# A Scalable All-optical VPN in Multiple PONs with a Two-stage TDM-WDM Architecture

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**Abstract** *We demonstrate optical VPN among different PONs using ASK/FSK format. The scalability is enhanced by using a bidirectional amplifier at the OLT and the FSK format combined with low-loss FBG reflectors for VPN traffic.*

## Introduction

Recently, passive optical network (PON) has been an attractive solution to provide broadband access. The PONs with all-optical virtual private network (VPN) functionality offering dedicated optical channels to connect VPN users [1], show advantages in high throughput and low latency by eliminating the processing bottleneck at the optical line terminal (OLT). The all-optical VPN also provides enhanced security for users at the physical layer. Several schemes have been reported to interconnect optical network units (ONUs) in an optical VPN based on waveband reflection [1,2] or by star couplers [3-5]. To enable optical VPN service in different access networks, an optical VPN scheme connecting the ONUs among different PONs was introduced [6]. 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.

In this paper, we propose and demonstrate a scalable optical VPN for connecting ONUs in different PONs in a two-stage time-division multiplexed (TDM) - wavelength-division multiplexed (WDM) architecture. In the OLT, a bidirectional fiber amplifier is used to amplify the upstream and downstream signals. By using an orthogonal amplitude-shift keying/frequency-shift keying (ASK/FSK) modulation format [7] in each ONU to simultaneously transmit the VPN and upstream traffic, a set of fiber Bragg gratings (FBGs) corresponding to different VPNs are needed in the OLT to reflect back the VPN signals from ONUs in the same VPN. This significantly reduces the loss that was induced by the two 1xm couplers used in the dynamic wavelength reflector in [6]. Compared with the scheme in [6], this proposal possesses three attractive features: (1) the scalability of the network is significantly improved; (2) the upstream and VPN traffic can be transmitted simultaneously by employing the orthogonal ASK/FSK format and (3) scheduling can be greatly simplified.

## Architecture of the optical VPN

Fig. 1 shows our scheme to build VPN connections for the ONUs based on a two-stage PON [6]. The lower stage consists of conventional WDM PONs, which are combined by a passive coupler at a higher stage and directed to an OLT through a feeder fiber. Since the WDM PONs share the same group of wavelengths, the upstream and downstream traffic on a wavelength of different PONs has to be time-division multiplexed. In each ONU, an orthogonally 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 1x2 coupler. One part goes through a circulator and an arrayed waveguide grating-router (AWG), and subsequently demodulated in the OLT. 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.

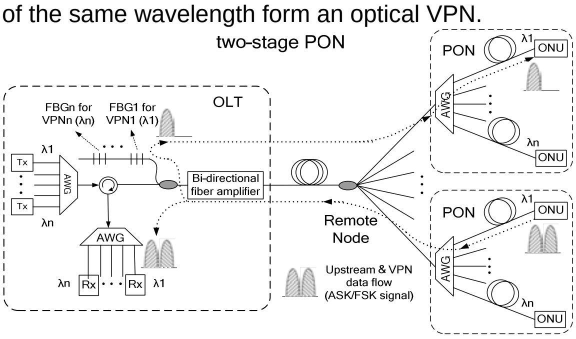


*Fig. 1 The optical VPN in a two-stage PON.*

At the OLT, a bidirectional fiber amplifier is installed close to the FBG, such that the upstream and downstream transmission losses can be compensated. Also, 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 [6]. Therefore, the network scalability can be significantly improved.

## Experiment

To verify the operation principle of the proposed scalable two-stage PON with optical VPN function, we perform an experiment to show the simultaneous transmission of the upstream, the VPN traffic, and the downstream signal.

The experimental setup is shown in Fig. 2. In the VPN

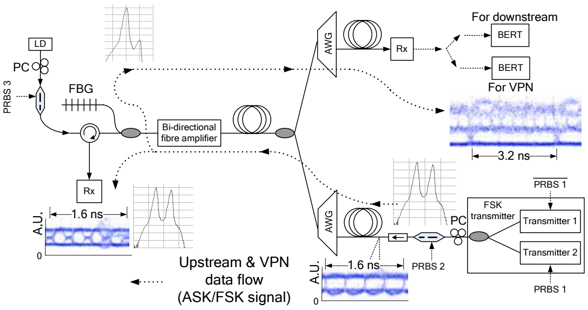


*Fig. 2 Experimental Setup. PC: polarization controller.*

and upstream cases, the VPN data is a 312.5-Mb/s non-return-to-zero (NRZ) data stream with a pseudo-random bit sequence (PRBS) length of $2^7$-1, marked as "PRBS 1" in Fig. 2. The data "PRBS1" and its inverse copy "$\overline{\text{PRBS1}}$" drive two transmitters in an ONU to generate two complementary optical signals at 1549.65 nm and 1549.85 nm, respectively. They are combined through a coupler to form an FSK signal modulated by "PRBS1". The FSK signal can be generated by an integrated FSK transmitter in practice. The intensity modulation on top of the FSK signal is subsequently achieved by a Mach-Zehnder modulator (MZM) driven by an NRZ data stream with a PRBS length of $2^{31}$-1 at a data rate of 2.5 Gb/s with an extinction ratio of ~4 dB. The ASK/FSK optical signal is transmitted upstream through a 12.5-km single mode fiber (SMF), an AWG, a splitter and another 12.5-km SMF to the OLT. After amplification, the optical signal is split into two parts, one passes through the circulator and demodulated by the ASK receiver in the OLT. The other part enters the FBG whose reflective band corresponds to the lower frequency component of the ASK/FSK signal. Thus half of the ASK/FSK signal is redirected downstream to the ONUs. At an ONU, the reflected partial FSK signal is demodulated to a 312.5-Mb/s NRZ signal.

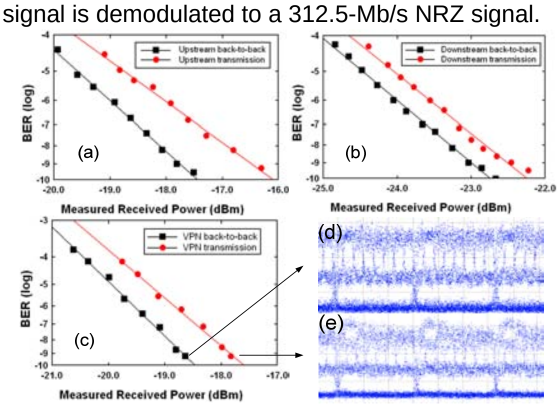


*Fig. 3 BER measurements for the upstream transmission (a), downstream transmission (b), and VPN transmission (c); eye diagram of the reflected partial FSK signal before transmission (d), and after transmission (e).*

The insets in Fig. 2 show the eye diagram of the ASK/FSK signal at the ONU before transmission and the one captured at the OLT side after 25-km transmission and amplification. The bit error rate (BER) performance in Fig. 3(a) indicates that the upstream transmission suffers ~1.4-dB penalty due to the low extinct ratio of the ASK signal. After being reflected by from the FBG, the power ratio between the two wavelengths of the FSK signal is ~23 dB, as shown by the inset of Fig. 2.

For the reflected VPN signal, Fig. 3(d) and (e) show that the demodulated eye diagrams before and after transmission have nearly the same shape. Yet the eye after the transmission displays more noise. Less than 1-dB penalty is observed in the BER measurement for the VPN transmission compared with the back-to-back performance. Although the intra-VPN traffic experiences a round-trip propagation, the bi-directional amplification compensates for the power loss and consequently improves the scalability of the network in evidence.

In the downstream case, a 10-Gb/s NRZ data stream with a PRBS length of $2^{31}$-1 drives the MZM in the OLT to generate the downstream optical signal, which then traverses from the OLT to the ONUs. The BER performance is shown in Fig. 3(b).

The proposed two-stage PON with VPN function shows much better scalable performance than the one in [6]. In a two-stage PON where each WDM PON typically connects 16 ONUs, a dynamic reflector with two 1x16 couplers would be needed in [6], which induces more than 24-dB power loss to the reflected VPN traffic. However, the proposed scheme that only requires an FBG reflector for each VPN and a bidirectional fiber amplifier can increase the power of the received VPN signals at the ONUs by ~30 dB. Therefore the scalability is significantly improved, thus more subscribers can be supported.

## Conclusions

We have proposed and experimentally demonstrated a scalable optical VPN scheme to connect the ONUs in a two-stage PON in conventional and VPN traffic at 2.5 Gb/s and 312.5 Mb/s, respectively. An orthogonal ASK/FSK modulation format is used enabling simultaneous transmission of the upstream and VPN data. A bi-directional amplifier and an FBG are employed at the OLT, instead of the large-loss dynamic wavelength reflector in [6], thus effectively improving the network scalability.


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