High-capacity symmetric dynamic indoor optical wireless communication equipped with user localization

DOI:
10.1109/LPT.2018.2853128

Document status and date:
Published: 15/08/2018

Document Version:
Accepted manuscript including changes made at the peer-review stage

High Capacity Symmetric Dynamic All-optical Indoor Wireless Communication Using Photonic Integrated Circuits

K. A. Mekonnen, *Student member, IEEE*, N. Calabretta, *member, IEEE*, J. H. C. van Zantvoort, E. Tangdiongga, *Member, IEEE*, A. M. J. Koonen, *Fellow, IEEE, Fellow OSA*

Abstract— We report on a novel all-optical system for ultra-high capacity indoor wireless communication with centralized light sources. Using optical cross-connect and reflective modulator photonic chips, bidirectional dynamic indoor wireless networks equipped with localization and tracking functionalities are realized. This novel system allows us to harvest the ultimate bandwidth of optical communication in the wireless domain in a more cost/energy efficient manner. Bidirectional transmission capacities in excess of 40 Gb/s per user are demonstrated experimentally.

***Index Terms*—Indoor networks, free-space optical communication, diffraction gratings, dynamic routing.**

I. Introduction

BANDWIDTH demand and interference among devices in indoor wireless networks is exceeding the capabilities of traditional radio techniques, which have been the core enabling technologies in providing wireless communications so far. Infrared optical wireless communication (IOWC) using steered narrow beams is a highly promising alternative to counter this bandwidth crisis in the radio frequency (RF) domain [1][2]. It brings the huge unlicensed bandwidth of optical communication into the wireless arena to allow ultrahigh data rates, enhanced security, and immunity to electromagnetic interference. The directive nature of the communication also eliminates interference among users.

Currently, the majority of the research in IOWC focuses on improving the downlink communication with respect to capacity, coverage and efficiency. Few progressive works are seen for the uplink. In addition, main network functionalities such as reconfigurability and user localization have been given little research attention so far. Such functions are key for cost/energy-efficiency, to meet changes in traffic patterns, for connection establishment, and to cope with indoor mobility.

Previously, we proposed a dynamic indoor IOWC system where the upstream was realized using 60-GHz radio [3]. While up to 40 Gb/s per user has been realized in the downstream, the upstream was limited to 20 Gb/s due to the 7-GHz unlicensed bandwidth limit of the 60-GHz signals resulting in asymmetric communication. In addition, radio beam steering using phased-array-antennas, and the down-conversion and multiplexing of 60-GHz signals lead to more complicated transceiver hardware at the radio access points and user terminals, where simplicity and cost/energy-efficiency are of paramount importance. Light emitting diodes (LEDs) and lasers can also be implemented for the upstream. The inherent bandwidth limitation and broad beam profile of LEDs necessitate a compromise on the link budget and data rate. Laser based upstream communication needs an additional beam steering at the user terminal which leads to latency and complicated transceiver hardware. In [4], we have demonstrated the use of the reversibility principle of optics to provide bidirectional IOWC, which doesn't need additional beam steering for the upstream. A wavelength reuse approach by first erasing the downstream modulation using a saturated semiconductor optical amplifier (SOA) was implemented. Although we achieved bidirectional 10 Gb/s (per user) communication links, a compromise was needed between the downstream and the upstream performances. Moreover, it increased the power consumption at the user terminal.

In this Letter, we propose a novel low-cost and low-power consumption, yet ultrahigh performance bidirectional IOWC using a crossed pair of diffraction gratings and photonic integrated circuits (PICs) to realize dynamic indoor wireless communication with user localization and auto-tracking functionalities. We use the same reversibility principle as in [4]; however, here, the downstream optical carrier is time-shared between the downstream and upstream communications in a half-duplex manner using a reflective amplified modulator (RAM) chip that can work in transmit and receive modes at the user terminal. The RAM consists of a reflective electro-absorption modulator (REAM) monolithically integrated with an SOA [5], whose wide amplified spontaneous emission (ASE) noise bandwidth in combination with the directional spectral filtering by the crossed-gratings, can be exploited for very accurate localization and tracking of the user's device. A very fast space-, wavelength-, and time-domain optical-cross-connect (OXC) chip is implemented to provide dynamic signal routing. This makes the solution simple and cost/energy-efficient. Bidirectional transmission rates of 10 Gb/s and >40 Gb/s per user are demonstrated using, on-off-keying (OOK) and discrete multitone (DMT) modulation, respectively.

II. In-building Wireless Network Architecture

The proposed in-building network architecture is shown in Fig. 1a as previously introduced in [6]. A residential gateway (RG) that terminates the access network performs dynamic signal routing to the appropriate rooms and hosts the central communication controller (CCC) to carry out the in-building control and management (C&M) functions such as user localization and tracking. Each room is equipped with one or

Manuscript submitted May 3, 2018; revised May 30, 2018; accepted June 25, 2018. This work was supported by the European Research Council under the Advanced Grant project BROWSE – Beam-steered Reconfigurable Optical-Wireless System for Energy-efficient communication.

K. A. Mekonnen, N. Calabretta, J. H. C. van Zantvoort, E. Tangdiongga and A. M. J. Koonen are with the Institute for Photonic Integration, Eindhoven University of Technology, Eindhoven, The Netherlands (e-mail: k.a.mekonnenn@tue.nl).

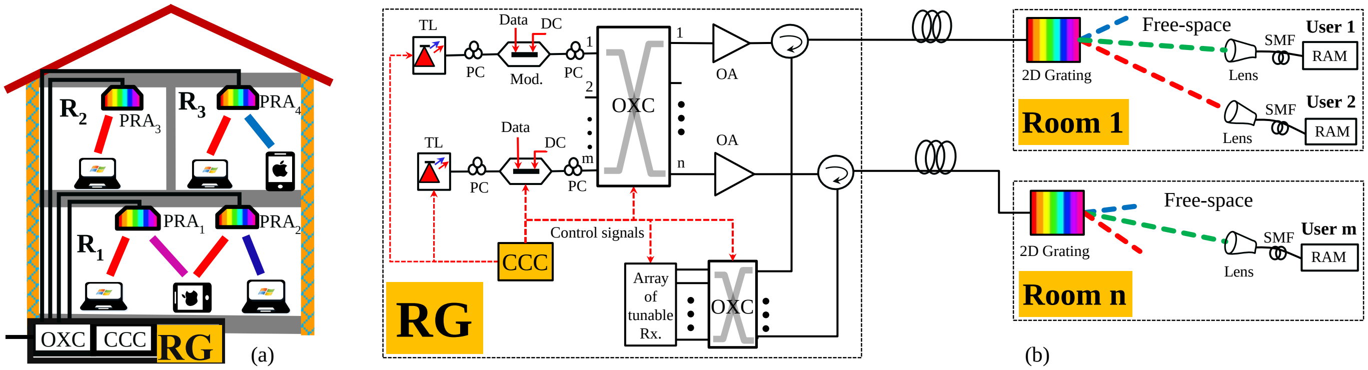

Fig. 1. (a) Proposed in-building network architecture; (b) Detailed bidirectional indoor network employing two OXCs at the RG for downstream dynamic routing and separation of upstream transmissions, 2D gratings based passive beam steering devices at the PRA, and RAM transceivers at the user terminals.

more pencil radiating antennas (PRAs) to steer optical signals to the individual users using a crossed pair of diffraction gratings, where one element has a relatively low diffractive power and the other one a high diffractive power. Detailed study of the beam-steering mechanism is presented in [2]. As illustrated in Fig. 1b, the RG also hosts the tunable transceivers to serve the users with appropriate wavelengths for the beam steering in each room, and OXCs (one for downstream routing and one for separation of multiple upstream transmissions). The upstream transmissions can also be separated from each other by using power splitters and tunable filters. At the PRA, the steering directions are determined by the wavelengths of the incoming optical signals from the feeder fiber as the 2D gratings diffracts incoming beams with different wavelengths to different directions. The user transceiver is equipped with a collimating optics to focus/collimate the down/up-stream beam.

The OXC allows us to share the tunable lasers (TLs) dynamically among multiple users at the same time (by implementing time-slotting) for further cost-efficiency as demonstrated in [7]. However, sharing between two users needs frequent tuning of the wavelength which reduces the net available time for data transmission. Sharing of a TL between downstream and upstream transmitters of the same user in a half-duplex manner gives a better compromise between cost and performance since the TL does not need to be tuned. When the optical axis of the user's collimator is aligned with the PRA, this technique also alleviates the requirement for additional steering hardware for the upstream due to the reversibility principle of optics. An integrated RAM implemented at the user terminal facilitates this technique because it works in transmit and receive modes [5]. It allows improved receiver sensitivity as well as higher transmission power for the user.

In an optical wireless communication system using pencil beams (of beam waist <10 cm), the localization system needs to be very precise for the beam to be received by the user. However, this cannot be achieved easily with current indoor localization techniques which are radio based. Hence, in this work, we introduce a new concept by combining radio and optical techniques. We use radio techniques to determine the location of the PRA (within accuracies of up to 30 cm) [8], and then take advantage of the wide ASE bandwidth of the RAM and spectral filtering functions of the 2D gratings constellation to determine the exact wavelength needed as shown in Fig. 2a. By using adaptive optics, the user terminal first sends a wide beam to the PRA. Then the 2D gratings filters the exact wavelength to which the user is aligned, based on its angular position (see Fig. 2b). The CCC performs monitoring of the wavelength and power received by the RG. The user device can be equipped with a electromechanical device in order to adjust the direction to which the ASE beam is directed. This enables us to maximize the received power at the RG (the power is the maximum when the center of the Gaussian beam hits the 2D gratings), and hence align the optical axis of the receiver's collimating lens with the 2D gratings. Finally, the CCC tunes the TL to the detected wavelength to start the communication, with a narrower beam (using adaptive optics) for high data rate operation. This also enables auto-tracking as the wavelength received at the RG changes with angle when the user moves.

III. Experimental Demonstration

Fig. 3 shows the experimental setup including the routing of infrared pencil beams in both directions, (also see [9]). The user terminal, equipped with a RAM, initiates the communication by sending the broadband ASE output of the SOA to the 2D grating via a collimating lens. The RAM was first packaged with a SMF pigtail and connected to the collimating optics which is also SMF-pigtailed. The gratings constellation filters the wavelength depending on the arrival angle of the signal as shown in Fig. 2. In this experiment we assumed that the position of the PRA is already known. This filtered signal was monitored

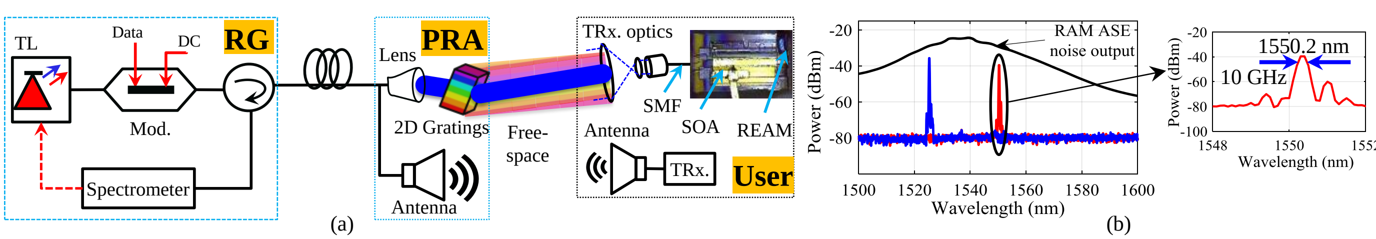

Fig. 2. (a) Concept of user localization and tracking utilizing the wide ASE noise bandwidth of the RAM and narrow optical filtering functions of the 2D gratings for improved accuracy. (b) Optical spectrum of the ASE noise output of the RAM before and after narrowband filtering by the 2D gratings from two angles.

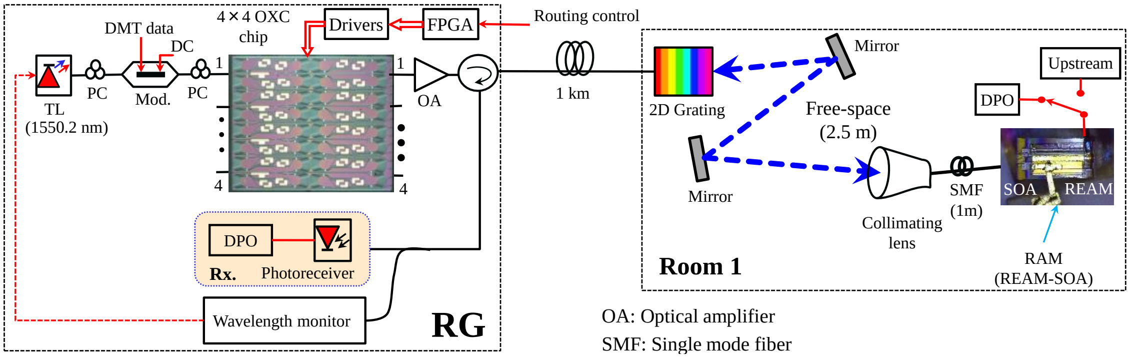

Fig. 3. Experimental setup with a 4×4 OXC chip for dynamic routing and RAM chip at the user for localization, data transmission and reception.

using an optical spectrum analyzer at the RG. The -3-dB bandwidth of the gratings constellation is 10 GHz as shown in Fig. 2b. Because the filtering is narrow, the wavelength required can be determined precisely. For this experiment the user was reached with 1550.2 nm wavelength.

In the downstream, the 1550.2 nm continuous wave (CW) light was modulated by the wireless data using an optical intensity modulator and routed to the 2D gratings at the PRA by using a 4×4 SOA-based OXC chip. The OXC chip is a broadcast-and-select switch with booster SOA and SOA-based wavelength selective switch (WSS) blocks. The details of the OXC chip are explained in [10]. The OXC chip was configured to switch the input signal to output port 1 by activating the gating SOA to this port using an FPGA. We performed the experiment using OOK as well as DMT modulation formats, which were generated by an arbitrary waveform generator (AWG) at a sample rate of 20 GSa/s, corresponding to 10 Gb/s for OOK and 10 GHz signal bandwidth in case of DMT. After amplification by an optical amplifier to compensate the fiber coupling losses introduced by the OXC chip at the RG and the 2D gratings at the PRA which was approximately 16 dB in total, the signal was launched into a 1 km fiber, and then, via a triplet lens collimator with focal length of 18.4 mm, steered by the 2D grating to the RAM (in receiving mode) located at a free-space distance of more than 2.5 m. The pencil beam waist was around 3.3 mm. The collimator's field-of-view was < 0.0340°, thus requiring careful alignment at the receiving end using an automated beam alignment system. The RAM has a bandwidth of >20 GHz. The downstream data was then recorded by a digital-phosphor-oscilloscope (DPO) and analyzed offline.

When it was the user's turn to transmit, the downstream data modulation would be turned-off and the 1550.2 nm optical carrier which was unmodulated would be sent to the user, modulated by the RAM and sent back to the RG. The CCC in the RG manages the time-slotting assignments for downstream and upstream communications. The minimum guard-time is equal to the end-to-end delay for the optical carrier sent from the RG to reach the user during the upstream transmission, which is around 300 ns for a 100 m optical fiber cable between the RG and the PRAs. An AWG was used to generate the upstream data using OOK and DMT modulation with a sample rate of 20 GSa/s. At the RG, the upstream optical signal was received by a 10 GHz photo-receiver and analyzed offline.

IV. Experimental Results

To minimize the losses incurred by the OXC chip, the booster SOA in the OXC chip was biased at 100 mA while any relevant gating SOA was biased at 40 mA. Under this condition, the optimum optical input power to the OXC chip was measured to be 0 dBm. ASE noise for lower input powers and SOA gain saturation for higher input optical powers limit the dynamic range of the OXC chip [10]. Fig. 4 shows the BER curves of the 10 Gb/s OOK downstream and upstream transmissions in the back-to-back (B2B) and transmission cases. The sensitivity of the PIN+TIA receiver was measured to be -16 dBm for the downstream and -14 dBm for the upstream at a BER of 1.0×10^{-9}. While inband reflections from the 2D gratings and other optical components resulted in a transmission penalty of 2.5 dB, the OXC chip that was used for downstream routing introduced a penalty of only 1 dB. The input optical power to the RAM was kept at -5 dBm for the BER measurements.

Fig. 5a and b elucidate the achievable data rates for the downstream link at different RAM biases and input optical power with an average bit-error-rate (BER) $<3.8\times10^{-3}$. This BER value is chosen to assess the performance because it can be reduced to $<1\times10^{-12}$ using hard-decision forward error correction (FEC) with a 7% redundancy. Advanced modulation formats such as DMT are typically implemented with FEC to reduce the higher BER values that arise because of the proximity of the symbols to each other. For optimum operation, the input optical power to the OXC chip was fixed at 0 dBm. By adjusting the downstream modulator's bias at the RG, gross transmission capacity of 40 Gb/s (corresponding to 37.2 Gb/s net transmission rate at BER $<1\times10^{-12}$) was achieved for REAM bias voltages of -1.25, -2.5 and -4V when the input optical power was above -5 dBm (corresponding to 0 dBm transmitted power from the RG since the 2D grating has a loss of 6 dB). As illustrated in Fig. 5a, the penalty introduced to the downstream DMT wireless signal when the RAM was used instead of a

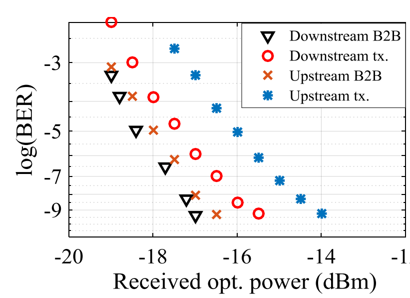

Fig. 4. BER measurements of the received downstream and upstream 10 Gb/s OOK wireless data with respect to the respective back-to-back cases.

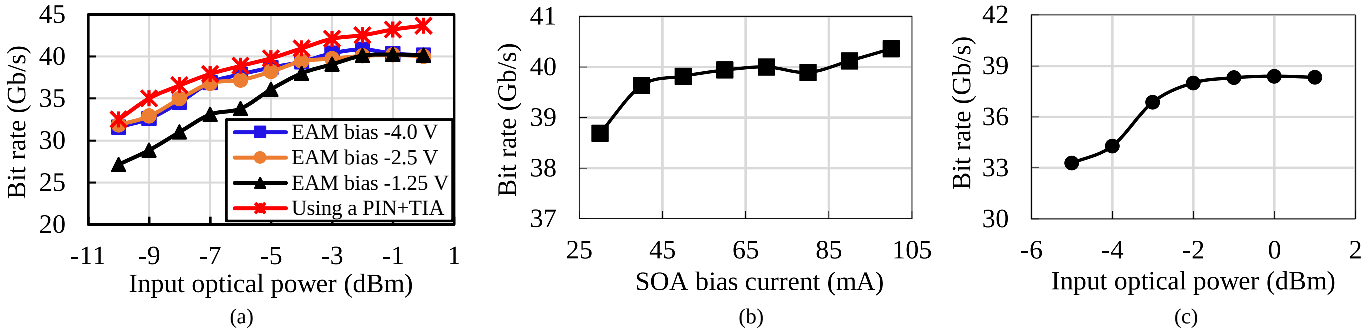

Fig. 5. (a), and (b) Downstream achievable data rates as a function of input optical power when the SOA was biased at 80 mA, and as a function of the SOA bias current when the REAM was biased at -4V, respectively; (c) Upstream achievable data rate when the RAM was biased at 80 mA and -1.25 V.

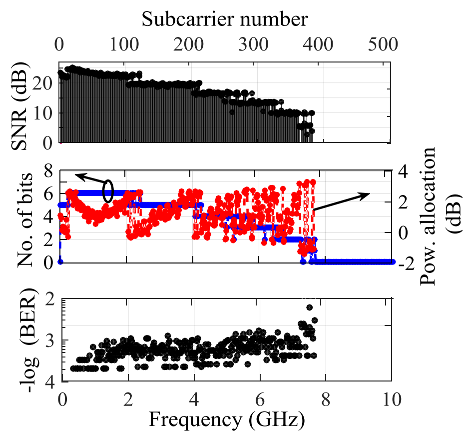

Fig. 6 SNR, bit-loading profile and BER of the upstream.

PIN+TIA was 5 dB, which corresponds to a 5 Gb/s reduction in the achievable data rate. This is due to the ASE noise of the SOA, and residual reflections at the junction between the REAM and SOA within the RAM chip, imperfection from free-space optics, and some back reflection noise that originated from the RAM and reflected by the 2D gratings. Note that some portion of the downstream signal is reflected back from the RAM since signal propagation in the RAM is bidirectional. The effect of the SOA bias current was minimal as shown in Fig. 5b. 40 Gb/s transmission rate was achievable when the bias current was above 30 mA at an input optical power of -5 dBm.

The upstream experiment was performed with the SOA in the RAM biased at 80 mA current. Under this condition, the RAM gave better modulation efficiency when the REAM was biased at -1.25 V. The saturated output power of the RAM was 2 dBm resulting in a received power of -5 dBm at the RG. As depicted in Fig. 5c, the achievable data rate increased with increasing input optical power to the RAM and stayed unchanged when the input power was above -2 dBm. This is because of SOA gain saturation, and increased unwanted reflected power from the 2D gratings when the input optical power to the RAM was increased (increasing the RAM input power means increasing the transmitted optical power from the optical source at the RG, which also increases the amount of optical signal reflected by the 2D gratings and affects the performance of the upstream). Nevertheless, 39 Gb/s transmission rate was achieved at pre-FEC BER $<3.8\times10^{-3}$. The SNR, BER, power- and bit-loading profile for the upstream transmission are shown in Fig. 6.

It has to be noted that the results shown here are repeatable to multiple wavelengths (or users) since the RAM has a broad bandwidth and the 2D gratings based beam steering provides nearly uniform performance over 1500-1630 nm range [11].

V. Conclusion

We demonstrated a highly dynamic all-optical bidirectional indoor wireless network employing a low-power fast-switching optical chip and RAM to provide low cost/power consumption, and ultimate capacities per user. Symmetric transmission at data rates of 40 Gb/s were achieved. By taking advantage of the ASE output of the SOA in the RAM, localization and tracking of the user can be performed more precisely which is being improved in an ongoing work. Therefore, complex localization algorithms can be avoided. Our solution is scalable to handle more users with high demand of bandwidth, hence presenting a future-proof solution to the indoor wireless data explosion.

Acknowledgment

The Authors would like to thank the III–V Lab, Alcatel-Thales, France, for providing the RAM chip.

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