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Indoor Optical/Radio Wireless Communication – Demonstration of High-Def Video Streaming using Steerable Infrared Beams

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Abstract — A hybrid wireless indoor system has been designed and validated which realizes ultrahigh-capacity transmission downstream by directing narrow infrared beams to mobile devices individually, using an AWGR-based module for wavelength-controlled 2D beam steering. For upstream, 60GHz radio techniques are employed which are also used to localize the devices and enable automatic infrared beam steering by a remotely located central communication controller. In a laboratory demonstrator, automatic mobile device localization and IR beam steering is demonstrated, and the transmission performance of conveying two high-def video streams optical-wirelessly to two users individually is demonstrated.

Keywords — Optical wireless communication; optical beam steering; arrayed waveguide router; video streaming

I. INTRODUCTION

The staggering growth of the demand for wireless connectivity, driven amongst others by the exploding volumes of broadband mobile services with video content and by the upcoming Internet of Things, is driving current radio-based wireless networks into serious congestion problems. Most of the wireless traffic is generated indoors, and solutions are being sought to offload huge traffic loads from current WiFi networks to alternative wireless network technologies. The mm-wave domain (unlicensed bands at 60GHz and beyond) offers attractive opportunities, THz bands are being explored as well, but when looking for additional frequency spectrum wireless communication in the optical domain can open up an unsurpassed amount of unlicensed new frequency space. Moreover, using optical techniques the wireless cell sizes can be reduced strongly, which is the key towards supporting the exponentially growing wireless traffic volumes according to Cooper’s law [1].

With Visible Light Communication (VLC), 320THz of bandwidth is accessible in the 400-700nm wavelength range. Much research efforts and first market introduction of VLC systems have been reported, largely aiming to extend the use of (existing) illumination systems to wireless data communication [2][3]. Alternatively, research is ongoing in exploiting the near-infrared window from 1460-1625nm, offering 20.9THz of bandwidth, by building on mature high-speed components widely available for fiber-optic communication. By means of narrow infrared beams, unshared high-capacity links can be established to devices individually, each capable of fiber-grade connectivity without being hampered by the medium access control restrictions in shared-medium communication. In the infrared range beyond 1400nm, the eye safety standards allow significantly higher beam powers than in the visible range; up to 10mW is permitted according to ANZI Z-136 and IEC 60825. The higher permitted light powers, increased photodetector responsivity as well as the high directivity of such narrow infrared beams can yield large link power budgets, significantly larger than with VLC, and therefore much higher data transfer capacity [3].

We have proposed a hybrid indoor wired/wireless network concept deploying beam-steered infrared light communication (BS-ILC) and have elaborated that in the European Research Council-funded project BROWSE - Beam-steered Reconfigurable Optical-Wireless System for Energy-efficient communication [4].

II. THE BROWSE SYSTEM

The BROWSE system concept is shown in Fig. 1. Within each room, for the downstream communication a so-called pencil-radiating antenna (PRA) is sending a narrow infrared beam to each mobile device. Each room contains at least two PRAs, which enables to circumvent line-of-sight blocking by providing an alternative path to the device. A PRA is fully passive and needs no local powering. It contains diffractive elements and can steer a beam in 2 dimensions just based on its wavelength. The data signal is carried to the PRA at that wavelength by a fiber. The indoor fiber network connects the

![Fig. 1 Indoor OWC system using λ-controlled 2D-steering of IR beams](image-url)
PRAs in the various rooms to a central site, where the Central Communication Controller (CCC) in cooperation with an Optical Crossconnect (OXC) takes care of the wavelength-tuning and routing of the data signals to the appropriate rooms and PRAs. Multiple beams can be emitted by each PRA by just feeding multiple data signals at the appropriate wavelengths to the PRA, carried by fiber after wavelength multiplexing in the CCC. The wavelength tuning range foreseen for the 2D beam steering is in the order of 100nm. The data speed envisaged per beam is at least 10Gbit/s.

For the upstream communication, each mobile device uses a mm-wave radio carrier in the 60GHz band (57-64GHz) and connects to an antenna at the PRA site. From there, the upstream traffic is carried by radio-over-fiber techniques to the CCC. This upstream link is also part of the control loop for the localization and tracking of the mobile devices.

III. BROWSE SYSTEM DEMONSTRATOR

To validate the BROWSE system concept, a laboratory system demonstrator has been built as outlined in Fig. 3. The actual realization is shown in Fig. 2. Mounted at the ceiling of the room, there are the wavelength-controlled 2D optical beam steering PRA module for the downstream optical wireless links, and the 60GHz receiver module for the upstream radio wireless links. A fiber connects both modules to the CCC. The 60GHz receiver module has a directional antenna which by panning and tilting can scan the user area in 2 dimensions in order to localize the mobile devices. The footprints of the optical beams which the PRA is able to emit are covering this area in a multi-cell pattern. Each cell is addressed by a beam at a specific infrared wavelength, and may host a mobile device. The mobile device is equipped with an optical receiver unit for the optical downstream link, and a 60GHz radio beam transmitter for the upstream link. In Fig. 2, on the laboratory table below two optical-wireless receivers are visible.

The 2D optical beam steerer was constructed according to the principle shown in Fig. 4. The wavelengths carried jointly by the input fiber are demultiplexed by an arrayed waveguide grating router (AWGR) into a large number \( N \) of output fibers, which are subsequently arranged by the 1D-to-2D interposer into a 2D fiber array. This array is put in front of a lens, and after the lens each wavelength is constituting a beam in a specific 2D direction given by the lateral position of the output fiber with respect to the lens optical axis and the focal length of the lens. In conjunction with the focal length of the lens, the spacing between the fibers was designed such that the footprints of the beams (actually, the \( e^{-2} \) intensity contours of these Gaussian beams) touch each other in the image plane, i.e. the area to be covered by the PRA in which the mobile devices are located [5]. The discrete number of output fibers implies an equal number of discrete cells which can be addressed.

By slightly defocusing the fiber array (i.e. putting it closer to the lens, beyond its focal plane), the coverage of the image area when varying the distance between the lens and the area can be improved. Denoting the distance from the lens to the image plane by \( b \), and the distance where the footprints exactly touch each other by \( b_0 \), Fig. 5 illustrates how the area coverage is changing when \( b \) is changed. At distances beyond \( b_0 \) the coverage is diminishing, whereas at distances shorter than \( b_0 \) there is an overlap of the footprints. The spacing \( d \) between the spots at a distance \( b \) from the lens is given by

\[
d = 2f \cdot \tan \alpha \cdot \left( \frac{b - f}{b_0 - f} - 1 \right)
\]

where \( f \) is the focal length of the lens, and \( \tan \alpha = \lambda / (\pi w_0) \) with \( w_0 \) being the mode field radius of the single mode fiber in the 2D fiber array; at \( \lambda=1.5\mu m \), \( w_0=4.5\mu m \) and thus \( \tan \alpha=0.106 \). The spacing \( d \) between the spots and the diameter \( D \) of the spots are plotted versus the distance \( b \) in Fig. 6. The defocusing parameter is defined as \( p=1-vf \) where \( v \) is the distance from the 2D fiber array to the lens; \( 0 \leq p < 1 \). For \( p=0 \) the array is in the focal plane of the lens and the beams are collimated, implying that the spot diameters stay nearly constant independent of \( b \). Whereas \( p>0 \) means putting the array closer to the lens, so then defocusing occurs and the beams are slightly diverging resulting in an increasing spot size when \( b \) increases. Fig. 6 shows that for \( p=0 \) (focused case; red graphs)
the spot spacing remarkably increases with distance $b$, the spot
diameter stays constant, and the area fill factor decreases
sharply beyond the design distance $b_0$. The area fill factor has
been defined as the area covered by all the spots, divided by the
total image area. It was calculated and plotted in Fig. 6 for an
hexagonal arrangement of the fibers in the 2D array (which
gives a somewhat better coverage than a square arrangement).
When introducing a defocusing $p=0.21$ (blue graphs), the spot
spacing has become clearly less dependent on $b$, the spot
diameter is increasing with $b$, and the area fill factor also has
become less dependent on $b$.

With defocusing also the dimensions of the steerer module
can be considerably reduced [5]. E.g., when a spot diameter of
12cm is desired in the image plane at distance $b_0=2.5$m from
the lens and a 2D array of 14×14 fibers is used, without
defocusing the required spacing between the fibers is 35.1mm,
the focal length of the lens 56.5cm, and its diameter 57.6cm.
With a defocusing $p=0.21$, the fiber spacing is 2.51mm, the
lens focal length 51.2mm, and its diameter 4.12cm. Hence the
introduction of a certain amount of defocusing is beneficial not
only for making the system’s performance less sensitive for the
distance from the mobile devices to the steering module, but
also for reducing the size of the beam steering module.

For the system demonstrator, a commercially available
high-speed f/0.95 camera lens with 50mm focal length has
been selected, containing 8 lens elements for minimizing lens
aberrations. A composite AWGR with a high output port count
was assembled by combining a commercially available C-band
AWGR having 96 ports with an L-band AWGR with 48ports,
spaced by 50GHz according to the ITU-grid, and with a -3dB
bandwidth of 35GHz and 24GHz, respectively. Following the
design equations reported in [5], a hexagonal 2D fiber array has
been assembled with a designed fiber spacing of 2.5mm; the
entry aperture of the camera lens allowed to fit 128 fibers. This
beam steerer setup enabled the coverage of an area of
1.6×1.6m² at a distance of 2.5m (corresponding to a maximum
half-angle of 18.6 degrees). Fig. 7.a shows the realized 128
fibers array, Fig. 7.b the assembly of this array with the 50mm
camera lens, and Fig. 7.c the assembly together with the
composite C+L band AWGR of which 128 output ports are
used. Fig. 10 shows a sample of the illuminated spots in the
image plane at 2.5m from the lens.

The prototype system demonstrator as shown in Fig. 2
hosts two optical free-space receivers; at each of these a lensed
collimator ($f=37.1mm$, $NA=0.24$) feeds via SMF the received
IR beam signal at about -16dBm to an SFP+ 10GbE
transceiver.

Fig. 4 Wavelength-controlled 2D beam steering using an arrayed
waveguide grating router

Fig. 5 Covering the image area by the beam footprints

Fig. 6 Spot spacing and area fill factor versus the distance from the image
plane to the lens, with defocusing parameter $p$

Fig. 7 Realizations of a) hexagonal 2D fiber array with 128 fibers, b) co-
assembled with camera lens, c) co-assembled with AWGR
The RF uplink consists at the user’s device of a 30dBi horn antenna driven by a 10dBm 61GHz carrier and can transmit up to 10Gbit/s. At the ceiling next to the PRA, there is a similar receiving horn antenna which by mechanical panning/tilting is iteratively aligned with this uplink beam. A Raspberry Pi3 board controls the alignment process, and thus determines the user device location. It sends the coordinates to the CCC which tunes the wavelength of the XFP transceiver such that the downstream IR beam is accurately pointed to the user’s device.

IV. BROWSE SYSTEM VALIDATION

The system’s performance has been validated in 10GbE (IEEE 802.3ae) high-def video streaming experiments as outlined in Fig. 8, where the BROWSE optical downlink/RF uplink paths are in the cloud. Four computers are involved. Servers 1 and 2 stream the video via their SFP+ transceivers embedded in NIC boards through the BROWSE cloud to clients 1 and 2. The NIC boards did not support wavelength tuning of the SFP+; hence the data signal from server 1 is on a fixed wavelength, and from server 2 the signal is first O/E converted and then wavelength-tuned by a tunable XFP transceiver controlled by the CCC. Both signals are combined by an optical coupler, power-boosted by an EDFA and via a single SMF fed to the AWGR-based beam-steering PRA. Due to limited availability of 60GHz components the return path could be established for one user only. The return path of client 2 is first O/E converted, modulated on a 61GHz carrier and transmitted via a 30dBi horn antenna. At the ceiling, a similar horn antenna after automatic mechanical alignment receives it and down-converts it to drive an XFP transceiver which connects to the Rx-port of the transceiver in server 2.

To demonstrate the IR beam steering, the location of the user device is determined by the 2D-scanning horn antenna at the PRA, looking for maximum received mm-wave power. The Raspberry controller conveys the spherical pan/tilt location coordinates found to the CCC which converts these into Cartesian coordinates. Using a look-up table containing the one-to-one relations of these coordinates to wavelengths, the CCC tunes the XFP transceiver’s wavelength such that the IR beam carrying the video stream of server 2 is accurately directed to the optical receiver of the user of client 2.

Simultaneous transmission by the IR beams of two high-def video streams embedded in 10GbE packets has been evaluated by bit-to-bit comparison of the received video with the original video, and yielded for the two users the BER curves shown in Fig. 9. The length of the video limits the measurable minimum BER to $3 \times 10^{-12}$; no errors occur for -19dBm received power at user 1 and -23dBm at user 2; the 4dB difference is mainly due to the spreading in the various transceiver characteristics. The inset shows the clear open eye diagrams of the received 10GbE packets.

V. CONCLUDING REMARKS

IR optical beams can provide ultra-high wireless capacity paths to individual devices, aided by mm-wave upstream techniques which also enable device localization. Closing the control loop by translating the device position into wavelength tuning for the 2D beam steering, autonomic system operation is achieved. Simultaneous transmission is shown of two high-def 10GbE video streams to two user devices individually.

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