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***Abstract*—Narrow infrared beams readily deliver high-capacity services to mobile users. The user can be localized in a self-calibrating way with passive retroreflector techniques. We demonstrated real-time video transmission using multiple beam steerers, circumventing line-of-sight blocking.**

Keywords— Optical wireless communication; optical beam steering; device localization; video streaming

I. Introduction

As the radio spectrum is getting seriously overcrowded due to the booming needs for wireless connectivity, new spectrum opportunities need to be found. The optical spectrum readily offers these: the visible spectrum (400-700nm, used amongst others for illumination) offers no less than 320THz of spectrum, and the infrared (IR) spectrum from 1500 to 1600 nm as used extensively in high-capacity optical fiber networks offers a respectable 12.5THz; both options significantly exceed what can be reached with radio mm-wave techniques, even with sub-THz techniques.

Visible light communication is typically using existing LED systems; these are primarily optimized for illumination, not for data transmission. Thus, their bandwidth is limited; moreover, their large footprint implies that this bandwidth is to be shared among many devices. A networked version of many small LED cells can increase the capacity per user, but at the cost of higher complexity [1] . We explored notably narrow IR beams which are to be steered individually, such that each one forms a ultra-high capacity wireless link addressing a single device [2] . It basically has the virtues of a fiber connection to the device, but without needing a fiber. Also, as it travels through air, not through fiber, it has minimum latency, as well as an intrinsically even higher bandwidth as it is not hampered by waveguide dispersion. Because a beam will be directed to go only there where and when needed, it is very power-efficient (not spoiling energy to places where it is not needed) and offers high privacy (reaching only the intended device, no others receive anything so cannot listen in). Moreover, IR light is 'eye-safe' beyond 1400nm, hence significantly higher power levels (up to 10mW) can be transmitted than in visible light. The thus attainable high link power budget enables very high data rates per beam. And the narrowness of a beam enables high spatial multiplicity, hence another significant increase of attainable data throughput.

In this paper, after discussing the indoor application scenario, we will focus on the user device localization needed for appropriate beam steering, and the extended system demonstrator setup.

II. Indoor Optical Wireless Communication with Infrared Steered Beams

We investigated the indoor scenario using narrow IR beams for optical wireless communication (OWC) as depicted in Fig. 1. In each room, at the ceiling there are multiple pencil radiating antennas (PRAs) which emit narrow beams in a direction which is determined by the wavelength of the light of the beam. Each beam serves a single mobile device in the room.

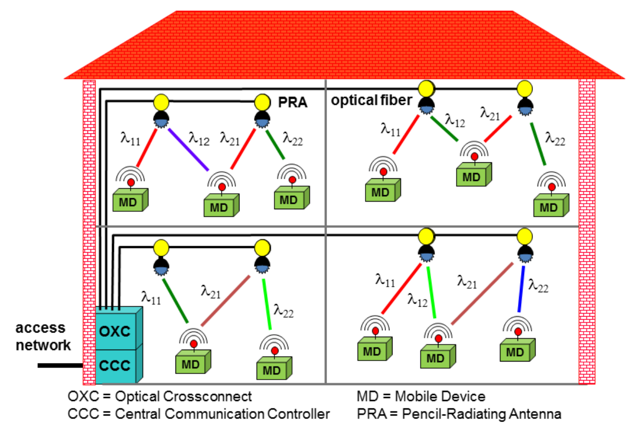

Fig. 1 Indoor OWC system using steered IR beams

A PRA is connected to the indoor fiber backbone network, which feeds the signal from a set of remote wavelength-tunable laser diode transmitters jointly located in the Central Communication Controller (CCC). The CCC interfaces with the access network, brings the services into the appropriate signal format for OWC transmission, by means of an optical cross-connect (OXC) puts them on the fiber which runs to the desired room, and puts them on the specific wavelength needed for steering the beams to the respective targeted devices.

III. Beam Steering

We proposed 2D beam steering by using wavelength tuning of the laser transmitters generating the IR beam signals in combination with a passive diffractive module in every PRA. We proposed a module exploiting a pair of crossed gratings, which yields two-dimensionally steering a beam by just varying its wavelength [3] . It can reach a continuum of positions along lines in the horizontal direction, and stepwise in the vertical direction. Another option we proposed is a module based on a high port-count AWGR (arrayed waveguide grating router) which acts as a demultiplexer, where the fiber output ports are arranged in a 2D fiber array and put in front of a lens, such that each input wavelength is translated into a narrow beam into a specific direction; see Fig. 2 [2] . Due to the discrete nature of the fiber array, this beam steerer can address a discrete two-dimensional set of cells in the user area. Together with the required beam spot size (typ. about 10cm) and the number N of output ports of the AWGR, the fiber pitch in the array and the focal length of the lens can be designed such that the beam spots form a contiguous set of discrete cells which optimally covers the user area [4] .

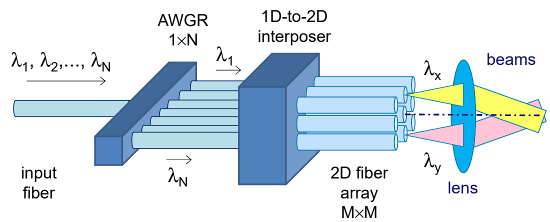

Fig. 2 AWGR-based 2D passive beam steerer

IV. Device localisation

In order to direct a beam into the right direction, we need to know accurately the position of the user's device. User localization in OWC has been topic of various research activities. Using multiple light sources at the ceiling, the user device can derive its position by means of tri-angulation [5] . Another option is to mount a camera at the ceiling which monitors the position of each user device by means of active tags on the device. In [6] a ring of LED tags emitting at 890nm around the receiving aperture of the device is positioned; the camera then can determine the device's position with an accuracy of 2.5mm at a distance of 3m. In [7] a low-cost camera is used in combination with 4 LED markers around the receiving aperture at the receiver. The 4 LEDs are blinking in a particular sequence, which defines the ID of the device. A simple Raspberry Pi processor performs the image processing after the camera. Device localization with an accuracy of 5mm at a reach of 3 m was achieved. These three methods all use active functions at the user device, which need power and thus drain the battery of the device.

We proposed a fully passive localization function at the device which does not drain precious power from its battery, by exploiting the unique properties of optical retroreflectors [8] . In contrast to a normal mirror, an optical corner cube (CC) reflector due to its geometry reflects an incoming beam exactly in the same direction as it came from. In order to localize a device, at the central site a tunable laser which is operated under the control of the localization processor is sweeping the laser's wavelength across its tuning range. Thus a beam is produced which is scanning the room. When the beam hits a device, by means of a CC mounted next (/around) the receiving photodiode a part of the beam is returned to the PRA site. Via the lens and the specific fiber port of the AWGR the returning signal then goes into the feeder fiber (as its wavelength obviously did not change) and continues back to the central site. There the localization processor registers that signal power returns at the wavelength at which at that moment the tunable laser was operating. In this way the laser's wavelengths are calibrated to the positions of the user devices.

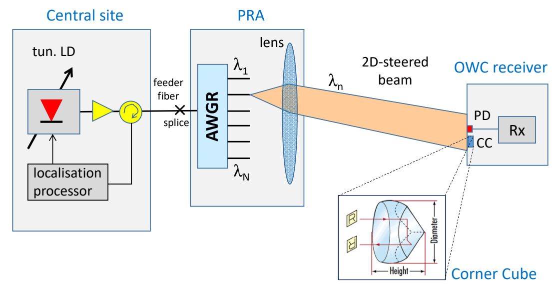

Fig. 3 Passive localization at user device by optical retroreflector

As illustrated in the inset of Fig. 3, each incoming ray is reflected by the CC the same direction, but with a small lateral offset which is proportional to the aperture of the CC. This offset does not have an impact when the 2D fiber array is in the focal plane of the lens. But when the fiber array is slightly defocused with respect to the lens (which is advantageous for improving the coverage of the user area at varying distance), this offset results in a weaker coupling into the feeder fiber. The offset can be minimized by reducing the aperture of the CC, but then the returned power decreases. Hence we have introduced an array of miniature CC-s, which embedded in a foil are readily available and widely used, e.g. in road signs.

Spurious reflections in the PRA and in the feeder fiber (e.g. caused by reflecting splices or connectors) may also affect the capability to distinguish clearly the returning signal. In our laboratory demonstrator, we used a commercially available wide aperture F/0.95 lens with f=50mm, composed of many elements which were anti-reflection coated for visible light and thus has spurious reflections for the IR beams. Moreover, there were optical connector joints between the AWGR and the 1D-to-2D interposer, also adding to the reflections inside the PRA. Hence we installed a small ∅1cm IR power detector very close to the lens, to monitor the power returning from the CC foil. When wavelength-scanning the user area with the ∅10cm IR beam, and using a ∅4cm CC foil mounted around the ∅3cm receiving aperture of the user device, the experiments showed clearly discernable power peaks, 8 to 10dB above the noise floor as shown in Fig. 4 [8] . The device localization accuracy is well within the IR beam's diameter, which is sufficient for establishing a good connection.

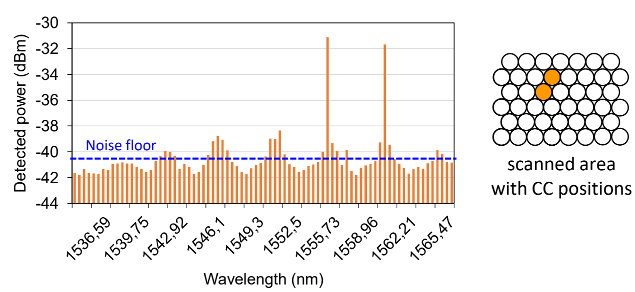

Fig. 4 Localization of the wireless devices

V. SYSTEM DEMONSTRATOR

Our laboratory demonstrator setup is shown in Fig. 5. It features two PRA-s, which in order to circumvent line-of-sight blocking can be selected by the optical cross-connect (OXC) in the central site (CCC). The OXC is composed of a 4×4 MEMS switch, with insertion losses of 7.0dB. Two user terminals are included, each equipped with a free-space optical receiver with ∅3cm aperture. A ∅4cm CC foil with a central hole of ∅3cm is mounted around this aperture.

Two high-definition video streams are transmitted from the CCC, each embedded in a 10 Gbit/s Ethernet stream. The video servers are equipped with SFP+ transceivers which are operated at a fixed wavelength. The tunable wavelength converter translates these video streams to the wavelengths appropriate for the 2D beam steering to the respective user terminals by the PRAs. Each user terminal is connected to a client for receiving the video stream, and displaying it on a monitor. The photo in Fig. 6 shows the physical details of the setup. Good real-time transmission of both video streams was achieved, with BER<$3\cdot10^{-12}$ at transmitted beam power of 6.0dBm and received power levels of -19 to -23dBm.

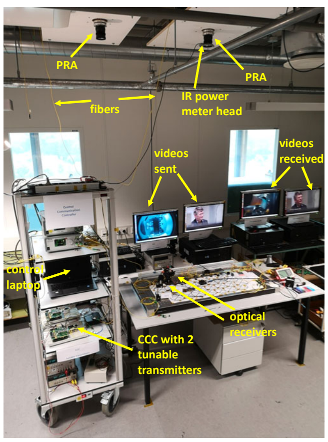

Fig. 6 Laboratory setup

VI. CONCLUDING REMARKS

Steering of narrow IR beams enables nigh-capacity optical wireless communication. Real-time wireless transmission of 10 Gbit/s Ethernet video streams to individual users has been shown, while supporting the beam steering by passive localization of the user by means of retroreflector techniques.

ACKNOWLEDGMENTS

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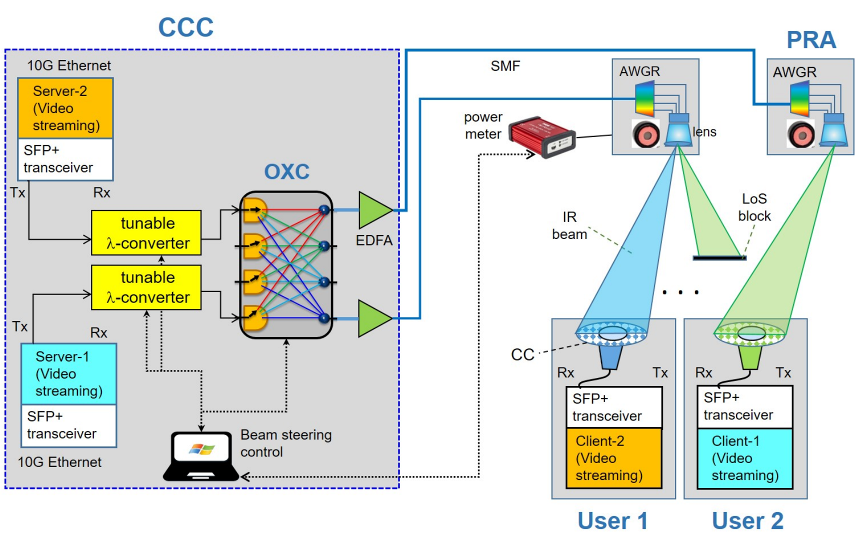

Fig. 5 Laboratory system demonstrator