

Positioning and Space-Division Multiple Access Enabled by Structured Illumination With Light-Emitting Diodes

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Abstract—Self-location of devices in an illuminated area can be realized using light-emitting diode array luminaires with integrated electronic smart control. These smart lighting sources project a rapidly displayed time sequence of spatial illumination patterns onto the scene, which enables positioning on a millisecond timescale. We demonstrate a prototype system based on a CMOS-driven 16×16 array of GaN light-emitting diodes and its application to space-division multiple access in a Gb/s optical wireless network.

Index Terms—Light-emitting diodes (LEDs), localization, navigation, position measurement, space-division multiple access, wireless optical.

I. INTRODUCTION

WITH the advent of light-emitting diode (LED) based solid state lighting, much excitement has centered around so-called “smart lighting”, which is energy saving on the one hand, but on the other, offers advanced functionality. This functionality may include intelligent intensity control, active color balance, electronic control systems and data transmission. These schemes are enabled by the favorable properties of GaN-based LEDs such as low power consumption, compact dimensions, easy integration with control electronics and color converters, availability of LEDs throughout the visible spectrum and fast modulation response.

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This paper has supplementary downloadable multimedia material available at <http://ieeexplore.ieee.org> provided by the authors. The supplementary file contains a video of real-time positioning and space-division multiple access using structured illumination. At first, it is shown how two detectors in the illuminated area receive a positioning signal transmitted at 2000 fps. Once their position is known, individual wireless optical data streams are sent to each detector at 1 Mb/s/channel. This is shown from two different angles. Afterwards, it is shown how the position of a single detector is traced in real-time. This material is 43.8 MB in size.

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

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Here, we report a scheme of smart lighting that allows accurate determination of the position of devices within the illuminated area. Stimulated by the development of LED based communications systems [2], LED-based positioning systems are the subject of considerable interest [3]–[6]. Earlier reports used a relatively small number of LED emitters and provide positioning through time difference of arrival ranging [3], [7], [8], allocation to fingerprinted luminaires, often combined with signal strength evaluation [9]–[11], probabilistic methods [4], or a range of different triangulation methods [3], [4], [12], [13].

This work presents a scheme where the position information can be retrieved from a time-sequence of spatial illumination patterns which provide fingerprint optical signals for each spatial site. The modulation format of each individual LED element is relaxed in this scheme as compared with other fingerprinting methods, and in particular projection-based approaches such as that reported by Taylor and Hranilovic [10]. Crucially, there is no requirement for orthogonal modulation in the method detailed here. The use of spatial illumination pattern sequences provides uniform illumination across the scene and is implemented using a single-chip transmitter. This scalable approach allows significant simplification at the receiver end, which is beneficial e.g. for applications related to the internet of things [14], whilst at the same time providing high positioning accuracy and speed. As shown schematically in Fig. 1, the LED light source comprises a dense array of microscopic LED elements which project a spatial-temporal pattern sequence onto the scene. The sequence is displayed at a pattern update rate beyond visual flicker recognition. Devices with a photodetector within the illumination area monitor the time sequence signal, uniquely defining their position within the scene. An uplink from the device to the pattern generator is not needed and the geometry of the array can be adapted to the geometry of the room. Based on this system, positioning within a time of less than 10 ms can be achieved using a single photodiode as receiver and computationally undemanding decoding.

One possible application of this positioning system is the provision of multiple-access in a multi-user Light-Fidelity (Li-Fi) system [15]–[19]. Here we demonstrate how the position information can be used to supply individual data streams to 16 connected devices with an aggregate data rate in excess of 1 Gb/s using on-off keying (OOK). This implementation of space-division multiple access provides a high overall data rate because the individual connected devices are not required to

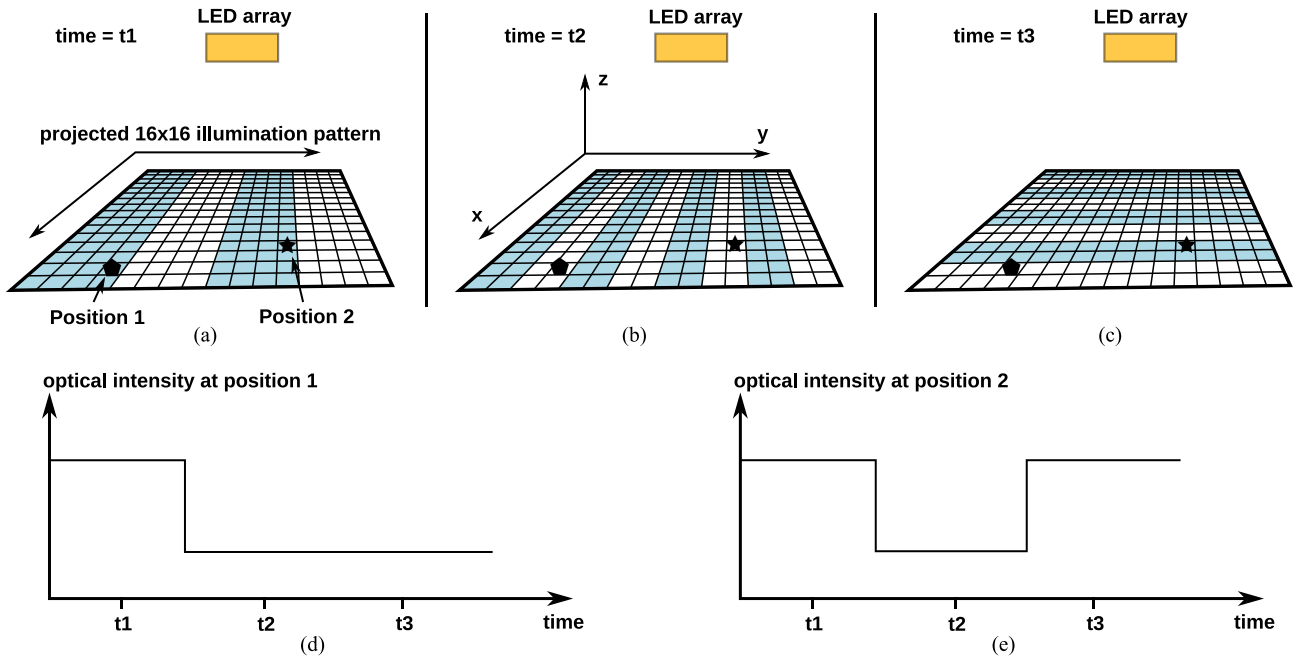


Fig. 1. Schematic of the positioning system. (a)–(c) illustrate three different times t_1 , t_2 , t_3 . At each of these times, a different illumination pattern is projected by the LED array, where the blue and white checkerboard squares correspond to grid sites with binary high or low optical intensity. Two exemplary positions within the projection area are indicated by a pentagon and a star. The time-sequence fingerprints corresponding to these two sites are shown in (d) and (e).

share transmitter bandwidth, and it also enhances security as the individual connections are highly directional and therefore less prone to interception.

The applications of this work are not limited to smart lighting. For example, the same approach can potentially be used in microscopy for automated location of a bright (e.g. fluorescent) object within the field of view.

II. POSITIONING WITH STRUCTURED ILLUMINATION

A. Local Fingerprinting With a Projected LED Array

A system has been developed to follow the schematic of Fig. 1. The light source comprises an $n \times m$ LED array and optics which project the array output onto the scene. Thus, any device equipped with a photodetector detects the emission of one corresponding pixel (“checkerboard square”) within the array. In the simplest case, positioning can now be achieved by raster-scanning through the array, i.e. one pixel is switched on at a time. Therefore, a device that is synchronized to the transmitter clock can identify from which pixel it receives a signal and thus knows its position.

A more practical implementation employs a sequence of suitable binary $n \times m$ patterns rather than raster scanning. For example, the Hadamard basis, which has been used for image compression and single pixel cameras [20], has the benefit that each pattern has half of the pixels switched on instead of a single pixel. This provides a higher illumination level suitable for lighting. Receiving devices record the intensity they receive from each pattern and can subsequently determine their position using a decoding algorithm. Since the position signal provided by the Hadamard basis is over-determined, we are able to use a subset of the Hadamard basis consisting of $k = 2 \log_2(N)$

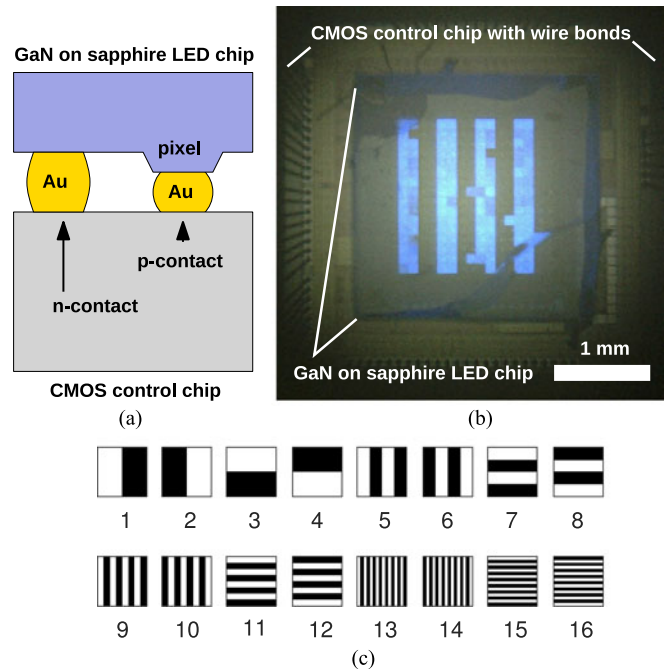


Fig. 2. The 16×16 micro-LED array with integrated CMOS control that was used for this work: (a) cross-sectional schematic of the integration of LED chip and CMOS chip, (b) plan view micrograph of the device displaying pattern number 9 of the pattern sequence, and (c) the 16 patterns used for positioning.

illumination patterns where N is the number of LED elements. In the case of a 16×16 array, as is used here to demonstrate the principle, we can therefore use a set of 16 patterns where all pixels have the same duty cycle of 50% and half of the pixels are switched on in each pattern. These 16 patterns are shown in Fig. 2(c) and the details of their properties are discussed below

in Section II-B. Note that the LED elements do not need to be arranged in a square or rectangular fashion but can be arranged in any suitable geometry.

Since the pattern sequence as well as an embedded clock signal for synchronization can be implemented in the transmission protocol, no uplink from the device to the structured illumination ceiling light is required. The scheme can be supplemented by technologies currently being developed for Li-Fi. For example, a fast modulation on top of the pattern sequence can enhance robustness to ambient light and compatibility with dimming. The knowledge of the device position can be exploited to provide individual data streams to devices in a multi-user Li-Fi environment.

B. Position Encoding in Spatio-Temporal Illumination Pattern Sequences

In our demonstrator system, the 16×16 spatial locations can be uniquely identified by an 8-bit fingerprint. If we transmit these 8 bits using Manchester encoding, a total of 16 on/off states will be transmitted. The 16 illumination patterns shown in Fig. 2(c) are chosen such that each spatial site is assigned a unique Manchester-encoded 8-bit sequence. The computational complexity in this setup is thus reduced to retrieving these 8 bits from the received optical signal.

Generalisation to arbitrary array sizes is done by first considering an $n \times m$ array where n and m are powers of 2. Then each spatial site can be uniquely identified by a fingerprint of $\log_2 n + \log_2 m$ bits, which is transmitted in a Manchester-encoded on/off sequence of the corresponding LED element. The assignment of location words to the spatial sites is in principal arbitrary and in our demonstration was chosen such that stripe-patterns were generated that are at the same time a subset of the $n \times m$ Hadamard basis. This way, the spatial patterns are orthogonal to each other, which is a convenient choice if a remote monitoring or tracking functionality based on single-pixel imaging [20] is added to the system. Manchester encoding maintains the same duty cycle for each LED and thus provides an even illumination level across the scene. Other array dimensions and non-rectangular configurations can also be addressed by assigning location fingerprints of sufficient length to the spatial sites. Synchronization with the transmitter clock is achieved by adding two illumination patterns as a start/stop bit where all LEDs are first turned off and then on.

It is possible to choose fingerprints longer than $\log_2 n + \log_2 m$ bits, for example in order to improve the signal to noise ratio (SNR) and error tolerance [14]. All of these sequences have in common that they encode the position information in a unique on-off sequence seen by the receiver, thus eliminating the computational effort needed by methods based on triangulation, time of arrival, or probabilistic approaches.

III. TRANSMITTER

We use a 16×16 array of $100 \times 100 \mu\text{m}^2$ GaN LED pixels (98% area fill factor) emitting at 450 nm. The LED array was bump-bonded to a custom-designed complementary metal oxide semiconductor (CMOS) driver chip enabling fully individual

control of bright pixels in a compact format [21]–[26]. A schematic and an optical micrograph of the device are shown in Fig. 2. A few defects are visible which can be short circuit (no occurrence on the particular device used here), open circuit (4 occurrences) or where neighboring pixels can be inadvertently interconnected (28 pixels affected). The number of defects in this prototype device can be reduced by optimizing the manufacturing process. For positioning, it is not required to use such a CMOS-integrated device but it has several advantages such as small footprint, simple projection and digital electronic interface.

The individual pixels in these devices respond with a full on-off modulation bandwidth of up to 110 MHz [24]. The pattern update rate is 2 kfps limited by a serial data link in the current electronic implementation. Future devices may be able to operate at Mfps frame rates. The 16×16 CMOS-controlled array has 16 individual data inputs which modulate the columns of the array. Note that these devices are designed for OOK and are capable of a maximal data rate of about 500 Mb/s for a single pixel [24]. However, when applying more sophisticated encoding schemes to LEDs of similar dimensions, data rates of several Gb/s from a single micro-LED have been demonstrated [27].

The logic inputs to the CMOS control chip were supplied through a field-programmable gate array (FPGA) operating at up to 150 MHz and the electrical power was supplied through a universal serial bus (USB) connection. This way, the entire device is driven through a single USB cable, which is a more practical implementation than our earlier work where the logic inputs were directly connected to high-speed bit error rate (BER) test equipment, voltages higher than the 5 V available from USB were applied and only few pixels were operated in parallel [24], [28], [29].

Fig. 3(a)–(d) show the current lab-scale implementation of the system. An aspherical lens with 8 mm focal length and a numerical aperture of 0.5 was used to project the patterns onto a plane at 40 cm distance, providing a scene illuminated area of $8 \times 8 \text{ cm}^2$. As indicated Fig. 3(a), photodetectors were placed arbitrarily within the scene. The operation is insensitive to the orientation of the photodiodes as long as the line-of-sight signal is incident within the field-of-view of the bare photodiode chip. Optics could be used to tailor the field of view if desired. Multipath propagation would lead to an increase of the background noise, i.e. reduction of the SNR. Due to the large depth of focus of the projection optics in this setup, positioning was observed to be insensitive to vertical displacements of the photodetectors out of the projection plane.

We have also verified experimentally that positioning can be achieved by the same system if retro-reflective elements are placed in the scene and the back-reflected optical signal is monitored by a remote photodetector which is placed next to the transmitter.

IV. DEMONSTRATION OF REAL-TIME POSITIONING

The optical position signal is received by DC-coupled Si-photodiodes with 1 MHz bandwidth. DC-coupling was chosen to facilitate the development of the prototype system, but as

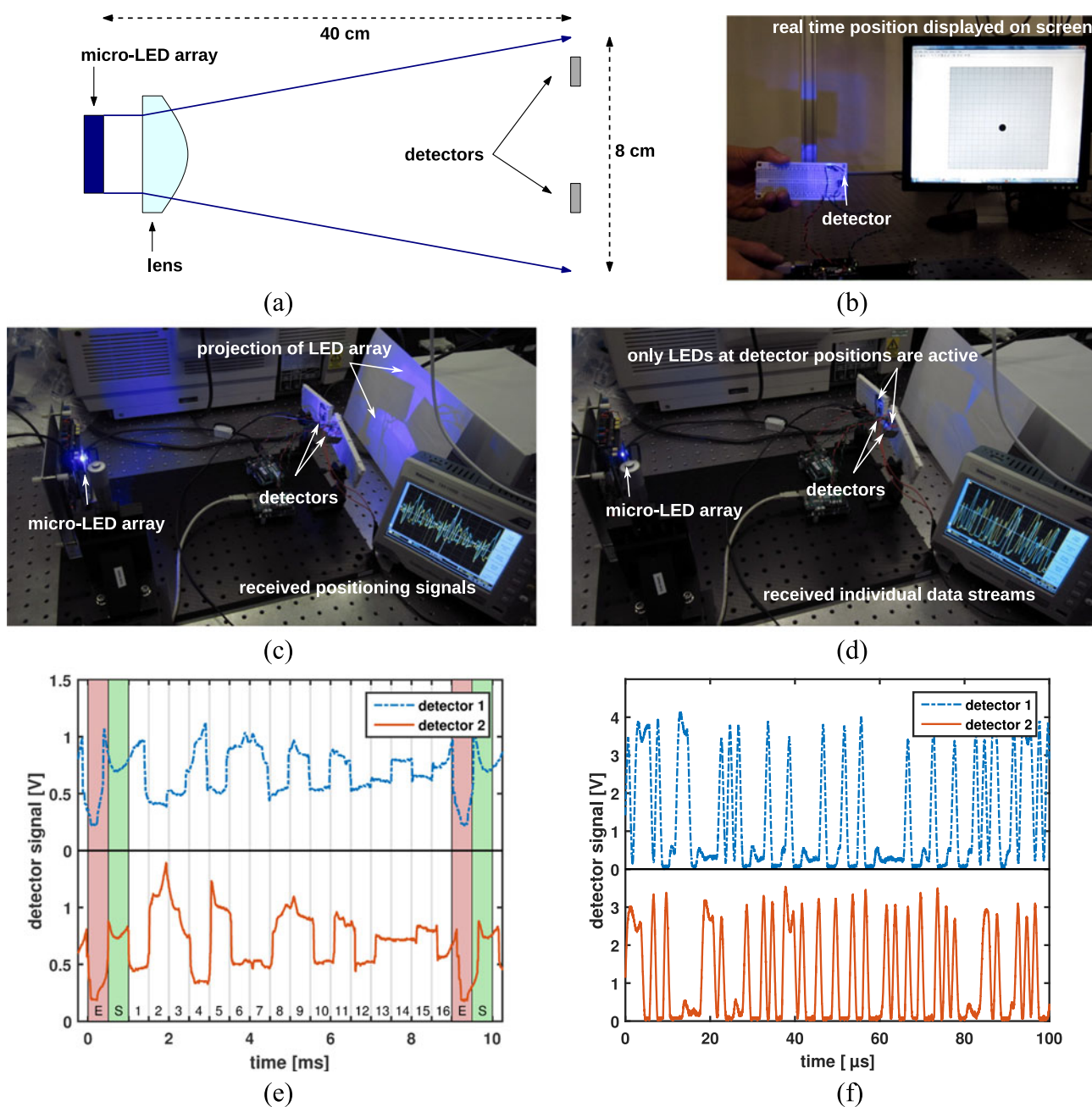


Fig. 3. Demonstration of positioning of detectors and subsequent individual data streaming: (a) Schematic of the setup. (b) Video-still from a real-time positioning demonstration at 333 fps. Photographs of (c) positioning at 2 kfps and (d) individual data streams sent to each detector at 1 Mb/s/channel. (e) Individual optical signals recorded in the positioning mode, corresponding to (c). The start bit interval is highlighted in green and marked with “S”, the stop bit interval is highlighted in red and marked with “E”, and the time intervals of the 16 patterns shown in Fig. 2(c) are indicated. The detector positions are $x_1 = 4.5$ cm, $y_1 = 5$ cm for detector 1 and $x_2 = 2$ cm, $y_2 = 3$ cm for detector 2. (f) Individual optical signals recorded in the data transmission mode corresponding to (d).

in other Li-Fi implementations AC-coupled detection can be used in order to make the system robust against low-frequency ambient noise. Fig. 3(b)–(d) show photographs of the system during operation and a video showing the system in operation can be found at [1]. The pattern sequence is displayed at a frame rate of up to 2 kfps. Above 1 kfps, no visual flicker was observed. We employ a pattern sequence consisting of 16 patterns plus a start bit (all LEDs on) and a stop bit (all LEDs off). Hence, position information is obtained within 9 ms as shown in Fig. 3(e).

Positioning at 2 kfps is demonstrated by sampling the photodiode signal with an oscilloscope and subsequent off-line decoding as shown in Fig. 3(c). Representative received optical signals are shown in Fig. 3(e). Real-time positioning was implemented by sampling and processing the photodiode signal with an Arduino Uno board. In this case, the synchronization with the embedded optical clock signal and position decoding are done on-line by the micro-processor. Real-time positioning is demonstrated in the video available at [1]. A video-still from this video is shown in Fig. 3(b). This demonstration is done at

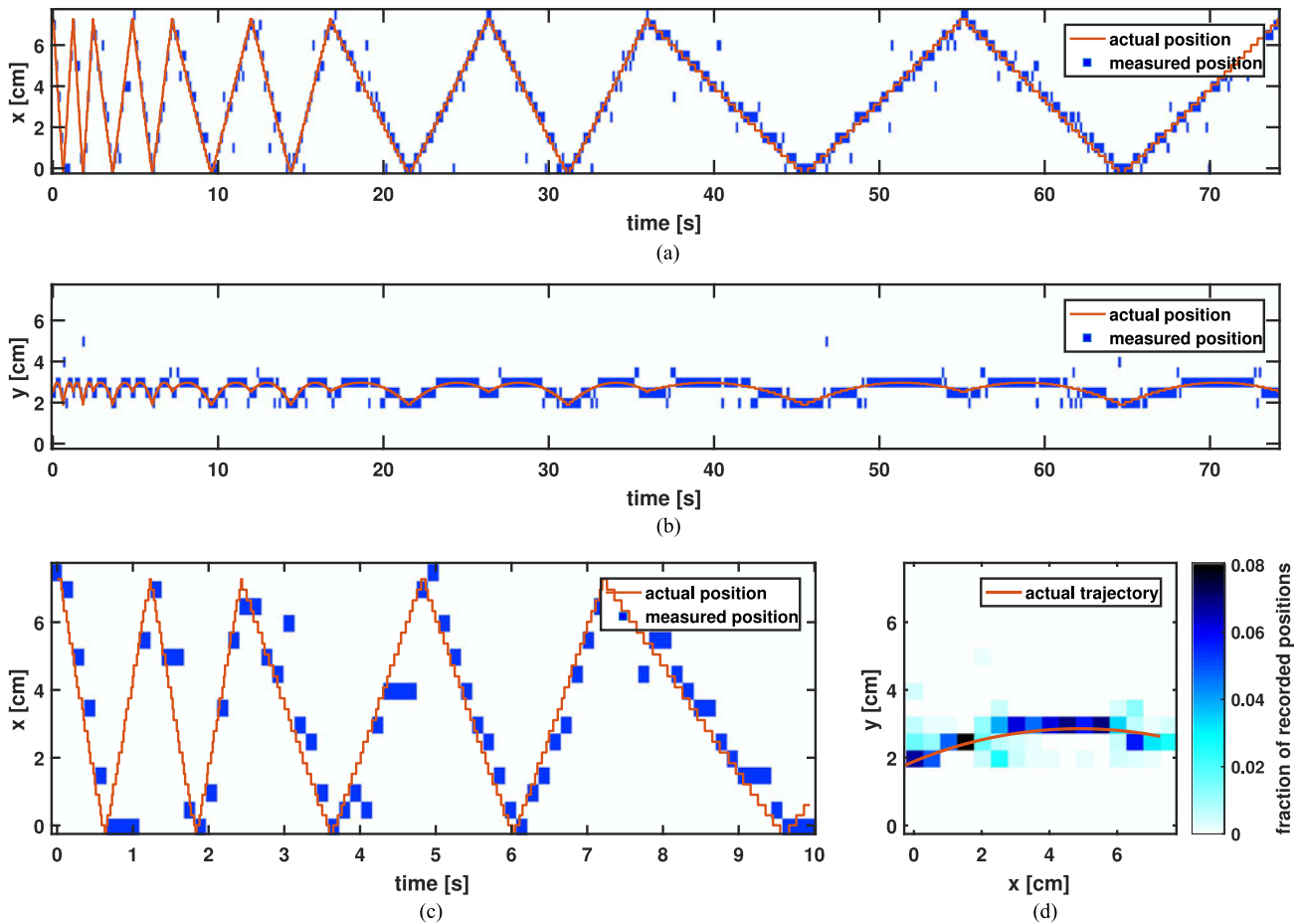


Fig. 4. Trajectory of a photodiode moved back and forth along a circular arc as shown in Fig. 5: (a) recorded x -coordinate and (b) recorded y -coordinate of the photodiode as a function of time. The solid line represents the position according the input signals to the motor. (c) Detail of (a). (d) Trajectory in the $x - y$ -plane. The solid red line shows the arc taken by the detector and the color coding indicates how often a given position was recorded by the positioning system during the experiment.

a frame rate of 333 fps, limited by the sampling capability of the Arduino board with 5-value median filtering. The processing capability of the Arduino chip was not limiting because the decoding algorithm is computationally cheap. Note that this prototype was operated under typical laboratory ambient lighting conditions.

Fig. 4 shows the real-time traced position of a photodiode that was moved back and forth along a circular arc of 43.2° and 103 mm radius by a stepper motor with 1.8° step angle. A schematic of this configuration is shown in Fig. 5. The position data was recorded by the Arduino board with a position update rate of 6.7 Hz, limited by the pattern rate of 333 fps and the overhead needed for the synchronization with the embedded optical clock signal. As can be seen in Fig. 4(c), position information is still obtained at motion speeds where more than one pixel is crossed during the time taken for one position update. A slight lag of about 100 ms is visible which is due to the number of transmitted symbols that need to be received for clock synchronization and location estimation. This means that an increase of the pattern rate will reduce this lag. No measures for error detection were taken and the position accuracy was 8.2 mm RMS, corresponding to 1.64 pixels. In Fig. 4 several spurious location estimates can be seen. 10% of the position readings deviated

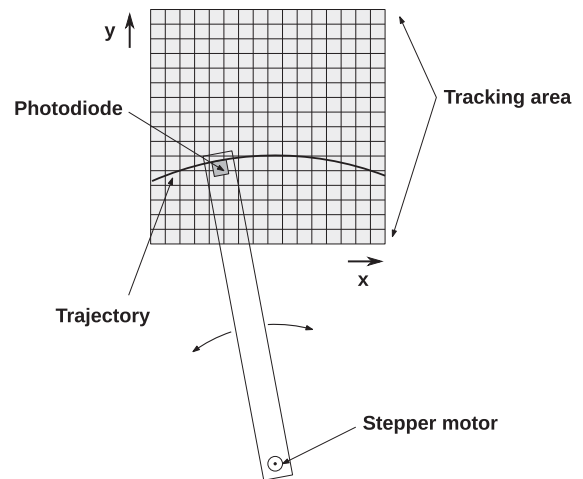


Fig. 5. Schematic of the setup used to demonstrate real-time tracking. The data recorded by this setup is shown in Fig. 4.

from the correct position by more than 10 mm (2 pixels). These erroneous readings are attributed to the operational defects in this demonstrator array mentioned above in Section III.

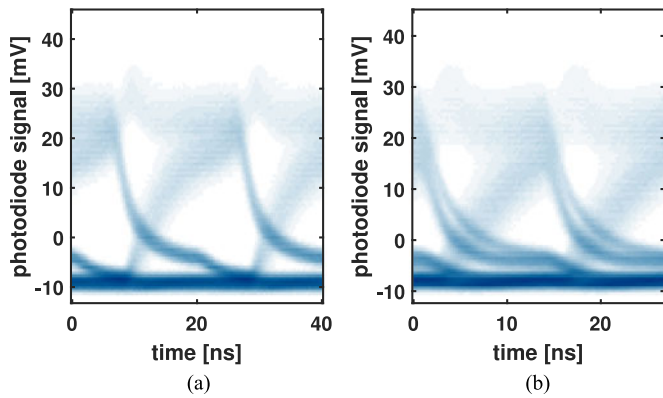


Fig. 6. Representative eye diagrams of one of 16 data channels operated in parallel at (a) 50 Mb/s/channel and (b) 75 Mb/s/channel.

V. APPLICATION TO MULTIPLE ACCESS IN A MULTI-USER LI-FI ENVIRONMENT

A multi-functional demonstration was designed to illustrate the spatial recognition of two separate detectors and subsequent individual data transmission to these detectors from a single arrayed LED source. For individual data transmission, two LEDs corresponding to the locations of the two detectors (and thus imaged to the detector) were switched on. Each of these two LEDs was modulated with an individual data signal at 1 Mb/s, limited by the bandwidth of the detector. This mode of operation is shown in Fig. 3(d) and the video at [1]. Representative received optical signals are shown in Fig. 3(f).

The data transmission rates of the individual data channels were assessed with an AC-coupled fast photodiode with 1.4 GHz bandwidth connected to an oscilloscope with 1 GHz bandwidth. In this case, 16 LEDs of the array were switched on, each carrying an individual data signal. The transmitted data streams consisted of 16384 bits per channel, which is limited by the memory available on the FPGA. The first 84 bits of these streams were set to a fixed sequence of 83 zeros and 1 one in order to provide a trigger signal for the detector. The remaining 16300 bits were filled with a pseudo-random bit sequence, where the sequences of the 16 different channels were uncorrelated with each other. Hence, the setup is useful for measuring a BER above 6.14×10^{-5} .

At 50 Mb/s per channel (800 Mb/s aggregate data rate), not a single bit error occurred and at 75 Mb/s/channel (1.2 Gb/s) the BER was 3.5×10^{-5} . In both cases, the measured BER is below the detection limit of 6.14×10^{-5} . At 85 Mb/s/channel (1.36 Gb/s) the BER was 8.7×10^{-4} and at higher data rates the BER exceeded 10^{-3} . Representative eye diagrams of one channel are shown in Fig. 6. Note that the off-state appears much more clearly defined than the on-state. This is because of the electrical cross-talk through the shared n-contact that affects pixels being switched on at the same time but does not affect pixels that are switched off [26].

By regular switching between positioning and data transmission mode, a single transmitter device can provide reconfigurable individual connections to moving network nodes in the area.

VI. CONCLUSION AND OUTLOOK

Lighting by smart arrays of LEDs with integrated CMOS control enables self-positioning of devices in the illuminated area within 10 ms. This is possible by structured illumination with a suitable spatial illumination pattern sequence. In principle, future implementations should allow positioning within less than $10 \mu\text{s}$ if the control electronics are specifically engineered to harness the MHz bandwidth of the LEDs. The accuracy and area coverage are scalable via the number of emitters and the projection optics used. Here, we demonstrated a precision of 5 mm over a distance of 40 cm, though in principle the projection of the array can be demagnified to microscopic dimensions or extended to cover areas of several meters across. There is scope to achieve a resolution better than the sampling grid by defocused projection and development of a suitable decoding algorithm using spatial interpolation, though this requires orthogonal modulation of the LEDs and increases the complexity at the receiver end [10].

The potential applications of this technology are wide-ranging. As an example, we have demonstrated wireless optical space-division multiple access to 16 connected users at an aggregate data rate of 1.2 Gb/s with a BER of less than 10^{-4} . The capability of doing so with a single-chip transmitter is an intrinsic property of the positioning method presented here. Again, improvement by dedicated engineering is possible. The underlying technology has been shown earlier to provide high optical power [26] which is required for projection over a few meters in this type of application.

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