Optical Wireless for Industrial Communication: Practical Results using IEEE Std 802.15.13

(invited paper)

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***Abstract*—We present recent work on a proof-of-concept of cell-free distributed multiple-input multiple-output (D-MIMO) based on the new IEEE 802.15.13 standard for optical wireless communication in industrial applications. The design includes a coordinator with multiple distributed optical frontends (OFEs) in a multiple-input single-output (MISO) configuration, as well as mobile devices. The coordinator is realized as a virtual network function, running on commodity server hardware. It controls the transmission of all distributed OFEs via a digital packet-switched fronthaul network. One or more distributed OFEs are dynamically combined to form a virtual cell for each mobile user. In this way, macro-diversity is provided to ensure robust low-latency transmission: If the line-of-sight to one OFE is blocked, the link is maintained via another one. We provide first performance results based on our field programmable gate array (FPGA) implementation of the Pulsed Modulation PHY (PM-PHY) specified in the standard. It supports on-off-keying (OOK) modulation with frequency-domain equalization at four selectable clock rates.**

***Index Terms*—OWC, LiFi, VLC, user-centric, IEEE Std 802.15.13, MISO, DPDK, FPGA, industrial**

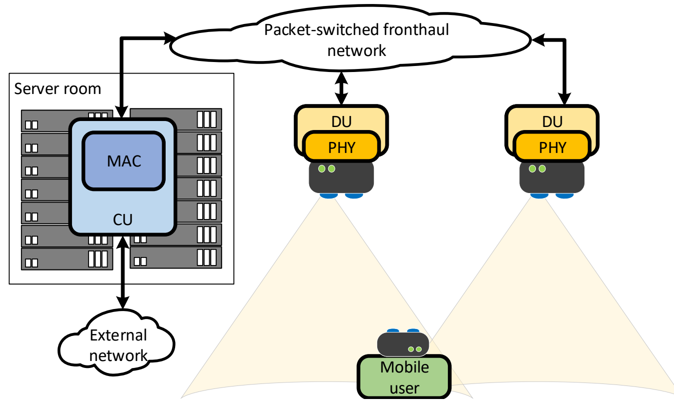


Fig. 1. Concept for the user-centric OWC system implementated by using a MAC-PHY split between the coordinator and the DUs. Mobile devices move within the coverage area and are served via LOS to one or more DUs.

I. Introduction

Future automation technologies require robust and efficient wireless data transmission [1], connecting mobile agents, such as humans with handheld devices and automated guided vehicles (AGVs) or other automation systems. While existing wireless technologies are constantly evolving, the physical properties of radio propagation fundamentally limit their ability to guarantee real-time transmissions. This is, because radio waves penetrate walls, which can result in unpredictable inter- and intra-technology interference from distant radio emitters [2]. Furthermore, licensing for modern cellular campus networks can be costly and the use of industrial, scientific and medical band (ISM) bands is subject to regulatory constraints that limit communication protocols. Light, when used as a communication medium, allows for sharply delimited propagation zones inside the same room and thus a high degree of spatial reuse. Light is unregulated as a wireless medium and thus deployable without limitations for the communication protocols, such as frequency licensing, duty cycling or mandatory listen before talk. Optical wireless communications (OWC), relying on intensity-modulated visible or infrared light from light-emitting diodes (LEDs) or laser could therefore be a valuable addition to the radio spectrum [3], [4].

However, the properties of light also impose challenges on these protocols. Firstly, efficient communication usually requires a line-of-sight (LOS) between the light emitter and the receiver, as reflections are usually too weak for higher data rates (100 Mbit/s and more). When the LOS is obstructed, communication is typically not possible, or only with very low data rates (few Mbit/s) via diffuse reflections. It has previously been shown that leveraging spatial diversity through multiple-input multiple-output (MIMO) with multiple transmitters and receivers can render communication robust against blockages [5]. Secondly, the small size of optical cells leads to frequent handovers when the user is mobile. Alizadeh Jarchlo et al. [6] investigated the outage duration in an OWC network and were able to reduce outage events down to 200 ms in a system with multiple OWC access points (APs) that were connected to a common backhaul network. For industrial applications, this outage should be further reduced.

One proposed system design approach to achieve this is to transmit and receive from multiple ceiling-mounted transceivers to and from a single user at the same time, as depicted in Fig. 1. In the literature, this is referred to by overlapping concepts of ”user-centric” [7] or ”cell-free” [8] networks and the term ”D-MIMO”. This allows to adapt the set of transceivers serving the users dynamically, following mobility and allowing for interruption-free connection. Moreover, signal quality at the cell edge is improved and blockages can be overcome through redundant LOS links. So far, the concept was mostly discussed in theory for OWC, with little data on the performance in realistic application scenarios. Beysens et al. [9] implemented DenseVLC, a cell-free OWC system based on the modified OpenVLC architecture [10]. A real-time implementation of the user-centric D-MIMO concept, based on an appropriate OWC standard, was, to our knowledge, not yet investigated. Such work is essential to identify major implementation challenges, obtain insights on the performance and pave the way for robust low latency transmission in real applications.

In this paper, we present recent work on implementing a testbed and providing a proof-of-concept of a real-time OWC system based on the new IEEE 802.15.13 standard for industrial OWC [11]. Our main contributions can be summarized as follows: We layed out a system design that describes how to realize cell-free OWC networks based on the active IEEE 802.15.13 standard while staying standards-compliant. We then validated the real-time implementation feasibility of the PM-PHY from IEEE Std 802.15.13 for the fist time over distances that are typical in factory halls by measuring packet error rates (PERs). We showed that the physical layer (PHY) is capable of transmitting frames over different distances with adaptive modulation. We conclude that the specified PHY is usable for further system-level experiments with D-MIMO OWC.

II. The 802.15.13 Standard

OWC was standardized in multiple efforts for different applications and ecosystems. IEEE Std 802.15.7, was completed in 2011 and revised in 2018. In its latest version, it focuses on optical camera communication (OCC), i.e., using digital cameras for communication, while high data rate LED and laser communication was spun off as IEEE Std 802.15.13-2023. International Telecommunication Union Telecommunication Standardization Sector (ITU-T) G.9991 (or G.vlc) extends the ITU-T G.hn recommendations for home networking through additional features for OWC. Currently, it is the basis for most of the OWC prototypes and first products, as it is the only modern OWC standard implemented in commercially available chipsets. IEEE 802.11bb-2023 is a recently published amendment of Wi-Fi, allowing existing PHYs layers to be used over the light medium. It focuses on the reuse of existing WiFi hardware in consumer settings.

IEEE Std 802.15.13 was first published in 2023 and focuses on simplicity and specialty applications, such as industrial wireless communication. The medium access control (MAC) sub-layer supports two deterministic medium access mechanisms, one based on adaptively scheduled time division multiple access (TDMA) and another based on polling. In

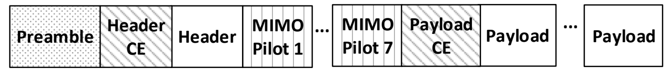


Fig. 2. PPDU structure of the PM-PHY with fields for frame detection, channel estimation and data transfer. The MIMO pilots and payload may consist of multiple blocks.

combination with the highly deterministic propagation of light, these centrally controlled access mechanisms allow for data delivery with predictable latency. To accommodate periodic real-time traffic that requires very low latency variation, essential protocol frames, e.g., for synchronization or network announcement can be sent at variable times, thus preventing medium occupation.

The standard specifies two PHYs - one based on OOK, referred to as ”PM-PHY” and one based on orthogonal frequency-division multiplex (OFDM), referred to as ”HB-PHY”. Both PHYs perform frame-based transmissions, with each frame consisting of a preamble for frame detection and channel estimation, as well as a header, carrying metadata that is required for frame demodulation and decoding. Furthermore, the frame structure of both PHYs includes pilot signals that allow concurrent MIMO channel estimation from multiple transmitters to a single receiver. These pilots are designed to allow for orthogonal transmission, preventing pilot contamination from neighboring transmitters. Lastly, the frame formats of both PHYs include a payload field, which carries the PHY service data unit (PSDU) in coded and modulated form. All fields that contain modulated data are segmented into blocks of 5.12 µs and are extended through prepending a cyclic prefix. This allows for the use of frequency domain equalization (FDE) as part of the receiving digital signal processing (DSP) chain, which can alleviate the effects of multi-path propagation, e.g., due to receiving signals from multiple OFEs. Fig. 2 depicts the physical layer protocol data unit (PPDU) structure of the PM-PHY. Further information on the standard can be found in [12].

III. D-MIMO Proof-of-Concept

The goal of our proof-of-concept implementation is to validate the feasibility of scalable D-MIMO based on the IEEE 802.15.13 standard and obtain performance insights on a practical real-time implementation. Following up, we present the design and our implementation thereof.

A. Design

For our D-MIMO approach, we consider a coordinator implementation with a split between MAC and PHY, as known from cellular networks, see Fig. 1. The coordinator’s MAC implementation resides in a so-called central unit (CU), while the PHY resides in one or more distributed units (DUs). The CU is connected to one or more DUs and forwards PSDUs for downlink transmissions to them and receives PSDUs from them upon successful uplink reception. This central control of transmissions allows for D-MIMO operation with relatively low complexity in contrast to when channel state information (CSI) needs to be exchanged between APs that participate in a transmission. Applying that concept from cellular networks to OWC with its high number of cells per area was also proposed, e.g., by Kizilirmak et al. [13].

Stimulated by the use of digital network technologies to transport fronthaul data in cellular networks, we investigate the use of Ethernet networks to connect the CU and DUs. Compared with dedicated analog lines for each DU, this makes networks easy to install and scalable, as the statistical multiplexing gain of packet-switched networks is leveraged. Additionally, this architecture makes it possible to implement the MAC as a virtual function on ordinary server hardware, as long as it has an Ethernet network interface, allowing to run it, e.g., in an existing server room.

B. Implementation

We implemented a minimal setup of the system described in the last section in order to obtain a first performance assessment. The system includes a PHY implementation for use as part of the DU and mobile unit (MU), as well as a MAC implementation of the fundamental protocol routines of the coordinator and the mobile device, residing in the CU and MU, respectively. In the following, we describe the recent state of our ongoing proof-of-concept implementation.

1) Physical layer: We implemented the PM-PHY from IEEE Std 802.15.13 on a Xilinx on a Zedboard with Zynq 7020 FPGA. We connected a 250 MSPS Analog Devices analog-to-digital converter (ADC) and a variable gain amplifier (VGA) via the FMC connector for reception (see Fig. 3 and 4). The PHY implementation supports most of the PHY's operating modes, specifically, the clock rates 12.5, 25, 50 and 100 MHz, leaving out 200 MHz due to resource constraints on the FPGA and the limited ADC sample rate. The PHY receives one transmit vector (TXVECTOR) per transmission, containing all necessary parameters to assemble the PPDU as well as the PSDU. Based on that information, first the header bits are generated. Header and payload are each scrambled and encoded in 8b10b line code and Reed-Solomon forward error correction. Preamble, channel estimation symbols, and the MIMO channel estimation symbols are retrieved from a read-only memory (ROM). After modulation and frame assembly, all parts of the PPDU are concatenated and buffered for transmission. Since the signal consists of ON-/OFF levels only, no digital-to-analog converter (DAC) is necessary and the signal is directly output via the Pmod pins. Fig. 5 depicts the main building blocks of the transmitter FPGA design.

In the receive direction, the PHY receives samples from the ADC and detects the frame based on correlation with the known preamble. The VGA's gain is controlled through an automatic gain control (AGC) core that analyzes the received signal strength during the frame start. To set the gain quickly, the AGC core is connected with the VGA through a parallel interface. An FDE equalizes the header blocks based on the coefficients obtained from the header channel estimation field.

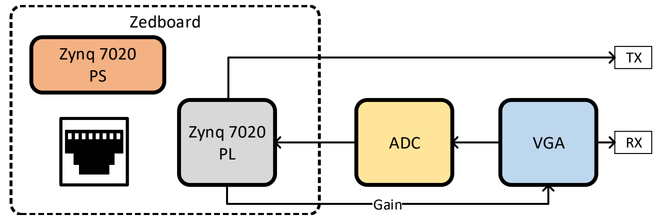


Fig. 3. Block diagram of the custom hardware used for the DU and MU. The PHY is running on the Zynq 7020 PL (FPGA). The Zynq 7020 PS (ARM CPU) runs the software stack of either the DU or MU.

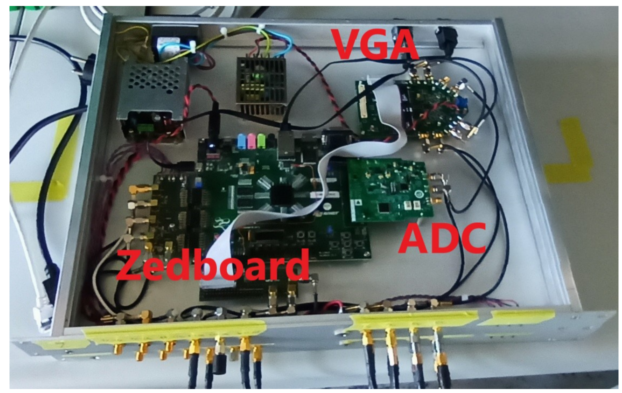


Fig. 4. The extended Zedboard hardware, used as a DU and MU in the system. A programmable VGA and a ADC, connected via FMC, are mounted with the Zedboard in a 19 inch housing.

It then demodulates the OOK signal and performs forward error correction (FEC) decoding. The demodulation clock rate, scrambler initialization, and cyclic prefix length for the payload are obtained from the demodulated header and the receiver pipeline is reprogrammed for payload demodulation. If the payload is modulated at a higher clock rate than the header, the FDE coefficients are updated based on the payload channel estimation field of the PPDU. Successfully decoded PSDUs are forwarded via the receive interface.

2) IEEE 802.15.13 MAC: We implemented a minimal feature set of the 802.15.13 MAC in the coordinator, as well as in

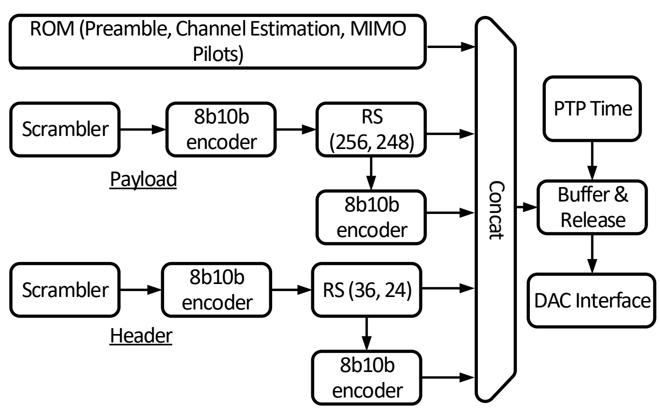


Fig. 5. Block Diagram of the PM-PHY transmitter implementation.

the mobile devices to allow transfer of Ethernet frames over the optical link. The coordinator's MAC is running as a userspace application on a usual Linux Ubuntu server, constituting the CU with the help of the Data Plane Development Kit (DPDK) framework. DPDK allows to bypass the kernel for networking functions and thus create highly parallelized userspace networking applications [14]. The coordinator receives frames from the Ethernet ports of the CU server, encapsulates them in the IEEE 802.15.13 frame format and forwards them to the DUs for transmission based on the MAC protocol rules. Vice versa, it receives encapsulated Ethernet frames from the DUs upon uplink reception and forwards them to the Ethernet ports connected with an external network after MAC processing.

The MAC features of the mobile device are implemented as a kernel module for Linux, running on the ARM core of the Zynq 7000 system-on-a-chip (SoC). The software stack receives uplink Ethernet frames from the Zedboard's network interface, encapsulates them, and transmits them in the assigned TDMA slots, passing them to the PHY that is implemented on the co-located FPGA. Conversely, it receives downlink frames from the PHY and passes them to the Ethernet port after extraction from the MAC frame.

3) System with MAC-PHY-Split: We integrated the PHY and MAC implementation in a system setup acting like a bridge, i.e., passing Ethernet frames between the CU's and the MU's Ethernet ports. In the overall system, the CU is connected with the DUs through an Ethernet switch. In our experimental system, we use a CTC Union IGS-1608SM-SE with precision time protocol (PTP) and SyncE functionality. The switch's integrated PTP master synchronizes the CU and all DUs to a common reference time. The coordinator software is running on a 10-core Xeon server central processing unit (CPU), using 8 cores for the data path in a pipeline architecture. We use the Ethernet clock signal to operate the time module within the DU in order to improve accuracy as described in [15].

Our DUs includes a simple software to receive TXVECTORs from the fronthaul network and pass them to the PHY via direct memory access (DMA). A time-trigger in the FPGA allows to transmit the PPDUs based on the synchronized PTP time. The MU is based on the same hardware as the DU but runs a different software on the two ARM cores, implementing parts of the MAC protocol at the mobile device side.

IV. Experiments

A. Experiment Setup

Previously, Hinrichs et al. [16] evaluated the PM-PHY in offline experiments. An evaluation based on a real-time implementation is therefore the next step. As a basis for future system-level performance evaluation, we performed initial performance tests of our real-time PHY implementation through point-to-point measurements over variable distances. We set up one transmitter and one receiver, consisting of the extended Zedboard hardware, in the laboratory as depicted in Fig. 6. Both are connected to custom-desigend LED-based OFEs through coaxial cables, carrying the differential analog signal.

TABLE I
NET DATA RATES FOR EACH OF THE TESTED CLOCK RATES [11].

Clock Rate (MHz)	Data Rate (Mb/s)
12.5	8.99
25	17.41
50	32.94
100	59.43

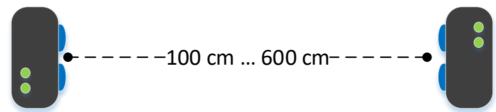


Fig. 6. Simplified experimental point-to-point topology with a transmitter and a receiver. The two OFEs are facing each other with a distance varying between 100 and 600 cm.

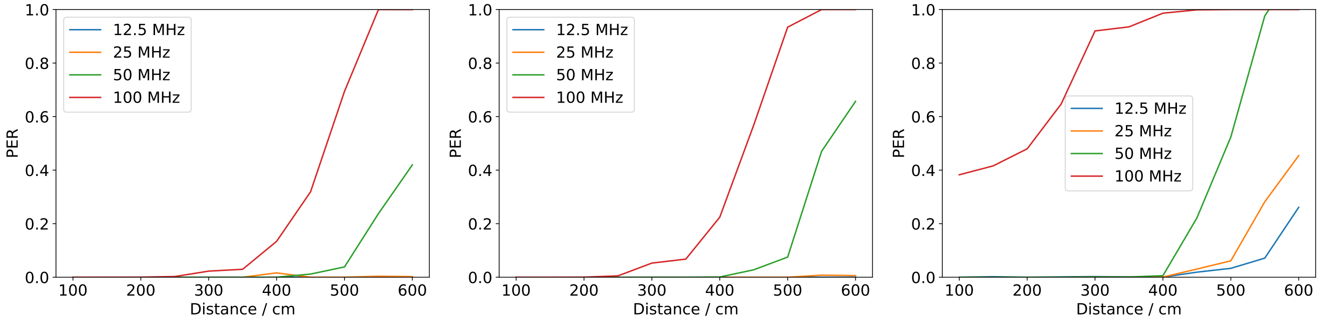
The OFEs were designed and built by Fraunhofer HHI and are mounted on tripods at a height of 1.8 m above the ground. We transmit frames and measure the PER while varying the distance between 100 and 600 cm. We perform 10k frame transmissions for each of the four supported modulation and coding schemes (MCSs), 12.5 MHz, 25 MHz, 50 MHz, and 100 MHz, as well as for three different PSDU (i.e., payload) sizes of 100, 400, and 1400 bytes. The net data rates for the maximum PSDU size, considering also the overhead through the PPDU header, are listed in Table I. For each transmission, the receiving PHY tries to decode and demodulate the PPDU in real-time and notifies the software about erroneous frames.

B. Results

The results show that our implementation supports real-time data transmission with all tested MCS and payload sizes. Fig. 7 depicts the PER vs. distance for all combinations. For larger payloads, the PER is slightly higher, which is a common effect, as more bits lead to more potential bit errors. For the PSDU size of 100 bytes, only the MCS with a clock rate of 50 and 100 MHz lead to significant packet errors at higher distances. All lower-rate MCSs can cover the distance of up to 600 cm with a relatively low PER. Note that the maximum distance is typical for communication between the ceiling and the shop floor in a manufacturing hall. For larger PSDUs, however, the error probability increases with distance and leads to significant packet loss for 25 MHz and 50 Mhz clock rates at higher distances as well. In contrast to previous simulations and offline experiments the results show for the first time that the PM-PHY from 802.15.13 is implementable in real-time on an FPGA. While its design is kept simple, it offers moderate data rates, which are sufficient to reliably transport short control frames, e.g., in automation systems.

V. Conclusion and Outlook

We presented our ongoing efforts to design and implement a proof-of-concept of a user-centric, cell-free optical wireless communication system based on the IEEE 802.15.13-2023 standard using innovative D-MIMO techniques. The design



(a) PSDU length 100 bytes (b) PSDU length 400 bytes (c) PSDU length 400 bytes

Fig. 7. PHY PER over distance for the PSDU lengths 100, 400 and 1400 bytes and clock rates 12.5, 25, 50, and 100 MHz.

allows for the use of common server hardware to operate the MAC sublayer of the coordinator. A functional split between the MAC and PHY and an Ethernet-based fronthaul network allows to scale up the number of ceiling-mounted OFEs per coordinator using low-cost Ethernet equipment. As a basis for future performance studies of the whole system, we demonstrated for the first time that our FPGA-based PHY implementation is capable of transmitting and receiving real Ethernet data over 600 cm at different clock rates. Work on this experimental system is still ongoing with new features to be implemented and tested.

In future works, we plan to extend our experiments to test the complete system and evaluate the performance of data transmissions with multiple cells covering a larger area and multiple mobile users served in parallel which is possible if their mutual distance is larger than one cell size.

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