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Bi-directional All-Optical Wireless Communication System with Optical Beam steering and Automatic Self-Alignment

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Abstract *A Gigabit Ethernet bidirectional OWC system with user-hosted automatic alignment of the upstream beams is demonstrated, using miniature retroreflectors and novel self-alignment algorithm. It provides individual narrow beams for high user densities. TCP measurements show transfer speeds of 940Mbit/s per user within 10 degrees Field-of-View. ©2022 The Authors*

Introduction

Optical wireless communication by means of 2D-steered narrow infrared beams (BS-OWC) holds great promise to surmount the bottlenecks of today's radio wireless systems, such as heavy congestion in WiFi networks. The infrared beam's small footprint enables users to be connected at high user densities without sharing capacity (which LiFi systems cannot); the individual wireless links each offer sufficient power budget (within eye safety limits) to allow a high data capacity with high privacy [1]. Most BS-OWC systems reported so far focus on downstream connectivity only. In [2], we showed GbE video streaming by downstream BS-OWC links with wide field-of-view. Bidirectional beam-steered systems reported mostly employed hybrid links (optical beam down, mm-wave radio up) [3][4][5]. Hybrid links, however, do not preserve the key advantages of OWC, such as security against eaves-dropping and EMI immunity. Alternatively, all-optical bidirectional systems reported simply duplicated the downstream link into an upstream one, e.g. using MEMS mirrors [6], or SLMs [7], or cover very short distances such as for docking systems [8]. It should be noted that in an indoor network, however, the downstream OWC links are typically emerging from a common point-to-multipoint (P2MP) multicasting unit mounted at the room's ceiling, whereas the upstream links are MP2P links from each user device to the ceiling's upstream receiver. Such asymmetry is not optimally served by duplicating the downstream link into an upstream one.

In this paper, we introduce and demonstrate an all-optical bidirectional BS-OWC system. It expands our previous BS-OWC GbE downstream-only video streaming system with a beam-steered GbE upstream link per user, established by automatic self-alignment.

System architecture

Fig. 1 shows the architecture of our all-optical bidirectional OWC system. The ceiling central unit hosts the passive pencil-radiating antenna (PRA) unit which directs narrow downstream (DS) optical beams in 2 dimensions according to their wavelength; the DS data are fed from λ-tunable laser transmitters [9]. Thus, each user is DS-connected by his private λ-beam (λ_1, λ_2, ...).

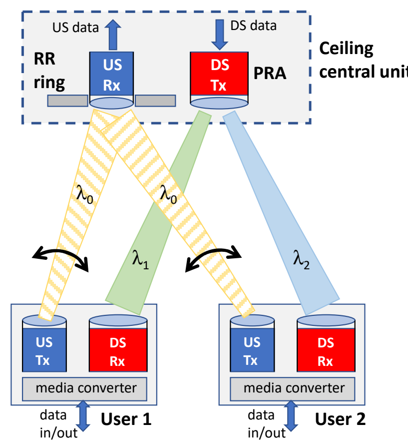


Fig. 1 Bidirectional BS-OWC system with automatic upstream beam self-alignment

For upstream, a beam with arbitrary wavelength (λ_0) is preferred, in order to avoid costly λ-tunable sources and their control circuitry. The upstream beam steering in 2 dimensions from the upstream transmitter (US Tx) towards the upstream receiver (US Rx) at the ceiling central unit therefore is done by mechanical means. This typically requires an optical feedback loop from the ceiling unit to each user to aid the pointing of the upstream beam and establishing the upstream path; it requires to set up the DS path first. To circumvent this bootstrapping issue, we propose a ring of retro-reflecting miniature corner cubes (RR ring) which surrounds the aperture of the upstream receiver (US Rx). Such RR ring can be cut from commercially available RR foils commonly used for e.g. road signage; we have demonstrated passive user localization with such RR foil technology before [10]. At the user, the US power reflected from the RR ring is monitored and enables automatically aligning the US beam to the US receiver, employing a dedicated RR hole-seeking algorithm. Multiple users can deploy the RR ring simultaneously for their US beam alignment, as the RR ring reflects an US beam to its originating user only. The US receiver at the ceiling will receive US beams from multiple users, so an US medium access control protocol is needed, e.g., a TDMA protocol similar to the ones in commercial TDMA PON systems [11].

Upstream optical path design

Fig. 2 shows the design of the US optical path, starting at the user site and covering a distance *d* ending at the PRA site at the ceiling. Similar to the DS path design [9], we choose some defocusing of the fiber w.r.t. the user's lens 1 in order to obtain a slightly diverging US beam which eases US alignment. Using thin lens analysis, the US beam diameter D_{beam2} at the PRA site with defocusing $p_1=1-v_1/f_1$ is

$$D_{beam2} = 2\,p_1 \tan\alpha_1 \left[d + f_1 \cdot \left(\frac{1}{p_1} - 1\right)\right]$$

The spot diameter D_c at the photodiode PD at the PRA site after lens 2, with some defocusing $p_2>0$ too which enlarges the receiving Field-of-View half-angle (FoV) α (see [2] for more details):

$$D_c = 2\,p_1\,tan\,\alpha_1 \cdot \left[f_2 + p_2\left\{d + f_1 \cdot \left(\tfrac{1}{p_1} - 1\right) - f_2\right\}\right]$$

$$\tan\alpha = \frac{|D_c - D_{PD}|}{2\,f_2\,(1-p_2)}$$

where D_{PD} is the photodiode's diameter.

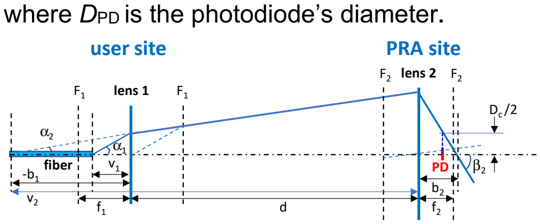


Fig. 2 Design of upstream optical path

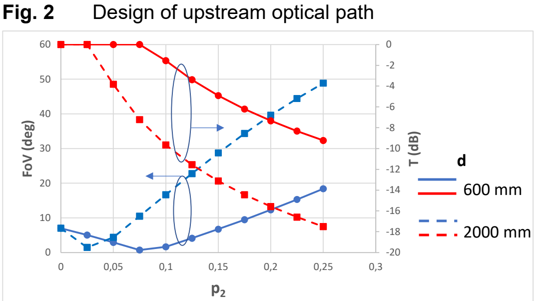


Fig. 3 Upstream beam coupling to US receiver (US beam spot D_{beam2}=15mm)

Assuming a uniform beam power profile and neglecting lens aberrations, a US beam diameter D_{beam2}=15mm needs a defocusing p_1=8.70% at a user-ceiling distance *d*=60cm, and p_1=2.53% at *d*=200cm. Fig. 3 shows how the beam-to-PD power coupling factor *T* and the half-angle FoV α depend on the defocusing p_2. Accepting $T>-10$dB implies $p_2<10\%$ and thus FoV $\alpha<17$ deg. which exceeds the FoV for the DS Rx (about 10deg., see [2]), as required.

Upstream beam steering

The US beam is steered in 2D by displacing the output fiber of the US transmitter laterally over Δx and/or Δy with respect to the axis of the US lens 1, as shown in Fig. 4.

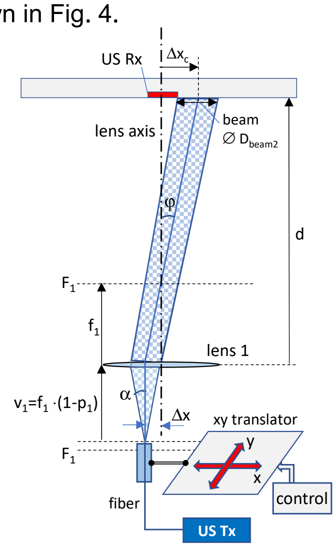


Fig. 4 2D angular steering of US beam

The xy translator stage uses NEMA11 stepper motors, driven by an Arduino controller board. The effective lens aperture of the lens limits the displacement Δx to $\Delta x_{max} = \frac{1}{2} D_{lens} - f_1(1-p_1)\tan\alpha$. The achievable maximum US steering angle is $\varphi_{max} = \operatorname{atan}\left[\frac{D_{lens}}{2\,f_1} - (1-p_1)\tan\alpha\right]$, and the lateral steering resolution at the US Rx site at the ceiling is $\delta x_c = \varepsilon_x \cdot (d/f_1 - 1)$ where ε_x is the resolution of the xy stepper motor stage. E.g., with a D_{lens1}=11.5mm and f_1=20mm with p_1=0.0271 for a US beam diameter D_{beam2}=15mm, and ε_x=30nm, the steering resolution δx_c=2.97mm and max. US steering angle φ_{max}=10.8 deg. which exceeds the max. DS steering angle of 10 deg. [9] as required.

Automatic upstream beam alignment

By scanning the US beam over the RR ring around the US Rx aperture, alignment of the US beam is automated. Fig. 7 illustrates the scanning in x- and y-direction, and Fig. 6 shows the analytical and experimental results of monitoring the reflected beam's power at the US Tx site.

Using the monitored power results $\{p_i\}$ taken at vector positions $\overline{r_i} = \binom{x_i}{y_i}$, the center of gravity(CoG) vector of the RR ring is

$$\overline{CoG} = \binom{x_{CoG}}{y_{CoG}} = \frac{1}{P_{tot}} \sum_{i=1}^{N} p_i \binom{x_i}{y_i} \text{ with } P_{tot} = \sum_{i=1}^{N} p_i$$

As the US Rx aperture is centered inside the RR ring, localizing the CoG by scanning also yields automatic alignment of the US beam into this

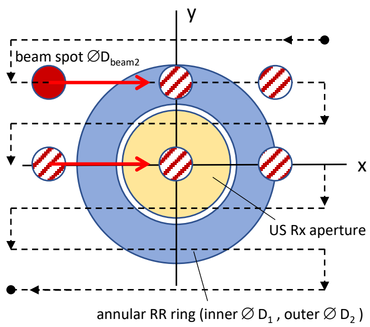


Fig. 7 Scanning the RR ring at the US Rx

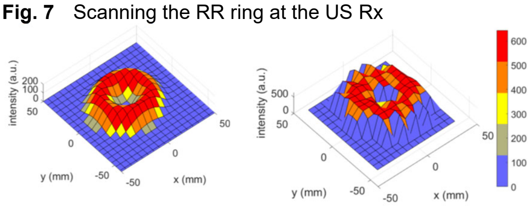


Fig. 8 Monitoring the reflected beam power from the RR, for D_{beam2}=15mm, RR inner D_1=25mm, outer D_2=62mm (left: analytical; right: experimental)

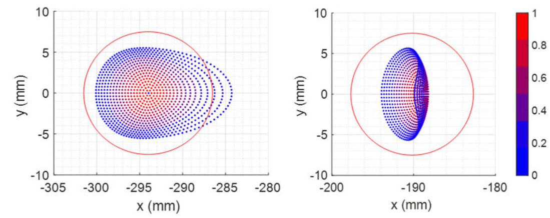
aperture. With arbitrary start position of the scanning, and a scan step size of 6mm at the RR ring, the accuracy of the beam alignment w.r.t. the US Rx aperture of ∅25mm is better than 40μm, well within the required precision.

The CoG algorithm requires that the beam spot preserves its circular shape during the RR scanning, hence the US lens should have minimal off-axis aberrations. Ray tracing done on several lens types shows that a triplet lens with f=20mm [12] gives much lower aberrations than e.g. a commonly used planoconvex lens; see Fig. 5 (η is fraction of power captured by ∅15mm aperture (red circle); β ellipticity of the spot, which indicates spot deformation and must be low for efficient lens coupling to the PD in the US Rx).

System demonstrator

Fig. 9 shows the configuration of the bidirectional OWC lab system, and Fig. 6 its user site and ceiling site (PRA). It adds the US part to our previous DS GbE video streaming setup with a reach of 2m. By λ-tuning, the 10dBm ∅10cm DS beams are 2D steered by an AWGR-based diffractive unit. Using a PD matrix and ∅50mm Fresnel lens the DS-Rx has a FoV≈10deg. [2].

In our new US link, a 2dBm ∅15mm US beam



a) triplet lens f=20mm: FoV_x=8.4deg., η=98%, β=12%

b) planoconvex f=20mm: FoV_x=5.4deg., η=100%, β=45%

Fig. 5 US beam spot at the RR ring (by ray tracing, with 1027 Gaussian beams from US Tx; red circle: ∅15mm)

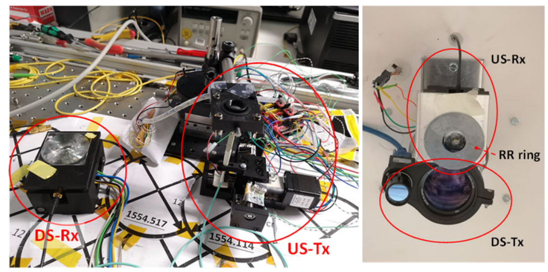


Fig. 6 User DS-Rx & US-Tx (left); PRA DS-Tx & US-Rx (right)

at λ≈1.5μm is launched using a triplet lens with f=20mm. The beam is mechanically 2D steered by a NEMA11 xy stepper motor stage, controlled by an Arduino board; the board performs the CoG automatic beam alignment algorithm aided by monitoring the reflected power from the RR ring at the user site with three low-bandwidth ∅1mm photodiodes. The US-Rx has a ∅25mm Fresnel lens with f=5mm, achieving a FoV≈12deg. GbE media converters (MCs) are used to convert the bidirectional GbE data from optical to RJ45/USB signals. Our CoG US beam alignment algorithm successfully achieved US connectivity within 10s for a step size of 6mm, and even within 4s for 7.5mm. Within the FoV range, bidirectional TCP test by Iperf measurements showed ~940Mbit/s in DS and ~939Mbit/s in US, without packet loss. Unidirectionally, Iperf in UDP test showed ~958Mbit/s US with 0.18% packet loss.

Conclusions

GbE bidirectional OWC transmission using automatic self-alignment of the upstream beam has been demonstrated for high-density user connections. TCP measurements show 940Mbit/s transfer speeds per user with a FoV≈10 deg.

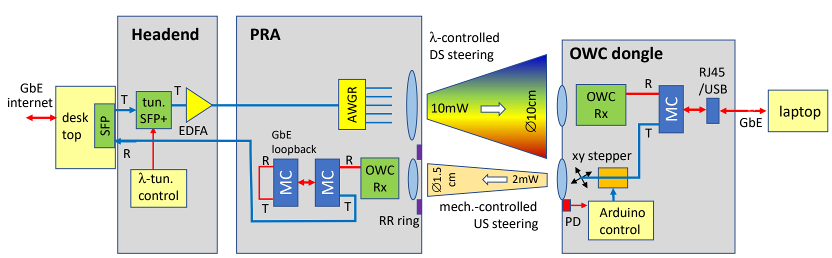


Fig. 9 Bidirectional OWC lab system (blue: fiber; red: copper lines)

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