A Two-Stage Metro-Access Integrated Network Enabling All-Optical Virtual Private Network

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Abstract *We present a two-stage TDM/WDM metro-access integrated network with all-optical VPN across different sub-PONs. This feeder-ring with access-trees based architecture is employed to provide VPN service covering a wider area.*

Introduction

Several schemes of passive optical networks (PONs) with all-optical virtual private network (VPN) function have been demonstrated in conventional architectures [1,2] or in a two-stage PON [3], which not only achieve high throughput and low latency, but also provide enhanced security for users. On the other side, recently several two-stage time-division multiplexed (TDM)/wavelength-division multiplexed (WDM) ring networks have been reported [4,5]. This feeder-ring/access-tree based topology is considered as a potential convergence scheme of access networks with metropolitan networks, in order to share hardware investment and provide bandwidth efficiency across the access and metro segments [4,5]. However, to the best of our knowledge, all-optical VPN in such a metro-access structure has not been demonstrated up to date.

In this paper, we propose and demonstrate an all-optical VPN scheme in a two-stage metro-access integrated network, where WDM sub-PONs via an $N\times N$ array waveguide grating (AWG) in each remote node (RN) connect to a TDM ring. The optical network units (ONUs) at the same wavelength in different sub-PONs are grouped into a VPN to build direct optical internetworking. In order to maximize the throughput of the network, the downstream, upstream and VPN signals are assigned in different wavebands separated by the free-spectral range (FSR) of the $N\times N$ AWGs, such that different types of traffic can be transmitted in parallel. Furthermore, to reduce the cost, optical carriers provided by the optical line terminal (OLT) are reused in each ONU by employing a coherent differential-phase-shift keying (DPSK) multiplexing technique [6], which consequently saves the number of laser sources in the network.

Principle and architecture

The general architecture of the proposed two-stage TDM/WDM metro-access integrated network is shown in Fig. 1(a). The basic topology consists of a single-fiber ring with tree sub-PONs attached to it. In each sub-PON, ONUs connecting to the RN are multiplexed in WDM manner, and different sub-PONs are time-division multiplexed. The AWG in each RN has the same FSR. Since the downstream, upstream and VPN wavelengths are assigned in three adjacent wavebands separated by the FSR, they can be simultaneously routed to the destined ONUs by a single AWG.

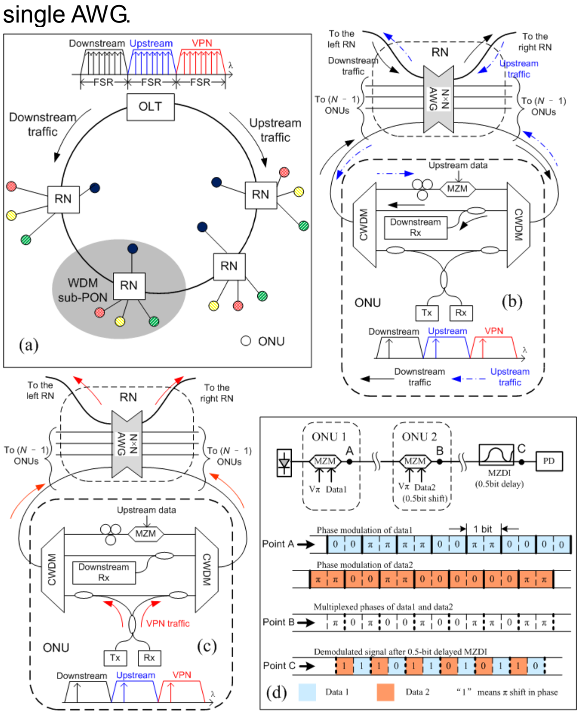

Figure 1: (a) General architecture of the metro-access integrated network. Structure of a sub-PON with (b) up-/downstream and (c) VPN traffic indicated. (d) Principle of the coherent DPSK signal multiplexing.

Fig. 1(b) shows the structure of a sub-PON including an RN and (N - 1) ONUs with downstream traffic indicated. When the downstream DPSK signal passes through an ONU, a small amount of the power is tapped for detection, while the other part goes through, and is sent back to the RN and directed to the next sub-PON.

In parallel with the downstream traffic, upstream signals circulate along the feeder-ring in the opposite direction. A centralized optical carrier at each wavelength is supplied by the OLT, and reused by all the ONUs at the corresponding wavelength. Here a coherent DPSK signal multiplexing technique is used to modulate the upstream data from each ONU onto the optical carrier to form a high-speed DPSK signal. Taking a two-ONU case for example (Fig. 1(d)), the optical carrier is successively DPSK-modulated by two data sources (Data1, Data2). After the first ONU, the phase information of the DPSK signal is marked in Fig. 1(d). In the second ONU, with a half-a-bit time shift relative to Data1, Data2 drives the Mach-Zehnder

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modulator (MZM) to re-modulate the phase of the optical signal to generate a multiplexed DPSK signal, which is the result of an XOR operation of the two data streams with a half-bit shift in time domain. Since the information of a DPSK signal is carried by the phase difference between the adjacent bits instead of the phase itself, the re-modulation does not influence the information carried by the bit transitions. Therefore, the output of the last ONU is a coherent DPSK signal with doubled bit rate [6]. Similarly, it could be easily extended to *M*-ONU multiplexing with a time shift of bit-duration/*M* in each ONU. After a circular trip, the upstream DPSK signal is received by a high-speed DPSK receiver in the OLT to obtain a stream of time-interleaved data from every ONU.

In the VPN case, a pair of transmitter and receiver is installed in the ONU and coupled to the CWDM Muxes through a 2×2 coupler and two 1×2 couplers, as shown in Fig. 1(c). Thus the VPN signal can be transmitted along both directions and received by all the ONUs at the same wavelength, i.e. the same VPN. In the destined ONU, the VPN signal is demultiplexed by the AWG and the CWDM Mux/Demux, and then split into two parts. One is coupled into the receiver for detection, while the other part passes through another CWDM Mux/Demux, goes back to the RN and subsequently travels to the next sub-PON. Thus on the same wavelength, the VPN communications should be scheduled in the TDM manner.

To ensure enough power budget and maximize the cascadability, a pair of Erbium-doped fiber amplifiers (EDFAs) or a bidirectional EDFA can be placed in each RN, to compensate the power losses from transmission, coupler splitting, and Mux/Demux. Remote amplification can be used to keep the RN passive [5].

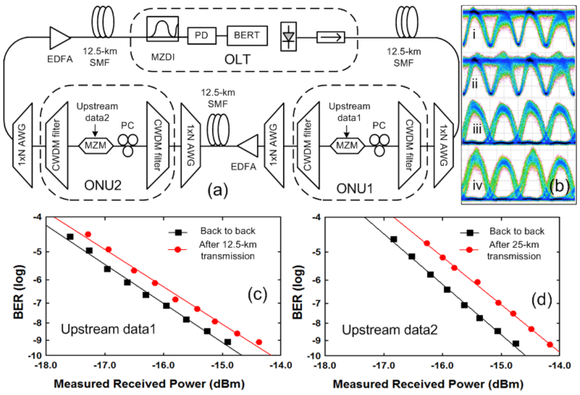

Figure 2: (a) Upstream experimental setup and (b) eye diagrams before and after MZDI. BER performances of the upstream (c) data1 and (d) data2.

Experiment

In this section, we experimentally verify the feasibility of the proposed two-stage TDM/WDM metro-access integrated network enabling all-optical VPN with two ONU nodes as a proof-of-concept demonstration. All the optical signals are generated by using independent 5-Gb/s data streams with a pseudo-random bit sequence (PRBS) length of 2^{31}-1.

In the upstream case, as shown in Fig. 2(a), the upstream light carrier from the OLT is successively modulated by the two MZMs in two different ONUs, and received by the DPSK receiver in the OLT. The lengths of single mode fibers (SMFs) between nodes are all 12.5 km. The DPSK receiver consists of a 100-ps-delay interferometer and a single-ended 9-GHz photodetector. In Fig. 2(b), (i) and (iii) show the back-to-back eye diagrams before and after the MZDI respectively, while (ii) and (iv) are the corresponding ones after transmission. Fig. 2(c) shows the bit error rate (BER) performances for the back-to-back case and after transmission. Less than 1-dB penalty is induced for the two ONUs.

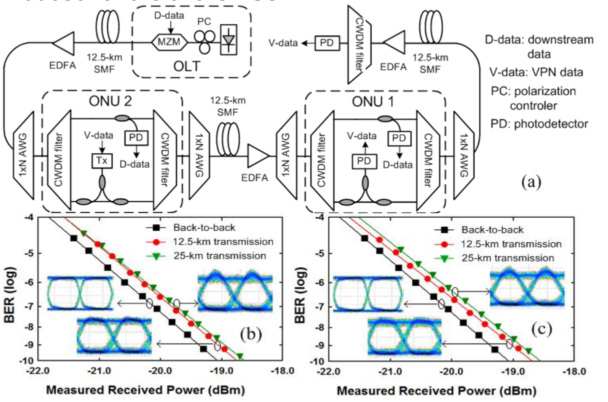

Figure 3: (a) Downstream and VPN experimental setup. BER performances of the 5-Gb/s (b) downstream, and (c) VPN ASK signals.

Figure 3(a) depicts the downstream and VPN setup. The optical signals are in amplitude-shift keying (ASK) format with ~10-dB extinction ratio. The BER performances for the back-to-back case and after 12.5-/25-km transmissions are tested. Fig. 3(b) and (c) show the downstream and VPN BER measurements respectively with optical eye diagrams inserted. About 0.5-dB penalty is observed after 25-km transmission, which is mainly induced by dispersion and noise.

Conclusions

We have proposed and experimentally demonstrated an all-optical VPN in a ring-based TDM/WDM metro-access integrated network to connect ONUs in different sub-PONs. With the two-stage configuration, it can provide cost-efficient broadband access and optical VPN service in a wide area.

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