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Location-Aware Time Domain Hybrid Modulation for Mobile Visible Light Communication

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Abstract: A location-aware time domain hybrid modulation (TDHM) scheme is proposed for mobile visible light communication. TDHM frames are constructed according to location information, which can increase capacity more than 20% for around 20% indoor areas.

1. Introduction

Recently, indoor mobile visible light communication (VLC) based on light-emitting diodes (LEDs) has attracted great interests [1], [2]. With user mobility, the change of receiver location and orientation will result in a variation of channel condition, leading to lower link quality and spectral efficiency (SE). To tackle the channel variation, link adaption is usually adopted. For multi-carrier transmission, orthogonal frequency division multiplexing (OFDM) with adaptive modulation can be employed to adjust modulation order for different subcarriers to improve overall system capacity [3]. However, for a single-carrier system, despite the advantages of simple implementation and high flexibility, the achievable SE with adaptive modulation is still limited because of the use of conventional discrete modulation formats, e.g., pulse amplitude modulation (PAM) [1], [3]. Thanks to time domain hybrid modulation (TDHM) proposed in coherent optical communication systems, flexible transceivers can achieve continuous trade-off between transmission reach and SE by mixing two discrete formats with specific ratios [4]. In [5], we have successfully introduced TDHM into VLC systems to overcome signal-to-noise ratio (SNR) variation caused by dimming control. In this paper, considering terminal mobility, we further propose a location-aware TDHM scheme for indoor mobile VLC. Terminal moving state information is employed to design modulation formats to adapt to the time-varying channel condition. We target to optimize the SE of single-carrier mobile VLC while maintaining reliable link quality. Results verify the effectiveness of the proposed scheme under different scenarios.

2. Principle of Proposed Scheme

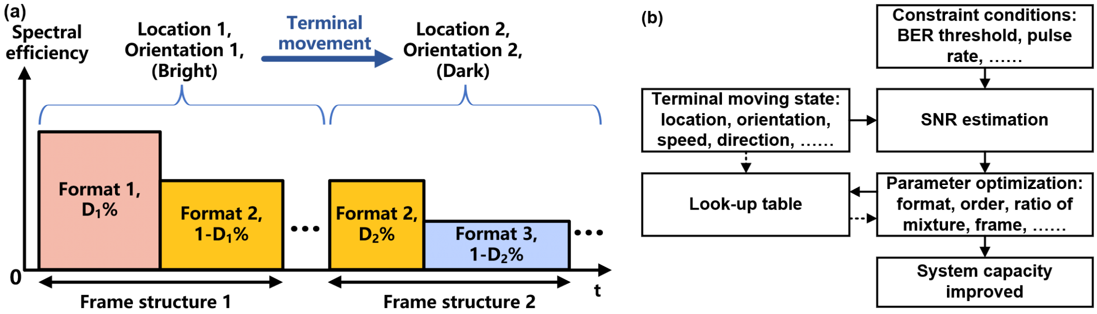

Fig.1. (a) Schematic diagram for location-aware TDHM; (b) block diagram for the proposed scheme.

In VLC systems, when a terminal moves or changes its orientation, both received optical power and SNR will fluctuate. For the conventional single-carrier modulation, a most efficient modulation format is selected to adapt to SNR variation. However, for mobile VLC systems, it is hard for a discrete modulation format to reach an optimal SE. For example, when a terminal is located between the transmission distances supported by two modulation formats (e.g., PAM2 and PAM4), only a lower format (i.e., PAM2) will be adopted to ensure reliable link quality. This clearly cannot achieve an optimal SE. To improve the SE, we propose a location-aware TDHM scheme, as shown in Fig. 1(a). Through time division multiplexing, two different modulation formats are transmitted alternately, by which the average SE can be adjusted adaptively according to the condition of mobile channel. When the terminal locates at a bright area, the two formats in frame structure 1 are mixed to achieve a higher SE. However, when the terminal moves to a dark area, the two formats in frame structure 2 are mixed with a lower SE to guarantee link quality. As long as the average bit error rate (BER) in each frame is lower than the forward error correction (FEC) threshold required (e.g., $BER_T = 4.6\times10^{-3}$ [6]), the system capacity can be improved through such a hybrid modulation effectively.

Fig. 1(b) shows the block diagram for the proposed scheme. The first step is channel modeling. The VLC channel mainly depends on the geometrical relationship between transmitters and a receiver [2]. Therefore, based on terminal moving state information including transmitters' coordinates ($\boldsymbol{T}_i$: (x_{ti}, y_{ti}, z_{ti})), receiver coordinates ($\boldsymbol{R}$: (x_r, y_r, z_r)), and receiver orientation like azimuthal/polar angles ($\boldsymbol{O}$: (α, β) in Fig. 2), mobile channel impulse response is given as [2]

$$h\left(t;\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)=\sum_{i=1}^{N_{LED}} w_i\left[H_{i,los}\left(0;\boldsymbol{T}_i,\boldsymbol{R},\boldsymbol{O}\right)\cdot\delta\left(t-\tau_{i,los}\right)+\int_{\tau_{i,nlos}=0}^{+\infty}A_{i,nlos}\left(\tau_{i,nlos};\boldsymbol{T}_i,\boldsymbol{R},\boldsymbol{O}\right)\cdot\delta\left(t-d\tau_{i,nlos}\right)\right], \tag{1}$$

where N_{LED} is the number of LED transmitters; for the ith LED, w_i is the weight index proportional to launched power, $\tau_{i,los}$ and $\tau_{i,nlos}$ are the signal time delays for line-of-sight (LOS) and non-LOS (NLOS) components, $H_{i,los}(0)$ is the normalized channel DC gain for LOS, and $A_{i,nlos}$ is the normalized channel gain for NLOS, respectively. Based on (1), the SNR at the output of the photo-detector can be estimated [7], which is written in the form of receiver moving state

$$SNR\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)=\frac{P_{r,sig}\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)}{P_{r,isi}\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)+N\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)}=\frac{\left[\gamma\int_{t_0}^{t_0+1/R_s}P_t m s\left(t\right)\otimes h\left(t;\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)dt\right]^2}{\left[\gamma\int_{t_0+1/R_s}^{+\infty}P_t m s\left(t\right)\otimes h\left(t;\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)dt\right]^2+\left[\sigma^2{}_{shot}\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)+\sigma^2{}_{thermal}\right]}. \tag{2}$$

Here $P_{r,sig}$ is the signal power, $P_{r,isi}$ denotes the inter-symbol interference, N consists of the shot noise variance σ^2_{shot} and the thermal noise variance $\sigma^2_{\mathrm{thermal}}$, γ is the receiver responsivity, t_0 is the initial time, R_s is the pulse rate, P_t is the average transmitting power per lamp, m is the modulation index, $s(t)$ is the normalized rectangle pulse, and $\otimes$ denotes the convolution operation, respectively. With the SNR in (2), the BER of the VLC system can be derived as [8]

$$BER\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)=\frac{1}{2}erfc\left(\frac{\sqrt{SNR\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)\cdot\log_2 L}}{2\sqrt{2}\left(L-1\right)}\right)\ for\ PAM\quad or\quad \frac{1}{2}erfc\left(\frac{1}{2\sqrt{2}}\sqrt{\frac{SNR\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)\cdot L\cdot\log_2 L}{2}}\right)\ for\ PPM\cdot \tag{3}$$

Here L is the modulation order, and we consider PAM and pulse position modulation (PPM) as candidates.

The next step is to select two modulation formats from the candidate set. After sorting all BER values from the highest to the lowest, we get BER_1 ($\boldsymbol{T}$, $\boldsymbol{R}$, $\boldsymbol{O}$), BER_2 ($\boldsymbol{T}$, $\boldsymbol{R}$, $\boldsymbol{O}$), …, BER_K ($\boldsymbol{T}$, $\boldsymbol{R}$, $\boldsymbol{O}$) corresponding to the candidate Format 1, Format 2, …, Format K, respectively. For each moving state ($\boldsymbol{T}$, $\boldsymbol{R}$, $\boldsymbol{O}$), if BER_k ($\boldsymbol{T}$, $\boldsymbol{R}$, $\boldsymbol{O}$) $\geq BER_T > BER_{k+1}$ ($\boldsymbol{T}$, $\boldsymbol{R}$, $\boldsymbol{O}$), then Format k and Format k+1 are selected to construct TDHM frames. The hybrid BER is given as

$$BER_{TDHM}\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)=\frac{D\cdot SE_k\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)\cdot BER_k\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)+\left(1-D\right)\cdot SE_{k+1}\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)\cdot BER_{k+1}\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)}{D\cdot SE_k\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)+\left(1-D\right)\cdot SE_{k+1}\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)}\leq BER_T, \tag{4}$$

where D is the proportion of Format k with a higher SE.

Subject to constraint (4), the final step is to find the optimal value of D, i.e., D_{opt}, through brute-force search. Since Format k, Format k+1, and D_{opt} are closely related to the terminal moving state ($\boldsymbol{T}$, $\boldsymbol{R}$, $\boldsymbol{O}$), we can use a look-up table to record their relationship. Thus, during user movement, the optimal parameters for TDHM signals are updated according to ($\boldsymbol{T}$, $\boldsymbol{R}$, $\boldsymbol{O}$). As a result, the system capacity R_b can be improved adaptively based on the channel condition:

$$R_b\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)=D_{opt}\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)\cdot SE_k\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)\cdot R_s+\left[1-D_{opt}\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)\right]\cdot SE_{k+1}\left(\boldsymbol{T},\boldsymbol{R},\boldsymbol{O}\right)\cdot R_s\cdot \tag{5}$$

3. Numerical Results and Discussions

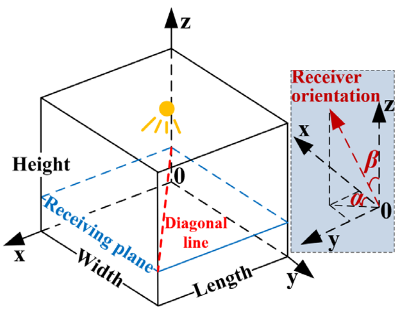

Fig. 2. VLC system model.

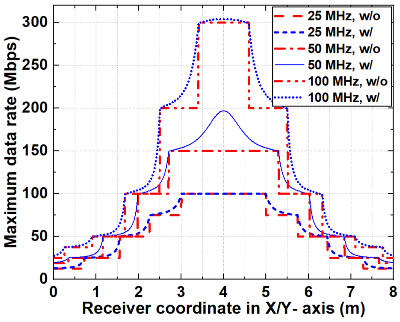

Fig. 3. Comparison of capacity.

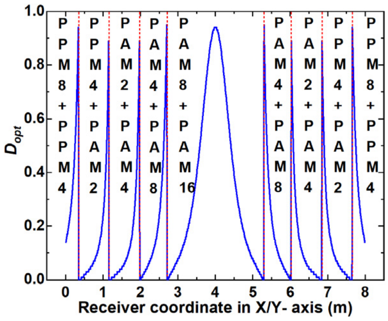

Fig. 4. Proportion of the format with a higher SE.

In Fig. 2, the size of an indoor VLC model is 8 m × 8 m × 3 m (length × width × height). A user terminal moves within the receiving plane at the height of 0.85 m. From Figs. 3 to 7, we consider a single LED luminaire installed at (4, 4, 3) with P_t of 18 W. We assume the receiver to face upward and mainly focus on LOS channel. However, for Fig. 8, four LEDs are installed at (3, 3, 3), (3, 5, 3), (5, 3, 3), (5, 5, 3) with P_t of 4.5 W. We consider a tiled receiver and include the 1st reflection. Other main system parameters are kept the same as in [2]. Take the red diagonal line of the receiving plane in Fig. 2 as an example, Fig. 3 shows the VLC system capacity at different locations with and without

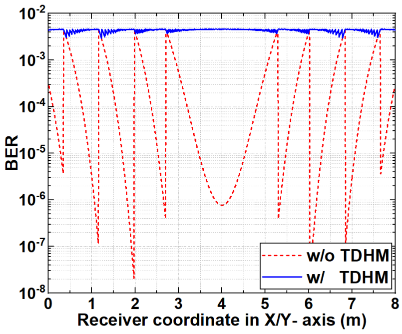

Fig. 5. Comparison of BER.

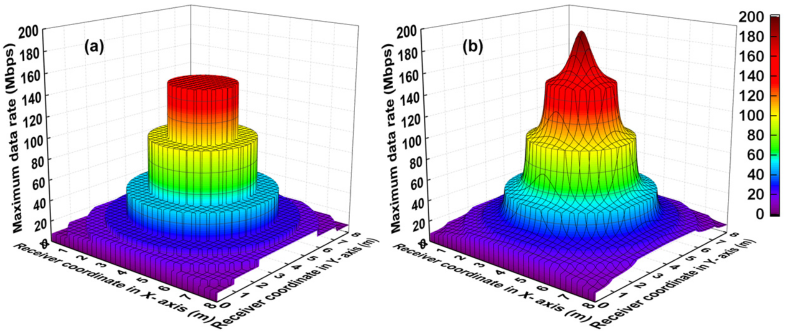

Fig. 6. Comparison of capacity within the receiving plane: (a) w/o TDHM; (b) w/ TDHM.

location-aware TDHM, respectively, using different pulse rate R_s. For the conventional single-carrier scheme, due to the employment of discrete formats, the system capacity will experience abrupt reductions when the terminal moves from center to corner. However, with the TDHM scheme, the capacity curves show continuous variations. This therefore helps compensate for the reduced data rate effectively, especially near the locations where modulation formats change. When R_s is 50 MHz, Fig. 4 shows the optimal combinations of TDHM formats and the corresponding D_{opt} at each location in the diagonal line. It can be seen that the diagonal range is divided into 9 regions to convey different types of TDHM signals. At center locations hybrid PAM signals are used, while at corner locations hybrid PPM signals are more suitable. Based on Fig. 4, Fig. 5 compares the BER performance in the diagonal line. As a trade-off for a higher SE, the BER with location-aware TDHM is always close-fitting to the FEC threshold of 4.6×10^{-3}. In Fig. 6, we compare the capacity in the receiving plane with and without TDHM, respectively, when R_s is 50 MHz. At (4, 4, 0.85), the maximum data rate can increase from 150 Mbps (only PAM8) to 197 Mbps (hybrid PAM8+PAM16).

With different R_s, Fig. 7 shows the complementary cumulative distribution functions (CCDFs) for the capacity improvement within the entire receiving plane. According to statistics, when R_s is 100 MHz, a capacity improvement of more than 20% can be achieved for 19.8% indoor areas. Moreover, such improvement is almost unaffected by the pulse rate and indoor reflections. Considering variable azimuthal and polar angles of the terminal orientation, Fig. 8 compares the maximum data rate at (4, 4, 0.85). Improved capacity can still be observed for a tilted VLC receiver.

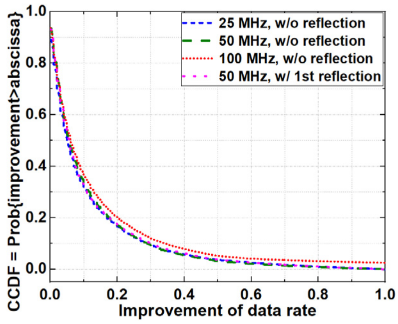

Fig. 7. CCDFs for capacity improvement.

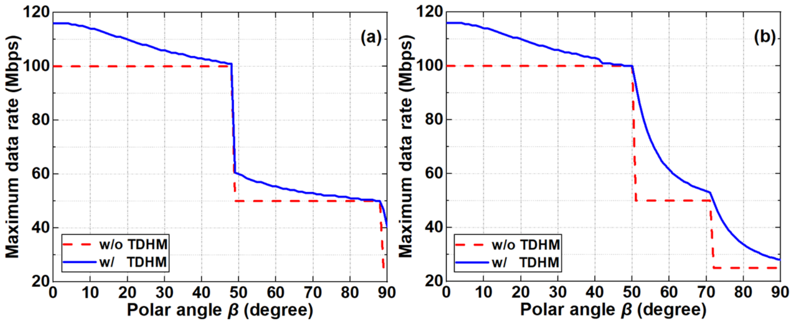

Fig. 8. Comparison of system capacity with a tilted receiver: (a) α=0°; (b) α=45°.

4. Conclusions

We propose a location-aware TDHM scheme for mobile VLC. Based on the receiver moving state information, hybrid frame structures are designed where two different signal formats are transmitted alternatively with optimal combining ratios. Results show that the location-aware TDHM can achieve system capacity improvement effectively when the VLC terminal changes its location and orientation.

5. Acknowledgment

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