Design and demonstration of room division multiplexing-based hybrid VLC network

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A room division multiplexing (RDM)-based hybrid visible light communication (VLC) network for realizing indoor broadband communication within a multi-room house is presented. The downlink information is transmitted by light-emitting diode lamps, whereas the uplink information is transmitted through WiFi. RDM is introduced to improve the VLC network throughput; in addition, the associated signaling localization and active handoff mechanisms are designed for implementation. The experimental platform demonstrates the effectiveness of the proposed hybrid architecture, along with the RDM and active handoff mechanisms.

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Light emitting diode (LED)-based indoor visible light communication (VLC) attracts great attention among researchers because it combines the advantages of both optical and wireless accesses using visible light as the carrier and free space as the channel[1]. Current studies on VLC primarily focus on system-level technologies such as dimming control, flicker mitigation, and advanced modulation mechanisms[2,3]. Based on these studies, the network-level VLC technology is examined[4−6].

The uplink mechanism is a fundamental problem for VLC networking, and several different schemes are available. The visible light uplink scheme[7,8] is suitable for use in electromagnetic-sensitive and security communication environments, wherein a relatively high uplink transmission speed can be reached. However, VLC owes its basic popularity to its being energy-efficient, because it utilizes green lighting LED lamps in the ceiling for both lighting and communication. However, when such communication requires hardware updating on all of the user terminals in order to integrate additional lighting devices, the deployment cost must also be considered neglected. More importantly, if a large number of users are distributed randomly in a large room, the scattered uplink visible signals can affect the indoor illumination and cause discomfort to the eyes. Therefore, VLC may not be the ideal choice in this scenario. The alternative scheme is to use infrared wave, in which the uplink information is transmitted by an infrared LED in the user terminal[1,6]. Given that the infrared wave has similar characteristics as the visible light, it can also be deployed in electromagnetic-sensitive locations such as hospitals and aircraft cabins. Additionally, it avoids the uplink visible light noise problem. However, the design of the transceiver for both visible and infrared light signals is still a challenge for system integration and size minimization. Moreover, eye safety is also a potential problem for infrared communication, because an excessively high invisible infrared power may cause discomfort or even damage to human eyes. Therefore, the performance of the downlink VLC and uplink infrared system requires further investigation.

Another uplink mechanism has yet to be discussed thoroughly, that is, the conventional radio frequency channel, in which the uplink information is transmitted through WiFi. This scheme is suitable for use in several electromagnetic-insensitive places such as residential homes, offices, and supermarkets. WiFi is capable of carrying uplink services, because uplink data traffic is always considerably less than that of the downlink direction in an access network. Thus, the implementation of a hybrid VLC network using mature WiFi technology as the uplink mechanism is promising in the near future.

In the current VLC network model, the downlink information is broadcast through all the LED lamps deployed at the ceiling[1], which realizes the uniform signal distribution within the entire room. However, this broadcasting operation is deemed inefficient in a multi-room house scenario, because it not only limits the network throughput, the network also cannot support flexible user access and bandwidth allocation[5]. The solution is to introduce a room division multiplexing (RDM) scheme, in which the information of a certain user is not broadcast by all LED lamps in the entire house but only by the LED lamps in the corresponding room where the user is located.

In this letter, we design a hybrid networking architecture using downlink RDM-based VLC and uplink WiFi for indoor multi-room broadband access. Moreover, we discuss the implementation mechanisms in detail. The literature has presented numerous heterogeneous interconnection schemes, including VLC+ power line communication[9], VLC+ Ethernet[10], and VLC + radio over fiber[11]; however, no study has yet to present a specific VLC+WiFi scheme. Meanwhile, time division multiplexing (TDM) is the basic multiplexing method discussed in current VLC research; here, RDM can be considered as the first step in deploying space division multiplexing in VLC, which has a great potential to increase network throughput.

Figure 1 presents the hybrid networking architecture of the downlink RDM-based VLC and uplink WiFi for indoor multi-room access. In this design, user service is

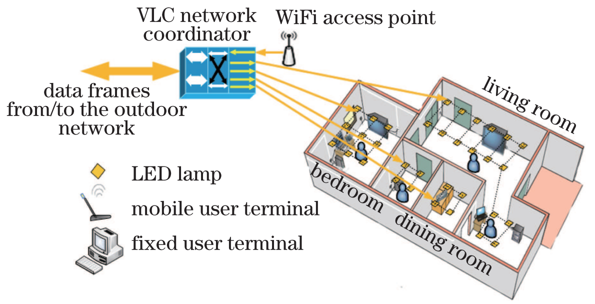

Fig. 1. Architecture of the RDM-based indoor multi-room hybrid VLC network.

transmitted to the VLC network from the outdoor devices, and is divided into several groups according to the user positions. The LED lamps in a certain room only broadcast the corresponding group of information for the users within that room. This scheme is the main principle of the proposed RDM, in which the optical signal is still distributed evenly in each room, but the signals between any adjacent rooms are separated naturally by the walls and doors without any interference. The network throughput is increased when the LED lamps in different rooms simultaneously transmit different information.

The VLC network coordinator is the core feature of VLC network configuration and management in this architecture; its functional modules and implemental specifications are defined in the Institute of Electrical and Electronics Engineers standard for VLC Std 802.15.7. Aside from these functions, the coordinator is also responsible for realizing the RDM-based service division and distribution as well as for providing bidirectional interfaces between the outdoor and indoor communication infrastructure, especially the indoor interfaces for uplink WiFi access and downlink LED lamps in this architecture. The user terminals, both fixed and mobile, are equipped with photodiodes (PDs) and WiFi transmitters for downlink receivers and uplink transmission, respectively. To accomplish the service division and distribution in the coordinator, a data buffer and a cross switching array should be configured for hardware operation; here, two software programs are required for user localization and handoff control. When a user enters the house, the localization program starts to determine the room where this user is. When a downlink data frame arrives, the coordinator reads out the MAC address, recognizes the user, determines the destination room, and then generates an operator to the cross-switching array to transmit this data frame to the corresponding output port. When the user moves to another room, the handoff control program starts to switch the user data to another output port.

User localization and handoff control are the two novel functions of the coordinator, which can help realize RDM. Many LED-based indoor localization mechanisms are presented[12,13]. However, one common problem of these mechanisms is that the LED lamps are designed for illumination and localization and not for simultaneous communication. Thus, in such mechanisms, the LED lamps should send certain signals to assist the user terminals for localization, rendering them incapable of broadcasting user services. Another proposed WiFi-based indoor localization mechanism has low localization accuracy for use in localization requirements.

In our proposed RDM scheme, the localization requirement is to differentiate the room where one user is. Here we present a signaling localization mechanism, which can easily be implemented in a VLC network. In the hybrid network (Fig. 1), the LED lamps in each room construct a cell identified by a certain *cell-id*, which is then added into the network control message periodically broadcast by the coordinator for user registration and system synchronization. Each user should send an acknowledgment (ACK) message back to the coordinator, which contains the *user-id* and the *cell-id* received, in order to identify that he is still in this room. Therefore, the coordinator can use the replied *cell-id* information to determine the room where the user is located.

Although it is suggested that VLC must be deployed in low-mobility situations, handoff operation is inevitable, considering that the user may move to another room using a mobile terminal in the presented multi-room house scenario. The abovementioned signaling localization mechanism is inefficient in handling such a cross-room handoff, because the localization is only determined after the user enters the room. If the user crosses the door, the information broadcast in the original room may be lost, and the communication can only be continued once the user is relocated in a new room. Such handoff is regarded as "hard handoff" in current mobile communication; however, it is not sufficiently efficient. To solve this problem, the handoff operation should be generated in advance when the user goes near the door. This situation is called "soft handoff," in which a new connection is setup before the old one disconnects; however, to realize soft handoff, an overlapped area should be readily available between two adjacent cells for handoff generation. Meanwhile, in our network, the optical signals between adjacent rooms are separated by the walls and doors; hence, such soft handoff is not suitable here.

We present an active handoff mechanism, which can be efficiently deployed in the VLC network. The aforementioned handoff mechanisms are passive handoffs, in which the user terminal executes the handoff operation passively under the instructions of the network management system. In conventional mobile communication, the positions of the base stations are always invisible to the user; therefore, the user cannot determine when the handoff should be generated. In comparison, in a VLC network, the cross-room handoff is caused by the active movement of the user, and the position of the door is visible to the users; hence, the handoff can be predicted. Therefore, we can now define an active handoff mechanism as follows. When the user terminal is about to move to another room while communicating, it sends an ACTIVE_HANDOFF message to the coordinator through the uplink WiFi channel, which contains the *user-id* and the from/to room information. Upon receiving this message, the coordinator starts to broadcast the user service data in both rooms where the user is located, and then generates a HANDOFF_ACK message back to the user terminal. This message contains the new *cell-id* and the new resource *unit_id*, through which the user can obtain the continuing service data in the new room. When the terminal receives the data frame with the new *cell-id* in the adjacent room, it sends a general ACK message back to the coordinator, which then ends the handoff procedure by ceasing to broadcast the service data in the original room. Figure 2 shows the block diagrams for the process of the common hard handoff and the presented active handoff mechanisms.

Figure 3 presents an example of the active handoff procedure. Three users (a, b, and c) are in room A and four users (d, e, f, and g) are in the adjacent room B. Users c and e want to transfer to rooms B and A, respectively. Figure 2 shows the different data slot sequences broadcast by the LED lamps in two rooms in different states during the handoff procedure. For simplicity, the downlink information is organized in a synchronous TDM format, and two periods of the data frames are presented, in which the free slots that have not been allocated are not expressed in the sequence.

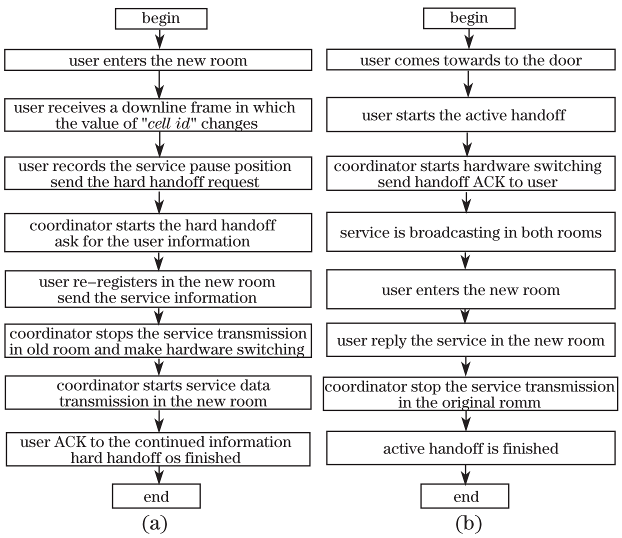

Fig. 2. Block diagrams for (a) the common hard handoff mechanism and (b) the presented active handoff mechanism.

state/ event	data slots sequence broadcasted in room A	data slots sequence broadcasted in room B
initial state	A a b c A a b c	B d e f g B d e f g
user c handoff-start	A a b c A a b c	B d e f g c B d e f g c
user e handoff-start	A a b c e A a b c e	B d e f g c B d e f g c
user c handoff-start	A a b N e A a b N e	B d e f g c B d e f g c
user e handoff-start	A a b N e A a b N e	B d N f g c B d N f g c

Fig. 3. Example of the proposed active handoff mechanism. A: header of the data frame in room A; B: header of the data frame in room B; N: empty time slot that can be assigned to new user; a—g: the data slot for certain user from user a to user g.

Theoretically, although this active handoff mechanism is different from the conventional passive handoff methods, it is feasible and efficient in the VLC network, because it realizes the service handoff with low operation complexity, low handoff delay, and without any loss of user information. The only issue to be addressed is the proper time for the user to send the ACTIVE_HANDOFF message. On the one hand, if it is sent too early, unnecessary double-broadcasting information is generated; on the other hand, if it is sent too late, the accomplishment of the handoff operation cannot be guaranteed. The proper generation time is thus determined by the system hardware, software configuration, and switching latency, which should be measured in the practical network.

To evaluate the performance of the RDM-based hybrid VLC network, we built an experimental platform and demonstrated the proposed service distribution, signaling localization, and active handoff mechanisms. Figure 4 presents the structure of the platform.

The coordinator was controlled by a computer, a field-programmable gate array (FPGA), and a wireless router. The computer was responsible for running software operations (i.e., user localization, handoff control and signaling) and was connected to the FPGA through a USB port for instruction assignment. Outdoor information was generated from a server computer, which was connected to the FPGA through the RJ45 Ethernet interface. The FPGA read out the MAC addresses of the incoming data frames and distributed them into different output ports under the control of the coordinator computer, which were then sent to different LED lamps. At the receiver, the optical signals were received by PDs, converted to electrical signals, amplified, reshaped, and then sent to another FPGA to return back into the Ethernet data formats. Finally, these signals were shown in the laptop, which utilized the wireless network adapter to send the uplink signaling messages to the wireless router. We defined associated signaling and handoff control messages based on user datagram protocol; furthermore, both the downlink data frames and the downlink control frames were sent by the LED lamps, whereas both the uplink data frames and the uplink control frames were sent through the radio channel. Figure 5 shows the photos of the entire platform as well its key parts.

In the platform, two LED lamps (LE_CW_ E2B) and two PDs (Si PIN S6801) were utilized to simulate a two-room house scenario. A piece of wooden board was also used to separate the two parts of the signals. We used the point-to-point line-of-sight channel for both uplink and

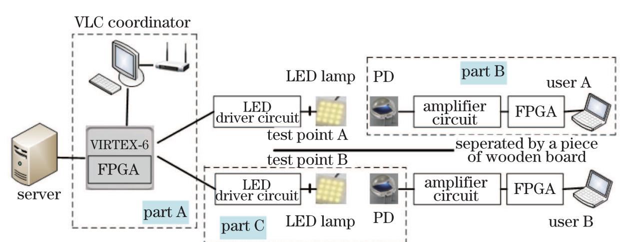

Fig. 4. Structure of the multi-room hybrid VLC experimental platform.

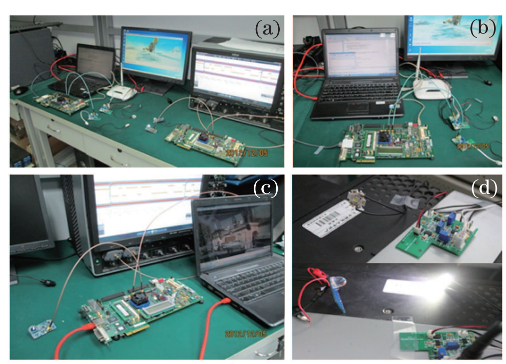

Fig. 5. Hybrid VLC experimental platform and its key parts: (a) the entire platform; (b) , (c), and (d) are photos of parts A, B, and C in Fig. 4.

downlink transmissions. The basic on-off keying modulation was also utilized. The drive current of LED was 530 mA, and the active area of the PD was 120 mm^2. The distance between the LED and PD was 5 cm (no optical focusing lenses were used). The basic function of the RDM is to increase network throughput, and the FPGA divides the service into two groups transmitted by different LED lamps. Figure 6 presents the waveforms of the two columns of transmitted/received signals in the two simulated rooms captured by the *Lecroy* oscilloscope. The speeds of the signals in the two rooms are both 22 Mb/s, with a BER of $<2.1\times10^{-9}$. These results show that using RDM improves the network throughput to 44 Mb/s.

Handoff latency is an important parameter in executing active handoff, and we design the following procedure for practical measurement. The user, laptop A, sends an ACTIVE_HANDOFF message to the coordinator using the uplink wireless channel. The coordinator computer receives the message, determines the user information, and sends a signaling message as a handoff order to the FPGA for data switching. Afterwards, laptop A receives the data for the other user. The software Wireshark is installed in laptop A, and the coordinator computer shows the exact system time when a message is sent or received. We randomly implemented the above procedure 15 times to measure the handoff latency. Figure 7 presents the results. The time measured by the coordinator computer expresses the hardware switching operation latency for the active handoff. Based on Fig. 7, this latency is less than 80 ms, implying that the coordinator can handle the user handoff requests without any additional queuing latency when the interval between any two requests is more than 80 ms. Meanwhile, the time measured by the laptop expresses the complete handoff latency for the active handoff. Figure 7 also indicates that the latency is less than 600 ms, implying that the minimal period for the user to start the active handoff procedure in advance is less than 600 ms. When the user starts the active handoff 600 ms before he crosses the door, the proposed mechanism can accomplish the software and hardware switching operations. This accomplishment can be guaranteed in practical situations. To compare the performance of the presented active handoff with the conventional hard handoff mechanism, we also implemented the process of hard handoff in our platform (following the block diagrams in Fig. 2). Figure 8 shows that although the hardware switching operation latency is similar to the active handoff (i.e., less than 90 ms), the entire handoff latency of the hard handoff is over 1 700 ms, which is much higher than that of the active handoff mechanism. Therefore, the proposed active handoff mechanism is feasible and

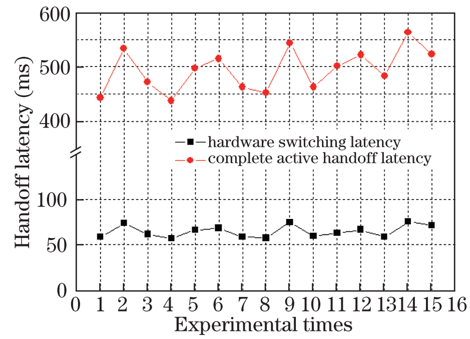

Fig. 7. Handoff latency for the proposed active handoff mechanism.

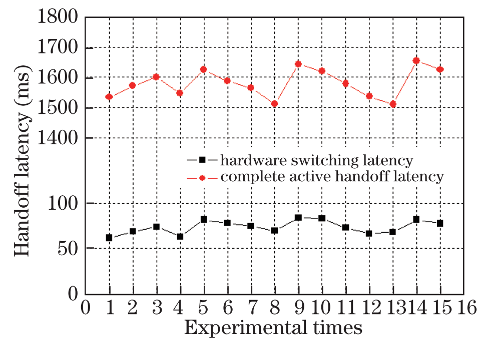

Fig. 8. Handoff latency for the common hard handoff mechanism.

can efficiently deal with the user mobility problem in the indoor multi-room RDM-based VLC network.

However, the drawback of the active handoff mechanism is the active intervention of the user. This is because a handoff mechanism, in which the switching operation is accomplished automatically by the network itself without user intervention, is a better choice for network design and a more practical choice for implementation. Therefore, our future work will focus on identifying a more efficient handoff mechanism and on discussing the feasibility of RDM and space division multiplexing in more complex VLC networks.

In conclusion, a RDM-based hybrid VLC network is designed for indoor broadband and flexible communication in an electromagnetic-insensitive multi-room house scenario. The uplink information is transmitted through WiFi technology, which sets an example for realizing the convergence for VLC and current wireless network. The RDM improves the network throughput and facilitates the introduction of space division multiplexing into the VLC network in the future. Signaling localization and active handoff mechanisms are also designed for RDM implementation. The experimental platform demonstrates the proposed hybrid network architecture and validates the performance of its mechanisms.

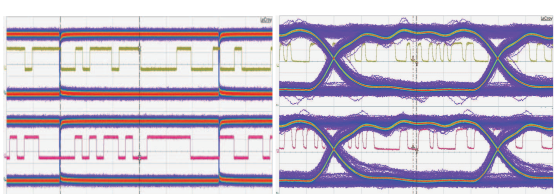

Fig. 6. Waveforms of transmitted/received RDM signals captured by the Lecroy oscilloscope.

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