Frequency-Scalable Coherent Radio-Over-Fiber Architecture for 100 Gbit/s Wireless Transmission

Jonas Tebart, Matthias Steeg, Florian Exner, Andreas Czylwik, and Andreas Stöhr

Abstract – This article presents a frequency-scalable fiber-wireless transmission architecture delivering high data rates in submillimeter wave bands. The proposed system uses photonic upconversion via high power photodiodes at the wireless front end and envelope detection via Schottky barrier diodes at the wireless receiver to avoid additional noise caused by the frequency drift of the local oscillator laser. This approach further provides flexibility of the radio frequency (RF), with optical heterodyning by using a tunable laser diode. Experiments in the 57 GHz to 71 GHz Federal Communications Commission band, as well as in terahertz bands foreseen for fixed wireless services around 300 GHz, highlight the potential for applications in 5G and beyond. The key to achieve high data rates is the combination of large bandwidth and modulation order: here, intermediate-frequency (IF) orthogonal frequency division multiplexing signals are used to transmit 16 quadrature amplitude modulation (QAM) at a 12.5 GHz bandwidth in a dual-polarization link to achieve 100 Gbit/s throughput. Therefore, the bias point of the electro-optical modulator is used to control the signal–signal beat interference generated from envelope detection to reduce the necessary IF. At an RF of 340 GHz, even 16 QAM at a 16 GHz bandwidth is realized, demonstrating a net throughput in excess of 100 Gbit/s. Finally, an extension of the wireless reach via lenses and amplifiers to multiple meters is shown.

1. Introduction

With the steadily increasing demand for higher and higher transmission rates, especially in the wireless sector, various concepts for high data rate communication are currently being investigated [1, 2]. Besides providing a high-speed user experience, a major role is taken by deploying high data rate front- and backhaul links of 5G cells, as well as fixed wireless services with 100 Gbit/s and more [1–3].

In this context, the use of terahertz (THz) bands is becoming more prevalent in proposed solution approaches, because vast transmission bandwidths are available [2, 3]; 120 Gbit/s over 1.4 m was delivered by using the first 2×2 multiple-input and multiple-output THz link with multiple channels [4]. Also, a much smaller 56 GHz wide radio frequency (RF) channel for 100 Gbit/s wireless transmission over 110 m with envelope detection receivers was used [5]. In contrast to that, 59 Gbit/s single-channel transmission at 325 GHz was achieved by using 64 quadrature amplitude modulation (QAM) modulation at a bandwidth of 10 GHz, demonstrating the capability for spectrally efficient links in the THz bands [6]. Recently, millimeter (mm) wave systems below 100 GHz used high bandwidth intermediate frequency (IF) transport by achieving over 80 Gbit/s [7]. Even higher throughputs of 260 Gbit/s were achieved via 16 QAM multichannel transmission within a bandwidth of 200 GHz [8], affirming the necessity of both bandwidth and modulation order.

However, the use of THz bands also has decisive disadvantages: besides the availability of RF sources with comparatively low output power, the transmission range is also limited by the significantly higher atmospheric attenuation and free-space path loss [2]. Furthermore, parts of the THz band are still unregulated or not yet designated for commercial use [3].

As we have recently reported, the decision by the Federal Communications Commission (FCC) to expand the communication spectrum in the V-band to 14 GHz has created a new opportunity to provide high data rate links within lower frequency ranges (57 GHz to 71 GHz) [9, 10]. Moreover, these frequencies are capable of providing fiber-wireless link extensions, with an expected reach of >1 km, thanks to available high-power amplifiers and high-gain antennas [11, 12].

To be able to serve both application scenarios, in 60 GHz and 300 GHz band, it is necessary to develop a frequency-scalable architecture, which, at the same time, requires only minimal adjustments for a function in the respective frequency band.

Thus, we herewith report a frequency-scalable and single-channel fiber-wireless transmission achieving 100 Gbit/s in the 300 GHz band, as well as in the 60 GHz band on the basis of coherent radio-over-fiber (CRoF) transport. The frequency scalability is achieved via photonic upconversion with free-running lasers and envelope detection downconversion, which avoids the phase noise from electronic multiplier chains at the wireless transmitter and receiver. Dual-polarization transport in the optical and wireless domains is used to double the capacity. An IF orthogonal frequency division multiplexing (OFDM) modulation scheme is used to provide QAM signals and optimized to yield a sufficient bandwidth, even at 60 GHz. Finally, 100 Gbit/

Manuscript received 29 August 2020.

Jonas Tebart, Matthias Steeg, and Andreas Stöhr are with the Department of Optoelectronics, University Duisburg–Essen, Lotharstraße 55, 47057 Duisburg, Germany; e-mail: jonas.tebart@uni-due.de, matthias.steeg@uni-due.de, andreas.stoehr@uni-due.de.

Florian Exner and Andreas Czylwik are with the Department of Communication Systems, University Duisburg–Essen, Bismarckstraße 81, 47057 Duisburg, Germany; e-mail: florian.exner@uni-duisburg-essen.de, czylwik@nts.uni-duisburg-essen.de.

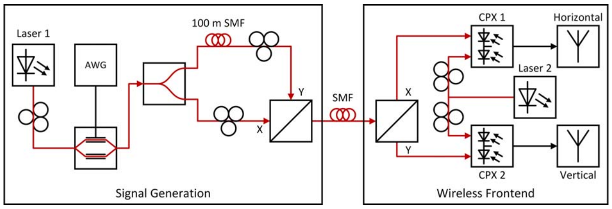

Figure 1. Transmission architecture of the dual-polarization fiber-wireless system.

s transmission results are shown, and ways to further increase the wireless reach are experimentally demonstrated.

2. Frequency-Scalable Fiber-Wireless Transmission Architecture

The fiber-wireless transmission system is based on a CRoF architecture and offers a transparent fronthaul network, while providing frequency scalability due to optical heterodyning at the wireless front end. The schematic architecture is given in Figure 1 and described in the following.

The baseband OFDM transmit signal is generated in the digital domain and converted to the analog domain by using an arbitrary waveform generator (AWG). After subsequent amplification, the waveform is modulated onto an optical carrier (laser 1) by means of a Mach–Zehnder modulator (MZM). Thereby, the optical carrier is provided by an integrable tunable laser assembly (ITLA) that includes an external cavity laser with low linewidths of 100 kHz and a frequency drift of 29.47 MHz at a laser frequency of 193.5 THz. Afterward, the modulated signal is transmitted to the wireless front end via single mode fiber (SMF), which supports long-reach fiber applications and distributed network architectures. Using a second ITLA (laser 2) as a local oscillator (LO) at the front end provides frequency tunable photonic upconversion. The desired RF signal is then generated through subsequent optoelectronic conversion via a J-band photodiode (PD) with a high output power of –14 dBm [11] or a coherent photonic mixer (CPX), which includes a balanced PD pair to double the output power to about –10 dBm in this setup [12]. This avoids the necessity of further amplifying the transmission signal before it is radiated into free space by using standard horn antennas with a gain of 23 dBi around 60 GHz and 26 dBi at 300 GHz, respectively.

To double the transmission throughput of the described system, polarization multiplexing (PM) is used. Therefore, two orthogonal waveforms are transmitted in the optical, electrical, and wireless domain according to the transmission architecture depicted in Figure 1. The modulated optical carrier is split into two paths in which decorrelation is achieved via adding an additional fiber coil. To achieve two orthogonal polarizations in the optical domain, polarization controllers are used, and a subsequent beam combiner allows for joint distribution via one SMF. At the wireless front end, the two polarizations are separated and converted to RF by using two CPXs with appropriately adjusted LOs. This way, the PM realized in the optical domain is transferred to the wireless domain by means of two orthogonal linearly polarized antennas horn antennas.

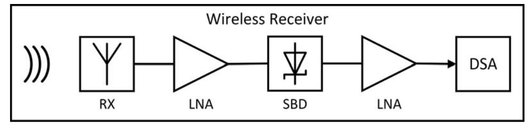

Figure 2. Wireless receiver for frequency-drift-insensitive envelope detection.

3. IF-OFDM Modulation for Frequency-Drift-Insensitive SBD Envelope Detection

In principle, the growing demand for ever increasing data rates can be served through various concepts. As such, the use of higher bandwidths or increasing the spectral efficiency of the transmission system is possible. Although adapting the transmission bandwidth is usually restricted through limitations imposed by the regulatory authorities, especially at the lower microwave frequency range, nonlinear system properties and the influence of noise are often a decisive factor hindering the increase of spectral efficiency.

To circumvent the noise limitations of a spectrally efficient transmission system, we have chosen an IF-OFDM modulation scheme as it enables using frequency-drift-insensitive Schottky barrier diode (SBD) envelope detectors at the wireless receiver for signal downconversion [6, 10]. Thereby, IF modulation is performed to allow phase recovery at the receiver for higher order modulation methods. Furthermore, OFDM is capable of providing channel estimation and multi-user communication features that benefit the large targeted bandwidth. A schematic overview of the wireless receiver is depicted in Figure 2. It consists of a horn antenna, which is identical to the transmitting antenna, the SBD, and an IF amplifier with 25 dB gain. Depending on the design, RF amplifiers with a gain of 35 dB at 60 GHz and about 28 dB at 300 GHz are also included in the receiver.

However, the envelope detector generates baseband components in addition to the downconversion to IF modulation, which causes signal–signal beat interference (SSBI) if these terms overlap with the aspired transmission band. One common approach to avoid the effect of SSBI is to use higher IFs, as this allows the data signal to be downconverted outside the baseband components [6, 13]. Because SSBI terms emerge in frequency ranges from DC up to the signal bandwidth, IFs of 1.5 times the bandwidth are usually applied, resulting in a higher overall bandwidth and thus in a reduced spectral efficiency [6, 10, 13]. Therefore, managing the SSBI level allows increasing the usable

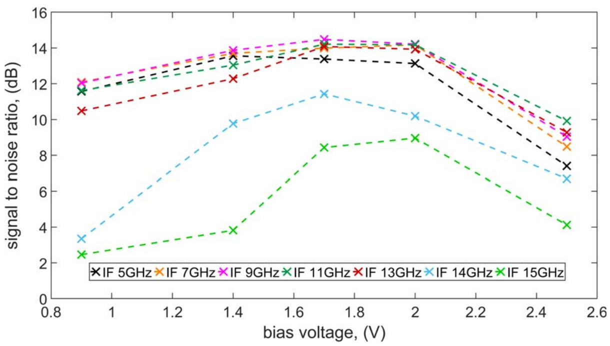

Figure 3. Impact of a bias voltage sweep on the SNR depicted for different IFs at signal bandwidth of 10 GHz.

bandwidth and achieving a more spectrally efficient, higher data rate communication.

As SSBI is generated due to nonlinear characteristics of the envelope detector [14], many solution approaches try to model the whole transmission system to use nonlinear compensation, e.g., via Volterra or Kramers–Kronig receiver models [5, 13]. Here, after simulations of the complete fiber-wireless transmission system, a simpler way of dealing directly with the IF-OFDM modulation via the MZM is found. Via controlling the power ratio between the carrier and the modulated sidebands, SSBI is decreased relative to the power of the data signal [10]. Therefore, the impact of the MZMs bias conditions on the signal-to-noise ratio (SNR) is analyzed and plotted for different IFs in Figure 3. Optimal bias voltages are achieved between 1.7 V and 2.0 V, slightly shifted from quadrature point (0.9 V) to minimum transmission point (3.4 V). As can be seen, only a marginal error vector magnitude (EVM) penalty is obtained when using no guard band at all. Limited by the performance at the band edges of the AWG with 20 GHz bandwidth, an EVM degradation is observed at higher IFs because a 10 GHz wide signal is applied.

4. The 100 Gbit/s Wireless Transmission Results at 60 GHz and 300 GHz

To demonstrate the proposed frequency scalability of the fiber-wireless transmission system, several transmission experiments in different bands were carried out. Starting within the regulated 60 GHz band, the system is extended to provide high data rate communications at 300 GHz, as well as 340 GHz.

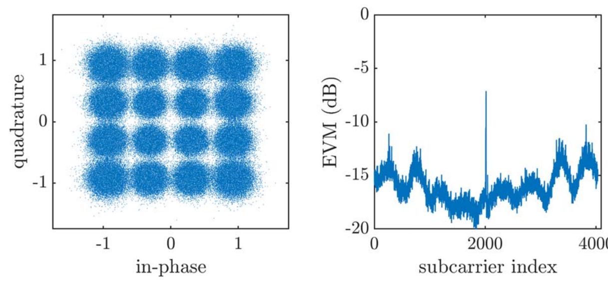

Figure 5. Constellation diagram (left) and EVM (right) after 100 cm wireless transmission in 60 GHz band with 12.5 GHz bandwidth.

Considering the V-band spectrum allocated by the FCC for communication, a spectrum of 14 GHz (57 GHz to 71 GHz) is available in this frequency range. Thus, a high spectral efficiency of at least $\sim$7 bit/s/Hz is necessary to provide 100 Gbit/s wireless transmission.

Therefore, we applied a 12.5 GHz wide 16 QAM OFDM signal and doubled the throughput of the link by using dual-polarization transport. Via managing the influences of SSBI, the IF is reduced significantly to only 8 GHz. The modulated IF signal is depicted in Figure 4.

After wireless transmission over 100 cm and subsequent downconversion to IF, digital demodulation allows analyzing the received signal regarding its transmission characteristics. The constellation diagram is depicted in Figure 5 (left) for one polarization and shows no warping, meaning low distortion. The corresponding EVM is illustrated in Figure 5 (right), with an average value of −16.3073 dB. This translates to a bit error rate (BER) of $2.21{\cdot}10^{-3}$, which is well below the 7% overhead hard-decision forward error correction (HD-FEC) limit of $3.8{\cdot}10^{-3}$ [14]. A photograph of the measurement setup is shown in Figure 6.

In the next step, the transmission system is scaled to submillimeter wavelengths. As outlined in the beginning, THz bands suffer from high transmission losses, as only sources with comparatively low output power are available, resulting in short wireless transmission distances.

Measurements performed at 340 GHz show low EVMs of −15.2574 dB and −14.2309 dB, with BERs of $3.47{\cdot}10^{-3}$ and $8.12{\cdot}10^{-3}$ at bandwidths of 16 GHz and 20 GHz, respectively, but only allowed a wireless

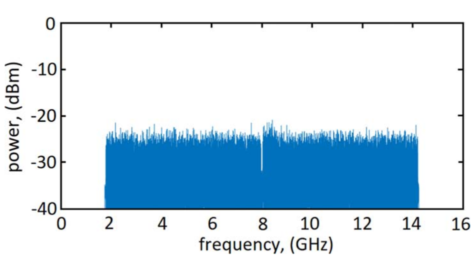

Figure 4. Modulated IF-OFDM signal with 12.5 GHz bandwidth at an IF of 8 GHz.

Figure 6. Measurement setup showing dual-polarization wireless transmission over 1 m in the V-band.

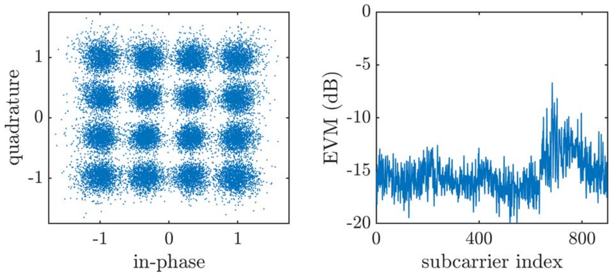

Figure 7. Constellation diagram (left) and EVM (right) after 50 cm wireless transmission at 300 GHz and 12.5 GHz bandwidth.

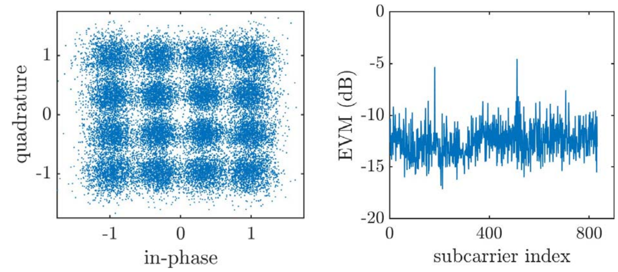

Figure 8. Constellation diagram (left) and EVM (right) after 275 cm wireless transmission at 300 GHz and 12.5 GHz bandwidth.

transmission range of about 2 mm, without using further amplification. Thus, different concepts to extend the wireless reach of the THz transmission system are investigated.

To support dual-polarization transport, electrical amplification is foreseen and allows extending the wireless transmission distance to approximately 50 cm. Due to the high amplifier noise figure of 12 dB, a SNR reduction of 2.5 dB is observed (12.74 dB), resulting in a BER of $1.81 \cdot 10^{-2}$ at a bandwidth of 16 GHz. The impact of dual-polarization transmission has also been investigated and showed only a small degradation of 0.2 dB, resulting in a SNR of 12.54 dB and a BER of $2.14 \cdot 10^{-2}$. Thus, low-density parity check convolutional codes with 20% overhead are necessary for correct signal reception. Still, this would amount to a net data rate of 102.4 Gbit/s at 340 GHz.

In contrast to electrical amplification, Teflon lenses are often used to extend the wireless reach of a transmission system at low cost and are thus considered here [4]. However, by using lenses, the concept of dual-polarization transport in one wireless channel is bypassed, because, in principle, two spatially separated channels are established.

Thus, the transmission characteristics for one polarization after 50 cm wireless distance are provided in Figure 7. A clear 16 QAM constellation diagram and an average EVM of –15.4183 dB are depicted for the 12.5 GHz wide signal, resulting in a BER of $3.66 \cdot 10^{-3}$, allowing for HD-FEC coding.

For a further extension of the transmission distance, the effects of additional electrical amplification at the receiver were also investigated. As can be seen in Figure 8, the expected degradation due to the high noise figure of the commercial J-band amplifier also occur here and result in an EVM of –13.1261 dB and a corresponding BER of $1.53 \cdot 10^{-2}$ at a wireless reach of 275 cm.

5. Conclusion

In this article, a flexible fiber-wireless architecture for realizing 100 Gbit/s throughput in different submillimeter wave bands is presented. It uses photonic upconversion at the transmitter and envelope detection at the wireless receiver to yield frequency scalability and avoid electrical LOs. Complex modulation is realized via IF-OFDM signals from an AWG for single-channel and wide bandwidth QAM transmission. Therefore, the SSBI is controlled via the biasing conditions of the MZM in contrast to digital signal processing heavy nonlinear Volterra or Kramers–Kronig schemes used in other works. On the basis of this approach, 100 Gbit/s dual-polarization fiber-wireless transmission is demonstrated in the 300 GHz band, as well as in the 60 GHz band. Finally, the extension of wireless reach via lenses and RF amplifiers is experimentally investigated and allowed for 275 cm wireless transmission.

6. Acknowledgement

The authors acknowledge financial support by the German Research Foundation (DFG) within the project Tera50+ as part of the SPP 1655.

7. References

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