Demonstration and Scalability Analysis of All-Optical Virtual Private Network in Multiple Passive Optical Networks Using ASK/FSK Format

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***Abstract*—We present a scalable all-optical virtual private network (VPN) in a two-stage passive optical network (PON) architecture to connect optical network units (ONUs) in different sub-PONs. It provides efficient access and VPN service covering a wider area. The scheme employs amplitude-shift keying/frequency-shift keying (FSK) orthogonal modulation formats, which are used for the VPN and upstream traffic at 625 Mb/s and 5 Gb/s, respectively. At the optical line terminal side, a fiber Bragg grating reflects one of the two frequency components in the FSK signal back to the ONUs in a same VPN. Using a bidirectional amplifier, the power budget and the scalability of the network are significantly improved, as evidenced by numerical analysis using the parameters in the experiment.**

***Index Terms*—Optical access network, optical virtual private network (VPN), passive optical network (PON), scalability.**

I. Introduction

RECENTLY, the passive optical network (PON) has become an attractive solution for broadband access taking its advantages of large coverage area, reduced fiber deployment, broadcast capability, and low cost. The PONs with all-optical virtual private networks (VPNs) that use dedicated optical channels to connect VPN users, can not only achieve a high throughput and low latency by eliminating the processing bottleneck at the optical line terminal (OLT), but also provide enhanced security for users [1]. Several schemes have been reported to interconnect optical network units (ONUs) in all-optical VPNs based on waveband reflection [1]–[4] or by star couplers [5]–[9]. To provide optical VPN service in a wider covering area using a two-stage PON structure [10], an optical VPN scheme connecting ONUs in different PONs was introduced in [11]. However, this scheme suffers a poor scalability due to a high loss resulted from 1) a long-distance round-trip propagation of the VPN traffic, and 2) the usage of two $1 \times m$ couplers in the dynamic wavelength reflector in the OLT to reflect the VPN signal.

In this letter, we propose and demonstrate a scalable all-optical VPN to connect ONUs in different sub-PONs in a two-stage time-division-multiplexed–wavelength-division-multiplexed (TDM-WDM) architecture. In the OLT, a bidirectional amplifier is used to amplify the upstream and downstream signals. By employing an orthogonal amplitude-shift-keying/frequency-shift-keying (ASK/FSK) modulation format [12], [13] in each ONU, this enables simultaneous transmission of 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. Such a scheme significantly reduces the loss that was induced by the two $1 \times m$ couplers used in the wavelength reflector in [11]. Compared with the scheme in [11], 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; and 3) scheduling can be greatly simplified. In [14], we performed a preliminary demonstration of a scalable all-optical VPN connecting multiple PONs in a two-stage TDM-WDM architecture at low data rates. However, no detailed analysis of scalability was provided. In this letter, we increase the upstream and VPN data rates to 5 Gb/s and 625 Mb/s, respectively. We also analyze the scalability of the network with detailed parameters. The results show the feasibility of supporting 160 ONUs using the TDM-WDM architecture and the ASK/FSK format.

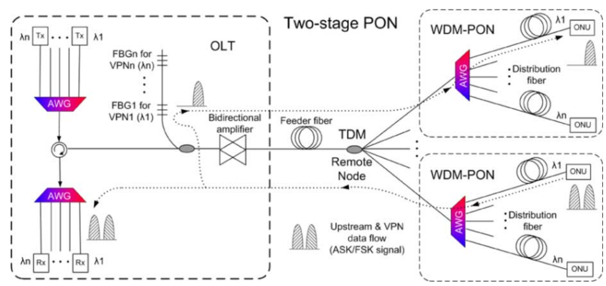

Fig. 1. Optical VPN using ASK/FSK format in a two-stage PON.

II. Principle of the Scalable Optical VPN Employing ASK/FSK Format in a Two-Stage PON

Fig. 1 shows our scheme to build all-optical VPN in the two-stage PON [11]. 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

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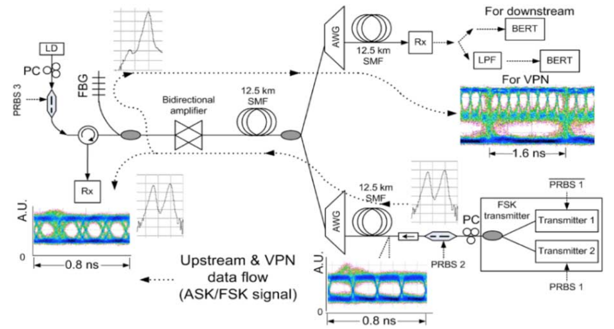

Fig. 2. Experimental setup. PC: polarization controller.

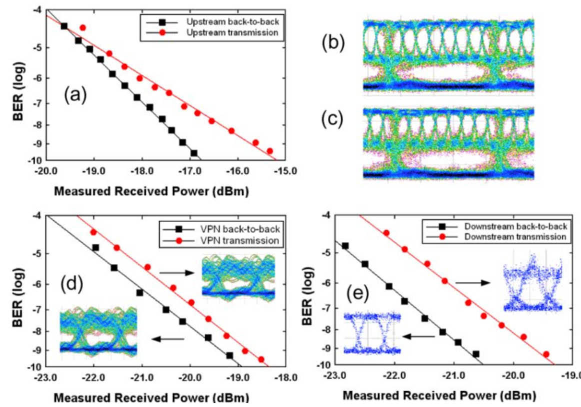

Fig. 3. (a) BER measurement for the upstream transmission; (b) electrical eye diagrams of the reflected partial FSK signal before transmission; (c) after the transmission; (d) BER measurements for the VPN traffic; (e) BER results for the downstream transmission.

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 (AWG) router, 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 nonreturn-to-zero (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 inputs. 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 [11]. 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.

III. Experiment

In this section, we perform an experiment to verify the operation principle of the proposed scalable two-stage PON with optical VPN function, where the downstream, upstream, and VPN signals are transmitted at 10 Gb/s, 5Gb/s, and 625 Mb/s, respectively. The asymmetric data rates can be seen in practice as typically ONUs have more downstream traffic demand than upstream demand in Internet access.

The experimental setup is shown in Fig. 2. In the VPN and the upstream cases, the VPN data is a 625-Mb/s NRZ data stream with a pseudorandom bit sequence (PRBS) length of $2^7 - 1$, marked as "PRBS1" in Fig. 2. The data "PRBS1" and its inverse copy "$\overline{\mathrm{PRSB1}}$" drive two transmitters in an ONU to generate two complementary optical signals at 1549.49 and 1549.36 nm, respectively. They are combined through a coupler to form an FSK signal modulated by "PRBS1." The FSK bit rate could be further increased by using an integrated FSK transmitter [15]. The signal can be generated by a tunable-laser-based FSK transmitter in practice to minimize the size and the power consumption. 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 5 Gb/s with an extinction ratio of ~5 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 reflection band corresponds to the upper frequency component of the ASK/FSK signal. Hence, half of the ASK/FSK signal is redirected downstream to the ONUs. Subsequently, the partially reflected FSK signal is demodulated to a 625-Mb/s NRZ signal at an ONU.

The insets in Fig. 2 show the eye diagrams of the ASK/FSK signal at the ONU before transmission and the one captured at the OLT side after 25-km transmission and amplification, where we observe ~55-ps dispersion-induced walkoff due to the relatively large wavelength spacing between the FSK tones. The bit-error-rate (BER) performance in Fig. 3(a) indicates that the upstream transmission suffers ~1.7-dB penalty due to the low extinction ratio, Rayleigh backscattering, and the dispersion experienced by the ASK signal. When further increasing the upstream bit rate, the wavelength spacing between the two FSK tones should be large enough to avoid beating between them. Reflected by the FBG, the power ratio between the two tones of the FSK signal is ~20 dB, as shown by the inset of Fig. 2.

For the reflected VPN signal, Fig. 3(b) and (c) shows the three-level optical eyes before and after the transmission, which are attributed to the residual 5-Gb/s ASK modulation on the "1" level of the 625-Mb/s FSK signal. The eye after the transmission shows more noise. However, a wider-opening two-level eye diagram can be obtained by applying a 650-MHz low-pass filter after the photodetector as shown in the insets of Fig. 3(d). Less than 1-dB penalty is observed in the BER measurement for the VPN transmission compared with the back-to-back performance both after the filtering. Although the intra-VPN traffic experiences a round-trip propagation, the bidirectional amplification compensates for the power loss and consequently improves the scalability of the network, as will be discussed in Section IV. 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

TABLE I
POWER MARGIN CALCULATIONS USING THE MEASURED EXPERIMENTAL PARAMETER

	VPN traffic in this proposal	VPN traffic in [11]
Transmitted power at ONU (dBm)	0	0
Dynamic reflector loss (dB)	----	20 log(M) + 11
Amplifier gain (dB)	42 [a]	21
FBG loss (dB)	10.7	----
Splitter loss at OLT (dB)	3.5 × 2 [b]	----
Splitter loss at remote node (dB)	10 log(N) × 2	10 log(N) × 2
12.5 km SMF loss (dB)	3.9 × 4	3.9 × 4
AWG loss (dB)	6 × 2	6 × 2
Sensitivity at BER = 10^{-9} (dBm)	-18.75	-21.7
Insertion loss (dB)	45.3 + 20 log(N)	38.6 + 20 log(N) + 20 log(M)
Power Margin (dB)	15.45 – 20 log(N)	4.1 – 20 log(N) – 20 log(M)

[a] The gain of the bidirectional amplifier
[b] "× 2" means that the optical signal experiences the loss twice.

from the OLT to the ONUs. The eye diagrams and BER performance are shown in Fig. 3(e).

IV. SCALABILITY ANALYSIS

In this section, we show that our proposal remarkably improves the network scalability, compared with the scheme in [11]. Table I shows the calculated power budget for the VPN traffic in this proposal and that in [11], where N and M are the numbers of WDM sub-PONs in the network and the ONUs in each WDM sub-PON, respectively. In Table I, the power margin is defined as the difference between the received optical power and the minimum optical power that is required by the receiver to achieve a BER of 10^{-9}.

In Table I, the difference in power margins is caused by the different optical componets used at the OLT in these two schemes. The scheme in this letter employs the bidirectional amplifier, the M FBGs in series, and the 1×2 coupler. The configuration brings a net gain of 24.3 dB. The input optical power to the bidirectional amplifier is controlled, such that no gain saturation occurs. However, in the scheme in [11], a dynamic reflector, consisting of two $1 \times M$ couplers with M FBGs and MZMs in between, results in a power loss of $20\log(M)+11$ dB. The round-trip propagation incurs the same loss in the two schemes, since the VPN signals pass through the same set of components. Consequently, the proposal in this letter shows an improvement of $11.35 + 20\log(M)$ dB in power budget, compared with the scheme in [11].

In a two-stage PON architecture consisting of typical WDM-PONs with $M = 32$ ONUs, our new scheme pocesseses a higher power margin than the previous one by ~41 dB based on the parameters in Table I. For the VPN traffic, the power margin is 15.45–20 log (N) dB. As a result, the two-stage architecture can support $N = 5$ WDM sub-PONs, serving 160 ONUs in total. The single-trip upstream and downstream signals suffer much less loss than the round-trip VPN traffic, thus their power margins are not of concern.

V. CONCLUSION

We have proposed and experimentally demonstrated a scalable optical VPN scheme to connect ONUs in different PONs with a two-stage TDM-WDM PON. An orthogonal ASK/FSK modulation format is used to enable simultaneous transmission of the upstream and the VPN data. The conventional upstream and downstream traffic are transmitted at 5 and 10 Gb/s, with the VPN data operating at 625 Mb/s. A bidirectional amplifier and an FBG are employed at the OLT, instead of the large-loss dynamic wavelength reflector in [11], thus effectively improving the network scalability as evidenced by the analysis and numerical calculations.

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