Distributed MIMO Experiment Using LiFi Over Plastic Optical Fiber

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***Abstract*—This paper shows the feasibility of a networked LiFi system using a distributed multiple-input multiple-output (MIMO) link for optical wireless transmission and a plastic optical fiber (POF) link as a fixed front-haul between distributed optical front-ends, and a centralized signal processing unit. The concatenation of POF and optical wireless links yields an easy-to-install all-optical LiFi system which is robust against both, blockage of individual light beams and electromagnetic interference. A significant cost-down appears by the use of colored LEDs to feed the POF link with multiple optical signals, and wavelength division demultiplexing filters. The spatial crosstalk in the wireless link and the spectral crosstalk over the POF link can be jointly compensated by the same end-to-end MIMO processing. A common signal model, which includes the combined effects of both links are provided to characterize the proposed all-optical LiFi system. We report the first experimental findings when using space-division multiplexing (SDM), i.e., multiple POFs, and wavelength-division multiplexing (WDM), i.e., multiple colors in the front-haul, indicating that the performance is mostly limited by the wireless link. Moreover, we show that the positions of mobile users in the wireless link, as well as gain variations and spectral crosstalk in the front-haul link, influence the singular values and the achievable data rates of the LiFi system.**

***Index Terms*—LiFi, Plastic Optical Fiber, MIMO, SDM, WDM, front-haul**

I. Introduction

As new bandwidth-demanding Internet of things (IoT) applications are growing rapidly, an increasing number of IoT devices will need wireless connectivity to the Internet. The next generation of IoT devices such as mobile robots, automated guided vehicles, drones and wireless endoscopes will produce a large amount of visual information coming from cameras, lidars, ultrasonic imaging devices etc., which will increase the demand for wireless capacity. The wireless spectrum is crowded, however, particularly in unlicensed radio-frequency (RF) bands. Moreover, the traditional approach to densify wireless access points will not be enough. New wireless spectrum will be needed to satisfy future IoT demands. Further, there are applications in which the use of RF is limited or not sufficient, such as in industry, medical or aviation scenarios where electromagnetic interference is considered critical.

A common objection against the use of OWC is that the link collapses when the line-of-sight is blocked. An effective countermeasure proposed in [1] is the emission of light from different spatially separated locations, similar to common practice in achieving homogeneous illumination. Such configuration can be considered as a distributed-MIMO (D-MIMO) link, by assuming that wireless access points in the infrastructure are the inputs and the mobile device has multiple outputs. It has been demonstrated in [2], [3] that the distributed MIMO architecture can significantly enhance robustness by sending the same signal from multiple sources. In [4] it is shown that the D-MIMO setup can also be used to multiplex parallel data streams for multiple users if they are spatially separated.

This study addresses the deployment of D-MIMO for OWC in combination with a low-cost fiber-optical fronthaul approach. We propose to use plastic optical fiber (POF) to distribute the optical wireless signals to distributed optical frontends. We study both, space- and wavelength-division multiplexing (SDM and WDM) which are used in a star and daisy-chain topology, respectively. The first proof-of-concept for using POF as a fronthaul for OWC and a first experimental setup for a bidirectional single-input single-output OWC over POF link were presented in [5] and [6], respectively, reporting data rates up to 900 Mbit/s. In this paper, we demonstrate a first SDM over POF link in a star topology together with OWC links in a 2x2 MIMO setup. The performance is evaluated for various scenarios by adapting RF MIMO principles to LiFi, where it is well known that the throughput depends critically on the number of non-zero singular values of the channel matrix, indicating separability, i.e., the ability to remove cross-talk by digital signal processing without excessive noise enhancement. In a rich scattering RF system, an antenna separation of less than half of the carrier wavelength creates independent separable channels [7], [8]. In contrast, intensity-modulated (IM) optical links must create separability of signals in other ways, e.g. by spatial separation and different orientation of the optical transceivers.

This idea can be further extended to use WDM to carry multiple streams to multiple optical frontends over the same fiber [9]. The WDM approach can be used in a daisy-chain topology which reduces the deployment cost. In [10], the concept of hybrid POF and OWC link using light-emitting diodes (LEDs) was demonstrated and 123 Mbit/s were achieved with discrete multitone (DMT). In [11], 14.77 Gbit/s WDM-over-POF transmission using four lasers was presented, indicating that POF as analog fronthaul is scalable to very high capacities.

The objective of this paper is to explore the concatenation of SDM-over-POF and WDM-over-POF to realize D-MIMO for OWC. We estimate the throughput based on experimentally measured and characterized POF channels including the WDM crosstalk and the spatial separability of the signals in the optical wireless domain. We claim that a single end-to-end MIMO processing suffices even if major cross-talk occurs in both parts of the link. This allows a major cost-down by using wide band LEDs in the POF link. Further, for the first time we demonstrate and quantify performance gains of D-MIMO over POF in an indoor environment to provide a high coverage area and serve multiple users, besides enabling the wireless system to be robust against potentially malicious electromagnetic interference. This paper is organized as follow: Section II, III and IV highlight the POF concepts for LiFi and develop the MIMO system model and the performance evaluation framework, respectively. Sections V and VI elaborate the experimental setup and results, respectively, followed by the Conclusions and further research topics.

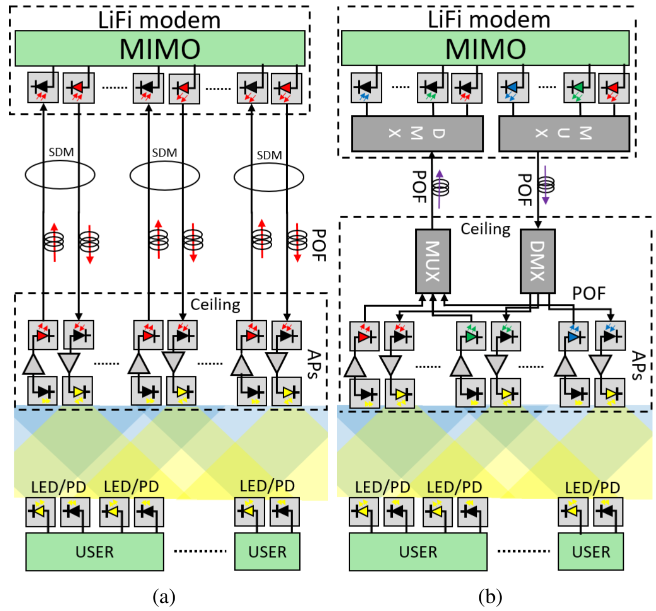


Fig. 1. (a) SDM approach and (b) WDM approach

II. POF concepts for LiFi

Standard POFs are made from polymethyl methacrylate (PMMA) as step-index 1-mm core diameter fibers. POFs are an attractive fronthaul solution for feeding the LiFi system due to its low cost, high data rates, immunity to electromagnetic interference, easy installation and small bending radius. Due to these advantages, POF is already used in other sectors (automotive, industrial, in-home, etc.). In this paper we study the use of POF as feeder link for the LiFi infrastructure and to accommodate the D-MIMO concept in the wireless link [6]. The feeder network can be realized by individual point-to-point connections using one POF for each optical frontend (OFE) and the same wavelength, which is denoted as space-division multiplexing (SDM). One can also reuse the same fiber using different wavelengths for each OFE, which is denoted as wavelength-division multiplexing (WDM). While WDM simplifies installation of the fiber, it implies a higher complexity in the optical subsystem. Both approaches are shown in Fig. 1. Using SDM, there is no crosstalk in the feeder network, while it can be significant in WDM if the optical spectra of POF transmitters do overlap. While this can be easily avoided by using lasers having narrow optical line widths, a significant cost-down can be reached when using LEDs which have wider spectrum and, thus, potentially more overlap. We show here that the related cross-talk can be removed by the MIMO processing used for the wireless link.

The WDM functionality is realized by means of WDM multiplexer (MUX) and demultiplexer (DMX). The MUX causes an insertion loss for every channel. Several off-the-shelf approaches can be found in the market. The main challenge is the DMX implementation with high performance. We chose dichroic filters at 45-degree incidence, due to scalability and low loss. While the DMX should ideally separate WDM channels without leakage from the neighbouring channels, a small crosstalk may occur in practice. It should be as small as possible (e.g. $<$20 dB) where the limit depends on the spectral efficiency targeted for the wireless link. Therefore, it is suggested to remove such additional cross-talk by the MIMO signal processing, which is already used for the wireless link.

III. MIMO system model for LiFi

A key contribution in this paper is a mathematical model for the concatenation of SDM over POF, WDM over POF, and thereby the whole D-MIMO LiFi link as just one modulation–frequency–dependent MIMO channel matrix $\mathbf{H}(f)$. The MIMO channel matrix describes the propagation behavior of parallel signals in the compound channel. The system consists of a centralized LiFi modem equipped with N_T light emitters, all at the same peak wavelength for SDM or centered at different peak wavelengths for WDM, which transmits information to N_U users each equipped with N_R photodetectors (PDs). We assume that orthogonal frequency-division multiplexing (OFDM) is used as a modulation scheme, by adding a constant bias and limiting the modulation amplitude so that the effects of clipping can be neglected. In its most generic form, the received signal vector $\mathbf{y} \in \mathbb{R}^{N_U N_R \times 1}$ by the users at the f-th OFDM subcarrier is computed by

$$\mathbf{y}(f) = \mathbf{H}(f)\,\mathbf{x}(f) + \mathbf{n}(f), \qquad (1)$$

where $\mathbf{H}(f)$ is the $N_U N_R \times N_T$ end-to-end analog channel matrix, $\mathbf{x}(f)$ is the $N_T \times 1$ transmit signal vector and $\mathbf{n}(f)$ is the $N_U N_R \times 1$ additive white Gaussian noise vector. The elements of $\mathbf{n}(f)$ are modeled as zero-mean complex-valued Gaussian random variables with variance $\sigma_n^2 = N_0 B$, where N_0 denotes the noise power spectral density and B is the modulation bandwidth. Each coefficient $x_i(f)$, for $i = 1, ..., N_T$, from $\mathbf{x}(f)$ is a complex number. The real-valued property of the optical waveform is reached after summation over all subcarriers and by an additional frequency up-shift to an intermediate frequency f_c which is typically half the total signal bandwidth. To ensure a fair operation, we constrained the total average transmission power per subcarrier to P_T, thus $\mathrm{E}[|\mathbf{x}(f)|_2^2] = P_T$.

Concatenating POF and OWC, the overall channel matrix $\mathbf{H}(f)$ can be written as the matrix product:

$$\mathbf{H}(f) = \mathbf{Z}(f)\mathbf{G}(f) \tag{2}$$

where $\mathbf{Z}(f) \in \mathbb{R}^{N_U N_R \times N_T}$ denotes the wireless MIMO channel and $\mathbf{G}(f) \in \mathbb{R}^{(N_{PD}=N_T)\times N_T}$ stands for the POF link. To reflect crosstalk in the spatial domain, the coefficients of $\mathbf{Z}(f)$ are computed by:

$$Z_{l,j}(f) = H_{\mathrm{LED}_j}(f) g_{\mathrm{TX}}(\phi_j) g(d_{j,l}) g_{\mathrm{RX}}(\phi_l) H_{\mathrm{PD}_l}(f), \tag{3}$$

which depends on the radiation pattern $g_{\mathrm{TX}}(\phi_j)$, the spatial layout, thus on the distance $d_{j,l}$ between the j-th OFE at the ceiling of the room, the angles ϕ_j, ϕ_l at which rays depart from the emitter and arrive at the receiver, respectively, $g(d_{j,l})$ describes the path loss of the wireless link, and $g_{\mathrm{RX}(\phi_l)}$ is sensitivity of the (PD) at the user device [12], [13]. The coefficients $H_{\mathrm{LED}_j}(f)$ and $H_{\mathrm{PD}_l}(f)$ represent the frequency responses of the LED plus its driver, and of the PD besides its trans-impedance amplifier in the OWC system, respectively.

To describe crosstalk in the wavelength domain, the coefficients of $\mathbf{G}(f) \in \mathbb{R}^{(N_{PD}=N_T)\times N_T}$ are given by:

$$G_{j,i}(f) = \int_{\lambda} S_i(f,\lambda) H_{\mathrm{POF}}(f,\lambda) R_j(f,\lambda) d\lambda. \tag{4}$$

For both SDM and WDM modes, the emitter can be a laser with a narrow spectrum and a fast response, described by for the i-th emitter as $S_i(f,\lambda) \approx S_i(f)\delta(\lambda - \lambda_i)$. For cost reasons, LEDs maybe preferred with a broader λ spectrum but have a low-pass modulation response. In the literature, POF is seen as a color-dependent dispersive medium and this behaviour is characterized by the coefficient $H_{\mathrm{POF}}(f,\lambda)$. Moreover, $R_j(f,\lambda)$ describes the responsivity of the j-th POF receiver due to the PD response and modified by the dicroic filters.

In the SDM scheme, signals are transmitted via separate POF links and, therefore, there is no crosstalk in the feeder network. In such case, $\mathbf{G}(f) = G_0 \mathbf{I}_{N_T}$ is diagonal, where G_0 represents the POF channel gain. In WDM, $\mathbf{G}(f)$ is a full matrix where the off-diagonal entries represent the cross-talk between different wavelengths.

In case of WDM, multiple wavelengths are used to feed the same POF. These are multiplexed at the transmitter and demultiplexed at each OFE. As demultiplexing is imperfect, each wavelength plus some cross-talk from other wavelengths reaches a specific OFE. At the OFE, the superimposed signals are forwarded over free space to the mobile user. Therefore, the entry $H_{l,i}(f)$ from $\mathbf{H}(f)$, which represents the specific path traveling from i-th emitter of the LiFi modem, to the l-th user PD, combined over all possible POF receivers, for $j = 1, ..., (N_{PD} = N_T)$, and corresponding j-th OWC LED, can be computed by:

$$H_{l,i}(f) = \sum_{j}^{N_T} Z_{l,j}(f) G_{j,i}(f) \tag{5}$$

where the sum comes from the cross-talk in the WDM stage. Consequently, the compound channel matrix $\mathbf{H}(f)$ typically contains severe cross-talk from both, WDM and OWC sections. For SDM, (5) can be simplified as $H_{l,i}(f) = Z_{l,i}(f) G_{i,i}(f)$.

The MIMO processing attempts to cancel the combined cross-talk in one and creates parallel channels in this way. If the compound channel matrix is rank-deficient, the elimination of cross-talk would cause excessive noise enhancement. In that case, the system would switch to a diversity mode transmitting the same signals from multiple OFEs realize the best achievable performance. A theoretical debate of the analysis of the channel is beyond the scope of this paper. But based on our measured LEDs to feed the POF shows that, fast low-power LEDs on the POF link do not limit the performance, except that the stronger attenuation at shorter wavelength at the PD may causes a link budget challenge. The impact of cross-talk in the wavelength domain was studied in [14].

IV. Performance evaluation

This section evaluates the throughput of the system by considering the singular value decomposition (SVD) of the measured end-to-end channel matrix $\mathbf{H}(f)$. The achievable rate is then evaluated by concatenating of either SDM or WDM in combination with the LiFi link. Our approach is similar to the capacity evaluation of RF channels reported in [15]. Assuming that channel state information is available at the LiFi modem, the formation of parallel non-interfering channels can be reached by decomposing the specific channel matrix $\mathbf{H}(f)$ at the f-th subcarrier using singular value SVD, which is given by $\mathbf{H}(f) = \mathbf{U}(f)\mathbf{D}(f)\mathbf{V}(f)^H$, where $\mathbf{U}(f) \in \mathbb{C}^{N_U N_R \times N_U N_R}$ and $\mathbf{V}(f) \in \mathbb{C}^{N_T \times N_T}$ are square unitary matrices and $\mathbf{D}(f) \in \mathbb{R}_+^{N_U N_R \times N_T}$ is a matrix whose diagonal elements contain the so-called singular values of $\mathbf{H}(f)$, $\xi_1(f) \geq \xi_2(f) \geq ... \geq \xi_K(f)$, where $K = \min(N_U N_R, N_T)$ denotes the rank of $\mathbf{H}(f)$ [8], [16].

For SDM, signals are separated by different POF links, there is no crosstalk in the feeder link. For WDM, the demultiplexer has to separate colors. There is a trade-off between narrow-band filtering to provide good WDM separation, and reducing the desired signal power if the LED has a wide spectrum [14]. In the optical wireless link, throughput suffers from cross-talk between the parallel channels overlapping in space. Our way to estimate the achievable throughput is based on adapting capacity expressions from [17] and normalizing the channel matrix as described in [15]:

$$R = \Delta_B \sum_{n=1}^{N} \sum_{k=1}^{K} \log_2 \left(1 + \frac{\mathrm{SNR}}{N_T \eta_H \Gamma} \xi_k^2(f_n) \right) \tag{6}$$

where N is the number of subcarriers, ΔB the bandwidth occupied by each subcarrier, η_H the average path loss of $\mathbf{H}(f)$

and $\Gamma = 10$ an empirical scaling factor taking into account the impairments like non-linear distortion (clipping) and imperfect constellation shaping [18]. We study the case of uniform power loading and equal power per OFE, thus SNR is considered to be equal to $P_T/(N_0 N \Delta_B)$ as described in [18]. To compute η_H we used the procedure in [15].

V. Experimental Setup

In the following section the experimental setup for the SDM link, WDM link, and OWC link is described. Furthermore, the D-MIMO measurement scenario is represented.

A. SDM-over-POF link setup

The transmission link for the SDM-over-POF system is shown in Fig. 2(a). The Avago transceiver (AFBR-59F3Z) is used as both, transmitter and receiver for the POF link. It contains a 650 nm LED together with a driver at the transmitter side and a PIN photo-diode together with trans-impedance amplifier at the receiver side for electro-optical and opto-electrical conversion, respectively. The transmitters are directly modulated within the linear region using Direct Current Offset (DCO)-OFDM. The waveform is generated by Matlab and loaded onto the parallel arbitrary waveform generator (AWG) Spectrum DN 2.662-08. At the receiver side, the received signal is plugged into a parallel analog-to-digital converter Spectrum DN 2.445-08 (also denoted as digitizer) by using a sampling rate of 500 MS/s. The received samples have been analyzed through offline Matlab processing, as described in [2]. The POF length is selected to 1.5 m for this setup, where the optical attenuation is less than 0.3 dB (attenuation factor is 200 dB/km).

B. WDM-over-POF link setup

The MIMO concept for the wireless link can be extended by using the WDM concept over the POF. It is realitzed by using two light colours (green and red) over the same POF, feeding the optical frontends. At this moment, only red LEDs are available. Therefore, for the initial measurements for WDM we used two lasers. The transmission diagram for the WDM-over-POF setup is shown in Fig. 2(b). The transmitter includes a power combiner from Diemount, that is used as a MUX, with insertion loss $I_L = 1.8$ dB and two Distributed Feedback Lasers (DFB) lasers at 520 and 658 nm from Graviton Inc. Each laser is directly modulated in the linear region and the coupling between the lasers and POFs is realized by butt joint (direct coupling). In the splitting node after 1 m POF, the DMX is implemented with bulk optical components. The off-the-shelf dichroic filter from Thorlabs are designed so that 45º angle of incidence is used. Its cut-off wavelength is 605 nm. For the alignment of the DMX, a cage system from Thorlabs is used. To analyze the crosstalk and losses, the Yokogawa AQ6374 Optical Spectrum Analyzer (OSA) is used. The output of the DMX is coupled into 5 m POF and then detected by a receiving PD and a trans-impedance amplifier. The Graviton-SPD2 is used for both, green and red channels. This receiver has 1.2 GHz detection bandwidth, noise equivalent power of less than -27.3 dBm. The receiver sensitivity is -18 dBm for the green (520 nm) and -22 dBm for the red (658 nm) wavelength corresponding to DMT modulation with BER=10^{-3}.

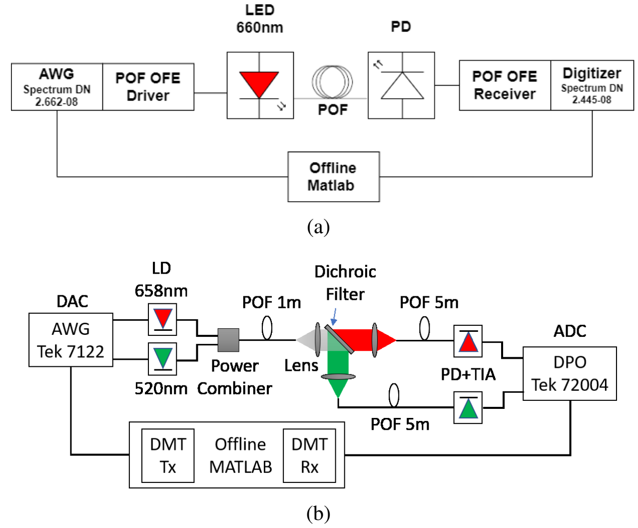


Fig. 2. SDM-over-POF setup (a) WDM-over-POF setup (b).

The DCO-OFDM waveform is generated using a Tektronix Arbitrary Waveform Generator (AWG) 7122 acting as a digital-to-analog converter. After detection, the signal enters an analog-to-digital converter and is sampled by a 50 GSa/s Tektronix 72004 Oscilloscope (DPO). A subsequent offline processing is performed in MATLAB. We clipped the data signal to reduce the peak power and to limit the dynamic range of the DMT signal. For the green channel a clipping level of 9 dB is applied and for the red channel one of 10 dB, defined as the ratio of the maximum allowed peak amplitude over the root-mean-square amplitude of the original DMT signal.

C. LiFi link

This section describes the distributed optical wireless link. The optical frontend has high optical transmit power using off-the-shelf high-power LEDs operating at 860 nm (OSRAM-SFH 4715 AS) and high sensitivity using large-area silicon PDs (PD, Hamamatsu S6968). The LED driver performs impedance matching for multiple LEDs operated in parallel producing around 2.5 Watts of average optical power emitted into a beam width of 90 ° full-width-at-half-maximum (FWHM). The LED driver uses a fixed bias current while the time-varying modulation current for the data signal is optimized to maximize data rate at the intended working distance. The Rx consists of one PD combined with a bootstrapped TIA to capture the light signal. The LiFi link can operate over several meters distance and offer mobility inside the beam while providing an overall 3 dB modulation bandwidth of around 80 MHz.

D. D-MIMO measurement scenarios

In this subsection, we present the measurement scenarios used for first D-MIMO experiments using SDM-over-POF and WDM-over-POF. While SDM-over-POF was measured as a whole, in case of WDM the channel response of the wireless link and of the WDM link were measured separately and combined afterwards to characterize the overall link performance. The experiment setup is illustrated in Fig 3. To combine the

TABLE I
LINK PERFORMANCE OF WDM-OVER-POF USING DMT

Wavelength (nm)	Crosstalk (dB)	Loss (dB)	Subcarrier Count	Clipping (dB)	Throughput (Gbps)
520	-13	3.2	128	9	2.5
658	-25.7	3.6	128	10	4.3

wired and wireless link in the SDM-over-POF setup, fixed gain amplifiers are used (see Fig 1 a), to equalize the gain of the POF link to unity. In our measurement, the distance between access points (APs) to users, user to user and AP to AP are defined as d_1, d_2 and d_3 respectively as shown in the Fig. 3. This measurement scenario is an example for the downlink of high bandwidth multi-user MIMO transmission currently defined for LiFi in the standardization project IEEE P802.15.13. As shown in Fig. 1 (a), each distributed link is operated in a bidirectional manner, but due to limited space we report on the downlink only in this paper. We compare two wireless scenarios. In the first scenario, the APs and users are located at d_1 = 100 cm, d_2 = 70 cm and d_3= 70 cm. In a second scenario, the users are placed as close as possible to each other d_2 = 5 cm, d_1 = 50 cm and d_3 = 35 cm. We did not collimate and tilt the detectors to improve angular selectivity, although this can further enhance the throughput.

VI. RESULTS

This section reports results of MIMO measurements both for a distributed link using SDM and WDM-over-POF. While the feeder link is operated in a transparent mode for SDM, i.e. losses over the POF, in electrical to optical conversion (e/o) and optical to electrical (o/e) modules are jointly corrected by an appropriate amplifier in the electrical domain, see [6]. First, the crosstalk in WDM mode has been explicitly measured here, then the throughput of the D-MIMO is presented.

A. WDM crosstalk over POF

To characterize the WDM-over-POF link, we measured losses due to light absorption by plastic material and crosstalk in the optical domain due to an insufficient side-channel rejection. The losses are by far not identical due to differences in color characteristics of active WDM components. This causes a different link budget and bandwidth per wavelength (520 nm and 658 nm). The emitting and received optical powers for the green laser are -1.8 dBm and -14.6 dBm, respectively, and +2 dBm and -11 dBm, respectively, for the red laser. Both lasers are biased at 80 mA.

Table I presents the link performance for the WDM-over-POF using DMT modulation without the wireless link. The difference in the crosstalk in both channels is due to the asymmetric channel powers. The red laser has more power than the green laser. The crosstalk from red into the green channel can be further reduced from -13 dB to -25 dB by an extra optical filter, which marginally improves the singular values ξ, but causes an additional loss of 6 dB. For both channels a BER $< 3 \times 10^{-3}$ is obtained, at an averaged received SNR= 12 dB for the green and SNR= 13 dB for the red channel, considering 100 MHz bandwidth. The difference on SNRs and throughput between the two channels stems from an asymmetry in link budget and frequency response per channel.

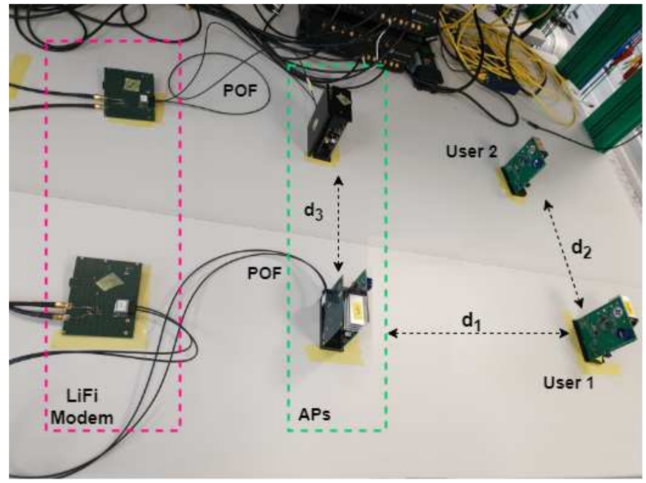


Fig. 3. Experimental setup for D-MIMO over POF with SDM approach

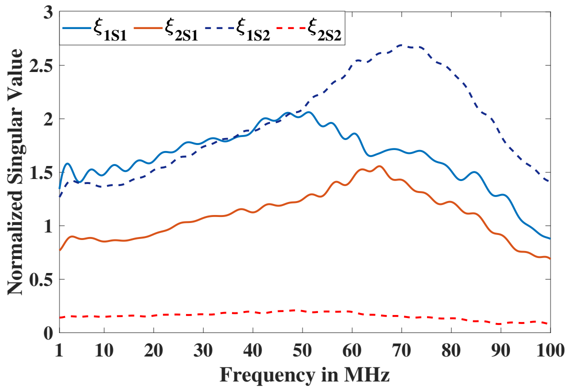
TABLE II
THROUGHPUT EVALUATION OF D-MIMO SETUP IN TWO DIFFERENT SCENARIOS.

D-MIMO SDM		D-MIMO WDM	
Scenario 1	586 Mbps	Scenario 1	484 Mbps
Scenario 2	421 Mbps	Scenario 2	369 Mbps

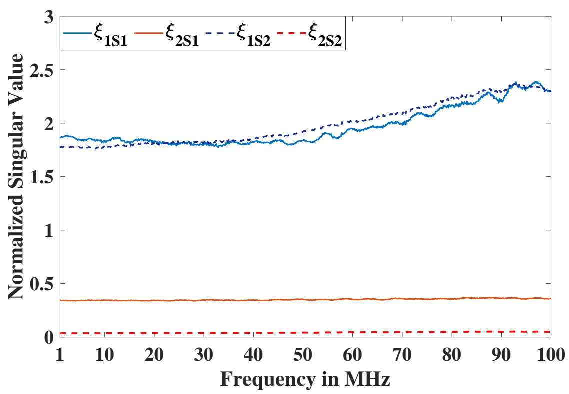
B. D-MIMO Throughput

This section characterizes the downlink channel properties for the 2×2 distributed MIMO system. Fig. 4 demonstrates the singular values of D-MIMO over SDM and WDM channel for two scenarios. In scenario 1, results indicate that two parallel data streams are possible and full spatial multiplexing can be used. In scenario 2, the mobile devices are too near to each other so that there is only one strong singular value, establishing a single degree of freedom, which means that only one data stream can be transmitted at the same time. This situation is in principal the same but slightly worse when including WDM-over-POF, when asymmetric losses and residual cross-talk are added.

From the singular values of $\mathbf{H}(f)$ and, by assuming the average SNR equal to 20 dB, the achievable data rate has been calculated according to (6). Performance is obtained for the two scenarios considering both cases, SDM- and WDM-over-POF including the wireless link. Throughput results are shown in Table II. From the table, it is clear that throughput of SDM as feeder is little higher than WDM. As the POF channels are spatially separated by independent fibre links in the SDM case, there is no spectral overlap between the channels, which increases the data rate. But more cables are needed on the ceiling. The WDM performance suffers from lower optical power of the green laser and lower responsivity for the green light. Most of the throughput comes from only one data stream in both scenarios 1 and 2. A potential way to overcome this issue is by using power loading techniques



(a)



(b)

Fig. 4. Down-link normalized singular values for SDM (a) or WDM (b), ξ_{1S1} and ξ_{2S1} for Scenario 1: spatially separated RX (solid lines) d_1 = 100 cm, d_2 = 70 cm, d_3 = 70 cm, and Scenario 2: (dashed lines), ξ_{1S2} and ξ_{2S2} for Scenario 2: co-located RX: d_1 = 50 cm, d_2 = 5 cm, d_3 = 35 cm.

in the spatial domain to designate more power to weaker channels. This is beyond the scope of this study and left for future work. An additional result comes from the comparison between Table I and Table II. As can be seen from Table I, the WDM link alone provides very high performance and the throughput reduces by adding the wireless link. Therefore, the overall link is mostly limited by the OWC link, not by the POF.

Conclusions

In this paper, we present a distributed MIMO link for optical wireless transmission combined with POF as a fronthaul using SDM and WDM techniques. For SDM we use multiple POFs to distribute the signal to the optical frontends, while for WDM we use multiple colors. A common signal model is proposed to evaluate the performance of the LiFi link, including characteristics of the fixed and wireless links. A first experimental setup for D-MIMO is presented. The performance of the link is evaluated for two scenarios in which access points and users are located apart or close to each other. The results show that the performance is mostly limited by the wireless link and it depends on the location of APs and mobile users. By placing APs and users at a reasonable distance, the throughput performance is increased. For closely-spaced users, diversity is better used than spatial multiplexing. Future work will focus on combining these fronthaul techniques into a prototype system and deploying it in a real scenario.

Acknowledgments

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References

[1] V. Jungnickel *et al.*, "Optical Wireless Communication for Backhaul and Access," in *2015 European Conference on Optical Communication (ECOC)*. IEEE, 2015.
[2] P. W. Berenguer *et al.*, "Optical Wireless MIMO Experiments in an Industrial Environment," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 1, pp. 185–193, 2017.
[3] P. W. Berenguer *et al.*, "Real-Time Optical Wireless Mobile Communication With High Physical Layer Reliability," *Journal of Lightwave Technology*, vol. 37, no. 6, pp. 1638–1646, 2019.
[4] S. M. Maravanchery *et al.*, "Distributed MIMO Experiments for LiFi in a Conference Room."
[5] S. M. Kouhini *et al.*, "Use of Plastic Optical Fibers for Distributed MIMO in Li-Fi Systems," in *2019 Global LIFI Congress (GLC)*. IEEE, 2019.
[6] S. M. Kouhini *et al.*, "Performance of Bidirectional LiFi over Plastic Optical Fiber (POF)," in *12th IEEE/IET International Symposium on Communication Systems, Networks and Digital Signal Processing-CSNDSP*. IEEE, 2020.
[7] V. Jungnickel *et al.*, "Capacity of MIMO systems with Closely Spaced Antennas," *IEEE Communications Letters*, vol. 7, no. 8, pp. 361–363, 2003.
[8] E. Biglieri *et al.*, *MIMO Wireless Communications*. Cambridge University Press, 2007.
[9] C. R. B. Correa *et al.*, "POF Feeding in Li-Fi systems with MIMO Approach," in *24th annual IEEE Photonics Benelux Symposium 2019*. IEEE, 2019.
[10] W. O. Popoola *et al.*, "Hybrid Polymer Optical Fibre and Visible Light Communication Link for In-home Network," in *2017 26th Wireless and Optical Communication Conference (WOCC)*, 2017.
[11] a. o. Jončić, "Four-channel wdm transmission over 50-m si-pof at 14.77 gb/s using dmt modulation," *IEEE Photonics Technology Letters*, vol. 26, no. 13, pp. 1328–1331, 2014.
[12] T. Fath and H. Haas, "Performance Comparison of MIMO Techniques for Optical Wireless Communications in Indoor Environments," *IEEE Transactions on Communications*, vol. 61, no. 2, pp. 733–742, 2013.
[13] J. M. Kahn and J. R. Barry, "Wireless Infrared Communications," *Proceedings of the IEEE*, vol. 85, no. 2, pp. 265–298, 1997.
[14] T. E. Bitencourt Cunha *et al.*, "Throughput of Optical WDM with Wide LED Spectra and Imperfect Color-detecting Filters," in *2020 29th Wireless and Optical Communications Conference (WOCC)*, May 2020.
[15] V. Jungnickel *et al.*, "Capacity Measurements in a Cooperative MIMO Network," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 5, pp. 2392–2405, 2008.
[16] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge university press, 2005.
[17] G. J. Foschini and M. J. Gans, "On Limits of Wireless Communications in a Fading Environment when using Multiple Antennas," *Wireless Personal Communications*, vol. 6, no. 3, pp. 311–335, 1998.
[18] S. Mardani *et al.*, "Sub-carrier Loading Strategies for DCO-OFDM LED Communication," *IEEE Transactions on Communications*, 2019.