Ultrahigh-capacity optical-wireless communication using 2D gratings for steering and decoding of DPSK signals

Citation for published version (APA):
Mekonnen, K. A., Tangdiongga, E., & Koonen, A. M. J. (2020). Ultrahigh-capacity optical-wireless communication using 2D gratings for steering and decoding of DPSK signals. In *Proceedings of the The Optical Networking and Communication Conference & Exhibition (OFC2020)* Article 9083057 Optical Society of America (OSA). https://ieeexplore.ieee.org/document/9083057

Document status and date:
Published: 13/05/2020

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.

Download date: 17. Nov. 2023

Ultrahigh-Capacity Optical-Wireless Communication Using 2D Gratings for Steering and Decoding of DPSK Signals

Ketemaw Mekonnen, Eduward Tangdiongga, and Ton Koonen
Institute for Photonic Integration, Eindhoven University of Technology, Den Dolech 2, 5612AZ Eindhoven, The Netherlands
k.a.mekonnen@tue.nl

Abstract: We demonstrate the use of a 2D-gratings beam-steering device also as a demodulator for multiple differentially-encoded optical-wireless signals. Using this novel concept, ~2bits/sec/Hz spectral-efficiency was achieved without any change in the system compared to on-off-keying.

OCIS codes: (060.2605) Free-space optical communication; (050.1950) Diffraction gratings;

1. Introduction

Interest in steered infrared optical-wireless communication (IOWC) as a promising alternative to traditional radio frequency (RF) techniques and visible light communication (VLC) [1,2] in indoor environments is increasing significantly thanks to its huge unlicensed bandwidth that allows large capacities per user as well as the benefit of deploying the mature and widely available components in conventional optical fiber communication system for a seamless integration with the future fiber-to-the-home infrastructure [3]. In our previous works, we have demonstrated dynamic indoor IOWC systems implementing a crossed-pair gratings-based beam-steerer to provide transmission capacities (per user) of up to 50Gb/s using discrete-multitone (DMT) modulations [4,5]. However, simplicity and cost-efficiency are usually given more emphasis than transmission capacity in indoor optical networks since installation and operational costs are borne by the individual users. Oftentimes, on-off-keying (OOK)-direct detection (DD) transceiver designs are preferred. However, with the 10GHz bandwidth that our beam steering module provides, only up to 13Gb/s error-free transmission speed was possible (assuming channel bandwidth of 75% of the bit-rate) unless advanced modulation formats such as DMT are implemented, which would complicate the user terminals.

In this paper, we propose a novel technique which involves the use of differential phase shift keying (DPSK) modulation in cooperation with the spectral filtering functionalities of the 2D gratings module, which converts the modulation to duobinary, to provide intensity modulated signals with higher capacities than standard OOK systems. Although, the primary use of the 2D gratings module is for the beam steering, in this work, we show that it can be exploited as a demodulator for multiple DPSK signals at a time to allow DD at the user terminals without requiring the costly and sensitive delay-interferometers (DIs). Using this concept, more than 24Gb/s wireless data transmission speeds were achieved (with the 10GHz bandwidth provided by the 2D gratings module), which is twice what standard OOK could provide, without any change in the system, except at the transmitter, where DPSK is implemented**.**

2. Indoor dynamic bidirectional wireless network architecture

The proposed indoor network architecture is depicted in Fig. 1. Each room is equipped with multiple pencil radiating antennas (PRAs) which can steer multiple optical pencil beams to the users using our 2D gratings based beam steering module [4]. The residential gateway (RG) hosts the tunable transceivers to serve the users with appropriate wavelengths for the beam steering in each room. An OXC is implemented to dynamically share these transceivers among the users and to provide capacity-on-demand. The central communication controller (CCC) performs the indoor network management and control including user localization and tracking. In order to provide bidirectionality, a wavelength reuse technique, which exploits the reversibility principle of optics whereby light at the same wavelength follows the same path that it traversed when the beam is reversed, can be implemented for the upstream communication as demonstrated in [6].

Optical DPSK is a binary modulation format where the information is encoded on the phase differences between the optical carrier and its 1-bit-period delayed replica. A DPSK signal can be written as: $S_{DPSK}(t) = E_0 \cos(\omega_0 t + \psi(t))$, where $\boldsymbol{\omega_0}$ is the angular frequency of the optical carrier, $\mathbf{E_0}$ is the optical field amplitude, and $\psi(t) = \sum_i \psi_i\, p(t-iT_b)$, where $\psi_i = \psi_{i-1} + (d_i - 1)\pi$, $\mathbf{p(t)}$ being a non-return-to-zero pulse, $\mathbf{T_b}$ the bit duration and $\mathbf{d_i} \in \{\mathbf{0}, \mathbf{1}\}$ is the information symbol and ψ_i is the phase of the optical signal for the i^{th} symbol. DPSK is a constant-envelope technique, and therefore is more robust to fiber nonlinearities than intensity modulation techniques such as OOK. This allows us to launch multiple

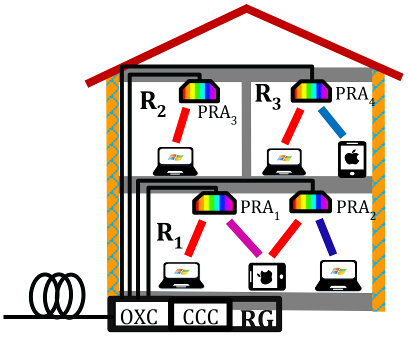
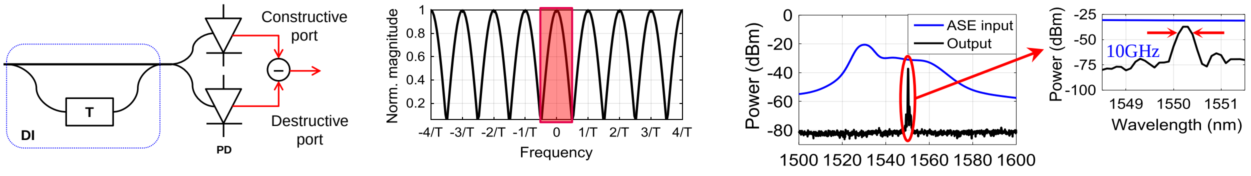


Fig. 1. Proposed indoor network architecture.



(a) (b) (c)

Fig. 2. (a) Optical DPSK receiver using a DI; (b) DI frequency response (the highlighted portion indicates the first arch of the cosine filter which can be approximated by using a Gaussian bandpass filter); (c) Spectral response of the 2D gratings module measured using the amplified spontaneous emission noise from an erbium-doped-fiber amplifier (EDFA).

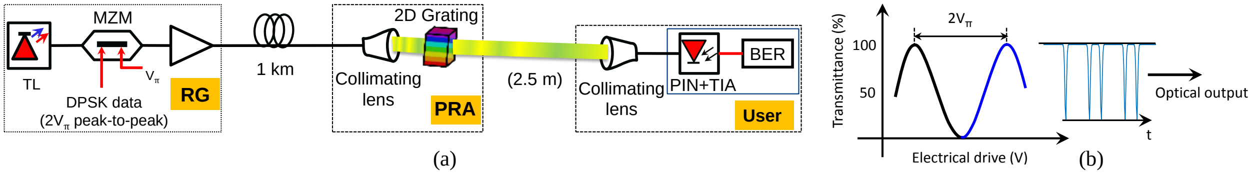
optical pencil beams with high powers into the optical fiber, which simplifies the access points since any need for amplification to tackle losses in the wireless channel can be performed at the central site. Moreover, the constant envelope of the DPSK signal facilitates optical carrier reuse at the PRAs for upstream communications [7].

An optical DPSK signal is usually demodulated at the receiver by using a one-bit-delay and multiply block (i.e., a delay-interferometer (DI)) as shown in Fig. 2a. Adding a signal to its one-bit-delayed replica using a DI can be written in the temporal domain as the convolution of the signal by $\delta(t)+\delta(t-T_b)$ where δ is the Dirac distribution. In spectral domain, this corresponds to multiplying the spectrum of the signal by $1+\exp(j2\pi fT_b) = 2\exp(j\pi fT_b) \times \cos(\pi fT_b)$. This is equivalent to transmitting the signal through a cosine filter whose magnitude response is frequency periodic with a period of 1/Tb as shown in Fig. 2b. Following the Nyquist theory, only the first arch of the cosine function can be used, which may be approximated by any Gaussian band-pass filter (BPF) having the same bandwidth [8]. The Gaussian BPF, effectively carves out a duobinary spectrum from the original DPSK signal. Fig. 2c illustrates this principle by employing the 2D gratings beam steering module as a Gaussian BPF of 10GHz bandwidth. In DPSK modulation, a π phase shift takes place at each bit time when the incoming bit is a “0”, and no phase shift takes place when the incoming bit is a ”1”. Narrowly filtering such a signal substantially reduces the envelope of the signal corresponding to a stream of “0-s” while leaving it almost unaltered for a stream of “1-s”. Thus, the 2D gratings module converts multiple DPSK modulated signals to duobinary ones [9] (equivalent to OOK in the optical domain). Moreover, duobinary signaling is known to shift a larger part of the signal’s spectrum towards the lower frequencies, thus enabling transmission of signals with larger bandwidths via the 2D gratings module.

3. Experimental demonstration and results

An experimental setup was constructed as shown in Fig. 3a. The downstream differentially-encoded optical wireless data was modulated on to an optical carrier generated from a tunable laser source at 1550.2nm wavelength using a Mach-Zehnder modulator (MZM) biased at its minimum transmission (V_π) with peak-to-peak voltage of $2V_\pi$ (Note that generating optical DPSK modulation in this way also causes the optical power to drop to zero on every bit transition, as well as suppression of the optical carrier as shown in Fig. 3b. The signal was then launched into a 1km optical fiber, after amplification to compensate the losses introduced by the MZM, the beam-steerer, and the coupling optics at the user terminal, which were approximately 16dB in total. At the PRA, the optical signal from the feeder SMF was collimated using a triplet-lens collimator of focal length 18.4mm (resulting in a beamwaist of 3.3mm) before it hit the crossed-gratings module which directed the pencil-beam to a PIN+TIA receiver located at a free-space distance of 2.5m. Although the experiment was performed for a free-space distance of 2.5m, the performance variation is negligible within a typical indoor scenario (room size <10m) since collimated pencil beams were implemented. The 2D steerer consists of two crossed gratings in which the first is a 80.7° (13.33 grooves/mm) blazed reflection grating and the second is a 1000 grooves/mm transmission grating, which resulted in a combined loss of 6dB, a bandwidth of 10GHz (see Fig. 2c), and coverage angle of 5.6° × 12.2°, corresponding to a 24.5cm × 54cm area at a free-space distance of 2.5m [4]. The transmitted power from the 2D gratings was kept below +6 dBm in all the measurements.

Fig. 4a depicts the bit-error-rate (BER) curves at the receiving-end when DPSK was implemented for varying bit rates. The threshold voltage and sampling instant of the error analyzer were optimized for each BER measurement. Please note that the direct detection sensitivity of the PIN+TIA receiver used was -14dBm at a BER of 1×10^{-9}. By



(a) (b)

Fig. 3. Experimental test bed using an MZM at the RG to generate the optical DPSK signal and a 2D gratings module at the PRA for optical pencil-beam steering and DPSK demodulation; (b) the MZM output signal showing intensity dips during each bit transition.

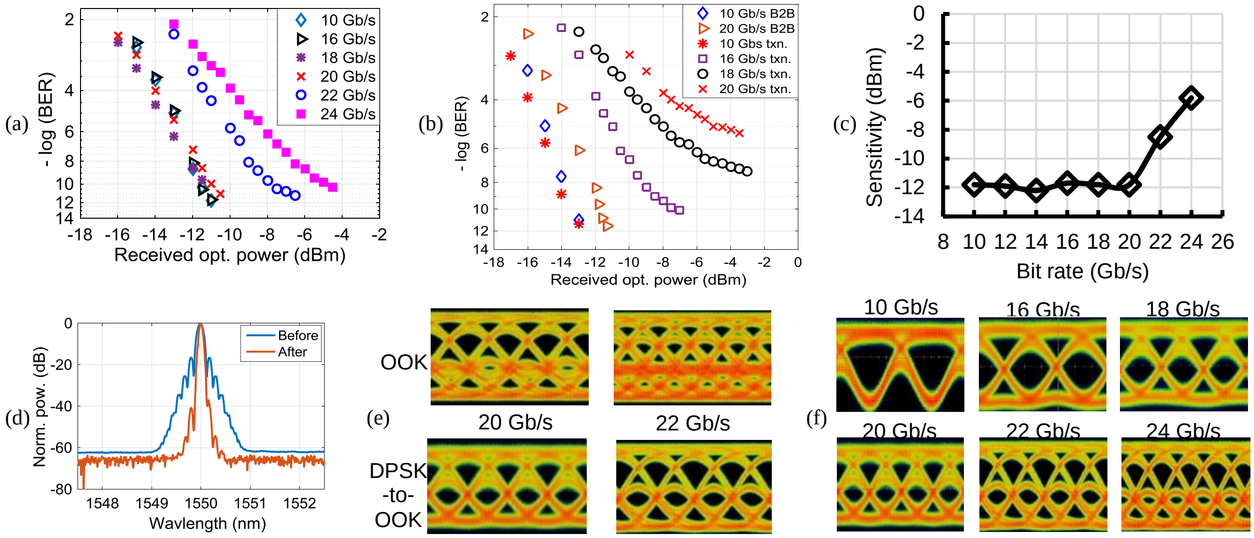


Fig. 4. (a) BER curves of DPSK modulated signals after transmission; (b) Back-to-back and transmitted BER curves of OOK modulated signals for varying bit rates; (c) Receiver sensitivity measurements at a BER of 1×10^{-9} for DPSK modulated signals of varying data rates; (d), (e) Eye diagrams of DPSK and OOK signals at 20Gb/s and 22Gb/s, and DPSK signals of different bit rates, respectively, after wireless transmission.

adjusting the threshold voltage, no additional penalty was incurred when transmitting at 20Gb/s compared to 10Gb/s. More than 24Gb/s error-free transmission was possible, albeit with a power penalty of 6dB, compared to 10Gb/s. This can be compared with the performance of OOK modulation, shown in Fig. 4b, in which only up to 16Gb/s error-free transmission was possible, even with a power penalty of >5dB because of the narrow channel bandwidth that the 2D gratings module provides. As shown in Fig. 4c, by optimizing the decision threshold, the sensitivity of the DPSK signal at a BER of 1×10^{-9} doesn't change when the bit rate was varied from 10Gb/s up to 20Gb/s, unlike the OOK modulated signal, where the penalty rises rapidly with increase in the bit rate (see Fig. 4b). In the OOK case, error floors start to appear for bit rates >14Gb/s (see Fig. 4c). Fig. 4d shows the spectrum of the DPSK signal at the user terminal (before and after the wireless transmission). As shown in the respective eye diagram in Fig. 4e, for bit rates of 20Gb/s and 22Gb/s, while the filtering of the OOK signal resulted in closing of the eye diagram, which makes it impossible to receive the signal without error, the filtering of the DPSK signal resulted in conversion of the modulation to OOK. Fig. 4f shows the eye diagram of the DPSK signal at the user terminal for different bit rates. We can see clear eye openings even at 24Gb/s data rate.

4. Conclusion

We presented a novel OWC system that can provide non-shared capacities of >24Gb/s per user, within a channel bandwidth of 10GHz by combining DPSK modulation with the narrowband filtering functionalities of the 2D gratings based beam steering module. Although the primary purpose of the 2D gratings module is for the beam steering, it was demonstrated here that it can also be exploited as a demodulator for multiple DPSK signals at a time to allow direct detection (with higher spectral efficiency) at the user terminals without requiring costly and tunable DIs.

This work was funded by the ERC-FP7 AdG project BROWSE and the PoC project BROWSE-PLUS.

5. References

1. D. O'Brien, R. Turnbull, H. L. Minh, G. Faulkner, O. Bouchet, P. Porcon, M. Tabach, E. Gueutier, M. Wolf, L. Grobe, J. Li, "High-speed optical wireless demonstrators: conclusions and future directions," J. Lightw. Technol., **30**, 13 (2012), p. 2181.
2. H. Haas, "Visible light communication," in OFC (2015), Paper Tu2G.5.
3. K. A. Mekonnen, E. Tangdiongga, A. M. J. Koonen, "High-capacity dynamic indoor all-optical-wireless communication system backed up with millimeter-wave radio techniques," J. Lightw. Technol. **36**, 19 (2018), p. 4460.
4. T. Koonen, J. Oh, K. Mekonnen, Z. Cao, and E. Tangdiongga, "Ultra-high capacity indoor optical wireless communication using 2D-cteered pencil beams," J. Light. Technol. **34**, 20 (2016), p. 4802.
5. K. A. Mekonnen, Z. Cao, N. Calabretta, E. Tangdiongga, A. M. J. Koonen, "50 Gb/s indoor optical wireless communication equipped with millimeter-wave backup system and localization and tracking," in ECOC (2017), p. 1.
6. K. A. Mekonnen, Z. Cao, E. Tangdiongga, and A. M. J. Koonen, "Towards dynamic ultrahigh capacity symmetric bidirectional indoor optical-wireless communication," in Proc. OFC (2018), paper M1F.6.
7. K. A. Mekonnen, J. van Zantvoort, N. Calabretta, N. Tessema, E. Tangdiongga, Ton Koonen, "High-capacity dynamic indoor network employing optical-wireless and 60-GHz radio techniques," J. Light. Technol. **36**, 10 (2018), p. 1851.
8. D. Penninckx, H. Bissessur, P. Brindel, E. Gohin, F. Bakhti, "Optical differential phase shift keying (DPSK) direct detection considered as a duobinary signal," in ECOC (2001), p. 456.
9. A. Lender, "The duobinary technique for high-speed data transmission," IEEE Trans. Commun. Electron., **82**, 2 (1963), p. 214.