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Conceptual Design for Indoor Visible Light Communication and Positioning Cooperative Systems

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ABSTRACT

Recently, how to achieve simultaneous high-speed data transmission and accurate positioning has been an interesting topic. Under the indoor illumination environment, the cooperation between visible light communication (VLC) and visible light positioning (VLP) has attracted increasing attention. In this paper, we review our recent proposed conceptual designs, which can realize cooperative VLC and VLP functionalities. By utilizing receiver location information, a location-based equalization (LBE) method is proposed for indoor VLC, where location-based equalizers are designed to compensate for multi-path channel distortion. By utilizing the estimated channel state information (CSI) during VLC process, a CSI-based VLP scheme is proposed, where the distances information between transmitters and the receiver can be extracted from received signals to enable VLPs. In order to integrate VLC and VLP within the same system, the spread-spectrum plugin of optical identification is inserted into the existing VLC frame structure to avoid signal mutual interference without breaking the existing VLC protocol.

Keywords: visible light communication, visible light positioning, cooperative design.

1. INTRODUCTION

With the fast development of solid-state lighting, light-emitting diodes (LEDs) have been widely adopted to replace current incandescent and fluorescent lamps. With white LEDs, indoor visible light communication (VLC) becomes popular due to its multiple functions including illumination, communication, and positioning [1-3]. Recently, VLC and visible light positioning (VLP) have experienced extensive but separate studies. However, in practical application, it is hard for VLC and VLP systems to be deployed within the same system or in the same indoor environment, because the signal mutual interference will result in an inherent system exclusion. Therefore, besides the effort of increasing the achievable system transmission rate and positioning accuracy, we have to consider the possibility to integrate VLC and VLP within a single system, or even create a cooperative relationship between them, from the practical point of view.

In order to facilitate cooperation between VLC and VLP, we have proposed several conceptual designs. In the first design regarded as “VLP assisted VLC”, we have proposed a location-based equalization (LBE) scheme. By utilizing the receiver coordinates to design the simple location-based channel equalizer, the multi-path channel dispersion can be alleviated effectively. In the second design regarded as “VLC assisted VLP”, we have proposed an indoor VLP scheme based on channel state information (CSI), where the distance can be calculated according to channel response experienced by received data signals. Finally, the third design can be regarded as “coexisting VLC and VLP”, where the spread-spectrum plugin of optical identification (OPID) is designed to embed VLP into VLC frame structure.

The rest of this paper is organized as follows. The LBE scheme for indoor VLC is described in Section 2. Section 3 shows a CSI-based VLP scheme, which is to realize positioning function in the exiting VLC system. An integrated architecture of VLC and VLP is demonstrated in Section 4. Conclusions and discussions are given in Section 5.

2. LOCATION-BASED EQUALIZATION FOR INDOOR VLC

In indoor VLC systems, due to multiple transmitters and indoor reflections, optical signals will experience a dispersive multi-path channel. This will lead to inter-symbol interference (ISI) and consequently degrade system bit error rate (BER) performance. Conventionally, intermittent training sequences with adaptive equalization algorithms and OFDM with a long guard interval (GI) can be adopted to counteract ISI deterioration, but at the cost of reduced transmission efficiency and limited mobility [4]. Thus, how to overcome BER degradation caused by ISI to maintain link quality for a mobile VLC terminal is a challenge.

Because indoor VLC is based on intensity modulation with direct detection (IM/DD), transmitted signal components in terms of optical intensity will form a simple and static channel. As long as the relative location of transmitters and receiver are fixed, the VLC channel will not change. In this case, with the aid of receiver terminal coordinates, the linear distortion of the VLC channel can be theoretically estimable. Therefore, it is possible to design an idealistic equalization scheme to compensate for the predictable multi-path dispersion. Based on these, we have proposed a location-based equalization (LBE) scheme for VLC systems in [5]. A schematic diagram of the LBE model is shown in Fig. 1.

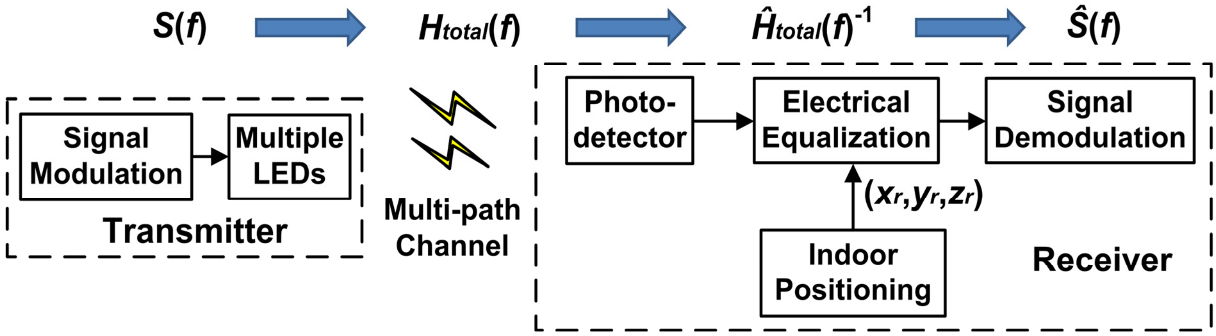

Figure 1. Schematic diagram of LBE.

In the proposed LBE scheme, after passing through the multi-path channel, optical signals are converted by the photodetector and then input to location-based electrical compensators. With measured receiver location by means such as VLP, the VLC channel parameters can be estimated and further used for electrical equalization to mitigate multi-path effects. Ideally, the multi-path channel distortion can be fully compensated by designed equalizers. However, due to the influence from additive noise, an indeterminate number of reflections, location errors and etc., it is quite difficult to design an optimal compensator to equalize the VLC channel perfectly in practical systems. But we can try to quantify the real VLC channel model by approaching to total channel gains $H_{total}(f)$, namely, $\hat{H}_{total}(f)$. Then electrical compensators can be designed with the transmission functions of $\hat{H}_{total}(f)^{-1}$. With $H_{total}(f)^{-1} \times \hat{H}_{total}(f)^{-1} \approx 1$, $\hat{H}_{total}(f)^{-1}$ is assumed to match well with $H_{total}(f)$. Therefore, before signal demodulation, the multi-path distortion has already been compensated effectively by adopting the location-based equalizer $\hat{H}_{total}(f)^{-1}$, regardless of its estimation errors. As a result, the quality of received signals can be significantly improved in advance of signal demodulation.

With the proposed LBE scheme, bit error rate performance of VLC system can be effectively improved even in the presence of location errors or link shadowing. In addition, the implementation of LBE scheme is simple, because the design of electrical-domain compensators for channel equalization only requires the knowledge of receiver location. There is no need to use adaptive calculation for the optimum filter coefficients with the aid of intermittent training sequences. Instead, the parameters of location-based equalizer only need to be updated when the receiver location changes. Therefore, the receiver location information serves the dual-function at the same time: positioning and equalization, making indoor VLC become a location-based (or VLP-based) value-added service.

3. VLP SCHEME BASED ON CHANNEL STATE INFORMATION

As discussed above, VLP can facilitate the performance improvement of VLC. In turn, VLC can help to realize positioning. For conventional VLP, multiplexing methods are used to separate positioning signals from different transmitters. At least three positioning signals are required to calculate enough distance information between transmitters and receivers for trilateration algorithms to locate the receivers [6-7]. However, if the design of existing VLC system does not consider the function of positioning in the beginning, it is hard to adding positioning function into VLC system in practical applications. This is due to the mutual interference between VLC and VLP signals. On the other hand, for VLC systems, the channel gains for different paths mainly depend on the transmission distance of optical signals. Because VLC systems feature IM/DD, the transmission distance can be calculated by referring to the CSI in terms of channel gains. As a result, it is possible to utilize estimated CSI to obtain the distance information to realize indoor positioning.

An example of a CSI-based VLP model is proposed in [8]. Here we consider using VLC for positioning in special scenarios with a limited number of LED lamps and a mirror. The block diagram of proposed positioning method is shown in Fig. 2. Due to the reflection of the mirror, two LEDs (T_1 and T_2) generate two virtual images (T_1' and T_2'), respectively. Then for each time slot, the transmission signal will become a mixed signal. For example, when T_1 is modulated, the receiver will receive multi-path signals coming from T_1 and T_1' simultaneously. Thus, when T_1 and T_2 are turned on alternately based on time division multiplex (TDM), after passing through independent VLC channels, two signals (r_1 and r_2) containing real and virtual signals will arrive at the receiver, respectively. Then, by estimating the CSI, we can get the channel frequency domain transfer functions (FDTFs), which contain channel response information of multi-path signals coming from real and virtual LEDs. The maximum and minimum values of FDTF are utilized to calculate channel response for each optical path. With the estimated channel response, it is easy to obtain the distance information used for positioning, consequently, indoor positioning function can be achieved in the existing VLC systems.

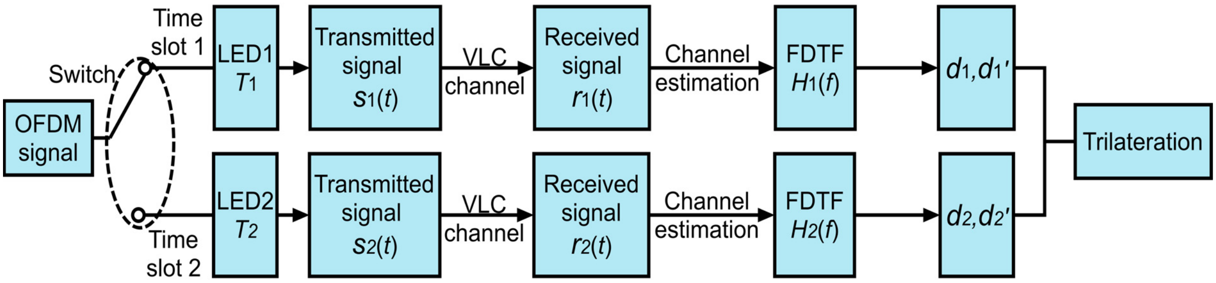

Figure 2. Block diagram of proposed positioning method.

The proposed CSI-based VLP model can overcome the limitation of using at least three LEDs for conventional trilateration algorithms, which has potential in special scenarios with a limited number of LED lamps. In addition, VLP can be achieved effectively with no need of sending reference signals at the transmitter side. Thus, with the proposed CSI-based VLP scheme, no additional hardware is required for existing VLC system to implement positioning.

4. AN HYBRID VLC AND VLP ARCHITECTURE

The above methods discuss the cooperation between VLC and VLP. However, the VLC or VLP systems are still designed independently. Conventionally, VLP signals are multiplexed either in time division multiplexing (TDM) or in frequency division multiplexing (FDM) to avoid mutual interference. As a result, VLP signals will occupy the limited time or frequency resources allocated for VLC. Based on this, we adopt another modulation domain of code division multiplexing (CDM) in the cooperative system. Here, we find a method to transmit VLC and VLP signals at the same time. By referring to the IEEE 802.15.7 standard, it can be found that both the reserved fileds and the region of medium access control (MAC) payload can be effectively utilized to insert the location information to support VLP and other location-based services [9]. Therefore, the location information field can be simply made as a plugin within the communication information filed.

In [10], the spread-spectrum plugin of optical identification (OPID) is inserted in the existing VLC frame structure to enable simultaneous transmission of VLP and VLC signals. As in Fig. 3, two different implementation schemes are designed to transmit OPID.

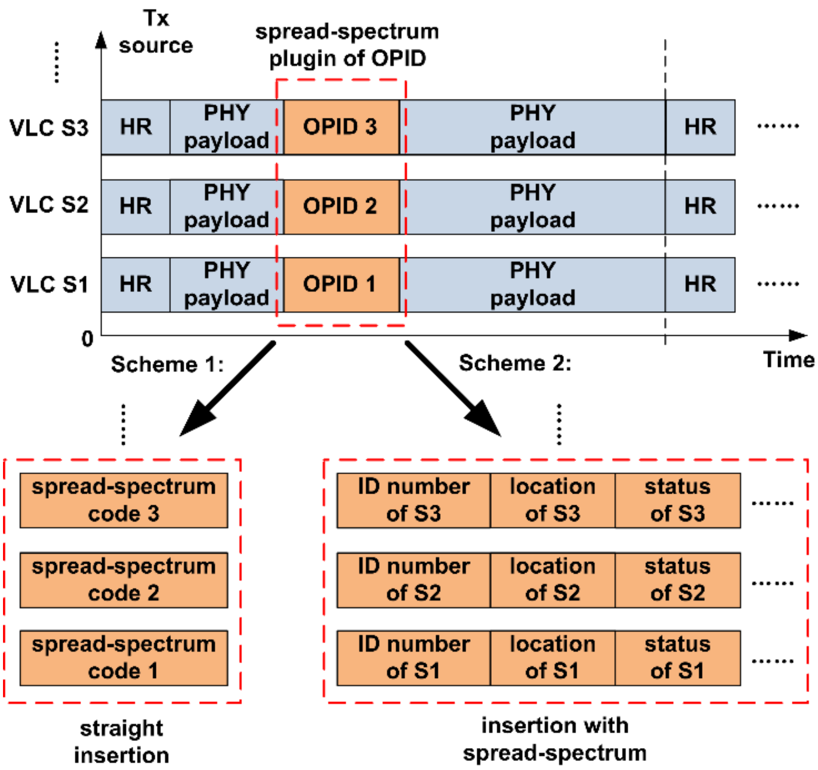

Figure 3. The proposed cooperative VLP and VLC system with the spread-spectrum plugin of OPID.

If only VLP is needed, we can simply adopt the spread-spectrum codes as OPIDs to identify different LED Txs, as shown in Scheme 1. The self-correlation property of the spread-spectrum code ensures the Rx to extract the received intensity of OPID, which can be further utilized to estimate the Rx location. In Scheme 2, the OPID contains the Tx ID number, Tx location, Tx status, and other information, all of which are spread with different spread-spectrum codes. At the Rx, a simple calculation of correlation can extract the desired location information field, with the communication information field counted as noise. Finally, both VLP and VLC signals are packaged together, but much easier for the Rx to separate.

With the aid of spread-spectrum plugin of OPID, the time slots reserved for the future extension function in the IEEE standard can be utilized to transmit positioning reference information in code division multiple access (CDMA) mode. In addition, the existing VLC frame structure can be kept untouched to facilitate simultaneous VLP and VLC, which is deemed to be a good solution to overcome the mutual exclusion between VLP and VLC systems. Moreover, with proposed implementation schemes, VLC can still support VLP, and in turn, VLP still benefits VLC. Such cooperative design is in accordance with the development tendency of 5G/B5G wireless communication systems.

5. CONCLUSIONS

With the increasing demand for achieving simultaneous high-speed data transmission and accurate indoor positioning, the cooperation between VLC and VLP will have become a trend. To facilitate the integration of VLC and VLP, we review our recent proposed conceptual designs in this paper. Firstly, a location-based equalization (LBE) method for indoor VLC is demonstrated. It designs location-based equalizers to compensate for multi-path channel distortion. Secondly, an indoor VLP scheme based on channel state information (CSI) is proposed. We use an example of a limited number of LED lamps to verify the feasibility of the VLP method. Finally, for integrating VLC and VLP within a single system, the OPID is designed to avoiding signal mutual interference without breaking the existing VLC protocol. Future, VLC system will not be limited to only one function of transmission or positioning. On the contrary, multiple functions can be simultaneously accomplished.

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