Virtual Private Networks in RoF-OFDM-PON with Physical-layer Network Coding

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Abstract—We propose and experimentally demonstrate an application of physical-layer network coding to realize virtual private network (VPN) on a radio-over-fiber based OFDM-PON. Two optical signals are combined together physically to share the same physical path and can be individually decoded at their respective destinations. The proposed scheme improves VPN throughput compared to conventional schemes.

Keywords—physical-layer network coding; virtual private network; radio-over-fiber; OFDM-PON

I. INTRODUCTION

Hybrid fiber-wireless (FiWi) technology, which integrates both wired and wireless services in access networks, has recently attracted much attention[1]. It greatly enhances the scalability and flexibility of heterogeneous service delivery over the access network. In particular, with the wide adoption of orthogonal frequency division multiplexing (OFDM) as the signal format for the radio signals in 4G/5G systems, radioover-fiber (RoF) based passive optical networks (PONs) delivering the OFDM-based services have been evolved and play an important role in realizing the future high capacity heterogeneous FiWi systems. [2,3].

Recently, peer-to-peer (P2P) services are getting quite dominant in the broadband access arena [4]. Bi-directional intra-PON P2P transmission, or virtual private network (VPN), are attracting increasing interests. Network coding (NC), an effective way to increase the net throughput of communication networks was introduced into optical communications to improve the intra-PON throughput [5]. One variant of NC, named as physical-layer network coding (PNC), was proposed and applied in wireless communications in 2006 [6]. Preliminary efforts have been made to apply PNC into optical communications to improve the VPN throughput [7].

In this paper, we investigate the application of PNC for simultaneously supporting wired and wireless VPN in a RoF-PON system, therefore paving the way for more flexible VPN configurations. Furthermore, compared to a conventional halfduplex VPN, the proposed PNC-based full-duplex VPN brings a considerable throughput improvement.

II. PRINCIPLES OF OPERATION

Fig. 1(a) shows a simplified architecture of the RoF-PON composed of N optical network units (ONUs). The ONUs as well as optical line terminal (OLT) are connected, via a specially designed remote node (RN), which connects the output ports of a $(N+1) \times (N+1)$ optical coupler to the port 1 of (N+1) optical circulators, respectively. There are two kinds of users in RoF-PON: wired users (denoted by P) having access to the conventional OFDM-PON service and wireless users (denoted by W). For the OFDM-PON wired connections, wired user P_1 and P_n are connected to the ONU₁ and ONU_n, respectively. For the wireless services, the wireless user W_1 was served by ONU₁, and W_n is wirelessly covered by ONU_n.

The configuration of one ONU, ONU₁, is depicted Fig. 1(b). The upstream and the downstream of the OFDM-PON here are full-duplex by adopting an optical red/blue filter. The wired data is modulated onto the subcarriers in a common OFDM modulation process, while the subcarriers that correspond to the frequencies of wireless services (wireless pipes) are left unoccupied. The wireless signal is received from the W_1 and combined with the OFDM-PON signal, via an electrical signal combiner [2].



Fig. 1. (a) Schematic view of a RoF-PON supporting PNC-based VPN, (b) ONU configuration, (c) non-PNC VPN data streams, (d) PNC VPN data streams



Fig. 3. (a) Symbol-level synchronization, (b) frame structure.

Consider the wired VPN firstly. As is shown in Fig.1(c), a pair of VPN users ONU₁ and ONU_n exchange data in a bidirectional manner. In a conventional VPN setup, ONU₁ sends its data D_A to ONU_n in the first time slot and the transmission of D_B from ONU_n to ONU₁ is in the second time slot. The exchanging process is indeed half-duplex. By employing the proposed PNC scheme, full-duplex VPN is realized to halve the time consumed, as is depicted in Fig. 1(d). ONU_1 and ONU_n simultaneously transmit D_A and D_B . The signals are encoded at the RN by a simple combination. The encoded signal are then broadcasted to all ONUs and OLT. For the decoding process at ONU₁, D_{PNC} is converted back into electrical signal. D_A is then subtracted from the encoded signal D_{OPNC} to retrieve D_B . D_B is similarly decoded at ONU_n. A 100% improvement in VPN throughput is achieved compared to conventional scheme. Compared to NC-based inter-ONU connection [5], the proposed PNC-based VPN bypasses the OLT to avoid the logical encoding operations, the workload and power consumption, and the storage occupation [7]. The PNC-based VPN in the wireless part resembles the wired part only with extra steps of wireless transmission and receiving.

As the PNC VPN is merged into the upstream data which is broadcasted to all ONUs and OLT, VPN and upstream data can be transmitted simultaneously by allocating different subcarriers to different services. Furthermore, the proposed scheme can also support multiple VPN connections simultaneously. Different VPNs are assigned with different subcarriers, while the pair of users in a VPN load data on the common subcarriers. Hence, the proposed scheme is highly flexible.

III. EXPERIMENTAL SETUP

We experimentally examined the feasibility of the proposed scheme. For OFDM signals, the decoding process is in the frequency domain. The PNC signal should be transformed into



Fig. 2. (a) Experimental setup, (b) Digital spectrum of the transmitted signal, (c) digital signal processing procedures

frequency domain before decoding. Therefore, the OFDM symbols of the two encoded signals should be synchronized. However, the insertion of cyclic prefix (CP) relieves this synchronization constraint to within-CP constraint [8], which is depicted in Fig. 2(a). Fig.2(b) depicts the frame structure. The preamble and postamble were non-overlapping symbols for the channel estimation of D_A and D_B , respectively.

Fig.3(a) shows the experimental setup. For simplicity, the transmission process from wireless users to ONUs were omitted. The modulation formats of OFDM subcarriers in wired and wireless portions were both OPSK. The wired and wireless signals were generated and combined in MATLAB to emulate the electrical coupler. The offline generated signal were then output from an arbitrary waveform generator (AWG) working at 10 Gsample/s. For the wired part, the FFT size was 256, of which 128 subcarriers were adopted as data subcarriers. The inverse fast Fourier transform (IFFT) transforms two ways of 5 Gsample/s QPSK data into two 5Gsample/s baseband complex signals. The complex signal was then digitally IQmixed [3] to 2.5 GHz radio frequency (RF) to form a 10 Gsample/s real-value band-pass signal. In each wired OFDM frame there was 500 symbols, including 10 symbols in preamble or postamble as training symbols for channel estimation, and 490 payload symbols. Overall, the wired signal was 2.37 Gbaud QPSK. For the wireless part, the FFT size and data subcarrier numbers were 256 and 128, respectively. Two ways of 50 Msample/s QPSK data were transformed into two time domain signals by IFFT. The baseband signal were then zero-order hold, digitally up-converted to 2.5 GHz and IQmixed to be a 10 Gsample/s signal. Each wireless frame contained 2 training symbols and 18 payload symbols. To converge wired and wireless signals, in the spectrum of the wired signals, the 5 subcarriers (one is DC in baseband) around 2.5 GHz were left blank for wireless pipes. The wireless data was 45 Mbaud QPSK. The wired and wireless signals were then combined in MATLAB. Fig. 3(b) shows the spectrums of the wired, the wireless, and the combined signals.

Two wavelength channels from external cavity lasers (ECL) were individually modulated by two electrical signals from an AWG), via two respective Mach-Zehnder modulators (MZM). The wavelengths of ECL1 and ECL2 were 1550.00 nm and 1549.60nm, respectively, with a 50-GHz frequency difference, to avoid the optical beating interference (OBI). The two optical output signals were then fed into two pieces of single mode fibers (SMF) of lengths 20-km, respectively. A variable optical attenuators (VOA) was inserted to equalize the powers of the two signals. The signals of the two paths were then combined by an optical coupler. A second VOA was then employed to control the input power to the photo diode (PD). The detected signal was then amplified by an electronic linear amplifier



Fig. 4. Experimental results: (a) Wired, (b) Wireless

(LNA). The two paths with or without a 0.5-m wireless transmission respectively corresponds to the wireless or wired transmission. The received signal was sampled by an oscilloscope at 50 Gsample/s. After offline digital signal processing (DSP) and decoding, the BER was calculated by error counting. Fig.3 (c) illustrates the required digital processing.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

Fig. 4 shows the experimental results. As the powers of D_A and D_B were identical, the received powers of PNC cases were 3-dB larger than those of non-PNC cases. This value had been deducted for fair comparisons. Fig.4 (a) shows the experimental results of the wired part. It could be learnt from the figure that the power penalties at BER=10⁻³ introduced by PNC to D_A and D_B were 1.5 dB and 1.7 dB, respectively. Fig. 4(b) shows the results of the wireless experiments. Only 0.8-dB and 1.1-dB received power penalties were observed as the cost of PNC at the BER level of 10⁻³. It should be clarified that even the powers of D_A and D_B were equalized, the modulation indices and characteristics of the two MZMs were not identical, which would lead to the performance differences between D_A and D_B . Nevertheless, the experimental results have shown that the proposed PNC-based VPN structure brought moderate power penalties, yet led to drastic throughput improvement.

V. SUMMARY

We have proposed and experimentally investigate the PNC-based VPN in a RoF-PON supporting heterogeneous services. The flexible VPN scheme can support wireless VPN and wired VPN simultaneously. The power penalties induced by the coding process were quite moderate, while the system throughout is largely improved. This work was supported by a research grant from Hong Kong RGC (Project no. 14200614).

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