Efficient user access and lamp selection in LED-based visible light communication network

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We present a network-level signaling mechanism for user access and service setup in light emitting diode (LED)-based visible light communication (VLC) networks and define the corresponding signaling messages. In this mechanism, lamp selection is an important step for realizing flexible user access and efficient resource allocation. Two basic selection schemes are proposed, and an enhanced bandwidth-based scheme is presented. Simulation results show the different advantages among these schemes.

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Recently, due to the large-scale deployment of white light emitting diodes (LEDs) as the next-generation green lighting, LED-based visible light communication (VLC) has attracted much attention. Current studies on VLC primarily focus on system-level technologies, such as dimming control, flicker mitigation, and novel modulation mechanisms, which aim to raise the transmission speed and signal quality. A previous study analyzed the in-door channel characteristics of multipath dispersion[1] and showed that VLC can provide a wider transmission bandwidth than infrared (IR) communications. A fast channel characterization algorithm was presented for VLC channel modeling considering the sophisticated reflections[2]. Moreover, discrete multi-tone modulation[3] and multiple pulse position modulation[4] were recommended for use in VLC systems to address the flicker problem. An effective model was also presented to reduce LED nonlinearity distortion in VLC systems[5]. As a collective achievement for current VLC system research, IEEE standard 802.15.7 presented the definition of the PHY and MAC layer technologies for VLC[6].

Based on the aforementioned system-level studies, the network-level VLC technology was analyzed. An Ethernet–VLC network interface was designed to realize IP broadcast applications[7], and a rapid link recovery scheme was proposed to guarantee link visibility[8]. However, such network has a basic problem that has not been studied thoroughly. The light wave of a LED is not as diffractive as the radio wave, making the coverage of one single LED lamp limited. Therefore, in a large in-door environment, such as a museum or a supermarket, multiple LED lamps are required to extend the coverage scale. In most of the current VLC experimental or simulation networks[2,7], all LED lamps transmit the same signal to obtain uniform signal power within the in-door environment. However, in this scenario, the bandwidth of the whole VLC network becomes very limited (similar to that of a single LED lamp). Thus, different lamps should carry different signals to realize broad-band access. This goal is achieved using the lamp-based space division multiplexing (SDM) method, in which one LED lamp acts as an individual channel. In such SDM VLC network, the selection of the proper LED lamp to achieve efficient user access and channel allocation becomes the key problem. Network signaling is required to solve such problem[9]. Hence, in this letter, we propose a network-level signaling mechanism for flexible user access and service setup in VLC networks. In addition, the corresponding signaling messages and efficient LED lamp selection schemes are identified.

A typical realization of the LED-based VLC network is presented in Fig. 1. LED lamp arrays are evenly distributed at the ceiling, and these lamps are connected to the outside communication infrastructure for information exchange. The next-generation broad-band access network is realized using the VLC+passive optical network (PON) architecture, in which LED lamps are connected to both electrical power lines and the optical network unit (ONU) to acquire the lighting power and the information, respectively. The LED coverage limitations require different LED lamps to handle the user service requests in different locations of the room. A network control module[9] called LED scheduler should be added between the ONU and the LED lamps. This module accomplishes the network signaling for user access and lamp selection.

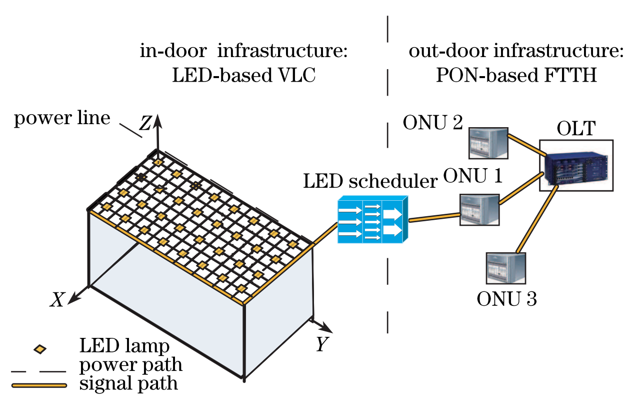


Fig. 1. Typical in-door LED-based VLC network model and the information connection with the out-door FTTH infrastructure. OLT: optical line terminal; FTTH: fiber to the home.

The PHY and MAC layer mechanisms should be implemented according to the specifications set in Ref. [6]. In this letter, we focus on the network-level signaling procedure and the lamp selection schemes.

The standard user access and service setup procedure in the VLC network requires the exchange of the signaling protocol messages between the user terminal and the LED scheduler. The formats of two basic messages, the VLC Request message and the VLC ACK message, are defined as

<VLC Request message> ::= {user ID, user position, user character, service ID, service QoS requirements},

<VLC ACK message> ::= {user ID, service ID, LED lamp ID, resource unit}.

When a user terminal starts a service, it should first send a VLC Request message to the LED scheduler (In this letter, the LED lamp is assumed to be a transparent device that does not handle the network signaling messages. Therefore, the signaling operations are implemented between the user terminal and the LED scheduler). This request message has five sessions. The <user ID> session specifies which user generates this request. Thus, the different users in the room have different user IDs. The <user position> session contains the exact user position represented by a two-dimensional position vector (i.e., x, y). The user position is an important parameter for the following LED lamp selection schemes. Therefore, each user terminal should be equipped with a position sensor that can provide real-time precise position information to the LED scheduler. The <user character> session is an optional session that contains the special character information of the user, such as the priority level. The <service ID> session specifies which service the user generates, and each service generated by this user has its own ID number. The information of both <user ID> and <service ID> can uniquely identify a certain service. The <service QoS requirements> contains the QoS parameters for this service, such as the required bandwidth. The information of this session is different from that in the <user character> session. The QoS is always used to express some technical factors such as bandwidth, delay, and bit error rate. Some nontechnical factors may not be easily mapped to the QoS parameters, but they are very useful in practical operations (e.g., the priority for recovery operations when failure occurs in the network). The *<user character>* session is set for such practical and scalability considerations.

When the LED scheduler receives this request, it reads out the above information and then accomplishes the LED lamp selection algorithm to decide which lamp should be used to handle the service. The LED scheduler creates and maintains a database that records the lamp selection and resource allocation status in the whole VLC network. Such information will be used in the LED lamp selection algorithms.

In response to the request message, the LED scheduler sends a VLC ACK message back to the user terminal to provide the lamp selection results. In this message, the <user ID> and <service ID> sessions are as same as those in the request message, specifying the service to which request this ACK responds. The <LED lamp ID> session specifies which LED lamp is selected to handle this service. The <resource unit> session shows which part of the bandwidth resource in this channel is allocated to this service. The format of the resource unit is based on the multiplexing mechanism used in the network, such as time division multiplexing. Then, the resource unit is a time slot number. If no lamp is available for the service request, the setup failure information will be filled in the last two sessions.

When the user receives the VLC ACK message, it should send a terminal ready message back to the LED scheduler, suggesting that it is ready to receive the data. Afterward, the LED lamp starts to send the information. (The terminal ready message is very simple and may be optional.) The whole standard signaling procedure is shown in Fig. 2.

The LED lamp selection is the most important step in the above service-setup procedure for realizing flexible user access and efficient resource allocation. According to various evaluation principles, different selection schemes can be employed. Two basic schemes, the distance-prior (DP) scheme and the service aggregation (SA) scheme, are presented and discussed. Then, an enhanced bandwidth-based (BB) selection scheme balances the advantages of the two basic schemes is proposed. We only focus on the static situation where the user position is fixed. The support of the mobile service access in VLC networks will be tackled in future studies.

Two assumptions are formulated to simplify the analysis: 1) All users have the same character, thus neglecting the information in the <user character> session; 2) as the bandwidth is considered as a typical example of the QoS requirements, all user services are assumed to have fixed bandwidth requirements. A service with variable bandwidth requirement can be supported by allocating the maximum required bandwidth. Other kinds of QoS requirements may be similarly operated.

In the DP scheme, the LED lamp nearest to the user is selected first. In the VLC network, the user terminal uses a photodiode (PD) to receive the downlink signal. The PD sensitivity determines the minimal required signal power to guarantee correct reception. The LED lighting has a Lambertian radiation pattern[3], as shown in Fig. 3. The room is considered large enough. Hence, the impact of the wall reflection is neglected, and the relationship between the transmitted P_{t} and received P_{r} powers is

$$P_{\mathrm{r}} = P_{\mathrm{t}} \frac{(m+1)E}{2\pi R^2} \cos^m(\phi) T_{\mathrm{s}}(\psi) g(\psi) \cos(\psi), \qquad (1)$$

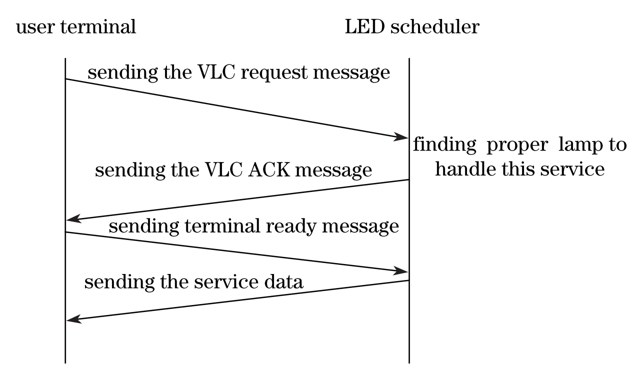


Fig. 2. Signaling procedure for user access and service setup in the VLC network.

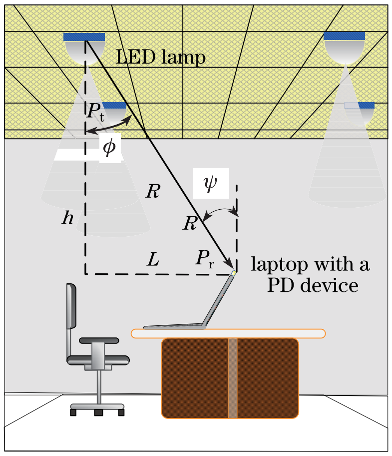


Fig. 3. In-door LED-based visible light communication scenario.

where m is the Lambertian index of LED, E is the equivalent receiving coefficient of PD, R is the distance between LED and PD, $T_s(\Psi)$ is the gain of the optical filter, and $g(\Psi)$ is the gain of the optical concentrator. According to the principle of the DP scheme, from Eq. (1), given a certain P_t, P_r is inversely proportional to R^2. Therefore, the closer the user is to the lamp, the higher will be the received signal. If the user position is (x_u, y_u), the selected LED lamp L_s, whose position in the ceiling is (x_s, y_s), can be expressed as

$$L_s = (x_s, y_s)|(x_s - x_u)^2 + (y_s - y_u)^2 = \underset{i=1}{\overset{N}{\text{Min}}}\,\{(x_i - x_u)^2 + (y_i - y_u)^2\}, \quad (2)$$

where N is the total number of LED lamps in the ceiling. The flowchart of the DP scheme is shown in Fig. 4(a).

Although easily deployable, the DP scheme has several disadvantages. The random distribution of the user positions causes relatively dispersed signals. Therefore, many LED lamps in the DP scheme may carry very limited services, which is not economical. Furthermore, the network management system cannot rapidly calculate statistical data from numerous scattered services. To address these problems, the SA scheme uses the fewest lamps possible to satisfy the service requirements. When the user request arrives, the LED scheduler first reads out the user position and the bandwidth requirements and then calculates which LED lamps can service this user.

A quantitative analysis is conducted, where a common scenario with Lambertian index m=1 is considered. The gain of the optical filter $T_s\Psi)$ and the gain of the optical concentrator $g\Psi)$ are always constant. Hence, we define $T_s\Psi)=T_{s0}$ and $g\Psi)=g_0$. Then, from Eq. (1), the following can be derived (Fig. 3) as

$$P_r = P_t\frac{ET_{s0}g_0}{\pi R^2}\cos(\phi)\cos(\psi) = P_t\frac{ET_{s0}g_0}{\pi R^2}\frac{h^2}{R^2} = P_t\frac{ET_{s0}g_0h^2}{\pi(L^2+h^2)^2}. \quad (3)$$

If the sensitivity of the receiving device PD is P_{sens}, the LEDs within the distance of L_M can cover this user

$$L_M^2 = h\sqrt{\frac{ET_{s0}g_0Pt}{\pi P_{sens}}} - h^2. \quad (4)$$

Therefore, for the user at (x_u, y_u), the LED lamp $L_s(x_s, y_s)$ should be within the distance of L_{uM} such that the set of the selected LED lamps can be given by

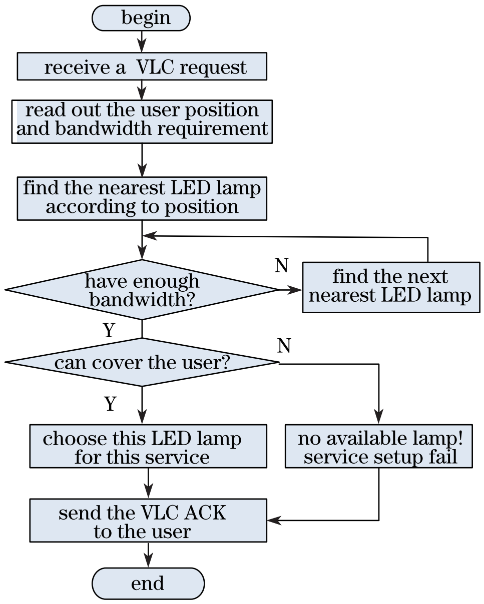
$$L_s \in \bigcup\{(x_s, y_s)\,|(x_s - x_u)^2 + (y_s - y_u)^2 < L_{uM}^2\}. \quad (5)$$

Then, in this set of LED lamps, the on-duty lamps that have already performed other services but still have sufficient available bandwidth for the current service, are selected. The lamp that has the narrowest bandwidth (suggesting that it has already performed most service requirements) is chosen to handle the current service. If no on-duty lamp is available, a lamp that has never been used is selected to perform this service. The flowchart of the SA scheme is shown in Fig. 4(b).

The SA scheme overcomes the service-dispersive and economic problems. However, a network with extremely aggregated services is not robust, as a failure may cause too much recovery operations. Therefore, we propose an enhanced BB selection mechanism that balances the advantages of the DP and SA schemes. Little service means that the service requires less than p% of the bandwidth that a LED lamp can afford. In the BB scheme, little service needs to be aggregated to the nearby LED lamp using the SA scheme. Other services that cost more than p% of the bandwidth will be directly handled by the DP scheme. Therefore, in case of little service, the selection result is the same as that of the SA scheme; therwise, the result is the same as that of the DP scheme. The value of p% depends on the comprehensive consideration on the network scale, service type, signal quality, network management overhead, operation cost, and network robustness.

The performances of the three aforementioned LED lamp selection schemes were simulated. The simulation parameters are shown in Table 1. The LED lamps were evenly distributed on the ceiling, with 2-m distance between them. Thus, a total of (4×9=36) lamps were installed. The receiver PD was placed on the table, which was 1 m high above the floor. Thus, the vertical distance between the LED lamp and the PD is 2 m. Using the parameters in Table 1 and Eq. (3), the LED coverage distance (L_M=2.4 m) was calculated. The bandwidth of a LED lamp was set as 200 Mb/s. The user service bandwidth requirement may be randomly selected in 10 fixed levels, namely, 100 and 500 kb/s and 1, 2, 5, 10, 20, 30, 40, and 50 Mb/s. During the simulation, a random-number generation program generates random user position vector (x, y), where $x \in (0, 10)$ and $y \in (0, 20)$. In each position, a user service with a certain bandwidth requirement is requested. Using various LED lamp selection schemes, different LED lamps may be selected to handle this service. Hence, the distance between the PD and the selected lamp varies, leading to different received signal powers. In the simulation, the received signal powers in different schemes are measured, and the corresponding LED lamp bandwidth allocation results.

The simulation was implemented in three groups. In each group, 50 random user positions were generated, and 50 services were then requested. In the first group



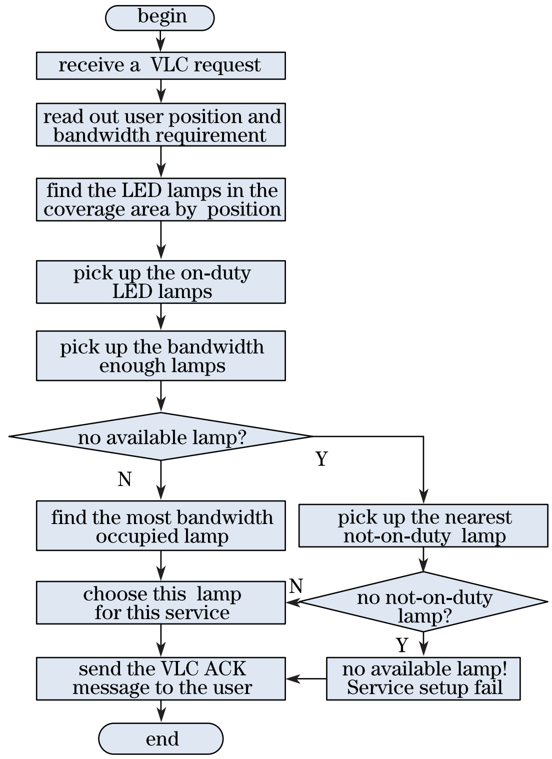


Fig. 4. Flowcharts of the lamp selection schemes. (a) DP and (b) SA.

Table 1. Parameters for the Simulation Scenario

Simulation Parameters	Parameter Value
Room Size (m^3)	10 × 20 × 3
Height of the PD Plane (m)	1
Transmitted Power of LED Lamp (mW)	50
Equivalent Receiving Coefficient E	0.8
Sensitivity of PD (mW)	0.52
Gain of the Optical Filter T_{s0}	1
Gain of the Optical Concentrator g_0	1
Bandwidth of the LED Lamp (Mb/s)	200

(service test point numbers 1 to 50), as this simulation is the first time for most of the LED lamps to carry information, the SA scheme has the same result as the DP scheme. Thus, the differences among these three selection schemes are insignificant. The results in this group were neglected. Meanwhile, the difference in the second (numbers 51 to 100) and third (numbers 101 to 150) groups are significant. Figure 5 shows the received signal power values using different LED selection schemes. The BB scheme was simulated using two different p values. p=1 stands for the service whose bandwidth requirement is less than 2 Mb/s, and p=5 stands for the service with less than 10 Mb/s bandwidth requirement. At some test points, the results of the two BB schemes are the same. Therefore, in Fig. 5, only one curve is drawn in each part of the figure. Based on the simulation results presented in Fig. 5(a), in the second group, the average received powers of DP, SA, BB (p=1), and BB (p=5) can be calculated as 2.56, 1.89, 2.28, and 2.21 mW, respectively. In addition, in the third group, the average received power for the aforementioned schemes are 2.65, 1.71, 2.39, and 2.26 mW, respectively. The difference between the DP and SA schemes in the third group is 0.94 mW, which is larger than that of the second group (0.64 mW). These results suggest that the services in the third group are more aggregated than those in the second group. The DP scheme has the highest received power, implying that the best performance is achieved if the effect of the ambient light and the signal interference from other channels is considered.

Furthermore, the bandwidth utilization conditions of all LED lamps were recorded in the simulation. The statistical result of the bandwidth utilization after three groups of simulations is shown in Fig. 6, which indicates the number of the lamps in the different bandwidth ranges occupied after three groups of requests. The services in the DP scheme are relatively dispersed; Hence, many lamps in the DP scheme have less than 40% bandwidth occupied. However, in the SA scheme, the bandwidth occupation ratio of most lamps is between 30% and 70%. Therefore, the SA scheme obtained the highest bandwidth utilization efficiency. The simulation results in Figs. 5 and 6 also indicate that the BB scheme has a balanced performance. The bigger the value of p, the closer the performance of the BB scheme to that of

SA. Therefore, a method for adjusting network performance between DP and SA was achieved.

In conclusion, a LED-based VLC network requires multiple LED lamps because the coverage of one single LED lamp is limited. Therefore, the key problem in such SDM network is the selection of the proper LED lamp to realize efficient user access and channel allocation. In this letter we present a signaling mechanism for user access and service setup, along with the definition of corresponding signaling messages. Two basic lamp selection schemes (i.e., DP and SA) and an enhanced BB selection scheme are presented to realize flexible user access and efficient resource allocation. The simulation results show the different performances of the schemes in terms of signal quality, resource utilization efficiency, and network robustness. The future research plan is to study the LED lamp selection problem in a more complex scenario, where the user positions dynamically change.

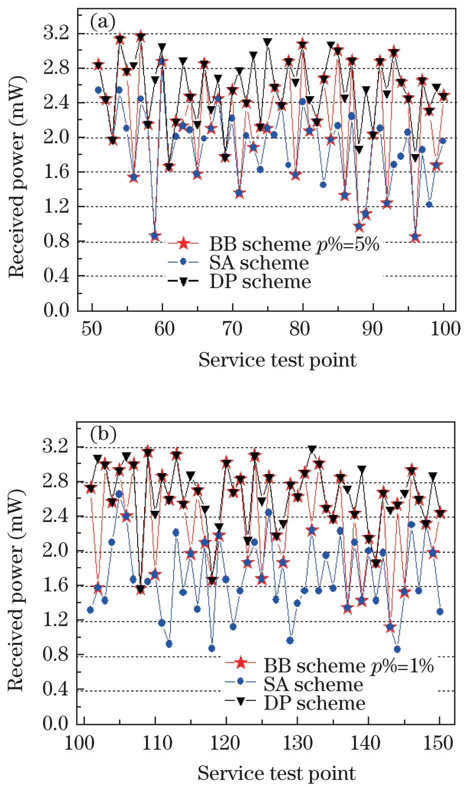


Fig. 5. Simulation results of received signal power using different LED lamp selection schemes. (a) Test point numbers from 51 to 100; (b) test point numbers from 101 to 150.

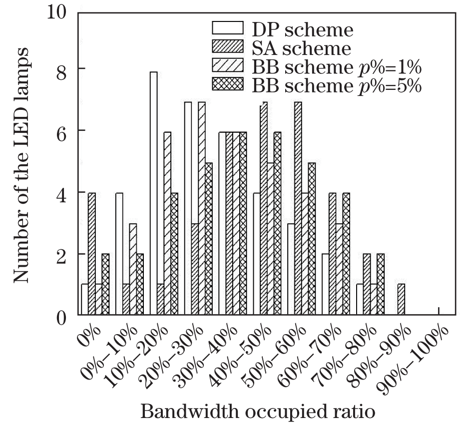


Fig. 6. Simulation results of bandwidth utilization status of all LED lamps using different LED lamp selection schemes.

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