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Mobile wireless light communication network

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Mobile wireless light communication (MWLC) is emerging as a promising technology for various air-sea-land applications. When light is used as the transmission medium, MWLC technology can achieve anti-electronic interference communication across air, land, and water environments. However, because of the beam directivity, MWLC is position-sensitive and faces severe alignment problems in practical applications [1]. The light-emitting diode (LED), emerging as a novel and efficient device with a broad emission angle, reduces alignment demands in motion scenarios and is expected to play an important role in mobile wireless light space communication and future enhanced satellite navigation [2]. For the deployment of 6G mobile communication networks, acquiring accurate location information on mobile terminals is becoming extremely useful, not only for location-based services but also for improving wireless communication performance in various ways, such as through-beam alignment and network optimization [3]. Therefore, this study reports an MWLC system using image recognition technology for automatic positioning and tracking. Furthermore, different light spectra have unique properties; for example, blue light is suitable for ocean scenarios, and white light is ideal for nighttime illumination. Combining MWLC systems in different spectra to establish a completely light-based mobile wireless light communication network (MWLCN) will result in high-speed and safe interconnections for multiple users and can simultaneously address communication challenges in various application scenarios. With devices such as unmanned aerial vehicles (UAVs), land vehicles, buoys, and autonomous underwater vehicles (AUVs), the MWLCN will enable high-speed dynamic connections in a wide range of scenarios.

Communication between moving nodes is a great concern of wireless light communication (WLC) technology for future large-scale applications. The MWLC system proposed in this study innovatively integrates visual-tracking features with light communication systems, enabling full-duplex dynamic connections within a velocity of 13 km/h. Multiple services of text, video, and audio are supported based on the transmission control protocol/Internet protocol (TCP/IP) at a maximum transmission rate of 2 Mbps, which broke through the transmission rate and practicability limitation of the previous study [4]. Electronic-noise-free MWLCN spanning space, land, and water is expected to play a significant role in the future multi-mode cross-medium communication network, as outlined in this study. This study combines an image recognition module, a three-axis gimbal stabilizer, and a light communication system to create a full-duplex MWLC system. Image recognition technology provides feedback positioning information to control the three-axis gimbal stabilizer, which can automatically track the target and maintain light path alignment for real-time mobile light communication. Two communication apparatuses are separately deployed on two boats to establish mobile bidirectional wireless data transmission via blue light and are also capable of underwater WLC by acting as fixed nodes. Notably, an MWLCN is constructed outdoors by integrating mobile buoy communication, underwater communication, and white light wireless communication (WLWC), as shown in Figure 1(a). By exploiting the characteristics of two spectra of blue and white light sources, the completely light-based water-land MWLCN achieves real-time information exchange and resource sharing across water and land environments. The process is bidirectional and both wired and wireless access are available, which provides flexible connectivity for multiple users. An MWLCN that integrates visual-tracking features and full-duplex WLC systems will pave the way for future multi-mode mobile communication networks spanning space, land, and water.

The mobile blue light wireless communication (BLWC) system includes a visual-tracking system and a full-duplex BLWC system. A camera, an image recognition module, and a three-axis gimbal stabilizer form the visual-tracking system, which is based on the way that the image recognition technology achieves automatic positioning and tracking in mobile scenarios. Real-time image information is captured at 30 frames per second by the camera and transmitted to the operating terminal wirelessly through the image recog-

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nition module. Once the target is selected at the terminal, the selection instruction is transmitted to the image recognition module and then transferred to the three-axis gimbal stabilizer through a high-definition multimedia interface (HDMI) connector; the stabilizer carries the full-duplex BLWC system for automatic tracking. The camera operates in telephoto and macro modes at short and long communication distances, respectively. The quality of the captured image is 1080P which is significant for positioning and tracking performance. The full-duplex BLWC system includes a transmitter and a receiver that can transmit and receive data simultaneously. The original signal of the transmitter is generated through a network driver from the message source of the network equipment, such as a web camera. A bias-tee circuit drives the transistor-transistor logic (TTL) signal modulated by the on-off key (OOK) modem. At the receiver, an avalanche photodiode (APD) combined with an optical filter is used as the core device for light-to-electricity conversion and for decreasing environmental noise. A signal processing circuit including a transimpedance amplifier (TIA), an operational amplifier (OPA), a high-pass filter, and a comparator (CMP) is used to amplify and convert the photocurrent from the APD, as well as to filter the 50 Hz indoor noise. The signal processing circuit generates 0–3.3 V TTL signals according to the light-intensity changes at the receiver caused by the modulated signals at the transmitter and sends them to the OOK modem for demodulation. PCs have both wired and wireless access to the system through the network driver and an integrated wireless module, offering flexible connectivity for multiple services such as text, video, and audio based on TCP/IP. Furthermore, other communication networks could also connect to the mobile BLWC system through the gateway. Ethernet switches, which act as bridges between different communication networks for service forwarding, are also permitted.

Figure 1(b) shows the detailed construction of the mobile BLWC system. The transmitter, the receiver, and the image-captured camera of the mobile full-duplex BLWC system are arranged at the front of the same panel, and the overall size of the system is 12.5 cm × 12.5 cm × 14 cm. A 3D-printed shell houses all the modules and is set on a three-axis gimbal stabilizer, which weighs only 0.87 kg. An optical bandpass filter is used to decrease the noise of the other bands in the environment, as the spectral response range of the APD (Hamamatsu, S8664-50K) is 320–1000 nm. A neutral density (ND) filter is used to change the received optical power of the receiver, making it suitable for different communication distances. The transmitter and the receiver are divided using an optical isolation part that can transmit and receive data simultaneously without mutual interference. At the transmitter, a blue LED is used as the core device because of its high-speed response and broad emission angle; it is packaged into an adjustable optical system that can be manually switched between scatter and focus modes. The dominant wavelength of the LED is 453 nm and the 3-dB bandwidth is measured at 4 MHz. The maximum communication distances of the system are 8 and 20 m in the scatter and focus modes, respectively.

The maximum transmission rate of the mobile BLWC system is 2 Mbps. An arbitrary wave generator (AWG) and a digital storage oscilloscope are used as the message source and the sink, respectively, to test the communication performance of the mobile BLWC system. A 2 Mbps pseudorandom binary sequence (PRBS) signal is generated by the AWG and input to the transmitter of the system. The signals flowing through the different points of the system are tested and shown in Figure 1(d). The amplitude of the transmitted signal is 2 Vpp, and the reverse voltage of the APD is set at 300 V. The 400-mV signal captured at the TIA and the 3.3-V TTL signal restored at the comparator are shown in the panels of Figure 1(d); they have the same length as the transmit signal shown at the top panel. An eye pattern is accumulated from the TIA signal at the receiver, which indicates a clear decision threshold through the communication channel. The time and amplitude scales are 200 ns and 100 mV, respectively, as labeled in Figure 1(e).

The relationship between the bit error rate (BER) and the received optical power of the system is measured by a BER analyzer and shown in Figure 1(f). A 2 Mbps PRBS signal with an amplitude of 5 Vpp acting as an output signal of the BER analyzer is generated and sent to the full-duplex BLWC system for transmission, while the TTL signal received by the system is used as the input signal for the BER analyzer. The BER of the system is characterized on the basis of the input and output signals of the analyzer transmitted through the mobile BLWC system. The APD is powered at a reverse voltage of 300 V and an optical density filter is used to change the received optical power at the receiver. As shown in Figure 1(f), the BER is in a high range of 10^{-2} when the light is relatively weak. Owing to the high gain of the APD, the BER decreases sharply from 10^{-4} to 10^{-9} when the received optical power increases slightly from 2.4 to 5.39 μW. When the received optical power is between 7.1 and 20 μW, the BER is tested over a long period and remains at a low value, under 10^{-9}. Furthermore, as the received optical power increases from 111 to 116 μW, the receiver reaches saturation, and the BER rises again to more than 10^{-2}.

The mobile BLWC system is operated under the TCP/IP scheme. To realize MWLC in motion, the constrained relationship within the communication process should obey

$$T_{\mathrm{ICM}} + T_{\mathrm{sta}} + T_{\mathrm{TCP}} \leqslant T_{\mathrm{v}}, \tag{1}$$

where T_{ICM} represents the delay of the image recognition module, T_{sta} represents the rotation delay of the three-axis gimbal stabilizer, T_{TCP} represents the maximum permitted delay of the TCP/IP, T_{v} represents the time taken for the moving nodes through the path. Consequently, the constrained relationship can be concluded as

$$v \leqslant \frac{\Delta L}{T_{\mathrm{ICM}} + T_{\mathrm{sta}} + T_{\mathrm{TCP}}}, \tag{2}$$

where v represents the maximum permitted velocity of the moving node and ΔL represents the length of the path during the T_{v}. This equation highlights that the maximum velocity of the MWLC in this scheme is constrained by the delays of recognition, rotation, and TCP/IP.

Using Packet Internet Groper (PING) commands to send Internet Control Message Protocol (ICMP) packets could characterize the network performance. Practically, the packet loss rate (PLR) of the system is measured remaining within 2% as the velocity increases from 0 to 13 km/h and the average delay of the system is tested at 7.7 ms. Finally, the MWLC system goes offline experimentally at 14 km/h, beyond the performance.

A water-land MWLCN is established outdoors, as shown in Figure 1. The network consists of a full-duplex WLWC system on land and a mobile full-duplex BLWC system in a pool; the two systems are connected via a wireless bridge.

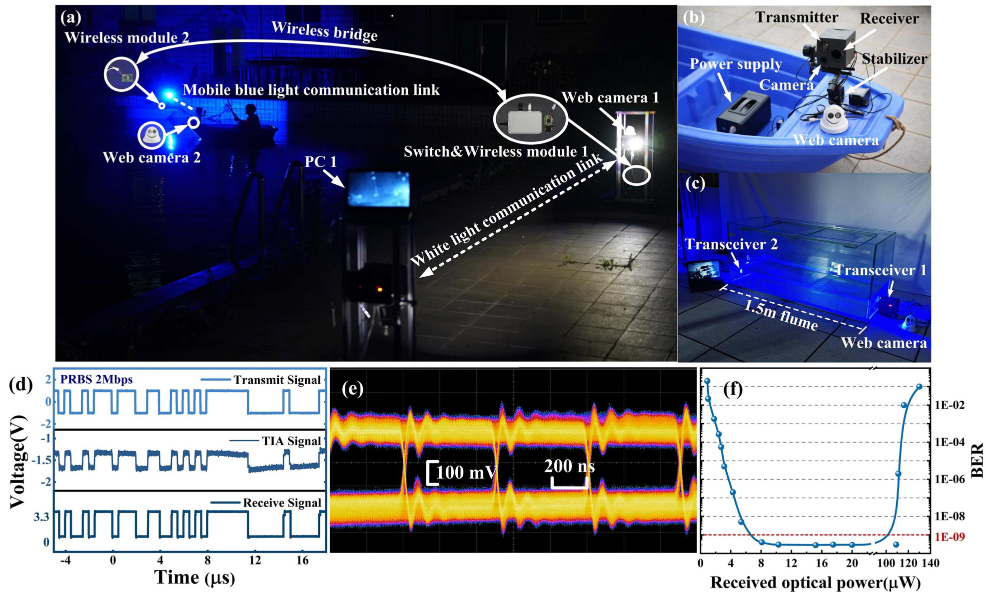

Figure 1 (Color online) (a) Architecture of the water-land MWLCN; (b) assembly of the mobile BLWC system; (c) underwater experiment using a 1.5 m flume; (d) signals flowing at different points at a transmission rate of 2 Mbps; (e) eye pattern at the TIA; (f) curve relating the BER and received optical power.

The wireless bridge is established using two wireless modules operating at 2.4 GHz in follow mode. At the WLWC links, PC 1 is wired to the WLWC system and used as the demonstration terminal of the network. On the opposite side, web camera 1, wireless module 1, and a WLWC system are connected to an ethernet switch. At the mobile BLWC links, web camera 2 and wireless module 2 are connected to the ends of the BLWC transceivers. The network provides flexible wired and wireless access for multiple users. Once the communication links are established, PC 1, wired to the network, can access both web camera 1 and web camera 2 through the WLWC links and mobile BLWC links, respectively, as shown in the demo Video. Furthermore, the PCs can directly access the network wirelessly through wireless modules. Multiple services are provided through TCP/IP in the network at a transmission rate of 2 Mbps. The WLWC system and the mobile BLWC system can independently operate as two different subnets in land and water communication scenarios. Additionally, when two light spectra are used, the water-land MWLCN can use the advantages of blue and white light spectra in water and land scenarios combined with Wi-Fi access technologies to achieve wireless optical interconnection in different scenarios. Moreover, the mobile BLWC system makes the network mobile, significantly enhancing its practicality.

Specifically, the communication distance of the WLWC system in the experiment is 10 m, and the maximum communication distance could exceed 100 m at a reverse voltage of 385 V for the APD. The total power consumption of the WLWC and the mobile BLWC systems is 24 and 38 W, respectively. The mobile BLWC achieves real-time mobile video communication for simulated buoy nodes, and the experimental communication distance is 6 m in scattering mode. Owing to the transmission window in the water, the mobile BLWC system could also achieve underwater WLC with fixed nodes. As shown in Figure 1(c), an underwater experiment is conducted using a 1.5 m flume. The ND filter is used to decrease the received optical power appropriately for the communication distance and to filter the reflected light caused by the glass, preventing self-interference; real-time video tasks are then performed on the PC. At a communication distance of 1.5 m, the ND value of the filters at each BLWC transceiver is 2000 when the reverse voltage of the APD is 350 V, indicating the symmetry of the full-duplex optical paths.

To dynamically maintain light alignment between two MWLC nodes, this work integrates image recognition features with WLC systems to experimentally demonstrate mobile full-duplex light communication under TCP/IP. The MWLCN combines both white and blue light sources ensuring seamless bidirectional connectivity across land and water environments, leading to a complete-mapping and decentralized mobile all-light network architecture.

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Supporting information Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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