Optical Interference Cancellation in Visible Light Identification System
Based on Wireless Mesh Network Topology

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ABSTRACT

Identification (ID) systems utilizing visible light are an interesting topic, and have been attracting the growing attention
of researchers recently. However, LED transmitters with a unique ID illuminate a limited coverage area, therefore, limiting
the communication coverage. In order to extend the communication coverage, we proposed wireless mesh networks
(WMNs) for relaying the information. Routing operations in WMNs might be challenging due to various factors. In this
paper we analyze the link error probability and optical power loss. Based on our proposed network topology, we further
found an effective scheme, multi-stage parallel interference cancellation (PIC), to alleviate the negative impacts due to
interference which comes from multi-user data transmission.

Keywords: VLID; WMN; Route selection; Interference cancellation

1. INTRODUCTION

Recently, visible light communication (VLC) systems have attracted attention due to progress in the field of visible
light technology [1]. Visible light has several attractive features distinct from those of radio frequency (RF) and infrared
(IR) [2]. LED and laser diodes (LD) are usually used as optical sources, but LEDs are preferred as strong candidates for the
next generation lighting technology [3] for several reasons including fewer safety concerns, a relatively long useful life
time, and a wider emission angle than those of LDs [4]. As a transmitter for optical wireless communication, LED lights
emit visible rays as the medium of data transmission.

As for the identification systems, the typical method in communication is to use radio frequency (RF) as the medium
transmission and it is known as RFID. Nevertheless, with the development of VLC systems, both the industrial and
scientific communities have recognized that visible light also can be used in ID systems, called VLID, and it has the
following advantages compared to those of RFID:

- VLC is harmless to our health.
- A friendly user interface.
- A lighting device is used as a transmitter without any traces of embellishment in the wireless communication
  environment.
- The visible light spectrum does not occupy the radio frequency spectrum; therefore the electromagnetic interference
  (EMI) can be avoided by VLC.

In the so-called VLID system, LED lights are usually used for transmitting the information and as illuminance sources.
Each light has its own ID which transmits its own information or data, for example, the information regarding an exact
location. In Japan, the products related to LED-ID positioning systems have been applied in museums, underground
subway stations, shopping malls, etc. It is claimed that VLID can replace GPS gradually in places where GPS is not
accurately used. Moreover, LED-ID can provide different multi-media services. Nevertheless, an LED-ID system also
faces some challenges because optical transmission is easily interrupted by obstacles between the transmitter and the
receiver, and each light source has its own limited illuminance coverage. For the case in which a user is out of the
illuminance coverage of the LED’s light, the user is not able to obtain the data from this LED’s light. Therefore, how to
extend the optical wireless communication coverage is a main issue on this paper. We proposed WMNs in order to extend
the coverage. WMNs represent a new trend of replacing conventional wireless local area networks (WLANs) due to its
greater flexibility and reliability.

In this paper, we introduced the basic concepts of VLID, and proposed a VLID system based on WMN topology.
Routing governs the flow of data packets through WMNs. An optimum route selection not only minimizes the amount of
network bandwidth used to transfer packets, but will also potentially enable networks to admit more packet loads in the
future. We discuss several representative factors on which intelligent route selection based, such as link errors and optical power loss. Furthermore, we also found that the multi-user interference (MUI) has a significant impact on the communication performance. We further proposed an effective scheme, multi-stage PIC, to alleviate this impact. Our essential target is to improve the end-to-end network performance. The remainder of this paper is organized as follows. In section 2, the route selection analysis is provided. We outline our proposed system model and provide the simulation results in section 3. Concluding remarks are presented in section 4.

2. ROUTE SELECTION ANALYSIS

2.1 Introduction of Indoor VLID system

As shown in Fig. 1, wavelength control is used to provide different wavelength visible lights which will be emitted through the different LED lights. Each LED light has its own illuminance coverage, where the non-overlapped wavelength channels are formed, guaranteeing the transmission within a neighborhood simultaneously. We place the optical relay in the overlapping area in order to obtain the data packets from two different LED lights. The optical relay is actually a transceiver which could transmit and receive the data packets simultaneously. If a user stands in an area where the LED illuminance coverage exceeds, in this case, the user needs the optical relay to forward the signals from this LED light.

![Fig1. Configuration of Indoor VLID System.](image)

2.2 Link Error Probability Analysis

Fig. 2 shows eight LED lights with different ID distributed in a model room. We suppose that all network links are equally loaded, though some links are bound to carry more traffic than others generally. On this premise, we can emphasize route selection regarding other factors, such as network link error probability. In this WMN, as shown in Fig. 2, each mesh node can be treated as relay or router for other mesh nodes when data packets are forwarded over multiple wireless hops, and it is used as a transceiver which has multiple wireless interfaces in order to increase the capacity of the mesh network and reduce the throughput degradation. The mesh nodes are statically distributed in this indoor circumstance. Different from RF transmission, no diffraction occurs in optical transmissions, which means that if the direct line of sight (LOS) is interrupted by obstacles, the optical wireless communication will be terminated by shadowing immediately. However, in an indoor environment, when people are moving, it will probably interrupt the ongoing optical propagation between the transmitter and the receiver. So, we proposed a WMN in our VLID system. If one optical propagation path is blocked, the receiver can select the optical signals through the other propagation link coming from the other relays or nodes immediately. This topology can guarantee the ongoing optical communication effectively. Moreover, as shown in Fig. 2, the user within ID area #1, for example, wishes to receive the signals from the ID area #4, it is obviously impossible without WMN, however, through the optical relay forwarding the data packets, the user in ID area #1 is able to obtain the packets from ID area #4. In this sense, the WMN can further extend the transmission coverage.

However, some factors also limit the multi-hop communication when WMNs are used in VLID systems. Not only does the throughput decreases, but also the link error probability increases. We use the Path Shadowing Probability [5] to describe the visibility.
\[ P_v(x) = \exp(-nwx) \]  
(1)

So, the path shadowing probability \( P \) can be defined as:

\[ P(x) = 1 - P_v(x) \]  
(2)

where \( x \) is the length of the portion of the propagation path that exists in the area lower than the height of the person, and \( n \) and \( w \) represent the population density and width of the human bodies. Fig. 3 shows simulation results considering three different population densities; 0.02 \( \text{m}^{-2} \), 0.1 \( \text{m}^{-2} \), 0.2 \( \text{m}^{-2} \). From Fig. 3 we can see that the link error probability due to the shadowing has a significant rise with the increase of multi-hops, it illustrates that the optimum path selection between source and destination is obtained with fewer hops. Besides, regarding the intelligent route selection, population density also should be taken into account. The high population density means high shadowing probability as depicted in Fig. 3. Therefore, intelligent forward data routing should avoid the dense population areas.

![Indoor Environment Network Topology](image)

Fig. 2 Indoor environment WMN and VLID distribution.

![Path-shadowing probabilities estimated from simulation](image)

Fig. 3 Path-shadowing probabilities estimated from simulation.

### 2.3 Optical Filter Gain

The receiver in a VLC system usually includes the optical filter which is employed in order to attenuate ambient, incandescent, or fluorescent light. The bandwidth of this type of filter should encompass the optical spectrum of the transmitter. The gain of the filter is provided by [6]:

\[ \text{Gain} = \frac{\text{Signal}}{\text{Noise}} \]
\[ T(\theta) = 1 - \frac{1}{2} (|\rho_{TE}|^2 + |\rho_{TM}|^2) \]  

where the reflection coefficient \( \rho \) is defined by the following two equations, provided in [7]:

\[ \rho = \frac{N_1 - \eta_2}{N_1 + \eta_2} \]  

(4)

\[ N_i = \begin{cases} 
\frac{n_i}{\cos \theta_i} & \text{for TE} \\
\eta_i \cos \theta_i & \text{for TM} 
\end{cases} \]  

(5)

where \( \theta_k \) is the incidence angle from medium \( k \) to medium \( k+1 \). We assume a single thin dielectric layer filter in our receiver model, the refraction formula is shown as follows:

\[ \frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1} \]  

(6)

where \( n_1 \) is the refractive index of the vacuum, \( n_2 \) is the refractive index of the concentrator, and \( \theta_1 \) and \( \theta_2 \) are the incidence angle and refraction angle, respectively. Based on the recursive equations (3)-(6), and, starting with \( N_2 = \eta_2 \), the filter gain \( T(\theta) \) for different incidence angles \( \theta \) is calculated, as shown in Fig. 4. Fig. 4 shows that, when the incident angle is less than 60 degrees, there is no distinct degradation. However, when the incident angle is greater than 60 degrees, degradation becomes very severe.

From Fig. 4, we can summarize that the incident angle at the receiver is also an important factor because it is related to the measurement of the received optical power. The incident angle is related to the location of the user, so the route selection should consider the location of the user in the terminal area. In general, an intelligent route would select an optimum relay which can provide the largest optical gain for a given terminal area.

![Fig. 4 The optical filter gain according to the angle of incidence, n1=1, n2=1.5.](image)

### 3. PROPOSED SCHEME

#### 3.1 Proposed System Description

Theoretically speaking, there should be no interference between different wavelength visible light channels; however, this assumption is not entirely true in practice. As shown in Fig. 1 and Fig. 2, many users can simultaneously receive the data packets across the entire network and the optical signals of all users will be translated into electrical signals (see Fig. 5), causing MUI at the receiver.
We propose the multistage PIC [8] for eliminating MUI by using spread codes; the proposed system is depicted by Fig. 5. Spatial division multiplexing (SDM) is used to implement the different LED lights transmitting different data. Frequency mapping accomplishes data transmission through different wave-length visible lights. Intensity modulation (IM) and photo-detector (PD) complete the conversion between the electrical signal and the optical signals. Spread codes are used to distinguish different users’ data, since users’ data are separated on the basis of their signature waveforms. The entire concept of PIC is based on the premise that the received signal can be reliably estimated. PIC, as shown in Fig. 5, follows an iterative process and subtracts the interference from other users. Channel estimation evaluates all users simultaneously and then PIC can be repeated over several stages. After under-going the optical wireless channels, the received electrical SNR is given by:

\[ SNR = \frac{\alpha^2 P_r^2}{R_b N_0} \]  

where \( P_r \) is the average received optical power, and \( R_b \) is the bit rate. \( N_0 \) is the power spectral density given by the optical power of the background light \( P_{bg} \), which is given as:

\[ N_0 = q\alpha P_{bg} \]  

where \( \alpha \) is the O/E conversion efficiency and \( q \) represents an elementary charge (1.6×10^{-19} C).

\[ \text{Input Bit Stream} \rightarrow \text{SDM} \rightarrow \text{Frequency Mapping} \rightarrow \text{Spread} \rightarrow \text{PIC} \rightarrow \text{Despread} \rightarrow \text{Frequency Demapping} \rightarrow \text{Output Information} \rightarrow \text{Channel Estimation} \rightarrow \text{Decision} \rightarrow \text{Optical signals} \]

\[ R(t) = \sum_{k=1}^{K} \alpha S_k(t) + n(t) \]

\[ Z_k = \frac{\sum_{i=1}^{N} C_i(t) \text{rect}(t - iT_c)}{\sqrt{2N_0/2}} \]

3.2 Interference Cancellation

Consider a VLID system with \( K \) users, assuming binary phase shift keying (BPSK) signaling, the transmitted optical signal for the \( k \)-th user is:

\[ S_k(t) = \sqrt{2E_k} b_k(t) c_k(t) \]  

where \( E_k \) is the transmitted power per l-th chip for the \( k \)-th user, \( b_k(t) \) is the \( k \)-th user binary transmitted data waveform, and \( c_k(t) \) represents the direct sequence spreading waveform which is defined as:

\[ c_k(t) = \sum_{i=1}^{N} C_i(t) \text{rect}(t - iT_c) \]  

where \( C_i(t) \) is the \( l \)-th chip of the signature waveform of user \( k \), \( T_c \) is the chip duration, and \( N \) is the processing gain. Since the data packets of more than one user can be transmitted at the same time through the wireless network, we assume all \( K \) users to be simultaneously active at any receiver. An optical wireless channel is usually modeled as additive white Gaussian noise (AWGN) channel. Therefore the translated electrical signals at the receiver can be given by:

\[ R(t) = \sum_{k=1}^{K} \alpha S_k(t) + n(t) \]  

where \( n(t) \) is an AWGN with the power spectral density of \( N_0/2 \). At the output of the desparser for user \( k \), the decision variable \( Z_k \) is given by:

\[ Z_k = \frac{\sum_{i=1}^{N} C_i(t) \text{rect}(t - iT_c)}{\sqrt{2N_0/2}} \]
\[ Z = \text{Re} \left\{ \frac{1}{T} \int_{-T}^{T} R(t) \exp(i\tau) \text{d}t \right\} \]

where * denotes the Hermitian operation. These decision variables are then used to regenerate the user's signals, which are cancelled from the received signal to form a modified received signal. The modified received signal then becomes:

\[ R'_i(t) = R(t) - \sum_{m=1}^{k} Z_m \cdot c^i_m(t - \tau_m). \]

The decision variable for the first stage for the k-th user becomes:

\[ \hat{Z}_k = \text{Re} \left\{ \frac{1}{T} \int_{-T}^{T} R'_i(t) \exp(i\tau) \text{d}t \right\} \]

PIC is used to further mitigate the MUI, which can be obtained from:

\[ \hat{Z}_k = Z_k - \sum_{i=1, i\neq k}^{k} g_{i,k} \]

where \( g_{i,k} \) represents the interference of the i-th user to the k-th user. This completes the first stage cancellation. This process can be repeated for s-stages to obtain better results. The corresponding BER can be expressed as:

\[ P^{\text{(s)}} = Q \left( \frac{1}{2 \text{SNR}} \left( 1 - \frac{K - 1}{3N} \right)^{\prime} + \frac{1}{(3N)^{\prime}} \right)^{\prime} \]

\[ \frac{\left( K - 1 \right)^{\prime} - (-1)^{\prime} \left( \sum_{i=1}^{K} E_i \right) + (-1)^{\prime}}{K} \left( \frac{\sum_{i=1}^{K} E_i}{\sum_{i=1}^{K} E_i} \right) \]

\[ \left( \frac{\sum_{i=1}^{K} E_i}{\sum_{i=1}^{K} E_i} \right) + (-1)^{\prime} \]

where \( E_i = E_2 = \ldots = E_k \) in (16).

### 3.3 Simulation Results

As analyzed above, we adopted Walsh spread code in the PIC scheme and chose pseudo-random code (simply as "random code") for the non-PIC scheme for comparison purposes. It is shown in Figs. 6-8 that significant performance improvement was obtained by employing the 2-stage cancellation into the PIC receiver.

It is clear from Figs. 6 and 7 that the 2-stage PIC shows a relatively better performance than the 1-stage PIC regardless of the number of users. It is logical that the users’ signature waveforms are mutually orthogonal by Walsh codes. However, the performance of the simulation using random codes obviously degrades with the increase of the number of users.

We assumed that the SNR at the receiver was 18dB, and from Fig. 8, we can observe that the 2-stage PIC shows an excellent performance among all schemes with an increase in the number of users. Therefore, we can conclude that the Walsh code has a better orthogonal quality than the random code in distinguishing different users’ data, and multi-stage PIC can further suppress the MUI effectively.
4. CONCLUSION

There are two main issues discussed in this paper: limited illuminance coverage and MUI at the receiver in a VLID system. The multi-hop WMN topology employed in the VLID system can indeed extend the coverage area, however, the
network performance will sharply degrade not only due to the error probability across the route selection, but also due to the interference caused by simultaneously multi-user data transmission. Regarding the transmission path, when multiple paths are involved, the main issue is how to select them optimally. An optimum route selection should take into account various factors, besides the throughput, the link error probability and optical power loss also have impact on reliability and communication performance, which are especially important in an optical wireless environment. In this paper, we analyzed the link error probability and the optical power loss, which optimum route selection should consider. Finally, we further proposed an effective scheme to mitigate the MUI from multi-users’ overlapping data packets.

In this paper, we extended multi-stage PIC to a spread spectrum system in an optical wireless data transmission channel employing spread codes to prevent MUI. In our proposed scheme, the multi-stage PIC is believed to be a key enabling technology for multi-users transmitting data simultaneously, and several computer simulations were carried out to prove the point.

REFERENCES


