Ultra-high Capacity Indoor Optical Wireless Communication using Steered Pencil Beams

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***Abstract*— Free-space indoor optical communication deploying pencil beams can offer ultra-high wireless capacity individually per user device. By means of 2D diffractive modules, such as a pair of crossed gratings, 2D steering of multiple beams by just tuning the wavelength of each beam can be achieved. The design aspects of an indoor system fed via an intelligent optical fiber backbone network are discussed. First experiments have shown a capacity of 42.8Gbit/s per infrared beam.**

Keywords — indoor wireless communication, diffractive optical beam steering, radio over fiber, optical signal routing, optical wireless communication

I. Introduction

The number of wireless communication devices is exploding all around us, in order to serve us with unobstructed broadband services, easy internet access everywhere, reliable monitoring of environmental conditions and health status, etc. Laptops, tablet computers, smartphones, wireless sensors and actuators are all fighting to get their necessary share of the radio spectrum. In the upcoming 5G wireless networks, 1000-fold capacity growth within the next ten years with respect to today's LTE wireless networks is foreseen [1]. Increasingly the limits to this growth are painfully getting clear, as the radio spectrum is getting congested and wireless devices are seriously interfering with each other. As a result, the throughput of the devices is impacted severely, and they may even be not able to establish a connection anymore.

An effective way to escape from the current radio spectrum congestion threat is to confine the radio coverage to small pico-cells with negligible interference among each other. Pico-cell network architectures also can yield a reduction of overall power consumption. Hence pico-cell network architectures are advocated in the evolving 5G radio standards. New spectrum bands are obtained by moving to new radio frequency bands, such as the bands of 60GHz and beyond, which with their inherent shorter reach also support the pico-cell concept. Dynamically routed radio-over-fiber indoor networks offer powerful energy-efficient pico-cell solutions [2][3]. An even more substantial step forward can be taken by optical free-space communication, i.e. by establishing wireless connections by using light. Optical light provides unsurpassed high carrier frequencies in an unlicensed spectrum, thus allowing plenty of room for spectrum sharing. Much research effort has been reported in visible light communication (VLC), which can piggy-back on existing LED illumination systems [4]. VLC systems are typically omni-directional, implying capacity-sharing of the light source by multiple user terminals. Also the received light intensity inherently goes down with the square of the distance to the source, which after the opto-electrical conversion in the photodetector implies that the electrical SNR at the receiver decreases with the fourth power of the distance to the source, and thus limits the reach.

In this paper, we discuss the design aspects of a system as proposed by us before in [5], which deploys directional narrow optical infrared pencil beams for the wireless paths, each aimed at a specific user terminal. Thus the full capacity of a beam is available to that terminal, and neither congestion nor interference with other terminals occurs. The pencil beam's directivity effectively alleviates the reach limitations, and saves energy by spatial allocation of capacity on demand.

II. Optical Beam-steered Indoor Communication

Our system concept (see [5]) is shown in Fig. 1. Inside a building, each room is equipped with pencil radiating antennas (PRAs), which each can emit multiple optical pencil beams. The capacity foreseen per beam is at least 10Gbit/s. Multiple PRAs per room are foreseen in order to provide full coverage of the room, and circumvention of possible line-of-sight blockings. Inside a PRA, a passive diffractive module steers a beam in two angular dimensions, by just varying the wavelength of the beam. Such scanning functionality has been proposed before, albeit in one direction [6]. Beam steering in two dimensions by active elements such as MEMS mirrors has been reported before (see e.g. [7]). It requires a separate mirror for each beam, and thus limits scalability towards large beam numbers. Moreover, the electro-mechanical tuning typically is slower than the tuning speed of a laser diode (which can have wavelength settling times less than 1μs). We propose to steer the beams in two dimensions by deploying two crossed diffractive elements (e.g. reflection gratings, see Fig. 2),where one element has a relatively low diffractive power, and the other one a high diffractive power. These elements together form a fully passive PRA module, which steers a beam in two dimensions according to its wavelength. The beam is continuously swept in one dimension by changing the wavelength over less than the large free spectral range (FSR) of the low-dispersive element, whereas it is swept multiple times in the orthogonal dimension when it traverses multiple small FSR-s of the other highly dispersive element. As a result, an area is scanned in 2 dimensions line by line, by just varying a single parameter, namely the wavelength of the beam. The wavelength of the beam thus also acts as a control channel of the beam steering, embedded in the data channel; hence a separate control channel is avoided, which relaxes network management and control. We propose to use infrared wavelengths beyond 1.4µm, where eye safety regulations allow higher beam powers than in the visible range; up to 10mW is allowed according to ANZI Z-136 and IEC 60825 standards. Multiple beams can be handled individually by just adding wavelengths, making this concept well scalable to large numbers of beams.

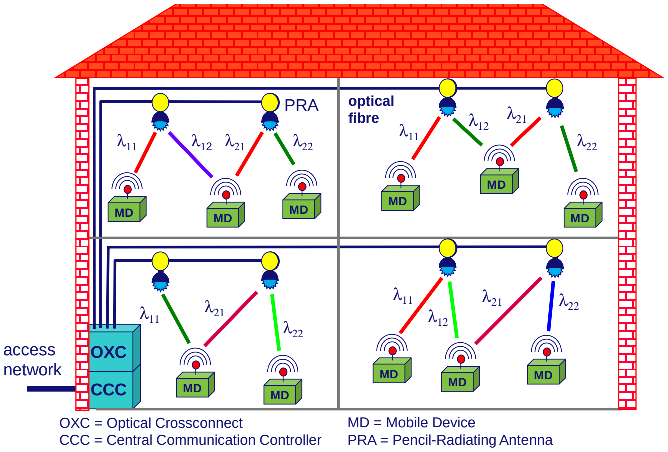


Fig. 1 Free-space indoor optical communication by pencil beams

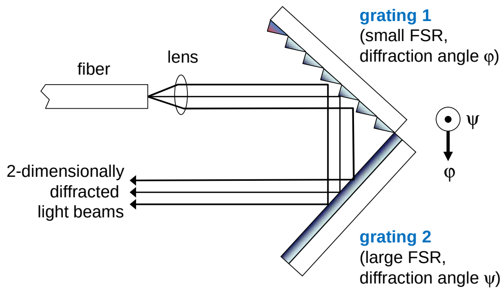


Fig. 2 2-dimensional optical beam steering by a pair of crossed gratings

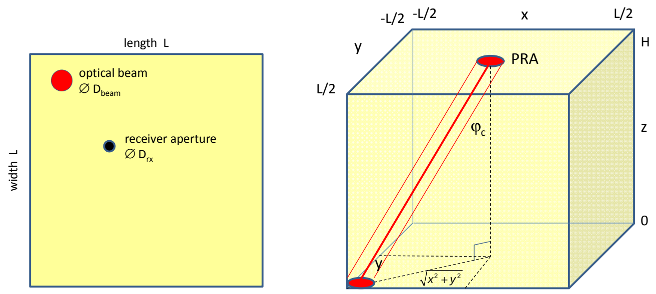
III. Design of the 2D Beam Steering Module

For specifying the functionality of the PRA, we assume that it has to cover an area of $L \times L$ by means of 2-dimensional scanning of this area with a beam having a diameter D_{beam} (see Fig. 3). The number of scanning steps needed is $N=(L/D_{beam})^2$. So when a wavelength tuning range $\Delta\lambda$ is available the tuning step size is $\delta\lambda=\Delta\lambda/N=\Delta\lambda\cdot(D_{beam}/L)^2$. Hence a lower bound for the beam diameter is given by $D_{beam}>L\ \sqrt{(\delta\lambda_{min}/\Delta\lambda)}$. When assuming that the receiver on the user terminal has an aperture with diameter D_{rx}, the PRA is fixed in the middle of the ceiling at height H, and the power intensity in the beam is uniform across its diameter, the lowest power received in the elliptical spot in the corner of the room is

$$P_{rx\_\min} = P_{beam} \cos\varphi_c \frac{A_{rx}}{A_{spot}} = P_{beam} \left(\frac{D_{rx}}{D_{beam}}\right)^2 \left(1+\frac{L^2}{2H^2}\right)^{-1}$$

which implicitly gives an upper bound to the beam diameter D_{beam} in order to guarantee an adequate minimum received power level. Fig. 4 shows how D_{beam} can be determined as a compromise between a minimum wavelength tuning step and a minimum receiver sensitivity. For covering an area with L=1.5m, H=2.5m, beam power P_{beam}=10mW, total wavelength tuning range $\Delta\lambda$=100nm, and receiver aperture diameter D_{rx}=1mm, when assuming a P_{rx_min}=-20dBm for a 10Gbit/s link and a $\delta\lambda_{min}$=50pm, D_{beam}=3cm. For the same beam diameter but with a larger receiver aperture D_{rx}=10mm, a much less sensitive receiver is needed, namely a P_{rx_min}=0dBm.

By using the line-by-line scanning technique, $M=L/D_{beam}$ lines are needed to cover the $L \times L$ area. As scanning one line is equivalent to passing through one FSR of the highly diffractive element, this FSR should be no more than $\Delta\lambda/M=(D_{beam}/L)\times\Delta\lambda$, which for the parameter values used before implies FSR_{max}=2nm. When a diffractive element is used based on interference among a number of beams, interference maxima occur when neighbouring beams have a path length difference equal to an integer multiple m (i.e. the interference order) of the wavelength λ. The FSR for such element is found from the relation $m\cdot\lambda=(m-1)\cdot(\lambda+\Delta\lambda_{FSR})$, so $\Delta\lambda_{FSR}=\lambda/(m-1)$. Combining this with the upper bound for the FSR derived above yields that the highly diffractive element should operate in an interference order of $m\geq1+(\lambda/\Delta\lambda)\cdot(L/D_{beam})$, which when operating at λ=1500nm and applying the same parameter values as used before implies $m\geq751$. Such high orders are far beyond the capabilities of regular diffraction gratings; they need specific multi-beam interference elements.



a) scanned area

b) scanning of room

Fig. 3 Scanning a room area with an optical beam

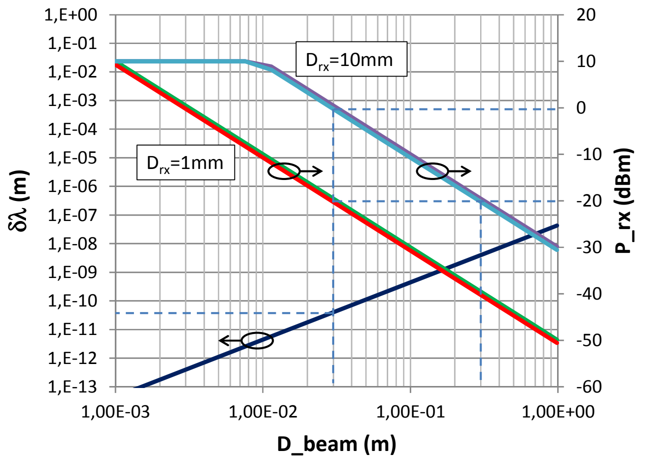


Fig. 4 Choosing the beam diameter (with L=1.5m, H=2.5m, P_{beam}=10mW, and D_{rx}=1mm or D_{rx}=10mm)

An element with high diffractive power operating in high order (and thus having a small FSR) is the arrayed waveguide grating (AWG) shown in Fig. 5. Neighbouring waveguides have an optical path length difference ΔL_x , and are spaced at the end facet by d_x. It can be derived that multi-beam interference maxima occur in direction φ for $d_x \cdot \sin\varphi + \Delta L_x = m \cdot \lambda$, and thus

$$\Delta\lambda_{FSR} = \frac{\lambda}{m-1} = \frac{\lambda^2}{\Delta L_x + d_x \sin\varphi - \lambda}$$

which implies that by designing the AWG with a large internal optical path length difference ΔL_x a small FSR and a high order *m* can be achieved.

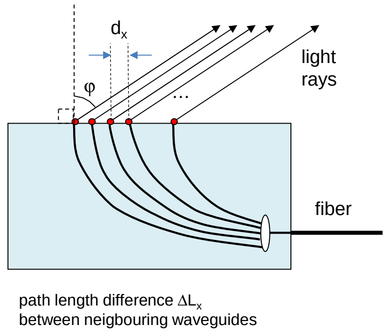


Fig. 5 Highly dispersive arrayed waveguide grating

An alternative solution for obtaining a small FSR and high order *m* is the VIPA – Virtually Imaged Phased Array [9][10], which relies on multi-beam interference generated by two reflective sides of a parallel plate. The interference order *m* is approximately equal to twice the optical thickness of the plate divided by the wavelength.

For the element with low diffractive power and large FSR (larger than the total wavelength tuning range $\Delta\lambda$), a diffraction grating operating in a lower order can be used as shown in Fig. 6. According to the well-known grating equation [8], $\sin\psi + \sin\theta_i = m \cdot \lambda / d$, where *d* is the groove spacing, the angular tuning range $\Delta\psi$ achieved when tuning over one FSR from λ to $\lambda + \Delta\lambda_{FSR}$ is

$$\Delta\psi = \psi_2 - \psi_1 = \arcsin\left(\frac{m}{m-1}\cdot\frac{m\lambda}{d} - \sin\theta_i\right) - \arcsin\left(\frac{m\lambda}{d} - \sin\theta_i\right)$$

$\Delta\psi$ is largest when $\psi_2 = \pi/2$, which yields $\cos\Delta\psi_{max} = 1 - (\lambda/d) \cdot m/(m-1)$. Moreover, $\psi_2 = \pi/2$ implies $\sin\theta_I = \lambda/d \cdot (m^2/(m-1)) \leq 1$, which yields an upper bound for the attainable $\Delta\psi$ given by $\cos\Delta\psi_{max} \geq 1 - 2/m$.

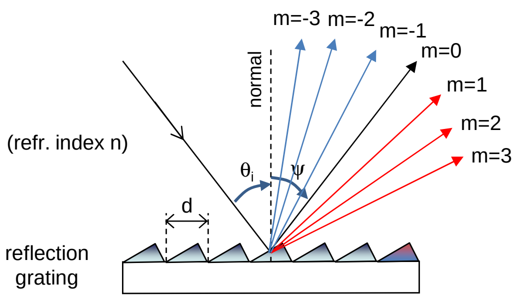


Fig. 6 Reflection grating operating in various orders *m*

Table 1 Maximum angular tuning range $\Delta\psi_{max}$ using a reflection grating, achieved for incidence angle θ_i

N (gr/mm)	Δψ_max (deg)	order m	tuning range Δλ (nm)	θ_i (deg)	Δψ_max bound (deg)
50	22,80	25	63	72,39	23,07
55	23,97	23	68	79,66	24,07
60	25,11	21	75	79,90	25,21
65	26,22	19	83	72,83	26,53
70	27,32	17	94	63,71	28,07
75	28,36	16	100	66,93	28,96
80	29,37	15	107	68,21	29,93

As shown in Table 1, when deploying a maximum wavelength tuning range $\Delta\lambda$ of 100nm (from 1.5 to 1.6µm), the maximum attainable angular tuning range is 28.36°, which can be achieved with a reflection grating of 75 grooves/mm at a large incidence angle of 66.93°.

IV. Design of the Indoor Fiber Backbone Network

A fiber backbone network is foreseen throughout the building in order to connect the PRAs located in the various rooms, as shown in Fig. 1. A point-to-point fiber link connects each PRA to the Central Communication Controller (CCC), where the tunable laser diodes are located. By means of an optical crossconnect (OXC), according to actual traffic demands these laser diodes are mapped to the appropriate PRAs in the appropriate rooms. At the CCC, autonomic network management is located to intelligently locate and track the (roaming) users' mobile devices (MDs), and to control the OXC settings and the wavelength tuning accordingly. Machine learning techniques will be applied which gather user behavior characteristics, in order to speed up localization, tracking and beam steering processes.

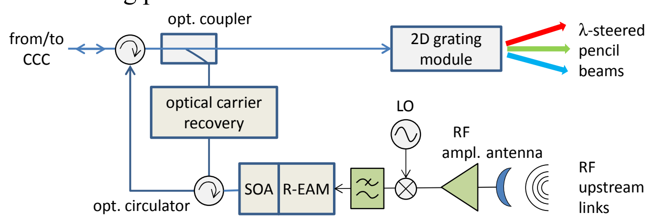


Fig. 7 Radio-over-fiber upstream path at PRA site, with optical carrier recovery

For the upstream path from the MD to the CCC, RF links in the 57-64GHz band are foreseen, to be picked up by an antenna at the PRA and carried over the fiber network. As illustrated in Fig. 7, at the PRA site a nearly clean optical carrier can be recovered from the downstream amplitude-modulated signal (constituting the steerable pencil beam). This carrier recovery by erasing the modulation can be done by an SOA operated in the gain-saturated regime, or an injection-locked Fabry-Pérot laser diode. Subsequently, a reflective modulator, composed of an SOA plus reflective electro-absorption modulator (R-EAM), is used to modulate the downshifted upstream RF signal onto this clean carrier. By means of a phased-array antenna at the PRA providing distinctive tunable nulls in the antenna pattern, also localization of the active MDs can be supported for aiding the optical pencil beam steering.

V. SYSTEM EXPERIMENT

The 2D beam steering concept has been experimentally verified in the laboratory setup shown in Fig. 8 [11]. A DFB laser transmitter operating at 1550nm followed by a polarization controller and *f*=18.4mm lens collimator launches the pencil beam onto a pair of crossed echelle reflection gratings. The first grating has 31.6 grooves/mm and is operated in order *m*=35, and the second one 79 grooves/mm operated in *m*=15. Silver coated mirrors are deployed to fold the total path length of 2.5 meters. After reception by a second lens collimator, the signal is photo-detected. The power of the pencil beam out of the first collimator was below 9.3dBm, so below the eye safety limit of 10dBm. The path loss up to the receiver, including the losses of the gratings, mirrors and alignment imperfections, was 14.9dB, leaving a received power of -5.6dBm. The dispersion of the gratings in conjunction with the limited aperture of this collimator determines the spectral characteristics of the pencil beam channel. Using the broadband ASE spectrum of an EDFA, these characteristics have been measured as shown in Fig. 9. A -3dB optical bandwidth is found of 17.07GHz. Discrete multitone (DMT) modulation with 512 tones has been used for adaptive bitloading per tone in order to accommodate the spectral characteristics of the 2D-diffracted pencil beam path plus the subsequent receiver. As shown in Fig. 10, a maximum loading with 7 bits/symbol (QAM-128) was observed, decreasing to 1 bit/symbol at the edge of the usable spectrum, located at about 11GHz. The gross bitrate achieved including DMT overhead was 42.8Gbit/s, and the net bitrate 37.3Gbit/s.

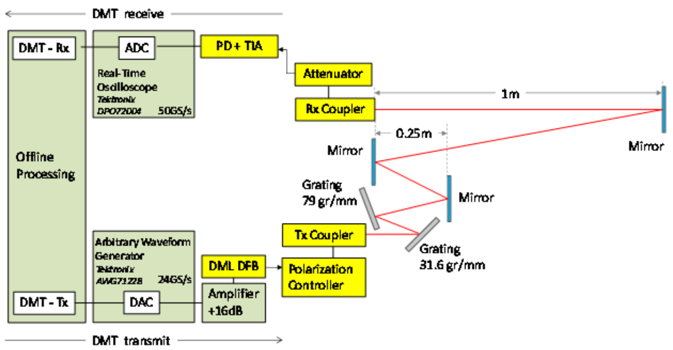


Fig. 8 2D beam steering experiment

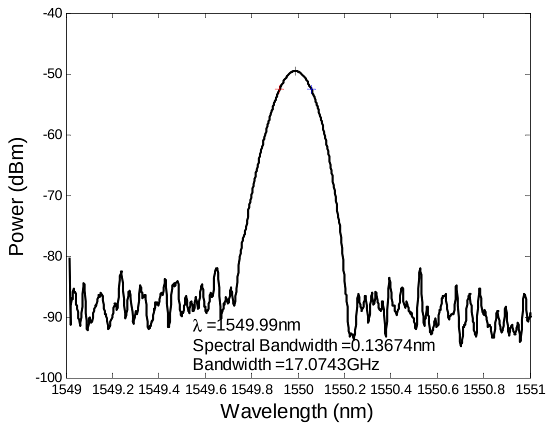


Fig. 9 Spectral characteristics of 2D-steered pencil beam channel

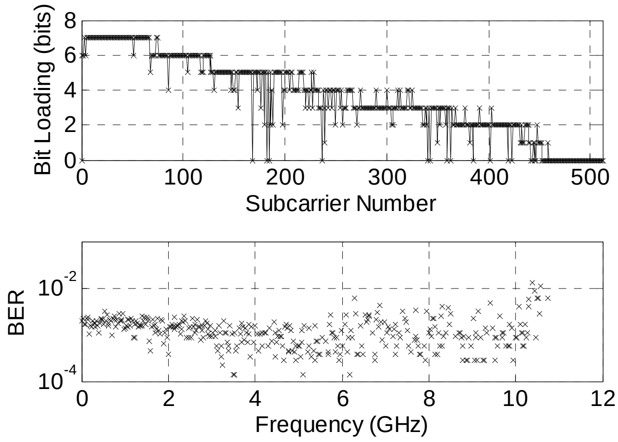


Fig. 10 DMT adaptive bit loading on the pencil beam channel

VI. CONCLUDING REMARKS

Free-space optical communication deploying 2D steerable narrow optical beams can offer the ultimate in wireless capacity per terminal. The proposed concept employs a pair of passive crossed diffractive elements which enables scaling to large numbers of beams, each individually steerable by tuning its wavelength in the 1.5µm infrared regime. Delivery of 42.8Gbit/s per beam over 2.5m reach has been demonstrated. Careful design of the diffractive stages is needed to provide adequate area coverage.

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