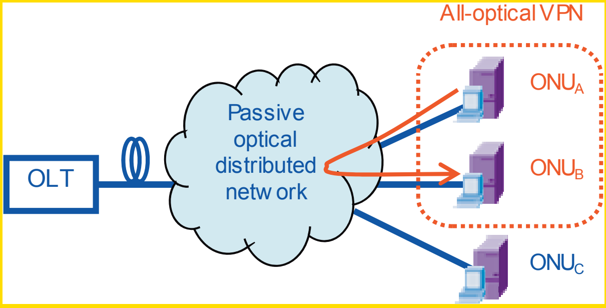
Abstract We review recent progress on all-optical virtual-private-network (VPN) schemes in passive optical networks (PONs). PON is a promising candidate in future access areas to provide broadband services with low cost. With all-optical virtual private network (VPN) function, PON can support efficient internetworking among end users with dedicated optical channels, thus enabling guaranteed bandwidth and enhanced security at the physical layer. Here, we discuss and compare existing schemes of all-optical VPNs in time-division-multiplexed (TDM) PONs, and also recently proposed schemes for deployment in wavelength-division-multiplexed (WDM) PONs and two-stage TDM/WDM PONs.



All-optical virtual private network in passive optical networks

Yikai Su [1,*], *Yue Tian* [1], *Elaine Wong* [2], *Nishaanthan Nadarajah* [2], *and Calvin C. K. Chan* [3]

[1] State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, 800 Dongchuan Rd, Shanghai, China
[2] Department of Electrical and Electronic Engineering, The University of Melbourne, VIC 3010, Australia
[3] Department of Information Engineering, The Chinese University of Hong Kong, Shatin, N. T., Hong Kong, China

Received: 17 May 2008, Revised: 3 August 2008, Accepted: 4 August 2008
Published online: 24 September 2008

Key words: Virtual private network, passive optical network, fiber Bragg grating, reflective semiconductor optical amplifier, local area network.

PACS: 42.79.Sz, 42.81.Uv

1. Introduction

While in the past decade the telecommunication backbone has experienced substantial growth, emerging multimedia applications, such as video-on-demand, video conferencing, interactive gaming, IPTV and e-learning, have pushed the access networks to their bandwidth limits. Voice-and text-oriented services have evolved to data- and image-oriented contents due to the popularity and growth of the Internet and worldwide web (WWW). The trend towards video-based services is continuing and requires much higher speeds in networks. In addition, it has been observed that the traffic patterns are becoming more and more symmetric [1]. This change of paradigm will require new access networks to support high-speed ($>$ 100 Mb/s), symmetric, and guaranteed bandwidths for future diverse services with good signal quality and data security [2].

Access networks mainly fall into three categories in physical transmission media: wireless, copper, and fiber. Wireless has a low outside plant deployment cost. WiFi (802.11) and WiMAX (802.16) are the standards for wireless broadband access. WiMAX is a recently adopted IEEE standard which was designed for fixed and mobile access networks. At a data rate of 70 Mb/s, it has a $\sim$ 5-km coverage range. WiFi is more mature than WiMAX, but it has a relatively small coverage range of only 100 m and a lower bit rate of 10–50 Mb/s. Despite these limitations, WiFi is more widely used for access today than WiMAX due to its maturity [3].

Although both WiFi and WiMAX are relatively low cost to deploy, they use a point-to-multipoint architecture, where bandwidth is shared by multiple users – in some cases hundreds, resulting in insufficient bandwidth to support high-speed applications. Consequently, WiFi and WiMAX

* Corresponding author: e-mail: yikaisu@sjtu.edu.cn

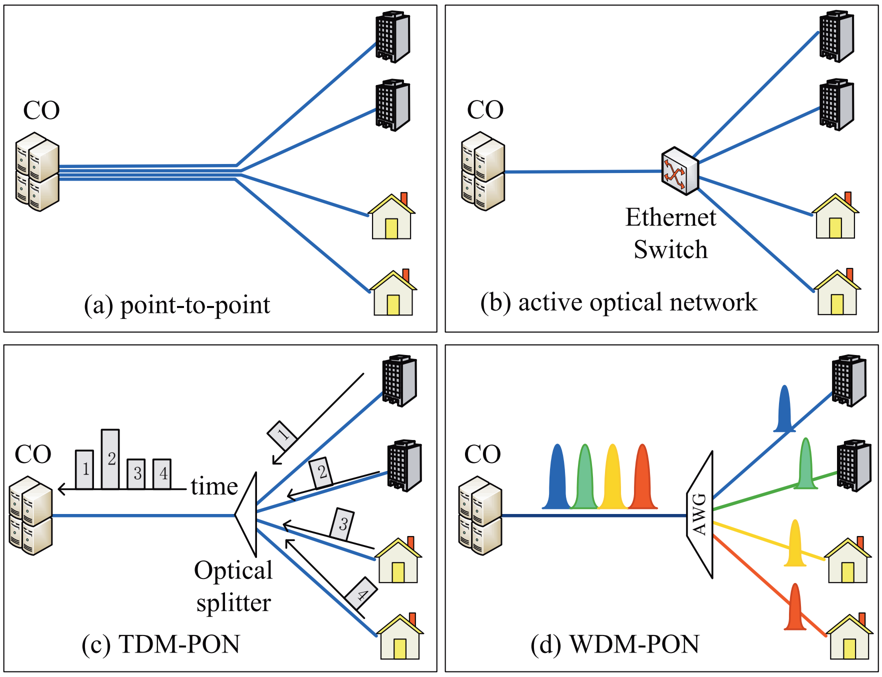


Figure 1 (online color at: www.lpr-journal.org) Four different approaches of FTTH/P: (a) point-to-point connection; (b) active optical network that has active equipments in the filed; (c) and (d) passive optical networks [2].

are useful for Web surfing applications, but impractical for higher-bandwidth and higher-revenue applications such as IPTV.

Another access media available to service providers is copper – more specifically, digital subscriber line (DSL) over copper. Unlike wireless, DSL uses a point-to-point architecture. Thus instead of sharing 50 Mb/s over all subscribers, DSL can provide 50 Mb/s to each end user. DSL is capable of 50-Mb/s transmission for loop lengths less than 300 ft, but can only provide 10 Mb/s over 10,000 ft [3].

A powerful access technology uses optical fiber. Single-mode fiber provides almost unlimited transmission bandwidth over very long distances. The end goal is to provide an optical fiber to each customer premise or home. This type of network is commonly referred to as Fiber to the Home/Premise (FTTH/P). In general, the term FTTH/P does not limit the type of fiber architecture used. Fig. 1 shows four different types of FTTH/P [3]. An access network can be architected using either dedicated or shared fibers. A dedicated fiber plant, often referred to as a point-to-point network, provides a dedicated fiber strand between each subscriber and the central office (CO).

In passive optical networks (PONs), there are no active elements between the CO and the customer premises. Such a network does not require any electrical power or active management compared with active optical network (AON). In addition, the lifetime of the outside passive plant is typically longer than 25 years to justify the capital expenditure (CAPEX) and maximize the savings in operational expenditure (OPEX). A PON possesses a higher reliability than AON because in the outside plant there are no electronic components, which are prone to failure. One of the important features of a PON is high speed and format transparency. When upgrading to higher bit rates, there is nothing to change in the outside plant for a PON. For these reasons, PON is by far the most attractive access technology in a high-bandwidth situation.

Recently, peer-to-peer Internet applications are getting more popular as users can share data or video among peers. Universities and enterprises desire to establish private local area networks (LANs) among their different buildings or branch sites. In addition, emerging large-scale e-science requires collaborative computing with the ability to interactively share, process, and visualize distributed data. Typically, these applications require access to massive collections of data objects (as large as several terabytes), which must be transferred with reliability, timeliness and security.

To meet the requirements of local area networking with high quality and wide bandwidth, virtual private network (VPN) is considered as an effective solution. VPN is a virtual networking service overlaying other network(s) to provide private and secure communications for a closed user group in different locations, making use of a shared network infrastructure. Multiple sites of a private network may therefore communicate via the public infrastructure, in order to facilitate the operation of the private network (Fig. 2) [4]. It offers several attractive advantages compared to private networks built on new infrastructures:

- Shared facilities can be lower cost – especially in CAPEX – than traditional routed networks over dedicated facilities.
- VPN provides flexible configuration of VPN users.
- VPN allows customization of security and quality of service as needed for specific applications.
- VPN can scale to meet bursty demands, especially when provisioned on shared infrastructure.

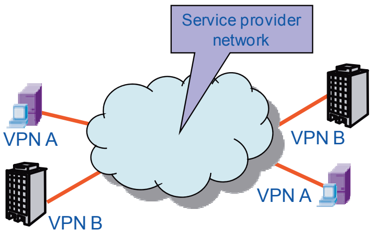


Figure 2 (online color at: www.lpr-journal.org) Virtual private networks.

2. All-optical VPN in PON

2.1. Optical VPN (layer 1 VPN)

Conventionally, VPNs are established electronically on layer 2 or layer 3 using tunneling technology to encapsulate the private packet into a new one with a new header including private address, e.g. using Frame Relay, Asynchronous Transfer Mode (ATM), Layer 2 Tunneling Protocol (L2TP), Point to Point Tunneling Protocol (PPTP) or Multi-Protocol Label Switching (MPLS) to provide a data link service (layer 2), or IP protocols to provide a layer 3 service between customer devices [5, 6].

Layer 1 VPN, or optical VPN, uses layer 1 switches (e.g., optical cross connect (OXC), reconfigurable add/drop multiplexer (ROADM), and generalized multi-protocol label switching (GMPLS) equipments to set up interconnections between customer devices as the basis for providing the VPN function. Optical VPN can be implemented in an opaque or transparent manner, corresponding to optical-electronic-optical conversion and all-optical processing, respectively. Opaque networks are advantageous in operations, administration, maintenance, and provisioning (OAM&P) functions, while transparent networks could reduce the CAPEX, and provide data rate transparency and better security. Generally, optical VPN refers to opaque networks. From the view of a customer, the optical VPN service is supposed to be as close as possible to an optical private line service, but at a reduced cost. Refs. [4,7,8] introduce general concept and architecture of layer 1 VPN. The virtual topology design and reconfiguration issue of VPNs over all-optical WDM networks are studied in [9]. Resource management models and algorithms are proposed and evaluated including path computation [10, 11], multicast-nodes and wavelength converting-nodes placement [12], and bandwidth provisioning and reconfiguration [13]. GMPLS is popular for the control and manage plane, whose implementation of layer 1 VPN is discussed in [14–18]. Also, the survivability design problem of the optical VPN is modeled and studied in [19].

Currently, International Telecommunication Union - Telecommunication Standardization sector (ITU-T) study group (SG) 13 has approved generic VPN architecture and service requirements (Y.1311 [20]), based on which layer 1 VPN service requirements (Y.1312 [21]) and architecture (Y.1313 [22]) have been developed and approved.

2.2. All-optical VPN in PON

All-optical VPN establishes transparent optical interconnections between customer devices, thus providing ‘express and private’ paths for users. Unlike optical VPN built on opaque networks that focuses on the control and manage protocol, all-optical VPN generally employs all-optical processing to isolate the VPN traffic and non-VPN traffic in the optical layer, and is less dependent on the control and scheduling in electrical domain. It is desirable to establish VPN connections in PON to provide high quality and cost-effective point-to-point or point-to-multipoint services. However, the traditional PONs are inefficient to provide private communications, since only the downstream and the upstream transmission links between the optical line terminal (OLT) and each optical network unit (ONU) are available. In a typical PON, the VPN traffic has to be transmitted via the upstream carrier to the OLT, where it is electronically buffered and scheduled, before it is modulated on the downstream carrier and re-directed to the destined ONU (Fig. 3a). This consumes the bandwidth of both the downstream and upstream carriers. In addition, the added round-trip propagation time between the ONU and the OLT, as well as the increased load to the OLT for electronic scheduling and routing of the inter-ONU traffic, inevitably impose extra latency to the inter-ONU VPN traffic. Moreover, the security of private ONU-ONU communications is vulnerable because of the broadcasting nature of the PON in the downstream direction.

All-optical VPN, which is based on dedicated optical channels to connect ONU users in a VPN group, can increase efficiency and reduce latency by eliminating the electronic processing in OLT (Fig. 3b). Furthermore, enhanced security is provided at the physical layer [23, 24]. This pa-

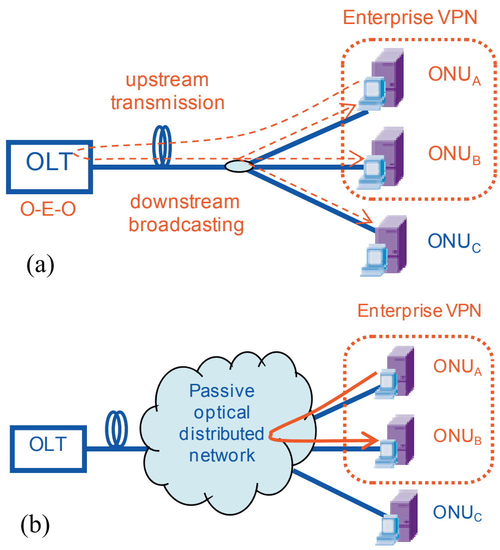


Figure 3 (online color at: www.lpr-journal.org) Traffic flows of (a) conventional VPN and (b) all-optical VPN in PON.

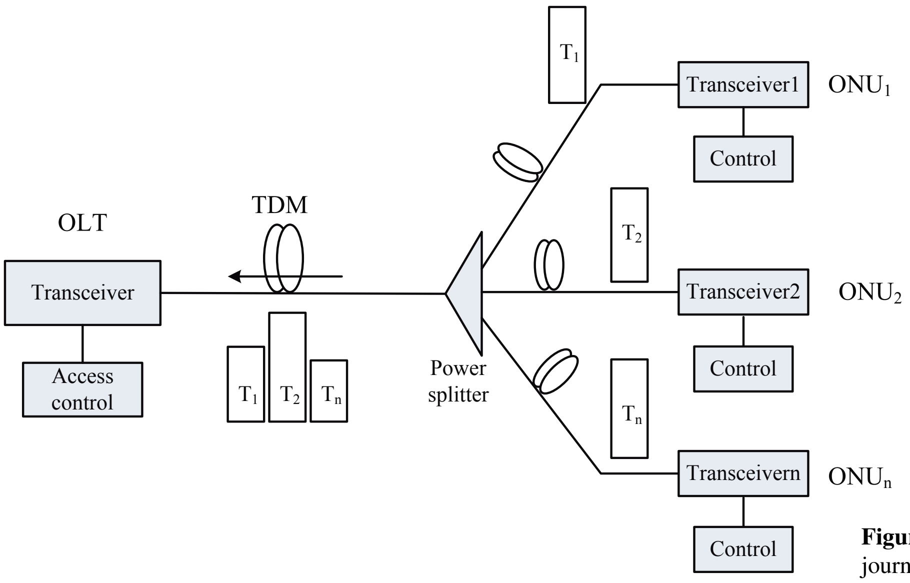


Figure 4 (online color at: www.lpr-journal.org) Architecture of TDM-PON.

per mostly reviews the optical transmission technologies used to facilitate the all-optical VPN.

To establish an all-optical VPN in a PON infrastructure, there are several technical challenges:

- To isolate the VPN traffic from the conventional upstream and downstream data traffic.
- To route the VPN traffic efficiently to the destined ONUs.
- To maintain the scalability after superimposing a VPN overlay on the conventional traffic.

Some previous schemes employed different wavelengths for the private VPN networking and public communication, respectively [24, 28, 31, 33–36, 39–42]. With a wavelength-sensitive component such as an optical filter or wavelength-division multiplexing (WDM) Mux/Demux equipped at the remote node or the ONU side, VPN data can be separated from the conventional downstream and upstream traffic. Hybrid orthogonal modulation formats are also used to differentiate the private and public communications [38, 43, 44]. In addition, specific sub-carrier bands [29, 30] or time slots [26, 27, 34, 35, 37] can be assigned to the different types of connections.

To redirect the VPN traffic downstream to the destined ONU, there are many approaches. The wavelength-selective reflection using fiber Bragg grating (FBG) is a good candidate for establishing all-optical VPN with specific wavelengths [24, 29, 30, 36–38, 42–44]. A star-coupler can directly route the private traffic to the ONUs with relatively low insertion loss [25–31, 33–35]. A cyclic N×N array waveguide grating (AWG) can efficiently route the communications among ONUs in a WDM-PON [39–41]. Reflective semiconductor amplifier (RSOA) [33–35] at the ONU side or fiber amplifier at the OLT side [43, 44] can be used to boost the VPN and/or upstream signals to enhance the scalability of the network.

3. All-optical VPN in TDM-PONs

Time-division multiplexing (TDM) is currently the most popular method for building a PON infrastructure to provide FTTH services. This technique relies on assigning dedicated time slots to the subscribers (Fig. 4). Each subscriber can then use the full upstream bandwidth of the optical link for the duration of its allocated time slot.

Most of the existing all-optical VPN schemes are built on TDM-PON. In the following we introduce previous works to realize all-optical inter-ONU communications or VPN function in TDM-PONs. Diverse technologies, e.g. WDM, sub-carrier modulation, wavelength-selective reflection, electronic code-division multiplexing (CDMA), hybrid modulation formats, are employed to establish the inter-ONU communications.

3.1. Wavelength reflection based inter-ONU broadcasting schemes

One of the earliest proposals of establishing all-optical VPN in a TDM-PON uses wavelength-selective reflection of VPN traffic to reroute and redirect transmissions among ONUs. In [24], the wavelength-selective reflection feature is implemented by a static FBG that is placed on the feeder fiber before the power splitter or star coupler (SC), as illustrated in Fig. 5. As in a conventional TDM-PON, downstream transmission from the OLT is broadcast to all ONUs while upstream transmission to the OLT from each ONU, on wavelength λ_0, is time-interleaved to avoid packet collisions. On the other hand, VPN traffic transmitted among ONUs is carried on a separate wavelength, λ_1. The FBG has a Bragg wavelength centered on λ_1, thus enabling all VPN transmissions from the ONUs to be rerouted back to the SC and thereby broadcast to all ONUs. All other traffic passes through the FBG with minimal loss.

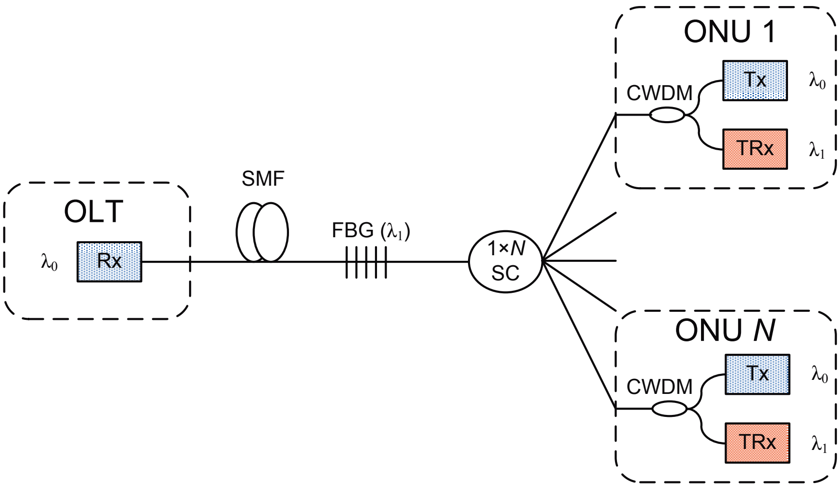


Figure 5 (online color at: www.lpr-journal.org) Schematic diagram of wavelength-reflector based PON using FBG. TX: transmitter, RX: receiver, TRX: transceiver [24].

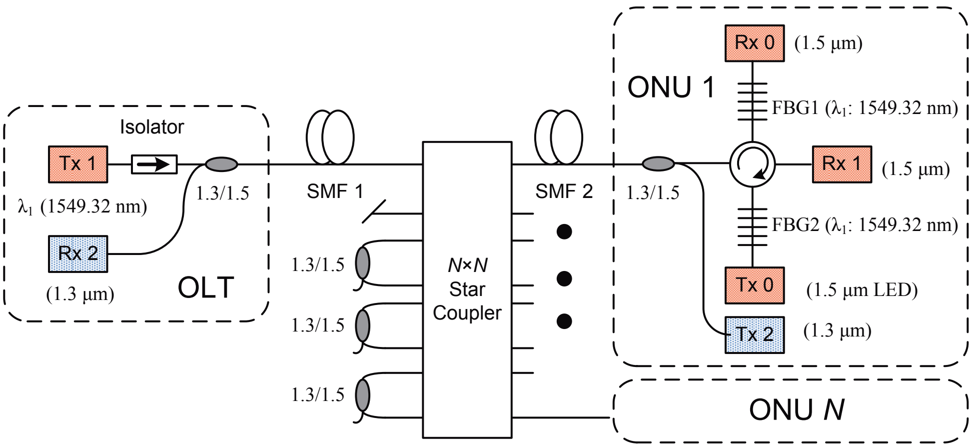


Figure 6 (online color at: www.lpr-journal.org) Schematic diagram of wavelength-reflector based PON with optical loopbacks [25].

A drawback of the proposed scheme in [24] lies in the usage of the static FBG in the fiber plant which is susceptible to environmental effects, although the fabrication of both devices with internal temperature control in an integrated chip using planar lightwave circuit (PLC) technology may be feasible to offset temperature drift of the FBG. Alternatively, the downstream, upstream and VPN wavelengths can also be placed reasonably far apart such that a wideband FBG can be used in the outside plant.

Such dependency on a central wavelength selective device in the outside fiber plant is overcome in [25]. Instead, each ONU is equipped with two FBGs, both centered at the downstream wavelength, in which temperature can be more easily controlled. For specificity, Fig. 6 shows the OLT equipped with a transmitter (TX1) to transmit downstream traffic on 1549.32 nm and a receiver (RX2) to receive upstream traffic from ONUs on 1.3 μm. Likewise, each ONU is equipped with a transmitter (TX2) to transmit upstream traffic on 1.3 μm to the OLT and a receiver (RX1) to receive upstream traffic from the OLT on 1549.32 nm. To facilitate VPN, each ONU is further equipped with an additional light-emitting diode (LED) transmitter (TX0), receiver (RX0), an optical circulator, and the previously mentioned FBGs centered at the downstream wavelength. The LED chosen for the proposed scheme has a wide spectrum centered around the 1.5 μm region.

To reroute and broadcast VPN traffic, optical loopbacks as configured in Fig. 6 are used instead of employing a central FBG prior to the SC as in [24]. At the ONU, the downstream and redirected VPN traffic (both residing on the 1.5 μm region) are separated by FBG1. The downstream traffic is reflected by FBG1 to be received at RX1 while the VPN traffic is received at RX0. The use of FBG2 is to provide isolation between TX0 and RX1. An advantage of using multiple loopbacks in conjunction with an $N \times N$ SC rather than just one loopback increases optical feedback power of the VPN traffic, reducing the overall splitting loss. The tradeoff however lies in the need to use a wideband incoherent light source such as the LED to ensure minimal interference crosstalk from the loopbacks, thereby limiting the transmission rate and upgradeability of the VPN.

3.2. $N \times N$ Star-coupler and WDM based VPN schemes

The redirection of VPN traffic as proposed in the schemes outlined in the preceding subsection suffers from high split-

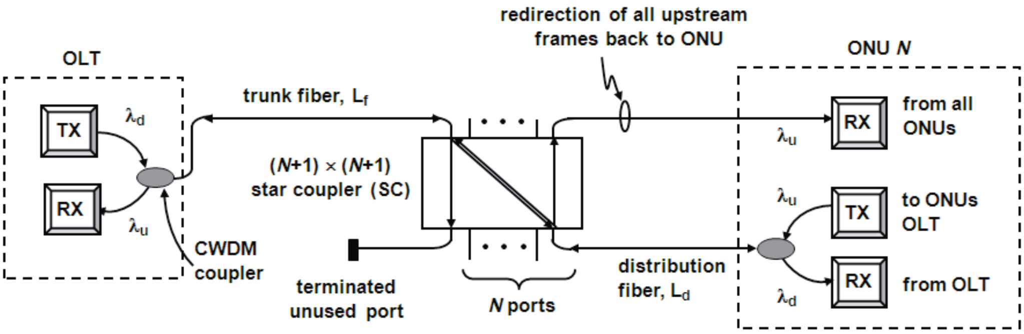


Figure 7 Schematic diagram of CSMA/CD-based PON architecture with $(N+1) \times (N+1)$ SC to redirect VPN traffic [26].

Table 1 Combination of MODE and LLID values in a PON-tag for transmission and reception on λ_u [26].

Transmission to	Service	MODE	LLID
OLT	Upstream access	P2P	OLT
Shared LAN	Unicast	P2P	Dest. ONU
	Multicast	P2P	Group
	Broadcast	SCB	Source ONU

Accept frame if		MODE	LLID	Service
Location	OLT	P2P	Matches own LLID	Upstream access
	ONU	P2P	Matches own LLID	Unicast
		P2P	Matches group LLID	Multicast
		SCB	No match	Broadcast

ting loss due to the requirement of passing through the SC twice. This results in a reduced number of customers that can be served. Such high splitting loss from the double-pass SC is overcome in schemes proposed in [26], [27] and [28], whereby each ONU is configured to connect to the SC via two distribution fibers, allowing VPN traffic to traverse the SC only once.

Fig. 7 illustrates the PON architecture that is proposed in [26]. The OLT is connected to N number of ONUs via a passive outside plant, comprising a trunk feeder fiber, a $(N+1) \times (N+1)$ SC, and $2 \times N$ distribution fibers. The PON uses the carrier-sense multiple access with collision detection (CSMA/CD) protocol as its upstream multiple access scheme. Note that the physical connection between the SC and the ONUs is designed to enable all traffic, including upstream traffic from any ONU, to be redirected back to all ONUs and the OLT. Each ONU has one fiber for the downstream and upstream traffic, and a second fiber that delivers redirected traffic, back to the ONU for detection by a burst mode receiver (BMR). The redirection of traffic on λ_u not only improves the efficiency of CSMA/CD by reducing the roundtrip propagation delay for carrier-sensing and collision detection, but also facilitates inter-ONU communication without sacrificing the bandwidth of λ_d.

Each transmitted frame from the ONU includes a PON-tag to differentiate between upstream and VPN traffic which in turn can be classified as unicast (point-to-point (P2P) emulation), multicast, and single copy broadcast (SCB) traffic. The PON-tag consists of a MODE value and a logical link identifier (LLID) in which the OLT and all ONUs are each assigned a unique value at initialization and at subsequent registrations. Each ONU is considered to have information on the LLID values of the OLT and the ONU's in its shared LAN, in addition to the group LLID value for multicast frames. Table 1 summarizes the possible combinations of the MODE and LLID values for transmission and reception at an ONU on λ_d. The filtering rules determine if a frame received at the OLT and ONUs is to be accepted or discarded.

To improve the security of the VPN, the use of low cost optical switches (OSWs) is proposed in [27]. Two independent sub-networks, namely access and VPN, are established whereby the VPN traffic is physically disconnected from the OLT. Fig. 8 illustrates the proposed architecture which is similar to that shown in Fig. 7 with an addition of two thermo-optic or opto-mechanical OSWs, namely OSW1 and OSW2, in each ONU. The OSWs are set to either cross or bar state depending on the mode of operation: normal mode for access and local mode for VPN. In normal mode, OSW1 and OSW2 are set to cross and bar states respectively. In this mode, the ONU receives downstream transmissions on λ_d at its BMR through OSW2 and transmits upstream traffic on λ_u from its BMT through OSW1. The upstream traffic reaches only the OLT as optical isolators are implemented at the SC to prevent redirection back to all ONUs. In local mode, OSW1 and OSW2 are set to bar and cross states respectively. In this mode, downstream signals are barred from reaching the BMR, and instead are routed to an antireflection port at OSW2. The local or VPN traffic is routed through OSW1 in bar state and directed to the SC which splits the signal into multiple copies to be broadcasted to all ONUs including the transmitting ONU. The VPN traffic does not reach OLT, hence isolating the VPN from the access network.

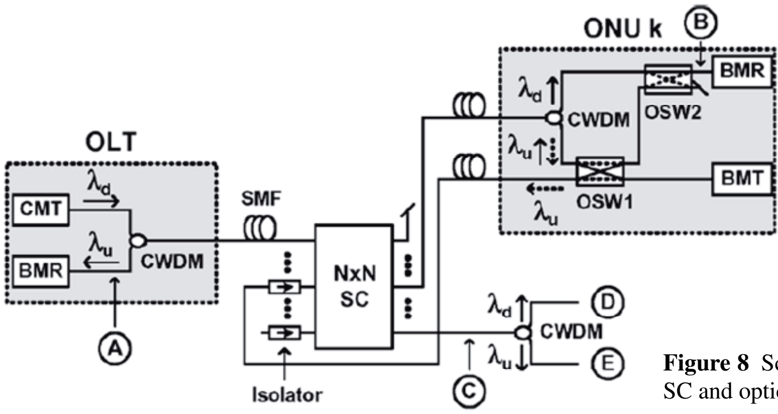


Figure 8 Schematic diagram of PON architecture with $N \times N$ SC and optical switches to facilitate VPN [27].

To relax the potential limitation of network efficiency by the switching speed of the OSWs in [27], a similar PON architecture is proposed to align the VPN traffic on a separate wavelength λ_L and replace the OSWs with high-speed tunable transceivers which tune between the upstream wavelength λ_u and the VPN wavelength, λ_L. For details, see [28].

3.3. RF multiplexed LAN schemes

As described in the previous optical layer LAN emulation schemes, the use of an additional optical source to provide LAN emulation over PON is not effective in cost-sensitive customer access networks, and therefore a multiplexing mechanism may be implemented to simultaneously support conventional upstream access traffic and LAN traffic on a single wavelength channel. Here, LAN emulation is implemented radio frequency (RF) subcarrier multiplexing. The upstream access traffic to the CO is carried at baseband, and is referred to in this work as upstream baseband data, while LAN traffic is carried on an RF carrier that is chosen to be out-of-band from the upstream access traffic. Compared to higher layer LAN emulation proposals, the proposed techniques using RF subcarrier multiplexing require low-cost electronics at each ONU, reduces the complexity and provides efficient bandwidth utilization of the downstream and upstream wavelength channels. In the following subsections, schemes using RF subcarrier multiplexing and the performances of both schemes are discussed.

Scheme 1 – LAN emulation using narrowband FBG

This section describes the LAN emulation scheme that employs a narrowband FBG placed close to the SC in the feeder fiber of the PON [29, 30]. The schematic diagram of this scheme, denoted Scheme 1, is shown in Fig. 9. At

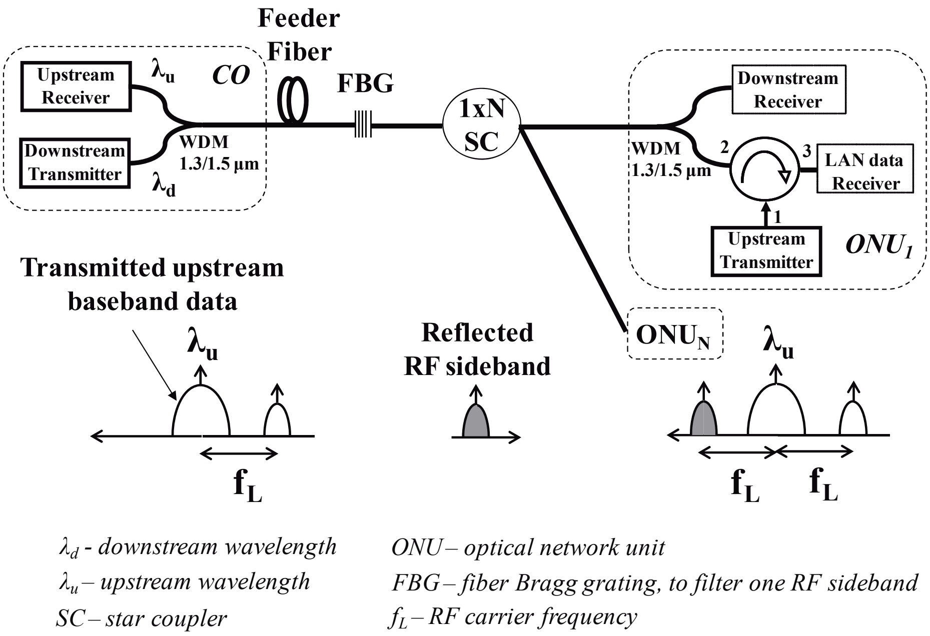


Figure 9 Physical architecture for LAN emulation (*Scheme 1*) using RF subcarrier multiplexing with a narrowband fiber Bragg grating placed in the feeder fiber for the optical loopback [29].

each ONU, upstream baseband data and LAN data signals are generated for the transmission in the upstream direction. LAN data is amplitude modulated onto an RF carrier that is chosen out-of-band from the upstream baseband data using a voltage controlled oscillator (VCO). These signals are then electrically combined and modulated onto the upstream wavelength λ_u. A narrowband FBG is placed in the feeder fiber close to the $1 \times N$ star coupler (SC), whereby N corresponds to the number of ONUs. The Bragg wavelength of the FBG is chosen such that FBG reflects one of the optically modulated RF sidebands and broadcast the LAN data to all ONUs. Alternatively, a double notch FBG may also be used such that both optically modulated RF sidebands are reflected back to the ONUs while the upstream baseband data is transmitted to the CO. As LAN data is amplitude modulated on to the RF carrier, it can be recovered by direct detection. This allows the LAN data receiver to be of low bandwidth even though a high frequency RF carrier is used for modulation. The bandwidth of the LAN data receiver may only be in the order of the transmission bit rate of the LAN data.

Scheme 2 - LAN emulation using fiber loopback

Fig. 10 illustrates the LAN emulation scheme in which the redirection of the optically modulated RF sidebands along with the upstream baseband data is performed by a $(N+1) \times (N+1)$ SC and additional short length distribution fibers. In this scheme, denoted as *Scheme 2* [29, 30], the $(N+1) \times (N+1)$ SC replaces the $(1 \times N)$ SC that was used in *Scheme 1*. The number of ONUs that are attached to the SC is N and one of the port facing towards the ONUs is terminated. Therefore, *Scheme 2* requires an additional port in the SC to support same number of ONUs as in *Scheme 1*. Each ONU in the PON is connected to the SC via two short length distribution fibers as shown in Fig. 10. Signals transmitted from each ONU on λ_u are therefore redirected back to each ONU through the second distribution fiber. As in *Scheme 1*, upstream signals consist of the baseband data to CO and LAN data that is modulated on an RF carrier to other ONUs. At each ONU, the looped back signals are detected and the upconverted RF LAN data is electrically separated from the upstream baseband data using an electrical band pass filter (BPF). Then, the RF LAN data is down-converted to baseband frequencies using a phase locked loop containing a VCO to recover the LAN data. In this scheme, the modulation of the LAN data on the RF carrier could be done in any arbitrary signal format such as amplitude shift keying (ASK), phase shift keying (PSK) or frequency shift keying (FSK), since coherent detection of RF signals is performed at the RF LAN data receiver for the recovery of the LAN data.

As these LAN emulation schemes using RF subcarrier multiplexing employ two different physical layouts, the performance also vary in terms of bandwidth requirements and upgradeability, dispersion tolerance in transmission of RF LAN data, and stability requirements of the optical source. The detailed discussions can be found in [29]. Furthermore, [30] extends the above described LAN emulation schemes to provide protection of ONUs against failure in the distribution fibers.

3.4. Electronic CDMA based VPN scheme

In the previously explained VPN schemes, LAN traffic is broadcast to all ONUs and therefore higher layer encryption mechanisms are required to provide security for the transmitted signals. However, using electronic code division multiple access (E-CDMA), physical layer security for the transmitted signals can be provided. In this scheme, each VPN is allocated a unique E-CDMA code, which is multiplexed with the data transmitted on the VPN. Likewise, reception of data from a particular VPN is only possible at ONUs that have access to the unique code for decoding. This proposed scheme shows that multiple VPN transmis-

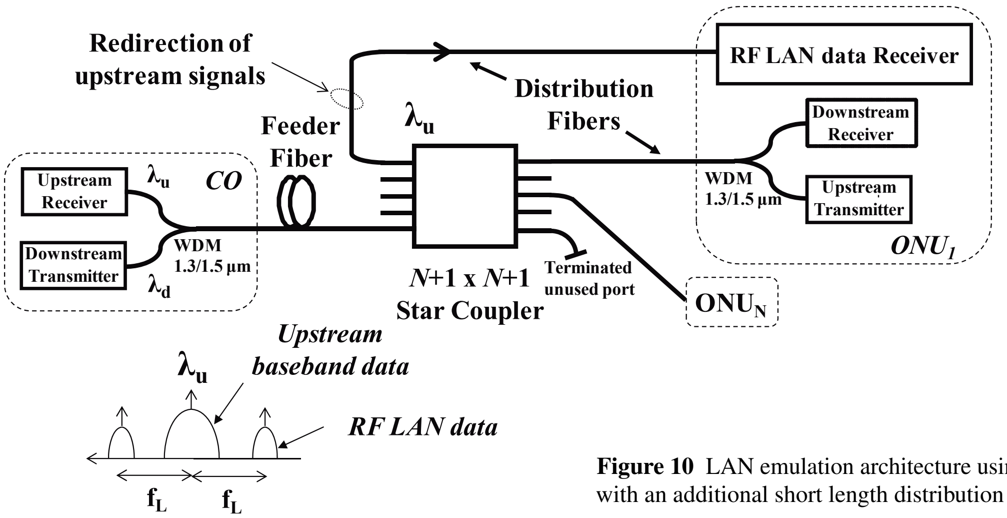


Figure 10 LAN emulation architecture using RF subcarrier multiplexing with an additional short length distribution fiber loopback [29].

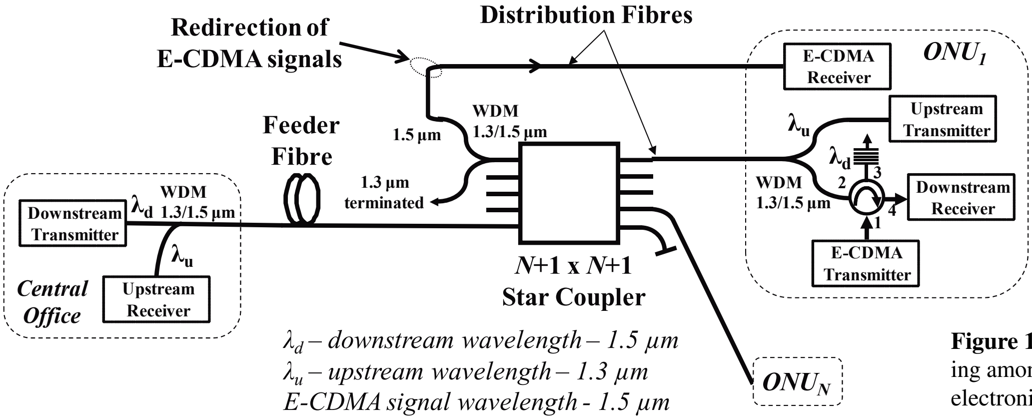


Figure 11 Virtual private networking among the users in a PON using electronic CDMA [31].

sions can be performed at any given time, rather than only during designated time slots for each ONU.

The proposed scheme for implementing secure VPNs over a PON is shown in Fig. 11. An $(N+1)\times(N+1)$ star coupler (SC) is used to split/combine optical signals to/from each ONU, whereby the number of customers connected to the SC is N. Each ONU is connected to the SC via two distribution fibers as shown in Fig. 11. The transmitted E-CDMA signal from an ONU on one distribution fiber is redirected back to each of the ONUs through the second distribution fiber. The E-CDMA signal transmission is performed using wideband optical sources such as Fabry-Perot laser diodes (FP-LD) or LEDs in the 1.5 µm window wavelengths while the upstream transmission to the central office (CO) is carried out using a wavelength source at the 1.3 µm window. Therefore, a 1.5 µm/1.3 µm coarse wavelength division multiplexing (CWDM) coupler is used at the SC to separate these wavelengths. The downstream signal from the CO to the ONUs is carried out using a distributed feedback (DFB) laser operating at 1.5 µm window wavelength. A FBG with a Bragg wavelength at the downstream wavelength is used in-conjunction with a circulator at each ONU to prevent reflections of the E-CDMA signals entering the downstream data receiver. Each VPN in the PON has a unique electronic code, which is electronically multiplexed with the data that is to be transmitted within a VPN. Several VPN transmissions can therefore be simultaneously performed using different electronic codes. Moreover, VPN transmissions can be carried out any time rather than in a pre-assigned timeslot as in time division multiple access (TDMA) protocol. Therefore, the requirement for a burst mode receiver for the reception of E-CDMA signals at each ONU is alleviated in this scheme. Since the transmitted data is electronically coded and can therefore only be decoded by a unique electronic code, this scheme provides physical layer security of the VPN signals. An unwanted side effect from using the multiple access capability of E-CDMA to implement simultaneous and multiple VPN transmissions is optical beat interference (OBI) from several optical sources. However, it has been shown that the OBI can be reduced by the use of incoherent light sources such as LED and the use of E-CDMA. Moreover, as the expected transmission distance between the ONUs is not large in a PON and the use of E-CDMA to carry VPN traffic, the dispersion induced penalty due to the use of wideband light sources is negligible. In [32], an optical CDMA over WDM PON scheme is proposed as a solution for the gigabit-symmetric FTTH system, which is a potential platform for all-optical VPN.

3.5. RSOA based VPN schemes

Recently, there has been a lot of interest in the elimination of the laser source at the ONU, thus avoiding its stabilization and provisioning all ONUs with wavelength independence for the next generation optical access network. PONs based on a RSOA placed at the ONUs enable a simpler, more cost effective, and easily upgradeable infrastructure for customer access networks. The use of RSOA enables laser-free operation of the ONUs for the upstream transmissions with higher flexibility and higher capacity upstream traffic and LAN traffic transport while providing easier migration towards WDM-PON. We show two different schemes for upstream transmission and LAN emulation using a single RSOA placed at each ONU. Unlike previous proposals, these schemes do not require high speed analog RF electronic components and circuits, optical sources and external modulators at each ONU to provide local customer networking in the PON, and therefore cost of providing customer networking is minimized. Moreover, as LAN traffic transmission can be performed at any time rather than in designated time slots, the requirement for a burst mode receiver at each ONU is eliminated. The local customer networking schemes are completely isolated from the remaining PON and hence provides improved security compared to the system proposed to EFM IEEE 802.3ah.

Scheme 1 - LAN traffic transport using broadband spectrum of RSOA

This section describes the LAN emulation scheme that employs the broadband spectrum of the RSOA for the transport

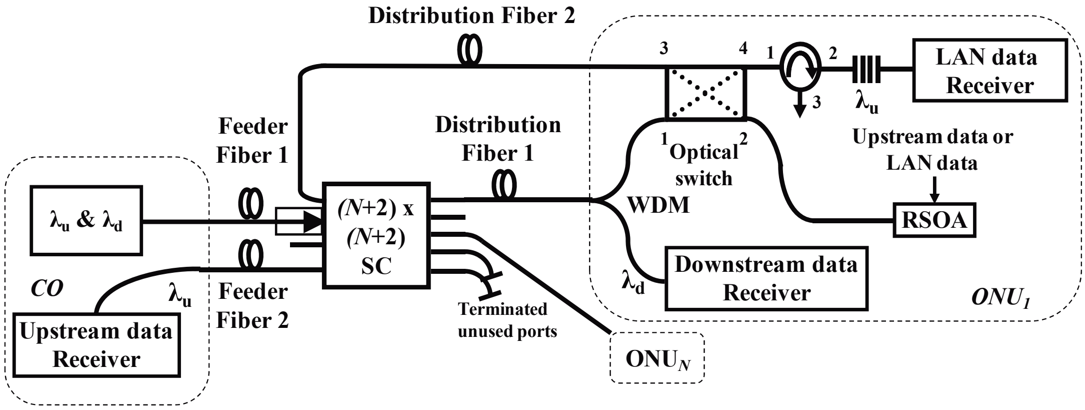


Figure 12 Transmission and LAN emulation using a single RSOA placed at ONUs, whereby LAN traffic transport is performed by the broadband spectra of RSOA [33].

of the LAN traffic in the PON. The proposed scheme for implementing upstream access and LAN emulation using a single RSOA is shown in Fig. 12. A $(N+2) \times (N+2)$ SC is used to split/combine the optical signals to/from each ONU, whereby the number of ONUs attached to the SC is N and each ONU is connected to the SC via two distribution fibers and the remaining two ports facing the ONUs are antireflection treated. An unmodulated wavelength channel, namely λ_U is transmitted from the CO to all ONUs for upstream transmissions along with the modulated downstream signals on a second wavelength channel, λ_D. At the ONUs, λ_D is separated from λ_U using a CWDM coupler. An OSW is used at each ONU to change the mode of transmissions. In the upstream transmission mode, the OSW is set to 'bar' state such that λ_U is used to wavelength seed the RSOA and the wavelength-seeded RSOA is then directly modulated with upstream traffic for transmission to the CO. Note that upstream signals propagate through the same distribution fiber as incoming downstream signals. However, a second feeder fiber is used between the SC and the CO for the transmission of upstream signals and an optical isolator is used at the port of the SC to prevent the upstream signals entering feeder fiber 1. In the LAN emulation mode, the OSW is set to 'cross' state such that RSOA is no longer wavelength seeded by λ_U. In this mode of operation, the broadband amplified spontaneous emission (ASE) spectrum of the RSOA is directly modulated with the LAN traffic and transmitted through distribution fiber 2 and broadcast to all ONUs through the SC. An FBG is placed in front of the LAN data receiver to suppress the unmodulated wavelength channel λ_U from the CO. The downstream wavelength channel λ_D can be chosen to be placed outside the bandwidth of the broadband ASE spectrum of the RSOA. Alternatively, a narrowband WDM coupler can be used such that only a small fraction of ASE power is sent to the downstream data receiver.

Another RSOA based architecture similar to [33] is depicted and discussed in [34], in which the separation of VPN and upstream traffic is completed in the remote node instead of in each ONU.

Scheme 2 – LAN traffic transport using wavelength-switchable transmitters based on self-seeding RSOAs

The proposed scheme for implementing upstream access and LAN emulation using a self-seeded RSOA is shown in Fig. 13. A $(N+1) \times (N+1)$ SC is used to split/combine the optical signals to/from each ONU, whereby the number of ONUs attached to the SC is N. At the ONUs, two FBGs with different Bragg wavelengths and an OSW are used to select the wavelength channels for the seeding of the RSOA. The reflective FBG slices broadband spectrum of RSOA and continuously feeds the sliced channel back to the RSOA for wavelength seeding. Self-seeding of RSOA means that the optical carriers at a user-defined wavelength can be able to oscillate and lase within the RSOA by creating an appropriate optical resonator. One of the methods to construct a resonator is by using an external passive wavelength-selective device, such as FBG. In our scheme, a reflective FBG is closely located at the RSOA output, such that the RSOA broadband spectrum is being sliced and is fed back into the RSOA. Thus, the RSOA is being stimulated to emit at the wavelength equal to the FBG. When the threshold of lasing condition is achieved, the RSOA will become continually seeded. Consequently, the RSOA is self-seeded and emit at a user-defined wavelength. The self-seeded wavelength channel can therefore be used for the upstream and LAN traffic transport. In the upstream transmission mode, the OSW is set to 'cross' state such that upstream wavelength channel λ_U is used to wavelength seed the RSOA. In the LAN mode, the OSW is set to 'bar' state such that LAN wavelength channel λ_{LAN} is used to wavelength seed the RSOA. In both operating modes, the self-seeded RSOA is directly modulated with upstream or LAN traffic and transmitted in the upstream direction. Upstream traffic is transported to the CO through distribution fiber 1 and feeder fiber while the LAN traffic transmission is performed using distribution fiber 1 to the SC and broadcast to all ONUs through distribution fiber 2. It should be noted that as the distribution part of the PON is short in dis-

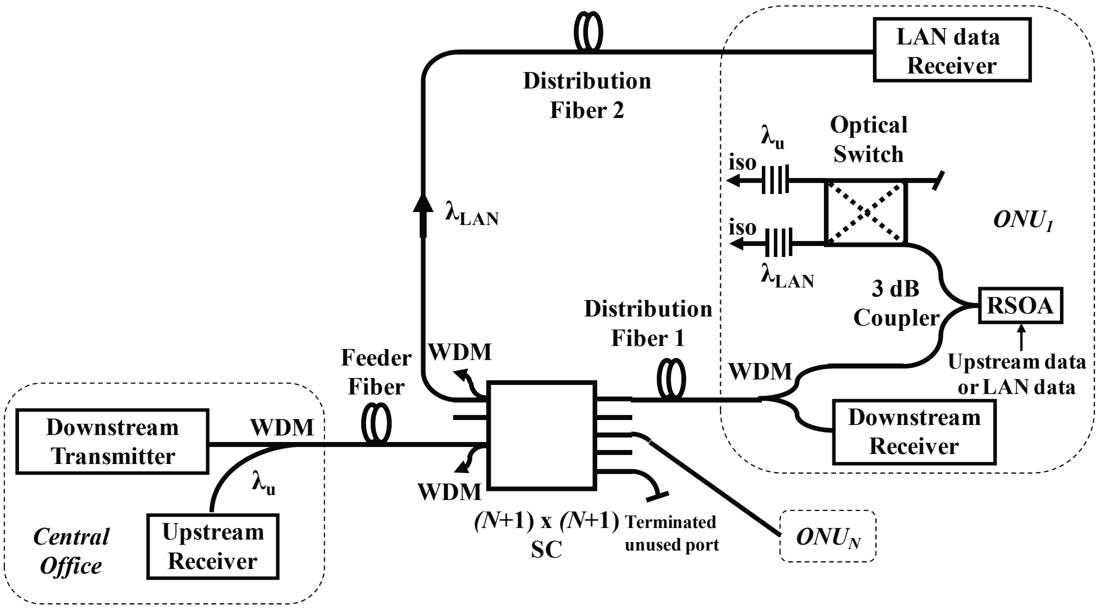


Figure 13 Upstream access and LAN emulation using a single RSOA, whereby traffic transport is performed by the self-seeding the RSOA using FBGs placed at the ONUs [35].

tance, the use of the secondary distribution fiber in all three schemes is not expected to increase the costs much since both distribution fiber cables can be placed in a single duct to provide optical layer LAN capabilities. As in *Scheme 2*, a CWDM coupler is used at each port of the SC facing the CO to prevent λ_U from reaching the ONUs and therefore LAN is completely isolated from the PON and provides improved security for the transmitted upstream signals.

3.6. Waveband-selective based VPN schemes

In this sub-section, we introduce a waveband-selective technique to partition the ONUs into different VPNs. Here, each ONU is assigned a wavelength, and a collection of adjacent wavelengths define a waveband. Based on such waveband partition of the wavelengths, the ONUs are grouped into different VPNs, where the ONUs are all-optically interconnected. Hence, in a PON, multiple VPNs can coexist by employing the waveband-selection technique.

Scheme 1 – VPN traffic transport using dynamic waveband reflection

In [36], a waveband-selective PON is proposed to enable all-optical VPN internetworking of ONUs within a same waveband, i.e. the same VPN. A dynamic waveband reflector is installed at the OLT side for each all-optical VPN. The reflector has two states: passing through and reflecting.

When the reflector of an all-optical VPN is in the state of passing through, the OLT and the ONUs in the corresponding all-optical VPN can exchange the non-VPN data. If there are several reflectors in this state, the upstream transmission should be packet-interleaved in time as in traditional PONs but at different wavelengths, since there is only one broadband receiver in the OLT to receive the data from all ONUs, as plotted in Fig. 14a. The transmitter of the OLT is fast tunable such that the packets can be sent to the intended all-optical VPN. In each all-optical VPN, the downstream transmission is received by ONUs in a broadcast manner.

By setting the reflector of an all-optical VPN to the state of reflecting, the VPN signal from an ONU is optically directed back to other ONUs in the same VPN. The receiver in an ONU is equipped with a waveband filter that covers the wavelengths in the all-optical VPN, so that the reflected VPN signals can be received. At this moment, the channel between the all-optical VPN and the OLT is disconnected, which stops the non-VPN traffic transmission.

This scheme has several features: the electronic processing of VPN traffic in the OLT is avoided by adding a set of dynamic waveband reflectors in the OLT; the contention between the VPN traffic in an all-optical VPN and the traffic in other all-optical VPNs is eliminated. Hence, compared to the traditional PONs, this design remarkably reduces the packet delay and improves the network throughput. However, there remain some limitations on the performances. Firstly, in a same all-optical VPN, the VPN traffic cannot be sent in parallel with the non-VPN traffic. Secondly, the VPN signal from an all-optical VPN is reflected by the reflector in the OLT and then split and broadcast by the star coupler to all ONUs in the PON, thus the security performance is poor.

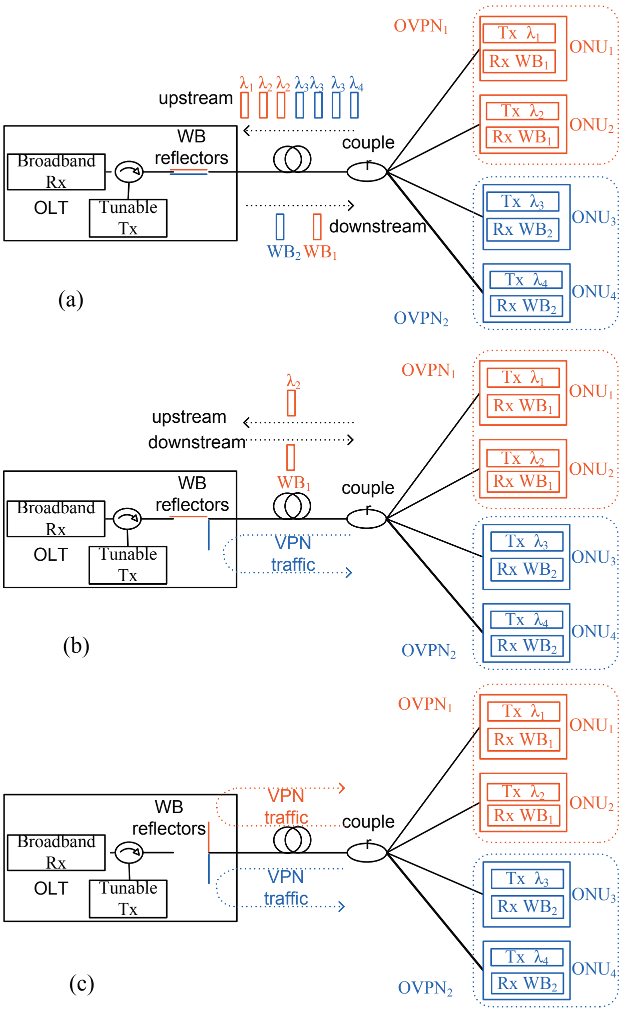


Figure 14 (online color at: www.lpr-journal.org) A waveband reflector based PON and three communication cases: (a) non-VPN transmission, (b) simultaneous transmission of non-VPN traffic and VPN traffic in different all-optical VPNs, and (c) parallel transmission of VPN traffic in different all-optical VPNs [36].

Scheme 2 – VPN traffic transport using Time-Division-Multiplexed-Frequency-Division-Multiplexing

Another scheme of all-optical VPN based on the waveband-selective PON employs time-division-multiplexed-frequency-division-multiplexing (TDM-FDM) signal format to transmit VPN and non-VPN data simultaneously and a waveband multiplexer is employed to improve the VPN traffic security [37].

The TDM-FDM format is typically generated by directly driving a semiconductor laser diode (LD). The driving signal to the LD is multiplexed in time from two-tributary data for the VPN traffic and non-VPN traffic, respectively. The two TDM tributaries possess different amplitudes, which cause certain frequency difference and result in an FDM signal. Therefore we term this format as TDM-FDM.

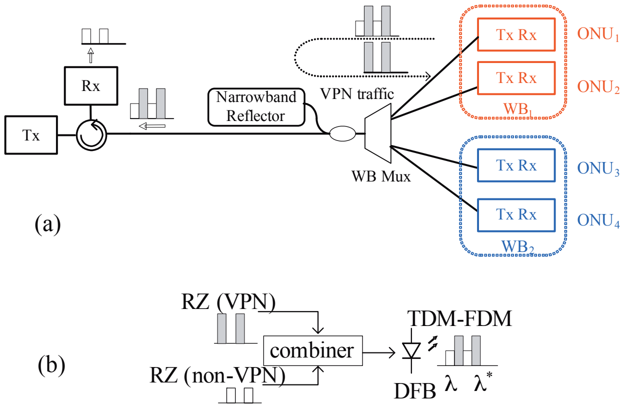


Figure 15 (online color at: www.lpr-journal.org) (a) Schematic of all-optical VPN using TDM-FDM format; (b) generation of the TDM-FDM signal format [37].

Fig. 15a gives a sample schematic. The VPN traffic is encoded to return-to-zero (RZ) format with a duty cycle of 50% or less. The non-VPN traffic is also formed to RZ format, however with lower amplitude. The choice of higher amplitude of the VPN data is due to the fact that the VPN data experiences double loss. The two tributaries are combined and then applied to an LD. The difference in the amplitude of the driving signal creates frequency shift of the optical signal in the two tributaries. The generation of the TDM-FDM signal format is illustrated in Fig. 15b.

At the coupler, one part of the FDM signal is optically de-multiplexed by a narrow-band filter (Fig. 15a), and the VPN traffic is reflected back and then delivered by the waveband multiplexer (WB Mux) to the all-optical VPN that the source ONU belongs to. The other portion of the traffic is received by the OLT which either electronically or optically de-multiplexes the non-VPN traffic tributary from the received signal.

In this scheme, simultaneous transmission of the VPN signal and upstream signal is enabled by employing the TDM-FDM format, which can be easily generated by using commercial components. The network only needs a passive reflector rather than a complex waveband reflector based on dynamic filters as in [36]. The WB Mux can direct the VPN data back to the all-optical VPN that the source ONU belongs to, instead of to all ONUs in the network, thus improving the traffic security.

However, the contention between the downstream traffic and VPN traffic still remains. In a same VPN, the upstream traffic can only be simultaneously transmitted with either the VPN data or downstream data, due to the contention between the VPN traffic and the downstream transmission.

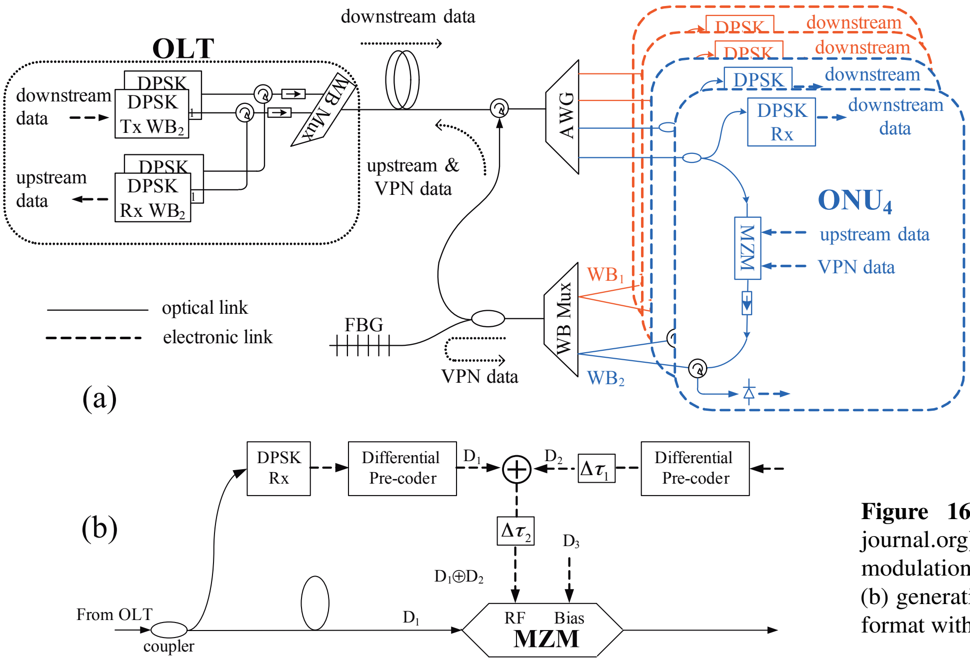


Figure 16 (online color at: www.lpr-journal.org) (a) Architecture of the hybrid-modulation based waveband-selective PON; (b) generation of the DPSK/IM modulation format with DPSK erasure [38].

Scheme 3 – VPN traffic transport using hybrid DPSK/IM format

To remove the contention among different types of traffic in a same VPN, another scheme based on waveband-selective PON is proposed using an orthogonal differential phase shift keying/intensity modulation (DPSK/IM) format to carry non-VPN and VPN data [38]. Particularly, the DPSK format is used for the non-VPN traffic and the IM format for the VPN traffic.

In this architecture as shown in Fig. 16a, there is a pair of transmitter and receiver at a waveband in the OLT for each VPN. The downstream packets are sent from the OLT to the ONUs in the DPSK format. The upstream signals, containing the upstream data and the VPN data, are split into two parts by a coupler. One is passed through a circulator to the OLT, while the other part is reflected by an FBG next to the coupler and broadcast within the VPN.

In this network, the orthogonal DPSK/IM modulation format is used to enable the simultaneous transmission of the VPN data and the non-VPN data. As shown in Fig. 16b, within an ONU, the downstream data in the DPSK format is erased and the upstream data is rewritten on the optical carrier. Meanwhile, the VPN data is superimposed onto the DPSK signal by modulating its intensity. DPSK data erasing and rewriting can be achieved by a single Mach-Zehnder modulator (MZM), as illustrated in Fig. 16b. Before re-modulation, a pre-coded data D1⊕D2 is obtained by an XOR operation on the demodulated downstream data D1 and the upstream data D2, which are both differentially pre-coded. The operation of D1⊕D2 on the input signal D1, when the MZM is biased at a null point, results in (D1⊕D2)⊕D1, which is D2. Frame synchronization is necessary between D1 and D1⊕D2, which can be controlled by an electronic buffer. The VPN data D3 is superimposed onto the DPSK signal by modulating the bias point of the MZM between the null point and a small fraction of V_π.

This architecture has some advantages over the previous two waveband-selective PON schemes. Firstly, no laser is needed in the ONU, because the downstream optical carrier is reused for upstream transmission. Secondly, only one single MZM is employed for DPSK erasing/rewriting and DPSK/IM formatting, which is cost-effective. Thirdly, the use of the DPSK/IM modulation format in this design completely removes the confliction between the VPN traffic and non-VPN traffic in a VPN. Fourthly, the non-VPN traffic of different VPNs can be transmitted in parallel, because a pair of tunable transmitter and receiver are used in the OLT for each all-optical VPN. Lastly, the use of the WB Mux improves the security of the VPN traffic by isolating one VPN from others.

4. All-optical VPN in WDM-PON

WDM is a highly efficient method for sharing a PON architecture. In this scheme, each subscriber is assigned a pair of dedicated wavelengths (Fig. 17); this is in contrast to the TDM case where a single pair of wavelengths is shared among all the subscribers connected to the PON. This means that each user can send data to the OLT at any time, independent of what the other users are doing. In other words, there is no interaction or coupling between the subscribers on a WDM-PON; this eliminates any management issues related to sharing the PON. Each subscriber gets a dedicated point-to-point optical channel to the OLT, although they are sharing a common point-to-multipoint physical architecture.

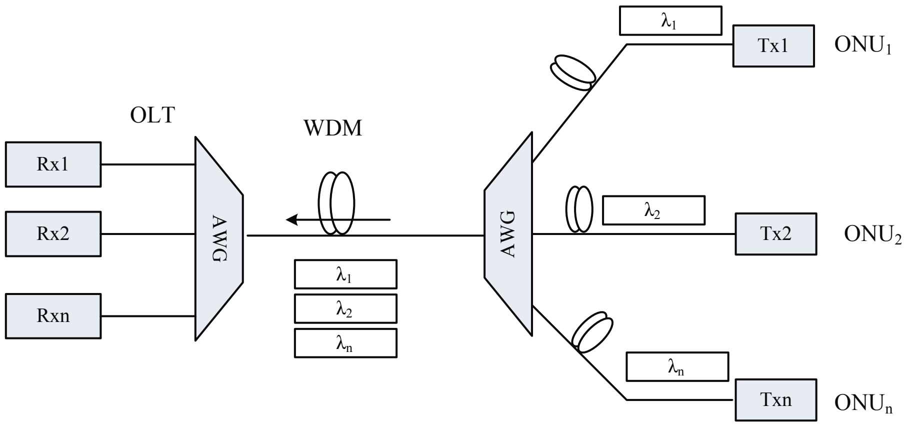


Figure 17 (online color at: www.lpr-journal.org) Architecture of WDM-PON.

To realize all-optical VPN communication in a WDM PON, the key is how to distinguishingly route the VPN traffic to the destined ONUs with only passive components available in an RN. Two schemes are demonstrated by using the cyclic $N \times N$ AWG as a router for VPN and conventional non-VPN traffic simultaneously.

4.1. All-optical VPN in WDM-PON with static optical links

In a conventional WDM-PON, AWG is used as a WDM Mux/Demux. Employing an $N \times N$ AWG with some ports on its one side linked by fibers, the upstream optical signals can be routed back to the ONUs according to the cyclic wavelength characteristic of the AWG. Thus it is possible to build an all-optical VPN in a WDM-PON.

The architecture of all-optical VPN over a WDM-PON using fiber links connecting specific ports of an $N \times N$ AWG with N users is shown in Fig. 18, where $N = 8$ for illustration. With a similar architecture to the conventional WDM-PON, the OLT is equipped with N downstream transceivers in the 1.55 µmwaveband. The $1 \times 2N$ (e.g., 1×16) AWG1 is employed at the OLT to multiplex and demultiplex the downstream and the upstream communications, respectively. Fig. 18b show a formation example of two VPNs (ONU-VPG1 & ONU-VPG2) in the WDM-PON, where five ONUs (ONU1-5) are involved in the ONU-VPG1 and the other three ONUs (ONU6-8) belong to the ONU-VPG2. At the RN, one 5×5 star-coupler and one 3×3 star-coupler are employed to duplicate and broadcast the inter-ONU VPN signals, via the $2N \times 2N$ AWG2 (e.g., 16×16) within their respective VPNs. The connection patterns between the star-couplers and the AWG2 are consistent with the VPN configuration. For VPN1, the input ports of the 5×5 star-coupler are connected to the I1, I3, I5, I7, I9 ports of the AWG2, while their output ports are connected to I2, I4, I6, I8, I10 ports of the AWG2, respectively. Similarly, the connection pattern for the VPN2 is illustrated in Fig. 18a. In the ONU, two transceivers are assigned for normal up-/downstream traffic transmission and inter-ONU VPN traffic transmission, respectively. Fig. 18c illustrates the wavelength assignment. The downstream and the upstream carriers are in the blue-band free-spectral range (FSR) of the AWG2, while the inter-ONU traffic carriers are assigned as the first wavelength λ_{2N+1} (say λ_{17}) in the red-band FSR of the AWG2. Therefore, in the RN and the ONUs, blue/Red (B/R) filters are utilized to combine and separate the inter-ONU carriers. The proposed scheme successfully enables the all-optical VPN connections in a WDM-PON by employing the wavelength routing of a $2N \times 2N$ AWG.

4.2. All-optical VPN in WDM-PON with dynamic VPN reconfigurability using RF-tone identifications

To realize dynamic all-optical VPN formation in WDM-PON, frequency-tunable RF tones are added to the VPN signals at the ONUs for identification and access control of different VPNs.

The general configuration of the WDM-PON with all-optical VPN using dynamic RF-tone identification is similar to the last scheme employing fiber links. At the RN, a $1 \times (N-1)$ star coupler is used. The input port of the star coupler is connected to the second input port of the AWG2, while the $(N-1)$ output ports of the star coupler are connected to the other $2k^{\text{th}}$ $(k = 2, 3, \ldots, N)$ input ports of the AWG2 as shown in Fig. 19a. As the downstream signal is modulated in DPSK format, the outgoing VPN signal is re-modulated on the downstream carrier, which is further delivered back to the AWG2 at the RN, via the upstream distribution fiber. With the cyclic property of the $2N \times 2N$ AWG and the downstream, upstream and VPN wavelengths properly assigned to the N ONUs, the VPN signal from each ONU is routed out from the port I2 of the AWG2, where it is power split into $(N-1)$ copies by the $1 \times (N-1)$ star coupler. Routed by the AWG2 again, the $(N-1)$ copies of signal are transmitted to the other $(N-1)$ ONUs, to achieve a broadcast functionality among the ONUs [40]. When receiving at the ONU, the VPN signal is selectively received with RF tones incorporated to

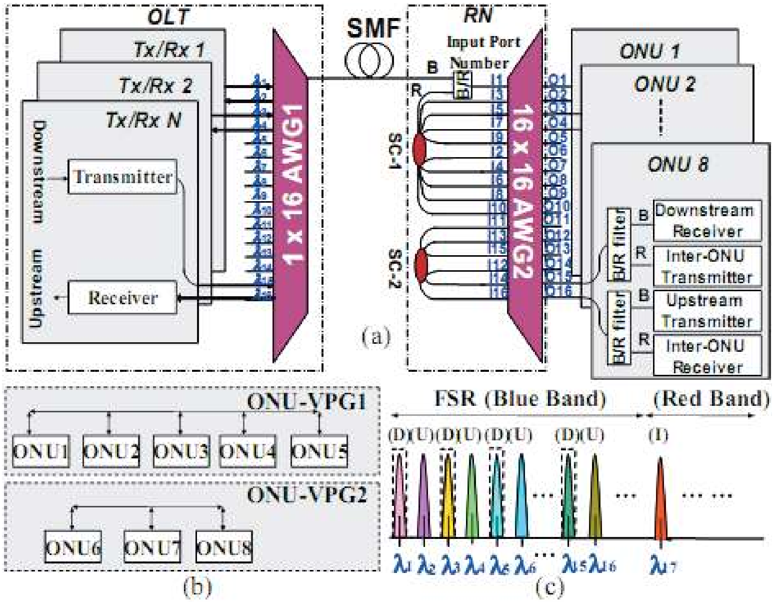
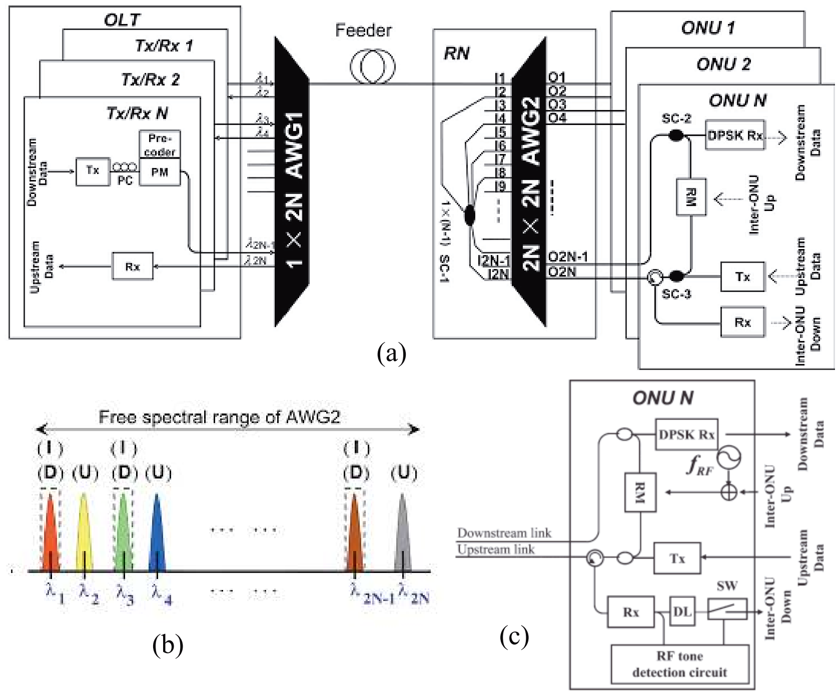


Figure 18 (online color at: www.lpr-journal.org) (a) Schematic diagram of proposed WDM-PONs with two-VPN configuration. (b) Logical connections of an example of two VPNs in a WDM-PON. (c) Wavelength assignment plan [39].



RF Tones	ONU-VPG#1	ONU-VPG#2	ONU-VPG#3	ONU-VPG#4
f_1	0	0	1	1
f_2	0	1	0	1

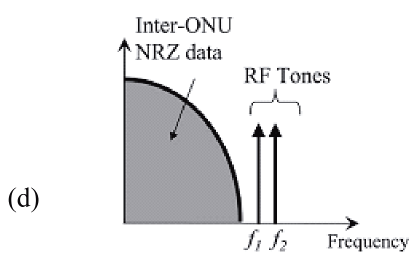


Figure 19 (online color at: www.lpr-journal.org) (a) Proposed ONU internetworking architecture for WDM-PONs (PM: optical phase modulator, RM: remodulation module, SC: star coupler, PC: polarization controller). (b) wavelength assignment plan (D: downstream wavelength, U: upstream wavelength, I: inter-ONU traffic wavelength). (c) modified ONU structure for ONU-VPG communication (DL: electronic delay line, SW: electronic switch, RM: remodulation module). (d) example spectrum for the VPN traffic with a two-RF-tone identification [41].

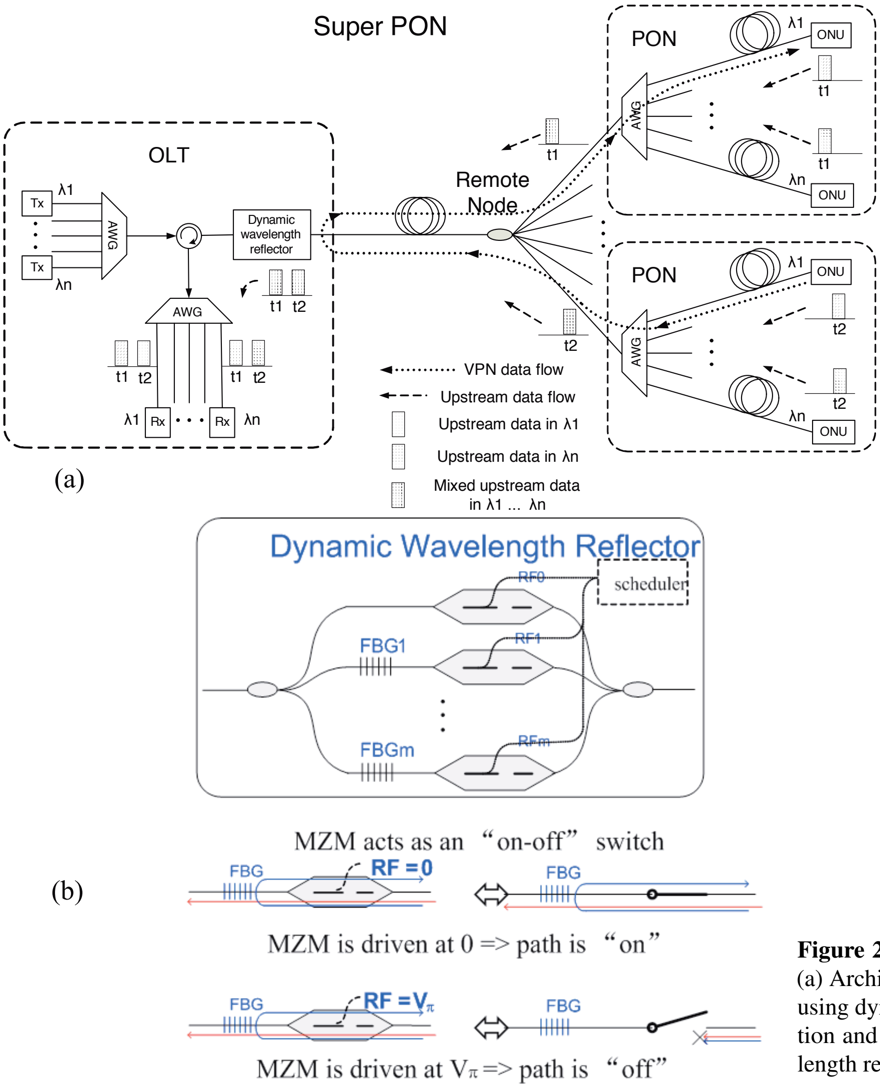


Figure 20 (online color at: www.lpr-journal.org) (a) Architecture of the two-stage TDM/WDM PON using dynamic wavelength reflection; (b) configuration and operation principle of the dynamic wavelength reflector [44].

the baseband data. Based on the VPN identification by the RF tones, only the signals from the VPN, which the ONU belongs to, are detected, and otherwise the baseband data are discarded. Fig. 19d depicts an example of a four-VPN case with two RF tones as identification. More details can be found in [41].

With proper modification to the RF tone detection circuits in the ONUs, the formation of the VPN can be updated, which increases the flexibility and reconfigurability of the network.

5. All-optical VPN in a two-stage TDM/WDM PON

Recently, a new type of PON with a two-stage architecture shows the advantages of wider coverage area and serving more ONUs with relatively low cost [42, 43]. Two schemes have been proposed to establish an all-optical VPN connecting ONUs in different sub-PONs on the lower stage.

5.1. Dynamic wavelength reflection based two-stage PON

Fig. 20a shows the architecture of the two-stage TDM/WDM PON with all-optical VPN based on a dynamic wavelength reflector. The lower stage consists of conventional wavelength-division WDM-PONs operating in burst mode to interleave the upstream and VPN traffic. They are combined by a passive coupler and directed to an OLT through a feeder fiber. A $1 \times N$ coupler at the remote node broadcasts the downstream traffic to each PON, where an AWG router separates the WDM channels so that point-to-point connections to each ONU are established. Since the PONs share the same group of wavelengths, upstream data originating from ONUs of the same color has to be multiplexed in the TDM manner. When the dynamic wavelength reflector is switched on, the transmitted packets from an ONU can be optically redirected back to the remote node and subsequently broadcast among all the ONUs using the same wavelength channel in different

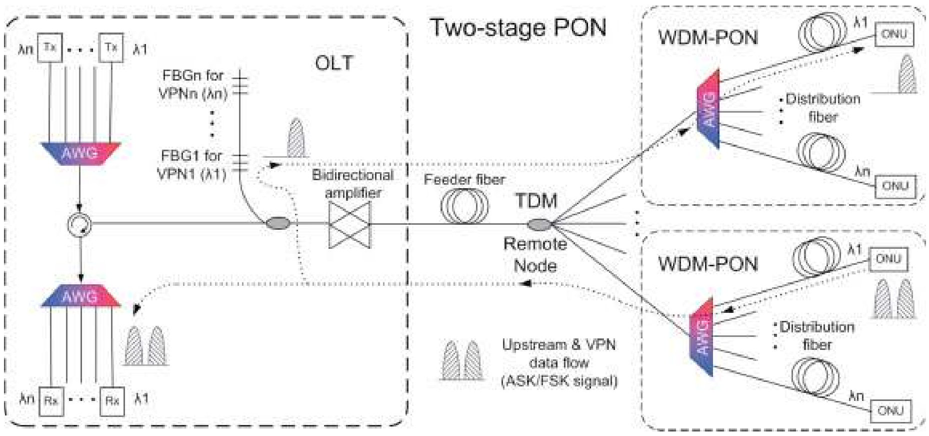


Figure 21 (online color at: www.lpr-journal.org) Architecture of the two-stage PON using ASK/FSK format [46].

PONs. Thus, an optical VPN is formed for these ONUs in a broadcast-and-select manner.

Fig. 20b illustrates the structure of the dynamic wavelength reflector. It consists of two $1 \times M$ star-couplers connected by a set of optical paths of equal lengths, with a Mach-Zehnder modulator (MZM) and one or more optional FBG embedded in each path. By driving the MZMs between the peak and the null of the transmission curve with RF signals, shown in Fig. 20b, data packets entering the dynamic wavelength reflector can be blocked, transmitted, or reflected. In each path, one or more FBGs can be installed to reflect one or more wavelengths. When an MZM is in the transmission mode, the downstream/upstream traffic falling into the FBG bandwidth is reflected, while the rest passes through. Therefore, by selecting the through paths, reflection of multiple wavelengths is possible. The OLT should schedule the state of the dynamic wavelength reflector to pass the regular upstream and downstream traffic and redirect the optical VPN data in their corresponding time slots. The number of optical paths is flexible and can be determined by the specific network scheduling. Optical amplification may be employed at the wavelength reflector to increase the scalability.

With the dynamic wavelength-selective reflection, the all-optical VPN function can be realized across different sub-PONs in the lower stage. However, this scheme suffers a poor scalability due to a high loss resulting from: (1) a long-distance round trip propagation of the VPN traffic, and (2) the usage of two 1xm couplers in the dynamic wavelength reflector which is installed in the OLT to reflect the VPN signal. Moreover, the VPN and non-VPN traffic have to interleave in time domain, which reduces the bandwidth of the non-VPN traffic and requires proper scheduling algorithm to avoid contention between VPN and non-VPN communication.

5.2. *Hybrid modulation format based two-stage PON*

To overcome the drawbacks of the scheme in [44], another proposal to build an all-optical VPN in a two-stage PON is demonstrated. With hybrid ASK/FSK modulation format employed to transmit the upstream and VPN data simultaneously, the scalability of the network is significantly improved, and the scheduling can be greatly simplified [45, 46].

As shown in Fig. 21, the lower stage consists of conventional WDM PONs, which are combined by a passive coupler at a higher stage in TDM manner and connected to the OLT through a feeder fiber. In each ONU, an ASK/FSK modulated optical signal is generated for the simultaneous transmission of the upstream and VPN data, where the FSK modulation is controlled by the VPN data and the signal intensity is modulated by the upstream data. The signal is transmitted upstream through the remote node and arrives at the OLT, where it is split into two parts by a 1×2 coupler. One part goes through a circulator and an arrayed waveguide grating-router (AWG), and subsequently demodulated in the OLT. For this upstream traffic, data originating from different PONs with the same wavelength are interleaved in time as conventional PONs. For the other part, one tone of the FSK signal is reflected by an FBG then broadcast and received as an NRZ signal among all ONUs on the same wavelength in different PONs. As a result, the ONUs of the same wavelength form an optical VPN. Also, VPN using different wavelengths in a waveband is possible by employing a waveband multiplexer combined with couplers at the input ports. Note that, to preserve the FSK information, the upstream ASK signal imposed on the FSK signal should have a relatively low extinction ratio. Both the VPN and upstream packets have to be scheduled because of the TDM nature at the higher stage.

At the OLT, by employing the ASK/FSK format, the FSK VPN traffic can be redirected back by using FBGs instead of a high-loss dynamic wavelength reflector in [44]. Also, a bidirectional fiber amplifier installed close to the FBG can compensate the upstream and downstream transmission losses and boost the redirected VPN signal back to ONUs. Therefore, the network scalability can be significantly improved.

Table 2 Technologies of traffic redirection and separation used in the preceding schemes.

		Traffic redirection			Traffic separation			
		Wavelength-selective reflection	$N \times N$ star coupler	$N \times N$ AWG	WDM	RF	CDMA	Modulation format
TDM-PON	Inter_ ONU broadcasting schemes	✔	✔		✔			
	SC based schemes		✔		✔			
	RF multiplexed schemes	✔	✔			✔		
	ECDMA schemes		✔				✔	
	RSOA based schemes		✔		✔			
	Dynamic waveband-reflection schemes	✔			✔			✔
WDM-PON	Static-link based schemes			✔	✔			
	RF-tone identification			✔	✔			
Two-stage PON	Dynamic wavelength-reflection based scheme	✔			✔			
	ASK/FSK based sheme	✔						✔

6. Summary and outlook

Table 2 summarizes the traffic redirection and separation technologies used in the preceding schemes to establish all-optical VPN communications. To redirect the VPN traffic, using wavelength-selective reflectors, e.g. FBGs, with a $1 \times N$ SC can reflect traffic at specific wavelengths, but suffers high splitting loss as the signal passes through the SC twice. $N \times N$ SC is an alternative to reduce the splitting loss, however as a trade-off, two distribution fibers are needed to connect the SC and each ONU. $N \times N$ AWG is an efficient candidate to de-multiplex the WDM channels and simultaneously route the traffic according to the wavelengths in a WDM-PON. Employing sophisticated electrical technologies, such as RF modulation and ECDMA, can separate the different types of traffic in electrical domain. WDM technique can provide better isolation and transparency to the VPN and non-VPN optical signals. Hybrid modulation formats are also utilized to provide an optical-domain separation without additional wavelength; however, signal interference between different modulation formats should be carefully managed. The progress in the field of all-optical VPN in PON is rapid and attracting attention from industry and academia. We review recent advances from conventional TDM-PON to emerging WDM- and two-stage PONs. The all-optical VPNs in the future are expected to cover larger area not only in access networks, but also possibly in metro networks or even wider areas. From service providers' point of view, VPN subscribers may change their groups, thus re-configurability is required to satisfy users' demands and provide more flexible services. Meantime, as an additional function on the shared infrastructures, all-optical VPN should not increase the cost of the infrastructures and degrade the quality of non-VPN services. Also, transparency to the modulation format and data rate is desired to facilitate the network upgrade in the future.

Acknowledgements This work was supported by the 863 High-Tech program (2006AA01Z255), and the Fok Ying Tung Fund (101067). Part of the work was supported by a research grant from Hong Kong Research Grants Council (Project No. CUHK4142/06E).

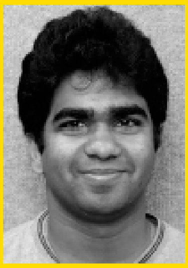
Yikai Su received the B. S. degree from the Hefei University of Technology, China in 1991, the M. S. degree from the Beijing University of Aeronautics and Astronautics, China in 1994, and the Ph. D. degree in EE from Northwestern University, Evanston, IL, USA in 2001. He was with Crawford Hill Laboratory of Bell Laboratories for three years before he joined the Shanghai Jiao Tong University (SJTU), Shanghai, China, as a Full Professor in 2004. He became the associate department chair of Electronic Engineering in 2006. He is the chair of the IEEE ComSoc Shanghai chapter, and a faculty advisor of the SJTU OSA student chapter. His research areas cover modulation formats and their applications in networks, and optical signal processing using silicon nanophotonic devices. He has about 150 publications in international journals and conferences, including about 40 IEEE Photonics Technology Letters papers, about 30 invited conference presentations, and 8 postdeadline papers. He holds 4 US patents with over 10 US or Chinese patents pending. Prof. Su is a senior member of IEEE and a member of OSA.

Yue Tian received the B. S. degree in communication engineering from Shanghai Jiao Tong University (SJTU), China, in 2006, where he is currently working toward the M. S. degree in communication and information system.

Since October 2005, he has been with the State Key Laboratory of Advanced Optical Communication Systems and Networks, SJTU, Shanghai, China. His research interests include the optical virtual private network, optical access networks and modulation formats.

Mr. Tian is a student member of IEEE and OSA. He serves as a Vice-President of Shanghai Jiao Tong University Student Chapter of OSA.

Elaine Wong received the Ph. D. degree from the University of Melbourne, Parkville, Australia, in 2002. She joined the Photonics Research Laboratory, Department of Electrical and Electronic Engineering, University of Melbourne, as a Research Fellow, where she carried out a research in the areas of optical local area networks, optical access networks, and optical performance monitoring. She is currently a Senior Research Fellow with the ARC Special Research Centre for Ultra-Broadband Information Networks and the Victoria Research Laboratory of the National ICT Australia. As a recipient of the Early Career Research Grant and Faculty of Engineering Research Fellowship, she spent the year 2006 with University of California, Berkeley. Dr. Wong is currently serving as a member of the Optical Networks and Systems Committee of the IEEE Lasers and Electro-Optics Society (LEOS).



Nishaanthan Nadarajah received the B. E. degree (first class honors) in telecommunications engineering from Royal Melbourne Institute of Technology (RMIT) University, Melbourne, Australia, in 2001 and his Ph. D. degree from the University of Melbourne in 2006. Since then, he has been working as a researcher with National Information and Communications Technologies Australia (NICTA), Victoria Research Laboratory, University of Melbourne, Parkville, Australia. His main research interests include optical access networks, 100 G Ethernet technologies, photonic packet switching, and optical label switching.

Calvin C. K. Chan received his B. Eng., M. Phil. and Ph. D. degrees from the Chinese University of Hong Kong, all in Information Engineering. In 1997, he joined the Department of Electronic Engineering at the City University of Hong Kong as a Research Assistant Professor. In 1999, he joined Bell Laboratories, Lucent Technologies, Holmdel, NJ, as a Member of Technical Staff. In 2001, he joined Department of Information Engineering at the Chinese University of Hong Kong and now serves as an Associate Professor. He co-supervises the lightwave communication research group at the same department. Dr. Chan has served as member of the Technical Program Committees of many international conferences, including the prestigious Optical Fiber Communication Conference (2005-07). Currently, he serves as an Associate Editor for OSA Journal of Optical Networking. He has published more than 180 technical papers in refereed international journals and holds one issued US patent. His main research interests include optical metro/access networks, data networking, high speed all-optical signal processing, optical packet switching and optical performance monitoring. He is a senior member of IEEE and a member of OSA.

References

[1] K. Cho, K. Fukuda, H. Esaki, and A. Kato, in: Proceedings of the Conference of the Special Interest Group on Data Communication, Pisa, Italy 2006, pp. 207–218.

[2] C. H. Lee, W. V. Sorin, and B. Y. Kim, IEEE/OSA J. Lightwave Technol. **24**, 4568–4583 (2006).

[3] F. Effenberger, G. Kramer, and T. Pfeiffer, IEEE Commun. Mag. **46**, 17–25 (2007).

[4] Z. Zhang, Y. Q. Zhang, X. Chu, and B. Li, Photonic Netw. Commun. **8**, 213–225 (2004).

[5] R. Cohen, IEEE Commun. Mag. **42**, 156–163 (2003).

[6] P. Knight and C. Lewis, IEEE Commun. Mag. **43**, 124–131 (2004).

[7] T. Takeda, H. Kojima, and I. Inoue, in: Proceedings of the 9th Asia-Pacific Conference on Communications, Penang, Malaysia 2003, Vol. 2, pp. 751–755.

[8] T. Takeda, OMJ4, in: Proceedings of the 31st Optical Fiber Communication Conference, Anaheim, CA 2006.

[9] J. Zheng, B. Zhou, and H. T. Mouftah, Photonic Netw. Commun. **8**, 255–266 (2004).

[10] T. Takeda, T. Ohba, I. Inoue, and S. Urushidani, IEICE Trans. Commun. E **88-B**, 3343–3352 (2005).

[11] J. M. Jo, S. J. Lee, K. D. Hong, C. J. Lee, O. H. Kang, and S. U. Kim, Photonic Netw. Commun. **13**, 19–30 (2007).

[12] K. M. Yong, G. S. Poo, and T. H. Cheng, Comput. Commun. (Netherlands) **29**, 2169–2180 (2006).

[13] C. Cavdar, A. Gencata, and B. Mukherjee, IEEE Commun. Mag. **46**, 60–66 (2007).

[14] S. French and D. Pendarakis, Photonic Netw. Commun. **8**, 227–238 (2004).
[15] T. Takeda, D. Brungard, D. Papadimitriou, and H. O. Braihim, IEEE Commun. Mag. **44**, 60–67 (2005).
[16] F. L. Verdi, M. F. Magalhães, E. Cardozo, E. R. M. Madeira, and A. Welin, J. Netw. Syst. Manag. **15**, 141–170 (2007).
[17] D. Benhaddow and W. Alanqar, IEEE Commun. Mag. **46**, 52–58 (2007).
[18] N. Ghani, M. V. Muthalaly, D. Benhaddou, and W. Alanqar, OSA J. Opt. Netw. **5**, 367–382 (2006).
[19] A. Haque and P. H. Ho, IEEE Trans. Reliab. **55**, 516–524 (2006).
[20] Network based VPNs-generic architecture and service requirements, ITU-T Recommendation Y.1311, ITU, Geneva, Switzerland (2002).
[21] Layer 1 Virtual Private Network Generic Requirements and Architecture Elements, ITU-T Recommendation Y.1312, ITU, Geneva, Switzerland (2003).
[22] Layer 1 Virtual Private Network Service and Network Architectures, ITU-T Recommendation Y.1313, ITU, Geneva, Switzerland (2004).
[23] Y. Su, invited paper ThO5, in: Proceedings of the 20th Annual Meeting of the IEEE Lasers and Electro-Optics Society, Lake Buena Vista, Florida 2007.
[24] C. J. Chae, S. T. Lee, G. Y. Kim, and H. Park, IEEE Photon. Technol. Lett. **11**, 1686–1688 (1999).
[25] C. J. Chae and H. Park, and J. H. Eom, IEEE Photon. Technol. Lett. **13**, 1133–1135 (2001).
[26] E. Wong and C. J. Chae, IEEE Photon. Technol. Lett. **16**, 2195–2197 (2004).
[27] A. V. Tran, C. J. Chae, and R. S. Tucker, IEEE Photon. Technol. Lett. **18**, 670–672 (2006).
[28] J. G. Kim and C. J. Chae, OTuG1, in: Proceedings of the 32nd Optical Fiber Communication Conference, Anaheim, CA 2007.
[29] N. Nadarajah, M. Attygalle, E. Wong, and A. Nirmalathas, IEEE/OSA J. Lightwave Technol. **23**, 2974–2983 (2005).
[30] N. Nadarajah, E. Wong, M. Attygalle, and A. Nirmalathas, IEEE/OSA J. Lightwave Technol. **24**, 1955–1967 (2006).
[31] N. Nadarajah, E. Wong, and A. Nirmalathas, IEEE Photon. Technol. Lett. **18**, 484–486 (2006).
[32] K. Kitayama, X. Wang, and N. Wada, IEEE/OSA J. Lightwave Technol. **24**, 1654–1662 (2006).
[33] N. Nadarajah, A. Nirmalathas, and E. Wong, Electron. Lett. **43**, 407–409 (2007).
[34] N. Nadarajah, E. Wong, K. L. Lee, and A. Nirmalathas, Opt. Commun. **273**, 246–251 (2007).
[35] N. Nadarajah, K. L. Lee, and A. Nirmalathas, IEEE Photon. Technol. Lett. **19**, 1559–1561 (2007).
[36] Y. Su, P. Hu, W. Hu, J. Zhang, L. Leng, H. He, X. Tian, and Y. Jin, We4.P95, in: Proceedings of the 31st European Conference on Optical Communication, Glasgow, UK 2005.
[37] Y. Su, X. Tian, W. Hu, L. Yi, P. Hu, Y. Dong, and H. He, OTuJ5, in: Proceedings of the 31st Optical Fiber Communication Conference, Anaheim, CA 2006.
[38] Y. Tian, Y. Su, L. Yi, L. Leng, X. Tian, H. He, and X. Xu, Tu4.5.6, in: Proceedings of the 32nd European Conference on Optical Communication, Cannes, France 2006.
[39] Q. Zhao and C. K. Chan, 10A2-3, in: Proceedings of the 12th OptoElectronics and Communications Conference, Yokohama, Japan 2007.
[40] Q. Zhao, X. Sun, Y. C. Ku, C. K. Chan, and L. K. Chen, JThB67, in: Proceedings of the 31st Optical Fiber Communication Conference, Anaheim, CA 2006.
[41] Q. Zhao and C. K. Chan, IEEE/OSA J. Lightwave Technol. **25**, 1970–1977 (2007).
[42] D. J. Shin, D. K. Jung, H. S. Shin, J. W. Kwon, S. Hwang, Y. J. Oh, and C. S. Shim, PDP4, in: Proceedings of the 29th Optical Fiber Communication Conference, Anaheim, CA 2004.
[43] G. Talli and P. D. Townsend, IEEE/OSA J. Lightwave Technol. **24**, 2827–2834 (2006).
[44] Y. Tian, X. Tian, L. Leng, T. Ye, and Y. Su, OWL6, in: Proceedings of the 32nd Optical Fiber Communication Conference, Anaheim, CA 2007.
[45] Y. Tian, T. Ye, L. Leng, and Y. Su, 10.6.6, in: Proceedings of the 33rd European Conference on Optical Communication, Berlin, Germany 2007.
[46] Y. Tian, T. Ye, and Y. Su, IEEE Photon. Technol. Lett. **19**, 1595–1597 (2007).

