[EN-A-075] Frequency Steerable 60 GHz Multibeam Antennas for 5G Hot-Spots

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Abstract: This paper reports on a periodic leaky-wave antenna (LWA) design, providing multibeam properties for 60 GHz 5G hot-spots. The LWA is 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 50-70 GHz and provides over 40° beam steering in the H-plane via frequency scanning. Since the LWA supports beam steering and multiple simultaneous beams using only one feeding port it provides a simple, compact and low-cost solution for new applications in mm-wave communications. The LWA allows cost effective and simple integration to 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 Radio-over-Fiber links by utilizing dense WDM channels to support multiple wireless users. This concept is demonstrated by lab experiments through three simultaneous OOK data signals of 1 Gbit/s each and by a week-long field trial in a shopping mall, where two 1.5 Gbit/s SDI video streams are 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 travelling, 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. To demonstrate its 5G technology field trials 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

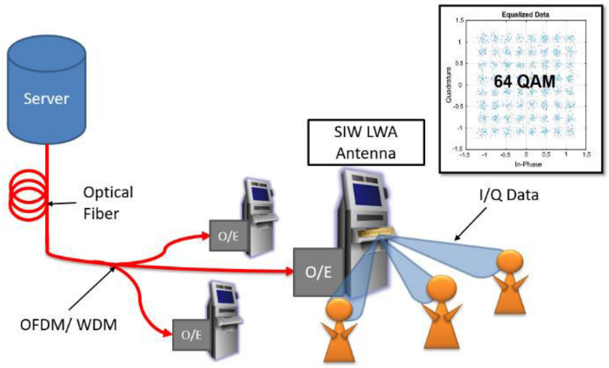

Figure 1 Schematic architecture of an optical distribution network connecting a server to multiple 5G hot-spots, which can each deliver data streams to mutiple users employing the presented SIW LWA.

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. They provide a simple mechanism for beam steering by frequency scanning [7], which 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 [8]. 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

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.

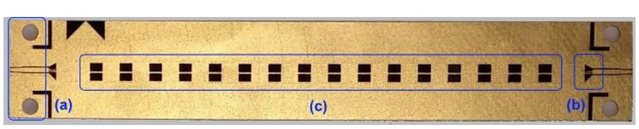

Figure 2 Fabricated laminate of the SIW LWA containing the grounded CPW interface for the ELCs (a), the coupled line transition (b) and the periodic LWA array (c).

2. UTILIZED ANTENNA STRUCTURE

In this work, periodic leaky-wave antennas (LWAs) are utilized, which are based on substrate-integrated waveguides (SIWs). In general, LWAs are guiding structures that are modified to leak power. 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 shift between the periodic radiating elements of the unit cells, which depends on the complex propagation constant of the modified waveguide [7]. 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 frequency. This means, that a LWA will radiate signals at different radio frequencies (RFs) into different directions, while only requiring a single RF feeding port [7]-[9].

The specific structure of the used LWA has been proposed in [9]. 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 [9]. The fabricated laminate of such a LWA is depicted in Fig. 2. 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

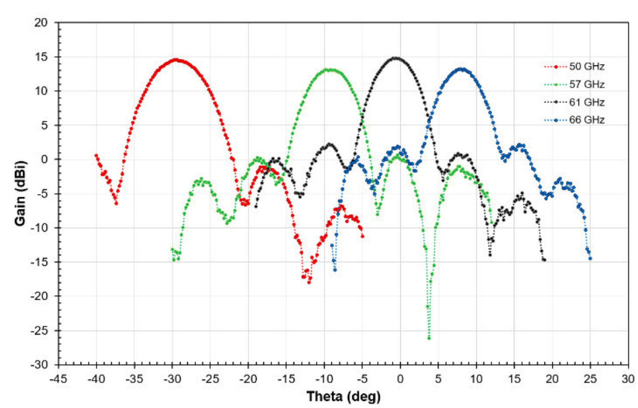

Figure 3 Radiation pattern of the SIW LWA as the measured gain over the beam angle theta at radio frequencies of 50 GHz (red), 57 GHz (green), 61 GHz (black) and 66 GHz (blue).

the coupled lines transition acts as a DC block they already provide one part of a bias-tee for the integration of photodiodes [10]. 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 GHz and 70 GHz, where it provides beam steering in excess of 40°. 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 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.

3. FIBER-WIRELESS COMMUNICATIONS

3.1 Radio-over-Fiber link

The introduced SIW LWA antennas are employed for fiber-wireless data transmission. In this work, the coherent Radio-over-Fiber approach is employed, which is illustrated in Fig. 4. Therefore, 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 radio access unit (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. As the RF corresponds to the beat frequency of the two optical waves, the frequency can be changed by tuning one of the laser frequencies. The RF signal is then amplified and radiated by the presented SIW LWA. Thereby the beam angle of the radiated signal can be steered by tuning either the signal or the LO laser. After the wireless transmission, the RF signal is received by the mobile unit by means of a horn antenna. The received signal is then amplified and downconverted by a zero-biased Schottky barrier diode detector (SBD). Thereby, no electrical LOs are required and no phase-locking of the lasers is required. Finally, the downconverted baseband signals are amplified and then analyzed at the data sink.

To produce bit error rate (BER) curves, an error detector acts as the data sink and analyzes the received PRBS-9 data signal, which is generated by a pulse pattern generator at the central unit. 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 at 57 GHz, 60 GHz and 63 GHz. As can be seen quasi error-free transmission is achieved and

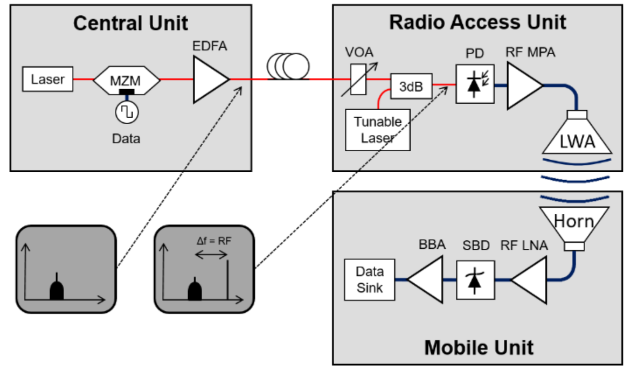

Figure 2 Schematic architecture of the utilized fiber-wireless communication system.

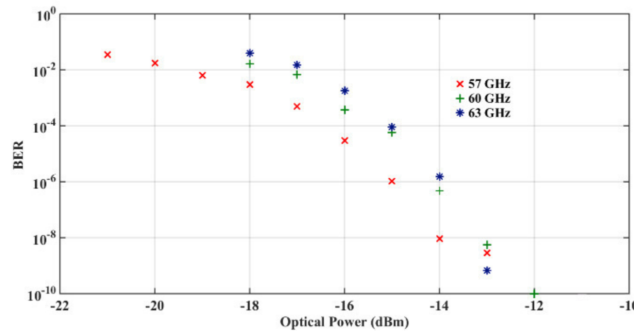

Figure 3 Measured bit error rate over optical power of 2 Gbit/s OOK signals, which are transmit over 2 m wireless distance at 57 GHz (red,), 60 GHz (green) and 63 GHz (blue).

the difference in required optical power is low across the different radio frequencies.

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 [11]-[12]. Therefore, QAM modulated OFDM channels are upconverted to an intermediate frequency (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, transmission 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 achieve an average SNR per subcarrier of 22.33 dB [12]. The constellation with an EVM of 7.65% can be seen in the inset of Fig. 1.

3.2 Optical WDM for multiuser support

In the previous measurements the data streams have been transmit and analyzed one after the other. Now we want to serve multiple users simultaneously. Therefore, wavelength division multiplexing is used, i.e. 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 spacing. The

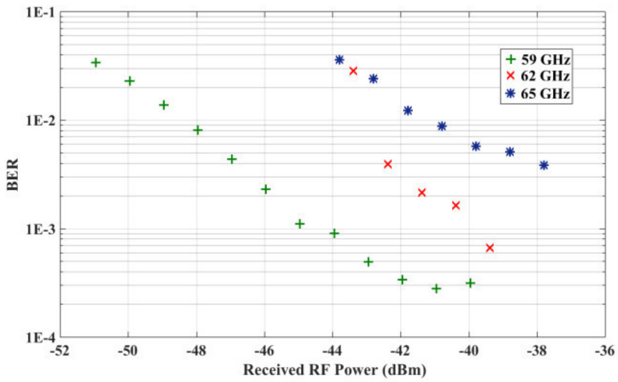

Figure 5 Bit error rate over received electrical power of the three 1 Gbit/s OOK signals at 59 GHz (green), 62 GHz (red) and 65 GHz (blue) after 2 m simultaneous wireless transmission.

LO laser is set so that the wireless signals are generated at RFs of 59 GHz, 62 GHz and 65 GHz. By means of the SIW LWA the signals are radiated at different beam angles and 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, which would require an additional local oscillator. Thus, all RF signals are downconverted to baseband and can be received by moving into the respective beam angles without further changes at the mobile unit. As no filters are utilized, the system solely relies on the directivity of the SIW LWA to maintain acceptable signal-to-interference-ratio (SIR) levels. 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. Therefore, the measured BER curves, plotted against the received RF power of the signals 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. After that an error floor due to the interfering signals has been observed.

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. Therefore, two optical carriers have been modulated with 1.5 Gbit/s video signals from HDMI-to-SDI scalerboxes. SDI stands for serial digital interface and is an OOK broadcasting standard for uncompressed video transmission. The signals are then transmit from a data center over 11 km SMF installed in the field to the server room of the shopping mall as depicted in Fig. 7. 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 RAU,

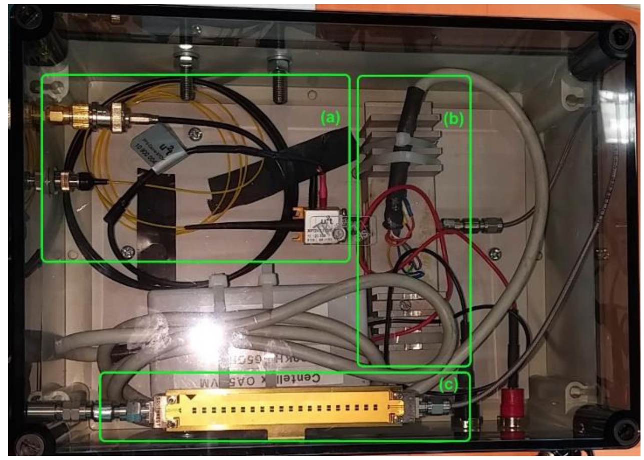

Figure 4 Fabricated hybrid integrated RAU for the shopping mall ceiling installation consisting of a high-speeed PD (a), a RF amplifier (b) and a SIW LWA antenna (c).

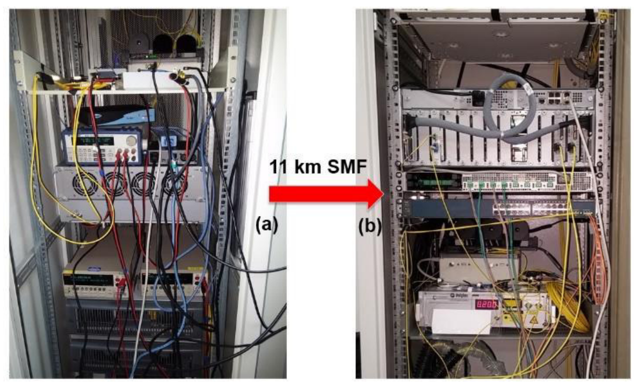

Figure 6 Field trial installation in the data center (a) and in the shopping mall server room (b), which are connected by a 11 km SMF.

depicted in Fig. 8, which is ceiling mounted in the shopping mall. There the RAU radiates the two video signals over 2 m wireless distance to be received by the mobile unit (demo vehicle), which is shown in Fig. 9. Both video signals at 50 GHz and 60 GHz could be successfully received by moving the demo vehicle to the respective beam angles. This was confirmed by the screen showing the high quality video streams, after the conversion from SDI-to-HDMI via a scalerbox on the mobile unit. The system was operational over the course of a full week, thus demonstrating the implementation of such a 5G hot-spot under real-life conditions.

5. CONCLUSION

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

Figure 7 RAPID5G demo vehicle as mobile user 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 4K high resolution screen to display the received video stream.

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 having a simple SBD receiver. Furthermore, it has been demonstrated to extend the system to support multiple users 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 of a field trial in a shopping mall has been illustrated. Therefore, two 1.5 GBit/s uncompressed video streams have been transmit simultaneously over 11 km SMF and 2 m wireless to a demo vehicle, to show the received video stream.

6. ACKNOWLEDGMENTS

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