Multiuser 5G Hot-Spots Based on 60 GHz Leaky-Wave Antennas and WDM Radio-over-Fiber

M. Steeg[1(✉)], M. Szczęsny[2], and A. Stöhr[1]

[1] Center for Semiconductor Technology and Optoelectronics (ZHO), University of Duisburg-Essen, Duisburg, Germany
{matthias.steeg,andreas.stoehr}@uni-due.de
[2] Office of Architecture and Network Planning, Exatel, Warsaw, Poland
michal.szczesny@exatel.pl

Abstract. This paper reports on photonic multiuser 5G hot-spots, that provide multiple beams by employing frequency steerable leaky-wave antennas. Therefore, a 60 GHz periodic leaky-wave antenna (LWA) has been developed, based on low loss substrate-integrated waveguide (SIW) technology, which is fabricated through standard PCB processes. The developed LWA operates in the V-band between 50 and 70 GHz and provides over 40° beam steering in the H-plane via frequency scanning. The capability for beam steering and multiple simultaneous beams from only one feeding port is combined with Radio-over-Fiber (RoF) techniques to provide a simple, compact and low-cost system for new applications in mm-wave communications. The proposed system enables centralized photonic beam steering in fiber-wireless transmission links, where up to 6 Gbit/s data rates are demonstrated using 64 QAM with IF-OFDM and simple receiver architectures. The multibeam capabilities provide a strong addition to RoF links by utilizing dense WDM channels to support multiple wireless users. Thereby, multiple low latency and high data rate wireless services can be provided via a single fiber-fed antenna. Finally, this concept is demonstrated by lab experiments, where three 1 Gbit/s OOK data signals were simultaneously transmitted and by a week-long field trial in a shopping mall, where two 1.5 Gbit/s real-time SDI video streams were transmitted.

Keywords: 5G mobile communications · Antennas · Beam steering · Millimeter-wave radio · Radio-over-Fiber

1 Introduction

The advent of the next generation of mobile communications 5G is expected to bring a revolutionary 1000-fold increase in mobile data traffic and a substantially larger number of connected users per cell [1]. In order to sort the various use cases to be enabled by the new technology, the ITU-R has proposed three use case families for 5G [2]. One of them is "enhanced mobile broadband" (eMBB), which is most closely

associated the overall increase in mobile data throughput. The eMBB family also covers the "5G Hot-Spot" scenario, which embraces all those use cases, where a large number of users in a limited area demand high data rate services [2, 3]. Thereby, applications include scenarios, where users wish to quickly download or access multimedia content while waiting or traveling, such as in an airport, a train station or on an airplane, a train. In the modern networking society, the use cases can further be expanded to office spaces, cafes or popular meeting places.

The EU-Japan project RAPID is researching technical solutions to support such high-capacity hot-spot scenarios especially for dense user areas, where the requirement for mobility is low but the user data rates are expected to be extremely high [4]. RAPID especially considers the use case scenarios of crowded infrastructure such as airplanes, train stations, motorways, etc., as well dense user areas in office buildings, shopping areas and malls and sports stadiums, where dedicated services are expected. For achieving this goal RAPID technology employs photonic techniques to exploit the large bandwidth at mm-wave frequencies. In order to demonstrate its 5G technology field trials in natural dense user environments in a football stadium and a shopping mall are designated.

The cornerstones to support the projected, significant increase in data traffic for 5G are seen in larger bandwidth, higher spectral efficiency and more, smaller cells [2, 5, 6]. Thereby, the large available spectrum at mm-wave frequencies, e.g., in the 60 GHz band can provide the necessary bandwidth for 5G communications and is thus considered as an enabling technology [3, 5, 6]. While the utilization of the mm-wave spectrum also brings new challenges, such as high free space path loss, innovative solutions are sought. One of the key demands for providing mm-wave mobile access is an antenna, which has a high gain to maintain a manageable link budget, while being steerable to support user mobility [5, 6]. In RAPID we further require an antenna, that supports multiple beams to provide uninterrupted, low-latency service to multiple users at the same time in densely populated environments.

In view of the large available bandwidth, but also the challenges that mm-waves provide for conventional phased array antenna techniques [6], we propose the utilization of leaky-wave antennas as a low-cost technology for 5G hot-spots. While the efforts to implement beam forming and beam switching solutions at 60 GHz have led to technological solutions, they either only provide a single steerable beam [7] or require multiple antenna feeds [8]. In contrast to that LWAs provide a simple mechanism for beam steering by frequency scanning [9], which requires only a single feeding port, can be implemented inexpensively and is compatible to FDMA techniques. Furthermore, they allow for new direction-of-arrival (DoA) estimation techniques, which are important for user localization in multiuser scenarios [10]. While LWAs are well known, e.g., in avionics and for radar applications, we want to illustrate their application for fiber-wireless communications. We will show that they can complement Radio-over-Fiber (RoF) techniques, which are often proposed because of their capability for centralizing network features. This architecture is depicted in Fig. 1, where a SIW LWA antenna in implemented in a WDM fiber-wireless communication system for multiuser support.
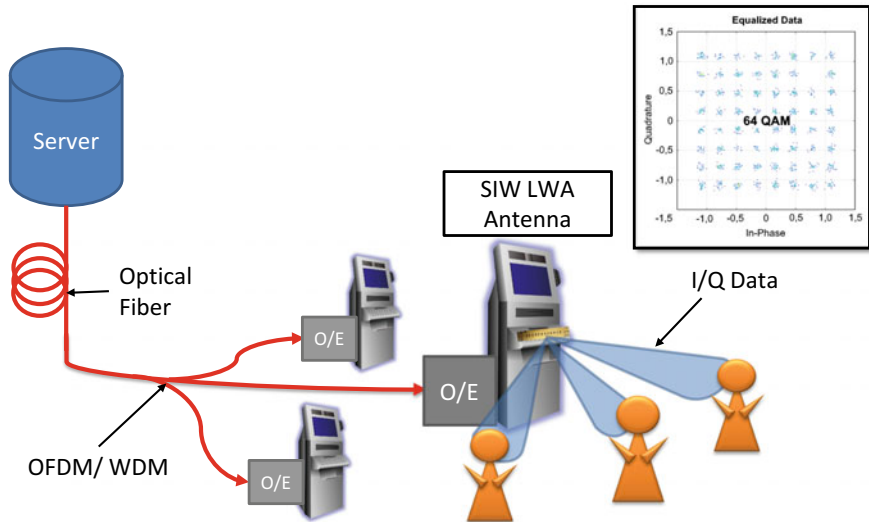
Fig. 1. Schematic architecture of an optical distribution network connecting a server to multiple 5G hot-spots, which can each deliver data streams to multiple users employing the presented SIW LWA

In this paper, the implementation of 5G hot-spots by the means of frequency steerable 60 GHz multibeam antennas is outlined. Therefore, leaky-wave antennas are employed in conjunction with dense WDM optical networks, which are extended via RoF wireless links. At first the utilized antenna structure and its performance is illustrated. After that the setup of the fiber-wireless communication link is described and RoF data transmission experiments are presented. Then the option to serve multiple wireless users via the connected optical WDM network explained and demonstrated by measurements. Finally, the demonstration of a 5G hot-spot is presented, which was employed to deliver two uncompressed video streams for a field trial in a shopping mall, before the paper is concluded.

2 Utilized SIW LWA Antenna Structure

2.1 Leaky-Wave Antenna Principle

In this work, periodic leaky-wave antennas (LWAs) are utilized, which are based on substrate-integrated waveguides (SIWs). In general, LWAs are waveguide structures that are modified to leak power for antenna operation. For periodic LWAs the waveguide is divided into unit cells, which are arrayed and periodically modified. Thus, they radiate similar to a linear array, with a beam angle that depends on the phase difference between the radiating elements of the arrayed unit cells. This phase shift between adjacent unit cells depends on the complex propagation constant of the modified waveguide [9]. Thereby, good power acceptance, simple feeding via the waveguide interface and a high directivity due to the array factor can be achieved.

Furthermore, as the phase difference between the periodic radiating elements of the LWA depends on the frequency according to their dispersion characteristic, a LWA scans its beam angle with changing the frequency. This means, that an LWA will radiate signals at different radio frequencies (RFs) into different directions, while only requiring a single RF feeding port [9–11].

2.2   Implemented SIW LWA

The specific structure of the used LWA has been proposed in [11]. It has been manufactured from a RO5880 laminate by standard PCB processes. The LWA employs longitudinal half-wavelength microstrip lines inset to the SIW as radiating elements, which are off-centered to improve broadside radiation [11]. The fabricated laminate of such a LWA is depicted in Fig. 2.
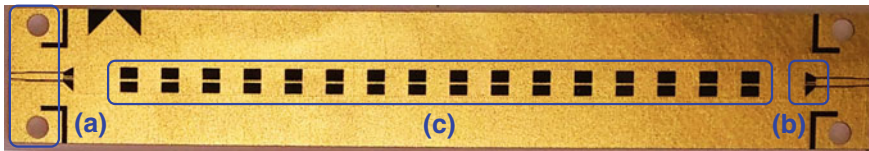

Fig. 2. Fabricated laminate of the SIW LWA containing the grounded CPW interface for the ELCs (**a**), the coupled line transition (**b**) and the periodic LWA array (**c**)

Apart from the periodic LWA array, the laminate contains a coupled line transition and holes and markers for the fixtures of the coaxial end launch connectors (ELCs) that are used to contact the antenna. Thereby, the coupled lines provide a transition from the SIW of the LWA to the grounded coplanar waveguide interface of the ELCs, while also providing impedance transformation to yield good matching. Since the coupled lines transition acts as a DC block they already provide one part of a bias-tee for the integration of photodiodes [12]. This gives the SIW LWA the potential to provide an integration platform for radio-over-fiber (RoF) photonic transmitters.

The presented SIW LWA operates in the V-band between 50 and 70 GHz, where it provides beam steering in excess of 40° in the H-plane. In Fig. 3 the radiation patterns at radio frequencies of 50 GHz and in the 57–66 GHz band are shown. It can be seen that the measured gain is around 14 dBi with ±1 dB deviation across the bandwidth with a sidelobe suppression of 13 dB. The SIW LWA is a linearly polarized antenna with a cross polarization discrimination (XPD) of 24.83 dB in the steering plane. The frequency scanning behavior of the SIW LWA can be observed from Fig. 3, demonstrating beam steering from –9.8° at 57 GHz through broadside around 61.5 GHz to 8.0° at 66 GHz.

Thus, the antenna beam can be steered, e.g., to follow a mobile user by changing the radio frequency. The four radiation patterns at different frequencies in Fig. 3 also illustrate that the SIW LWA can generate multiple beams to support multiple users simultaneously, which is demonstrated in the following sections. Therefore, different data signals are radiated at different RFs to be received by multiple users at different positions.
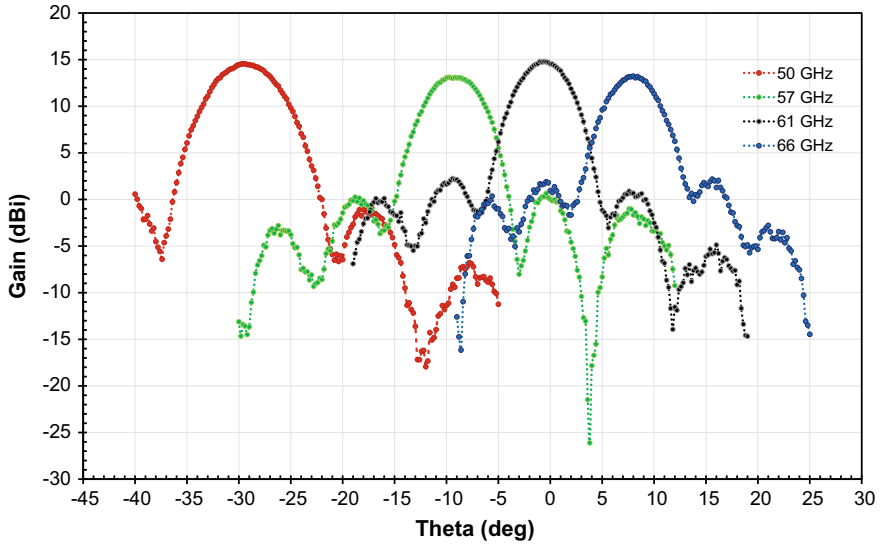
Fig. 3. Radiation pattern of the SIW LWA as the measured gain over the beam angle theta at radio frequencies of 50 GHz (red), 57 GHz (green), 61 GHz (black) and 66 GHz (blue)

2.3   Application of LWAs for 60 GHz Communications

Due to the large overall bandwidth and lack of necessary electrical control signals, the SIW LWA synergizes well with RoF systems, which utilize the vast optical bandwidth. In this paper it is employed for fiber-wireless communications, where it creates unique possibilities for centralized photonic beam steering to a coherent RoF link. With this approach, which is detailed in the next section, the RF of the radiated data signals is obtained from the optical frequencies of the LO and data signals. A transparent link is established from the data source to the data sink and the beam direction can be controlled via the laser frequency. It should be mentioned that for a full 5G communication system, besides beam steering it is also necessary to localize the mobile users. In this regard LWAs also provide new solutions for DoA estimation for multiple users [10]. While we focus on RoF communication with the presented SIW LWAs in this paper, we have also developed a simple technique for estimating the DoA of a user requesting service from the hot-spot. Therefore, a frequency upchirp signal send by the user, and often used for the preamble of OFDM waveforms, can be employed to choose the correct beam angle based on the LWA response [13].

3   Fiber-Wireless Communications

3.1   Employed Radio-Over-Fiber Approach

Radio-over-Fiber is a straightforward approach to connect remote antenna station to an optical fiber network by directly transmitting the wireless signals. Usually three

different analogue RoF schemes are differentiated based on where the baseband data signals are upconverted to the RF [14]. Thereby, it is assumed that always electrical mixers are used, which are located either at the central unit (CU) or at the radio access unit (RAU). In contrast to that, we have used a coherent RoF approach, where the baseband or intermediate frequency (IF) signal, generated at the CU, is photonically upconverted at the RAU by employing an optical local oscillator (LO) [15]. This approach is employed in conjunction with the introduced SIW LWA antennas for fiber-wireless data transmission with the setup illustrated in Fig. 4. The combination of optical upconversion with the LWA enables unique photonic beam steering capabilities, as outlined in the following. At the CU a laser generates an optical carrier, which is modulated by the data signal by means of a Mach–Zehnder modulator (MZM). Then the signal is amplified by an optical amplifier and transmitted over 10 km standard single mode fiber (SMF), emulating the optical distribution network. After the transmission, the signal arrives at the RAU, where an optical local oscillator (LO) from a tunable laser diode is added. Then a high-speed photo diode generates the RF signal, containing the data, through heterodyne detection of the arriving optical carrier from the data signal and the LO. As the RF corresponds to the beat frequency of the two optical waves, the frequency can be changed by tuning either the laser frequency of the optical carrier or of the LO. The RF signal is then amplified and radiated by the presented SIW LWA. Since the beam angle of the LWA can be changed through the RF, the radiated signal can be steered by tuning either the signal or the LO laser. This means that the system provides photonic beam steering functionality either locally at the RAU or centralized from the CU. After the wireless transmission, the RF signal is received by the mobile unit (MU) by means of a horn antenna. The received signal is then amplified and downconverted by a zero-biased Schottky barrier diode detector (SBD). As the SBD works as an envelope detector, it does not depend on the RF of the
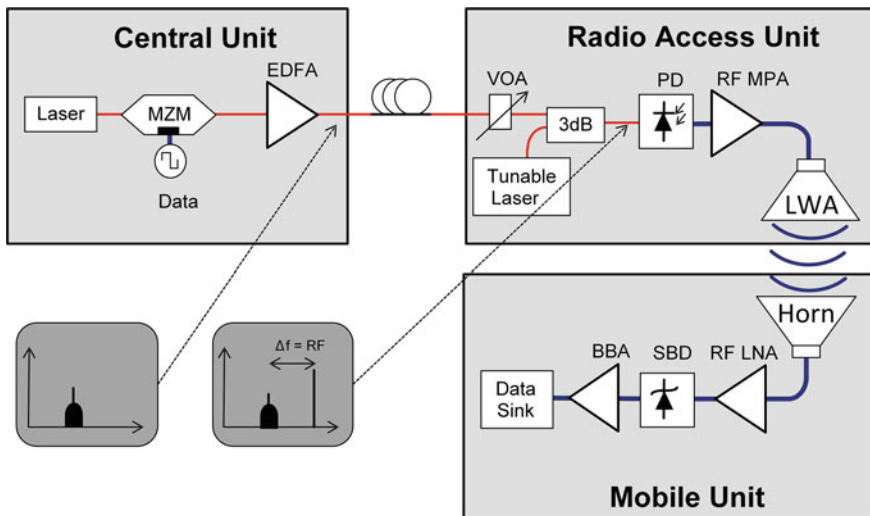

Fig. 4. Schematic architecture of the utilized fiber-wireless communication system

received signal and no electrical LOs are required at the MU. Furthermore, it is insensitive to RF drift and phase noise, which means that phase-locking of the lasers is not necessary. Finally, the downconverted baseband signals are amplified and then analyzed at the designated data sink.

3.2 Single Link OOK and IF-OFDM Measurements

At first single link transmission experiments using the outlined setup from Fig. 4 have been carried out. Therefore, a PRBS-9 (pseudo random binary sequence) baseband data signal is generated by a pulse pattern generator (PPG) at the CU and modulated onto the optical carrier. To produce bit error rate (BER) curves, an error detector acts as the data sink to analyze the received signal. The optical power is changed by a variable optical attenuator (VOA) to yield different signal-to-noise (SNR) values at the receiver. The measured BERs of 2 Gbit/s OOK data signals after wireless transmission over 2 m are presented in Fig. 5. As can be seen quasi error-free transmission is achieved and the difference in required optical power is low across the different radio frequencies from 57 GHz over 60 to 63 GHz. This means that the link budget is flat across the 60 GHz band, even though different beam angles are used.
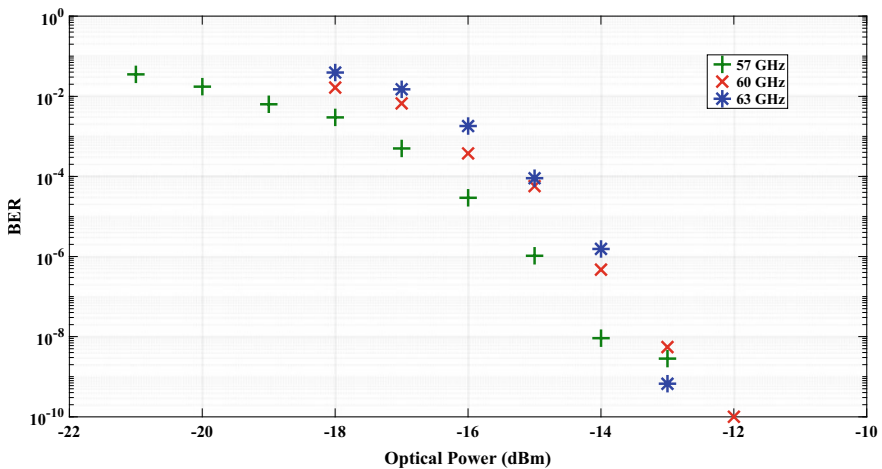

Fig. 5. Measured bit error rate over optical power of 2 Gbit/s OOK signals, which are transmit over 2 m wireless distance at 57 GHz (green), 60 GHz (red) and 63 GHz (blue)

The data rate of the RoF link can be further increased by employing higher order modulation techniques. In order to employ QAM modulation, while retaining the simple SBD receiver, IF-OFDM techniques can be employed [16, 17]. Therefore, QAM modulated OFDM channels are upconverted to an IF before being modulated onto the optical carrier. This way the SBD downconverts the received RF signal to the IF, so that the I/Q information is conserved. By using a digital sampling oscilloscope to analyze the data, 0.5 m wireless transmission with a throughput of 6 Gbit/s could be achieved with 64 QAM modulation at a bandwidth of 1 GHz. An IF of 1.5 GHz was

used to avoid signal-signal beat interference (SSBI) and an average SNR per subcarrier of 22.33 dB was achieved [17]. The constellation with an EVM of 7.65% can be seen in the inset of Fig. 1.

3.3   Optical WDM for Wireless Multiuser Support

In the previous measurements the data streams at different RFs and beam angles have been transmitted and analyzed one after the other. Now we want to serve multiple users simultaneously. Therefore, optical wavelength division multiplexing is used, i.e., three optical channels are used to provide data for three users. In this case, three signal lasers operating at different optical frequencies are each modulated by a MZM with individual data from different PRBS sources. These three signals each carry 1 Gbit/s OOK data and are generated with 3 GHz ultra-dense optical channel spacing. By utilizing optical heterodyning to generate the RF channels, all three wireless signals can be generated by one PD. The 3 GHz difference between the laser frequencies translates into an equal difference between the generated RFs and so the channel spacing is preserved. This means that in contrast to a conventional RoF system no optical filters are necessary [15]. Because of the ultra-dense spacing, the optical signals occupy only a small bandwidth of 8 GHz in total. Furthermore, the RAU can remain unchanged as the PD and the LWA antenna have sufficient bandwidth to generate and radiate all three signals. The LO laser is set to a wavelength 62 GHz away from the median channel, so that the wireless signals are generated at RFs of 59, 62, and 65 GHz, all within the 60 GHz band. By means of the SIW LWA the signals are radiated at different beam angles of –3.5°, 2°, and 7.5°. They can be received after 2 m wireless transmission at distinct positions by the mobile units. Again, a simple SBD detector is used for downconversion. In contrast to an electronic mixer no additional local oscillator is required, and the mobile unit does not need to be aware of the received signal RF to detect its data. Thus, all RF signals are downconverted to baseband and can be received by simply moving into the respective beam angles without further changes at the mobile unit. So, when moving a mobile unit in the steering dimension, the received RF signal changes according to the relative angle to the RAU. The best signal quality is achieved at –3.5° for the 59 GHz signal, 2° for 62 GHz and 7.5° for 65 GHz, respectively. Within ±2° around these angles the signal quality gracefully decreases. For larger angles the signal quality drops rapidly, as the gain drops according to the radiation pattern and eventually the power of interfering signals increases. As the beam width in the E-plane is around 75°, the directivity is limited in the dimension orthogonal to the steering direction. Thus, the mobile unit can be moved up to 0.5 m orthogonal to the beam steering direction and the signals can still be received, when angling the horn antenna accordingly. The successful reception of three simultaneously transmitted 1 Gbit/s OOK signals, yielding a total data rate of 3 Gbit/s, is confirmed by the BER measurements. Like for the single link a VOA is utilized to change the signal power of the combined optical channels. The measured BER curves are plotted against the received RF powers of the detected signals at the mobile unit and are presented in Fig. 6. BERs of 3.805 E-3, 6.654 E-4 and 2.779 E-4 have been achieved at –37.79 dBm and 65 GHz, at –39.38 dBm and 62 GHz and at –40.95 dBm and 59 GHz, respectively. When the signal powers were further increased an error floor due to the
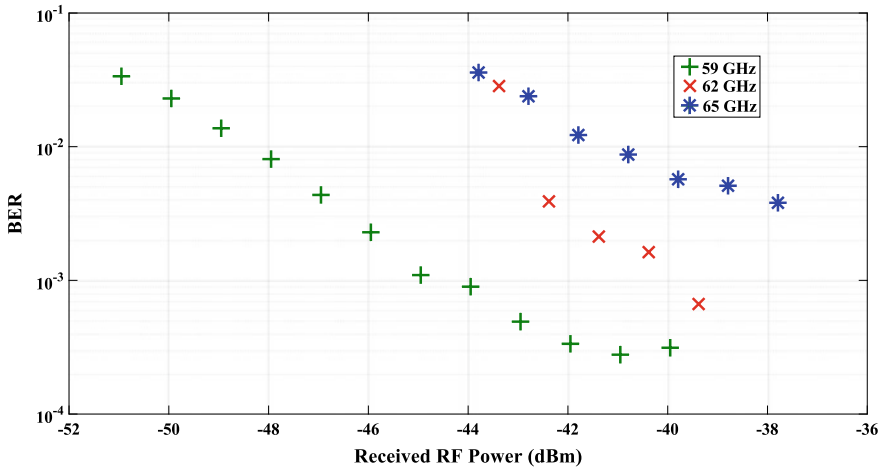
Fig. 6. Bit error rate over received electrical power of the three 1 Gbit/s OOK signals at 59 GHz (green), 62 GHz (red) and 65 GHz (blue) after 2 m simultaneous wireless transmission

interfering signals has been observed. As no filters are utilized and the SBD down-converts all incoming 60 GHz band RF signals to baseband, the other two signals interfere with the desired signal. Thereby, the system solely relies on the directivity of the SIW LWA to reduce undesired RF signals and maintain acceptable signal-to-interference-ratios (SIR).

4   5G Hot-Spot Demonstration for Video Streaming in a Shopping Mall

The system, described in the previous system has been utilized to implement a 5G hot-spot for a field trial demonstration in a shopping mall in Warsaw, Poland. Thereby, the 5G hot-spot supplies multiple users wirelessly with high data rate video streams. The field trial architecture contains transmission across four different locations as illustrated in Fig. 7: from a data center, where the optical carriers are modulated, over the shopping mall server room, where the optical LO is added, to the RAU, where the RF
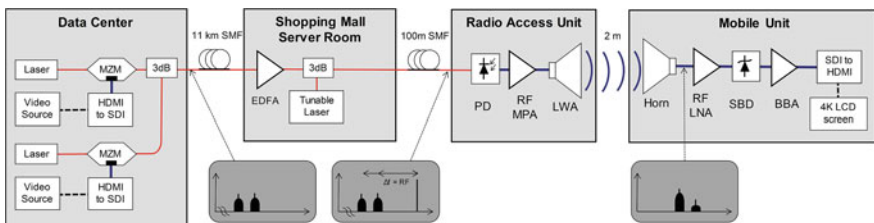

Fig. 7. Installed field trial architecture for the 5G video streaming demonstration in a shopping mall
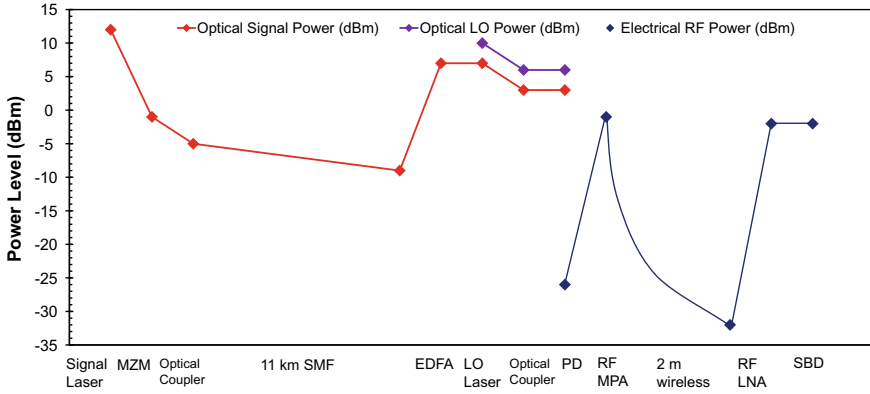
Fig. 8. Level diagram of the optical and RF link of the field trial system with indicated components

signals are generated and radiated to the mobile unit. An optical and RF level diagram is provided in Fig. 8. To demonstrate multiple data streams two optical carriers have been modulated with two different 1.5 Gbit/s SDI video signals by MZMs. SDI stands for serial digital interface and is a broadcasting standard for real time, uncompressed video transmission. The SDI signals are OOK baseband data streams with an amplitude level of 800 mV peak-to-peak. The SDI signals were generated via HDMI-to-SDI scalerboxes, which are commercial broadcast converters that generate the SDI signals from video stream input via an HDMI interface. The scalerboxes do not support buffering, an uninterrupted video stream confirms that the data stream is continuously available with a good signal quality. The central unit, which generates the two optical video signals was installed in the data center. From there the signals were transmitted within one WDM channel over 11 km SMF, installed in the field, to the server room of the shopping mall as depicted in Fig. 9. At the shopping mall the signals are extracted via a wavelength filter, amplified and combined with an optical LO signal. After that they are transmit over 100 m SMF to the hybrid integrated photonic RAU, depicted in Fig. 10. This RAU contains the high-speed PD, an RF amplifier (Gain: 25 dB; $P_{RF} =$ −1 dBm) and the LWA (Gain: 14 dBi) and is ceiling mounted in the field trial area of the shopping mall. There the RAU establishes two wireless video streams by simultaneously radiating each of the two video signals at a distinct beam angle of −30° for the 50 GHz signal and −1.5° for the 60 GHz signal. After wireless transmission over 2 m they were received by the mobile unit. In this case the mobile unit is the demo vehicle, shown in Fig. 11. It contains a horn antenna (Gain: 23 dBi), RF LNA (Gain: 30 dB; NF: 4.5 dB), SBD for downconversion and baseband amplifier (BBA) as depicted in Fig. 7. The data sink of the mobile unit is another scalerbox, which converts the video signals from SDI back to HDMI to be displayed by a large 4 K LCD screen. Both video signals at 50 and 60 GHz could be successfully received by moving the demo vehicle to their respective beam angles. This was confirmed by the screen showing the high-quality video streams on the mobile unit. Therefore, an SDI amplitude of 250 mV peak-to-peak was received at the demo vehicle. The system was
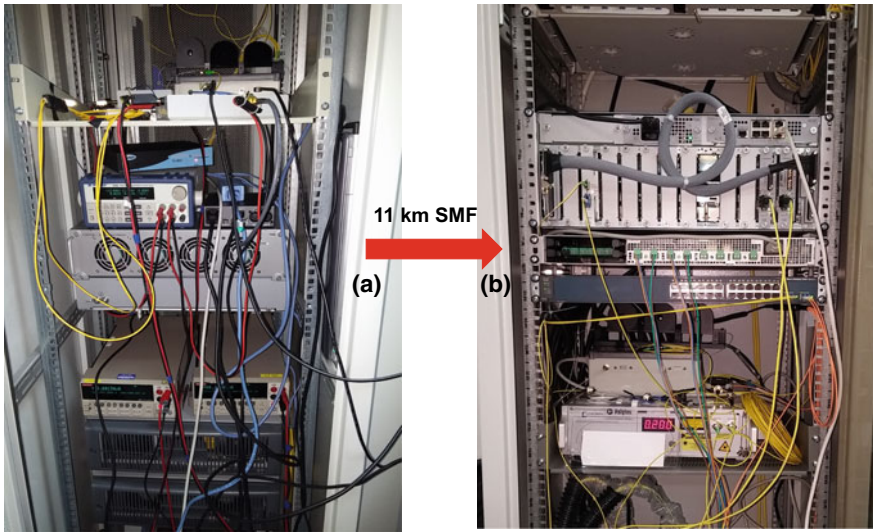
Fig. 9. Field trial installation in the data center (**a**) and in the shopping mall server room (**b**), which are connected by a 11 km SMF
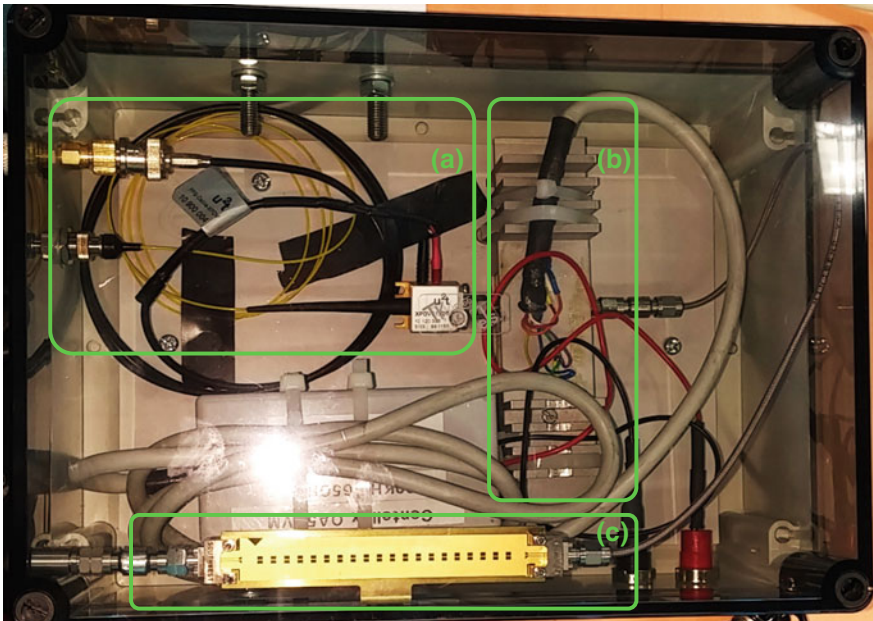

Fig. 10. Fabricated hybrid integrated RAU for the shopping mall ceiling installation consisting of a high-speed PD (**a**), a RF amplifier (**b**) and a SIW LWA antenna (**c**)

Fig. 11. RAPID5G demo vehicle used as mobile unit in the shopping mall, containing a receiver horn antenna, a RF amplifier, a SBD detector, a baseband amplifier a SDI-to-HDMI scalerbox and a 4 K high resolution screen to display the received video stream

operational over the course of a full week, thus demonstrating the implementation of such a 5G hot-spot under real-life conditions.

With this demonstration we provided an example for the generation of multiple simultaneous antenna beams providing a real-time high data rate service. One example, where such high data rates are required in real time is virtual reality (VR). We consider connecting multiple VR users wirelessly to an access point as a strong use case for 5G hot-spots for which multiple, steerable beams are essential.

5   Conclusion

In this paper, the implementation of 5G hot-spots via a combination of leaky-wave antennas and Radio-over-Fiber techniques has been demonstrated. The radiation patterns of the utilized PCB based LWA structure show gains around 14 dBi between 50 and 70 GHz. Beam steering and multiuser support are provided by the frequency scanning behavior of the LWA. It has been outlined, how to employ RoF techniques to

use the LWA for beam steering by changing the wavelength of the optical carrier. This setup has been employed to perform 2 Gbit/s OOK data transmission and up to 6 Gbit/s IF-OFDM-QAM data transmission, while utilizing a simple SBD receiver. Furthermore, it has been demonstrated to extend the system to support multiple users with multiple RF beams by employing dense WDM channels by transmitting three 1 Gbit/s OOK signals with 3 GHz spacing. Finally, the implementation of 5G hot-spots for a week-long operation during a field trial in a shopping mall has been illustrated. Therefore, two 1.5 Gbit/s uncompressed real-time video streams have been transmitted simultaneously over 11 km SMF and 2 m wireless to a demo vehicle, which acts as the mobile unit to show the received video stream.

References

1. CISCO (2015) Cisco visual networking index: global mobile data traffic forecast update, 2014–2019, pp 1–42
2. Jiang D, Liu G (2016) An overview of 5G requirements. 5G mobile communications, 1st edn. Springer Publishing, New York
3. Chandra K, Venkatesha Prasad R, Niemegeers I (2015) An architectural framework for 5G indoor communications. In: 2015 international wireless communications and mobile computing conference (IWCMC), Dubrovnik, pp 1144–1149. https://doi.org/10.1109/iwcmc.2015.7289244
4. Stöhr A et al (2017) Radio technologies for 5G using advanced photonic infrastructure for dense user environments (RAPID). http://www.rapid-5g.eu/
5. Rappaport TS et al (2013) Millimeter wave mobile communications for 5G cellular: it will work! IEEE Access 1:335–349. https://doi.org/10.1109/access.2013.2260813
6. Weiler RJ et al (2014) Enabling 5G backhaul and access with millimeter-waves. In: 2014 European conference on networks and communications (EuCNC), Bologna, pp 1–5. https://doi.org/10.1109/eucnc.2014.6882644
7. Marnat L et al (2017) V-band transceiver modules with integrated antennas and phased arrays for mmWave access in 5G mobile networks. In: 2017 11th European conference on antennas and propagation (EUCAP), Paris, pp 2786–2790. https://doi.org/10.23919/eucap.2017.7928489
8. Zhu J, Peng B, Li S (2017) Cavity-backed high-gain switch beam antenna array for 60-GHz applications. IET Microw Antennas Propag 11(12):1776–1781.https://doi.org/10.1049/iet-map.2016.1129
9. Oliner AA, Jackson DR (2007) Leaky-wave antennas. Antenna engineering handbook, 4th edn. McGraw-Hill, New York

10. Paaso H et al (2017) DoA estimation using compact CRLH leaky-wave antennas: novel algorithms and measured performance. IEEE Trans Antennas Propag 65(9):4836–4849. https://doi.org/10.1109/tap.2017.2724584

11. Steeg M, Khani B, Rymanov V, Stöhr A (2016) Novel 50–70 GHz compact PCB leaky-wave antenna with high broadside efficiency and low return loss. In: 2016 41st international conference on infrared, millimeter, and terahertz waves (IRMMW-THz), Copenhagen, pp 1–2.https://doi.org/10.1109/irmmw-thz.2016.7758489

12. Khani B, Rymanov V, Steeg M, Buck A, Dülme S, Stöhr A (2015) Compact e-band (71-86 GHz) bias-tee module for external biasing of millimeter wave photodiodes. In: 2015 international topical meeting on microwave photonics (MWP), Paphos, pp 1–4. https://doi.org/10.1109/mwp.2015.7356673

13. Husain B, Steeg M, Stöhr A (2017) Estimating direction-of-arrival in a 5G hot-spot scenario using a 60 GHz leaky-wave antenna. In: 2017 IEEE international conference on microwaves, antennas, communications and electronic systems (COMCAS), Tel-Aviv, pp 1–4. https://doi.org/10.1109/comcas.2017.8244845

14. Novak D, Nirmalathas A, Lim C, Waterhouse R (2009) Fiber radio technology. Microwave photonics: devices and applications, 1st edn. Wiley, Chichester

15. Steeg M, Babiel S, Chuenchom R, Stöhr A (2015) 10 GHz channel spacing ultra-dense WDM networks transparently extended by mm-wave coherent RoF links. In: 2015 IEEE international conference on communications workshops (ICCW), London, pp 324–328. https://doi.org/10.1109/iccw.2015.7247199

16. Stöhr A, Shih B, Abraha ST, Steffan AG, Ng'oma A (2016) High spectral-efficient 512-QAM-OFDM 60 GHz CRoF system using a coherent photonic mixer (CPX) and an RF envelope detector. In: 2016 optical fiber communication conference and exposition (OFC), Anaheim, CA, pp 1–3. https://doi.org/10.1364/ofc.2016.tu3b.4

17. Steeg M, Stöhr A (2017) High data rate 6 Gbit/s steerable multibeam 60 GHz antennas for 5G hot-spot use cases. In: 2017 IEEE photonics society summer topical meeting series (SUM), San Juan, pp 141–142. https://doi.org/10.1109/phosst.2017.8012690