100 Gbit/s V-band Transmission Enabled by Coherent Radio-over-Fiber System with IF-OFDM Envelope Detection and SSBI Suppression

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Abstract

In this paper, the successful demonstration of a 100 Gbit/s wireless backhaul link in the V-band is reported for the first time. The proposed system has potential for real-world deployment since it exploits the contiguous unlicensed spectrum of 14 GHz in the 60 GHz V-band between 57 GHz and 71 GHz. Optical baseband modulation and free-running lasers for photonic up-conversion are employed in the wireless transmitter and simple Schottky-barrier diodes (SBD) for envelope detection are used in the wireless receiver. This combination makes perfect use of the scalability of photonic technology with respect to modulation bandwidth while being robust against phase-noise and frequency drifts at the same time. By utilizing a dual-polarization (DP) 16-QAM IF-OFDM signal no local oscillator is required at the wireless receiver. To achieve the required high spectral efficiency for 100 Gbit/s wireless transmission in the available spectrum as well as a low baseband bandwidth, signal-signal beat interference (SSBI) has been substantially reduced. This is attained by analyzing non-linearities in the wireless transmitter for identifying and setting the optimum power relation between the IF carrier and the OFDM signal.

Experimentally, we report 100 Gbit/s wireless V-band transmission using a DP IF-OFDM 16-QAM modulation over 1 m distenace. The achieved overall BER before FEC and overall wireless spectral efficiency are $2.4\cdot10^{-3}$, and ~7 bit/s/Hz, respectively. For simplicity, experiments were carried out in a laboratory environment. By using commercially available high-gain antennas and RF power amplifiers, the link budget could be increased by about 70-80 dB which would lead to longer wireless distances in the range of several 100 meters up to kilometers.

1 Introduction

The global surge in demand for high-speed broadband and the need to improve connectivity and user experience is the driving force for new short-range wireless communications and fixed wireless access (FWA) links [1, 2]. Especially for front- and backhauling of 5G cells, 100 Gbit/s wireless links are needed [2].

The FCC has recently allocated unlicensed spectrum at 64-71 GHz to enable cost-effective broadband wireless systems [3]. When pairing this spectrum with the already existing unlicensed 57-64 GHz frequency band a 14 GHz wide channel is obtained in the V-band. Such regulation activities provide opportunities for developing broadband 100 Gbit/s wireless systems in the V-band.

Presently, wireless systems supporting single channel data rates of 100 Gbit/s and above have only been realized in the upper millimeter-wave or terahertz bands [4-5]: In [4], even 260 Gbit/s wireless transmission over 0.5 m was demonstrated using multiple channels over an enormous 200 GHz spectral range from 0.3 THz to 0.5 THz. In [5], Harter *et al.* have shown single channel 100 Gbit/s wireless transmission using QPSK modulation and a Kramers-Kronig receiver, exploiting a 56 GHz wide RF channel. Those experiments rely on the tens of GHz bandwidth available in the THz range and provide medium spectral efficiency to achieve high throughput. However, at the moment these THz bands are either not designated for commercial wireless communications or are still unregulated [2-3].

Moreover, despite their high throughput achievements, the limited reach of terahertz transmission systems impedes their exploitation for backhauling applications. The high atmospheric attenuation and free-space path loss of THz waves as well as the limited saturation output power of available THz amplifiers, limits their transmission distance [2].

Thus, the challenge is to develop cost-effective, regulatory-conform 100 Gbit/s capable wireless links within the available 14 GHz wide V-band spectrum. By improving the spectral efficiency to decrease the required bandwidth, 100 Gbit/s wireless links can be implemented in the V-band, allowing timely commercial exploitation: For the V-band, power amplifiers and high-gain antennas are readily available and thus transmission distances in the km range are feasible. In fact, we have already demonstrated >200 m wireless extensions of fiber links in the 71-76 GHz band with >1 km expected reach [6].

Previously, we proposed a cost-effective photonic assisted J-band wireless system based on simple envelope detection [7]. We used free-running lasers, conventional external optical modulation, a photonic terahertz emitter and a SBD wireless receiver to make the system frequency scalable and cost-effective. Thus, the system does not require an electronic terahertz local oscillator (LO) and is insensitive to phase-noise [7-8]. In this previous work, we demonstrated single channel 59 Gbit/s wireless transmission via 64-QAM IF-OFDM modulation [7]. While the system only used 10 GHz OFDM bandwidth, another 10 GHz had to be added as a guard band to deal with signal-signal beat interference (SSBI).

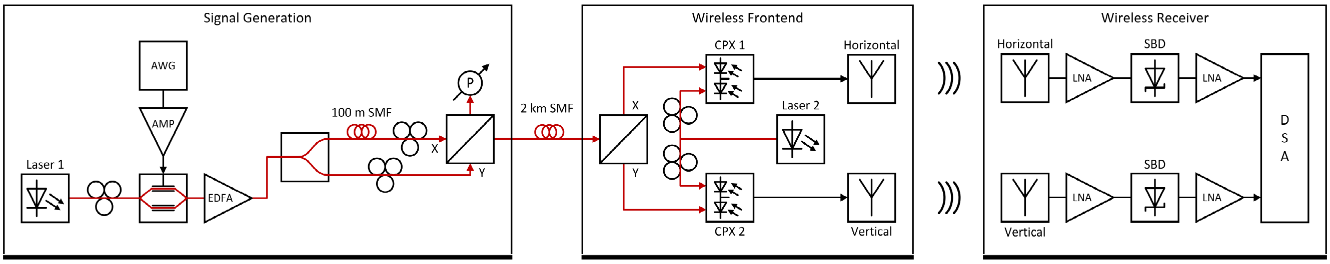

Figure 1. Schematic architecture of the utilized fiber-wireless transmission system operating in the 60 GHz band

In this paper, we report on a single RF channel 100 Gbit/s wireless transmission in the V-band using a bandwidth of only 12.5 GHz. To our knowledge, this is the first V-band wireless system reaching a 100 Gbit/s data rate. The dual-polarization IF-OFDM 16-QAM V-band signal is received using a simple envelope detector. The guard band is reduced to below 2 GHz, which is achieved thanks to suppressing SSBI by optimizing the IF-to-OFDM power ratio via bias control of the Mach-Zehnder modulator.

The paper is organized as follows: At first the architecture of the fiber-wireless V-band transmission system is outlined. Then the implemented digital modulation and receiver parts are described. After that the IF-OFDM modulation with the employed SSBI suppression is explained. Finally, the achieved 100 Gbit/s fiber-wireless transmission experiments are presented.

2 Fiber-wireless dual-polarization V-band transmission system using envelope detection

2.1 Experimental system architecture

The bottleneck for highest data rate single channel transmission usually lies in the digital-to-analog converters (DACs), which are needed for spectrally efficient higher order modulation with forward error correction (FEC) coding [1]. To maintain a signal-to-noise ratio (SNR) close to the limitations given by the DACs for wideband operation, we exploited a transparent coherent Radio-over-Fiber (RoF) front-haul [7]. Thereby, the modulation is performed at IF to allow self-heterodyne down-conversion of the RF signal at the wireless receiver using envelope detection. This approach allows to use complex modulation with a simple wireless receiver employing a SBD [7-8].

The schematic architecture of the dual-polarization fiber-wireless transmission system is depicted in Fig. 1 and described in the following.

First, an OFDM-QAM signal is digitally generated at an intermediate frequency (f_{IF}) and then converted to the analog domain using an arbitrary waveform generator (AWG) with a sampling rate of 60 GHz and a max. amplitude of 500 mV (Keysight M8195A). The IF signal is then amplified and modulated onto an optical carrier provided by a free running, telecom laser (Laser 1) by means of a Mach-Zehnder modulator (MZM).

After optical signal amplification using an Erbium-doped fiber amplifier (EDFA), optical dual-polarization transmission is employed to increase the throughput. Therefore, after the EDFA the optical signal is split into two equal paths; one of them is delayed by a 100 m single mode fiber (SMF) coil to de-correlate the two paths and provide fair dual-polarization emulation.

Polarization controllers are utilized to set orthogonal polarization states for the two paths, which are combined via a polarization beam combiner (PBC). Correct polarization settings are confirmed through a power monitor at the unused output port of the PBC.

After transmission over 2 km standard SMF, the signal is polarization demultiplexed using a polarization beam splitter (PBS). Next, both polarizations are individually up-converted to the same V-band RF using coherent photonic mixers (CPX) [6] and a polarization controlled LO laser (Laser 2).

The resulting RF signals contain the OFDM data. They are centered around the beat frequency of the free-running lasers (f_{RF}) with an offset of f_{IF}. The signals are then radiated by 23 dBi WR15 horn antennas, of which one is vertically and one horizontally polarized.

After 1 m wireless V-band transmission, limited by the lab space, the co-polarized RF signal is received using another WR15 horn antenna. The receiver polarization is then changed by rotating the horn antenna 90° to receive the other RF signal. The received signals are amplified by a 35 dB LNA and down-converted to IF by a SBD envelope detector (VDI WR12ZBD-F). Finally, after subsequent amplification the signal is received by a digital sampling oscilloscope (Keysight DSAZ634A), where the digital demodulation is carried out.

2.2 Digital modulation and signal processing

The implemented link exhibits non-neglectable frequency selective behavior as seen in Fig. 2, even though the wireless channel is assumed to only consist of a line of sight component. Despite their high peak-to-average-power ratio (PAPR) this makes OFDM multicarrier

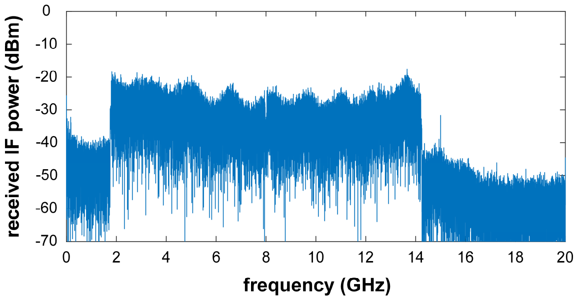

Figure 2. Spectral power distribution of the received IF signal at the DSO

transmission an attractive candidate. High PAPR is an issue in the presence of non-linear components such as MZMs and power amplifiers [9].

In detail, 40 OFDM frames were transmitted, each consisting of a preamble and 4 data symbols – only limited by the memory of the AWG. A Zadoff-Chu sequence with 4096 values is chosen as the preamble and used for zero-forcing at the receiver for channel estimation and equalization. The IFFT length for each data symbol is 4096. Thereof, 4032 subcarriers carry 16-QAM data, whereas 16 additional subcarriers are used as pilots to compensate carrier-frequency offset. For time synchronization and to ensure that no inter-symbol-interference occurs, 5% cyclic-prefix is added to each data symbol and the preamble.

3 Demonstration measurements for spectral-efficient high data rate link

3.1 IF-OFDM with SSBI suppression for QAM envelope detection

Employing envelope detection for signal down-conversion creates signal-signal beating terms. In case these terms occupy the designated signal band they result in SSBI. SSBI is well understood in optical and RoF links, where it is generated by the photodetector [8-9]. The application of coherent RoF with optical heterodyne detection by the CPX [6] prevents SSBI generation in the RF signal through photodetection.

SBD envelope detectors are employed for RF signal down-conversion because they offer some advantages for fiber-wireless transmission systems. They provide a simple receiver, that is robust against laser frequency drift and phase noise, which is a limiting factor in non-linear electronic down-converters relying on multiplier chains [2]. Furthermore, they do not require an LO at the receiver and are frequency-agnostic within their range of operation. However, SBDs as envelope detectors produce the aforementioned SSBI and require IF modulation to retain the phase information after down-conversion. For single sideband transmission, the SSBI terms are created from DC up to a frequency equal to the bandwidth of the data signal. By increasing the IF the down-converted data signal can be moved out of the SSBI. Therefore, an IF equal to 1.5 times is needed, which effectively reduces the spectral efficiency by half [7-8].

Here, another approach is taken: by controlling the power ratio of the carrier and the sideband, the SSBI can be decreased relative to the power of the data signal. In our system we controlled the carrier power via the MZM bias voltage. In order to find the optimum point, we simulated the fiber-wireless link, including the transmitter and receiver noise levels as well as the MZM driver amplifier and the optical EDFA. In Fig. 3 the simulated EVM is plotted against the MZM bias voltage for different IFs for a data bandwidth of 10 GHz. As can be seen, the EVM for the minimum IF case (5 GHz) can reach an EVM close to the noise limited case without SSBI (IF = 15 GHz). This is achieved by shifting the bias point from quadrature closer to the maximum transmission point, thus increasing the carrier power. The optimization also considers adjustment of the total signal power input to the MZM.

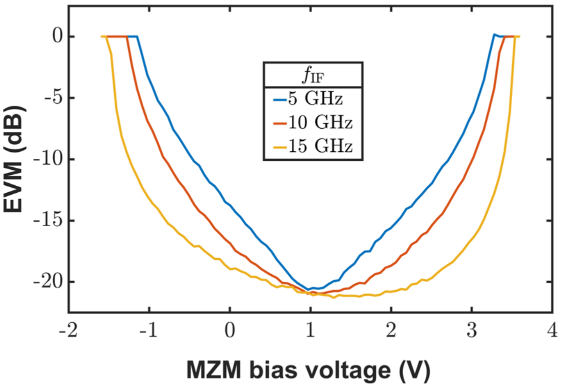

Figure 3. simulated optimal EVM of the system over the bias voltage of the Mach-Zehnder modulator

The outlined SSBI reduction via MZM biasing is implemented. The effect can be observed in Fig. 2, which shows the spectral power density of the received signal. For the 12.5 GHz bandwidth OFDM signal f_{IF} could be reduced to only 8 GHz. Since the out-of-band power density is >20 dB weaker, no significant interference to the signal is detected.

Thus, we were able to increase the spectral-efficiency and data rate by decreasing the IF, while limiting the SSBI.

In contrast to other works on SSBI reduction based on Volterra non-linear compensation [8], no knowledge of the transfer function of the transmitter nor receiver is necessary. It also requires no DSP effort, which is essential for implementation in real-time systems, where limited DSP resources are available.

These works differ from our system in the fact that here optical heterodyne detection is used to generate the RF. As a result, no SSBI is produced by the photodetection and the main source of SSBI is the direct detection of the RF signal performed by the SBD.

3.2 100 Gbit/s results in the V-band

We have transmitted a dual-polarization 16-QAM OFDM data signal with 12.5 GHz bandwidth at an IF of 8 GHz. The received spectral power distribution of this signal is displayed in Fig. 2. It shows a strong frequency selectivity,

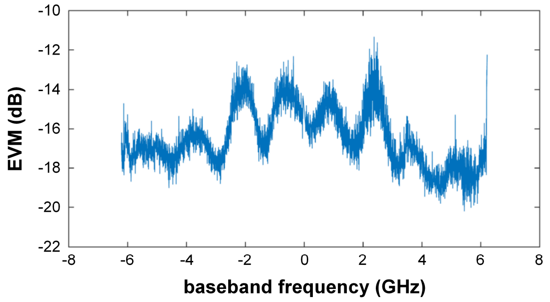

Figure 4. EVM per subcarrier plotted over the complex baseband frequency of the 12.5 GHz OFDM signal detected at the wireless receiver

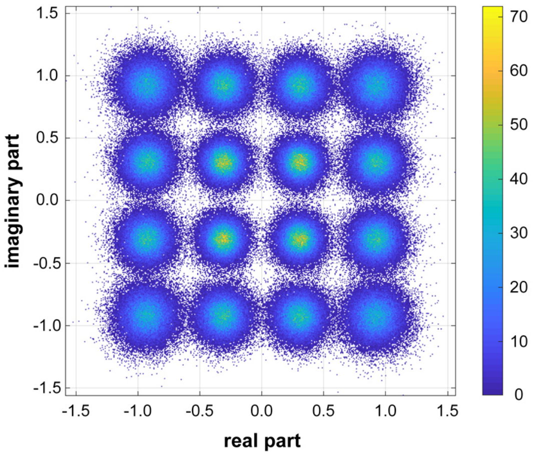

Figure 5. Constellation diagram of the received 16 QAM signal after digital demodulation

which is handled through OFDM based channel estimation. This translates to a large +/- 3 dB fluctuation of the EVM per subcarrier, which is illustrated in Fig. 4 depending on the complex baseband frequency. The average EVM of both polarizations is -16.2 dB, resulting in an overall BER of 2.4×10^{-3} – below the 3.8×10^{-3} limit for 7% overhead HD-FEC [9].

The received 16-QAM constellation of one polarization after zero-forcing demodulation is depicted in Fig. 5. The constellation plot shows no warping and affirms the transmission quality. The total occupied RF bandwidth of the signal is 14.25 GHz, meaning that the link with a gross throughput of 100 Gbit/s achieved ~7 bit/s/Hz spectral efficiency. Thus, a V-band link with a 100 Gbit/s data rate has been successfully demonstrated, which can be implemented within a license-free spectrum.

5 Conclusion

We have successfully implemented a cost- and spectral-efficient dual-polarization fiber-wireless link operating in the 60 GHz band. By employing an SBD in conjunction with IF-OFDM transmission, we achieved complex modulation with a simple receiver that is insensitive to RF phase noise e.g. from free-running lasers. Through modelling of the RoF transmission system, we successfully exploited MZM bias control for optimizing IF-to-OFDM power ratio and suppressing SSBI at the receiving envelope detector. This enabled the transmission of a 12.5 GHz wide dual-polarization IF-OFDM 16-QAM signal at 8 GHz IF, achieving a total data rate of 100 Gbit/s. To our knowledge, this is the first demonstration of 100 Gbit/s single channel wireless transmission in the V-band within the license-free 57-71 GHz spectrum.

6 Acknowledgements

The authors acknowledge financial support by the DFG project "Tera50+ – A 60–1000 GHz Wireless Measurement System with 50 GHz Bandwidth" as part of the Priority program SPP1655 "Wireless 100 Gbit/s and beyond".

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