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Optically Controlled Beam-steering Wireless Systems

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Abstract: Wavelength-controlled 2D steering of mm-wave beams and infrared beams provides high communication capacity, privacy and energy efficiency. Using diffractive elements and accurate user localization, delivery of multiple 10GbE video streams by infrared beams is demonstrated. © 2020 The Authors

OCIS codes: (060.2605) Free-space optical communication; (050.1970) Diffractive optics; (060.4265) Networks, wavelength routing

1. Introduction

The demand for wireless connectivity keeps growing fast, fueled by broadband services requested by smartphones, laptops, tablets, by the many wireless devices constituting the Internet-of-Things, machine-to-machine communication which also enable artificial intelligence, etc. This connectivity demand not only is about ever higher capacity, but also entails sometimes contradicting requirements as lower latency, seamless mobility, reduced energy consumption, and enhanced privacy. Cooper's Law [1] states that reduction of the wireless cell sizes is the key for further supporting wireless capacity growth. This requires more antenna sites; but as their coverage area is reduced they can be operated at lower power and the total energy consumption of the network may not need to grow [2].

A powerful way to create more small cells while not increasing the number of antenna sites is to partition the area covered by the antenna site into multiple sectors. One or more directive antennas at the site can send wireless beams with a relatively small footprint each, and steer these beams on demand to those places where and when capacity is requested. Using well-confined and –directed beams implies that the beam energy is most efficiently deployed and creates a large link power budget, thus enabling high data rate transfer. Because of techno-economic constraints, it is preferable to minimize the number of active functions at the antenna site, and to consolidate these mostly at a single central site from which many antenna sites can be fed. By means of radio-over-fiber techniques such remote antenna feeding with centralized RF signal processing can efficiently be done [2].

This paper deals with techniques which enable that next to this signal processing also the steering of the beams can be remotely controlled via the optical fiber feeding the antenna site. It focusses on indoor use, as illustrated for instance in a multi-room building in Fig. 1. An indoor fiber backbone network provides wireless services from/to the residential gateway (which interfaces with the broadband access network) to the individual rooms, in which antennas bring these services by well-directed beams to the respective user devices. Steering of mm-wave beams for RF communication as well as of optical beams for optical wireless communication is discussed.

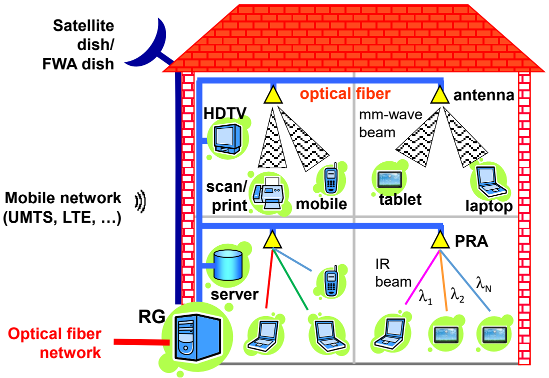

Fig. 1 Indoor wireless broadband service delivery by steerable beams (RG: residential gateway; PRA: pencil beam radiating antenna)

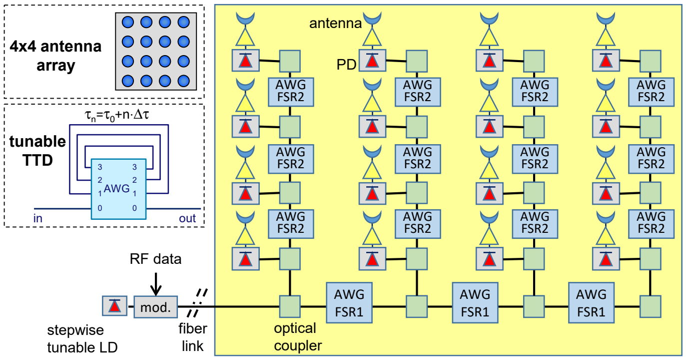

Fig. 2 Stepwise wavelength-tunable 2D mm-wave beam steering

2. Optically controlled mm-wave beam steering

To establish sufficient power budget for high-speed data transfer at mm-wave frequencies, a directive antenna with sufficient antenna gain is required as pointed out by Friis' equation [3], e.g. a horn antenna. Steering the mm-wave by mechanically directing the horn antenna is slow and does not allow to track fast moving users. A phased antenna array can effectively steer a mm-wave beam by varying the phase difference between the antenna elements, which can be done much faster. The phase difference determines the direction in which the radio waves emitted by the antenna elements constructively interfere. Provided that the spacing between the elements is less than half the wavelength of the mm-wave, there are no second order antenna lobes. Tunable electronic phase shifters may be used to realize the phase differences, but these consume a relatively large area in an integrated circuit. Moreover, due to their bandwidth limitations the phase shifters cause beam deformation ('beam squint') for broadband signals. Such deformation may be avoided by tunable true-time delay lines (TDL-s), which can efficiently be realized by integrated optical waveguides. As shown in an inset in Fig. 2, by using an arrayed waveguide grating router (AWGR) having *N* feedback loops with different lengths, we can create an optical TDL of which the delay time is stepwise tuned by changing the wavelength of the incoming RF signal. The TDL tuning is periodic with a wavelength period equal to the free spectral range (FSR) of the AWGR. By creating a 2-dimensional (2D) array as shown in Fig. 2, where the TDL stages in the row have a small FSR_1, and ones in the columns a large FSR_2 (being multiple times FSR_1), the phase differences at the 2D antenna elements are tuned stepwise during a wavelength sweep $\Delta\lambda \geq FSR_2$ such that the radio beam emitted by the 4×4 phased antenna array is swept once in the vertical direction and multiple times in the horizontal direction [4]. Thus a grid of $N \times N$ spots can be addressed line-by-line wise, where each spot corresponds with a specific wavelength to which the remote laser transmitter is tuned. Multiple beams can be steered independently by using multiple remote tunable transmitters. A 2×2 TTD integrated circuit was realized in silicon-on-insulator technology, designed with 7-loops TDL elements. It showed linear group delay characteristics when tested in a broad 10-20GHz mm-wave range [4]. Transmission of 8Gbit/s QAM-16 signals at 38GHz carrier frequency was demonstrated with a 1×2 TTD InP circuit with ±37.6° steering at 0.26m reach [5].

3. Optically controlled steering of narrow IR beams

By means of narrow infrared beams, wireless delivery of broadband services can be greatly facilitated. Optical wireless communication is license-free and does not consume precious radio spectrum, it offers a spectrum range way beyond what radio technologies can offer (320THz in the visible 400-700nm range, and 12.5THz in the commonly used infrared fiber window 1500-1600nm), and it offers improved privacy as it does not penetrate walls. High-speed optical components are readily available from the mature fiber optics communication systems market. As wavelengths beyond 1400nm are eye-safe, the use of infrared beams up to relatively high powers (≤10mW) is allowed [6]. Hence with narrow beams high link power budgets can be realized, and thus high data rates. Moreover, such beams each will address just a single device, and therefore no capacity sharing and no congestion issues will occur. In addition, privacy is strongly improved as no other persons can listen in.

We developed the system concept shown in the lower part of the building in Fig. 1, where in each room at the ceiling so-called pencil beam radiating antennas (PRAs) each direct multiple narrow infrared beams accurately to the respective user devices. We developed beam steering technologies which employ diffractive optical techniques, by which the direction of a beam is determined by its wavelength and tuning its wavelength will alter its direction. The wavelength of the signal thus not only acts as the carrier of the data, but also as the control channel for the beam steering: the control channel is embedded in the data channel, and no further bookkeeping is required to keep track which control channel is associated with the data channel, which eases network management. Notably we proposed a pair of crossed gratings [6] and also a combination of a high port count AWGR with a 2D fiber array interposer and a wide-aperture lens [7]. The latter concept is illustrated in Fig. 3. With an 80-ports C-band AWGR, we showed transmission of up to 112Gbit/s PAM-4 per beam over 2.5m reach [8]. The concept was elaborated and validated in a laboratory demonstrator [7] showing real-time transfer of multiple high-definition video signals embedded in 10GbE streams, each sent to specific receivers by steerable narrow infrared beams with a footprint diameter of ca. ∅12 cm. The composite AWGR was assembled by combining a C-band and an L^--band AWGR, operating jointly over 1530-1625nm. It has 129 ports with 50GHz spacing and -3dB channel bandwidths of 35 and 24GHz in C- and L-band, respectively. A commercially available wide aperture F/0.95 50mm focal length lens was used.

Accurate beam steering obviously requires localization of the user devices. Tri-angulation localization algorithms based on received signal strength (RSS), angle-of-arrival (AoA), or differential time of arrival (DToA) are well known, and require active signal sources either at the room's ceiling or at the user device, as well as localization signal processing at the opposite side. We explored localization by means of a camera mounted at the ceiling, which can localize multiple user devices simultaneously [9]. For this, each user device has four visible LED tags arranged around its optical receiving aperture which blink in a particular sequence acting as the ID of that device. After having determined the location coordinates, these have to be mapped and calibrated to the specific wavelengths which direct the beam to those locations. A localization accuracy of less than 5mm was achieved.

We also explored another localization method which does not require any active function at the user device, and thus does not deplete its precious battery resources [10]. It uses a matrix array of miniature corner cube reflectors, mounted as a circular foil in the circumference of the optical receiving aperture, which re-directs any incoming beam back to the beam-emitting PRA. By tuning its wavelength, a beam is scanning the user area, and by monitoring the returned power instantaneously during the scanning the device localization is directly mapped to the appropriate wavelength without requiring any further calibration. The localization accuracy was well within the footprint of the infrared beams, as required. Fig. 4 shows our laboratory system demonstrator, featuring the localization function by means of ∅4cm corner-cube reflector foils mounted around the ∅3cm receiving aperture and a ∅1cm aperture power monitor mounted next to the PRA. Two PRAs are provisioned which each cover a service area of 1.3×1.3m^2 (full angle 29.1° ×29.1°). The downstream signals are routed on demand to the appropriate PRA by a 4×4 MEMS-based optical crossconnect at the central communication controller site. Two 10GbE high-definition video streams can individually be directed to the users, with a reach of about 2.5m.

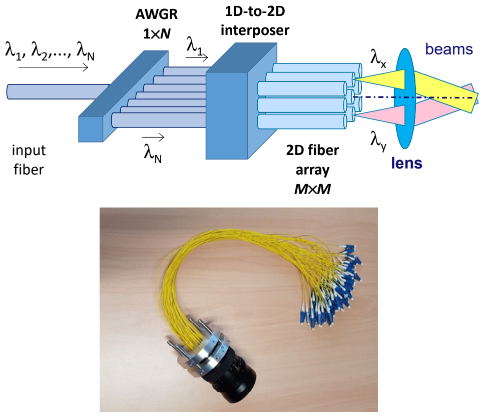

Fig. 3 Optical beam steering using an AWGR, 2D fiber array and lens; photo of assembled fiber array + lens module

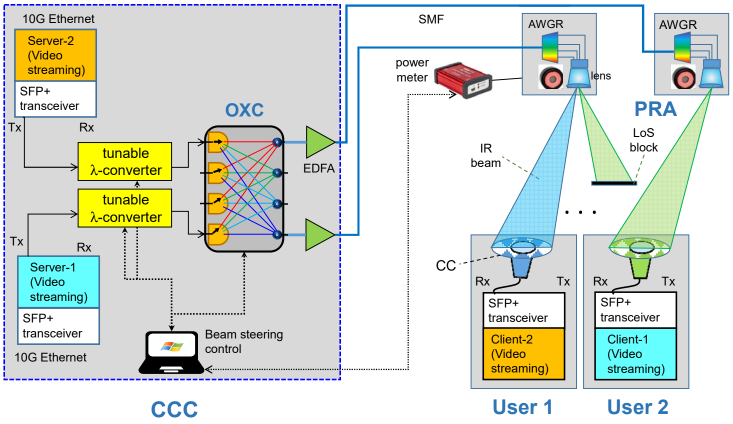

Fig. 4 Laboratory system demonstrator (OXC: optical crossconnect; CCC: central communication controller)

5. Concluding remarks

Pico-cell network architectures which are essential for realizing high capacity wireless communication are greatly aided by optical technologies, which not only enable delivery of the broadband data signals to complexity-reduced antenna sites but also can control efficiently the beam steering. By remotely tuning the wavelengths carrying the data signals, optically-fed phased array antennas can 2-dimensionally steer mm-wave beams, and also steer narrow infrared beams which achieve ultra-high capacity wireless links to multiple users individually. With infrared beams, we demonstrated up to 112Gbit/s PAM-4 capacity per beam, and demonstrated delivery of multiple high-definition video signals embedded in 10GbE streams including localization of the user devices using passive miniature corner cube array techniques or active camera-observation techniques.

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