Vision-based Localization for Indoor Beam-steered Optical Wireless Communication System

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Optical wireless communication (OWC) has been considered as a promising alternative communication technology to cope with the rising bandwidth demand for indoor wireless network. Deploying steerable narrow infrared beams, OWC enables to provide a high-capacity link to user devices. For appropriately directing the narrow IR beams, the location of the user device needs to be known accurately. Using a low-cost optical camera, we demonstrated an accurate and fast localization technique for ultra-high capacity beam-steered optical wireless communication. Multiple user devices have been localized simultaneously within 10ms and 50ms without and with ID tags respectively for less than 5mm accuracy at a reach of 3m.

Introduction

Recently, the available radio spectrum is exhausted by the booming demand for wireless connectivity. The number of wireless devices is exploding in order to provide us mobile connection, internet access, reliable monitoring services. Driven by the growing demand for bandwidth-hungry services such as uncompressed 4K/8K ultra-high definition TV, the rising volume of wireless data has to be carried. As the radio spectrum is getting congested, wireless devices are severely interfering with each other. As an effective way to escape from the current radio spectrum congestion threat, optical wireless communication (OWC) has been considered as a promising alternative communication technology to cope with the rising demand for indoor wireless bandwidth [1].

There are two main research domains in OWC as visible light communication (VLC, a.k.a LiFi) and beam-steered infrared light communication (BS-ILC). VLC employs visible light for communication that occupies the spectrum from 380nm to 750nm. VLC enables to combine the illumination and communication purposes into the existing light-emitting diode (LED) illumination system. However, these regular LEDs have been designed for optimum illumination purposes, thus have a limited modulation bandwidth. Alternatively, BS-ILC deploys the steerable narrow beams that launch the light only to the requested position, hence multiple beams can independently serve user devices within a single light antenna. Thus, each device can get a non-shared capacity without interfering other devices. The directivity of a beam guarantees better power efficiency. However, this ultra-high performance can only be achieved with small footprints, the system needs to know the exact location of user devices with respect to the light antennas. There are various localization techniques developed over the years that employed radio [2] or light signals [3]. All these works have resulted in accuracies of several tens of cm, require relatively high power, slow localization for multiple targets and above all complex structures.

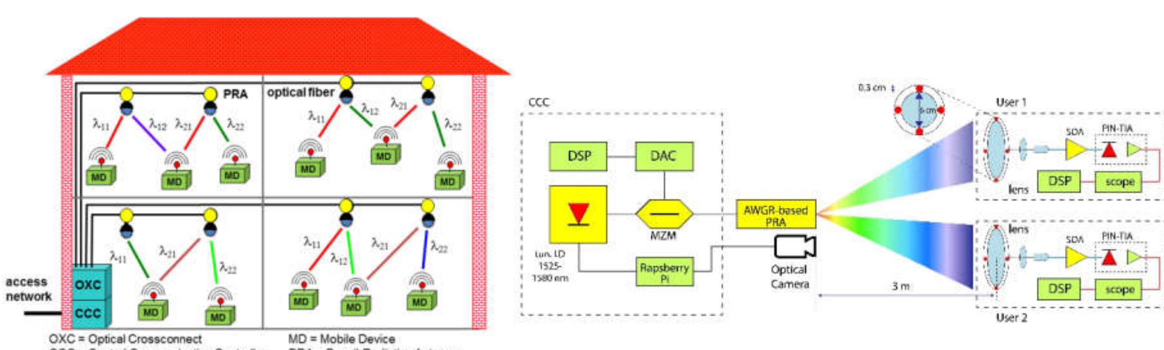
To make the localization reliable, we propose an accurate and fast localization and identification system using a low-cost optical camera. The infrared (IR) LEDs is employed around each optical receiver unit. The identification of user devices is assigned and encoded into the blinking sequence of LEDs. The camera, which is located at the PRA, captures the illumination of LEDs placed at the user side. An image processing algorithm is developed to determine simultaneously not only the exact locations of the multiple user devices relative to the optical access points, but also the identification (ID) of each user devices. With the camera resolution of 1280x720 at 100fps, the positioning accuracy is archived less than 5mm at a reach beyond 3m. Multiple user devices are localized within 25ms.

Optical beam-steered indoor communication

Our system concept is shown in Fig. 1a. The fiber to the home connection is networked with the central office, and is terminated at the building by a central communication controller (CCC). A fiber link connects the CCC to the pencil-beam radiating antennas (PRAs). At the ceiling of each room, multiple pencil radiating antennas (PRAs) are installed as access points to transmit the optical signals to the end user devices. Each PRA is designed with fully passive optics. By deploying an arrayed waveguide grating router (AWGR), PRA is able to steer multiple beams into different directions simultaneously under control of the beam's wavelength [4]. By means of an optical OXC, these tunable lasers are routed to the appropriate PRAs in the appropriate rooms according to actual traffic demands.

Due to the narrow optical beam employed in the system, the user device position needs to be determined as accurate as possible. To launch a beam to a target user device, the important parameter to be found is the angle θ of light direction from PRA to the user device. To determine this parameter, an optical camera system is proposed as shown in Fig. 1b. Assumed that the optical camera is placed near PRA, user devices are captured, then x- and y-coordinate of user devices in the image plane can be used to estimate accurately the desire angle. In this study, we propose an image processing algorithm to find the precise position and ID of user devices based on the captured image of user devices. The localization system consists of a low-cost camera and four IR-LED tags mounted on a top of each user device. IR-LED tag is designed to be efficiently recognized and distinguished from each other, and LEDs are encoded to convey the optical signal. An IR-bandpass optical filter is integrated into the camera lens to remove the ambient visual objects and emphasize the IR-LED tags.

The proposed algorithm contains two stages. Firstly, the position of user devices is determined based on the geometric relation of four LEDs in the filtered image. Secondly, the ID of user devices are demodulated from the following encoded data framework. In



(a) (b)

Fig. 1: (a) Pencil beam wavelength steerable OWC concept; (b) Experimental setup for the vision-based localization.

the first stage, the original image is converted from the color scale to gray scale. An adaptive threshold value is applied to filter the grayscale image to the black and white image. With the high intensity, LED is only presented as the white pixel area. To reduce the computation time, only contour pixel of LED is used to find the white-area center. After detecting the center positions of each white area, the next task is to determine the position containing four white areas. Because the LED tag is designed with the known ratio between the LED size and the distance of four LEDs, the algorithm can easily find appropriate areas considered as user positions, resulting in detecting the first phase of identification. Then these user device positions are stored into a table of user.

To transmit the identification from LED tag to camera, a five-phase data frame work is proposed as shown in Fig. 2. The user device starts the synchronization phase by turning on all four LEDs. The next guard bit phase is used to separate the synchronization and the upcoming data, and to support signal decoding. Each LED has an on and off state to indicate a logic level 1 and 0, respectively. Because the ID of each user device is encoded by a binary number, it is important to determine the least significant bit (LSB) and the direction of converting bit. In the guard bit phase, one designated LED is active to assign the LSB and clockwise direction is selected to decode the signal. After detecting the first phase of identification, only the pixel surroundings of user positions in the following image are cropped to reduce the processing time. Guard bit and ID phases are analyzed and processed from these cropped images to compute the light launch angle and the user ID. Two ID phases are used to transmit the user ID with the corresponding code by four LEDs. A total of 8 bits are used to encode the user ID equivalent to the possibility of identifying 256 users. This number of user device is chosen in accordance to the needs of a medium size room. If the number of user device increases, then our concept can easily cope with it by adjusting the number of ID encoding bits. The ID information can further be used for continuous tracking when the same user decides to move to another position served by a different beam.

Experimental Results

Fig. 1b shows the proof-of-concept experimental setup including the optical communication system and camera. The low-cost camera is installed near the. The data from the camera is processed in the Raspberry Pi 3 to control the tunable laser. At the receiver side, a 2.5cm aperture collimator captures the beam, which is then coupled into a single mode fiber to feed the APD-TIA receiver. Four LEDs of diameter 3mm are placed around the collimator. The resolution of the localization camera was kept at 1280×720 (corresponding to a frame rate of 100fps) to cover an area of 3.2m×1.8m at a free-space distance of 3m.

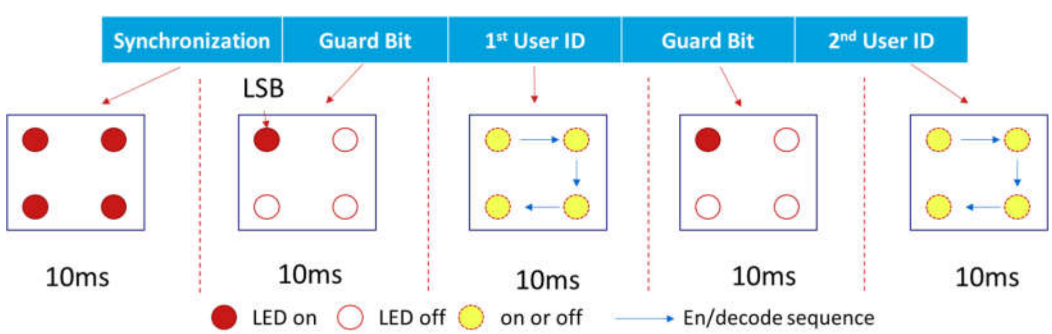


Fig. 2: Proposed data framework.

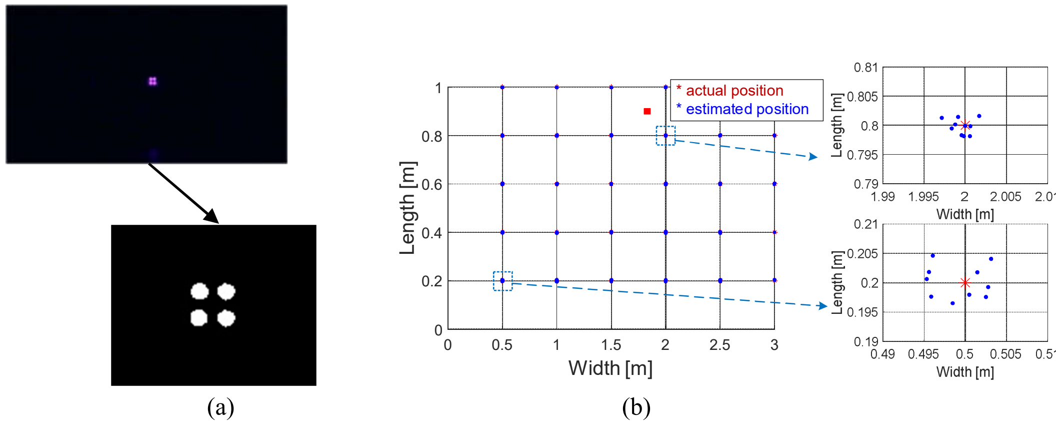


Fig. 3: a) Original and processed images of user device; b) Experimental measurements at reference grid at the distance of 3m between PRA and user;

Fig. 3a shows the images of the coverage area containing a four-LED. The individual LEDs are clearly visible on the filtered image which can then be processed to determine the location of the user. We carried out an experiment by placing one user device at 30 different spread-out positions on the user plane and determine the positioning error at these positions. At each position, the experiment was repeated 10 times. Fig. 3b shows the location of the user returned by the algorithm, taking the actual location as a reference. In all the tested positions, it was possible to locate the user within an accuracy <5mm. The best localization error (<1mm) was achieved for positions near the center of the user plane. The error increased when the user device moved away from the center of user plane. The prime cause of this variation is the tangential distortion of the image sensor of the camera.

Conclusions

Using a low-cost camera and real-time image processing on a simple Raspberry Pi, we demonstrated a localization and tracking system that can detect simultaneously the position and ID of user devices within 50ms. The position accuracy of less than 5mm at a reach beyond 3m was archived, indicating the high potential of this camera technology supported by LED-based tagging to be deployed in ultra-high capacity beam-steered indoor OWC systems.

Acknowledgments

This work has been carried out in the framework of the TU/e-KPN flagship Smart-One program. Funding from the European Research Council in the Proof-of-concept project BROWSE+ is also gratefully acknowledged

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