Multi-wavelength optical access networks: architectures and enabling technologies

Calvin C. K. Chan and Chinlon Lin
Centre for Advanced Research in Photonics, Department of Information Engineering
The Chinese University of Hong Kong, Shatin, N.T., HONG KONG SAR.

ABSTRACT

In this paper, we will discuss the network architectures and the enabling technologies to realize a robust multi-wavelength optical access network. Various network topologies employing the dense WDM or coarse WDM technique; as well as several network enabling technologies such as data re-modulation technique, fiber link protection and traffic restoration, etc. will be described. Besides, some future trends and applications of multi-wavelength optical access networks will also be discussed.

Keywords: optical networks, WDM

1. INTRODUCTION

The recent availability of low cost optical components has triggered the deployment of optical access networks to further deliver broadband data services to the subscribers. Conventional optical access networks employ a tree topology that the optical line terminal (OLT) or the central office delivers services via a long fiber feeder; and the optical power is then split at the remote node (RN) to reach many optical network units (ONUs). A single wavelength is employed from the OLT for the carrying the downstream traffic, mainly for service distribution, while a relatively lower bit rate upstream wavelength may also be employed to carry the requests from the subscribers back to the OLT. However, both the upstream and the downstream bandwidths have to be time-shared among all ONUs. With the enormous bandwidth offered by optical fibers, we can apply wavelength division multiplexing (WDM) technique such that each ONU will be served by a dedicated set of wavelength channels to communicate with the OLT. The ranging problem in conventional time-shared optical access networks can also be eliminated since all upstream wavelengths will be multiplexed at the RN without any signal collision. Each ONU can enjoy a dedicated bandwidth, which is also scalable according to the need of the individual ONU. These further enhance the system capacity and network flexibility. Symmetric two-way communication can be supported and enables the optical access networks not only for service distribution, but also for data networking. Therefore, multi-wavelength optical access is a promising solution to support a robust and large-scale optical access network.
In this paper, we will discuss various feasible WDM access network architectures to support two-way communication. The enabling technologies including dense-WDM (DWDM), coarse WDM (CWDM), spectral slicing of light-emitting-diode (LED) and the options for WDM multiplexers/demultiplexers will be described. Besides, a practical network architecture which comprises centralized light sources (CLS) at the OLT will be discussed. With this CLS arrangement, no wavelength-registered laser source is needed at the ONUs and thus greatly eases the network maintenance. In addition, several protection architectures for WDM access networks will be presented.

2. WDM ACCESS NETWORK ARCHITECTURES

Over the past decade, various network architectures for WDM access networks have been proposed [1]. Most of them feature at the transmission characteristics and wavelength routing of both the downstream and the upstream wavelength channels. Among all different approaches, the earliest proposal was a broadcast and select network, named LAMBDANET [2], in which a star network topology was employed. In such broadcast and select network, each node emits a distinct wavelength channel, which is then split to all other nodes, via an $N \times N$ optical star coupler. Thus each node receives ($N-1$) wavelength channels from all other nodes. By incorporating an optical filter or a wavelength demultiplexer at each node, it can select the destined wavelength channel. This approach is simple and can achieve multi-access among all network nodes. Later, there has been a new class of WDM access networks, called WDM passive optical networks (PONs), emerged in which it employs a tree topology and there is no active component at the RN. Fig. 1(a) shows a generic WDM-PON [3], where a wavelength router is placed at the RN to route a set of downstream wavelength channels as well as another set of upstream wavelength channels. The periodic transmission property of the wavelength router is employed. Fig. 1(b) shows a WDM-PON [4] where the downstream wavelength channels are demultiplexed by one wavelength demultiplexer while the upstream wavelength channels are multiplexed by another wavelength multiplexer at the RN. Fig. 1(c) shows the spectral-sliced WDM-PON [3,5] where the network architecture is similar to Fig. 1(b). However, the upstream data is modulated on a broadband LED at the ONU and the wavelength multiplexer at the RN filters out a narrow band of LED bandwidth to form the upstream wavelength channel. This is known as spectral slicing of the LED. This can save the cost of the transceivers at the ONUs. Fig. 1(d) shows the composite WDM-PON [6] where the upstream traffic from all ONUs are carried by the same wavelength using time-division multiplexing (TDM) technique while the downstream traffic are carried by WDM signals. Burst-mode receivers are needed at the OLT to detect data packets of different amplitudes and phases due to the near-far effect. Fig. 1(e) shows the WDM-PON with fiber-loopback at the ONU [7]. All the light sources are located at the OLT. An optical modulator is placed at each ONU to modulate the reserved time slots (un-modulated) on the downstream wavelength with the upstream data. This can greatly ease the wavelength management at the ONUs. Apart from these tree-structured WDM-PON architectures, WDM access networks can also be realized using ring topology. A hub node and multiple ONUs are connected in series in form of a ring. The hub node sends out multiple wavelength channels, each of which is destined for one ONU. A single-wavelength add-drop multiplexer is needed at each ONU to select the assigned
wavelength channel for both downstream signal reception and upstream transmission. Thus, this approach is simply a ring topology physically but functions as a star topology logically. In most cases, dual ring topology is used so as to provide protection capability.

3. **DWDM, CWDM, LED SPECTRAL SLICING**

In WDM access networks, the channels are represented by distinct wavelengths over the transmission window of fiber. The wavelengths are defined in equally-spaced wavelength grids, standardized by ITU. The most commonly used channel spacing for dense-WDM (DWDM) is 100 GHz or 200 GHz. However, with this narrow channel spacing, the DWDM wavelengths have to be well-stabilized, by means of temperature stabilization or wavelength locking techniques, to avoid any possible wavelength drift due to environmental changes when the ONUs are deployed in the field. Any
wavelength drift will lead to severe crosstalk to the neighboring channels. Moreover, the drifted wavelength will also get deviated from the filter passband of the in-line WDM components, such as the wavelength multiplexers/demultiplexers, optical filters, etc. So, the signal power will be largely filtered off and the signal will also be severely distorted. In order to relax such stringent requirement, coarse-WDM (CWDM) is proposed and has recently been standardized to provide 18 wavelengths, spaced by 20 nm, over the fiber transmission window from 1270 nm to 1610 nm. Such wide channel spacing inevitably allows large wavelength drift, thus the wavelength transmitters do not need to incorporate any temperature control circuit. This greatly reduces the cost and the power consumption of the transmitters. If the CWDM wavelengths are chosen around the high water absorption spectrum (around 1400 nm) of the optical fiber, a new kind of optical fiber with the water absorption peak removed should be employed to avoid the excessive absorption. As the CWDM components require a wide passband (~13 nm), CWDM multiplexers and CWDM add-drop multiplexers are mostly realized by thin-film technology. Apart from DWDM and CWDM, the WDM sources can also be realized by slicing the optical spectrum, by means of narrowband optical filters, of a broadband light source, such as LED [8,9] or optical amplifier’s amplified spontaneous emission (ASE). This becomes a relatively lower cost option for a WDM source than using multiple discrete DFB lasers, as one can simultaneously obtain multiple wavelength channels from one single broadband source. The main problem of using LED spectral slicing is the incoherent nature of the output light, which definitely limits the transmission span. Besides, a high power LED or a LED followed by an optical amplifier, may be needed to compensate for the losses incurred in the transmission link. In addition, broadband light source with flat spectrum is highly desirable to enable the sliced wavelength channels to have equal power levels. Other alternatives for WDM sources include Fabry-Perot lasers [10], multi-frequency laser [11], etc.

4. WAVELENGTH MULTIPLEXER/DEMULTIPLEXERS

Most of the technologies to realize wavelength multiplexers or demultiplexers are based on planar lightwave circuit (PLC) as they have good potential for monolithic integration with other components. Examples are arrayed waveguide gratings [12], thin-film [13], echelle grating, diffraction grating [14], etc. Apart from PLC technologies, wavelength demultiplexers can also be implemented using fiber Bragg gratings [15]. In order to ensure the devices made by these technologies to be practical and deployable in optical access networks, two critical issues, namely the polarization sensitivity and the thermal sensitivity, have to be carefully considered. Polarization dependency leads to severe polarization dependent loss while thermal dependency leads to mismatch in the laser wavelength and the multiplexer passband, which translates to high loss in signal power. Recently, various techniques have been reported to achieve polarization insensitive [16,17] or athermal [18-20] wavelength multiplexers. Thus, they are suitable to be deployed in the field.
5. WDM ACCESS NETWORKS WITH CENTRALIZED LIGHT SOURCES

In this section, we will discuss a WDM access network architecture using centralized light sources at the OLT [7], which has emerged as an attractive and low-cost solution to support bi-directional transmission. Fig. 2 shows a typical WDM access network with $N$ ONUs. The OLT generates the high-speed downstream data on each wavelength channel. The $N$ downstream wavelengths are multiplexed and transmitted over a fiber feeder before the wavelengths are demultiplexed at the RN and each of them is routed to the respective ONU. At the ONU, the downstream is partially split and fed into an optical receiver for downstream data reception. The rest of the signal is fed into an upstream data transmitter where the downstream signal power is re-modulated with the upstream data. The re-modulated upstream carrier is finally routed back to the central office via the RN. With this architecture, the downstream carrier received at the ONU is re-used as the upstream data carrier. Therefore, no wavelength-registered dedicated light source is required at the ONU, thus relaxing the wavelength management.

![Figure 2: A typical network architecture for a bi-directional WDM access network with centralized light sources. The upstream transmitter at the ONU does not require any wavelength-registered light source.](image)

To efficiently insert the upstream data onto the downstream carrier, various data re-modulation scheme for the upstream transmitters at the ONUs have been proposed. One approach was to transmit blank time slots in the downstream signal and they were modulated with the upstream data at the ONU via either an optical modulator [7] or a semiconductor optical amplifier [21]. However, this reduced the available bandwidth for the downstream data. Another approach was to suppress the data content of the downstream carrier by using saturated semiconductor optical amplifiers [22] or intensity modulation with the complementary form of the detected downstream data [23]. Thus, the data-suppressed downstream carrier could then be intensity-modulated with the upstream data. In [24], the downstream
data was modulated at a higher frequency spectrum, leaving the baseband spectrum to be re-modulated with the upstream data via a reflective modulator at the ONU. In [25], an amplified-spontaneous-emission (ASE) injected Fabry-Perot laser diode (FP-LD) was proposed as a WDM source at the remote ONU to transmit the upstream data traffic. However, it required completely un-modulated ASE wavelengths from the central office and thus could not support downstream traffic with the same set of wavelengths. In [26-28], the upstream transmitter at the ONU was realized by using a FP-LD which was injection locked by the downstream wavelength carrying the downstream data, and concurrently directly modulated by the upstream data. Thus, the upstream carrier had the same wavelength value as the downstream carrier. In addition, the side-mode suppression ratio (SMSR) of the generated upstream signal was greatly enhanced (>30 dB) due to injection-locking, thus it enabled data transmission over a longer network span. However, different downstream data modulation formats might induce residual crosstalk to the re-modulated upstream signal. Several downstream data modulation formats, including on-off keying (OOK) [26], binary phase-shifted keying (BPSK) [27], and optical differential phase-shifted keying (DPSK) [28], have been investigated. With careful design, error-free operations were achieved for both the downstream and the upstream data transmission over an access network span of 50 km.

6. PROTECTION ARCHITECTURES

Network survivability is a critical issue to achieve a reliable access network. Any kind of network failure due to link breakage or component failure will interrupt the broadband services to the subscribers and definitely translates into enormous loss in data and business. Thus, fault management is one of the crucial aspects in network management to monitor and detect any network failure occurred. Upon having detected a network failure, the network management unit will be alarmed to perform the appropriate remedy so as to re-route or restore the data traffic, thus minimizing the data loss. To facilitate such network protection and restoration, the network architecture has to be specially designed to provide network path redundancy and incorporated with automatic protection switching mechanism to re-route the affected data traffic into the alternate protection paths. The main goal is to enhance the network reliability.

Most optical access networks employ a point-to-multipoint or a star network topology, thus any link breakage between the RN and an ONU will suspend all services on that link and isolate the affected ONU from the OLT. To alleviate this disastrous situation, it is desirable to have fault-tolerant network architectures, which can detect the link failure and automatically restore the network traffic via other alternative or backup paths. The ITU-T Recommendation on PON (G.983.1) [29] have suggested four possible fiber duplication and protection switching scenarios, as shown in Fig. 3, though they were regarded as optional protection mechanisms. Note that the RN only comprises 1×N optical power splitter(s) in ITU-T G.983.1, but those protection architectures can also be applied to WDM-PON by replacing the optical power splitters by wavelength demultiplexers. Fig. 3 shows the four suggested protection architectures with different levels of protection. Fig. 3(a) duplicates the fiber feeder between the OLT and the RN only. Fig. 3(b) doubles
the optical transceivers at the OLT and also duplicates the fiber feeder between the OLT and the RN. Protection switching is done by switching the data to the backup optical transceiver at the OLT. Fig. 3(c) doubles not only the OLT side facilities but also the RN and the ONU sides. Failure at any point can be recovered by switching to the backup facilities. Fig. 3(d) incorporates an additional power splitter circuit to cope with the case that not all ONUs have duplicate optical transceivers, due to some environmental constraints.

Recently, several protection architectures for WDM access networks have been proposed. In [30], a self-healing DWDM/SCM modified star-ring architecture was proposed, in which two adjacent RNs were connected by a ring, and each ring was connected with multiple ONUs. The RN was incorporated with some protection switches so that in case of fiber cut between itself and the OLT, the traffic on both of its attached rings would be bypassed and forwarded to its adjacent RN so that the affected ONUs can still be in contact with the OLT. In [31], a self-protected WDM-PON architecture was proposed. Two adjacent ONUs were grouped and the corresponding downstream and upstream wavelengths were connected to the OLT via the same output port of the AWG at the RN. This was achieved by utilizing the periodic spectral property of the AWG and with proper wavelength assignment. The two ONUs in the same group were connected by a piece of protection fiber and a pair of protection switches were incorporated into each ONU for signal re-routing. In case of fiber cut between a particular ONU and the RN, the protection switches in the ONUs in the same group will be activated. Both the affected downstream and upstream wavelengths will be re-routed to its adjacent ONU before being routed back to the OLT via the same AWG output port. In this way, the normal traffic on the adjacent ONU was not affected while the OLT could still keep in connection with the affected ONU. Thus, the OLT would be transparent to such fiber failure.
7. FUTURE TRENDS

The ultimate goal of optical access is to realize the dream of Fiber-to-the-Home (FTTH), which have been researched over the past 20 years. The evolution for the access scenario is mainly driven by the bandwidth demand and the economic situations. Nowadays, more broadband internet technologies and services have been further extended to the subscriber’s homes. Thus, the demand for bandwidth per home has been increased to a few tens of Mb/s and even more. This greatly triggers the evolution of the optical access architecture towards FTTH. In order to enhance the feasibility of realizing FTTH, the costs of WDM components have to be further reduced to make the ONUs at the subscriber side more cost-effective. Besides, robust, reliable and scalable network architectures and ONU structures are highly desirable. With the multi-wavelength access network technologies, the transmission capacity and the span can be greatly enhanced, and the access networks are evolving to be more robust to support interactive services as well as data networking services. Moreover, additional new services can be overlay to the existing infrastructure and thus facilitates the provisioning and upgrading. Currently, the most feasible solution is to employ CWDM technologies in the Fiber-to-the Building (FTTB) scenario, which are the most cost-effective and can greatly ease the network management. Future network capacity upgrade can also be easily performed by replacing the CWDM components with the DWDM components.

8. SUMMARY

The WDM technologies offer great enhancement in the transmission capacity and the network span. Nowadays, the access networks are evolving to be more robust to support interactive services as well as data networking services. In this paper, various network architectures for multi-wavelength access networks employing DWDM or CWDM technique; as well as several network enabling technologies such as data re-modulation technique, protection architectures, etc. have been discussed. It is expected that with the ever-increasing demand in bandwidth at the subscriber side, multi-wavelength access network is a promising solution to gear towards the realization of future FTTH.

ACKNOWLEDGEMENTS

This work was partially supported by a research grant from the Research Grants Council of Hong Kong SAR (Project No. CUHK4216/03E).

REFERENCES


