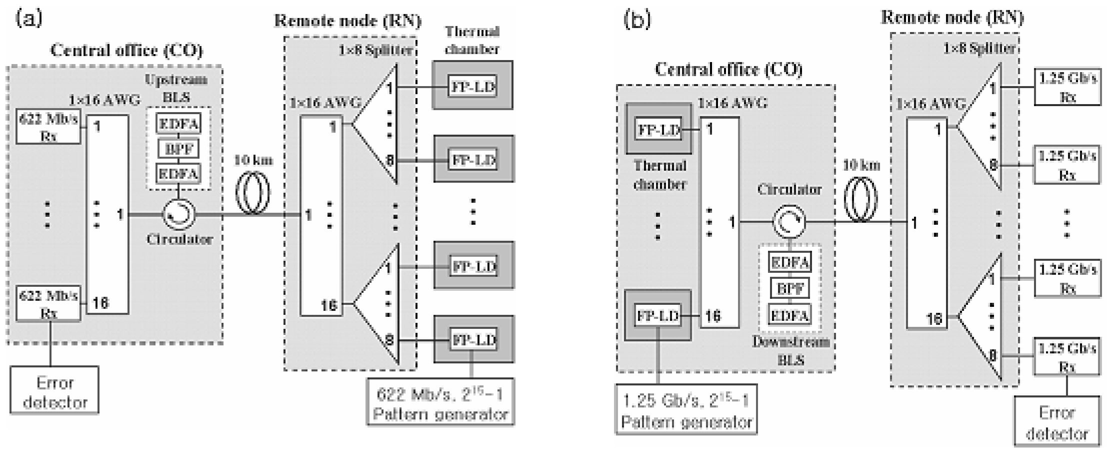

Figure 2-9 WDM/TDM-PON with wavelength-selection-free transmitters (a) upstream (b) downstream [32]

In another approach, a network architecture was proposed [47] to demonstrate a compromise between TDM and WDM-PONs in terms of capacity and cost, while offering centralised management of bandwidth allocation in the OLT, serving all colourless ONUs at data rates of 2.5 Gbit/s for distances of 30 km [47]. As shown in Figure 2-10, the network architecture is based on two cascaded DWDM AWGs interconnecting the optical transmission equipment in the OLT with N×M ONUs using N wavelengths over multiple FSRs of the M×M AWG.

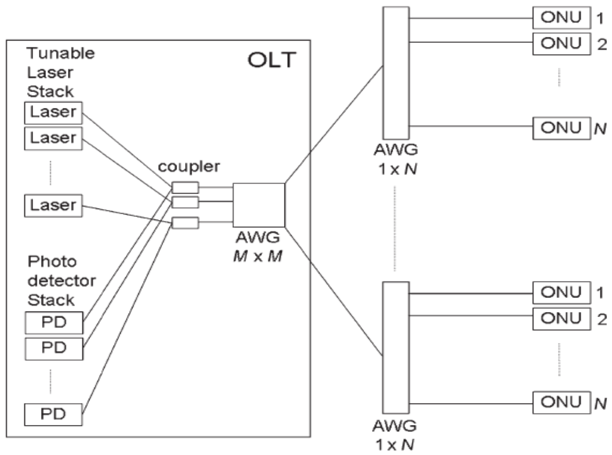

Figure 2-10 WDM/TDM-PON using cascaded AWGs [47]

In the OLT, a tunable laser stack is employed for unicast transmission, allowing dynamic bandwidth allocation since time-slots can be dynamically assigned depending on transmission requirements. The architecture shares each laser by a factor of N on a TDM basis, offering cost sharing of the OLT among all users [47]. Yet, in its initial deployment, for which the number of scattered ONUs is relatively low, the network still requires to deploy all lasers in order to be able to access ONUs connected to any 1×N AWG ports, and as a result the relative cost of OLT resources in the short-term to the number of ONUs may be higher than in the case of fully populated PONs.

2.2.4 Coarse WDM-PONs

In a search for another potential low-cost solution for a flexible high-speed optical access network architecture, CWDM has been investigated. CWDM has the potential to be a cost-effective technology for developing optical access networks [46], particularly in low channel count, and as a result it has already been brought from concept to commercialisation [48] in a short period of time. The CWDM wavelength plan utilises 18 channels, 20 nm spaced [49], allowing for CWDM devices [50] to utilise at least 7 nm-wide passband window around each of the coarse channels. Such broad channels relax the tolerances for thermal management [26] and optical loss requirements, allowing for reduced network complexity and flexible network power budget management respectively.

In an earlier European project [51] the concept of CWDM fibre rings has been evaluated, covering an access domain and providing large bandwidth in a flexible way and at reasonable cost. The basic access network architecture [52], shown in Figure 2-11, consists of a ring structured feeder and distribution areas [52]. The feeder part covers an area between the CO and several RNs for passive signal distribution and aggregation of wavelengths, while the distribution part connects the subscribers to the feeder ring. In the feeder part, a 20 km bidirectional dual-fibre CWDM ring enables the transmission of up to 18 CWDM channels [49] each of which provides data rate of 2.67 Gbit/s to support a total of 1800 customers, each at average data rate of 100 Mbit/s [51]. The hub in the OLT processes the entire traffic in the access network and acts as gateway towards the metro backbone. At the RNs, passive optical add-drop multiplexers (OADMs) drop a given channel downstream onto the distribution ring and add the same channel upstream onto the feeder ring. In each distribution ring, customers share the bandwidth of the same channel using different access technologies.

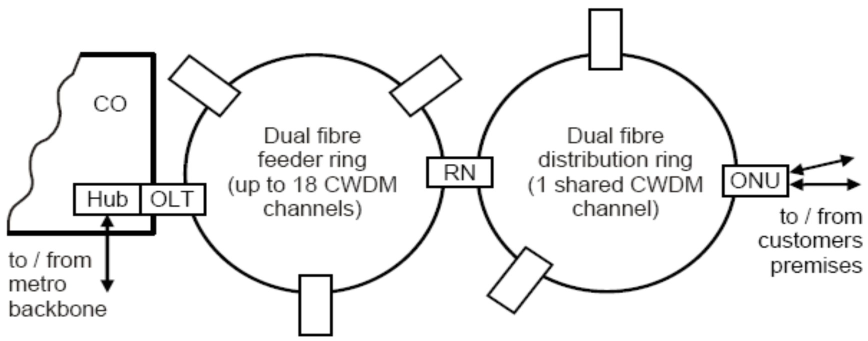

Figure 2-11 A ring based CWDM access network [52]

Using similar philosophy, a different research group has been focusing on a network architecture [53] achieving a flexible migration path from current TDM to future WDM-PONs. The architecture utilises a single-fibre collector ring with RNs attached to it, providing a point to point WDM connection between the OLT and each RN to serve standard TDM-PONs. In each RN, a pair of CWDM band splitters is used to add and drop wavelengths for upstream and downstream transmissions respectively. When increased number of customers in a PON demands higher bandwidth for future broadband applications, DWDM multiplexers can be inserted in the RNs to provide a dedicated DWDM channel between each customer and the OLT [53]. Thus, CWDM has the potential to become a viable technology for a near-future upgrade, while DWDM deployment can be expected in a later stage of network evolution [46].

Access networks based on a ring topology required an increased number of network head-end locations corresponding to the number of PONs, in contrast to most deployed PON architectures, based on a tree topology allowing maximum coverage with minimum network splits to avoid the use of amplifiers in network head-end locations [1]. Consequently, such architectures lack in potential to support the increasing demand for long-reach solutions that aim to consolidate network remote nodes to allow direct connectivity of the access network with the backbone network.

2.3 Summary

This chapter offered a revision of the characteristics of PON standards and their benefits in developing current and future access networks. Yet, to remove the bottleneck in today's access networks in terms of bandwidth utilisation, reach and penetration and consequently welcome upcoming bandwidth-demanding online services while keeping cost low, a number of research directions for developing next-generation PONs were presented.

The reported solutions focused on three major research paths. Increasing the speed and reach/split of the existing PON standards to 10 Gbit/s and beyond, engineered over distances of at least 100 km and servicing thousands of customers, employing higher number of wavelengths in a PON to allow both improved network throughput and greater number of media-rich services and also to ensure compatibility with next-generation access networks. Finally, to adapt the costly densely penetrated PON scenario to provide greater security and dedicated bandwidth for each customer.

Until the costs for deploying densely penetrated PONs are justified, CWDM has been also proposed as a promising cost-effective solution to provide flexibly multiple wavelengths in a PON. Although CWDM has been employed mainly in ring topologies connecting several physical PON locations in a metro/access configuration, it has not been used as an access routing mechanism to serve different PON technologies connected in a form of a tree topology. Its potential to inter-operate with DWDM could offer network transparency, scalability and smooth migration to future access networks by means of implementing decentralised routing to serve concurrently growing number of standard and densely penetrated PONs in a single infrastructure. The research questions and solutions associated with the application of coarse routing to integrate currently deployed and WDM-PONs have been the study of this thesis and will be presented extensively in the chapters to follow.

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