

Accurate indoor localization for beam-steered OWC system using optical camera

Citation for published version (APA):

Pham, N., Mekonnen, K. A., Tangdionga, E., Mefleh, A., & Koonen, A. M. J. (2020). Accurate indoor localization for beam-steered OWC system using optical camera. In *Proceedings of the 45th European Conference on Optical Communication (ECOC 2019)* Article 9125807 (IET Conference Publications; No. CP765). Institution of Engineering and Technology (IET). <https://doi.org/10.1049/cp.2019.1079>

DOI:

[10.1049/cp.2019.1079](https://doi.org/10.1049/cp.2019.1079)

Document status and date:

Published: 30/06/2020

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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ACCURATE INDOOR LOCALIZATION FOR BEAM-STEERED OWC SYSTEM USING OPTICAL CAMERA

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Keywords: Indoor communication, localization, optical beam steering, optical wireless communication.

Abstract

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 25ms for less than 5mm accuracy at a reach beyond 3m.

1. Introduction

Optical wireless communication (OWC) has been considered as a promising alternative communication technology to cope with the rising demand for indoor wireless bandwidth [1]. OWC can exploit an enormous amount of yet unregulated spectrum (2600x the size of currently available radio spectrum) and can efficiently reuse this huge spectrum by spatial multiplexing because the signal range is limited and in most cases confined to a room. Visible Light Communication (VLC) typically builds on the existing light-emitting diode (LED) ambient illumination system, and re-uses the LEDs for data modulation. These LEDs typically have been designed for optimum illumination purposes, and have a limited modulation bandwidth. The VLC system thus covers a wide area, in which multiple user terminals have to share its capacity. Beam Steered – Infrared Light Communication (BS-ILC) brings the light only there where and when needed. Multiple beams may independently serve user devices within the room, hence each device can get a guaranteed (non-shared) capacity without conflict with other devices. Moreover, infrared light beams are allowed to be operated at higher power than visible light beams, as the eye safety threshold for infrared light is higher. Together with the directivity of a beam, this implies that the received signal-to-noise ratio with BS-ILC can be substantially higher than with VLC, enabling a higher data rate and longer reach at better power efficiency. Current BS-ILC

prototypes facilitate multiple beams with over 100 Gbit/s per beam [2]. This ultra-high performance can only be achieved with small footprints, hence 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 [3] or light signals [4]. All these works have resulted in accuracies of several tens of cm-s, require relatively high power, slow localization for multiple targets and above all complex structures. An interesting approach was proposed exploiting a camera-based localization technique [5] where LEDs for user tagging were used leading to a localization accuracy of several mm-s. The high accuracy was obtained using 12 infrared LEDs encircling the detector, required 100 images for processing, and the use of an infrared camera. All these will lead to higher power consumption, longer processing time, and higher costs.

In this paper, we propose an accurate and fast localization/tracking technique using a low-cost camera and simple image processing on a Raspberry Pi platform. Four visible light LEDs are employed around the optical receiver of user devices. The identification of user devices is assigned and encoded into the blinking sequence of LEDs. The camera, which is located at the light antenna, captures the illumination of LEDs placed at the user side. An image processing algorithm is developed to determine simultaneously not only the exact position of the multiple user devices relative to the

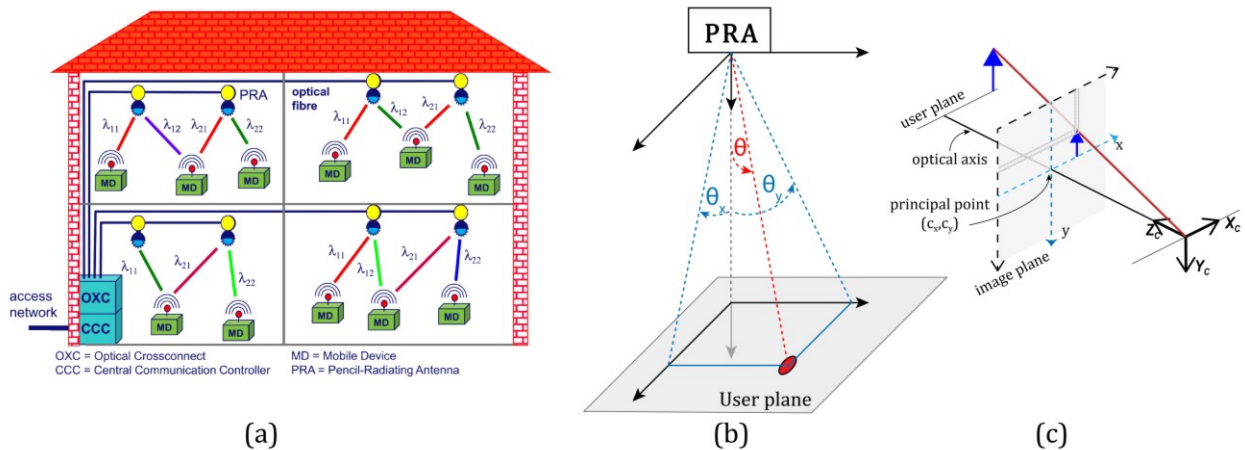


Fig. 1: (a) AWGR-based beam-steered OWC concept; (b) Steering angle from PRA to user; (c) Camera pin hole model.

light antenna, but also the ID of each user device. With a camera resolution of 1280×720 , a positioning accuracy of less than 5mm is achieved for a distance beyond 3m. Multiple user devices are successfully localized within 25ms, which represents the record on this field.

2. Localization Concept

Fig. 1(a) presents the concept of our indoor OWC system, including a central communication controller (CCC), a transparent optical cross-connect (OXC) switch and pencil-radiating antennas (PRAs) [6]. CCC dynamically routes the data streams to the appropriate PRAs with the appropriate wavelength via the OXC in order to launch the beam to the target user devices. Each PRA contains an arrayed waveguide grating router (AWGR) module with a large number of output fiber ports. The output fibers are arranged in a 2D array, and put in front of a lens to realize 2D beam steering functions. Next, due to the narrow optical beam employed in the system, the user device position needs to be determined as accurate as possible.

As shown in Fig. 1(b), in order to launch a beam to a target user device, the only important parameter to be found is the angle θ of light direction from PRA to the user device. The proposed idea is to use an optical camera to determine this parameter. The optical camera is composed of millions of light-sensitive areas or pixels. A simple camera model is described as Fig. 1(c). Assumed that the optical camera is placed near the PRA, x- and y-coordinate of user devices in the image plane can be used to estimate accurately the required angle as the similarities between Fig. 1(b) and 1(c). In this study, we propose an image processing algorithm to find the precise position and identification (ID) of user devices based on the image of user devices in the real world. The localization system contains a low-cost camera and four LED markers mounted on a top of each user device. Markers are designed to

be efficiently recognized and distinguished from others, and LEDs are encoded to convey the optical signal.

The proposed algorithm contains two stages. Firstly, the pixel areas corresponding to the LEDs is filtered in every entire image frame. Secondly, the position and ID of user devices are determined using the algorithm which consists of five-phase data framework as a synchronization phase, guard-bit first phase, ID first phase, guard-bit second phase and ID second phase. The user device starts the synchronization phase by turning on all four LEDs. The next guard bit phase not only separates the synchronization with the upcoming data but also supports 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. 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 cope with it by adjusting the number of ID encoding bits.

To enhance the performance, the image captured by the camera is converted to grayscale levels. An adaptive thresholding is applied to filter the original grayscale images to the black and white images. Each LED with an appropriate intensity is indicated as a white pixel area with a value of 255 and the rest of the image is indicated as a black pixel area with a value of 0. After determining the position of the white areas in each frame corresponding to each LED, the next task is to determine the position containing four white areas. Because the LED marker is designed with the known ratio between the LED size and the distance of four LEDs and the known shape formed from four LEDs, the algorithm can find that the

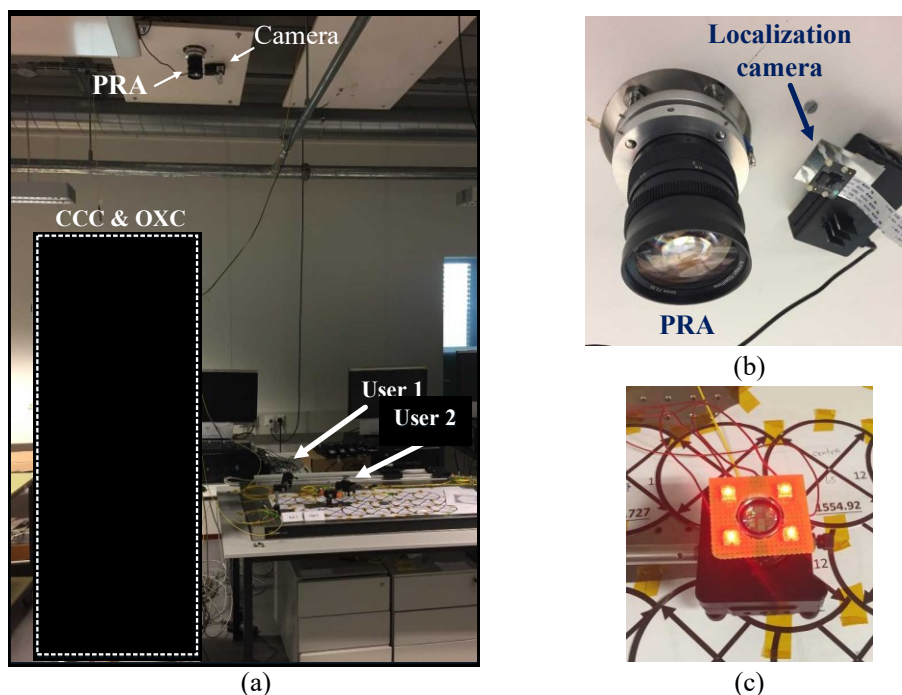


Fig. 2: Photo of (a) Laboratory demonstrator; (b) PRA with a localizing camera setup; and (c) LED marker.

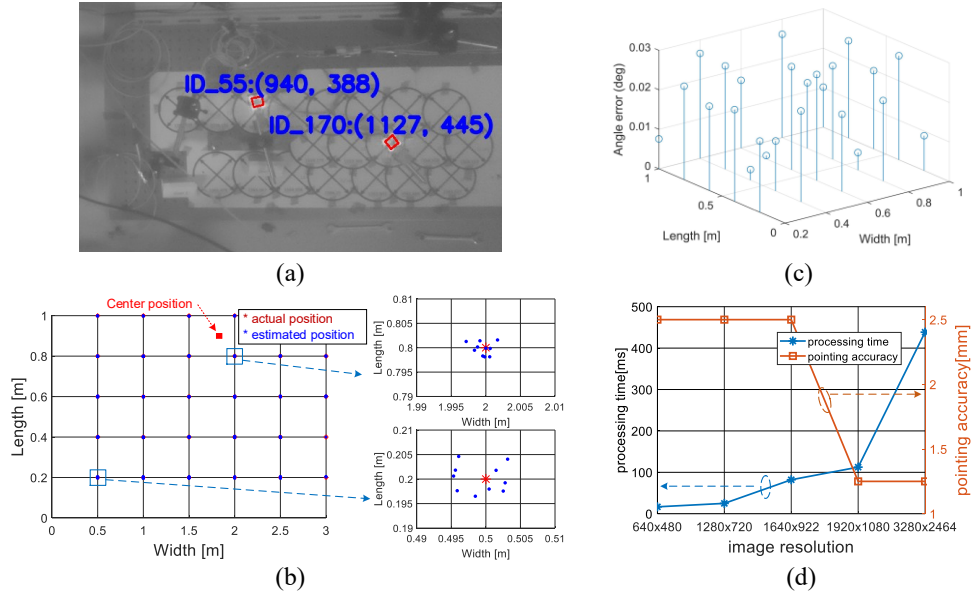


Fig. 3: Experimental results: (a) Estimated position of 2 user devices on a processed image; (b) Experimental measurements at reference grid at the distance of 3m between PRA and user; (c) Experimental angle errors within a coverage area of 1m×3m; (d) Performances under the various camera resolutions.

appropriate pixel areas are considered the user positions, resulting in detecting the synchronization phase of user devices. Then these user device positions are stored into a table of user. In the following image, only the pixel surroundings of user positions are cropped to further 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. 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.

3. Experimental Results

Fig. 2(a) shows the proof-of-concept experimental setup including the optical communication system and camera. The AWGR-based PRA uses a tunable laser from 1525 to 1580nm. The outputs of the AWGR feed a 9×9 2D fiber array with 1.3mm pitch. By deploying PAM-4 signal modulation, 112Gbit/s transmission per beam could be achieved [2]. The low-cost camera is installed near the PRA as Fig. 2(b). 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 as shown in Fig. 2(c). The resolution of the localization camera was kept at 1280×720 (corresponding to a frame rate of 40fps) to cover an area of 3.2m×1.8m at a free-space distance of 3m.

Fig. 3(a) shows the captured image of the coverage area at the user plane containing two user devices, each with its own ID. The developed algorithm determines the ID and x, y coordinate of each device with respect to a central point in the image. Compared to the actual positions on the user plane, the algorithm was able to locate the users within an error of 1.5mm on average.

To ensure the reliability of the achieved results, we also carried out the experiment by placing one of the users at 30 different spread-out positions on the user plane and determine

the localization error at these positions. At each position, the experiment was repeated 10 times. Fig. 3(b) 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. The localization performance can also be translated to angular errors as shown in Fig. 3(c). The average localization accuracy was 0.0137°.

The localization accuracy depends on the resolution of the camera used. The relationship between the camera resolution, processing time and pointing accuracy of the camera used in our setup is illustrated in Fig. 3(d). A higher resolution offers better positioning errors (the highest resolution of 3280×2464 produces the lowest pointing error, 1.25mm) because it contains more details than a lower resolution. However, it also requires more processing time. Hence, the appropriate camera resolution is chosen as a compromise between the pointing accuracy and the processing time.

4. Conclusion

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/tag of multiple user devices within 25ms. The position accuracy of less than 5mm at a reach beyond 3m was archived. The average angle accuracy of 0.0137° indicates to our opinion the high potential of this camera technology supported by LED-based tagging to be deployed in ultra-high capacity beam-steered indoor OWC systems.

5. Acknowledgements

This work has been carried out in the framework of the TU/e-KPN flagship SmartOne program.

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