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Abstract. Light-Fidelity (Li-Fi) is a wireless communication technology, which uses light as the medium of communication. In this paper, we discuss Li-Fi as a communication strategy for building dynamic factory layouts. Advantages of Li-Fi are the low energy consumption, the straightforward implementation, the cost-efficient maintenance and the easy identification of factory layouts. This paper focuses on designing a customized Li-Fi transceiver, which provides point-to-point and full-duplex communication within an Industry 4.0 learning factory. Furthermore, we propose a conceptual model for the adaption of Li-Fi communication in distributed factory planning applications. Finally, we describe the prototypical implementation of the proposed conceptual model. The primary scientific contribution of this paper is to present the reliability of a custom-designed four-way Li-Fi transceiver inside an industry 4.0 learning laboratory.

Keywords: Li-Fi (Light-Fidelity) transceivers. · Industry 4.0 learning laboratory. · full-duplex communication. · dynamic factory layouts. · factory planning applications.

1 Introduction

In recent times, the majority of production processes takes place in static factory layouts. However, the usage of modular structures to quickly change factory layouts promises a significant improvement in terms of flexibility compared to static factory layouts.

Wireless communication technology is one of the critical factors for designing modular and distributed structures inside a factory. On the other hand, radio frequency (RF) technology is mostly used for setting up modular factory structures among many existing communication technologies. Nevertheless, RF has several limitations, including interference, high latency, spectrum deficiency and factory layout identification.

Currently, we are developing an Industry 4.0 Learning Laboratory to demonstrate the state of the art concepts and technological advances. In addition, one

of the considered research fields is to build stand-alone factory modules with wireless communication capabilities.

Our previous work illustrates the importance of Li-Fi communication and proposes a concept for an industry 4.0 learning laboratory [14]. The authors propose the application of Light-Fidelity (Li-Fi) due to its benefits such as high bandwidth, speed, immune to interference from electromagnetic sources and Line of Sight (LOS) communication. The main goal of this paper is to implement a Li-Fi communication protocol and design a Li-Fi transceiver for the distributed factory modules. Meanwhile, we need to address the following research questions:

1. What is the need for a Li-Fi transceiver to build stand-alone factory modules?
2. How to adapt the Li-Fi communication protocol for building dynamic factory layouts in the industry 4.0 learning laboratory?
3. What is the reliability of Li-Fi communication in an industry 4.0 learning laboratory?

Furthermore, the research questions are addressed by integrating the four-way Li-Fi transceivers into the stand-alone laboratory modules. In particular, the paper describes the software implementation of a Li-Fi protocol, the hardware design of a Li-Fi transceiver, and investigating the protocol's reliability.

The structure of this paper is organized into five sections. Section 2 summarizes the related work in Li-Fi communication and our concept for an Industry 4.0 learning laboratory. Section 3 illustrates the software and hardware implementation of Li-Fi communication. Section 4 presents our experiments and results. Section 5 is dedicated to the conclusions and outlook.

2   Related Work

This section describes our work on an Industry 4.0 learning laboratory and presents the results of a literature study on Li-Fi communication.

2.1   Industry 4.0 Learning Laboratory

Our Industry 4.0 learning laboratory is an updated version from an older model factory with a static layout to educate the students in analyzing and planning production and logistics processes [6]. Further research was carried out regarding modulizing the factory, extending the flexibility to design and implement dynamic system structures. Hofmann et al. implemented a factory system structure in a virtual commissioning tool before its physical implementation [6]. Lang et al. introduced modular plug-and-play conveying systems for distributed factory structures. Currently, each factory module in the laboratory is equipped with an RFID reader-writer, controlled by an Arduino-Mega 2560 single-board micro-controller with RS 485 communication [10]. Later on, the research extends towards stand-alone modules with the integration of Li-Fi communication.

2.2   Literature Study on Li-Fi Communication

Li-Fi is a high speed bi-directional, fully connected, visible-light wireless communication system and is complementary to Wi-Fi, which uses radiofrequency for communication. A speed up to 10 Gbps can be obtained using Li-Fi, which is 250 times more than that of a super-fast broadband [8]. The visible light spectrum and the IR spectrum are unregulated and provide 780 THz of bandwidth. The visible light spectrum ranges from 380 to 780 nm in wavelength [4]. In IEEE 802.15.7 standards, there is a definition of a physical and MAC layer for short-range wireless communication using visible light as the communication medium [16]. Li-Fi's two main benefits are the high data transmission rate and the high level of data transmission security [7]. In Li-Fi, the receivers must be positioned in specific locations like the transmitters can have a line of sight. Kim et al. [9] propose a scheme for device management and data transport in IoT networks using Visible Light Communication (VLC). The authors use the unidirectional transmission to send the location-based VLC data. From the VLC receiver, the data is forwarded to aggregation agents and a central server in the network. Mariappan et al. [11] proposed a concept of "Internet of Light"(IoL) and Integrating IoT agent on IoL gateway to create a heterogeneity gateway for IoT devices. Recently, Zhang et al. [17] introduced an indoor positioning system based on VLC, with asynchronous transmitters. Chowdhury et al. present an overview of industrial communications using VLC technologies such as device-to-device (D2D), machine- to-machine (M2M), chip-to-chip, device/machine-to-user, user-to-device/machine [3]. Schmid et al. [15] propose the concept of Light Emitting Diode (LED) as a photodetector to receive optical messages using the same LED that is used for transmission, which reduces the complexity of the device. The achievable data rates in Li-Fi are in the ascending order of phosphorous coated LED, red, green and blue (RGB) LEDs, Gallium Nitride (GaN) micro LEDs and laser-based lighting [4].

2.3   Conceptual Model

Fig. 1 illustrates the conceptual model with various laboratory modules. Each block in the figure represents a stand-alone module equipped with the Li-Fi transceiver. The conceptual model considers a master-slave architecture. Initially, we test the working of Li-Fi transceivers with the layout as shown in Fig. 1.

The RFID reader detects the destination information from slave one and forwards it to the master node. The master node processes the information, communicates with slave one and forwards the information through different slaves to the destination. Once the product reaches the destination, then the slave sends an acknowledgement to the master node.
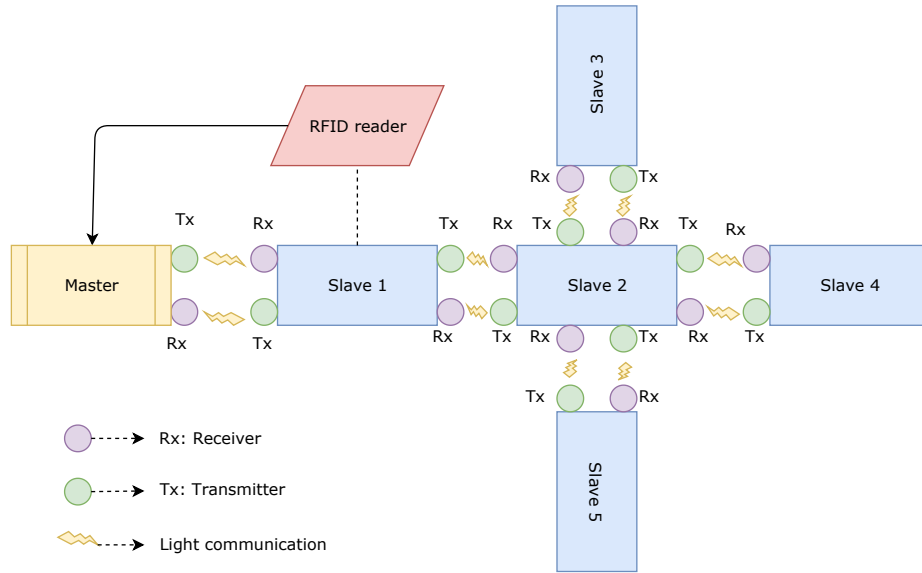
Fig. 1. Conceptual Model

3   Implementation

3.1   Software Implementation of Li-Fi Protocol

We choose RIOT-OS for developing the Li-Fi protocol and control logic of various laboratory modules. In addition, RIOT-OS provides a variety of functions for implementing the Li-Fi protocol. The operating system provides the multithreading functionality for designing the four-way transceivers for each factory module [1, 2, 5, 12]. During the implementation of the protocol, we used the frame
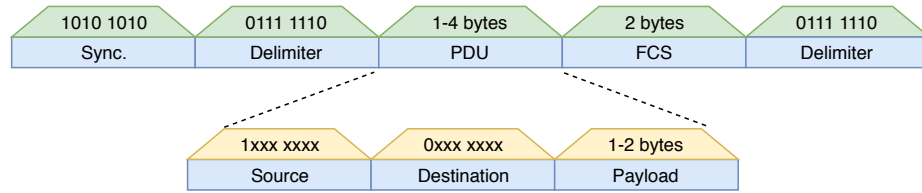

Fig. 2. Frame Format of Li-Fi Communication Protocol

format as shown in Fig. 2 is derived from the High-Level Data Link Control (HDLC) protocol as discussed [13]. Manchester encoding technique used for clock recovery during communication. On–off keying (OOK) modulation scheme provides a simple solution for data transmission using Light-emitting Diode (LED)

and Light Dependent Resistor (LDR). The Cyclic Redundancy Check (CRC) is chosen for error detection in the frame. Here we have used CRC-16-CCITT standard. Each module in the factory has to communicate with the neighbouring nodes. So, a single node requires more than one transceiver interface. The full-duplex multiple transceiver interfaces are realised and accessed simultaneously using multi-threading functionality. The laboratory consists of many modules which indeed required multi-hop communication. We implemented flooding as a routing algorithm which requires limited resources in terms of Random Access Memory(RAM) and Read Only Memory (ROM). Every node can transmit and receive data from neighbouring nodes. Therefore, we have used the flooding algorithm for transmitting data to destination with intermediate nodes. Every node which receives data can re-transmit the data through other transceivers except the transceiver which received data. Each module in the factory encoded with a unique device ID can be used as the layer two address for identifying the modules. The neighbouring module identification can be achieved with the point to point communication.

Li-Fi Transceiver functions

The functions shown in Fig. 3 are used to design the Li-Fi transceiver. The main transmission and reception functions are defined in the "LiFi class". The public function send_data() initiates the transmission. The private functions such as send_sync(), send_delimiter(), send_byte() are responsible for creating the frame of data for transmission. The encoding is carried by man_one() and man_zero(). The public function receive() is responsible for the reception of data. The private functions such as get_classifier(), sync_clock() and get_delimiter() are used for identifying incoming data. The get_bit() function is used for decoding the Manchester data. The basic idea is to implement multiple transceivers with full-duplex communication because each factory module has to send and receive data simultaneously. The decision nodes in the factory planning laboratory have four neighbouring nodes, and each node has to access all the neighbouring nodes. Each node requires four Li-Fi transceiver interfaces to access the neighbouring nodes simultaneously. The multi-threading functionality allows creating multiple and concurrent threads for transceivers. Each transceiver is assigned two threads, one for transmission and another one for reception. All threads access the same shared memory, and these threads can access based on the thread priority. Each transceiver interface performs concurrent execution of data transmission and reception. Fig. 4shows the parameters used for communication. The CLOCK cycle contains 10 TICKs and each TICK of 3 ms. In one CLOCK cycle, one bit of data is transmitted. The classifier is calibrated using the MINIMUM HIGH LOW DIFFERENCE, which is set to 50.

3.2 Hardware Design of Li-Fi Transceiver

We used Arduino-Mega 2560 as a development board because it is an inexpensive and powerful tool to interface with the sensors and supports different develop-

```
class LiFi {
// private functions
 private:
 //transmitter functions
        void man_one();//<-- sending manchester one
        void man_zero();//<--sending macherster zero
        uint8_t send_byte(uint8_t b, uint8_t ones_in_a_row);//<-- sending one uint8_t of data
        void send_sync();
        void send_delimiter(void);
//receiver functions
        int get_classifier();
        int get_level();
        int sync_clock();
        int get_delimeter();
        int get_bit();
        int get_byte(uint8_t *dest);
        int receive_frame(uint8_t *buf, uint8_t buf_size);
//public functions
public:
 //transmitter fuctions
        LiFi(int sPin, adc_t rPin);
        void send_data(const uint8_t *data, uint8_t data_len);
//receiver functions
        int receive(uint8_t *buf, uint8_t buf_size);
};
```

Fig. 3. Pseudo code of Li-Fi Transceiver

```
#define TICK 3//<-- number of milli seconds per tick (--> use for delay())
#define CLOCK_HALF 5 // <-- number of ticks per half clock
#define CLOCK (2 * CLOCK_HALF) // <-- number of ticks per clock (1 data bit)
#define GET_CLASSIFIER_TICKS (TICK * CLOCK * 3)
#define MINIMUM_HIGH_LOW_DIFFERENCE 50 // <-- used in get_classifier()
```

Fig. 4. Li-Fi Communication Protocol Parameters

ment platforms. The Arduino-Mega 2560 uses a 16 MHz crystal oscillator for the controller clock. The Arduino has analog and digital General Purpose Input and Output (GPIO) pins and an inbuilt Analog to Digital Converter (ADC). Universal Serial Bus (USB) interface used to program the Arduino board. The components required to build a Li-Fi transceiver are Arduino controller, LED as a transmitter, LDR as a receiver, two 270 ohm resistors. Fig. 5 shows the circuit schematic of a four-way Li-Fi transceiver.

4   Experiments and Results

This section describes the experiments conducted to identify maximum communication distance and the protocol's reliability with various parameters of the protocol. With the verified parameters of the protocol, integration of Li-Fi communication in Industry 4.0 learning laboratory is tested with the prototype.
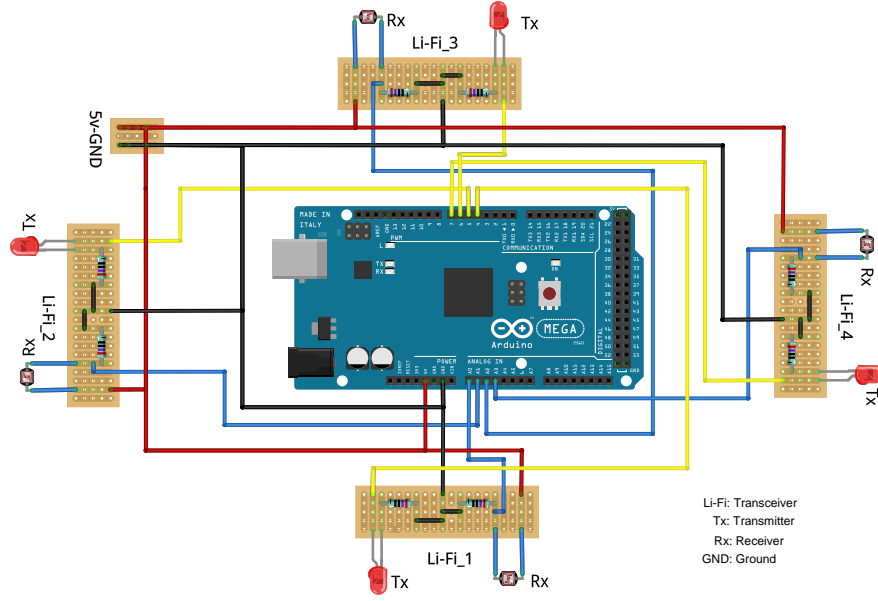
Fig. 5. Four-way Li-Fi Transceiver

4.1 Maximum Communication Distance

This experiment aims to find the maximum communication distance and identify a suitable transceiver pair with different color transmitting LED and LDR as the receiver. After a series of iterations with different color LEDs as transmitters, the obtained maximum communication distances are as illustrated in Table 1.

Table 1. Maximum Communication Distance with different color LEDs and TICK sizes

Color of LED	with 3 ms TICK	with 4 ms TICK
YELLOW	3 cm	13 cm
RED	6 cm	17 cm
GREEN	4.4 cm	23 cm
BLUE	8 cm	30 cm
WHITE	30 cm	68 cm

4.2 Reliability of Li-Fi Communication

This experiment aims to find the reliability of Li-Fi communication between two modules, based on different communication distances, payloads and with 3 ms

TICK size. The protocol's reliability is verified with a white LED as a transmitter and LDR as a receiver. The data frame shown in Fig. 2 is transmitted 100 times with different payloads and verified how many times the data is successfully received. The communication distance is varied from 5 cm to 20 cm. Table 2 illustrates the reliability of the Li-Fi communication.

Table 2. Reliability with different communication distances with 3 ms TICK size

Payload	5 cm	10 cm	15 cm	20 cm
1 B	99%	97%	96%	96%
2 B	99%	98%	96%	96 %
3 B	98%	96%	95%	94%
4 B	97%	96%	95%	93 %
5 B	97%	95%	93%	91%

4.3 Integration of Li-Fi Communication in an Industry 4.0 Learning Laboratory

The main objective of this experiment is to test the Li-Fi transceiver in the Industry 4.0 Learning Laboratory and finding the reliability of multi-hop communication. Fig. 6 shows the layout of the Industry 4.0 learning laboratory with Li-Fi transceivers and stand-alone factory resources. The hardware required for this experimental setup of the prototype is factory modules equipped with Arduino-Mega 2560, RFID reader, tags, Li-Fi transceiver modules, relay modules, 9-volt batteries for the power source. This experimental setup creates a distributed structure with the turntable as a decision node and Master node with the RFID reader and source and three sink nodes. Reliability of multi-hop Li-Fi communication with 3 ms TICK achieved as 95% on three hops.

5   Conclusion and Future Work

In this paper, we demonstrated the implementation of the four-way Li-Fi transceiver and communication protocol. Based on the experimental results discussed in the above section, the Li-Fi communication protocol was evaluated. The maximum communication distance achieved with 3 ms TICK is 30 cm with a white LED as a transmitter and LDR as a receiver. Furthermore, the Li-Fi transceiver provides 99% reliability in terms of communication with single hop and 95% with three-hops concerning the optimal parameters of the Li-Fi protocol. As we are developing dynamic layouts in the laboratory, the four-way transceiver on each factory module can serve the purpose of dynamic factory planning application.

To summarized, Li-Fi is a suitable communication method for the Industry 4.0 Learning Laboratory. Due to its high data transmission rate, Li-Fi can contribute to applications with real-time requirements. Moreover, the design of the
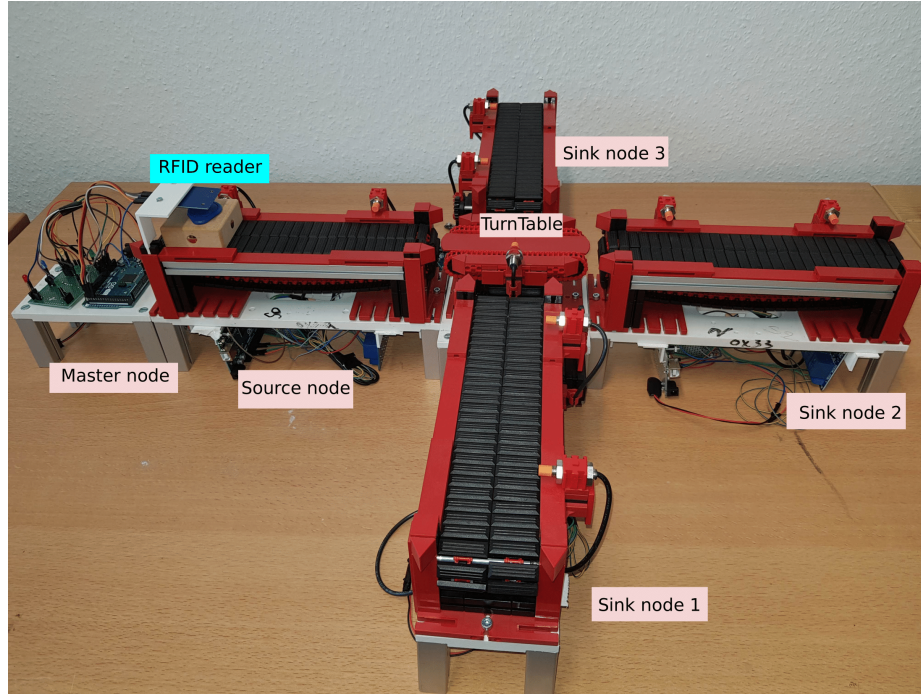
Fig. 6. Prototype of Industry 4.0 learning laboratory with Li-Fi Communication

Li-Fi transceiver is inexpensive, and the hardware implementation and setup is straightforward. In this paper, the communication speed achieved is less compared to the actual speed of Li-Fi, which is in terms of Gbps. The speed can be increased with high-speed processors. For example, the Arduino-Mega 2560 provides an ADC clock with 9.6154 kHz, which impacts communication speed. However, the communication speed is sufficient for the Industry 4.0 Learning Laboratory.

As of now, the Li-Fi has been successfully integrated into our Industry 4.0 Learning Laboratory. For further research, one can explore various areas of the proposed field. For instance, the routing algorithm can be improved by implementing dynamic routing techniques and can increase communication speed by choosing a controller which provides a high ADC clock. Furthermore, the error correction and re-transmission of data can improve the efficiency and robustness of the communication. Each transceiver interface performs concurrent execution of data transmission and reception.

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