Short Range Wireless Transmission Using a 295–315 GHz Superheterodyne Link Targeting IEEE802.15.3d Applications

Dominik Wrana[#1], Laurenz John[*], Benjamin Schoch[#], Sandrine Wagner[*], Ingmar Kallfass[#]

[#]Institute of Robust Power Semiconductor Systems, University of Stuttgart, Germany

[*]Fraunhofer IAF, Fraunhofer Institute for Applied Solid State Physics (IAF), Freiburg, Germany

[1]dominik.wrana@ilh.uni-stuttgart.de

Abstract— **This paper presents the setup and results of a simplex short range wireless transmission experiment in the lower THz frequency range between 295 and 315 GHz. Using a superheterodyne link architecture with intermediate frequencies in the E-band, a transmit power around 0 dBm and a total antenna gain of 40 dBi, data rates of up to 10 Gbps over a transmission distance of 1.5 m are achieved. Using real-time modems as well as pseudo-random bit sequences and applying complex modulation schemes as high as 32-QAM, the link's maximum performance as well as the interoperability with real-time data sources is evaluated. In addition the compatibility of the hardware with the channel scheme defined by the IEEE802.15.3d frequency standard is demonstrated.**

Keywords— **THz communication, wireless communication, IEEE802.15.3d, real-time transmission.**

I. Introduction

The steadily increasing demand for higher data rates towards 100 Gbps and beyond in wireless communication systems requires the exploitation of higher frequency ranges where large bandwidths are available. Recent standardization has identified and allocated the lower terahertz (THz) frequencies in the range between 250 and 320 GHz as defined by the IEEE802.15.3d standard [1]. Using different channel bandwidths ranging from 2.16 GHz up to 69.12 GHz high data rates can be achieved in single or multi-channel scenarios. The standardization in the frequency range 275 to 450 GHz is pushed forward simultaneously by other organizations like the ITU as well [2]. Possible applications for long range fixed point services are the implementation of backhaul systems for mobile communication networks or equipping rural and remote areas with highspeed internet access where fiber connections are not an option. While those scenarios require transmission distances of at least several hundreds of meters there are also short range applications like data showers or chip-to-chip communication [3].

II. Measurement Setup

All measurements reported in this paper are based on the hardware setup depicted in Fig. 1. At the center of this superheterodyne THz wireless link, fully integrated H-band transmit (Tx) and receive (Rx) modules based on a 35 nm InGaAs mHEMT technology [4] are used for up- and down-conversion of IF signals to and from E-band frequencies in the range between 80 and 87 GHz. The corresponding monolithic microwave integrated circuits (MMICs) are reported in [5]. In order to increase the transmit power and thus increase the possible transmission distance an additional solid-state power amplifier (SSPA) module with a saturated output power between 7 and 9.5 dBm in the frequency range from 280 to 320 GHz similar to the one presented in [6] is used. With up to 27 dB of small signal gain the output related 1 dB compression point (OP_{1dB}) ranges from 2.5 to 6.5 dBm in the respective frequency range. The local oscillator (LO) signals in the frequency range between 72 and 76 GHz are generated incoherently using two frequency synthesizers which drive frequency multiplier modules. The output power is adjusted to the required LO drive level of 4 dBm and the signal is filtered with a 71 to 76 GHz wavguide band-pass filter (BPF) for suppression of unwanted harmonics. In order to provide and receive the intermediate frequency (IF) signals between 80 and 87 GHz to and from the link, custom E-band frequency extensions, each driven by a dielectric resonator oscillators (DRO), are used. At the transmitter the IF signals are additionally filtered using a 80 to 87 GHz band-pass filter. For the transmission experiments the IF input power of the Tx and the input power of the SSPA are adjusted to -10 dBm and -28 dBm respectively which ensures sufficient linear operation of the devices with respect to the input-related 1 dB compression point (IP_{1dB}). The air interface of the 1.5 m line of sight (LOS) scenario is realized using WR-3.4 corrugated horn antennas with an antenna gain ranging from 20 to 25 dBi over the full H-band frequency range.

A. PRBS / AWG Setup

For the initial link setup and IEEE802.15.3d standard compliance testing an arbitrary waveform generator (AWG) with a sample rate of 64 GSa/s is used for generation of quadrature baseband signals. The received baseband signals are captured using a real time oscilloscope with 80 GSa/s while the demodulation and processing of the data is done offline using vector signal analyzer software. To reduce the influence of the in-band LO leakage from the frequency extension at 83.5 GHz on signal quality, for presented results relating to a signal bandwidth below 3.5 GHz a single-sideband transmission is

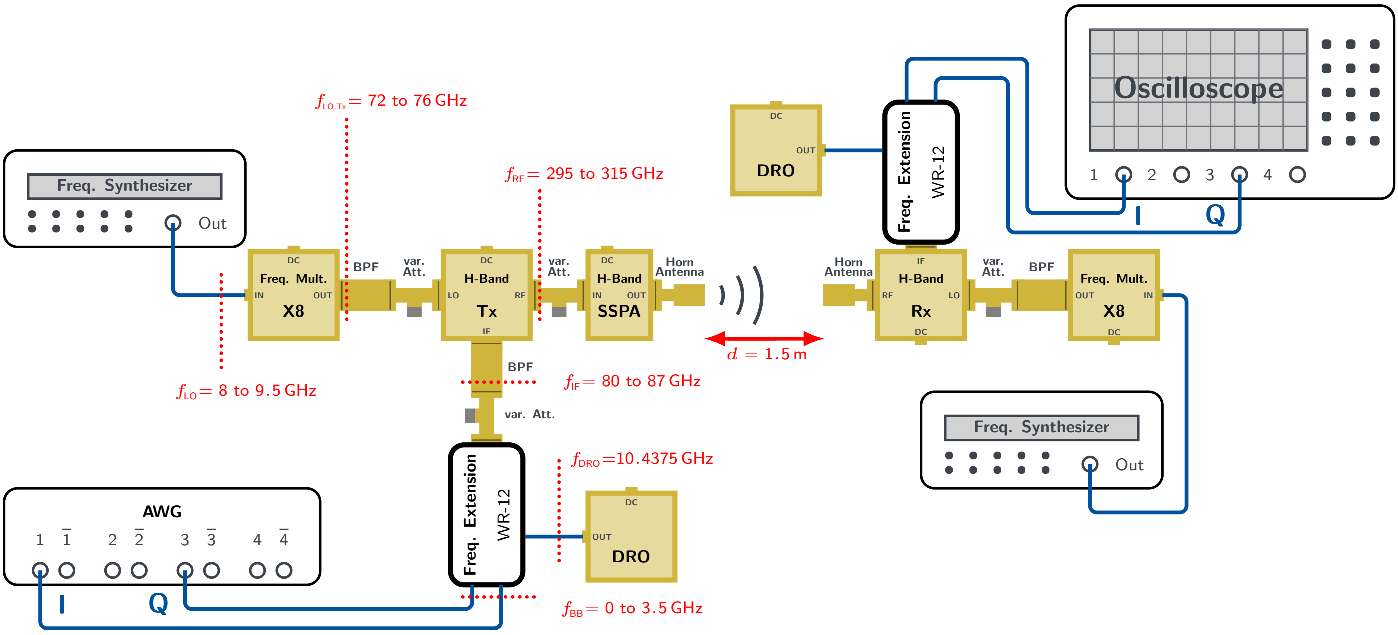


Fig. 1. Block diagram of the RF hardware used for the presented transmission experiments, here connected for the PRBS / AWG measurement scenario.

used. This is realized by a frequency offset which is applied to the modulated signal during its generation in the AWG before feeding it to the quadrature frequency extension. The offset is chosen to be

$$f_{\text{offset}} = \frac{\text{SR} \cdot (1+\alpha)}{2} \tag{1}$$

with SR representing the symbol rate and α being the roll-off factor of the applied root-raised cosine (RRC) filter. The roll-off factor is kept constant during all measurements at a value of 0.35.

B. Real Time Modem Setup

In order to validate the link's ability of handling real data, commercially available broadband modems with an IF bandwidth of up to 2.5 GHz and a data rate of up to 10 Gbps as well as adaptive coding and modulation capabilities are used as data source and sink as shown in Fig. 2. The frequency extension at the transmitter is fed with differential in-phase (I) and quadrature (Q) signals provided by the Tx modem. The received single-ended I and Q signals are processed by the Rx modem. The back channel between the modems is realized with a single ended wired connection using coaxial cables. The modems internally perform pulse shaping by applying a root-raised cosine filter with roll off of α = 0.5 to the signal. Additionally adaptive coding is used in order to decrease the bit error rate. Thus the maximum achievable net data rate varies adaptively. Since the modems are not capable of applying a frequency offset during the signal processing the implemented scenario is based on a zero-IF and thus also double sideband (DSB) transmission.

C. Link Budget

The antennas are aligned by adjusting the receive antenna in its x-, y- and z-axis for maximum receive-power level. For verification of the power levels the link budget is calculated taking into account the tranmission distance d = 1.5 m as well as RF frequencies f_{RF} between 295 to 315 GHz. The resulting free space path loss (FSPL)

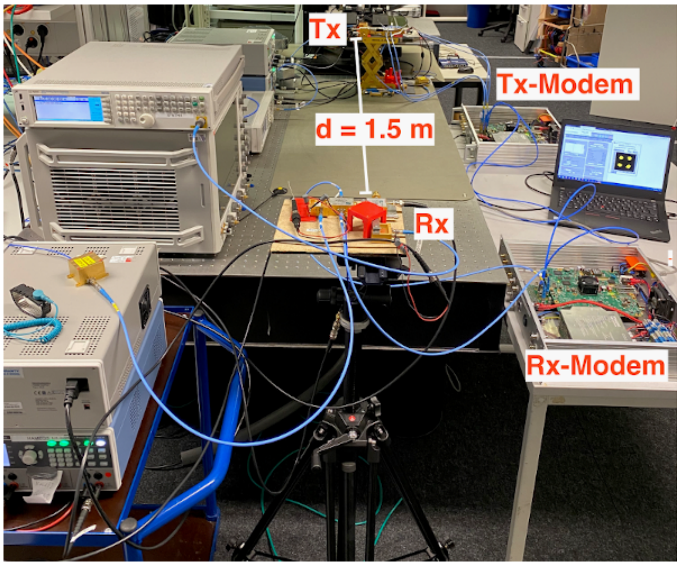


Fig. 2. Laboratory setup for the real time data transmission using broadband modems.

$$\text{FSPL} = 20 \cdot \log(d) + 20 \cdot \log(f_{\text{RF}}) + 32.44 \tag{2}$$

equals approximately 87 dB. The thermal noise power present at the receiving antenna at an ambient temperature T_{A} = 300 K within the maximum operating bandwidth B of 6.75 GHz is calculated to be

$$P_{\text{noise,dBm}} = 10 \cdot log(k \cdot T_{\text{A}} \cdot B) + 30 = -75.5\,\text{dBm}. \tag{3}$$

Considering a RF transmit power of 0 dBm as well as a total antenna gain of 40 dBi the received signal power and the signal-to-noise ratio at the receiver antenna lie at -47 dBm and 28.5 dB respectively, willingly neglecting additional impairments like atmospheric or feeder loss which is not expected to be significant in the used scenario. With an estimated receiver noise figure of 10 dB the signal quality degrades even further which prohibits the use of modulations schemes with higher order than QPSK in order to achieve reasonable bit error rates (BER), at least when using the full bandwidth.

III. Measurement Results

A. *PRBS / AWG Setup*

Table 1 shows a selection of succesfull transmissions using the PRBS / AWG setup. The maximum data rate of 10 Gbps has been achieved using QPSK modulation and a double side-band transmission. The use of larger bandwidths in this scenario is prevented by the band-pass filter used. Using the single side-band scenario the highest spectral efficiency for a baudrate of 1 GBd has been reached with 32-QAM modulation, resulting in a data rate of 5 Gbps. In additon several channels with bandwidths of 2.16 GHz and 4.32 GHz defined by the IEE802.15.3d standard have been tested using QPSK, 8-PSK and 16-QAM modulation schemes. The shown EVM_{rms} values are calculated with respect to constellation maximum.

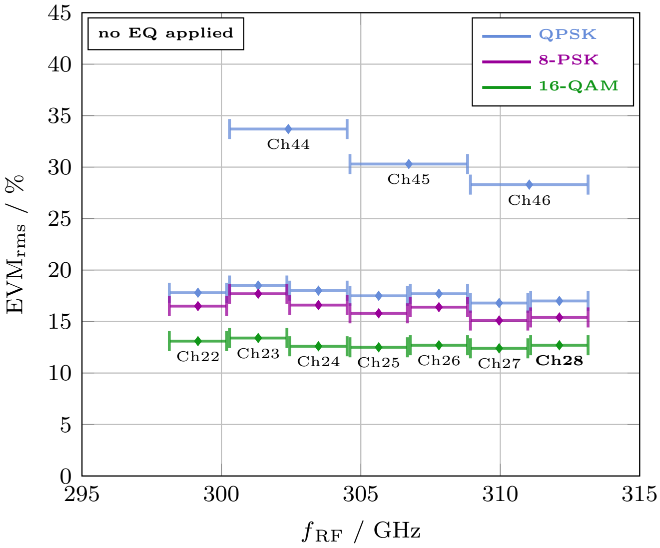


Fig. 3. Measured EVM_{rms} for different modulation schemes vs. RF center frequency and the corresponding IEEE802.15.3d channel bandwidth.

The link's flexibility of addressing various IEE802.15.3d channels by varying the LO frequency in the range between 72 and 76 GHz is demonstrated using QPSK, 8-PSK as well as 16-QAM modulation. Fig. 3 shows the measured root-mean square error vector magnitude (EVM_{rms}) transmitting 1.6 GBd in channels 22 through 28 and 3.2 GBd in channels 44, 45 and 46. While with the smaller bandwidth higher order modulations are possible due to sufficient SNR performance, for the larger bandwidth only QPSK signals could be recovered without equalization applied.

B. *Real Time Modems*

Testing the real-time transmission capabilities of the link broadband modems are used. Sweeping the LO frequency between 72 and 76 GHz, as shown in Fig. 4, the modems are not adaptively switching to higher order modulation schemes which is justified by the low SNR in range between 15 and 16 dB over the whole frequency range from 299.5 to 311.5 GHz. However, a stable connection is established using QPSK modulation at 1.425 GBd which results in a gross data rate of 2.85 Gbps.

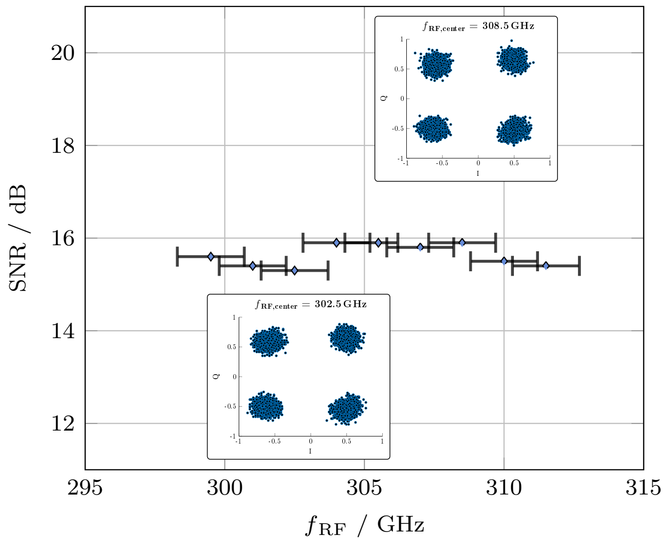


Fig. 4. Displayed SNR received by the modem for different RF center frequencies.

IV. State of the Art

Table 2 lists transmission experiments implementing similar scenarios using real-time modems as data source for short range THz wireless links. While [8] shows comparable performance over a shorter distance of only 0.6 m, [7] shows a significantly higher total data rate. This is achieved by spatial multiplexing of channels, a larger IF bandwidth as well as coherent LO generation. The later one reduces influences like phase noise and carrier offsets and thus improves the signal quality significantly. A larger transmission distance is presented in [9] with sligthly lower data rates which is enabled by the use of highly directive cassegrain antennas.

The limitations of this work relate mostly to the available bandwidth at the frequency extension as well as the antenna gain. Increasing the later one with highly directive Cassegrain antennas as presented in [10] the transmission distance and or the available SNR can be increased significantly in order to perform e.g. a long-range transmisson over several hundreds of meters.

Table 1. Selection of constellation plots of maximum performance and IEEE802.15.3d application using the PRBS / AWG setup.

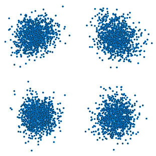
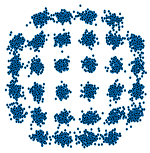
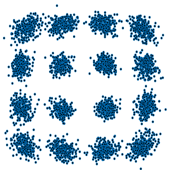
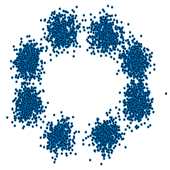
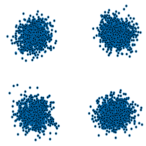
	Maximum performance		**IEEE802.15.3d**		
Channel ID	-	-	27	46	46
$f_{\mathrm{RF,center}}$ **/ GHz**	308.5	309.5	309.96	311.04	311.04
$f_{\mathrm{IF,center}}$ **/ GHz**	83.5	84.5	84.6	83.5	83.5
Bandwidth / GHz	6.75	1.35	2.16	4.32	4.32
Data Rate / Gbps	10	5	6.4	9.6	6.4
Modulation Scheme	QPSK	32-QAM	16-QAM	8-PSK	QPSK
Constellation					
$\mathbf{EVM_{rms}}$ **/ %**	23.7	6.5	10	19.9	19.7
SNR / dB	12.5	19.7	17.4	14	14.1

Table 2. Comparison of real-time short-range wireless transmission experiments using THz transceivers at a carrier frequency around 300 GHz.

	$f_{\mathrm{RF,center}}$ **/ GHz**	**Data Rate / Gbps**	**Modulation Scheme**	**LO Setup**	**Transmission Distance / m**	**Antenna Gain / dBi**
This Work	295 - 315	2.85	QPSK	incoherent	1.5	2x20
[7]	300	100	QPSK	coherent	0.5	2x23
[8]	300	2.8	QPSK	incoherent	0.6	2x23
[9]	294	1.68	16-QAM OFDM	incoherent	10	2x39

V. Conclusion

In this paper we successfully demonstrated a short-range wireless transmission over 1.5 m using a superheterodyne THz link with IF frequencies in the E-band. Using PRBS, data rates of up to 10 Gbps have been achieved using QPSK modulation in a zero-IF scenario. Applying a frequency offset in the signal generation enables the usage of higher order mdulation schemes up to 32-QAM with a data rate of 1 GBd. The link's compatibility with the IEEE802.15.3d standard has been demonstrated using channels 22 through 28 and 44 through 46. Using commercially available broadband real-time modems with a 5 GHz RF bandwidth as data source and sink has proven the link's capability for future integration into real communication networks.

Acknowledgment

This work in the frame of project ThoR has received funding from Horizon 2020, the European Unions's Framework Programme for Research and Investigation, under grant No. 814523 as well as from the National Institute of Information and Communication Technology (NICT) in Japan. The authors would like to thank their colleagues at Fraunhofer IAF for excellent wafer growth, processing, characterization and packaging.

References

[1] *IEEE Standard for High Data Rate Wireless Multi-Media Networks–Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer*, Std.

[2] *World Radiocommunication Conference 2019 - Final Acts*, 2019.

[3] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos, "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond," *IEEE Access*, vol. 7, pp. 78 729–78 757, 2019.

[4] A. Leuther, A. Tessmann, M. Dammann, H. Massler, M. Schlechtweg, and O. Ambacher, "35 nm mHEMT Technology for THz and ultra low noise applications," in *2013 International Conference on Indium Phosphide and Related Materials (IPRM)*, 2013, pp. 1–2.

[5] I. Dan, C. Grötsch, L. John, S. Wagner, A. Tessmann, and I. Kallfass, "A Superheterodyne 300 GHz Transmit Receive Chipset for Beyond 5G Network Integration," in *2021 European Microwave Week (EuMW)*, 2022.

[6] L. John, A. Tessmann, A. Leuther, P. Neininger, T. Merkle, and T. Zwick, "Broadband 300-GHz Power Amplifier MMICs in InGaAs mHEMT Technology," *IEEE Transactions on Terahertz Science and Technology*, vol. 10, no. 3, pp. 309–320, 2020.

[7] C. Castro, R. Elschner, T. Merkle, and C. Schubert, "100 Gbit/s Terahertz-Wireless Real-Time Transmission Using a Broadband Digital-Coherent Modem," in *2019 IEEE 2nd 5G World Forum (5GWF)*, 2019, pp. 399–402.

[8] G. D. Ntouni, T. Merkle, E. K. Loghis, G. Tzeranis, V. Koratzinos, N. D. Skentos, and D. Kritharidis, "Real-time Experimental Wireless Testbed with Digital Beamforming at 300 GHz," in *2020 European Conference on Networks and Communications (EuCNC)*, 2020, pp. 271–275.

[9] Y. Morishita, T. Teraoka, Y. Kashino, H. Asano, T. Sakamoto, N. Shirakata, K. Takinami, and K. Takahashi, "300-GHz-Band Self-Heterodyne Wireless System for Real-Time Video Transmission Toward 6G," in *2020 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT)*, 2020, pp. 151–153.

[10] J. Antes, F. Boes, T. Messinger, U. J. Lewark, T. Mahler, A. Tessmann, R. Henneberger, T. Zwick, and I. Kallfass, "Multi-Gigabit Millimeter-Wave Wireless Communication in Realistic Transmission Environments," *IEEE Transactions on Terahertz Science and Technology*, vol. 5, no. 6, pp. 1078–1087, 2015.