Bidirectional WDM-over-POF with Spatial Diversity DMT Gigabits per Second Transmission Using POF as Luminaires

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Abstract *A bidirectional spatial diversity link for indoor optical wireless communications applying wavelength division multiplexing over 1mm core size plastic optical fibre and 1m free space is experimentally demonstrated. Discrete multitone modulation on red and green wavelengths demonstrates almost symmetrical 2Gbps for down/uplink.*

Introduction

The increasing demand on wireless connections is leading to the overcrowd of the electromagnetic spectrum. This leads to a search for new opportunities in the electromagnetic spectrum. One of the main options is the optical wireless communication (OWC), which offers high bandwidth in the unlicensed light spectrum. A promising solution among the OWC is the visible light communication (VLC), a.k.a. LiFi. The main advantage of LiFi is to provide both illumination and data communication, which can be incorporated to the already existing lighting. Light emitting diodes (LEDs) are usually used as the light source for the LiFi systems[1]. Although being low cost, the already existing illumination LEDs have narrow bandwidth and high nonlinearity, thus limiting their application. Other LEDs techniques, such as small area LEDs (μ-LEDs) can provide larger bandwidth. However, these LEDs suffer from efficiency droop, needing additional techniques to mitigate this and consequently increasing the price and undermine the reasons to use them[2]. In our previous work we proposed to use optical fibres that are remotely fed by a broadband laser diode (LD) that it is centrally located in the house [3]. The main advantage of this system is that the ceiling units are passive, requiring no electrical powering and no maintenance, which brings operational benefits.

Several optical networks infrastructure can be used to carry the data from the home central unit to each room. The silica fibres, single- or multi-mode, have low losses and excellent transmission performance, however, they require professionals for installation which increases the price, thus they are not easy to deploy in a home network. To overcome these problems, we propose to use the 1-mm core size polymethyl methacrylate (PMMA) step index (SI) plastic optical fibre (POF). This standard POF is considered due to its low cost, due-it-yourself (DIY) technology[4]. In addition, this POF works in the visible wavelength, which enables visual link testing, that eases the installation. A major drawback for POF is its strong intermodal dispersion, which can be overcome by the use of efficient modulation formats and Gbps transmission can be achieved[5]. Wavelength division multiplexing (WDM) can also be used to increase throughput. In addition, the use of WDM enables the use of distributed multiple input multiple output (D-MIMO) in the wireless link, which supports user's mobility density variation and guarantee a consistent link performance[6, 7]. With the use of D-MIMO and spatially diversity, the major drawback of the OWC systems, the lack of connection with blockage of the line-of-sight, can for a large part be overcome.

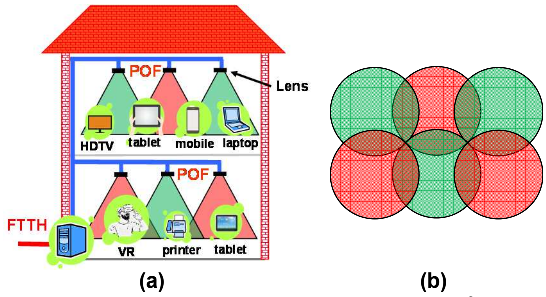

Fig. 1: An in-home network employing luminaire-free LiFi transmission systems using POF and lens (a) and footprint of the luminaires showing partly overlapped areas (b).

For these reasons this work proposes a spatial diversity concept using two-POF based luminaires transmission. The wireless channel is composed by two POF-end faces: 658nm (red) and 520nm (green), with a lens placed in a defocused position to extend the coverage area, and consequently increase the number of users, as seen in Fig. 1. We demonstrate an almost symmetrical peak data rate of 2Gbps for down/uplink. We believe that this setup is scalable to have more wavelength channels, thus more throughput and more dense coverage, and it can be combined with spatial multiplexing for increasing network flexibility.

WDM-over-POF for spatial diversity

Fig. 1(a) shows the concept of the proposed in-home network, where the LiFi provides the last meter connectivity. The connection between the central unit and each room is realized by POF. The user devices receive the wireless signal from the POF-end faces. Due to its large numerical

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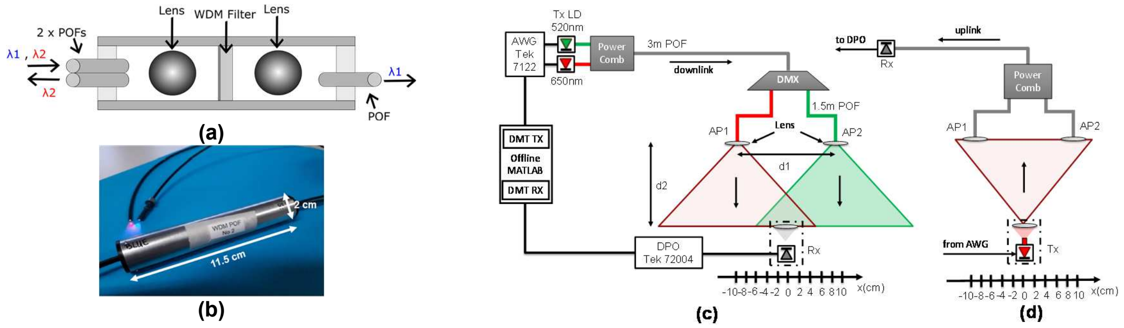

Fig. 2: Schematic of the DEMUX (a), prototype of the DEMUX (b) and schematic of the WDM-over-POF with VLC link for the downlink (a) and uplink (b).

aperture (NA=0.5), light out of POF is strongly diverged. At the ceiling, a lens placed in front of the POF-end marks the area to be covered. The lens can be placed in a focused (narrowing) or defocused position (enlarging the area), thus adapting to the number of users to be served and allowing for user mobility.

The WDM is characterized by the performance of multiplexer (MUX) and demultiplexer (DMX). A MUX combines all input wavelength channels to a single output and its performance is mainly characterized by insertion loss of each channel. The characterization for the DMX is realized regarding insertion loss and crosstalk, leakage that can occur due to insufficient separation between adjacent channels. Such crosstalk effects need to be carefully minimized. The schematic used for implementing this approach can be seen in Fig. 2(a). It consists of two confocal ball lenses system, where the fibres are situated at the front and back focal points. Between these lenses an optical WDM filter is fitted, separating the two wavelengths. The coating on the filter reflects the lower wavelength (405 nm, blue or 520 nm, green) back through the first ball lens and couples into the receiving POF. The fibres are aligned in parallel to each other and the claddings are touching. The higher, red wavelength passes through the filter and the second ball lens to be couple out to the other receiving fibre. The optical cut-on wavelength is 605 nm. The prototype is presented in Fig. 2(b), it is compact and can be used as MUX or DEMUX and can easily be placed on the ceiling.

The system's diagram for the downlink is presented in Fig. 2(c) and for the uplink in Fig. 2(d). The architectures for the downlink and uplink are different because the light from a mobile device can be at any color and therefore the uplink receiver must be wavelength transparent. To implement the downlink two DFB LDs and one 2x1 power combiner are used at the transmitter side. The power combiner used is from Diemount and has loss of 1.8dB. The LDs emit visible wavelength at 520nm (green), with emitting power of -1.8dBm, and 658nm (red), with emitting power of +2dBm. Both LDs are directly modulated in their linear region and butt-coupled into the POF. After passing through the power combiner, the multiwavelength beam is transmitted through 3m POF and then demultiplexed. In the POF-end face, a lens is placed in a defocused position and a coverage area of 30cm diameter is created, as seen in Fig. 3. In the receiver side, the signal is received and detected by an optical receiver composed by a silicon photodiode (PD) and a transimpedance amplifier (TIA). The receiver has a bandwidth of 1.2GHz. The receiver sensitivity is wavelength dependent and the sensitivity for the green is around 50% of the red light. Consequently, more power is needed for the green light to achieve similar performance as the red light.

For implementing the uplink in the transmitter side, the red LD is used as the light source, the signal then reaches the wireless channel and in the receiver side the beam is coupled into 4m POF. The signals then pass through the power combiner and then 1m POF and reaches the PD receiver. The power combiner is used to make the uplink wavelength transparent. To evaluate the link performance when a user moves from one cell to another a transmission using discrete multitone (DMT) modulation is realized.

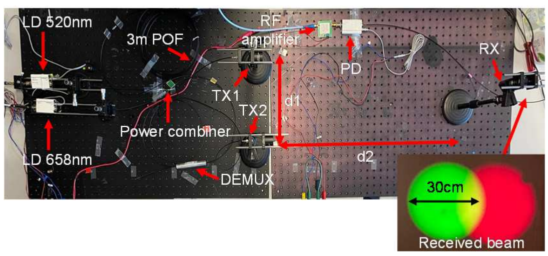

Fig. 3: Experimental setup using 2 wavelength channels.

Results

To characterize the WDM-over-POF the losses caused by light coupling and crosstalk due to the leakage between adjacent channels are measured with the Yokogawa optical spectrum analyser (OSA). A crosstalk of -15dB and loss of

3.4dB is measured for the green channel and a crosstalk of -28dB and loss of 4dB for the red. The asymmetric losses and crosstalk level are related to the different emitting power of each LD and lower losses in the reflected path. To evaluate the performance of the system and provide higher spectral efficiency, a DMT modulation format is used. DMT is a baseband form of the orthogonal frequency division multiplexing (OFDM), however, DMT has a prior knowledge of the channel that allows the use of bit and power loading to optimize the signal. Passband parallel signals using quadrature amplitude modulation (QAM) are transmitted. One pilot signal with 64 subcarriers is transmitted to estimate the channel. The 64 subcarriers are used to maximize throughput with a BER with values around 1E-3. One drawback of the DMT is its high peak-to-average power ratio (PAPR). A clipping (ratio between the max allowed peak amplitude and the rms amplitude) of 9dB is used to reduce the PAPR and limit the dynamic range. The signal to fed both red and green channels, is generated by the Tektronix arbitrary waveform generator (AWG) 7122, thus the same data is used to feed the two access points (APs). The AWG is used as a digital-to-analog (DAC) converter. After being generated by the AWG the signal goes through the MUX, then DEMUX and reaches the VLC channel. The VLC channel performance is measured by moving the receiver in the x axis. The distance between each AP (d1) is set as 20cm and the distance between AP and user (d2) is 1m. In the detection side the signal is received by the PD and then enters the analog-to-digital converter (ADC) and it is sampled by 50GSa/s by the digital phosphor oscilloscope (DPO). To deploy signal-to-noise ratio (SNR), throughput and BER counting, an offline signal processing is realized.

In Fig. 4 the throughput per receiver position is presented for downlink and uplink. For the downlink, red squared curve, it can be noticed that in position inside the overlapping area the performance is decreased. This is caused by destructive interference that happens because of the different optical path and by the fact that two different light sources are used making interference difficult to manage, in contrast with our previous work where a single source was used[3]. It is also possible to notice a difference in the performance for AP1 and AP2, this is caused by the difference in emitting power of each LD and receiver sensitivity at each wavelength. For the uplink, represented by dotted blue line curve, the performance is almost constant. This is attributed to the wavelength transparent architecture of the uplink. The performance is slightly better than the downlink because the losses provided by this architecture are lower, no DMX in uplink. The difference in the performance of each user position is related to the received signal strength that increases or decreases the SNR, and consequently affecting the throughput. In Fig. 4 the constellations for the down/uplink are presented. It is possible to notice that a clear separation among the levels can be seen, even for the position 0, representing an excellent performance of the system. The longer wireless link and the high crosstalk in the overlapping area decrease the link performance, however, we believe that the influence of crosstalk can be mitigated by digital signal processing in the receiver.

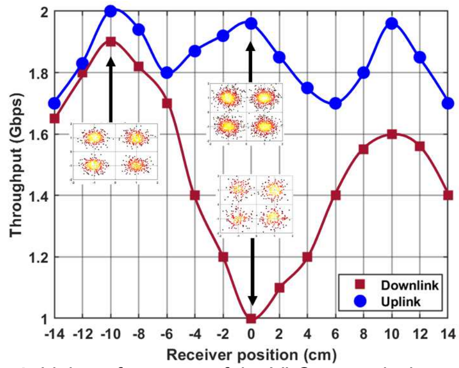

Fig. 4: Link performance of the VLC transmission with WDM-over-POF for downlink and uplink applying DMT modulation.

Conclusions

A bidirectional spatial diversity indoor system with WDM to accommodate non line of sight and user movements was presented. The experimental results were given for downlink and uplink using two channels, one at 658nm and the other at 520nm. The DMT modulation was used to characterize the system's performance and a total peak throughput 1.9Gbps was achieved for downlink and 2Gbps for uplink. The decrease in the performance in position 0 is related to the high crosstalk experienced in the receiver. In addition, the asymmetric performance in the downlink among the two channels is related to the different emitting power of each LD and receiver's sensitivity. Further work will include the optimization of the receiver, reduction of the effect of the downlink crosstalk and use of spatial multiplexing. We showed that the proposed POF as luminaires system is a potentially low-cost and an attractive technique to increase high-capacity indoor systems.

Acknowledgements

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