Wireless digital data transmission at 300 GHz

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Recently, analogue video signal transmission at 300 GHz has been demonstrated using a versatile Schottky mixer based measurement system designed for terahertz communication channel modelling and propagation studies. In this reported work, digital signal transmission at 300 GHz using this system is demonstrated and analysed. The performance of the digital transmission setup is characterised with respect to phase noise and modulation errors. For demonstration, high data rate digital video signals have been transmitted over a distance of up to 52 m.

Introduction: The exponential growth of wireless data rates seen over the last thirty years, and the continuously increasing demand for unoccupied bandwidth, will lead to the extension of communication systems to higher frequencies in the lower terahertz (THz) range [1]. Owing to the existence of a suitable atmospheric transmission window such systems could operate at 300 GHz. The design of future digital THz communication systems will require channel characterisation with regard to path loss, phase noise, modulation and coding analysis at these frequencies, which has not been done yet.

In this Letter we present a setup for digital signal transmission based on a 300 GHz transmission system designed for channel measurements and propagation studies [2]. We discuss its phase noise and examine the performance of digital video broadcasting (DVB) transmission with special regard to link quality. Furthermore, we demonstrate the potential of digital signal transmission at 300 GHz by establishing a 52 m indoor link for 1080p full scale high definition television data which is a remarkable advance compared to the previous analogue video transmission experiment [2].

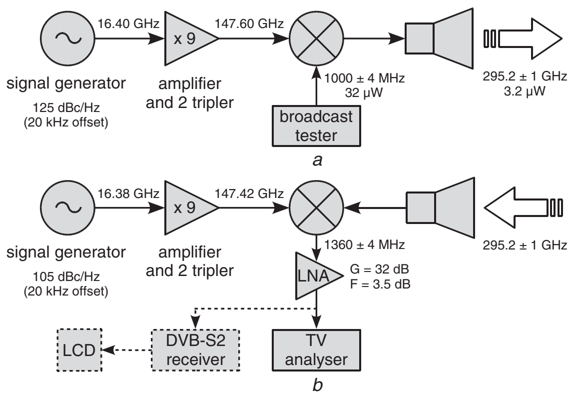


Fig. 1 *Block diagram of digital transmission setup*

a Transmitter
b Receiver

Setup: The 300 GHz transmission setup consists of autarkic transmitter and receiver units based on Schottky mixers, which are used to convert baseband signals with frequencies between 0 and 10 GHz and a maximum power of −3 dBm up to approximately 300 GHz (Fig. 1). The subharmonic mixers are pumped by frequency multiplier chains driven by two low phase noise signal generators used as tunable local oscillators. Transmitter and receiver are identical in construction aside from different frequencies used as input to the local oscillator chains (16.40 GHz at the transmitter against 16.38 GHz at the receiver) for noise suppression, resulting in an intermediate frequency of 360 MHz at the receiver output of the super-heterodyne system. A Rohde & Schwarz SFE broadcast tester directly connected to the mixer of the transmitter is used to generate DVB-T and DVB-S2 data streams of scalable frequency and power as input signals. On the receiver side either a Rohde & Schwarz ETL TV analyser for measurements on DVB-T signals or a DVB-S2 set-top-box is connected to the output to demonstrate high quality data transmission. To exploit the full dynamic range a transmission distance of 10 cm for the phase noise measurements and of 10 to 70 cm for the modulation analysis was chosen whereas two polyethylene lenses providing additional directional gain were used for the DVB-S2 demonstration to overcome high path losses.

Phase noise: To estimate the transmission performance and find suitable modulation schemes for the digital transmission link the phase noise performance of the 300 GHz transmission setup has to be evaluated first. The measurements were carried out using a spectrum analyser and a sinusoidal input signal of 1 GHz with a power of −5 dBm. The signal originating from a low phase noise signal generator (−130 dBc Hz^{-1}, 20 kHz offset) attached directly to the input of the transmitter was chosen to have the same frequency as the digital transmission. Even though the two local oscillators feature low single-sideband phase noise their contribution to the overall noise performance is predominant and constitutes the limiting factor when using high-order digital modulation schemes. This is because frequency multiplication inevitably leads to an increase of the phase noise level. Furthermore, the phase noise of both local oscillators is convolved into the intermediate frequency range, decreasing the signal-to-noise ratio at the receiver side substantially. Leading to inter-carrier interference, phase noise may heavily deteriorate the performance of modern modulation techniques such as OFDM (orthogonal frequency-division multiplex) [3]. Fig. 2 shows the noise floor of the received upper sideband signal evaluated between 1 kHz and 1 MHz. The phase noise level is below −73 dBc Hz^{-1} between 1 and 3 kHz and well below −80 dBc Hz^{-1} above 3 kHz. This noise performance is considerably good for a multiplier chain based transmission setup, being suitable for excellent transmission quality.

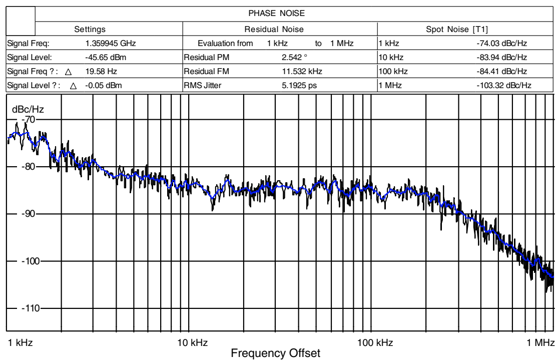


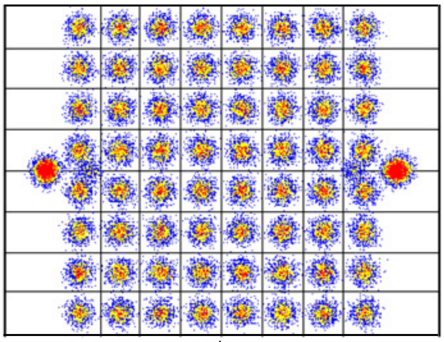
Fig. 2 *Measured phase noise of 300 GHz transmission setup using baseband input signal of 1 GHz with input power of −5 dBm*

Digital transmission performance: Because future THz communication systems will undoubtedly use digital modulation schemes for data transmission, the influence of channel characteristics at 300 GHz and local oscillator phase noise on digital modulation has to be investigated. The broadcast tester generates a DVB-T signal with a centre frequency of 1 GHz and a channel bandwidth of 8 MHz. Owing to the high crest factor and a maximum allowable mixer input power of −3 dBm the signal power was limited to −15 dBm (−3 dBm peak envelop power) at the input of the transmitter resulting in a radiated signal power of 3.2 μW. To overcome high path losses a low noise amplifier was used to amplify the received signal to a level strong enough for the TV analyser. For transmission distances of 10, 30, 50 and 70 cm we analysed signal power, carrier-to-noise ratio (C/N), bit error rate (BER) and error vector magnitude (EVM), ensuring a signal integrity sufficient for proper demodulation of the DVB-T stream. Because of the excellent noise performance, the highest possible transmission mode designated for DVB-T was chosen. In detail, this mode uses a 64-QAM with a Viterbi forward error correction (FEC) code rate of 7/8 and a guard interval of 1/32, resulting in an MPEG transport stream bit rate of 31.668 Mbit/s in an 8 MHz channel. For this mode a C/N of 20.2 dB is necessary to ensure a quasi-error-free transmission in an AWGN (additive white Gaussian noise) channel [4]. For the multi-carrier OFDM system 1512 active subcarriers were chosen (2k mode) since both 4 and 8k modes exhibited temporary drop-outs and the demodulation process failed. We assume that inter-carrier interference caused by system phase noise is responsible for the drop-outs since the higher modes use a smaller carrier spacing, being more sensitive to inter-carrier interference [3]. The results of the measurements together with the calculated free space losses are shown in Fig. 3*a*. Concerning the

BER, one can see that the critical limit of 2.0×10^{-4} before Reed Solomon error correction for a quasi-error-free transmission is not exceeded up to 70 cm. Nevertheless the decoding of the MPEG stream was barely successful at this distance. To leave a mark of the good transmission performance the constellation diagram of the received 64-QAM DVB-T signal is shown in Fig. 3*b* for a transmission distance of 30 cm with a BER of 2.6×10^{-8}. As typical for OFDM systems, phase noise shows up by the ideal signal states being expanded to form circular clouds centred at the nominal constellation points. However, these clusters are small enough not to exceed the demodulator's decision thresholds and to ensure a quasi-error-free transmission up to 70 cm.

Transmission distance (cm)	Free space loss (dB)	Signal power at analyser input (dBm)	C/N (dB)	BER before Reed Solomon	EVM (rms)
10	62.0	-36.4	35.4	$< 10^{-9}$	3.41%
30	71.5	-45.4	26.9	2.6×10^{-8}	4.40%
50	76.0	-50.4	21.5	1.2×10^{-4}	6.15%
70	78.9	-52.0	20.4	3.4×10^{-3}	6.89%

a



b

Fig. 3 *Modulation analysis*

a Measured modulation parameters of received 64-QAM DVB-T signal in 2k mode with centre frequency of 1 GHz and input power of −15 dBm indicating digital signal quality for different distances
b Constellation diagram for transmission distance of 30 cm

Demonstration of transmission capabilities: To demonstrate the capabilities of the 300 GHz transmission system we chose a DVB-S2 signal containing a 1080p full scale high definition television data stream, also being generated by the broadcast tester SFE. A commercial DVB-S2 set-top-box was used to demodulate the transmitted signal, which was subsequently displayed on an off-the-shelf LCD TV set. For the transmission we employed the commonly used 8-PSK modulation, a symbol rate of 32.017 MS/s and a roll-off factor of 0.15, achieving a gross bit rate of 96 MBit/s in a 36.8 MHz-wide channel. With an FEC code rate of 9/10 an MPEG-2 net bit rate of 85.78 MBit/s could be attained [5]. With DVB-S2 being a single-carrier system with a crest factor lower than in multi-carrier systems, the input power applied to the mixer was increased to −10 dBm. By using the two polyethylene lenses resulting in an overall antenna gain of 40 dB per unit the transmission range could be increased up to 52 m. A quasi-error-free transmission link could be established even when the input power had been reduced by 8 dB to a radiated signal power of 1.6 μW. Apart from the collimation of the 300 GHz radiation into a nearly parallel beam, this is due to the powerful FEC system based on an highly-efficient inner LDPC code concatenated with an outer BCH code.

Conclusion: We have shown first measurements regarding modulation analysis and BER at 300 GHz in a 64-QAM modulated OFDM channel. Additionally, by transmitting a 96 MBit/s DVB-S2 signal over a distance of 52 m, we undoubtedly showed the feasibility of high data rate communication links in the lower THz frequency range using high-order modulation schemes with a suitable forward error correction. The results indicate that the system limits have not been reached, yet. However, further investigations at ultra-high data rates will require a suitable unidirectional data source.

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One or more of the Figures in this Letter are available in colour online.

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5 DVB-S2 specification ETSI EN 302 307 v1.1.2, 'Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications'