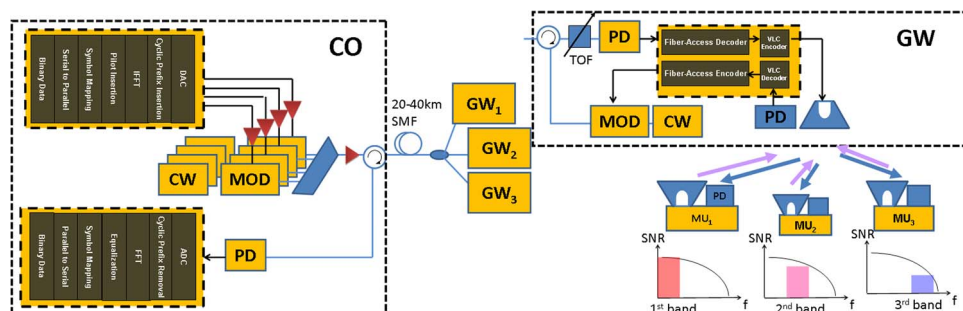


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Network Architecture of Bidirectional Visible Light Communication and Passive Optical Network

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Abstract: Network architectures to combine the fiber network outside the building and the visible light communication (VLC) access network inside the building are important for effectively distributing the high-capacity data to different users. In this paper, we propose a bidirectional network combining the VLC access network and the time-wavelength-division-multiplexed passive optical network (TWDM-PON). Orthogonal frequency division multiplexed modulation is used since it offers high spectral efficiency for both the TWDM-PON and the VLC access network. Low-cost phosphor-based white-light light-emitting diodes are (LEDs) used; hence, the VLC access network can combine with the lighting systems.

Index Terms: Free-space communication, optical communications, light-emitting diode (LED).

1. Introduction

The bandwidth demands for broadband services have recently been increasing rapidly. In order to meet these bandwidth demands, the Full Service Access Network (FSAN) has begun to look for future-proof access solutions, and the second-stage next generation passive optical network (NG-PON2) has been proposed [1]. Several different NG-PON2 architectures have been proposed, such as, orthogonal frequency division multiplexed (OFDM) PON [2], [3], and time-wavelength-division-multiplexed (TWDM) PON [4], [5]. Among them, TWDM-PON is considered as a promising architecture for NG-PON2 since it can provide a much higher data rates by stacking multiples optical line terminals (OLTs) and reuse the existing optical distribution network (ODN). Hence, the implementation cost can be reduced. Although the fiber-based access networks can provide huge bandwidths, issues still exist of how to distribute the bandwidths to different users flexibly and efficiently. Wireless signal distributions using wireless fidelity (WiFi) and radio-over-fiber (ROF) [6], [7] have been proposed. Recently, optical wireless communication using visible light, known as visible light communication (VLC) [8]–[12], has been

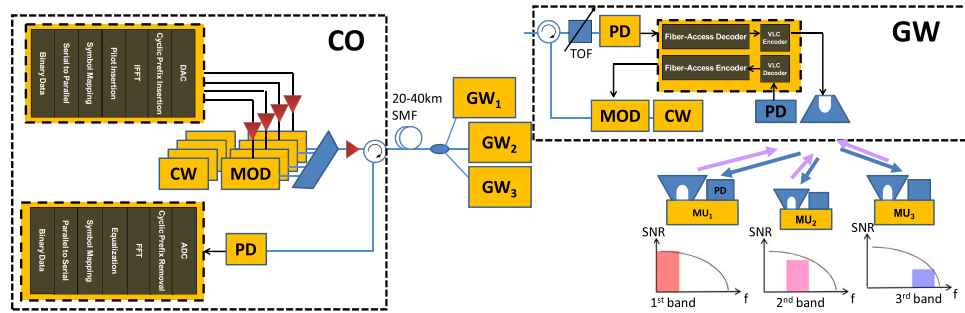


Fig. 1. Proposed bidirectional network architecture combining the VLC access network and the TWDM-PON. Central office (CO); gateway (GW); mobile unit (MU); modulator (MOD); photodiode (PD).

considered as another promising means to distribute the wireless data. As VLC is license-free and can provide an extra electromagnetic (EM) (i.e., visible) spectrum instead of the congested traditional radio-frequency (RF) spectrum for communications, VLC can be a promising candidate for the future fifth-generation (5G) wireless networks [13]. Besides, since VLC transmission is directional and confined in an illumination zone, it can support a high wireless communication capacity with high security. This is because there are small interferences among different illumination zones (known as the VLC atto-cells).

However, most of the VLC studies are focused on point-to-point links [8]–[10], and VLC access networks are usually neglected. Studies of network architectures for combined the fiber network outside the building and the optical wireless access network inside the building are essential. Recently, several VLC local area network (LAN) architectures have been demonstrated [14], [15], such as using the VLC access points (VAPs) for the multiple access. However, they used colored light emitting diodes (LEDs) and may not be suitable for VLC networks offering communication and lighting simultaneously. In this work, we propose a bi-directional network combining the VLC access network and the TWDM-PON. OFDM is used since it offers high spectral efficiency for the modulation bandwidth limited LED in the VLC access network. Low-cost phosphor-based white-light LEDs are used; hence, the VLC access network can combine with the lighting systems.

2. Proposed Architecture and Experiment

Fig. 1 shows the proposed bi-directional network architecture combining the VLC access network and the TWDM-PON. In the TWDM-PON central office (CO), baseband electrical OFDM signal is generated by using Matlab programs, and the signal processing of the OFDM transmitter (Tx) consists of serial-to-parallel conversion, quadrature amplitude modulation (QAM) symbol mapping, pilot insertion for synchronization, inverse fast Fourier transform (IFFT) to produce different OFDM subcarriers, cyclic prefix (CP) insertion, and digital-to-analog conversion (DAC). A continuous-wave (CW) laser is modulated by the baseband electrical OFDM signal via an optical modulator (MOD). Four channels at different wavelengths are multiplexed by using wavelength division multiplexer (WDM mux) or passive fiber couplers in the TWDM-PON. In the experiment, Mach–Zehnder modulator (MZM) serves as the MOD. The DAC has an analog bandwidth of 4.8 GHz and sampling rate of 12 GSample/s. The FFT size of the OFDM signal is 512 and CP length is 1/32. Except for the direct current (DC) component, 255 subcarriers are bit-loaded according to the obtained signal-to-noise ratio (SNR) after the 20 and 40 km fiber standard single mode fiber (SMF) transmissions. Then, the TWDM-PON signal is detected at the gateway (GW) located between the TWDM-PON and the VLC access. The GW is located at the interface between the inside and the outside of a building. As the TWDM downstream signal is consisted of 4 wavelength channels, a thin-film tunable optical filter (TOF) or silicon based TOF [16] can be used to wavelength de-multiplexed each wavelength channel, which is then received by photo-diodes (PD) connecting to an ADC with an analog bandwidth of 3.5 GHz and sampling rate of 40 GSample/s.

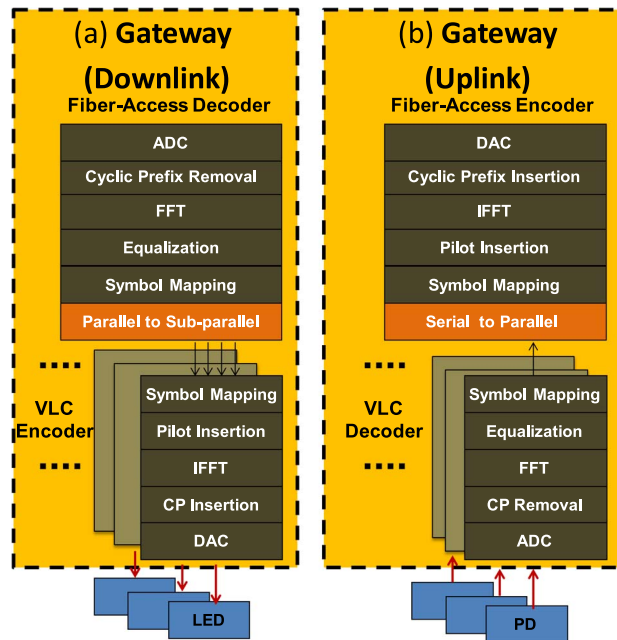


Fig. 2. Signal processing used for both downlink and uplink in the GW. Analog-to-digital conversion (ADC); digital-to-analog conversion (DAC); inverse fast Fourier transform (IFFT); cyclic prefix (CP).

In the downlink direction of the GW, a fiber-access decoder, as shown in Fig. 2(a), is used. The processes include the analog-to-digital conversion (ADC), synchronization, CP removal, FFT, one-tap equalization, symbol mapping, and parallel-to-sub-parallel conversion (PSC). In the PSC, different parallel data will be regrouped for the VLC encoders, which are used to directly modulate different white-light LED Tx's (Edison, EDEW 3LS5) located at different apartments in a building. Inside an apartment, all the mobile units (MUs) are served by the same downlink LED lamp; hence, the downlink transmission is based on broadcasting. In the proposed GW, as shown in Fig. 2(a), the PSC module inside the GW (downlink) will divide the total signal bandwidth to different "VLC Encoders" connected to the LEDs. As the bandwidth to each LED is about 30 MHz; hence, low bandwidth electrical cables can be used between the "VLC Encoders" and the LED lamps. After the 200 cm to 80 cm optical wireless free space transmission, the visible signal is received at the MU via a silicon-based positive-intrinsic-negative (PIN) receiver (Rx) (Hamamatsu, S6968). It has the detection wavelength range of 350–1100 nm with responsivity of 0.63 A/W.

The VLC uplink path is also shown in Fig. 1, illustrating the multiple access of the uplink is based on different frequencies. The uplink data is divided into several frequency up-converted OFDM bands, and in the proof-of-concept demonstration, three MUs are used. Each MU transmits a particular frequency up-converted OFDM band. Typical phosphor white-light LEDs with direct modulation bandwidth of ~1 MHz are used. By using the electrical equalization implemented in the driving circuit of the white-light LED, a 30 MHz 3-dB modulation bandwidth can be achieved. For simplicity, we equally divided the 30-MHz into 3 bands for the 3 MUs (each MU operates in 10 MHz). Dynamic bandwidth adjustments for different MUs can also be achieved. When the VLC uplink is detected by the PD, the processes of VLC decoding and fiber-access encoding as shown in Fig. 2(b) are deployed. Then, the aggregated data obtained from the VLC uplink signals will be used to encode another CW laser source and sent back to the CO via the TWDM-PON.

3. Results and Discussion

We first evaluate the signal performance in the TWDM-PON part. Fig. 3(a) shows the bit error rate (BER) performance against the received power in the GW. BER lower than 3.8×10^{-3} ,

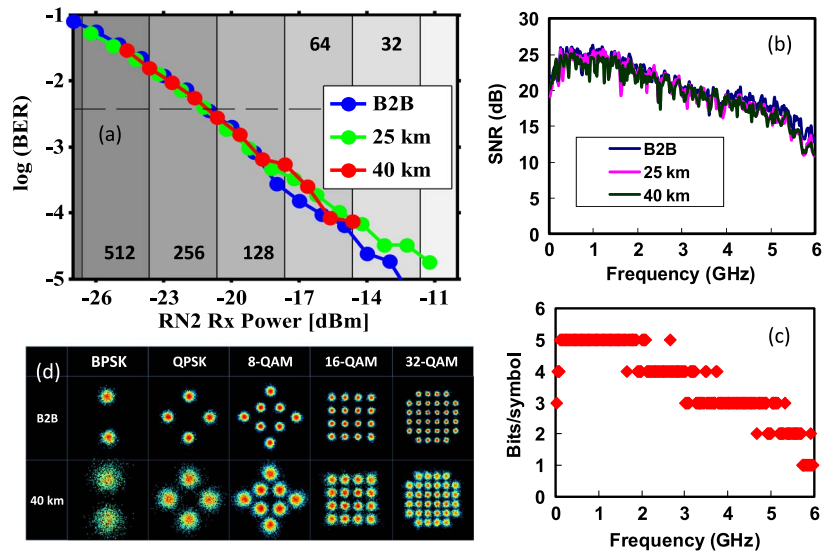


Fig. 3. (a) Measured BER against received power at the GW. (b) SNR. (c) Bit-loading of the OFDM subcarriers. (d) Corresponding constellations of different levels of QAM modulation.

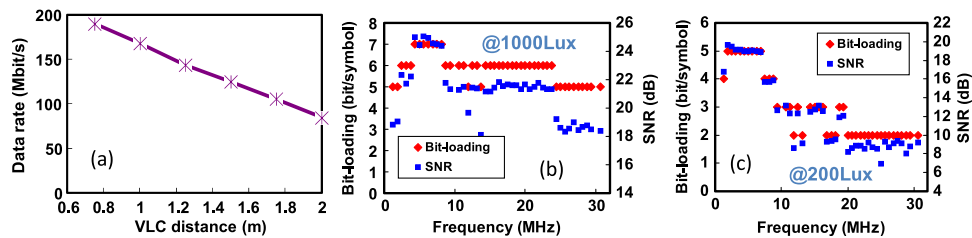


Fig. 4. (a) VLC downlink data rates against different free-space transmission distances, bit-loading, and the SNRs of the OFDM subcarriers in the 30-MHz bandwidth at (b) 1000 and (c) 200 lx.

7% forward error correction (FEC) requirement is obtained with 256 ODN split-ratios, even after 40 km SMF transmission. These satisfy the requirement of NG-PON2. Less than 1 dB power penalty can be observed between the back-to-back (B2B) and the 40 km SMF transmission without dispersion compensation. Fig. 3(b) shows the SNR of the 255 OFDM subcarriers occupying 6 GHz bandwidth. The SNR drop at high frequency is due to the limited analog bandwidth of our DAC and ADC. Bit-loading is applied as shown in Fig. 3(c) based on the SNR obtained in each OFDM subcarrier; and the corresponding constellations of different levels of QAM modulation are shown in Fig. 3(d). We can observe that the QAM levels of up to 32-QAM can be used in the lower frequency band carrying 5 bit/symbol. As a result, the experimental net data rate of each wavelength is ~ 20.2 Gbit/s; and in the total data rate of the TWDM-PON is ~ 80.8 Gbit/s.

In the VLC access network, a typical phosphor white-light LED is used for the communication and lighting simultaneously. The white-LED has a direct modulation bandwidth of ~ 1 MHz. By using our electrical equalization scheme implemented in the driving circuit of the LED lamp, a 30 MHz 3-dB modulation bandwidth can be achieved. Fig. 4(a) shows the VLC downlink data rates against different free space transmission distances. The decrease of VLC data rate when increasing the transmission distance is due to the decrease of received optical power at the Rx, which also reducing the SNR. We measured the illuminance at 200 cm and 80 cm are 200 lux and 1000 lux, respectively, by a lux-meter. Data rate of 190 Mbit/s can be achieved at 80 cm free space distance; while data rate of 84 Mbit/s can still be achieved even the illuminance is only 200 lux, satisfying the FEC requirement. The corresponding bit-loading scheme and the

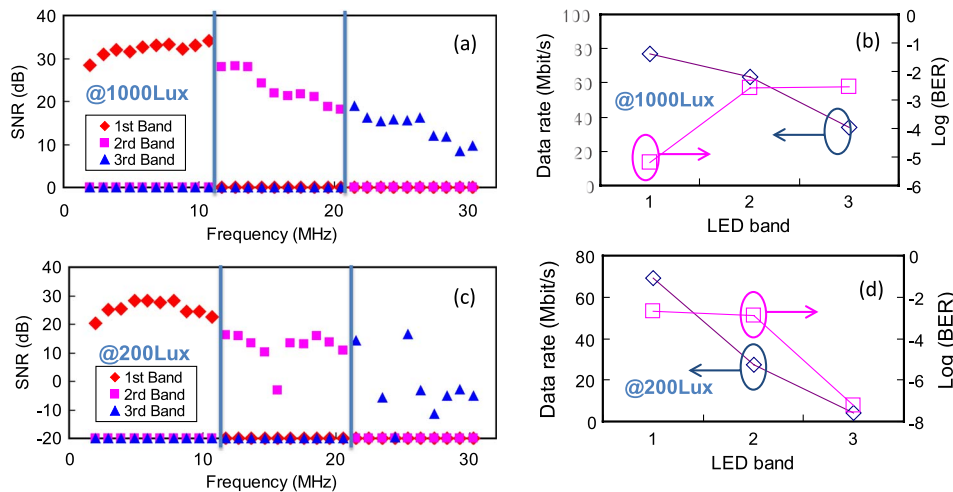


Fig. 5. (a) SNR and (b) data rates and BER of the three LEDs using different frequency up-converted OFDM bands at 1000 lx. (c) SNR and (d) data rates and BER of the three LEDs using different OFDM bands at 200 lx.

OFDM subcarrier SNRs in the 30 MHz bandwidth at 1000 lux and 200 lux are shown in Fig. 4(b), and (c), respectively.

Fig. 5(a) shows the SNRs of the three LEDs from three different MUs using different frequency up-converted OFDM bands at 1000 lux in the uplink free space transmission measured at the GW. After different upstream data from the MUs are received at the GW, the electrical upstream OFDM signal can be generated as illustrated in Fig. 2(b). Hence, the upstream optical OFDM signal sending to the CO can be produced via the upstream MOD shown in Fig. 1. In this demonstration, the white-light LEDs are used for the uplink, infrared (IR) LEDs can also be used. We can observe in Fig. 5(a) that due to the 30-MHz bandwidth of the LED driving circuit, the higher frequency Band-3 has lower SNRs. By observing the frequency within 10 MHz, a higher SNR can be achieved in the uplink when compared with the downlink [as shown in Fig. 4(b)]. This is because by only applying one band of signal to an LED, much higher driving power can be used before the LED response becomes nonlinear [17]. This is even more important for the OFDM signal, which has a high peak-to-average ratio (PAPR). Fig. 5(b) shows that data rates of about 77 Mbit/s, 64 Mbit/s and 34 Mbit/s can be achieved for the 3 MUs. When the illuminance decreases to 200 lux as shown in Fig. 5(c), the SNRs of the three LEDs will drop accordingly, but can still show better performance when compared with the downlink [as shown in Fig. 4(c)] due to the same reason as discussed before. Fig. 5(d) shows that data rates of about 70 Mbit/s, 27 Mbit/s, and 4 Mbit/s can be achieved for the 3 MUs even at very low illuminance of 200 lux; and all the BERs satisfy the FEC requirement. In the LED band-3 case, the better BER performance at low illuminance [see Fig. 5(d)] when comparing with that at higher illuminance [see Fig. 5(b)] is due to the decrease in data rate in band-3. The data rate decreases from 34 Mbit/s @ 1000 lux to 4 Mbit/s @ 200 lux. This can also be observed in the SNRs shown in Fig. 5(c), illustrating that only a few subcarriers can be used.

4. Conclusion

We proposed a bi-directional network combining the VLC access network and the TWDM-PON. A GW was proposed acting as the interface between the inside and outside of the building. In the TWDM fiber access part, a net data rate of ~20.2 Gbit/s at each wavelength was experimentally achieved with 256 ODN split-ratios and after 40 km SMF transmission. In the VLC access network, phosphor-based white-light LEDs with direct modulation bandwidth of ~1 MHz were used. By using our electrical equalization scheme implemented in the driving circuit of the LED lamp, a 30 MHz 3-dB modulation bandwidth can be achieved. Data rate of 190 Mbit/s–84 Mbit/s

can be achieved. The uplink multiple access in the VLC network was based on using different upconverted frequencies. In the proof-of-concept demonstration, three MUs were used, and each MU transmitted a particular frequency up-converted OFDM band.

References

- [1] R. W. Heron and E. Harstead, "FSAN NG-PON2 updates," presented at the *Opt. Fiber Commun. Conf./Nat. Fiber Optic Eng. Conf.*, 2013, paper OW4D.5.
- [2] N. Cvijetic, "OFDM in optical access networks," presented at the *Opt. Fiber Conf.*, 2011, paper OMG3.
- [3] C. W. Chow *et al.*, "WDM extended reach passive optical networks using OFDM-QAM," *Opt. Exp.*, vol. 16, pp. 12096–12101, 2008.
- [4] Z. Li *et al.*, "Experimental demonstration of a symmetric 40-Gb/s TWDM-PON," in *Proc. IEEE OFC*, 2013, pp. 1–3.
- [5] Y. Luo *et al.*, "Time- and wavelength-division multiplexed passive optical network (TWDM-PON) for next-generation PON stage 2 (NG-PON2)," *J. Lightw. Technol.*, vol. 31, pp. 587–593, 2013.
- [6] J. Y. Sung, C. W. Chow, C. H. Yeh, Y. Liu, and G. K. Chang, "Cost-effective mobile backhaul network using existing ODN of PONs for the 5G wireless systems," *IEEE Photon. J.*, vol. 7, no. 6, Dec. 2015, Art. no. 7201906.
- [7] L. G. Yang *et al.*, "Coding for stable transmission of W-band radio-over-fiber system using direct-beating of two independent lasers," *Opt. Exp.*, vol. 22, no. 21, pp. 26092–26097, Oct. 2014.
- [8] Y. C. Chi *et al.*, "450-nm GaN laser diode enables high-speed visible light communication with 9-Gbps QAM-OFDM," *Opt. Exp.*, vol. 23, pp. 13051–13059, May 2015.
- [9] W. Y. Lin *et al.*, "10 m/500 Mbps WDM visible light communication systems," *Opt. Exp.*, vol. 20, no. 9, pp. 9919–9924, Apr. 2012.
- [10] C. H. Chang *et al.*, "A 100-Gb/s multiple-input multiple-output visible laser light communication system," *J. Lightw. Technol.*, vol. 32, no. 24, pp. 4723–4729, Dec. 2014.
- [11] Z. Wang, C. Yu, W. D. Zhong, J. Chen, and W. Chen, "Performance of a novel LED lamp arrangement to reduce SNR fluctuation for multi-user visible light communication systems," *Opt. Exp.*, vol. 20, pp. 4564–4573, 2012.
- [12] Y. Liu *et al.*, "Visible light communication using receivers of camera image sensor and solar cell," *IEEE Photon. J.*, vol. 8, no. 1, Feb. 2016, Art. no. 7800107.
- [13] S. Wu, H. Wang, and C. H. Youn, "Visible light communications for 5G wireless networking systems: From fixed to mobile communications," *IEEE Netw.*, vol. 28, no. 6, pp. 41–45, Nov./Dec. 2014.
- [14] Y. Wang, N. Chi, Y. Wang, L. Tao, and J. Shi, "Network architecture of a high-speed visible light communication local area network," *IEEE Photon. Technol. Lett.*, vol. 27, no. 2 pp. 197–200, Jan. 2015.
- [15] Y. Wang, J. Yu, and N. Chi, "Symmetrical full-duplex integrated passive optical network and optical wireless communication transmission system," *J. Opt. Commun. Netw.*, vol. 7, no. 7, pp. 628–633, Jul. 2015.
- [16] C. W. Chow, C. H. Yeh, K. Xu, J. Y. Sung, and H. K. Tsang, "TWDM-PON with signal remodulation and Rayleigh noise circumvention for NG-PON2," *IEEE Photon. J.*, vol. 5, no. 6, Dec. 2013, Art. no. 7902306.
- [17] C. H. Yeh, H. Y. Chen, C. W. Chow, and Y. L. Liu, "Utilization of multi-band OFDM modulation to increase traffic rate of phosphor-LED wireless VLC," *Opt. Exp.*, vol. 23, no. 2, pp. 1133–1138, Jan. 2015.