High-Density Indoor Optical Wireless Communication by Directed Narrow Beams

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Abstract *An overview is given of our short-reach OWC system concept and key techniques for remote steering of multiple narrow beams, accurate calibration-free user localization, and scalable wide field-of-view receivers. Bidirectional communication of GbE high-definition video services is demonstrated including interfacing to common user laptop equipment.*

Introduction

Optical wireless communication (OWC) by means of narrow optical beams can offer very high density of high-capacity connections to individual users at minimum latency, while offering high privacy and security, and immunity for electro-magnetic interference [1]. Such pencil beams may be regarded as individual virtual fiber connections. For indoor (or other short-reach) OWC systems, some vital key functions are fast 2D steering of multiple beams, automatic localization of the users, and beam reception with wide-aperture wide Field-of-View receivers.

This paper gives an overview of the design and implementation of these key functions, and their integration into an OWC laboratory system demonstrator (scalable to many users) showing all-optical bi-directional GbE communication to individual users.

Indoor OWC

The proposed indoor system architecture (Fig. 1) comprises a fiber backbone network feeding pencil-beam radiating antennas (PRAs) in each room which can emit multiple beams to individual users. The PRA hosts only passive functions for 2D beam steering based on diffractive elements thus enabling the beam steering to be done by tuning remotely the wavelength of the optical sources in a central communication controller unit (CCC). Flexibly routing traffic streams among PRAs is done by the centralized optical cross-connect (OXC). Upscaling to more users does not need modifications in the PRAs, but just adding more wavelengths in the CCC; this eases flexible service provisioning, system maintenance and robustness.

2D beam steering

Beam steering technologies reported include active and passive modules. Active steering modules may use spatial light modulators [2], MEMS micromirrors [3], mechanical source translators [4]; next to the signal's data channel,

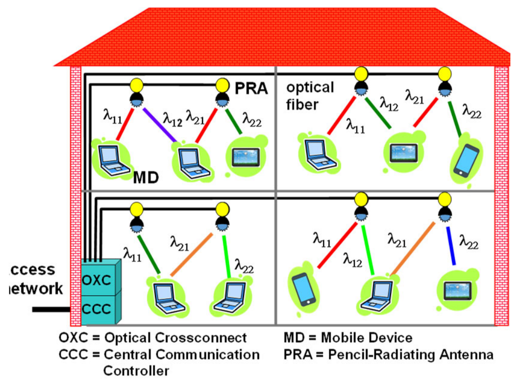


Fig. 1: Indoor OWC system architecture deploying 2D-steered narrow IR beams

they need a separate control channel per user which compromises network control and scalability. Passive steering modules may use diffractive means such as planar diffraction gratings [5], phased array gratings [6], multiple tilted Bragg gratings in a glass volume [7], polarization gratings [8]. Beam steering is done by wavelength-tuning the optical data signal, so the tuning control channel is embedded in the data channel and no separate bookkeeping of data and control channels is needed which eases network management. The λ-tuning can be done as fast as the tunable transceiver in the CCC allows, i.e. in the ns to µs regime, whereas the active modules need tuning times in the ms regime. Hence, we opted for the 2D passive steering, and after exploring a pair of crossed diffraction gratings [9], we have preferred the module based on an large port-count arrayed waveguide grating router (AWGR) of which the fiber output ports are rearranged in a square matrix and put in a slightly defocused position with respect to a large numerical aperture lens (see Fig. 2) [10]. The robust 2D module consisted of a composite C+L$^-$-band AWGR with 144 ports spaced at 50GHz with -3dB bandwidth 35GHz in C- and 24GHz in L$^-$-band, of which 129 ports via the 1D-to-2D interposer could be accommodated in the entry aperture of a commercial f=50mm camera lens with f/D=0.95. By defocussing the fiber array, we created slightly diverging beams with diameter ∅12cm at 2.5m distance; thus, we achieved a full-angle coverage of 35°×35° [10]. In an earlier experiment with only the C-band AWGR and 80 ports, we demonstrated 112Gbit/s PAM-4 transmission, i.e. 80×112 Gbit/s = 8.96 Tbit/s throughput with 17°×17° full-angle coverage [11].

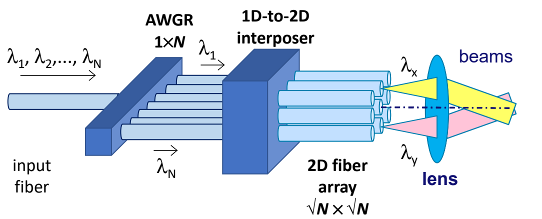
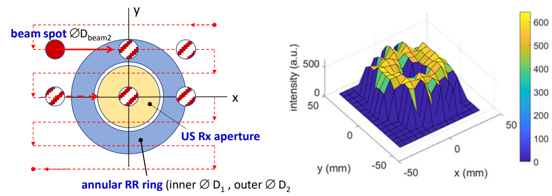


Fig. 2: 2D discrete beam steering employing an AWGR

Localization

Steering the beams requires accurate localization of each user. This may be done by e.g. triangular algorithms with active beacons at the room's ceiling [12], or camera observation of LED tags at the user device [13][14]; these methods require power-consuming functions at the (typically battery-operated) user device. Moreover, they need return communication paths to close the steering control loop, which are not present when initializing the link setup. In order to avoid this chicken-and-egg issue and to minimize power consumption at the user, we devised a single-sided optical localization method by means of an optical retro-reflector ring (RR ring) [15][16]. The RR ring was made out of circular foil containing a dense matrix of miniature corner cube reflectors, and was mounted around the receiver's aperture. By scanning with a narrow optical beam, the intensity of the reflected light is measured at the transmitter side. From the crater-shaped intensity pattern, the center of the receiver's aperture is localized accurately by a center-of-gravity algorithm (implemented in an Arduino). It may be noted that, by using retro-reflection and beam scanning, this process is auto-calibrating, and does not need further bookkeeping to map user location to the correct wavelength for the beam-steering. Moreover, unlike in the camera-based observation method, no parallax error to be compensated is incurred.

For the downstream localization, scanning the whole user area (129 cells) took some 15 seconds, mainly consumed by acquisition of the reflected light and the scanning control software (in LabVIEW) [15]. For the upstream localization, we used mechanical beam steering by moving the upstream laser's fiber pigtail in front of a lens (thus allowing an arbitrary-wavelength laser at the user, which minimizes costs) [16]. We deployed NEMA11 stepper motors with a high 30µm resolution. The localization time was less than 10 seconds, mainly limited by the stepper motor speed. With the +2dBm upstream beam diameter of ∅15mm, receiver aperture of ∅25mm, and RR ring outer diameter of ∅62mm, the location accuracy was better than 40µm, which amply meets the system's needs.



a) scanning the aperture of the upstream receiver
b) monitoring the reflected power from the RR ring

Fig. 3: Localizing the upstream receiver (at the ceiling)

Broadband optical receiver with wide FoV

To establish a high-capacity link, capturing sufficient power from the optical beam without needing tedious alignment of the optical receiver is a key challenge. The receiver should have a large entry aperture combined with a large angular field-of-view (FoV); their joint optimization is compromised by the law of etendue [17]. Wide FoV solutions have been proposed by using non-imaging optics (such as relatively large compound parabolic concentrators, CPCs) [3], by angular diversity receivers (ADRs) using multiple photodiodes followed by individual (power consuming) transimpedance amplifiers (TIAs) [18][19], by breaking etendue's law by wavelength conversion in a phosphorescent slab waveguide [20] or fiber [21], or by separating wavelength collection and detection functions using an integrated optical circuit with surface grating coupler (SGC) and waveguide fast UTC photodiode [22].

To limit complexity and reduce power consumption, we have proposed a receiver architecture deploying a novel 2D matrix of photodiodes (PD matrix) which comprises N×N serial/parallel connected photodiodes [23][24]. It has been shown analytically and proven experimentally that, notwithstanding the N^2 times larger detection area, this PD matrix has the same bandwidth as a single photodiode. Moreover, it needs only a single TIA, thus minimizing complexity and power consumption (particularly noteworthy at the battery-operated user device). Due to the need for a single TIA only, the SNR performance of a PD matrix receiver is better than of an ADR. In combination with a large aperture lens, and by putting the PD matrix in a slightly defocussed position, we showed effective optimization of the compromise between the receiver's FoV and the captured power.

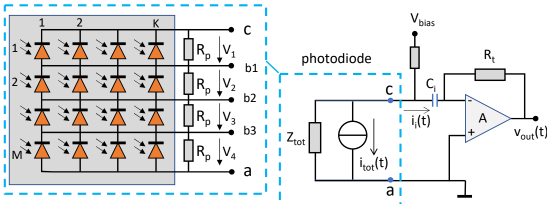


Fig. 4: Wide FoV receiver using matrix of photodiodes

Our PD matrix concept is scalable to larger sizes; this is confirmed for a 20×20 PD matrix in [25]. Fig. 5 shows how the FoV can be significantly increased with respect to a single PD, while preserving its large bandwidth.

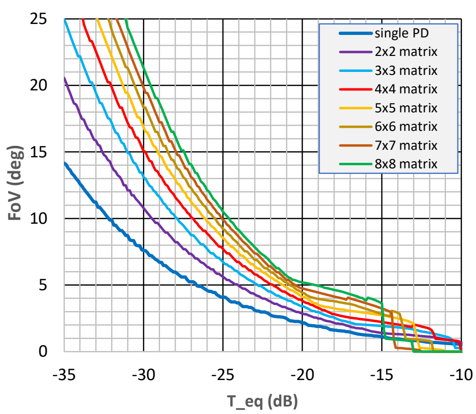


Fig. 5: Increasing the FoV by upscaling the PD matrix (T_eq: equivalent beam-to-PD matrix coupling loss)

Bi-directional OWC system demonstrator

Bi-directional OWC systems were reported which duplicate downstream techniques for upstream (e.g.,[2][3]); this complicates the ceiling module in multi-user systems. In hybrid OWC systems, radio technologies may be used for upstream [27]; however, EMI immunity is compromised.

To preserve all the key benefits of OWC and limit complexity of the ceiling's module, we conceived the bidirectional OWC system setup shown in Fig. 6, in which we have integrated and validated our beam steering, localization and PD matrix receiver techniques in a laboratory system setup. At the user's receiver, the +10dBm ∅100mm downstream beam is captured with a large NA Fresnel lens (*f*=10mm, *D*=50mm) in combination with a 4×4 matrix of ∅150µm PD-s. Our receiver was accommodated into a modified commercial GbE media converter, which provides GbE I/O RJ45 interfaces to user equipment, i.e. a laptop. At the ceiling's receiver, the +2dBm ∅15mm upstream beam is captured with a ∅25mm *f*=5mm Fresnel lens, and the same 4×4 PD matrix. The setup provides successful bidirectional GbE (1.25Gbit/s) operation up to a full-angle FoV of 20°, and live streaming of high-def has been shown [28][29]. For the shared upstream transmission, a TDMA protocol similar to the ones deployed in commercial TDMA PON systems may be deployed [30].

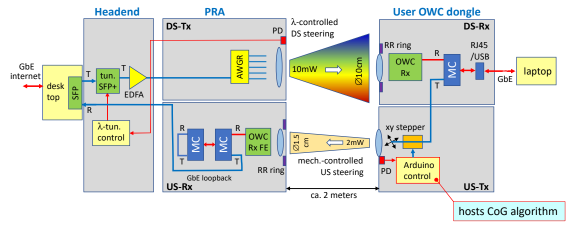


Fig. 6: Bidirectional OWC system demonstrator

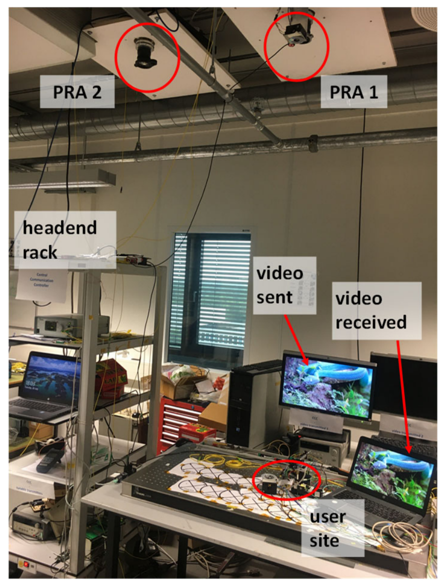


Fig. 7: Bidirectional OWC GbE system demonstrator

Concluding remarks

We demonstrated OWC's capabilities to provide high-speed (GbE and beyond) connectivity to densely spaced users by means of narrow 2D-steered IR beams. Moreover, our laboratory setup includes automatic beam alignment per user without needing user intervention. It showed the practical feasibility of OWC for e.g. high-definition live video streaming and similar broadband applications for nomadic users. Further reduction of localization times (presently limited by hardware speeds) may enable also full-mobility support.

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