High-capacity optical wireless communication using two-dimensional IR beam steering

Citation for published version (APA):

Koonen, T., Gomez-Agis, F., Huijskens, F., Mekonnen, K. A., Cao, Z., & Tangdiongga, E. (2018). High-capacity optical wireless communication using two-dimensional IR beam steering. *Journal of Lightwave Technology*, 36(19), 4486 - 4493. [8356049]. <https://doi.org/10.1109/JLT.2018.2834374>

DOI:

[10.1109/JLT.2018.2834374](https://doi.org/10.1109/JLT.2018.2834374)

Document status and date:

Published: 01/10/2018

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

High-Capacity Optical Wireless Communication using 2-Dimensional IR Beam Steering

Ton Koonen, *Fellow, IEEE, Fellow, OSA*, Fausto Gomez-Agis, Frans Huijskens, Ketemaw Mekonnen, *Student member, IEEE*, Zizheng Cao, *Member, IEEE*, Eduward Tangdiongga, *Member, IEEE*

Abstract— Free-space narrow infrared beams can offer unprecedented data capacity to devices individually, as they can provide non-shared connections that have a large link power budget. By means of a fully passive module based on a high port count arrayed waveguide grating router (AWGR), many infrared beams can be 2D steered individually using wavelength tuning. By applying defocusing techniques, a compact beam steering module has been realized. Simultaneous communication at up to 112Gbit/s PAM-4 per beam has been shown with an 80-ports AWGR, thus offering a total wireless throughput beyond 8.9Tbit/s. Wireless provisioning of multiple ultrahigh-definition video streams has been demonstrated in a proof-of-concept laboratory setup.

Index Terms— optical wireless communication, optical beam steering, arrayed waveguide grating router

I. INTRODUCTION

THE booming demand for wireless connectivity, generated by the fast growth of broadband mobile devices as well as the proliferation of small sensing and actuating devices (the “Internet of Things”) is at the verge of exhausting the available radio spectrum. A vast alternative domain of wireless connection resources can be opened by optical wireless communication (OWC), which is receiving increasing interest in research and first commercial prototype equipment. Two main OWC technology directions may be distinguished [1][2]: Visible Light Communication (VLC) communication which employs modulated wide-spread beams of visible light typically emerging from illumination systems, and beam-steered infrared light communication (BS-ILC) which employs narrow well-directed beams of infrared light emerging from a dedicated fiber-based infrastructure.

VLC techniques transport data while piggy-backing on LED illumination systems [3][4]. The visible spectrum of 400 to 700nm offers a bandwidth of no less than 320THz. The wide coverage provided by an illumination infrastructure

typically includes multiple user devices, and thus requires sharing of VLC’s capacity by means of appropriate MAC protocols, which may result in congestion issues at higher traffic loads. Moreover, VLC needs the illumination system to be switched-on, which may not always be desired (e.g., in bright daylight conditions), and entails extra power consumption in addition to the power needed for communication. The white light emitting LEDs used in illumination systems are typically based on a blue LED with phosphor coating, and have a limited bandwidth. Advanced spectrum-efficient modulation techniques are needed to achieve data rates beyond 1 Gbit/s; by using OFDM with 256 subcarriers and adaptive bit-loading followed by pre-equalization, a net rate of 2.0 Gbit/s was achieved over 1.5 m in free-space [5]. A multi-color LED emitting white light can increase the data rate further; thus wavelength multiplexing using an RGBY LED and bit-loaded OFDM yielded 9.51 Gbit/s over 1 m [6].

Alternatively, one may use relatively narrow light beams, which are so narrow that each of them serves only a single user device. This avoids capacity sharing among these devices and thus congestion issues. By bringing the light signals only there where and when needed, it can be more power-efficient and offers better privacy protection. We have proposed an indoor broadband OWC system concept deploying 2D-steerable narrow infrared (IR) beams with >10Gbit/s unshared capacity per beam [7][8]. By using infrared beams with wavelengths $\lambda > 1400$ nm, eye safety standards allow emission powers up to 10dBm [9], which is at least 15dB more than the allowed power of a visible-light beam. In addition, the confined narrow infrared beams bring a higher light intensity at the user’s device than the widely diverging VLC beams. Hence, the narrow infrared beam communication provides significantly higher link power budgets than those achievable with VLC and thus enables transport of much higher data rates. Moreover, by operating in the S+L+C band (1460-1625nm, representing 20.9THz of bandwidth), there is a wide choice of optical devices available from the mature fiber telecommunication market. Systems with actively controlled beam steering elements have been reported, such as with microelectromechanical system (MEMS)-based mirrors [10], or with spatial light modulators (SLM-s) [11]. Each beam can carry 10Gbit/s or more, but requires a separate steering element.

We have explored passive beam-steering modules which

Manuscript received February 1, 2018; revised April 22, 2018; accepted April 26, 2018. This work was supported by the European Research Council under the Advanced Grant project Beam-Steered Reconfigurable OpticalWireless System for the Energy-Efficient Communication. (Corresponding author: Ton Koonen.)

The authors are with the Institute for Photonic Integration, Eindhoven University of Technology, Eindhoven 5612 AZ, The Netherlands (e-mail: a.m.j.koonen@tue.nl; F.Gomez.Agis@tue.nl; f.m.huijskens@tue.nl; k.a.mekonnen@tue.nl; z.cao@tue.nl; e.tangdiongga@tue.nl).

are using wavelength-dependent beam diffraction, are easily scalable and can handle many beams simultaneously. The module is based on two orthogonal gratings which enables 2D beam steering by just tuning the wavelength of each beam [7][12]; adding beams just means adding wavelengths. We have achieved more than 42Gbit/s per beam using DMT modulation [13]. In this paper, we propose an alternative passive module for the wavelength-controlled 2D beam steering, which is based on a readily available high port-count arrayed waveguide grating router (AWGR). This setup offers similar performance but is easier to assemble and requires less alignment effort.

II. BEAM-STEERED INDOOR OWC SYSTEM CONCEPT

The indoor OWC system concept using 2D-steerable IR beams we proposed is shown in Fig. 1 [7]. In each room, multiple pencil-beam radiating antennas (PRAs) are installed. A PRA contains passive diffractive optics, and can emit multiple beams of which each is 2D steered under control of its wavelength. The wavelength of each beam thus acts as an embedded control channel, which simplifies the management of the indoor traffic flows as it avoids the need of implementing a separate control network. By using multiple PRA-s per room, line-of-sight blocking can be circumvented, as one PRA can take over the duties of another one. Each PRA is fully passive; it contains no moving parts and does not need electrical powering nor electrical control signals. Its optical data signals are fed remotely via the indoor fiber backbone network from a central site in the building, where all network management and control functions are located. At this central communication controller (CCC), tunable transceivers together with a transparent optical crossconnect (OXC) module take care that the user data streams are each dynamically routed to the appropriate PRA in the appropriate room with the appropriate wavelength. The return path for each user is established by 60GHz radio-over-fiber techniques, and also serves to close the control loop for user localization and tracking [14].

Fig. 1 Indoor OWC system deploying λ -controlled 2-dimensional IR beam steering

III. BEAM STEERING MODULE BASED ON AWGR

We previously have proposed and explored an arrangement with two cross-aligned diffraction gratings, which provides 2D beam steering by wavelength tuning [7][12]. The beam steering follows a line-by-line scanning process, where by increasing the wavelength the beam's footprint runs smoothly along a horizontal line, but at the end of that line makes a stepwise jump to the next line. For this, one of the gratings needs to operate in a high interference order, and the other one in a single low order. The full wavelength tuning range comprises several orders (each covering a so-called free spectral range) of the high-order grating, but at most only one order of the low-order grating. This setup requires highly-efficient gratings with low polarization dependency, and careful highly stable mechanical adjustment of these gratings.

As an alternative approach which requires less alignment effort while using AWGR modules which are readily available commercially, we propose the beam steering module concept shown in Fig. 2 [15][16]. The $N \times M$ output fibers of the AWGR are arranged in an $N \times M$ 2D fiber array, which is put in the object plane of a lens. The position of a fiber in the object plane determines in which 2D direction its corresponding beam is emitted after the lens.

Fig. 2 2D steering of IR beams using a high port-count AWGR

By putting the fiber array in the focal plane of the lens, collimated beams will be emitted with diameter $D_0 = 2f \tan \alpha$ where $\tan \alpha = \lambda / (\pi \cdot w_0)$ with mode field radius w_0 of the single mode fiber. Each collimated beam creates a spot in the image plane with diameter $D_{spot} = D_0$. To cover a square image area of size $L \times L$ with no spacing between adjacent spots, $N=M$ and the number of AWGR ports needed is $N \times M = M^2 = (L/D_{spot})^2$. The spacing Δy of the fibers in the 2D array needs to be $\Delta y = L / [M \cdot (b/f - 1)]$ where $f = \pi w_0 L / (2\lambda \cdot M)$ is the lens focal length, and b is the distance between the image plane and the lens. E.g., for $D_{spot} = 3\text{cm}$, $\lambda = 1.5\mu\text{m}$, $w_0 = 4.5\mu\text{m}$ (so $\tan \alpha = 0.106$), $L = 1.5\text{m}$ and room height $b = 2.5\text{m}$, we need an array of $M \times M = 2500$ fibers with $\Delta y = 1.80\text{mm}$ and $f = 14.1\text{cm}$. For a given image area, a larger spot size D_{spot} will reduce the AWGR port count needed; but obviously also requires a larger aperture at the receiver in order to assure that enough power is detected to handle the large data rate. Commercially available AWGR-s operating in C-band are typically offered with port counts up to 96. In previous experiments [15], we used an AWGR with 80 ports, so $M=9$.

To cover an area of only $0.75 \times 0.75 \text{m}^2$ using a spot size $D_{spot} = 8.3 \text{cm}$, a large condenser lens was needed with $f = 39.3 \text{cm}$ and diameter $D_{lens} = 21 \text{cm}$, and fiber spacing $\Delta y = 15.5 \text{mm}$ which yielded a 2D fiber array total size of $12.4 \times 12.4 \text{cm}^2$.

The size of such rather bulky setups can be reduced significantly by a defocusing approach: when putting the fiber array out of focus and closer to the lens, the emitted beams are slightly diverging and the spot diameter D_{spot} increases. Conversely, for a given coverage area and a given acceptable spot diameter D_{spot} , defocusing results in a significantly smaller focal length and diameter of the lens, and smaller spacing between the fibers in the array, and thus to a significant reduction of the size of the beam steering module. The relative defocusing parameter p (with $0 \leq p < 1$) can be defined by $v = (1-p)f$ where the object distance between the array and the lens is given by v . In order to cover an $L \times L$ area at distance b_0 from the lens while having no spacing between the spots, from Fig. 3 using paraxial geometric optics it can be shown that the required lens focal length f , lens diameter D_{lens} , fiber spacing Δy , spot diameter D_{spot} as a function of distance b , and beam divergence dD_{spot}/db are

$$f = \frac{1}{1-p} \left(\frac{L}{M \cdot 2 \tan \alpha} - p \cdot b_0 \right)$$

$$D_{lens} = (M-1) |\Delta y| + 2f(1-p) \tan \alpha$$

$$\Delta y = 2f \tan \alpha \left(\frac{f}{b_0 - f} + p \right) = \frac{L}{M} \cdot \frac{L - p b_0 M \cdot 2 \tan \alpha}{-L + b_0 M \cdot 2 \tan \alpha}$$

$$D_{spot}(b) = 2 \tan \alpha \cdot \{f + p(b - f)\}$$

$$\frac{d D_{spot}(b)}{d b} = 2 p \cdot \tan \alpha$$

Fig. 3 Reducing the beam steering module by defocusing the fiber array

Fig. 4 illustrates the impact of the defocusing on the module's size. As shown in Fig. 4.a, for an 81 ports AWGR and coverage area of $0.75 \times 0.75 \text{m}^2$ with room height $b_0 = 2.5 \text{m}$, no defocusing (so $p=0$) yields a lens focal length $f = 39.3 \text{cm}$, fiber spacing $\Delta y = 15.5 \text{mm}$ and lens diameter $D_{lens} = 20.8 \text{cm}$ for a spot size $D_{spot} = 8.3 \text{cm}$ (which was used in [15] and [17] to realize a beam supporting up to 35Gbit/s OOK data transmission). However, using a defocusing of 12% (so $p = 0.12$), we find $f = 10.5 \text{cm}$, $\Delta y = 3.67 \text{mm}$, and $D_{lens} = 4.90 \text{cm}$ only, while the spot size stays the same and

hence the transmission capacity also. Clearly, defocusing can reduce the size of the beam steering module considerably without affecting the system's performance. A larger defocusing also decreases the lens speed needed, so increases the f-number f/D : it increases from $f/D = 1.83$ for no defocusing ($p=0$) to $f/D = 2.15$ for $p=0.12$.

Similarly, for an AWGR with a larger port count, the coverage area can be increased while the defocusing keeps the module compact. As shown in Fig. 4.b: when adopting the same spot size $D_{spot} = 8.3 \text{cm}$, for a 196 ports AWGR ($M = 14$) at room height $b_0 = 2.5 \text{m}$, a $1.16 \times 1.16 \text{m}^2$ area can be covered with a defocusing factor $p = 0.135$ yielding $f = 61.2 \text{mm}$, $\Delta y = 2.08 \text{mm}$ and $D_{lens} = 3.83 \text{cm}$. Experiments in our laboratory setup with 9.5dBm transmitted beam power and at the receiver a Keplerian telescopic $10 \times$ beam compressor with an aperture diameter of 5cm have shown that a spot size $D_{spot} = 12.0 \text{cm}$ allows a data transmission rate of more than 10Gbit/s in OOK modulation format. For this spot size, with $M = 14$ and $b_0 = 2.5 \text{m}$ an area of $1.68 \times 1.68 \text{m}^2$ (equivalent with an angular coverage of $18.6^\circ \times 18.6^\circ$) can be covered with $p = 0.21$ yielding $f = 51.2 \text{mm}$, $\Delta y = 2.51 \text{mm}$, and $D_{lens} = 4.12 \text{cm}$ (implying an $f/D = 1.24$ number of the lens, which is readily available e.g. for camera lenses).

Fig. 4 Reducing the module size by defocusing, when opting for a beam diameter $D_{spot} = 8.3 \text{cm}$ and applying a) AWGR with 81 ports ($M = 9$), or b) AWGR with 196 ports ($M = 14$)

Another advantage of the defocusing approach is a better fill factor of the covered area. Fig. 5 shows how the beams from two neighboring fibers each diverge when defocusing is introduced and the distance b between the lens and the image plane increases. Without defocusing ($p=0$) the beams are collimated and do not diverge. If the lens focal length f and fiber spacing Δy values have been set according to the equations given before for a given lens-to-image plane distance b_0 , the spots will exactly touch each other in the image plane where the distance b to the lens equals b_0 . E.g., for $b_0=250\text{cm}$ and spot size $D_{\text{spot}}=12\text{cm}$, this is shown in Fig. 5.a for $p=0$ where the beam's divergence $dD_{\text{spot}}/db=0$, and in Fig. 5.b for $p=0.21$ where $dD_{\text{spot}}/db=0.0445$ (i.e. a divergence half-angle of 1.28deg.).

Fig. 5 Impact of defocusing on the beam profiles a) without defocusing ($p=0$) and b) with defocusing $p=0.21$

Fig. 6 shows how the spots are covering the image plane; herein the e^{-2} intensity contours of the Gaussian spot footprints are shown. The spots exactly touch each other when $b = b_0$, as shown in Fig. 6.a. When the image plane is moved to a larger distance from the lens (so when $b > b_0$), the spacing between the spot centers Δy_c increases ($\Delta y_c = \Delta y \cdot (b/f - 1)$). Without defocusing (i.e. $p=0$), the spot diameter D_{spot} stays constant and becomes smaller than the spot spacing Δy_c , hence the fill factor decreases when b increases (see Fig. 6.b). For $b < b_0$, overlap between the spots occurs (see Fig. 6.c). Fig. 7 shows how the spot diameter, the spacing between the spots, and the fill factor (i.e. the summation of the footprint areas of all spots divided by the total coverage area) evolve for a hexagonal

stacking of the fibers in the 2D array when the distance b of the image plane to the lens is increased, both for the collimated-beams case ($p=0$) and the defocused case ($p=0.21$). The design assumptions for this were a spot diameter $D_{\text{spot}}=12\text{cm}$ at room height $b_0=2.5\text{m}$, and $M=196$ ports. Clearly by means of defocusing the dependency of the fill factor on the distance b to the lens is reduced.

Fig. 6 Filling the image area by the beam spots

Fig. 7 Improving the area fill factor by defocusing

IV. SYSTEM EXPERIMENTS

Experimental demonstrations of the AWGR-based beam steering concept have shown its versatility to provide ultra-high wireless data transmission to devices individually, with capacities per beam using OOK ranging from 10Gbit/s [15] up to 35Gbit/s OOK [17], and using PAM-4 up to 112Gbit/s [18].

The first AWGR-based beam steering laboratory experiment applying defocusing is shown in Fig. 8 [16]. It uses a laser diode tunable from 1525 to 1580nm and emitting 0dBm optical power, a PRBS $2^{23}-1$ generator of NRZ-OOK data driving a Mach Zehnder modulator (MZM), a variable optical attenuator followed by an EDFA, and a Gemfire 1×80 ports AWGR with channel center wavelengths from 1529.10 to 1569.80nm , spaced by 50GHz and -3dB channel bandwidth of 0.28nm (35GHz). For the focused case (i.e. $p=0$), a condenser lens was needed with focal length $f=40\text{cm}$, diameter $D_{\text{lens}}=20\text{cm}$ and a fiber array pitch $\Delta y=15.0\text{mm}$. The emitted power was 9.5dBm , i.e. below the 10dBm eye safety limit for $\lambda > 1.4\mu\text{m}$. At the receiver side, a telescopic lens system with 6cm aperture was used for beam narrowing, followed by a mid-IR filter which suppresses ambient light and passes the IR beams, and subsequently a 6mm aperture fiber collimator feeding the APD-TIA receiver via a $50\mu\text{m}$ core MMF. For the defocused case, we took $p=0.12$, allowing

Fig. 8 Experimental setup applying the defocusing technique

a much smaller achromatic doublet lens with $f = 10.0\text{cm}$ and $D_{\text{lens}} = 50.2\text{mm}$, and smaller fiber array with pitch $\Delta y = 3.7\text{mm}$. NRZ-OOK data transmission at 10Gbit/s and at 20Gbit/s over 2.5m in free-space were realized, and the performance was measured for a central spot (HS-1) and a next-neighbor spot (HS-2). As shown in Fig. 10, the BER curves measured at 20Gbit/s for both HS-1 and HS-2 show nearly identical system performance for the focused and defocused cases, with a penalty of about 2dB with respect to back-to-back operation (due to lens aberrations and slight misalignments). Hence it can be concluded that the system performance is not reduced by the defocusing, whereas the system has become much more compact.

Fig. 10 20Gbit/s performance without and with defocusing

In a second laboratory experiment, shown in Fig. 9, by deploying the same AWGR 112Gbit/s transmission per beam could be achieved using PAM-4 signal modulation [18]. In order to overcome the bandwidth limitations of the AWGR (with a -3dB bandwidth of 35GHz) and of the driver electronics, digital signal processing (DSP) was applied which provided spectrum compression by coding the data into a PAM-4 format as well as further equalization. PAM-4 signals with raised-cosine 0.2 roll-off waveforms at 42GBaud and at 56GBaud were digitally generated using 19 taps and a 9-taps pre-compensation filter, and uploaded into a Keysight M8196A arbitrary waveform generator operating at 84GS/s. The output of a tunable laser was modulated by the PAM-4 signals in a single-drive 40GHz Mach-Zehnder modulator. After amplification in an EDFA, the signal is fed into the 80-ports AWGR and via the 9x9 2D fiber array and an $f = 40\text{cm}$ focal length lens with diameter of 20cm launched into free-space as a collimated beam (without defocusing, so with $p = 0$). The beam's power was +10dBm, so below the eye safety threshold. The beam's diameter was 8.5cm, and it was coupled into a receiver at a distance of 3.4m. The receiver's lens system has an aperture of 50mm, and consists subsequently of a first lens with $f = 50\text{mm}$, a second lens with $f = 5\text{mm}$, and a third lens with $f = 4.51\text{mm}$ which couples the light into a 10 μm core single-mode fiber (SMF). The received power was -9.5dBm. Further optical amplification was done by a linear semiconductor optical amplifier (SOA), providing a gain of 10dB. Subsequently the signal was detected by a

Fig. 9 AWGR-based beam-steered OWC system transmitting up to 112Gbit/s PAM-4 per beam

70GHz PIN photodiode followed by a 35GHz RF amplifier. Alternatively, we demonstrated recently a compact photonic integrated circuit where the light collection function by means of surface gratings was separated from the high-bandwidth detection function using a UTC photodiode with bandwidth $>67\text{GHz}$ [19]. The detected signal was digitized by an 80GS/s Keysight MSOV334A oscilloscope, followed by off-line DSP.

The BER performance was measured for 42GBaud PAM-4 signals (84Gbit/s) and 56Gbit/s PAM-4 signals (112Gbit/s; 100Gbit/s net after removing 12% HD-FEC overhead). The measured BER curves are shown in Fig. 11; at 42GBaud, for a received power of -7.5dBm the BER was $1.7 \cdot 10^{-3}$ (below the HD-FEC limit), and at 56GBaud the BER was below the HD-FEC limit for a received power of -4.5dBm (with an error floor appearing due to bandwidth limitations). In the insets of Fig. 11 also the clear PAM-4 eye patterns can be observed.

Fig. 11 BER performance of the received PAM-4 signals at 42 and 56GBaud.

Thirdly, a demonstrator setup as shown in Fig. 12 has been built in our laboratory in order to provide a proof-of-concept of our AWGR-based beam-steered optical wireless communication system for the simultaneous wireless delivery of high-speed video streams. We have shown before in a bidirectional system setup 35Gbit/s NRZ-OOK downstream transmission with an 80-ports AWGR (without defocusing, so $p=0$, using a large $f=40\text{cm}$ condenser lens with 20cm diameter), and 5Gbit/s ASK upstream transmission by means of 60GHz UWB radio technology [17]. We also showed real-time 10G Ethernet transmission in TCP/IP sessions before [20]. The setup, shown in Fig. 12, demonstrates in downstream the delivery of two steerable IR beams each transporting a 10Gbit/s OOK signal, and in upstream a ultra-wideband (UWB) 60GHz radio channel for user localization and signaling. The IR beam-steering PRA was designed according to the design equations given in Section III for a 14×14 2D fiber array, a ceiling-to-table distance $b_0=2.5\text{m}$, and spot diameter at the table of 12cm. By choosing a defocusing parameter $p=0.21$, these design constraints yield a lens focal length $f=51.2\text{mm}$, lens diameter $D_{\text{lens}}=41.2\text{mm}$ (so $f/D=1.24$), and fiber spacing $\Delta y=2.51\text{mm}$. A C-band AWGR with 96 ports was combined with an L-band AWGR with 48 ports, where the output ports have an ITU grid channel spacing of 50GHz, and a -3dB bandwidth of 35GHz and 24GHz, respectively. The output fibers were assembled into a honeycomb matrix array of 129 fiber ferrules spaced at

a $\Delta y=2.6\text{mm}$ pitch which fits into the aperture of a commercial high-speed $f=50\text{mm}$ camera lens with $f/D=0.95$. The table area covered by the PRA when doing the 2D beam steering amounted to $1.6 \times 1.6\text{m}^2$. Two optical beam receivers were employed, each equipped with a lensed collimator ($f=37.1\text{mm}$, $NA=0.24$) feeding the received signal with a power of about -16dBm via a single-mode fiber to an SFP+ transceiver capable of 10G Ethernet transmission. For the ease of use, future work will aim to create a compact dongle-type receiver equipped with a surface-illuminated photodiode directly followed by the receiver electronics, and with adequate optics to create a large angle-of-view as well as a sufficiently large aperture. The SFP+ transceivers were hosted in network interface cards (NICs), and were streaming high-definition video from two servers. One transceiver emitted at a fixed $\lambda=1559.92\text{nm}$ and thus provided a beam out of port #65 of the 2D fiber array, whereas the other transceiver was tunable across the C-band and thus provided a second steerable beam.

For the upstream 60GHz UWB link, the user's terminal was equipped with a horn antenna with 30dBi gain which emits towards a steerable similar horn antenna of a 60GHz RF receiver mounted next to the PRA at the ceiling (see Fig. 12). At this receiver, half of the received power is monitored by an RF power meter which serves as a sensor for the user localization. For this, the horn antenna is steered by a mechanical pan/tilt system, controlled by a Raspberry Pi 3 board. This board thus determines the user's coordinates and communicates these to the central communication controller (emulated on a laptop) which controls the tunable transceiver and thus closes the loop for controlling the 2D beam steering.

A photograph of this laboratory demonstrator setup is shown in Fig. 13, indicating the PRA, the steerable 60GHz horn antenna near the PRA, and the optical beam receiving

Fig. 12 Beam-steered OWC laboratory demonstrator

cells on the table's surface. Fig. 14 shows the realized 2D array of 129 fibers, and the assembly of the fiber array with the $f=50\text{mm}$ wide aperture camera lens. This commercially available multi-element camera lens has a high speed of $f/0.95$. It was designed basically for portrait photography, hence has very low lens aberrations and thus provides that the shape of the spots is retained even in the outer parts of the covered area. In the setup simultaneous independent transmission by two IR beams of two high-definition video streams was successfully demonstrated, each embedded in a 10G Ethernet connection and running at a video data rate of about 4.6Gbit/s.

Fig. 13 Photo of the laboratory demonstrator

Fig. 14 Photos of a) 2D fiber array, and b) assembly of fiber array and camera lens

V. CONCLUSIONS

Based on a high port-count arrayed waveguide grating router with its output fibers arranged in a 2D array and a high-speed lens, individual wavelength-controlled 2D steering of narrow infrared beams can be realized. Thus many ultra-high capacity wireless links for high-bandwidth wireless services can be

created. Capacities up to 35Gbit/s NRZ-OOK and 112Gbit/s PAM-4 per beam with a reach beyond 2.5m have been shown. With an 80-ports C-band AWGR, a total wireless system throughput beyond 8.9Tbit/s can be achieved. By extension to a 192 ports (=96+48+48) 3-elements composite AWGR operating in C- and L-band, throughput volumes beyond 21Tbit/s become feasible. By applying a defocusing technique, the size of the passive beam steering module is decreased considerably without affecting the system's performance. Wireless delivery of multiple high-speed ultrahigh-definition video streams by means of multiple narrow infrared beams has been shown in a laboratory proof-of-concept demonstrator. Autonomic localization of the user's devices is aided by a 60GHz UWB radio return path.

VI. REFERENCES

- [1] A.M.J. Koonen, "Indoor optical wireless systems: technology, trends, and applications," *J. Lightw. Technol.*, vol. 36, no. 8, Apr. 2018, pp. 1459-1467. DOI 10.1109/JLT.2017.2787614.
- [2] A.M.J. Koonen, "Optical wireless systems: technology, trends and applications," webinar IEEE Phot. Soc., Feb. 21, 2018, <https://www.photonicsociety.org/education-careers/webinars/optical-wireless-communication-webinar>
- [3] H. Haas, "Visible light communication," in *Proc. OFC2015*, Los Angeles, March 22-26, 2015, paper Tu2G.5.
- [4] A.M. Khalid, et al., "1-Gb/s transmission over a phosphorescent white LED by using rate-adaptive discrete multitone modulation," *IEEE Photon. J.*, vol. 4, no. 5, pp. 1465-1473, Oct. 2012.
- [5] X. Huang, S.Chen, Z. Wang, J.Shi, Y. Wang, J. Xiao, N. Chi, "2.0-Gb/s Visible light link based on adaptive bit allocation OFDM of a single phosphorescent white LED," *IEEE Phot. J.*, vol. 7, no. 5, Oct. 2015, DOI: 0.1109/JPHOT.2015.2480541.
- [6] Nan Chi, et al., "High speed LED based visible light communication for 5G wireless backhaul," in *Proc. IEEE Summer Top.*, Newport Beach, CA, USA, Jul. 11, 2016, paper MC1.2.
- [7] A.M.J. Koonen, C.W. Oh, E. Tangdiongga, "Reconfigurable free-space optical indoor network using multiple pencil beam steering," in *Proc. OECC/ACOFT 2014*, Melbourne, July 2014, paper Tu3F-1.
- [8] A.M.J. Koonen, F. Gomez-Agis, Z. Cao, K.A. Mekonnen, F.M. Huijskens, E. Tangdiongga, "Indoor ultra-high capacity optical wireless communication using steerable infrared beams," in *Proc. MWP2017*, Beijing, Oct. 2017, keynote paper.
- [9] 2017. [Online]. Available: https://en.wikipedia.org/wiki/Laser_safety
- [10] K. Wang, A. Nirmalathas, C. Lim, K. Alameh, and E. Skafidas, "Full-duplex gigabit indoor optical wireless communication system with CAP modulation," *IEEE Photon. Technol. Lett.*, vol. 28, no. 7, Apr. 2016, pp. 790-793.
- [11] A. Gomez, K. Shi, C. Quintana, M. Sato, G. Faulkner, B.C. Thomsen, and D.C. O'Brien, "Beyond 100-Gb/s indoor wide field-of-view optical wireless communications," *Phot. Technol. Lett.*, vol. 27, no. 4, Feb. 2015, pp. 367-370.
- [12] A.M.J. Koonen, C.W. Oh, K. Mekonnen, Z. Cao, E. Tangdiongga, "Ultra-high capacity indoor optical wireless communication using 2D-steered pencil beams," *IEEE/OSA J. of Lightw. Technol.*, vol. 34, no. 20, Oct. 2016, pp 4802-4809.
- [13] C.W. Oh, E. Tangdiongga, A.M.J. Koonen, "42.8 Gbit/s indoor optical wireless communication with 2-dimensional optical beamsteering," in *Proc. OFC2015*, Los Angeles, March 22-26, 2015, paper M2F.3.
- [14] K.A. Mekonnen et al, "PIC-enabled dynamic bidirectional indoor network employing optical wireless and millimeter-wave radio techniques," in *Proc. ECOC2015*, Düsseldorf, Sep. 2016, paper W.1.E.3.
- [15] A.M. Khalid et al, "10 Gbps indoor optical wireless communication employing 2D passive beam steering based on arrayed waveguide gratings," in *Proc. IEEE Summ. Top. 2016*, Newport Beach, July 2016, paper Tu2C.3.
- [16] A.M.J. Koonen et al., "High-capacity optical wireless communication using AWG router for 2-dimensional IR beam steering," in *Proc. OECC2017*, Singapore, July 31 - Aug.4, 2017, paper 1-4K-3.

- [17] A.M. Khalid, P. Baltus, R. van Dommele, K.A. Mekonnen, Z. Cao, C.W. Oh, M. Matters, A.M.J. Koonen, "Bi-directional 35-Gbit/s 2D beam steered optical wireless downlink and 5-Gbit/s localized 60-GHz communication uplink for hybrid indoor wireless systems," in *Proc. OFC2017*, Los Angeles, Mar. 2017, paper Th1E.6.
- [18] F. Gomez-Agis, S. P. van der Heide, C. M. Okonkwo, E. Tangdiongga and A. M. J. Koonen, "112 Gbit/s transmission in a 2D beam steering AWG-based optical wireless communication system", in *Proc. ECOC2017*, Göteborg, Sweden, Sept. 17-21, 2017, Paper Th.2.B.1.
- [19] Z. Cao, et al., "200 Gbps OOK transmission over an indoor optical wireless link enabled by an integrated cascaded aperture optical receiver," in *Proc. OFC2017*, Los Angeles, Mar. 2017, paper PDP Th5A.6.
- [20] A.M. Khalid, M. Torres Vega, K.A. Mekonnen, Z. Cao, A. Liotta, A.M.J. Koonen, "Real time 10Gb-ethernet transmission over 2D indoor passive beam steered optical wireless system based on high port arrayed waveguide gratings", in *Proc. ECOC2016*, Düsseldorf, Sep. 2016, paper W.4.P1.SC4.40.

He received a Graduate Student Fellowship of IEEE Photonics Society in 2014. He holds two Chinese patents and one US provisional patent.

Eduward Tangdiongga (IEEE S'01, M'10) received the M.Sc. and Ph.D. degrees from the Eindhoven University of Technology, The Netherlands, in 1994 and 2001, respectively. In 2001, he joined COBRA Research Institute working on ultrafast optical signal processing using semiconductor devices. In 2016, he became an Associate Professor on advanced optical access and local area networks. His current research interests include passive optical networks, radio over (single mode-, multimode-, and plastic) fiber, and optical wireless communication.

Ton Koonen (IEEE F'07, OSA F'13) is full professor in Eindhoven University of Technology (TU/e) since 2001. Since 2004, he is chairman of the group Electro-Optical Communication Systems, and since 2012 vice-dean of the department Electrical Engineering. Since 2016, he also is Scientific Director of the Institute for Photonic Integration at TU/e. Before 2001, he worked for more than 20 years in applied research in industry, amongst others in Bell Labs - Lucent Technologies. Ton Koonen is a Bell Labs Fellow (1998), IEEE Fellow (2007), OSA Fellow (2013), and Distinguished Guest Professor of Hunan University, Changsha, China (2014). In 2011, he received an Advanced Investigator Grant of the European Research Council on optical wireless communication. His current research interests are optical fiber-supported in-building networks (including optical wireless communication techniques, radio-over-fiber techniques, and high-capacity plastic optical fiber (POF) techniques), optical access networks, and spatial division multiplexed systems.

Fausto Gomez-Agis received the PhD degree in electronics and communications in 2008 from École Nationale Supérieure des Télécommunications, Paris, France. From 2008 to 2011 he was with the ECO group, department Electrical Engineering, Eindhoven University of Technology (TU/e), The Netherlands, where he worked on optical signal processing and clock-recovery techniques. From 2007 to 2011 he was a visiting researcher at Fotonik group, Technical University of Denmark (DTU), Denmark. From 2011 to 2013 he was with FOTON CNRS, Lannion, France, involved in linear optical sampling and optical instrumentation. From 2013 to 2016, he was with Yenista Optics in France working as a product line manager. He is currently again with the ECO group, TU/e, involved in optical wireless communication within the ERC project BROWSE. He is (co-)author of over 40 journal and conference papers and holds 1 international patent.

Frans Huijskens graduated in applied physics at the Technical College of Dordrecht, The Netherlands, in 1979. From 1981 to 1984, he was an Electronic Test Engineer at Siemens Gammasonics. In 1985, he joined the Electro-Optical Communications Group of Eindhoven University of Technology. He worked on passive fiber couplers, on phase- and polarization-diversity coherent systems, on demonstrator setups of optical cross-connecting and optical packet switching, and on packaging of optical integrated devices. Recently he has focused on demonstrator setups of optical wireless communication.

Ketemaw Addis Mekonnen (IEEE S'15) received the B.Sc. degree in electrical engineering from Mekelle University, Ethiopia, in 2007. He received the double M.Sc. degree in the Erasmus Mundus Master on photonic networks engineering program from Scuola Superiore Sant'Anna, Italy, and Aston University, U.K., in 2013. He is currently working toward the Ph.D. degree in Eindhoven University of Technology, The Netherlands. His current research interests include dynamic optical routing, radio over fiber, signal processing, and optical wireless communication.

Zizheng Cao (IEEE S'11, M'15) received the M.Eng. degree in telecom engineering (awarded "Outstanding thesis of master degree" of Hunan Province) from Hunan University, Changsha, China, in 2010. He received the Ph.D. degree (Cum Laude) from Eindhoven University of Technology (TU/e) in 2015. Since then he is working at TU/e, where he currently is Assistant Professor. His research interests include integrated photonics circuits, microwave photonics, advanced DSP, and optical wireless communication.