Plugo: a Scalable Visible Light Communication System towards Low-cost Indoor Localization

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***Abstract*— Indoor localization is critical to many location-aware applications, however, a low-cost solution with guaranteed accuracies has not yet come. Visible Light Communication (VLC-) based localization techniques are very promising to fill this gap. In this paper, we propose Plugo, a novel VLC system with random multiple access towards low-cost indoor localization. Compared to conventional RF-based approaches that rely on dedicated wireless access points as location beacons, the proposed system has the potential to deliver better accuracies with reduced cost. Specifically, we build a handful of compact VLC-compatible LED bulbs out of low-cost off-the-shelf components (around $10 total cost for each assembly) and recover VLC signals using a cheap photodiode receiver. The basic framed slotted Additive Links On-line Hawaii Area (ALOHA) is exploited to achieve random multiple access over the shared optical medium. We show its effectiveness in beacon broadcasting by experiments, and further, demonstrate a preliminary localization result with sound accuracy by using fingerprinting-based methods in a customized testbed.**

I. Introduction

Accurate indoor localization enables a wide range of location-aware applications [1], such as pedestrian way-finding and ground robots navigation. Despite concerted efforts for decades by the industry and academia, the indoor localization problem remains unsolved [2]. Previous research on robot localization mainly focused on high-cost extrinsic sensors (e.g., RGB-D cameras and laser range finders) and complex algorithms with high computational demand [3] to obtain high accuracy. For wide adoption in daily applications, however, the critical challenge lies in providing adequate location accuracies while reducing the deployment overhead. In recent years, Visible Light Communication (VLC-) based solutions have shown promising potentials to fill this gap [4] [5]. Different from RF-based counterparts that rely on dedicated hardware infrastructure [6], [7], VLC-based approaches leverage existing LED lights instead.

In general, VLC-based systems employ modulated LEDs as artificial landmarks, use cameras [1], [8] or photodiodes (PD) [9] as sensors, and determine locations either through geometry model-based methods [1], [9] (e.g., triangulation and trilateration) or data-driven methods [10] (e.g., fingerprinting). To obtain location fixes, multiple lights are required to be observed simultaneously by the camera or PD. Besides, there is a growing consensus that a decentralized, uncoordinated VLC system with one-way communication is preferred for localization purpose [8], because of the better scalability to large-scale scenarios and less deployment cost. To this end, asynchronous multiple access schemes are desired in the beacon broadcasting process.

As for the state of the art, camera-based systems (e.g., Lumicast [8]) can deliver decimeter-level positioning accuracies on commercial smartphones. Spatial division multiple access (SDMA) is exploited by such systems thanks to the spatial resolution of cameras [1]. However, they suffer from high power consumption, computational overhead, and limited coverage owing to the narrow field of view (FOV) of front-facing cameras [11]. By contrast, PD-based solutions are more energy-efficient, lightweight, and have larger coverage. Considering the lack of spatial discrimination of PDs, several asynchronous multiple access schemes were proposed, e.g., frequency division multiple access (FDMA) [12] and code division multiple access (CDMA) [13].

Normally, a fixed frequency carrier or pseudo-noise sequence is allocated to each light in advance. When it comes to a large-scale environment (say with thousands of lights), however, the number of frequency carriers or pseudo-noise sequences available to use are limited. An RF-carrier allocation scheme was proposed in [12] to mitigate the inter-cell interference by reusing a limited number of carriers in non-adjacent cells. That is, one had to guarantee that none of any adjacent lights shared the same frequency carrier during installation. Such a stringent constraint may burden the time and human-labor in practical deployment at scale. This problem is common for fixed multiple access schemes, but it has long been overlooked by many researchers.

To circumvent this situation, a radical idea is to dynamically assign a limited number of communication resources (e.g., time slots, frequency carriers, and optical CDMA codes) in a random fashion to all the beacons involved–random multiple access [14]. In this context, each beacon in the VLC system competes with one another equally for communication resources. Collisions occur when two different beacons compete for the same resource (e.g., time slots). But this problem can be easily worked out through multiple observations. As a result, random access schemes scale better to large-scale scenarios. To the best of our

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knowledge, Epsilon [9] was the first experimental system in this community that involved random multiple access–channel hopping. The basic framed slotted ALOHA[1] (BFSA) random multiple access scheme was first introduced in [15], but it was only evaluated by simulation.

In this paper, we demonstrate the implementation of the BFSA-based random multiple access scheme with practical issues taken into account. Accordingly, we propose **Plugo** (named after "Plug and Go"), a PD-based VLC system that is capable of providing reliable beacon broadcasting over a shared optical medium from multiple LED bulbs to a single PD receiver. It deviates from the general VLC systems [16] developed in the wireless communication community that pursues high data throughput along with bidirectional communication. The key differentiation points of Plugo are threefold: 1) decentralized architecture, 2) one-way communication, and 3) random multiple access. Compared with our previous work [10], [13], [17], Plugo moves a small step further towards the expected localization technology.

Specifically, we stress our novel contributions as follows:

1) Development of a scalable VLC system using PD sensors towards low-cost indoor localization, which can be deployed by plug-and-go;
2) Experimental demonstration of a BFSA-based random multiple access scheme by solving the inter-frame flicker problem especially for localization usages.

The remainder of this paper is organized as follows. Section II and Section III describe the detailed system design and implementation respectively; Section IV demonstrates the evaluation results; Section V concludes this paper.

II. System Design

In this section, we will first give an overview of the system architecture, and then introduce the key issues in the system design, namely communication using OOK, random multiple access, and inter-frame flicker mitigation.

A. System Overview

As shown in Figure 1, Plugo comprises a set of VLC-compatible LED bulbs as positioning beacons and a PD receiver attached to a user device (e.g., smartphones) via an audio jack. The system architecture is decentralized without any backbone connection among these bulbs. Each bulb broadcasts its unique beacon identity to the receiver by one-way communication over a shared optical channel. The user device equipped with a receiver takes continuous observations of multiple light beacons overhead retrieving each beacon identity along with the corresponding received signal strength (RSS). VLC-based localization is feasible built upon these observations, e.g, by RSS fingerprinting or multi-sensor fusion [18]. To ease system debugging like firmware update and parameter configuration, we propose a standalone wireless programming system exploiting the RF channel. It consists of a backend and a number of wireless programmers residing in LED bulbs. Over-the-air (OTA) programming and remote configuration can be thus achieved. Note that RF links are used for debugging purposes only and are not involved in beacon broadcasting.

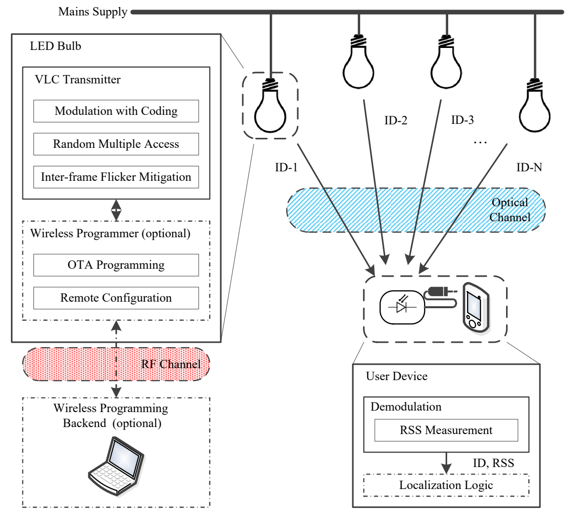

Fig. 1: The Plugo system composed of a set of LED beacons, a PD receiver, and optionally a wireless programming system.

B. Communication using OOK

A high data throughput is not necessary for beacon broadcasting. We prefer a simple modulation scheme affordable by low-cost hardware components. To be specific, we choose the OOK modulation with Manchester coding which is also adopted by the IEEE 802.15.7 [19] PHY-I layer specification. Constraints on the modulation frequency f_{mod} come from many factors such as the response time of LEDs, the perception bandwidth of PDs, the sampling frequency of the Analog-to-digital converter (ADC), etc. As for a proof-of-concept system implementation, we empirically choose $f_{mod} = 10\,\mathrm{kHz}$ which is interpretable by a USB soundcard with a maximum sampling frequency of 48 kHz.

TABLE I: Data Frame Structure

SOF		Data		EOF
SFD	Sync	Payload	Checksum	$\sim$SFD
4 bits	8 bits	32 bits	8 bits	4 bits

The data frame structure is shown in Table I. The duration of each frame is 5.6 ms at the chosen modulation frequency. Figure 2 illustrates its content in a raw VLC signal fragment. It is 56 bits long[2], and is composed of three sections, namely, start-of-frame (SOF), Data and end-of-frame (EOF). SOF further contains a special frame delimiter (SFD) to indicate the start of a new frame and a Sync sequence for clock synchronization. The SFD here is indeed a 4-bit logic high symbol that never occurs in the normal Manchester coding data. The Sync sequence is 8-bit long with alternate high and low logic symbols that carry timing information.

[1]ALOHA stands for Additive Links On-line Hawaii Area. It was originally proposed in the late 1970s for wireless medium access control.

[2]The "bits" refer to raw data frame bits that incorporate both the special control symbols and Manchester coding data symbols.

Similarly, the EOF contains a 4-bit logic low symbol ($\sim$SFD) to indicate the end of a frame. The data section consists of a 2-byte payload and a half-byte checksum, which are both encoded by Manchester coding. The payload carries a unique identification code for each bulb. A 2-byte long code could easily cover a normal indoor environment with tens of thousands of lights. The checksum is generated by a simple XOR operation to verify the payload integrity. Once data corruption is detected at the receiver side, the message will be discarded. We do not perform any data retransmission under this circumstance, as the light beacon could not detect the potential transmission failure due to the lack of an uplink. Instead, the corrupted message could be recovered by subsequent observations.

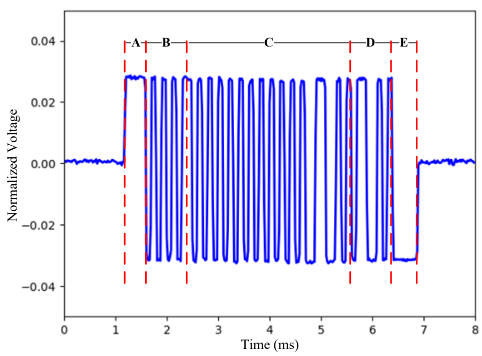

Fig. 2: A typical raw VLC signal fragment containing a full data frame. It is shown in a bipolar form as we adopt a USB sound card with AC coupling to acquire the analog signal from the receiver front end. The signal amplitude is normalized to [-1.0, 1.0]. From A to E: SFD, Sync, data payload, data checksum, and EOF.

C. Random Multiple Access

We adopt the BFSA [15] scheme to achieve random multiple access over the shared optical medium in a decentralized VLC network that supports one-way communication. It defines a transmission frame structure composed of a fixed number of time slots. Each light beacon randomly selects a time slot in the frame and transmits its beacon message within that slot. If any two adjacent lights select the same time slot or two overlapping time slots, there will be a transmission failure because of the conflicts. However, the corrupted messages could be safely recovered later.

The success rate $P_{success}$ is an important metric to evaluate the system performance. It is defined in [15] as the probability of successful transmission from all transmitters inside a coverage vicinity to a given receiver. Supposing perfect synchronization among these transmitters, the theoretical value could be calculated by the following formula,

$$P_{success} = \frac{\left\langle {N \atop n} \right\rangle}{N^n}, \tag{1}$$

where N is the number of time slots per frame, n is the number of transmitters, and $N > n$. As for an asynchronous system, starting points of the time slots from different lights are probably misaligned. The success rate will decrease when more collisions happen. $P_{success}$ increases with the number of time slots per frame N. Meanwhile, the communication bandwidth needed for each transmitter is also N times the original. We have to make a trade-off between the success rate and communication bandwidth available on low-cost hardware components.

The LED bulb performs data transmission when the desired time slot comes and then goes to idle states. The Manchester coding data is DC balanced thus eliminating the intra-frame flicker of the bulb during the data transmission. However, how to mitigate the potential inter-frame flicker during the idle states remains a problem.

D. Inter-frame Flicker Mitigation

Flicker refers to the visible fluctuation of the light brightness. It further comprises intra- and inter-frame flicker. In this context, the intra-frame flicker has been eliminated by Manchester coding. Thus we focus on the mitigation of the inter-frame flicker. According to the IEEE 802.15.7 standard [19], one can make the LED light transmit a dummy data message during the idle states to prevent flicker. The modulation frequency of the dummy message can either be in-band or out-of-band. In a particular case, the light can be driven by a suitable DC current without modulation. The idea is straightforward–the overall brightness of the LED bulb will keep consistent as long as the DC intensity during the idle time slots equals to the average intensity during the active time slots. However, the desired DC current varies from one bulb to another due to the manufacturing tolerance. It is tedious to determine it one by one in practice. In our context, it is infeasible to modulate the dummy message by an in-band frequency as it can induce severe interference to other nodes who are broadcasting beacon messages. We prefer to modulate it by a high out-of-band frequency, e.g., 100 kHz in the current implementation. It can be removed easily by a low-pass filter on the receiver. The dummy message here is indeed repeated "01" symbols which provide an equal average intensity to that of the beacon message.

III. Implementation Details

In this section, the hardware design of LED bulbs, the PD receiver and wireless programming are described in detail.

A. VLC-compatible LED Bulbs

We have designed a compact LED bulb which is easy to use in a plug-and-go fashion. The bulb is designed with a standard E27 screw base so that it can be easily installed to a lamp socket. The schematic of the LED driver is shown in Figure 3. It consists of an AC-DC power supply, a DC-DC buck converter, a voltage-controlled current source (VCCS), a low-cost MCU (STM32F030F4P6), a debug connector, and a LED plate. The AC-DC power module provides an output of 12 V with a maximum power of 4.5 W. We choose a 3 W LED plate, considering the power tolerance. The DC-DC converter steps down 12 V to 5 V to power other circuits. The LED current is adjusted by the VCCS under the control of the MCU. The signal modulation, encoding, and the random multiple access control are all implemented within the MCU as firmware. We build the bulbs upon a set of low-cost off-the-shelf LED bulb components and a customized controller circuitry, as shown in Figure 4.

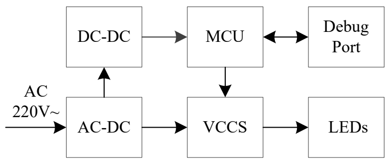

Fig. 3: Schematic diagram of the LED bulb driver circuitry

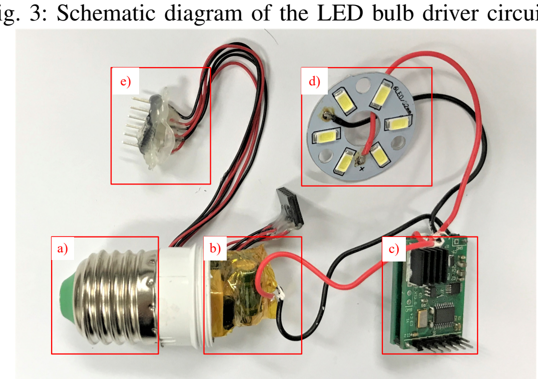

Fig. 4: The primary components of LED bulbs. a) a standard E27 screw base, b) an off-the-shelf AC-DC power supply, c) a VLC controller that integrates a DC-DC converter, a voltage controlled current source and a MCU, d) a LED plate, and e) a debugging connector. The bulb case and shade are omitted for brevity.

B. PD Receiver

The schematic of the designed receiver circuitry is shown in Figure 5. It is composed of a cheap PIN PD (SFH203P from OSRAM), a trans-impedance amplifier (TIA) with DC bias correction, a low-pass filter (LPF), and a small lithium battery. We connect the receiver to a USB soundcard via an audio jack. The signal acquisition and demodulation are implemented on the computer with the *python-alsaaudio*[3] library. Figure 6 shows the assembled circuitry.

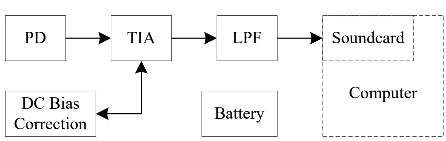

Fig. 5: Schematic diagram of the PD receiver circuitry

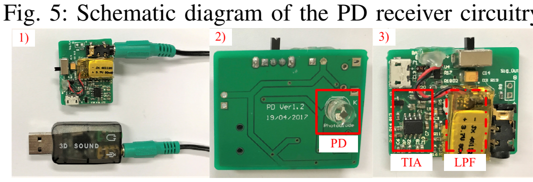

Fig. 6: 1) The receiver circuitry connected with a USB sound card via the audio jack; 2) Top view of the PCB showing the PD (highlighted in the red rectangle); 3) Bottom view of the PCB showing the TIA and LPF (covered by the lithium battery).

The ambient interference comes from sunlight along with the fluorescent or incandescent lights. It includes a large DC bias, some strong low-frequency components (100 or 120 Hz), and high-frequency harmonics. Besides, the dummy message broadcasting in our system also introduces a significant high-frequency component. A large DC bias may cause saturation of the receiver circuitry. To circumvent this situation, we involve an error integrator to TIA so as to correct the induced DC bias. The output signal is biased to a fixed value despite the ambient interference. We adopt a fourth-order Butterworth low-pass filter to remove the significant high-frequency interference from the dummy broadcasting. We do not take care of the low-frequency interference in the current implementation.

[3]https://larsimmisch.github.io/pyalsaaudio/

C. Wireless Programming System

It aims to fulfill two primary functions, namely over-the-air (OTA) programming and remote configuration, which are very useful for debugging in large-scale scenarios. The system consists of a master node (Figure 7-1) connected to a computer as the backend and a number of slave nodes (Figure 7-2) attached to the LED bulbs. They are assembled on the basis of a shared hardware design albeit running different versions of firmware. We build several hardware prototypes using off-the-shelf components including an MCU board with a USB interface and a low-cost 2.4G RF communication module. To cover a broader area, the RF module in the master node bears a larger transmission power considering that the data traffic occurs mainly in the downlink.

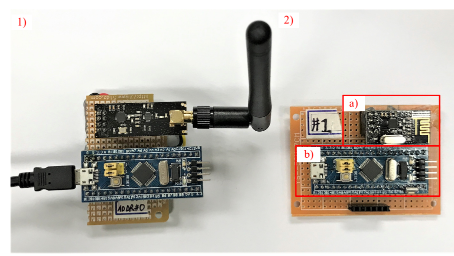

Fig. 7: The wireless programming system prototype. 1) The master node with a high-gain antenna; 2) The slave node consisting of a RF module and an MCU boad.

IV. System Evaluation

In this section, we will first evaluate the effectiveness of the BFSA-based random multiple access scheme during the beacon broadcasting process of Plugo using a hardware-based testbed with four customized VLC-compatible LED bulbs, as shown in Figure 8. Thereafter, we implement a fingerprinting-based localization algorithm which uses Gaussian process regression (GPR) [20] based on our previous work [10], [17], and present a preliminary localization result demonstrating the localization accuracy and robustness.

A. Beacon Broadcasting with BFSA

Figure 10 shows a sample of raw VLC signals received simultaneously from four LED bulbs. It is clear that beacon messages are randomly distributed in the time domain. In most cases, they are separated neatly and can be successfully recovered. When collisions occur, as shown in Figure 10-b),

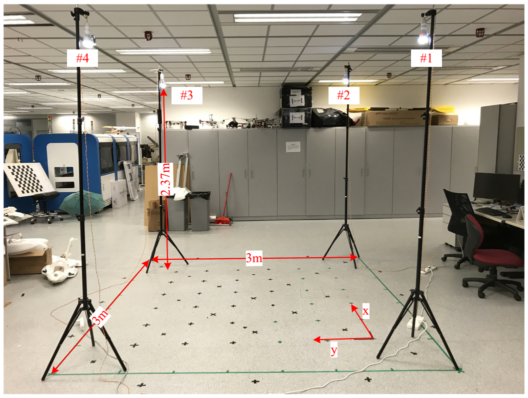

Fig. 8: A $3\,\mathrm{m} \times 3\,\mathrm{m}$ testbed with four LED bulbs. The x-axis and y-axis are labeled with single-end arrows.

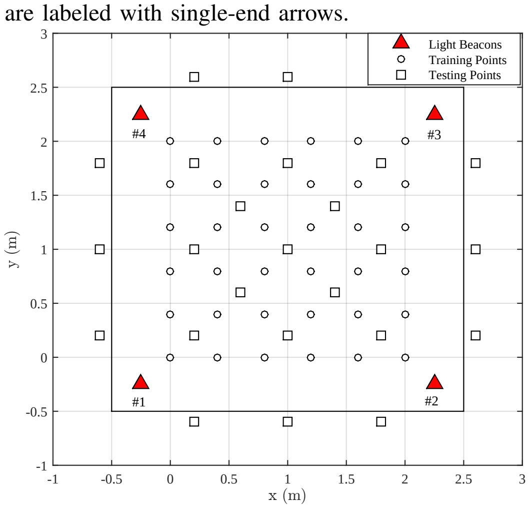

Fig. 9: Testbed floor plan showing the training and testing points.

messages involved will be corrupted. However, we can safely retrieve them by continuous observations later on. Figure 10-a) shows a special case. The received message is decodable and checked to be correct. However, there exists a noticeable fluctuation in the signal waveform which is indeed corrupted by others. The RSS measurement is distorted in this situation and may further degrade the localization performance. As a result, we would prefer to discard it. Besides, we measure the success rate $P_{success}$ of the BFSA-based multiple access scheme and compare it with the theoretical result in Figure 11. It is shown clearly that $P_{success}$ increases with the number of time slots per frame N. The measured values are inferior to the theoretical ones due to the lack of synchronization among the lights.

B. Localization using Plugo

We first use GPR [20] to build a fine-grained light intensity map upon sparse fingerprint samples, and then perform online localization based on maximum-likelihood-estimation (MLE). To be specific, we create a 2D grid with 6×6 points spaced at 0.4 m and collect fingerprints at these positions as training samples for GPR, as shown in Figure 9. Then we evenly select 25 extra positions for evaluation covering both the central and border area. We locate these points with an accuracy of 2 cm using a commodity laser range finder.

During the experiment, we turn on the four bulbs and keep other lights off. This is because the maximum power (3 W) of the LED bulbs is much lower than the normal power rating of other fluorescent lights. The low-frequency components with high energy from these lights will cause the saturation of the receiver circuitry. However, we claim that this will not be a problem if we use higher-power LED lights as we can choose a smaller amplifying gain to prevent the saturation.

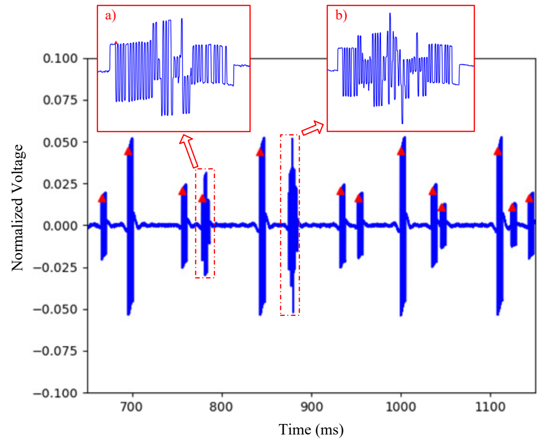

Fig. 10: A fragment of raw VLC signals received from four LED bulbs. The decodable messages are marked by red triangles. a) and b) show magnified views of typical corrupted signals.

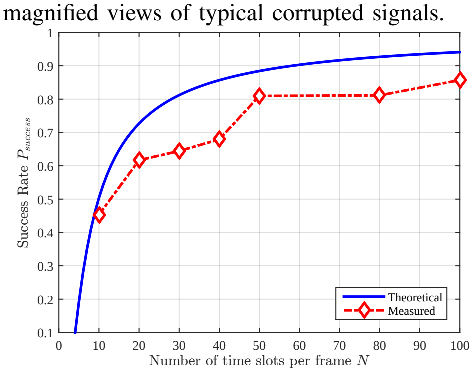

Fig. 11: Success rate versus number of time slots per frame.

The estimated positions along with the groundtruth are plotted in Figure 12. The maximum localization errors occur near the testbed borders. This is because we only collect fingerprint samples in the central area of the testbed. The generated light intensity map does not fit well the intensity distribution in the border area. Figure 13 plots the empirical CDF of the position errors with the solid curve. The average error is 0.14 m and the 90-percentile error is 0.33 m. To evaluate the robustness to lights failure, we deliberately switch off light #4 and redo the experiment. The position error CDF is shown by the dashed line in Figure 13. The localization accuracy is slightly degraded. But we still achieve an average error of 0.17 m and a 90-percentile error of 0.50 m. We show its efficacy in real-time localization in the demo video which can be found on `https://youtu.be/azYi-NLtj2g`.

C. Discussions

Admittedly, the proposed Plugo system is only scalable to networked communication at this stage from multiple light

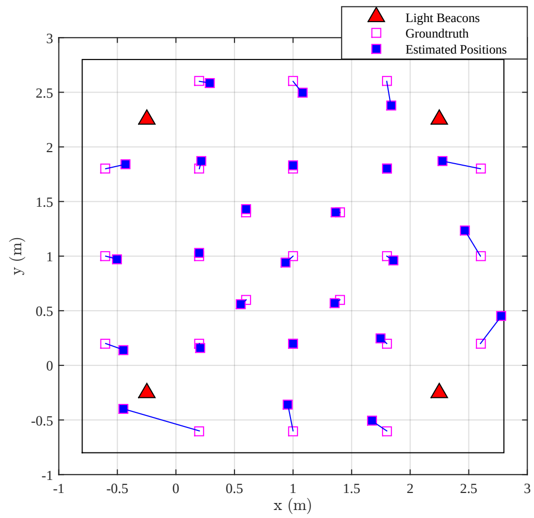

Fig. 12: Localization results at 25 static positions.

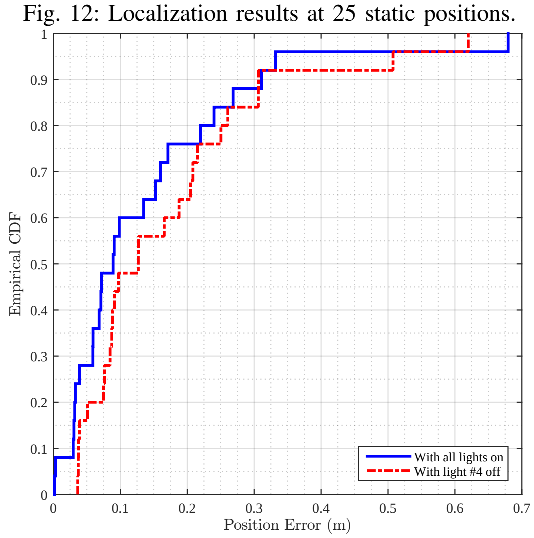

Fig. 13: Position estimation error CDF when four lights are turned on (solid) and one light off (dashed).

beacons to a PD receiver. Its application in localization is demonstrated in a rather small testbed due to the lack of enough VLC bulbs during this experiment. We argue that the scalability in communication founds the basis for scalable localization. We credit our contribution mainly to the VLC part in this paper with an emphasis on its fundamental importance and appealing application perspectives for a scalable and low-cost indoor localization solution. Moreover, the delivered accuracy is good enough for many indoor applications like the localization of service robots. With the motion measurements from wheel-encoder odometry on the ground robots and their powerful computational resources onboard, more accurate localization could be feasible on the basis of the proposed VLC system, say in a low-cost and scalable fashion.

V. Conclusions

In this paper, we presented the design, implementation, and evaluation of Plugo, a dedicated VLC system for low-cost localization using photodiode receivers. It featured a decentralized architecture, supported one-way communication, and enabled random multiple access. Plugo was composed of a set of low-cost VLC-compatible LED bulbs, a photodiode receiver, and optionally, a wireless programming system for debug purposes. The bulbs were with compact design favoring fast deployment by plug-and-go. Moreover, a BFSA-based random multiple access scheme was implemented with practical issues taken into account. Experiment results showed that Plugo was able to achieve reliable beacon broadcasting over the shared optical medium. A preliminary localization result was demonstrated in a $3\,\mathrm{m} \times 3\,\mathrm{m}$ square testbed with an average accuracy of 0.14 m and a 90-percentile accuracy of 0.33 m.

References

[1] Y.-S. Kuo, P. Pannuto, K.-J. Hsiao, and P. Dutta, “Luxapose: Indoor positioning with mobile phones and visible light,” in *Proc. MobiCom’14*. ACM, 2014, pp. 447–458.
[2] D. Lymberopoulos, J. Liu, X. Yang, R. R. Choudhury, V. Handziski, and S. Sen, “A realistic evaluation and comparison of indoor location technologies: Experiences and lessons learned,” in *Proc. IPSN’15*. ACM, 2015, pp. 178–189.
[3] M. Liu, F. Pomerleau, F. Colas, and R. Siegwart, “Normal estimation for pointcloud using GPU based sparse tensor voting,” in *Proc. ROBIO*. IEEE, 2013, pp. 91–96.
[4] J. Armstrong, Y. Sekercioglu, and A. Neild, “Visible light positioning: a roadmap for international standardization,” *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 68–73, 2013.
[5] T.-H. Do and M. Yoo, “An in-depth survey of visible light communication based positioning systems,” *Sensors*, vol. 16, no. 5, p. 678, 2016.
[6] Y. Sun, M. Liu, and M. Q.-H. Meng, “WiFi signal strength-based robot indoor localization,” in *Proc. ICIA*. IEEE, 2014, pp. 250–256.
[7] Y. Guo, K. Huang, N. Jiang, X. Guo, Y. Li, and G. Wang, “An exponential-Rayleigh model for RSS-based device-free localization and tracking,” *IEEE Trans. Mobile Comput.*, no. 1, pp. 1–1, 2015.
[8] A. Jovicic, “Qualcomm Lumicast: A high accuracy indoor positioning system based on visible light communication,” 2016.
[9] L. Li, P. Hu, C. Peng, G. Shen, and F. Zhao, “Epsilon: A visible light based positioning system.” in *NSDI*, 2014, pp. 331–343.
[10] K. Qiu, F. Zhang, and M. Liu, “Let the light guide us: VLC-based localization,” *IEEE Robot. Autom. Mag.*, vol. 23, no. 4, pp. 174–183, 2016.
[11] C. Zhang and X. Zhang, “Pulsar: Towards ubiquitous visible light localization,” in *Proc. MobiCom’17*. ACM, 2017, pp. 208–221.
[12] H.-S. Kim, D.-R. Kim, S.-H. Yang, Y.-H. Son, and S.-K. Han, “An indoor visible light communication positioning system using a RF carrier allocation technique,” *J. Lightw. Technol.*, vol. 31, no. 1, pp. 134–144, 2013.
[13] F. Zhang, K. Qiu, and M. Liu, “Asynchronous blind signal decomposition using tiny-length code for visible light communication-based indoor localization,” in *Proc. ICRA*. IEEE, 2015, pp. 2800–2805.
[14] L. Jean, Paul, “Wireless communication: the interactive multimedia CD-ROM,” http://www.wirelesscommunication.nl/reference/chaptr06/randacc.htm.
[15] W. Zhang, M. S. Chowdhury, and M. Kavehrad, “Asynchronous indoor positioning system based on visible light communications,” *Optical Engineering*, vol. 53, no. 4, pp. 045 105–045 105, 2014.
[16] D. Karunatilaka, F. Zafar, V. Kalavally, and R. Parthiban, “LED based indoor visible light communications: State of the art,” *IEEE Commun. Surveys Tuts.*, vol. 17, no. 3, pp. 1649–1678, 2015.
[17] K. Qiu, F. Zhang, and M. Liu, “Visible light communication-based indoor localization using Gaussian process,” in *Proc. IROS*. IEEE, 2015, pp. 3125–3130.
[18] M. Liu, L. Wang, and R. Siegwart, “DP-Fusion: A generic framework for online multi sensor recognition,” in *Proc. MFI*, 2012, pp. 7–12.
[19] S. Rajagopal, R. D. Roberts, and S.-K. Lim, “IEEE 802.15. 7 visible light communication: modulation schemes and dimming support,” *IEEE Commun. Mag.*, vol. 50, no. 3, 2012.
[20] C. E. Rasmussen, “Gaussian processes for machine learning,” 2006.