Adaptive Physical-layer Network Coding over Visible Light Communications

Yang Hong, Lian-Kuan Chen and Xun Guan
Department of Information Engineering, The Chinese University of Hong Kong, Hong Kong SAR, China
Author e-mail address: yanghong@ie.cuhk.edu.hk

Abstract: We propose and experimentally demonstrate the adaptive physical-layer network coding to boost throughput of VLC-based two-way relay networks. Experimental results show that the network capacity can be improved by 100% with ~2.5-dB SNR penalty.
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1. Introduction

Despite of the advantages such as free license and higher achievable speed [1], visible light communications (VLC) has limited transmission distance and requires line-of-sight links, which restrict its application for inter-vehicle and underwater communication systems. Networking via relaying among multiple terminal nodes can be an efficient way to improve the transmission distance as well as the system coverage for future VLC-based networks. The relay-assisted technique was investigated for a half-duplex VLC system [2], in which the half-duplex constraint is imposed to avoid interference between terminal nodes at the expense of network efficiency. With the help of physical-layer network coding (PNC), which was originally proposed in wireless communications to improve throughput of two-way relay (TWR) networks, it is possible to make use of the interference to improve network capacity by 100% [3]. Recently, the application of PNC has been reported in optical fiber systems for system capacity enhancement and network protection [4].

In this paper, we propose and experimentally demonstrate a 600-Mb/s adaptive PNC (APNC) for VLC networks. The performance of the proposed APNC scheme is evaluated by comparing the conventional scheduling scheme and the PNC scheduling scheme in VLC networks. We show that BER performance of the proposed APNC scheme outperforms that of conventional networking scheme and the PNC scheme. Experimental results show that 100% capacity improvement can be achieved with only around 2.5-dB SNR penalty.

2. Principles

Consider a basic TWR network unit shown in Fig. 1, in which node 1 and node 2 want to exchange information with each other. While the direct link is blocked or is too long, reliable communication can be achieved via a relay node R. For the conventional network scheduling, as illustrated in Fig. 1, the interference is avoided by using four time slots to exchange two packets (x_1 and x_2) between the two terminal nodes occupying the same frequency band. In contrast, by utilizing the interference, PNC scheme can transmit the two packets simultaneously to the relay node R in the first time slot. The combined packet x_R is broadcasted to the two terminal nodes in the second time slot. With PNC decoding, the target packets can be recovered simultaneously at the two nodes, resulting in 100% improvement of network throughput [3]. To facilitate channel estimation for PNC decoding, training symbols (TS) are appended to data packets, as shown in Fig. 1, to avoid collision.

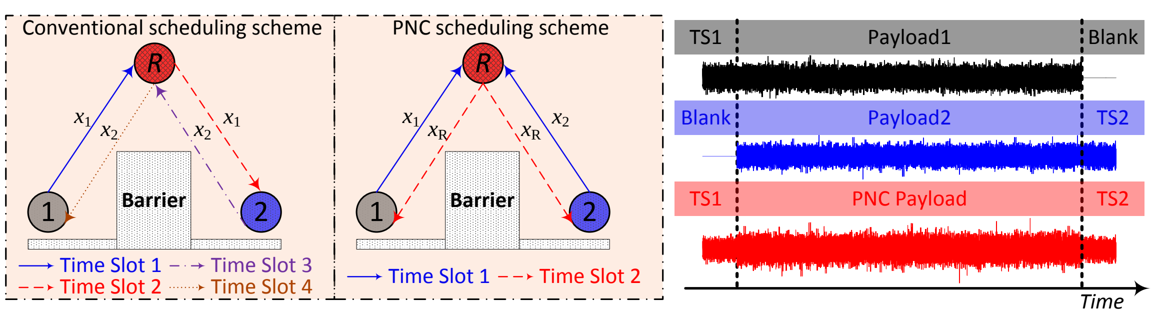

Fig. 1. Conventional scheduling and PNC scheduling (left) and packet structure for PNC over the OFDM-based TWR VLC network (right).

Without loss of generality, we take node 1 as an example to illustrate the PNC decoding at terminal nodes. Assume that the overlapped orthogonal frequency division multiplexing (OFDM) signal in time-domain at node 1 is given by $y_1(t) = x_1(t+\tau_1)*h_1(t) + x_2(t+\tau_2)*h_2(t) + n(t)$. In which, $x_1(t+\tau_1)$ and $x_2(t+\tau_2)$ are the OFDM signals using the same frequency band; τ_1 and τ_2 are the corresponding time delay; $h_1(t)$ and $h_2(t)$ represents the impulse responses from node 1 and node 2 to the relay node R, respectively; and $n(t)$ is the additive noise. In this work, OFDM modulation format is used for the two terminal nodes, hence, the time asynchrony within the cyclic prefix (CP) length can be tolerated, i.e., $(\tau_2 - \tau_1) \leq t_{CP}$. After fast Fourier transform (FFT), overlapped signal in the frequency domain is denoted by $Y_1(k) = X_1(k)H_1(K) + X_2(k)H_2(k) + N(k)$. k is the subcarrier index with $1 \leq k \leq N$; N denotes the number of modulated subcarriers; and $X_1(k)$ and $X_2(k)$ represent the data carried on the k-th subcarrier of node 1 and node 2, respectively. First, the estimated channel response $H_1(k)$ is utilized to compute $Y_1(k)/H_1(k)$ for the extraction of the local self-information. After subtracting $X_1(k)$, the resulting signal is equalized by the inverse channel response, $H_1(k)/H_2(k)$, to reconstruct the transmitted signal from node 2, and the obtained signal can be expressed as

$$\left(\frac{Y_1(k)}{H_1(k)} - X_1(k)\right) \cdot \frac{H_1(k)}{H_2(k)} = \left(X_2(k)\frac{H_2(k)}{H_1(k)} + \frac{N(k)}{H_1(k)}\right) \cdot \frac{H_1(k)}{H_2(k)} = X_2(k) + \frac{N(k)}{H_2(k)}. \tag{1}$$

Through the aforementioned processing, the signal from node 2 can be recovered at the destination node 1, and similarly for the signal detected at node 2. Therefore, the information exchange between the two terminal nodes via relay node R can be realized.

3. Experimental setup and results

The experimental setup of the OFDM-based TWR VLC network using PNC is depicted in Fig. 2. At node 1 and node 2, the offline generated OFDM signals were fed into two channels of an arbitrary waveform generator (AWG). After amplification, the two signals were coupled with the DC biases by bias-tees, and the resulting signals were used to drive two green lasers (Tx_1 and Tx_2, Osram PL520), respectively. The signals coming from two nodes were combined together at relay node R with a single photodiode. Subsequently, the detected signal was amplified by a trans-impedance amplifier (TIA), followed by a gain tunable electrical amplifier (EA). The amplified signal, together with a DC bias, was then used to modulate Tx_R (Osram PL520). At the receivers of the terminal nodes (Rx_1 and Rx_2), the received signals were the interfered signal forwarded from relay node R. Note that convex lenses were used in front of transmitters to enhance the detected signal power at receivers. With the help of PNC decoding described in Section 2, the target signal was reconstructed at each terminal node. In the experiments, the block size of FFT was 256; the sampling rate of AWG and digital phosphor oscilloscope (DPO) were 300 MS/s and 6.25 GS/s, respectively; the length of CP was 1/16 of one OFDM symbol; and 127 out of the 256 subcarriers were modulated with data in each OFDM symbol. The bias voltages for Tx_1, Tx_2 and Tx_R were optimized to 6.8V, 7.0V and 6.8V, and the corresponding amplification gains of EAs were 12 dB, 15 dB and 12 dB, respectively.

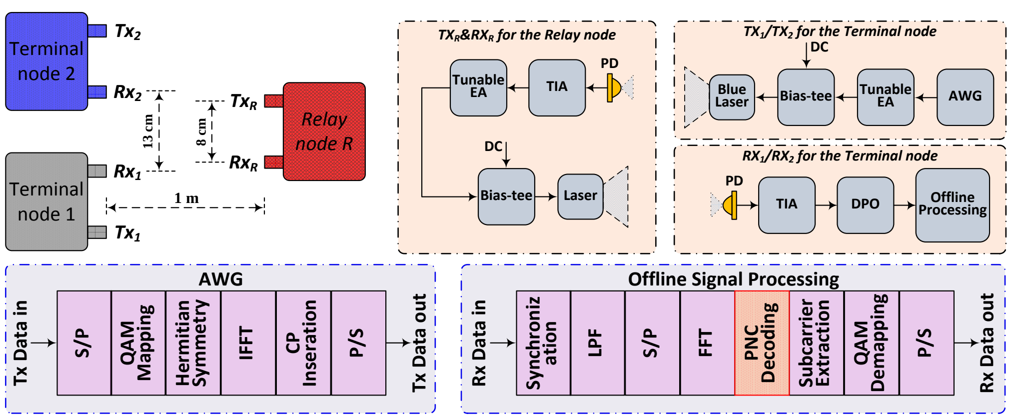

Fig. 2. Experimental setup of the OFDM-based TWR VLC network using PNC.

Firstly, the transmissions of conventional 4QAM-OFDM and 4QAM-DMT, i.e., adaptive-loaded DMT [5] with total bits and power equal to 4QAM-OFDM, were performed on the two links (link 1-R-2 and link 2-R-1). Fig. 3 shows the corresponding signal-to-noise (SNR) performance over OFDM subcarriers and the corresponding signal constellations. Note that the constellations have been rescaled for better presentation. The BER performance of link 1-R-2 and link 2-R-1 with 4QAM-OFDM are 1.65×10^{-3} and 1.14×10^{-3}, respectively. With the help of adaptive-loaded DMT, BER performance of the two links can be further improved to 4.18×10^{-6} and 1.97×10^{-6}, respectively. To boost the VLC network capacity with 100% enhancement, there are two potential schemes: (i) doubling the QAM modulation level for the OFDM signals with four time slots or (ii) using the PNC scheme presented in this work with two time slots.

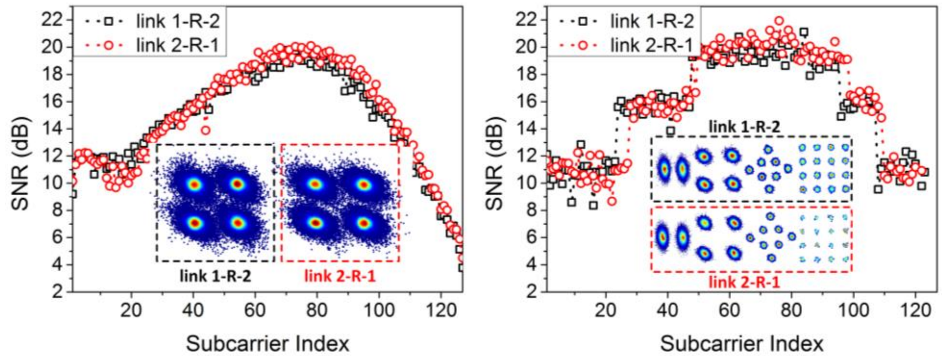

Fig. 3. SNR performance over the subcarriers: 4QAM-OFDM (left) and 4QAM-DMT (right).

In Fig. 4, we show the SNR penalty of the transmission with and without PNC scheme. The corresponding BER performance of the two links using conventional PNC are 1.27×10^{-2} and 1.23×10^{-2}, respectively. To further enhance the BER performance, we propose a PNC scheme with adaptive loading, termed as APNC scheme. Results show that the BER performance can be further improved to 3.96×10^{-4} and 5.32×10^{-4} for the two links, respectively. For both PNC and APNC schemes, it can be seen that at lower frequencies, the SNR penalty is not significant. However, at higher frequencies, the SNR penalty is around 5 dB. The average SNR penalty is ~2.5 dB for the system using PNC/APNC to realize 100% capacity improvement. The progressing of APNC decoding at different stages (as described in Section 2) and the corresponding decoded signal constellations are also shown in Fig. 4.

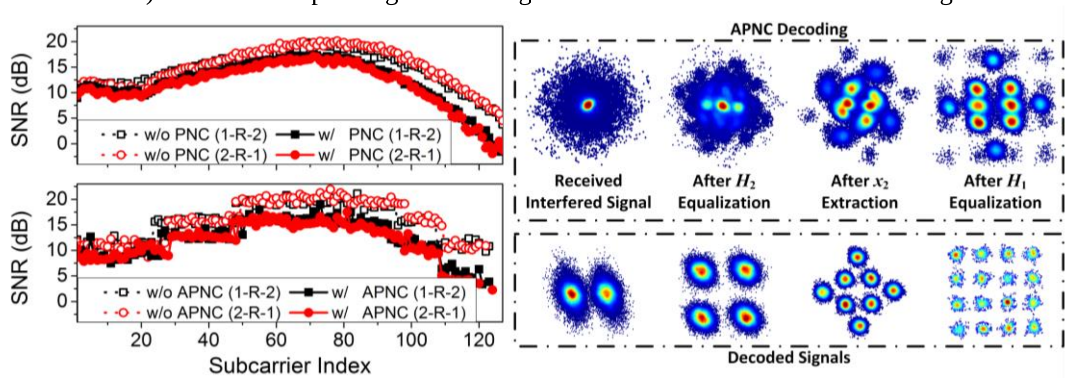

Fig. 4. SNR penalty of the system with PNC/APNC (left) and the progressing of APNC decoding and the corresponding decoded signal constellations for link 1-R-2 (right).

As above-mentioned, the network capacity enhancement can also be realized by doubling QAM modulation level while using the conventional scheduling. Experiments have been conducted and detailed BER comparison between the two solutions is given in Table 1, showing the proposed APNC scheme exhibits the best BER performance.

Table 1. BER comparison for the system with and without PNC/APNC.

	16QAM-OFDM	**w/ PNC**	**16QAM-DMT**	**w/ APNC**
Link 1-R-2	2.38×10^{-2}	1.27×10^{-2}	4.56×10^{-3}	3.96×10^{-4}
Link 2-R-1	2.62×10^{-2}	1.23×10^{-2}	6.62×10^{-3}	5.32×10^{-4}

4. Conclusion

In this paper, to the best of our knowledge, we propose the first APNC scheme to double the capacity of VLC networks. Experimental results show that the BER performance of the proposed scheme outperforms the conventional network scheduling scheme and the PNC scheme. By utilizing the proposed scheme, the network capacity can be improved by 100% with around 2.5-dB SNR penalty. For a 600-Mb/s APNC-based TWR VLC network, BERs of 3.96×10^{-4} and 5.32×10^{-4} can be achieved for the two links, respectively. This work was supported in part by HKSAR RGC grant (GRF 14215416) and UGC grant (AoE/E-02/08).

5. References

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