In-building Optical Wireless Positioning Using Time of Flight

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Abstract: We present a LiFi positioning and communication system based on the ITU-T G.9991 standard. Accuracies as low as 3 cm in x,y,z direction have been achieved, utilizing an optimization approach for the LED behavior.

1. Introduction

In the future of industrial IoT applications, communications with higher rates, lower latency and more reliable connections are fundamental requirements [1,2]. In addition, indoor positioning with centimeter accuracy is also a key feature for future smart manufacturing, which can facilitate more new applications like real-time positioning systems in industry to allow the tracking of Automated Guided Vehicles [3,4]. LiFi (Light Fidelity) is an optical wireless communication system for high throughput high-density networks [5], which ideally addresses the accuracy requirements for indoor positioning. The unique properties of light avoid the common multipath and shadowing challenges for radio-based indoor positioning techniques [6], and allow cm accuracy. So far, different approaches based on Received Signal Strength (RSS), Angle of Arrival (AOA) or Time Difference of Arrival (TDOA) have been demonstrated [7]. An important aspect of LiFi is the simple integration of positioning and communication into the same system, which enables a wide range of applications and cost-effective installation and operation. In our previous papers [8,9], such a LiFi systems has been demonstrated based on the ITU-T G.9991 standard for optical wireless communications. The positioning algorithm estimates the time-off flight between LiFi frontends, utilizing the framing and channel estimation from ITU-T G.9991. Feasibility and positioning accuracy were verified through experiments in the laboratory and in a conference room scenario.

In this paper, we demonstrate the LiFi positioning system in a real factory environment and introduce an optimization approach to address the observed angle dependency of the optical frontends.

2. Architecture and System Concept

The digital signal processing and position algorithm of our system is shown in Fig. 1(a). Based on the ITU-T G.9991 standard, an OFDM signal (100 MHz bandwidth) with trainings and synchronization sequences is generated and evaluated. The positioning is based on a time of flight estimation from the mobile unit (Rx) to each ceiling unit (Tx). The actual 3-D position of the Rx unit is then calculated by combing the known Tx positions with the ranging information. The TOF is calculated by combining a course and fine time measurement using the OFDM. A detailed description can be found in [9]. Fig. 1(b) shows the measurement setup in the factory hall, with the red dots indicating the evaluation points for positioning. The LiFi cell is set up, with six ceiling units (Txs), placed in a rectangular plane with 1.5 m distance and covering 4.5 m^2. Initial transmission experiments with the system have shown date rates of up to 500 Mbit/s inside the LiFi cell.

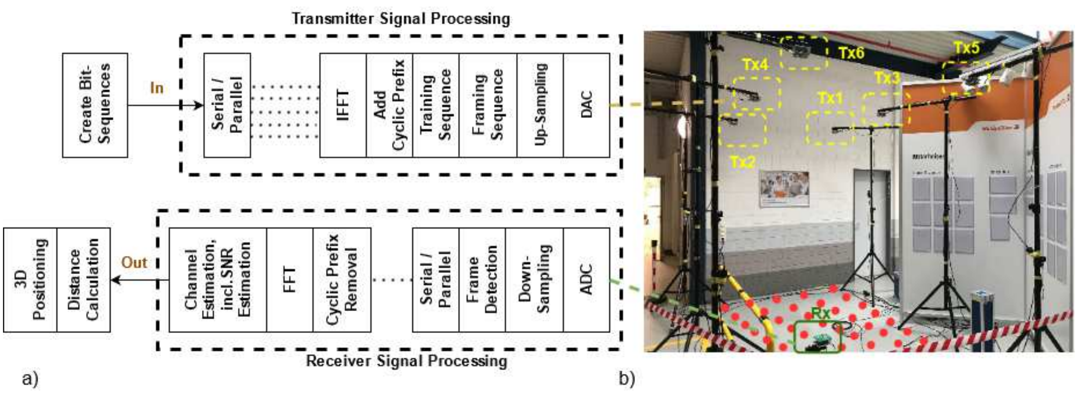

Fig. 1: a) Block diagram of OFDM transmitter and receiver for proposed LiFi positioning system. b) measurement setup in the factory hall. Red dots indicate evaluation points.

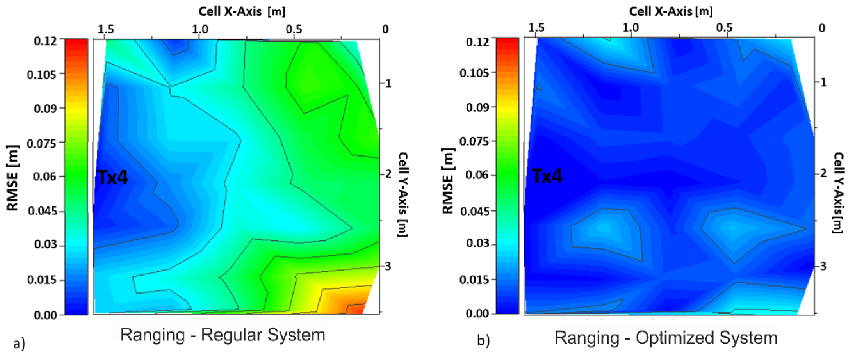

Fig. 2 RMSE ranging error of Tx4 for a) regular measurement and b) with optimization approach.

The six Txs consists of a custom-designed LED driver and the off-the-shelf LEDs. Each Tx is driven by a separate channel of a digital-to-analog converter (DAC) at 625 MS/s. The signals of all Tx are received and superimposed on the Rx, which consists of five large-area silicon photo-diodes with 150 mm^2 photosensitive area each and a custom designed transimpedance amplifier. The signal is then connected to a ADC and sampled at 500 MS/s. Furthermore, an initial calibration is performed to compensate the inherent delays from cables, devices and optical frontends and one additional electrical channel between the DAC and ADC is used as a reference signal, to allow time synchronization between the Txs and Rx.

3. Results and Optimization Approach

In Fig. 2 a) the heatmap of the ranging root mean square error (RMSE) is exemplarily shown for Tx4. The RMSE distribution shows lower values close to Tx4 and increasing values towards the corners, due to the poorer signal-to-noise (SNR) conditions at higher distances. For all Txs the average ranging RMSE is between 2.6 and 6.8 cm as can be seen in the first line of Table 1. The 3D positon can be calculated from the ranging information and the known positions of the ceiling units. In Fig. 3 (a-c) the corresponding X,Y, Z RMSE heatmaps are shown. The X direction shows higher errors in the middle of the cell, while Y and Z show higher errors in the top left corner. The small areas with very high errors (>15 cm) can be attributed to poor SNR conditions at these points. The overall RMSEs for X,Y and Z direction are 7 cm, 6 cm and 3 cm, respectively.

In order to estimate the location of the Rx more accurately, the relation of the ranging error and the LED propagation angle is investigated. As mentioned in our previous work [8,9], a higher tilted angle between Tx and Rx showed a linear increasing error, instead of just an increased variation around zero, regardless of the SNR and distance conditions. The reason behind this behavior can probably be traced back to the propagation properties of the LED, but needs further investigation. The linear behavior of the error can be used for an optimization approach by introducing a correction factor, if an initial coarse angle estimation is available. The correction factor can be calculated separately for each Tx, with the help of an initial calibration measurement. The positioning measurement is then implemented as follows: First, the usual ranging is performed to each visible Tx, followed by a rough 3-D estimation of the Rx. Second, the angle between Tx and Rx is calculated from the initial 3-D estimation and the correction factor is applied on the initial ranging information. This in turn provides a corrected ranging information and further a corrected 3-D position.

In the Fig. 4 (b) the heatmap of the ranging RMSE with optimization is exemplarily shown for Tx4. There are two interesting observation to be made. First, the overall RMSE is clearly decreased and second, the high RMSEs especially at the corners could be reduced drastically. The results for all Tx are summarized in Table 1, with a clear improvement of about 50% for Tx2,4,5,6 and of about 15% for Tx1,3. Overall, the average ranging RMSE for all Tx are now between 1.1 and 4.2 cm. Using the optimized ranging estimation, the 3-D position can be calculated and compared to the actual value.

Table 1: Ranging RMSE with and without optimization

Ranging RMSE (m)	Tx1	Tx2	Tx3	Tx4	Tx5	Tx6
Regular	0.042	0.068	0.029	0.041	0.044	0.026
Optimization	0.038	0.042	0.022	0.011	0.02	0.014

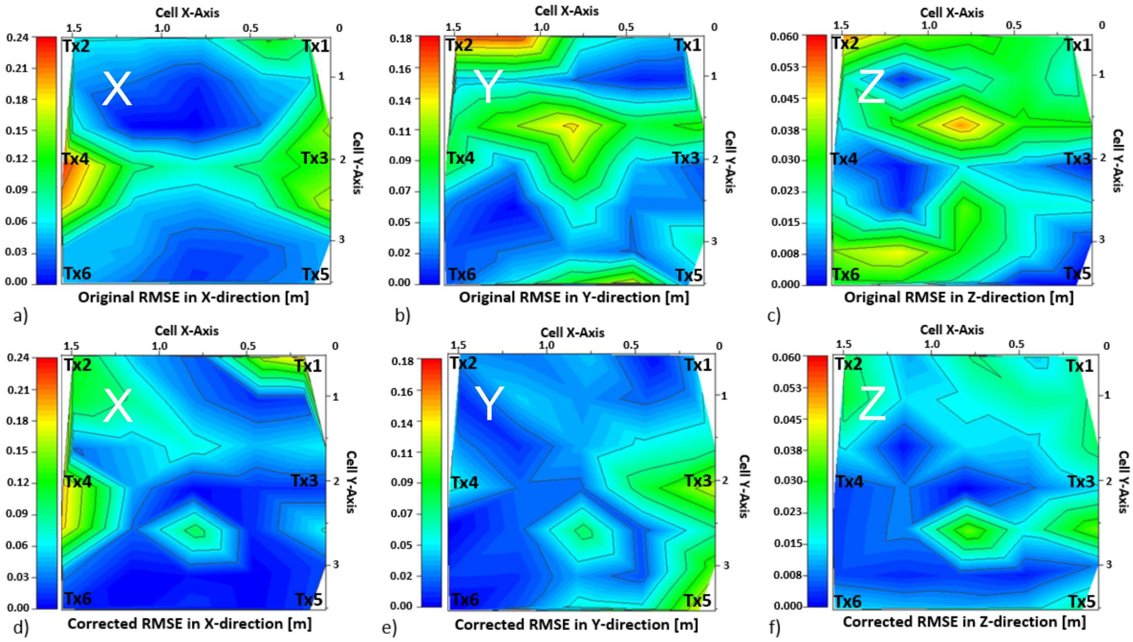

Fig. 3(a-c) a) X,Y and Z direction RMSE for (a-c) regular measurement and (d-f) with optimization approach.

The RMSEs of the optimized position information for X,Y and Z-direction are shown in Fig. 3 (d-f). It can be seen that the areas with higher RMSEs, i.e., green, yellow and red, are significantly smaller after optimization. Furthermore, the areas with very high errors, e.g., in the top left corner for Y and Z and the middle left area for X direction, could be minimized as well. The actual RMSE values for the X,Y and Z-directions and the total RMSE are summarized in Table 2. The RMSE for each direction could be reduced by about 2 cm, down to 5, 4 and 1 cm in X,Y and Z-direction, respectively. The mean RMSE over all three direction could be reduced from 5.3 down to 3.3 cm.

Table 2: X,Y and Z RMSE with and without optimization

X,Y,Z RMSE (m)	X	Y	Z	Total RMSE
Regular	0.07	0.06	0.03	0.053
Optimization	0.05	0.04	0.01	0.033

4. Conclusion

In this paper, we present a LiFi based positioning and communication system in real factory environment. The system allow data rates up to 500 Mbit/s and positioning accuracies of about 7, 6 and 3 cm in X, Y and Z-direction, respectively. An optimization approach is introduced to address the LED propagation behavior at different angles. For the 3-D information, the accuracy could be improved to about 5, 4 and 1 cm for X, Y and Z-direction, respectively, and the overall RMSE of the position information is reduced to from 5.3 to 3.3 cm. The discussed LiFi positioning approach is be implemented using the existing LiFi standards ITU-T G.9991 for communication and can be considered as a potentially valuable tool with great promise for smart factories.

5. References

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