

Optical VPN in PON Using TDM-FDM Signal Format

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Abstract: We demonstrate a simple and low-cost PON with optical VPN functionality using a directly modulated laser diode to generate TDM-FDM format. This format enables that one tributary of the transmitted signal be reflected to ONUs in the same optical VPN.

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1. Introduction

Passive optical networks (PONs) [1-2] have become an attractive approach to providing broadband access due to their simple architectures and low cost. Virtual private network (VPN) technologies, on the other hand, can be used to offer a wider range of services without incurring much extra cost based on existing infrastructures. Optical-layer VPN in a PON is an effective technique to increase the throughput and reduce the latency of the network [3], while providing security for optical network unit (ONU) users. To date, optical VPNs in PONs have only been studied by a few groups [3]-[5]. Recently we demonstrated a waveband (WB) PON [3] to implement optical VPN based on a traditional PON architecture, however such scheme does not allow simultaneous intra-VPN data transfer and non-VPN communications.

In this paper we propose and demonstrate a new optical VPN in a PON architecture using a time-division-multiplexed (TDM)-frequency division multiplexing (FDM) modulation format in ONUs. Such a format can be conveniently generated by directly driving a semiconductor laser diode. The driving signal to the laser diode is time multiplexed from two tributary data for the intra-VPN and the non-VPN traffic, respectively. The two TDM tributaries possess different amplitudes, which cause certain frequency difference that results in a FDM signal. Therefore we term this format as TDM-FDM. One tributary of the upstream TDM-FDM traffic is directed back to the optical VPN by a wavelength reflector, while the other tributary is de-multiplexed at the OLT. The proposed scheme has several attractive features: it does not require expensive modulators to generate such a format; the driving signal can be easily obtained using matured commercial components; the scheme requires only one pair of transmitter and receiver in each ONU as opposed to two [4]; the proposed optical VPN enables simultaneous data transfer of intra-VPN and non-VPN traffic, which is not possible with the previous proposal [3]; the network only needs a fixed reflector rather than a complex WB reflector based on dynamic filters as in [6]; and the passive reflector can be placed close to the 1xN coupler thus eliminating the loss associated with the OLT feeder fiber for the VPN traffic.

2. TDM-FDM format and the optical VPN architecture

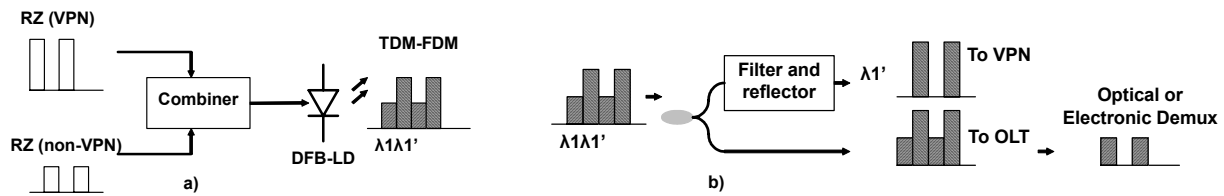


Fig. 1 a) TDM-FDM signal generation in an ONU, b) FDM signal de-multiplexed and reflected to the optical VPN

We first illustrate the generation of TDM-FDM format in Fig. 1a. In each ONU, intra-VPN traffic is aggregated and coded to return-to-zero (RZ) format with a duty cycle of 50% or less. Traffic destined to the OLT is also formed to RZ format, however with a lower amplitude. The choice of higher amplitude of the VPN signal is due to the fact that intra-VPN traffic experiences double loss, as will be explained later. The two tributaries are combined and the signal is applied to a laser diode. The difference in the amplitude of the driving signal creates frequency shift of the optical signal in the two tributaries. Part of the FDM signal is then optically de-multiplexed by a narrowband filter (Fig. 1b), and this VPN traffic is reflected back to the VPN that the ONU belongs to. The other portion of the traffic is received by the OLT which performs either optical or electronic de-multiplexing of the non-VPN traffic tributary

from the received signal. This simple scheme would enable a cost-effective implementation of optical VPN in a PON.

We then provide an example of 4 ONUs grouped into two optical VPNs to explain the operation of the proposed PON. Fig. 2a shows the downstream case, where the OLT sends packets to ONUs by tuning the transmitter to the proper wavelength. Within a WB (optical VPN), the downstream packets are broadcast and selected by the destined ONU. In the upstream case (Fig. 2b), to differentiate the intra-VPN traffic from the OLT traffic, a narrowband filter is placed next to the coupler. The VPN traffic of λ_1 ' is then optically reflected back to the VPN from which they originate. Scheduling is needed to avoid contention with the downstream traffic from the OLT. The non-VPN traffic of λ_1 passes through the other port of the coupler and is received by the OLT.

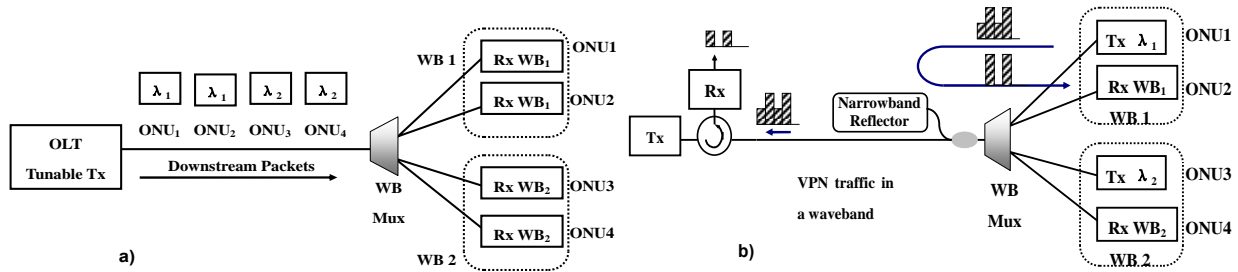


Fig. 2 a) Downstream case of data communication from the OLT to the ONUs, b) Upstream traffic to the VPN and to the OLT.

3. Experiment

To verify the operation principle of the optical VPN in the PON, we perform an experiment to demonstrate the intra-VPN optical networking with simultaneous data transfer to the OLT. Fig. 3 shows the experimental setup. The bit error rate tester (BERT) outputs 1.25-Gb/s non-return-to-zero (NRZ) data with a pseudo-random bit sequence (PRBS) length of $2^{31}-1$, which is then converted to RZ format by external circuits. The RZ signal possesses a ~50% duty cycle. The RZ signal is then power split to two branches by an RF splitter. The powers of the two signals are boosted by RF amplifiers; in one branch the signal is delayed and attenuated to cause different amplitude and phase from the one in the other branch. The signals are then re-combined to drive a DFB laser diode (LD). The difference in amplitudes of the two tributaries causes certain frequency shift in order to generate a TDM-FDM signal. The resulting TDM-FDM signal from an ONU is sent upstream and passes through a 3-dB coupler, one of its output ports is connected to a fiber Bragg grating (FBG) with a 0.1-nm bandwidth centered around 1549.6 nm as the narrowband reflector. In practice, multiple FBGs would be needed in cascade configuration, or the multi-channel reflector can be made more compact using a micro-electromechanical-system (MEMS) based reflector [6]. In the FBG, the tributary signal corresponding to λ_1 passes through and is terminated, while the one of λ_1 ' is reflected back to the ONUs in the same VPN. The remaining signal passes through the other port of the couple and traverses through a 12-km single mode fiber (SMF) before reaching a receiver in the OLT. The signal is optical-to-electrical converted and the non-VPN tributary (λ_1) is selected for error detection. BER testing is performed for the receivers in the second ONU and in the OLT, respectively.

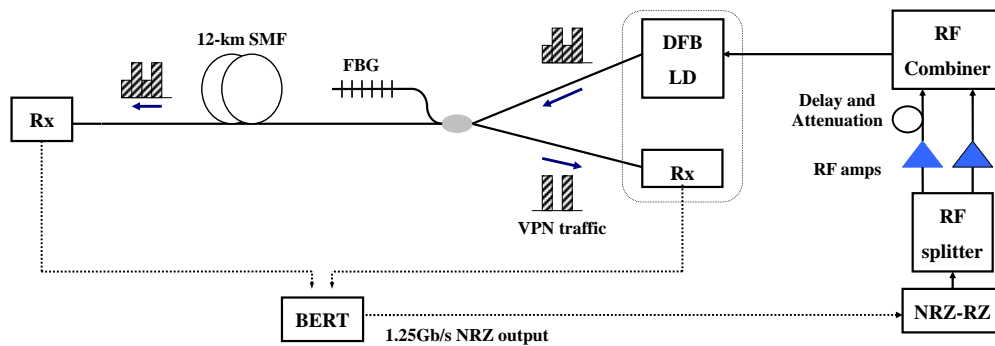


Fig. 3 Experimental setup to demonstrate the optical VPN feasibility in PON.

Fig. 4a shows the eye diagram of the electrical driving signal, whose two tributaries possess different amplitudes. The signal is inverted to satisfy the input requirement of an inverting amplifier in the LD transmitter box (HP83430A). Some ripples on the driving signal waveform can be attributed to the non-ideal response of the two RF amplifiers and possible reflections from the RF splitter and the combiner. Fig. 4b shows the resulting optical signal with different amplitudes and wavelengths. The amplitude ratio of the high-to-low tributaries is controlled to be ~ 2 . It is estimated that the two tributaries differ by ~ 0.1 nm in wavelength, as evidenced by the optical spectrum in Fig. 4c. This is due to the fact that the output wavelength of the DFB LD is dependent on the injected current. On reflection by the FBG, the eye diagram of the λ_1 ' tributary is provided in Fig. 4d. The distortion of the signal waveform is related to the chirp associated with the direct modulation of the DFB LD, as well as certain filter offset that is intentionally introduced to avoid crosstalk from the adjacent tributary, which is closely spaced in wavelength.

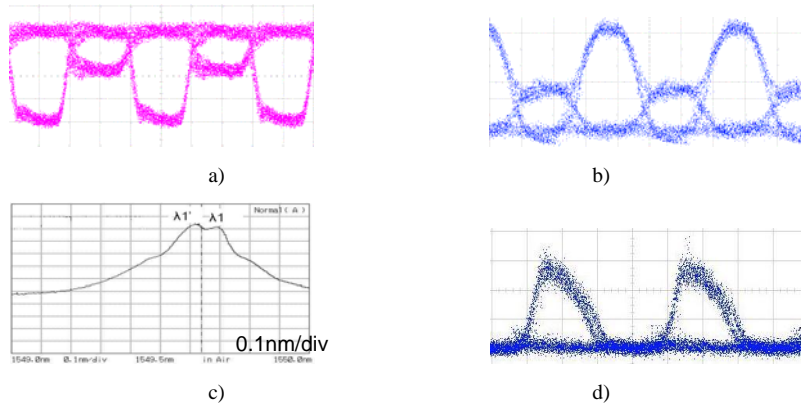


Fig. 4 a). Multiplexed electrical RZ signal for driving the DFB LD, b) the resulting optical TDM-FDM signal, c). the corresponding spectrum of the TDM-FDM signal (resolution: 0.07 nm), and d). the de-multiplexed tributary for the optical VPN. Time scale: 200 ps/div.

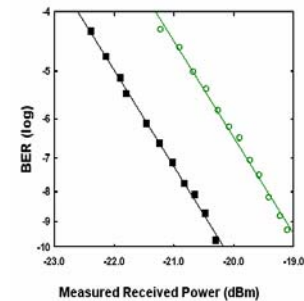


Fig.5 Measured BER performance for the two tributaries, square: VPN traffic, circle: non-VPN traffic

Fig. 5 provides the BER measurement results. In the OLT, the non-VPN data is optical-to-electrical converted and measured for the lower-amplitude tributary, and the measured average powers are corrected by a factor of 1/3 to stand for the non-VPN tributary. Compared with the back-to-back receiver sensitivity of -23 dBm, the penalties are ~ 2.5 dB for the VPN traffic, and ~ 3.5 dB for the non-VPN traffic. It is expected that the penalties can be reduced if filters with narrower bandwidth were available and better electronics could be employed. The experiment verifies the feasibility of building an optical VPN in PON using a new modulation format combined with narrowband filtering. Such an optical VPN would provide high throughput and low latency in broadband data access by taking advantage of optical inter-networking among ONUs [3]. The experiment also shows simultaneous intra-VPN data transfer and non-VPN communication from the ONU to the OLT.

4. Conclusion

We propose and demonstrate an optical VPN scheme in a PON. The technique is based on a directly modulated laser diode, which generates TDM-FDM format containing two tributaries for the VPN and non-VPN traffic, respectively. One tributary of the transmitted signals is reflected to ONUs in the same optical VPN. We perform an experiment to show the physical feasibility of such an optical VPN.

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