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Toward user mobility for OFDM-based visible light communications

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We propose and experimentally demonstrate a mobile visible light communications (mobi-VLC) transmission system. The impact of user mobility on the performance of the mobi-VLC system is characterized, and we propose the use of the channel-independent orthogonal circulant matrix transform (OCT) precoding to combat the packet loss performance degradation induced by mobility. A mobile user terminal is used to detect the signal from a blue laser placed at 1 m away from the moving track. Various moving speeds (20, 40, 60, and 80 cm/s) and lateral moving distances (30, 40, and 50 cm) of the user terminal are investigated. The effectiveness of the OCT precoding is evaluated by the comparison with the conventional orthogonal frequency division multiplexing (OFDM) scheme and the adaptive-loaded discrete multi-tone (DMT) scheme. Experimental results show that the system performance degrades with the increase in user mobility speed and in moving distance. Furthermore, the OCT precoding provides performance improvement that is superior over that of conventional OFDM schemes, and it exhibits lower packet loss rate than that of adaptive-loaded DMT. No packet loss for 300 Mb/s transmission is achieved with a 30 cm lateral moving distance at 20 cm/s.

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Due to the rapid development of solid-state lighting technologies, visible light communications (VLC), providing illumination and data transmission simultaneously, has drawn increasing attention in recent years [1]. By reusing the ubiquitous lighting infrastructure, VLC can provide seamless wireless access without spectrum license and electro-magnetic interference issues. In addition to the VLC-based indoor communications, various potential applications using VLC have been proposed, including indoor positioning [2], inter-vehicle communications [3], and underwater communications [4]. Currently, one key factor that limits high-speed VLC transmission is the low 3 dB modulation bandwidth of the commonly used light-emitting diode (LED) transmitter in the VLC system [5]. In addition to the LED, a blue–violet laser-based VLC transmission has also been investigated to enhance the overall system bandwidth, thus boosting the system capacity [6]. Recently, a blue laser, together with a phosphorous diffuser to generate the white light [7], has been proposed as a promising candidate to promote the practical implementation of high-bandwidth VLC-based wireless access systems. However, most of the prior works are based on stationary point-to-point system setups, i.e., the LED/laser transmitter and the receiver are fixed, and convex lenses are utilized at both sides to maximize the detected signal intensity; thus, a much higher data rate can be realized. For practical communications systems, especially the aforementioned VLC-based inter-vehicle and underwater applications, it is essential for the systems to support user terminal mobility. Very few works on the performance of mobile VLC (mobi-VLC) systems have been reported. The performance of a color-clustered VLC network with user mobility is numerically studied in [8]. In [9], investigation of a laser-based indoor VLC system supporting user mobility is presented. The two investigations, however, are only numerical studies without experimental verification. A self-adaptive space-time block coding scheme is proposed to mitigate the interference between two VLC nodes, thus improving the handover capability for VLC-based networks [10]. The experiments are conducted at several stationary points without user mobility. User mobility has significant impact on VLC systems, mainly due to the mobility-induced fluctuation of detected signal intensity. Furthermore, compared with the stationary scenarios, inter-symbol interference (ISI) is more severe in the mobi-VLC systems when a multipath effect exists.

In this Letter, we present the first experimental characterization of the impact of user mobility on the transmission performance of the mobi-VLC system. A mobile platform with controllable lateral moving distances and moving speeds is implemented to emulate various mobile user scenarios. To reduce the packet loss rate of the quadrature amplitude modulation (QAM) orthogonal frequency division multiplexing (OFDM)-based mobi-VLC system, we propose using our recently demonstrated channel-independent orthogonal circulant matrix transform (OCT) precoding [11] to combat the mobility-induced performance degradation. The main idea of OCT precoding is to linearly precode the transmitted signal with a channel/signal independent orthogonal circulant matrix constructed by the Zadoff–Chu sequence. The original signal can be recovered by multiplying the received signal with the corresponding inverse matrix. With the OCT precoding, a relatively uniform signal-to-noise ratio (SNR) profile is achieved

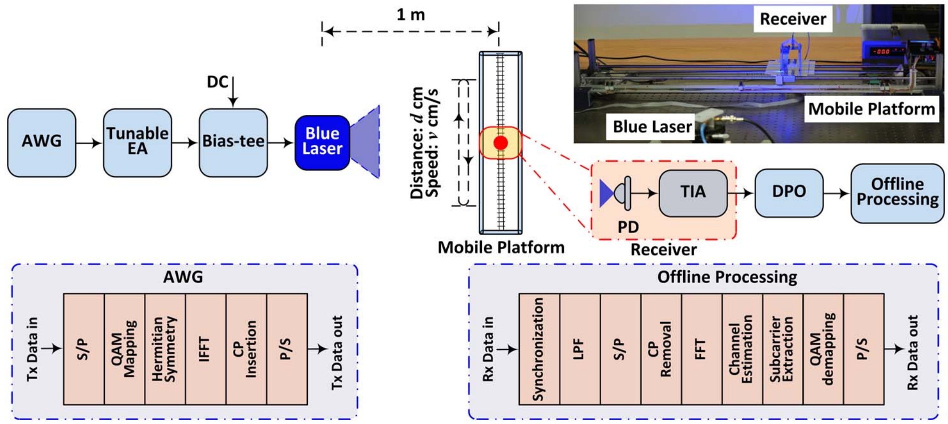

Fig. 1. Proposed mobi-VLC system using conventional OFDM. Inset: photo of the system setup.

over the signal bandwidth, resulting in significant BER performance improvement. Detailed principles of the OCT precoding can be found in [11]. The performance of the discrete multitone (DMT) with adaptive loading is also evaluated in the mobi-VLC system for performance comparison. Experimental results show that, for the mobi-VLC transmission at a data rate of ~300 Mb/s, the OCT precoding offers significant packet loss rate reduction and outperforms that of the adaptive-loaded DMT because of its channel-independent property and enhanced ISI tolerance.

Figure 1 shows the experimental setup of the proposed OFDM-based mobi-VLC system with a stationary transmitter and a mobile receiver. The output of an arbitrary waveform generator (AWG, Tektronix 7122 C) was amplified by a gain tunable electrical amplifier (EA) and then was coupled with the direct current (DC) bias via a bias-tee (Mini-Circuits ZFBT-6GW+). Subsequently, the resulting signal was used to drive a single blue laser (Osram PL450B). The laser beam divergence is $\theta\| \times \theta\perp = 11 \ \mathrm{deg} \times 25 \ \mathrm{deg}$, and the total output power is 80 mW. After free-space transmission, the light was detected by a receiver module, which consists of a PIN photodiode (Hamamatsu S10784 with a cutoff frequency of 250 MHz) and a trans-impedance amplifier circuit. The receiver module was installed on a mobile platform with a controllable lateral moving distance, d cm, and a controllable moving speed, v cm/s, to emulate the user mobility. Note that the lateral distance d denotes the moving distance with a constant speed v. The actual moving distance of the receiver module is slightly larger to accommodate the acceleration and deceleration of the step motor at both ends of the traveling path. The output of the receiver module was then recorded by a digital phosphor oscilloscope (DPO, Tektronix TDS7254) for further offline signal processing. The block size of fast Fourier transform was 256; the sampling rate of the AWG and the DPO were 300 MS/s and 625 MS/s, respectively; the length of the cyclic prefix (CP) was 1/32 of one OFDM symbol, and 127 out of 256 subcarriers were modulated with data for each OFDM symbol. Five-hundred OFDM packets were captured automatically by the DPO during the movement of the receiver module to investigate the impact of user mobility and moving distance on the packet loss rate performance. Each OFDM packet consisted of 200 OFDM symbols and 20 pilot symbols, and all the experiments were conducted under normal ambient illumination (~400 lx).

First, the transmission characteristics were measured for the stationary case with the receiver fixed at different offsets to the center point of the moving track. Figure 2 shows the bit error rates (BERs), illumination and signal-to-noise ratios (SNRs) at the receiver module with different offsets. Note that the bias voltage and amplification gain were optimized to 6.0 V and 25 dB, respectively. Generally, the blue laser has a symmetrical emission distribution as the BER performance, the illuminance, and the SNR performance are symmetrical to the center of the track on the mobile platform. The measured illuminance at the receiver is within the 300–1500 lx ISO standard illuminance [12]. For around a 300 Mb/s transmission, the minimum BER of 7.48×10^{-5} can be achieved at the center of the track, where the maximum and minimum SNRs over the OFDM subcarriers are 17.05 and 8.93 dB, respectively.

We then investigate the impact of various mobile user scenarios on the performance of the proposed mobi-VLC system. The packet loss rate of the received 4QAM-OFDM packets with different moving speeds is shown in Fig. 3(a). Note that a lost packet denotes a packet with a BER higher than the 3.8×10^{-3} FEC limit. The lateral moving distance of the receiver module varies from 30 to 50 cm. It is shown that the packet loss rate will increase, along with the increase in the lateral moving distance, due to the emission distribution of the blue laser depicted in Fig. 2. Furthermore, for any given lateral distance, when the moving speed is below 40 cm/s, the degradation is

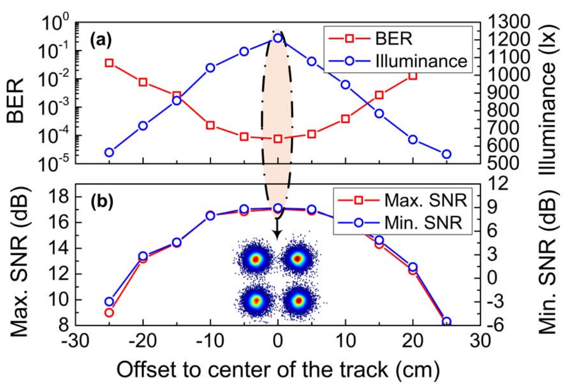

Fig. 2. Measurements of (a) BER and illuminance and (b) maximum and minimum SNR over the OFDM subcarriers versus the offset to the center of the moving track for the stationary scenario.

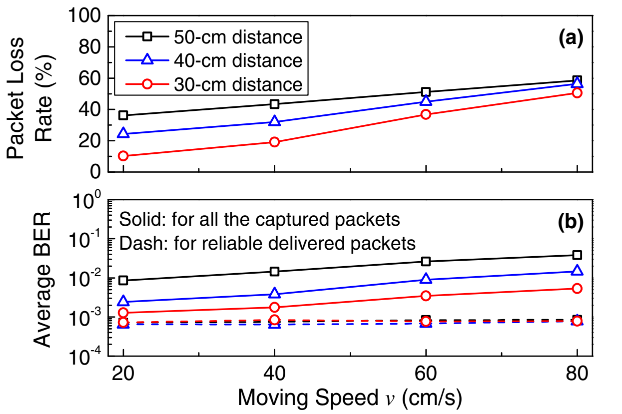

Fig. 3. Performance of the mobi-VLC system with different lateral distance and different moving speeds: (a) packet loss rate and (b) average BER for all captured packets and average BER for the reliable delivered packets.

less significant, with a packet loss rate lower than ∼40%. However, a higher moving speed will result in a larger increase in packet loss rate. The packet loss rate can be higher than 50% for the 80 cm/s case. A comparison of the average BERs for all 500 captured packets, as well as the average BERs for the reliable delivered packets (packets with BERs lower than the 3.8×10^{-3} FEC limit), is given in Fig. 3(b). Similar to the packet loss rate performance, the average BER for all recorded 4QAM-OFDM packets will increase, along with the increase in lateral moving distance and the moving speed. In contrast, in the scenario that only reliable delivered packets are counted, the average BER will hold at around 7.0×10^{-4} for all cases.

The BER distribution of the 500 captured 4QAM-OFDM packets for the moving speed varying from 20 to 80 cm/s are given in the form of box charts and distribution curves in Fig. 4. The detailed implementation of system configurations is given in the descriptions of the experimental setup. In general, the BER performance of captured packets will degrade when the lateral distance is increased from 30 to 50 cm. For any given lateral distance, it can be seen that with the increase in moving speed, the number of OFDM packets with poor BER performance will also increase, resulting in the ascent of the 10% to 90% distribution range, as well as the average BER of the system.

To reduce the packet loss rate of the mobi-VLC system, we propose using our recently proposed channel-independent OCT precoding to combat the mobility-induced system performance degradation. Meanwhile, the DMT with adaptive bit and power loading is also implemented for performance comparison. It is worth noting that for the OCT precoding, no prior knowledge of the channel state information (CSI) is required since the coding and decoding are channel independent. However, for the adaptive-loaded DMT scheme, to adaptively allocate the bits and power to different OFDM subcarriers, additional CSI estimation is needed before data transmission. In the experiments, the implementation of DMT is based on the off-line processing. At the beginning, for each setting of lateral distance and moving speed, 20 OFDM training packets are captured during the movement of the mobile user to estimate the average time-varying channel property. This averaged CSI is used to perform the bits and power allocation.

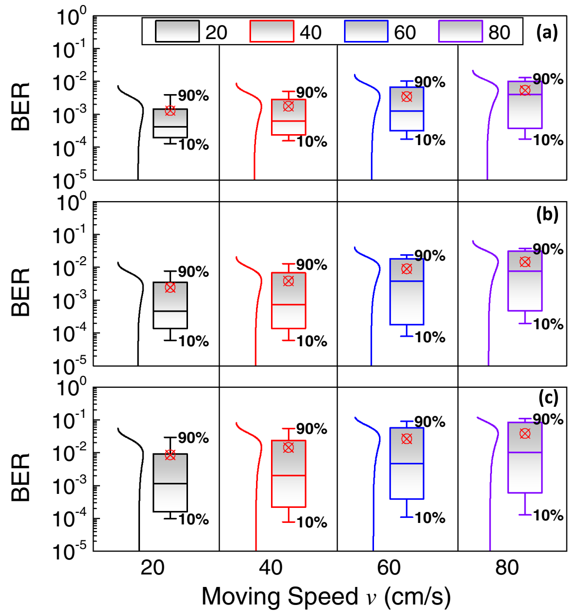

Fig. 4. Statistical analysis of the user mobility's impact on the BER performance of the system with a lateral distance of (a) 30, (b) 40, and (c) 50 cm. (The curves and red marks denote the BER distributions and the average BERs of all captured packets for those scenarios).

Figure 5 shows the packet loss rate comparison of the system with the conventional OFDM, the adaptive-loaded DMT, and the OCT precoding, respectively, under different user mobility and lateral moving distance. It is shown that both the adaptive-loaded DMT and the OCT precoding are effective for reducing the packet loss rate. The channel-independent OCT precoding exhibits better improvement than the adaptive-loaded DMT scheme. This is because, albeit DMT with adaptive bit and power loading can provide optimal performance for stationary point-to-point cases, its performance highly depends on the stability of the channel and the accuracy of CSI estimation. With the OCT precoding, packet loss rates of 0, ∼10%, and ∼20% can be achieved for 30, 40, and 50 cm lateral moving distance, respectively, when the data rate of the mobi-VLC system is around 300 Mb/s and the moving speed is 20 cm/s. Besides, for all the three schemes, the packet loss rate will increase with the increase in the lateral distance of the user terminal, as expected.

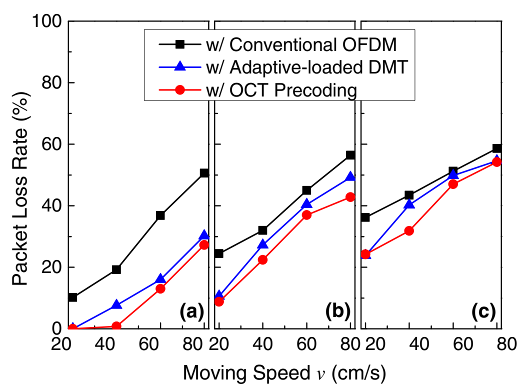

Fig. 5. Packet loss rates with the conventional OFDM, the adaptive-loaded DMT, and the OCT precoding, respectively, versus user mobility with a lateral distance of (a) 30, (b) 40, and (c) 50 cm.

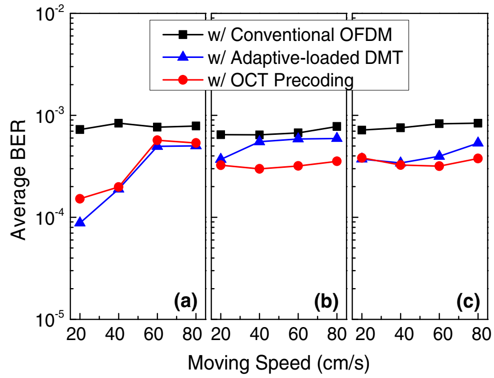

Fig. 6. Comparison of the average BERs of the reliable delivered packets with the conventional OFDM, the adaptive-loaded DMT, and the OCT precoding, respectively: (a) 30 cm lateral distance, (b) 40 cm lateral distance, and (c) 50 cm lateral distance.

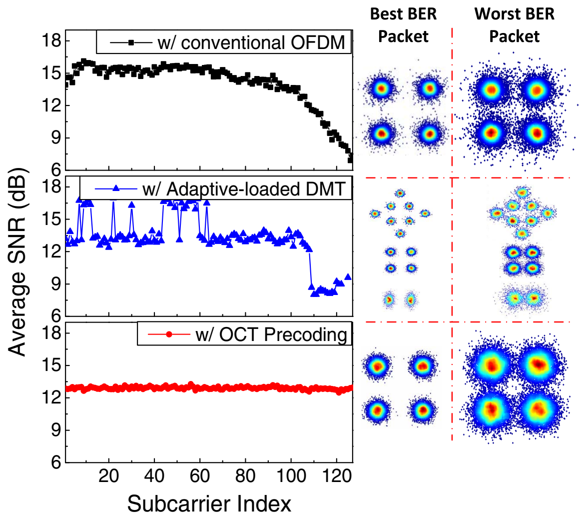

Fig. 7. Average SNR profiles of all reliable delivered packets for the mobi-VLC system using the conventional OFDM, the adaptive-loaded DMT, and the OCT precoding. Insets: signal constellations of the packet with the best BER performance and the packet with the worst BER performance.

By using the OCT precoding, in addition to the significant reduction of the packet loss rate, the average BER for the reliable delivered packets (packets with BERs lower than the 3.8×10^{-3} FEC limit) is also lower than that of the conventional OFDM scheme. The comparison of average BER for the reliable delivered packets of the mobi-VLC system with different moving speeds and different lateral distances is shown in Fig. 6. It is seen that, except for the case with 30 cm lateral distance, the OCT precoding also provides better average BER performance for the reliable delivered packets than that of the adaptive-loaded DMT.

Figure 7 shows the average SNR profiles of all reliable delivered packets using the aforementioned three schemes for the mobi-VLC system with 50 cm lateral distance and 80 cm/s moving speed. The corresponding signal constellations for the packet with the best and the worst BER performance among all reliable delivered packets are also shown in Figure 7. It is clear that the ladder-shaped SNR profile over the OFDM subcarriers is achieved by the adaptive allocation of bits and power. A flat SNR profile with less than 1 dB fluctuation can be obtained for the mobi-VLC system using the OCT precoding. Besides, for both the OCT precoding and the adaptive-loaded DMT, no error bit is recorded for the packet with the best BER performance while, for the conventional OFDM scheme, the best BER for the captured packets is 1.97×10^{-5}. It is also worth noting that the adaptive tracking scheme used in [13] can also be utilized to further improve the performance of the mobi-VLC system.

In conclusion, to the best of our knowledge, the first experimental characterization of user mobility impact on the transmission performance of mobi-VLC system is presented in this Letter. We show that the average BER of the transmitted packets and the packet loss performance are degraded with the increase in user moving speed and the increase in lateral moving distance. Furthermore, we propose using the OCT precoding to combat the mobility-induced performance degradation of the mobi-VLC system. Experimental results show that the OCT precoding offers significant reduction of packet loss rate and outperforms the DMT with adaptive bit and power loading. This is attributed to the channel-independent property and enhanced ISI tolerance of the OCT precoding. No packet loss and ~20% packet loss rate can be achieved for 300 Mb/s transmission with 30 and 50 cm lateral distances, respectively, at 20 cm/s moving speed.

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