A Cost-Effective Approach for Ubiquitous Broadband Access Based on Hybrid PLC-VLC System

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***Abstract*—Visible light communication (VLC) using the light emitting diode (LED) will become an appealing alternative to the radio frequency communication technology for indoor wireless broadband access. However, VLC needs a ubiquitous network as its backbone to avoid becoming an information isolated island. Power line communication (PLC) systems could easily solve the informative problem of VLC while powering the LED lamps at the same time, which is considered as a good partner of VLC for the cost-effective implementation. In this paper, a novel and cost-effective framework of ubiquitous indoor broadband access based on deeply integrated VLC and PLC technology with only low-cost modification to the current infrastructure is therefore proposed. The broadband access network supports duplex transmission through each LED using the decode-and-forward (DF) working mode. This paper will present our recent research progress in this area, including a prototyping of duplex voice communications network based on hybrid PLC and VLC in our lab. Our research and development plan in this area for the near future will also be covered.**

***Key words*—Visible light communication (VLC), power line communication (PLC), indoor broadband access, decode-and-forward (DF).**

I. Introduction

With the increasing demand of high-rate data access, the wireless spectrum resource is becoming more and more crowded and hence extremely rare. Besides, the state-of-art wireless communications systems are subject to different kinds of severe interferences. In order to overcome the bottleneck of wireless communications, there are many emerging alternatives that have drawn much research attention. One of the most competitive approach is visible light communication (VLC). The widely deployed light-emitting diode (LED) for illumination is a promising communication access point using VLC techniques. Up to 100 MHz of bandwidth that is unregulated in VLC could be exploited, and recently the VLC standard, IEEE 802.15.7 (LiFi), is developed [1].

However, VLC must access the backbone network in case of being the so-called *information isolated island* [2] to realize the communication purpose. In VLC, the most straightforward solution is to connect different LED lamps with separate network cables, which, however, requires huge modifications on the existing indoor wiring and is neither cost-effective nor practical [3]. In the past few years, the power line communication (PLC) technique has been widely applied in smart grid and smart home [4], [5]. The integration of PLC and VLC is therefore investigated based on the observation that almost all the LED lamps are connected to power cables [6]. This motivates the feasibility of using the power line as a backbone powering the LED lamps, and also serving as the local access of the information source for the VLC systems. With this arrangement, the power network and illumination network can be locally combined to serve the communication purpose naturally. In this way, it will save the additional cables and be installed more easily [7].

To the best of the authors' knowledge, there is limited existing research on the integration and network framework of PLC and VLC. In our previous work, a hybrid PLC-VLC transmission based broadcasting system is introduced and experimental results are reported, which is an effective approach to indoor broadband broadcasting [8]. On the other hand, the decode-and-forward (DF) and amplify-and-forward (AF) frameworks in the unique PLC-VLC integrated channel are not adequately studied on, although they have been investigated in wireless communications. Besides, in the conventional research on PLC-VLC integration, infrared or RF is adopted as a lower rate uplink, which is asymmetric to the high-speed downlink VLC [7]. The duplex symmetric VLC is lack of investigation. To address these issues, in this paper, a cost-effective approach of hybrid PLC-VLC based broadband access network that supports duplex VLC is proposed. The main contributions are demonstrated as follows:

- A cost-effective and efficient proposal for the PLC-VLC integrated network based on the duplex DF is introduced and analyzed.
- The duplex DF-based proposal could support multi-user broadband access, where cooperative communications could be utilized to mitigate intercell interference.
- A typical demo of the duplex DF-based integrated PLC-VLC communications framework is implemented and field tested, where a cost-effective symmetric VLC uplink is implemented to support high QoS duplex transmission, without requiring other modifications on protocols or

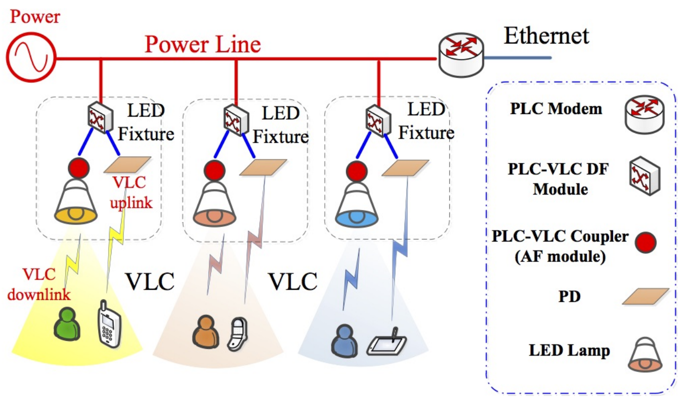

Fig. 1. The proposed framework of duplex DF underlying broadband access network.

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II. The Framework of PLC-VLC Integration Based Broadband Access

In this section, we present a proposal for the framework of the integrated PLC-VLC transmission based broadband access system. The proposal is based on the DF duplex working mode, whose definition comes from relay techniques and is similar to that in the area of wireless communications and cooperative communications. DF mode is adopted for both downlink and uplink transmissions to build up a symmetric duplex broadband access network that could support various kinds of duplex high-speed communications services.

Firstly, we propose the framework of the hybrid PLC-VLC based broadband access network using DF for both downlink and uplink, which supports duplex broadband communications, as illustrated in Fig. 1. In the typical duplex broadband access network as shown in Fig. 1, multiple LED fixtures are connected to one power line. The power lines are connected to the PLC modem that is exchanging information with the backhaul Ethernet. The LED lamps send different data signals via VLC to end users independently, while the users receive the signal by the handheld terminals. The terminals support uplink transmission via VLC. The detector in the LED fixture receives the uplink signal that is demodulated and transmitted to the PLC backhaul afterwards. The multiple end users share the PLC-VLC channel resource through the control of the DF modules using frequency division multiple access (FDMA) or time domain multiple access (TDMA).

Each LED fixture is composed of a PLC-VLC DF module, a PLC-VLC coupler, an LED lamp, and a photo diode (PD). The functionality of the PLC-VLC DF module is bi-directionally exchanging information between PLC and VLC, by demodulating and decoding signals from one side (PLC or VLC) and modulate the desired signal to the other side (VLC or PLC). The signal at the PLC side could be modulated broadband signal such as the orthogonal frequency division multiplexing (OFDM) signal, while the same OFDM signal as well as the on-off keying (OOK) signal and the variable pulse-position modulation (V-PPM) signal specially designed for VLC can be a good choice at the VLC side. The DF module can cope with the interaction and transformation between the signals at both sides. The modulated VLC signal is then coupled to the LED lamp through the PLC-VLC coupler that can be also regarded as the AF module since it just amplifies the input signal and forwards it without any change to its modulation.

In the proposed framework, each LED fixture can be regarded as a base station that sends signals within a cell in wireless communications, and there is similarly inter-cell (inter-LED) interference. The inter-cell interference at the conjunction area of different cells (LED coverage areas) is an obstacle to QoS. Cooperative communication technique is a promising choice to mitigate the inter-cell interference. Exploiting the PLC backhaul that is naturally connected to all the LED fixtures, the information required by inter-cell interference mitigation can be dispersed easily, and each LED will send information in a way that minimizes inter-cell interference to improve channel capacity. Then, the reception could be interference-free.

Furthermore, the proposed framework is implemented in a laboratory test demo. The field test demo supports duplex data transmission (such as voice, video, etc.). Through the demo, the feasibility and efficiency of the proposed PLC-VLC broadband access network can be validated, which is reported in detail in Section III.

III. Demo of the Duplex PLC-VLC Broadband Access Network

Laboratory test of a broadband duplex transmission platform that supports duplex voice and data transmission is done for the proposed PLC-VCL integration based framework, which is set up as shown in Fig. 2. A number of LEDs are deployed in an underground tunnel, where power lines are connecting them. The central unit on the ground could communicate with end users in the tunnel through the monitor and microphone, while the end users can have duplex access to the network and communicate with each other or with the central unit by the handheld terminals. The PLC master (modem) is the hub between the power line and the central unit that switches the TCP/IP formatted data from the central unit to the modulated OFDM signal to transmit on power lines. The LED fixture shown in Fig. 2 is a concrete implementation of that in

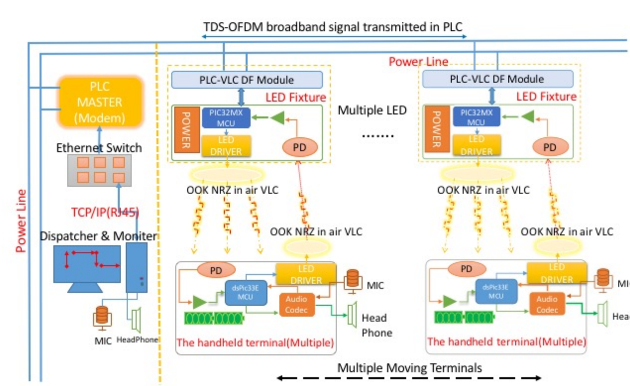
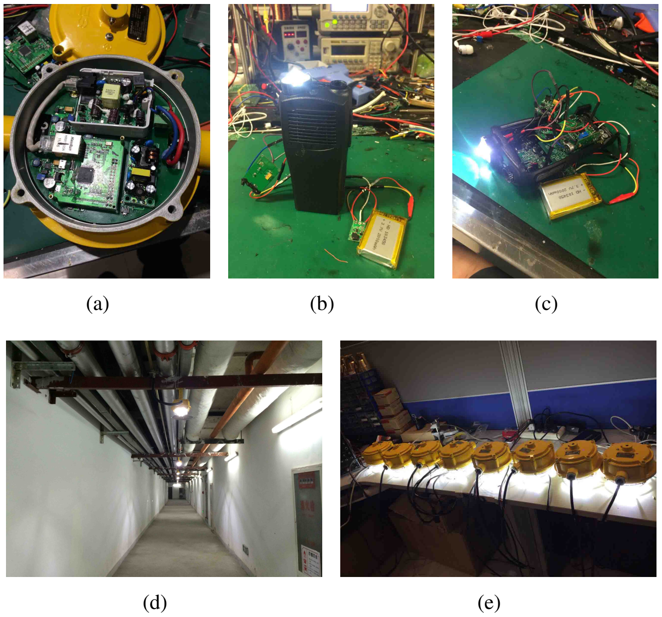


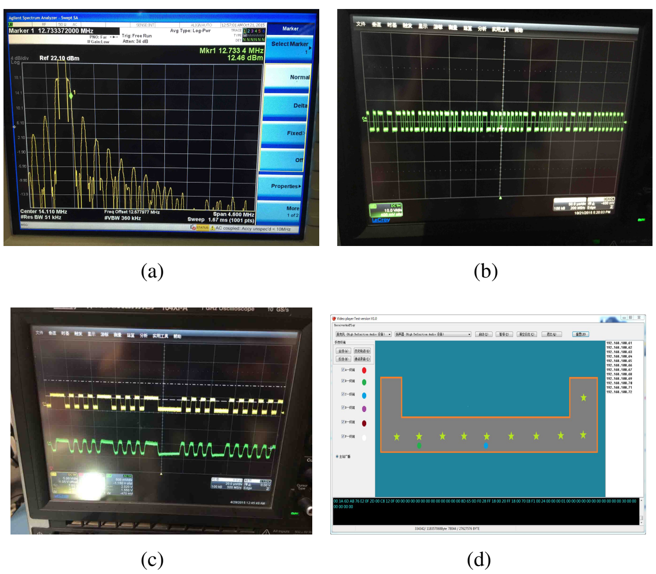
Fig. 2. The diagram of the demo of duplex broadband access network based on PLC-VLC integration.



(a) (b) (c)

(d) (e)

Fig. 3. The implementation of PLC-VLC integrated duplex communications network: (a) The LED fixture with DF module and PLC-VLC coupler; (b) Duplex VLC handheld terminal; (c) Rx & Tx modules in handheld terminals; (d) Overview of PLC-VLC access network; (e) Capsulated LED fixtures.



(a) (b)

(c) (d)

Fig. 4. The test data of the PLC-VLC integrated demo (a) Received spectrum at handheld terminal; (b) The OOK modulated transmit signal at the LED fixture; (c) The VLC transmitted and received time-domain waveforms; (d) The monitor software at the central unit of the demo network.

Fig. 1. Each LED fixture includes a PLC-VLC DF module for duplex demodulation and modulation, an LED driver (PLC-VLC coupler), and a PD for receiving uplink VLC signal. The end users are carrying handheld terminals and moving in the tunnel under the LEDs. The handheld terminal is composed of a PD to receive the downlink VLC signal, a duplex codec module to obtain the desired information data or modulate the uplink VLC signal, as well as the LED driver for uplink.

The power line length is over 100m apart (the delay is around 0.5 μs), where OFDM signal is transmitted with 16QAM modulation and the LDPC code. The information is coded by NRZ and is modulated as an OOK signal and transmitted via VLC for both uplink and downlink.

The implementation and devices of the PLC-VLC integrated demo for test are shown in Fig. 3. The DF module as well as the PLC-VLC coupler and the PD are capsulated in the LED fixture with a secure lamp case as shown in Fig. 3(a), while multiple capsulated LEDs are shown in Fig. 3(e). The handheld terminal embedded with the receive and transmit modules is shown in Fig. 3(b) and Fig. 3(c). The overview of the entire PLC-VLC integrated broadband access network in the underground tunnel is reported in Fig. 3(d), where many LEDs and the power lines connecting them are depicted.

The proposed demo is tested and the transmit and receive spectrums and time-domain waveforms are reported in Fig. 4. All the data, spectrums and waveforms are field tested and recorded using the spectrum analyzer and the oscilloscope. Fig. 4(a) reported the received spectrum of the downlink VLC signal at the handheld terminal. It is observed that the received downlink VLC signal spectrum is an OOK spectrum. Fig. 4(b) shows the time-domain waveform of the downlink OOK modulated VLC signal. The time-domain NRZ formatted waveforms of the source information data generated by one end user and the decoded data at another receive end user are shown in Fig. 4(c), where it can be noted that the finally decoded information exactly matches the originally transmitted information from either another end user or the central unit. In Fig. 4(d), the monitor software at the central unit outside the tunnel shows the communication status of all LED fixtures and end users in the demo network. It can be observed that two end users are communicating with each other, represented by the green and blue dots in Fig. 4(d).

The experimental test results validated that the performance of the proposed PLC-VLC integration broadband access network is satisfactory and cost-effective. With the distance between the LED and the receive terminal over 3 meters, duplex broadband communications including voice, video and high-rate data with data rate of over 5 Mbps are supported with high QoS (BER could reach below 10^{-5} with the field test time over 3 days) by the proposed network. The data rate could be easily extended to 30 Mbps for this system. Multi-users could communicate with each other interference-freely without collisions. The proposed duplex symmetric PLC-VLC framework enjoys superior performance with respect to conventional PLC-VLC integration systems.

IV. Future Work

Based on the proposed frameworks, further research, application and development could be carried out to improve the performance and applicability of the proposal. Some promising topics and issues worth investigating include but not limited to

- Aggregated channel modeling and advanced channel estimation of the PLC and VLC integrated system for an improved performance: Based on the aggregated characteristics of PLC and VLC channels, one can take advantage of the sparsity of the channel and exploit compressive sensing for high accuracy channel estimation. In our previous work, the channel state information (CSI) of the PLC channel is obtained based on Bayesian compressive sensing [9]. Considering the parametric sparsity of the PLC channel, the topology of the power line network is reconstructed based on Bayesian compressive sensing as well [10]. Another compressive sensing based method of channel estimation is introduced to cope with channels with long delay [11].

- Non-Gaussian noise and interference cancellation: The importance of cancellation of narrowband interference and impulsive noise in the aggregated PLC-VLC channel should be emphasized on. Narrowband interference and impulsive noise are quite common in PLC and VLC systems. Note that the narrowband interference has the sparse nature in the frequency domain, while the impulsive noise in the time domain is also sparse in nature. Hence, sparse signal processing theories, including compressive sensing and sparse Bayesian learning, can be applied to effectively solve this issue. In our previous work, a compressive sensing based narrowband interference cancellation method is proposed for PLC [12]. A novel framework is further proposed to reconstruct the narrowband interference and impulsive noise simultaneously based on compressive sensing, which is able to recover the non-Gaussian noise and interference accurately and cancel them from the information data [13].
- Advanced modulation techniques for PLC and VLC transmission: Among the VLC modulation technologies such as ACO-OFDM, DCO-OFDM, SC-OFDM, etc., it is necessary to determine which is the best choice in the context of PLC-VLC integration. The benefit that can be achieved by using APSK instead of QAM in the PLC transmission is also interesting. A possible solution is to design the same OFDM modulated signal for both PLC and VLC transmission, so both the hardware and protocol could be simple and cost-effective.
- Multiple access schemes in the multi-user network: TDMA is applicable in the proposed network and demo, while non-orthogonal multiple access is a promising technique that could improve multi-user capacity effectively, such as sparse code multiple access (SCMA) and bit division multiplexing (BDM).
- The duplex mode for symmetric PLC-VLC transmission: The VLC uplink transmission scheme should be further investigated to adapt to the QoS requirements. Although the duplex mode in the demo is TDD, whether to choose TDD or FDD duplex mode needs further investigation.

V. Conclusions

The mechanism, methodology, implementation and field test of the PLC-VLC integrated network for ubiquitous broadband access are presented in this paper. To provide flexible and cost-effective alternatives for implementation of broadband access, a proposal for the duplex DF based broadband access network is described, which can be adapted to many different scenarios while maintaining high QoS. Through the natural and simple combination of the electricity and illumination infrastructure, broadband access is promisingly ubiquitous available yet cost-effective. Hence, this is of much importance in context of the ever scarcer RF spectrum resources and increasing demand of high-rate communications needs.

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References

[1] *IEEE Std 802.15.7-2011, IEEE standard for local and metropolitan area networks–part 15.7: Short-range wireless optical communication using visible light*, IEEE Std., Jun. 2011.

[2] T. Komine and M. Nakagawa, “Fundamental analysis for visible- light communication system using led lights,” *IEEE Trans. Consum. Electron.*, vol. 50, no. 1, pp. 100–107, Feb. 2004.

[3] J. Rufo, J. Rabadan, F. Delgado, C. Quintana, and R. Perez-Jimenez, “Experimental evaluation of video transmission through led illumination devices,” *IEEE Trans. Consum. Electron.*, vol. 56, no. 3, pp. 1411–1416, Aug. 2010.

[4] H. C. Ferreira, L. Lampe, J. Newbury, and T. G. Swart, *Power Line Communications - Theory and Applications for Narrowband and Broadband Communications over Power Lines*. Chichester, UK: Wiley, 2010.

[5] S. Galli, A. Scaglione, and Z. Wang, “For the grid and through the grid: The role of power line communications in the smart grid,” *Proceedings of the IEEE*, vol. 99, no. 6, pp. 998–1027, Jun. 2011.

[6] T. Komine and M. Nakagawa, “Integrated system of white led visible light communication and power-line communication,” *IEEE Trans. Consum. Electron.*, vol. 49, no. 1, pp. 71–79, Feb. 2003.

[7] H. Ma, L. Lampe, and S. Hranilovic, “Integration of indoor visible light and power line communication systems,” in *IEEE Int. Symp. Power Line Commun. Appl. (ISPLC)*, 2013, pp. 291–296.

[8] J. Song, W. Ding, F. Yang, H. Yang, B. Yu, and H. Zhang, “An indoor broadband broadcasting system based on plc and vlc,” *IEEE Trans. Broadcast.*, vol. 61, no. 2, pp. 299–308, Jun. 2015.

[9] W. Ding, Y. Lu, F. Yang, W. Dai, and J. Song, “Sparse channel state information acquisition for power line communications,” in *Communications (ICC), 2015 IEEE International Conference on*, 2015, pp. 746–751.

[10] X. Ma, F. Yang, W. Ding, and J. Song, “Topology reconstruction for power line network based on bayesian compressed sensing,” in *Power Line Communications and its Applications (ISPLC), 2015 International Symposium on*, 2015, pp. 119–124.

[11] W. Ding, F. Yang, C. Pan, L. Dai, and J. Song, “Compressive sensing based channel estimation for ofdm systems under long delay channels,” *Broadcasting, IEEE Transactions on*, vol. 60, no. 2, pp. 313–321, 2014.

[12] S. Liu, F. Yang, C. Zhang, and J. Song, “Compressive sensing based narrowband interference cancellation for power line communication systems,” in *IEEE Global Communications Conference (Globecom’14)*, Dec. 2014.

[13] S. Liu, F. Yang, W. Ding, and J. Song, “Double kill: Compressive sensing based narrowband interference and impulsive noise mitigation for vehicular communications,” *IEEE Trans. Veh. Technol.*, 2015.