Optical Beam Steering using Mode-Coupling Control in Plastic Optical Fibre

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Abstract: An all-fibre beam steering solution, based on mode coupling in 240-μm core size POF, is presented. Using DMT modulation over 90-cm wireless link and steering full angle of 9°, a throughput of 1.6 Gbps is achieved for visible light.

1. Introduction

The high demand for bandwidth caused by the growth in wireless interconnected devices, on the Internet of Things (IoT), leads to a congestion in the electromagnetic spectrum. For this reason, new spectrum must be considered. Optical wireless communication (OWC) is a key option as it offers large bandwidth in the unlicensed optical spectrum. Two technologies are leading the OWC study field, the beam-steering and visible light communication (VLC). Several methods have been proposed to implement beam steering, such as active and passive techniques. Passive beam-steering can be realized by the use of diffraction gratings, arrayed waveguide gratings and virtually imaged phased array [2-4]. The active beam-steering techniques can be implemented using optical phase arrays, steering mirrors, and spatial light modulators (SLMs) [5-7]. Traditionally, SLMs shape the wavefront pixel-by-pixel. In order to have enough space on the control electrodes of each pixel, the spacing among adjacent pixels cannot be reduced, which results in limited resolution and grating lobes. The use of momentum spaced controlled SLMs (MSC-SLMs) can overcome this limitation, once the wavefront of the incident signal is decomposed in multiple orthogonal modes, and in consequence, the desired wavefront shaping is synthetized in real space. In this paper we focus on the MSC-SLMs, because it is an all-fibre method, it does not require any device like liquid crystal SLM, mode (de)multiplexers or MEMS. In [7], the use of MSC-SLMs using multimode fibres (MMFs) and mode-coupling controllers (MCCs) was presented. In this paper we propose to replace the MMF by plastic optical fibres (POFs). POFs have been one of the main technologies considered for short reach transmission due to their do-it-yourself solution and electromagnetic interference (EMI) free. In addition, the POF used in this paper operates in the visible wavelength range (400 – 700 nm), which enables visual link testing and eases the installation. The major drawback of this type of POF the high losses when used in long distances. For this reason, POFs are commonly used for indoor scenarios, with lengths up to 100m. In this paper we make use of the modal dispersion in the POF as an advantage in our system. Once we can control the mode coupling, we can shape the optical signal wavefront and use it to steer the beam. *The work is performed in the EU-H2020 825651 project ELIoT (Enhance Lighting for the Internet of Things).*

2. MSC-SLM POF beam steering concepts

Steering narrow optical beams has an advantage that optical power is used efficiently since majority of the optical power is directed to users, see Fig. 1(a). WDM signals are transmitted through POF and are demultiplexed to form several access points (APs), i.e. each AP emits light at a different wavelength, which is then sent wirelessly to users. Each AP is equipped with a beam steerer which directs the light to users positioned at a certain angle θ_1 or θ_2 from APs. In our concept, we used the POF ESKA SK-10 that has a core diameter of 240 μm, thus not the standard 1-mm core diameter POF because the thicker the core the larger number of modes will be excited and more difficult the mode coupling control will be. As previously mentioned, POFs suffer from modal dispersion due to the large number of modes propagate through the fibre. However, when geometrical changes or index imperfections, such as bending, applying pressure, twisting, it is possible to select a mode or introduce coupling from one mode to another. Thus, if the mode coupling control can be realized, we can use it to shape the wavefront of the optical signal coming from the POF. Several devices can be used as mode couplers for POF, but in this work we used the idea of the cylinder mixer, where the fibre passes through the cylinders forming "eights". In addition, we also couple the light into the fibre with an angle, and in consequence, not all the modes will be filled during transmission through POF.

The ESKA POF is connected to a red laser diode (λ=658 nm) and then POF loops are made in the mode converter. With the bending and tension applied in the POF, we can control the mode coupling and, consequently, the distribution of the light field in the fibre. This system is called fibre-based SLM (F-SLM). After the F-SLM, the light is transmitted through a collimator and then a lens is placed in a defocused position, as presented in the schematic in Fig. 1(b). The idea behind the system is that when changing the number of loops and increasing tension in the POF, we can excite few modes, and not all of them. Thus, in an area of 15 cm in diameter, we can steer the mode in a specific angle, as seen in Fig. 1(c-f). With our system, we realized a beam forming in this 15-cm region after 90 cm VLC channel propagation, achieving a steering angle of approximately 9°.

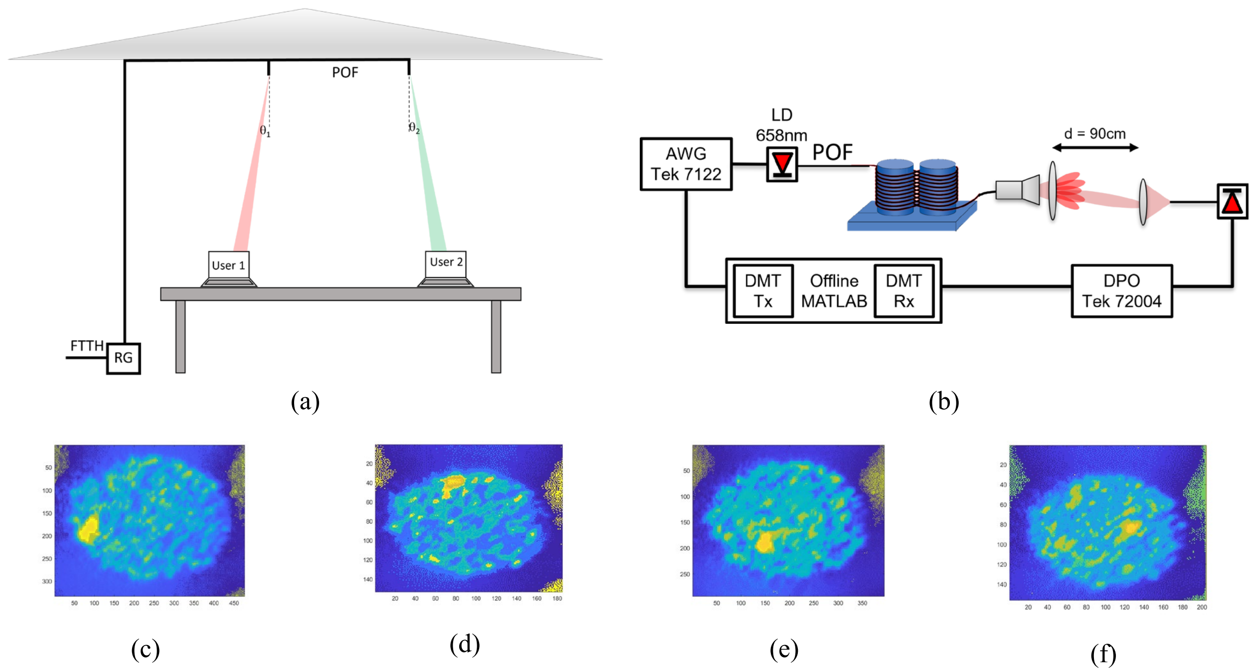
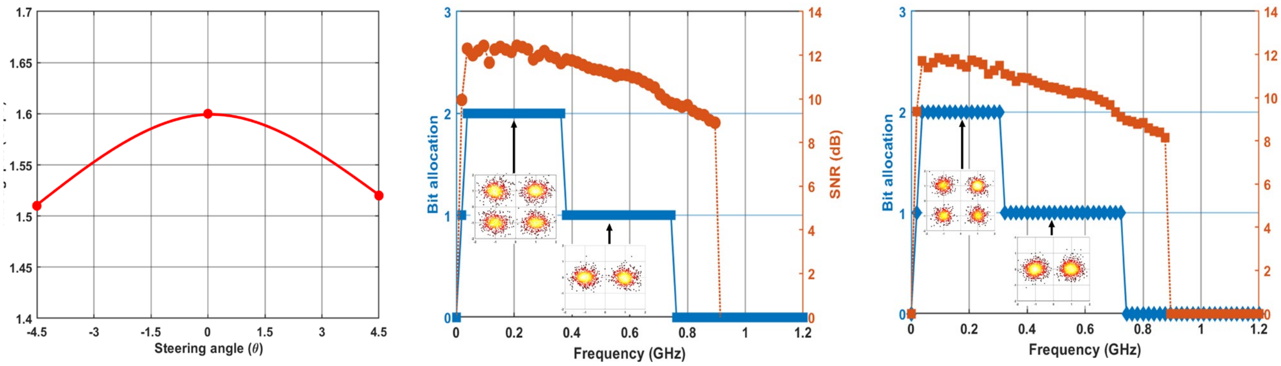


Fig. 1. Concept of indoor communication network using POF and narrow beams (a). Schematic setup (b) where the red path refers to the optical wireless link and output patterns of different positions of beam-steering (c-f).

3. Experimental results

To evaluate the system's performance and achieve high spectral efficiency, a discrete multitone (DMT) modulation is used. DMT is the baseband form of the orthogonal frequency division multiplexing (OFDM) that has a prior knowledge of the channel, which allows use of power and bit loading to optimize the system. Passband parallel signals are transmitted using quadrature amplitude modulation (QAM). In our system a pilot signal with 64 subcarriers is transmitted to estimate the channel. The 64 subcarriers maximize the system's throughput guaranteeing a bit error rate (BER) below the FEC level (< 1E-3). The major drawback of DMT system's is its high peak-to-average power ratio (PAPR), however, this can be overcome with the use of a clipping (ratio between the maximum allowed peak amplitude and the rms value amplitude). In addition, the use of clipping also limit the dynamic range of the signal.

The signal is generated by an arbitrary waveform generator (AWG), that is used as a digital-to-analog (DAC) converter, and the data then fed the red laser. After being generated, the signal follows through the POF, passes the mode converter and then a triplet collimator, with an effective focal length of 18mm, followed by a plano-convex lens. It then reaches the VLC link, that has a length of 90 cm between transmitter and receiver. At detection, the signal is received by a receiver composed by a photodiode and a transimpedance amplifier, and it is then sampled at 50 GSa/s by a digital phosphor oscilloscope (DPO), that is used as an analog-to-digital (ADC) converter. Afterwards, an offline signal processing is realized to estimate throughput, signal-to-noise ratio (SNR) and BER counting. The measurements were realized in three different positions, so we could analyze the system's performance when the beam is steered in the middle of the coverage area, represented by angle 0°, and in the boarder of the coverage area, represented by the angles -4.5° and 4.5°. The throughput results for the system can be seen in Fig. 2(a). It is possible to note that the highest throughput is achieve when the beam is steered in the middle, this happens because the received power is higher at this position, consequently improving the system's performance. However, once our coverage area is small, the impact on the system's performance when the beam is steered in the boarders, is not so significant. In Fig. 2(b) the SNR and bit allocation for the user placed at 0° angle is presented. In addition, the constellation for each bit allocation is presented, and a clear and equal separation among the levels can be seen, which indicates a good performance. All the presented results have a BER below the FEC level (< 1E-3).



(a) (b) (c)

Fig. 2. Link performance of the proposed all fibre beam steering with POF: (a) Total throughput vs steering angles, and (b) received SNR and bit allocation at 0° angle and (c) at -4.5° angle.

3. Conclusions

We presented an all-fibre beam steering using POFs operating at a single wavelength, where we take advantage from the mode coupling to shape the wavefront of the signal. Our system has a VLC link of 90 cm and a steering angle of approximately 9° (full angle). To evaluate the system's performance, we realized transmissions using DMT modulation format and achieved 1.6 Gbps throughput when the beam is steered with a 0° angle. When the beam is steering with -4.5° or 4.5° angle, the received power is lower, but is still able to achieve more than 1.5 Gbps. The experimental results are given for the link using single color light source. However, the concept is expandable to include multiple wavelengths in the feeder POF to make, by using a wavelength demultiplexer, multiple access points, each employing a beam steerer to serve multiple users. To increase the steering angle, a better mode control mechanism is required, which can be realized by using piezoelectric actuators. In addition, the steering angle can also be increased by using special lenses, such as four-element, air-spaced lenses, that can provide high beam quality. Once this system is an all-fibre solution, it brings operational and installation benefits which include low losses, wide availability of components and relatively easy to make. We believe that this concept could make POF-based indoor wireless networks to be highly power efficient in obtaining gigabit-per-second throughputs.

4. References

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