Optical Fiber Technology 20 (2014) 61–67

Contents lists available at ScienceDirect

Optical Fiber Technology

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All-optical OFDM network coding scheme for all-optical virtual private communication in PON

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ARTICLE INFO

Article history:
Received 26 August 2013
Revised 21 November 2013
Available online 27 December 2013

Keywords:
All-optical OFDM
Network coding
VPN
PON
Pulse stretching

ABSTRACT

A novel optical orthogonal frequency division multiplexing (OFDM) network coding scheme is proposed over passive optical network (PON) system. The proposed scheme for all-optical virtual private network (VPN) does not only improve transmission efficiency, but also realize full-duplex communication mode in a single fiber. Compared with the traditional all-optical VPN architectures, the all-optical OFDM network coding scheme can support higher speed, more flexible bandwidth allocation, and higher spectrum efficiency. In order to reduce the difficulty of alignment for encoding operation between inter-communication traffic, the width of OFDM subcarrier pulse is stretched in our proposed scheme. The feasibility of all-optical OFDM network coding scheme for VPN is verified, and the relevant simulation results show that the full-duplex inter-communication traffic stream can be transmitted successfully. Furthermore, the tolerance of misalignment existing in inter-ONUs traffic is investigated and analyzed for all-optical encoding operation, and the difficulty of pulse alignment is proved to be lower.

1. Introduction

PON technology has emerged to satisfy the high-bandwidth access requirement of consumers and application service. In traditional PON architectures, each optical network units (ONU) upstream traffic is sent to the optical line terminate (OLT), where signals are processed and buffered electronically, and then it is broadcasted to all ONUs of a PON. However, private and direct communication service between two ONUs within a PON is not supported. Following the increasing demands for private inter-communication of ONUs, all-optical VPN technology has gained great attention [1–4]. All-optical VPN supports inter-ONU traffic stream redirecting to the destined ONU via dedicated optical channel without electronic processing in OLT. It is regarded as an effective technique to enhance security, increase throughput and reduce latency and burden of the network [1]. To date, several all-optical VPN schemes have been investigated in wavelength division multiplex PON (WDM-PON) [1,2], time division multiplex and wavelength division multiplex PON (TDM-WDM PON) [3], and OFDM-PON [4]. Compared with other proposed schemes, it is remarkable that Zhang et al. [4] proposes a more flexible scheme based on OFDM technology for dynamic bandwidth allocation, but traditional electronic operation will still restrict higher speed transmission. Moreover, the full-duplex communication between two ONUs is not supported in these reported schemes. To address these issues, we have proposed a novel all-optical OFDM network coding scheme to support VPN traffic communication efficiently and flexibly.

The future of optical access network research has gradually developed toward ultrahigh data rates of 40+ Gb/s transmissions, but it poses challenge to the current hardware electronic devices [5]. As a modulation technology of high spectrum efficiency, all-optical OFDM has become a potential technology for high-speed optical fiber transmission due to its overcoming the speed limitation of the electronic devices. Therefore, when all-OFDM technology is introduced to access network, higher spectrum efficiency and transmission rate will be achieved [6]. Meanwhile, flexible OFDM subcarrier bandwidth allocation is helpful for the variable network demand, such as multi-granularity traffic transmission and dynamic spectrum allocation.

Network coding [7] is an attractive solution to enhance transmission efficiency, robustness and resource utilization for broadband networks, so it has been investigated in optical network. In recent years, the integration of network coding within NG-PON has aroused a lot of attention for the potential performance improvement [8]. Based on network coding technology, two downstreams can be combined and then transmitted to ONUs in the same timeslot and frequency. The all-optical VPN with network coding has many advantages, such as efficient utilization of energy

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1068-5200/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.yofte.2013.11.008

and network resource [9], enhancing security of downstream transmission and so on. At present, all-optical network coding schemes have been investigated. Manley et al. [10] proposed an all-optical network coding infrastructure for all-optical multicast network. The coding node architecture supports the encoding operations based on the Galois fields GF(2^m). It overcomes the disadvantages brought by optical–electrical–optical (OEO) conversion, but it is too complicated and difficult to realize. Menendez and Gannet [11] adopted photonic bitwise exclusive-OR (XOR) network coding element to protect all-optical multicast networks. The encoding mechanism is simple, but it is lack of universality and flexibility for the various applications in optical network. Furthermore, how to keep synchronization of optical signals for all-optical logic encoding operation also need to be considered.

In this paper, we focus on investigating an all-optical OFDM network coding scheme for all-optical VPN in PON system. It does not only provide a feasible way to realize higher speed transmission, but also improves the efficiency and flexibility. In the following discussion, the proposed all-optical OFDM network coding scheme is depict and analyzed. The all-optical XOR encoding operation is performed on two group OFDM orthogonal subcarriers of all-optical VPN signals. Because the practical implementation on network coding is restricted by the optical signal synchronization, the process of stretching pulse is adopted in our proposed scheme for reducing the difficulty of optical signal pulse bitwise alignment. The tolerance of misalignment between the inter-ONUs traffic can be improved for all-optical XOR encoding operation.

This paper is organized as follows: in Section 2, the all-optical OFDM network coding scheme for all-optical VPN is illustrated. In Section 3, we provide the simulation model for inter-ONU communication in PON system. The all-optical VPN traffic with 10 Gbit/s and 40 Gbit/s symmetrical upstream/downstream is simulated over 20 km transmission. Moreover, the transmission performance is analyzed and discussed. In Section 4, our conclusion is summarized.

2. Principle and architecture

2.1. Network coding scheme for VPN

Fig. 1 illustrates the two scenarios of two inter-ONUs exchanging data packets with each other through OLT. Suppose ONU-1 and ONU-2 are two peer-ONUs in a VPN, and data packets *b* and *c* need to be exchanged in inter-ONU communication. In traditional TDM-VPN, in order to avoid collision, *b* and *c* are transmitted to OLT individually in two time slots via a single fiber, and then the two data packets are broadcast to two ONUs sequentially. The data exchange process is performed in four separate time slots (TS), as shown in Fig. 1(a). Fig. 1(b) shows the implementation principle of network coding in all-optical VPN. When network coding technology is introduced to all-optical VPN, the OLT enables to combine the two data packets by linear logic operation, such as bitwise XOR operation. The encoded data packet $b \oplus c$ is broadcast to the both ONUs in one time slot. At ONU-1 and ONU-2, both the copy of the data packets sent to OLT before and the encoded data packet received from the OLT are utilized to decode. *b* and *c* data packets destined to ONU-2 and ONU-1 respectively are recovered by XOR operation. For example, ONU-1 can recover data packet *c* by computing $b \oplus (b \oplus c)$, and ONU-2 can recover data packet *b* by computing $c \oplus (b \oplus c)$.

With our proposed network coding VPN scheme, OLT can save energy consumption by reducing the downstream packet transmitting time, so it can improve energy efficiency and link throughput [9]. Meanwhile, as an encryption method, network coding technology enables to protect VPN traffic from eavesdropping in downlink, because the encoded inter-communication traffic cannot be retrieved accurately by the other ONUs.

2.2. Architecture of the all-optical OFDM network coding in OVPN

Optical OFDM has been proved to be a promising candidate for high-speed optical fiber transmission. A serial high-speed traffic stream is modulated on multiple parallel orthogonal subcarriers, so relative parallel low-speed traffic streams are generated. The fast Fourier transform and inverse fast Fourier transform (FFT/IFFT) is an important process for optical OFDM transmission. Each subcarrier stream can generate OFDM stream by IFFT, and in contrast, OFDM stream can be decomposed to parallel orthogonal subcarriers by FFT. Currently, FFT/IFFT is implemented by the electronic digital signal processing (DSP) in many optical OFDM systems, where digital-to-analog converter (DAC) and analog-to-digital converter (ADC) are necessary. The real-time processing of optical OFDM is limited by the speed of the electronic processing in FFT/IFFT, DAC and ADC, so that all-optical OFDM technology has attracted wide concern for overcoming the problem. Many all-optical devices and circuits are proposed for the all-optical FFT/IFFT [12–14]. In this paper, Array Wave Grating (AWG) is adopted as multiplexer and de-multiplexer to realize FFT/IFFT function [12]. Different from previous all-optical VPN scheme in OFDM-PON, our proposed scheme supports all-optical OFDM traffic stream transmitting for inter-communication, so higher speed transmission can be achieved. Furthermore, all-optical OFDM is potential to provide flexible resource allocation, scalable system capacity and efficient transmission.

Fig. 2 shows the allocation scheme of OFDM subcarrier frequencies for PON communication. The allocation of subcarrier frequency and subcarrier number can be scheduled based on the bandwidth demand of ONUs dynamically. As inter-communication traffic, OVPN-upstream1 and OVPN-upstream2 come from ONU-1 and ONU-2 separately, and they are coupled to be OVPN-upstream transmitting to OLT. Then OVPN-upstream1 and OVPN-upstream2 are combined to be OVPN-downstream by network coding operation at OLT. OVPN-upstream is allocated a group of continuous orthogonal OFDM subcarrier frequencies those are different from OVPN-downstream subcarrier frequencies. OVPN-downstream can save up to 50% on subcarrier number than OVPN-upstream

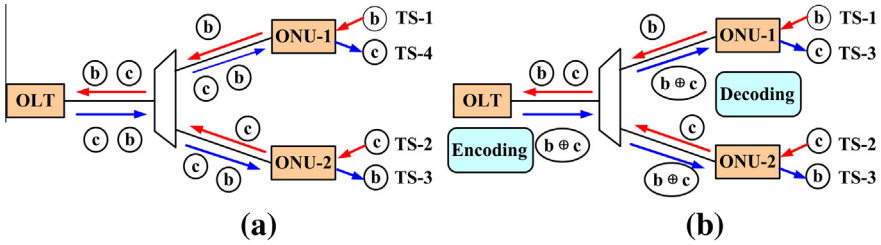

Fig. 1. Operation principle of inter-ONU communication in all-optical VPN. (a) Traditional TDM-VPN and (b) all-optical VPN with network coding.