Short-Range Full-Duplex Real-Time Wireless Terahertz Link for IEEE802.15.3d Applications

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***Abstract*—This paper presents experimental results of a short-range real-time full-duplex wireless link operating at frequencies between 285 and 315 GHz. Using modems with integrated E-band frontends in conjunction with H-band transmitters and receivers a superheterodyne link architecture is implemented. Over a line-of-sight distance of 0.5 meter a maximum troughput of 11.09 Gbps is achieved using complex modulation formats as high as 64-QAM. The wide LO input frequency tuning range of the H-band transmitter and receiver modules from 70 to 76.5 GHz as well as the availability of multiple modem channels with up to 2 GHz bandwidth enable the compatibility of the link with the IEEE802.15.3d frequency standard and its channels 15 through 28. The testbed is operated with two standalone PCs generating, sending, receiving and processing real traffic data over a 10 Gbps Ethernet connection to the modems.**

***Index Terms*—real-time, duplex, wireless communication, THz**

I. Introduction

Implemention and realization of future wireless communication networks for 6G and beyond applications require increased capabilities of the analog RF frontend components. To cope with the demand for higher data rates in backhaul or data center applications either modulation schemes with higher spectral efficiency or moderate modulation schemes in conjunction with large available bandwidths, for instance in H-band which extends from 220 to 325 GHz, are used. Terahertz communication, as defined by the IEEE802.15.3d standard, focuses on the frequency region from 252 to 325 GHz in order to enable data rates of 100 Gbps and beyond. To achieve those data rates either single channels with bandwidths as high as 69.12 GHz or multiple aggregated channels with bandwidths as low as 2.16 GHz are forseen by the standard [1].

Driven by the standardization of the International Telecommunication Union (ITU) [2] which allocated the frequency bands from 71 to 76 GHz as down-link (DL) and 81 to 86 GHz as up-link (UL) for fixed wireless systems, commercialization has brought modems with integrated E-Band RF frontends to market, intended for fixed-point terrestrial links. Such comercially avialable millimeter wave modems typically offer data troughput of up to 10 Gbps using channel bandwidths of up to 2 GHz while applying modulation schemes as high as 256-QAM. Most advanced devices achieve even 20 Gbps by expanding modulation capabilities up to 1024-QAM [3].

The H-band hardware [4] used in this experiment is specifically designed for compliance with the IEEE802.15.3d standard by using variable local oscillator (LO) frequencies (70 to 76.5 GHz) as well as a broadband intermediate frequency (IF) interface, covering the whole E-band, in order to address multiple channels in a large radio frequency (RF) bandwidth from 285 to 315 GHz. This enables the simultaneous transmission in multiple channels as it is required for a duplex link using frequency divison multiplexing (FDD).

II. Link Components

The core hardware components used in this THz real-time full-duplex wireless link are two pairs of H-band transmitter (Tx) and receiver (Rx) as well as additional solid-state power amplifier (SSPA) modules. Along with a set of modems with built-in E-band frontends a superheterodyne link architecture is implemented.

A. THz Link

The Tx and Rx modules both contain monolithic microwave integrated circuits (MMICs) with an identical LO path formed by a frequency multiplier by a factor of three and an amplifier which drives a fundamental resistive mixer. Considering the injected LO frequency in the range of 70 to 76.5 GHz this results in an LO frequency of 210 to 229.5 GHz at the mixer. On the Tx MMIC the mixer is followed by a power amplifier to provide linear output power above -5 dBm with respect to the input related 1-dB compression point (IP_{1dB}). Additional solid-state power amplifier (SSPA) modules based on [5] are used to further increase the linear transmit power up to 8 dBm with respect to the output related 1-dB compression point (OP_{1dB}). Integrated onto the Rx MMIC a low-noise amplifier (LNA) is used for pre-amplification of the received RF signals prior to the mixer. The LO as well as the IF interfaces of the split-block waveguide modules are realized in WR-12 while the RF ports are WR-3.4.

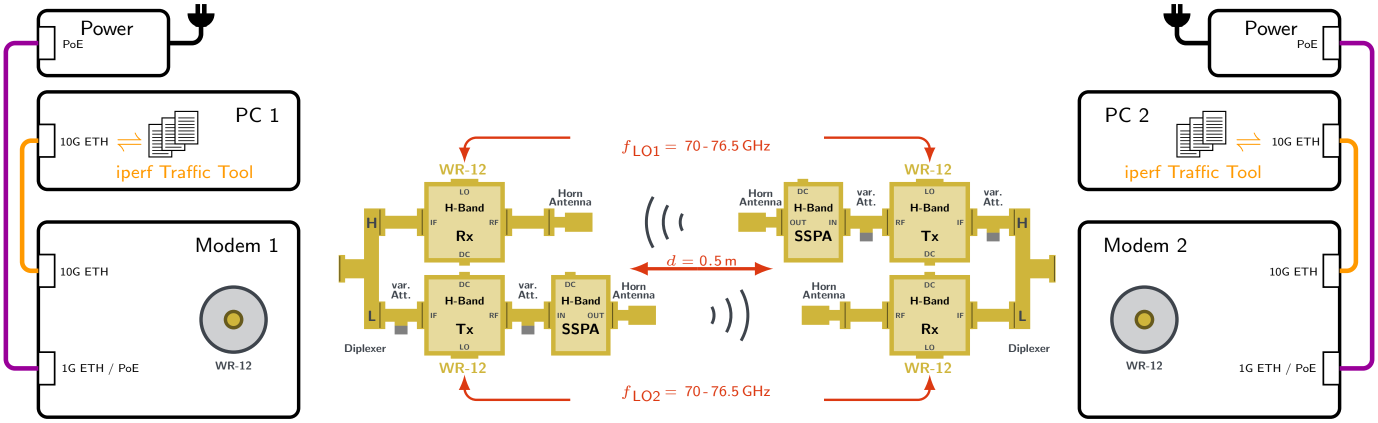

Fig. 1. Block diagram of the measurement setup used to determine the performance of the THz full-duplex real-time wireless link.

B. Modem Hardware

The modems include baseband data processing capabilities as well as quadrature E-band RF frontends including a WR-12 interface for RF connectivity. Using FDM, the modems are capable of handling a channel-related data throughput of up to 10 Gbps using channels with a maximum bandwidth (BW) of 2 GHz. The separation of UL and DL frequency band is done using WR-12 diplexers which provide insertion loss lower than 3 dB along with strong side-band suppression of more than 60 dB as shown in Fig. 2. Occupying the full channel BW while applying root-raised cosine filtering with a roll-off of 0.25 a fixed baudrate of 1.6 GBd is used in conjunction with quadrature modulation schemes up to 128-QAM. This leads to a maximum theoretically achievable simplex troughput of 11.2 Gbps. Taking into account the applied forward error correction (FEC) with an FEC rate of 0.87, redundancy is added which decreases the value to about 9.74 Gbps.

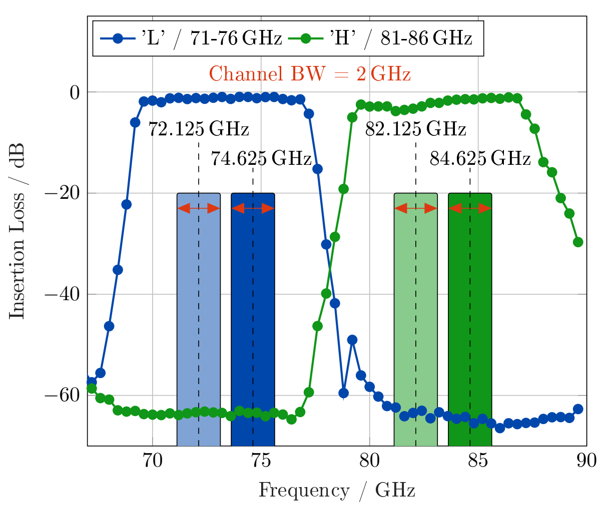

Fig. 2. Measured frequency response of the waveguide diplexer used for separation of the up- and down-link frequency bands together with a qualitative representation of the channels selctable within modem 1 and 2 respectively.

C. Frequency Plan

The transmission experiments build on a frequency plan based on the IEEE802.15.3d standard. Taking into account the upper and lower limit of the LO frequency tuning range of 70 and 76.5 GHz as well as the lowest and highest IF channel frequencies of 72.125 and 84.625 GHz the addressable RF channel IDs range from 15 to 28. Considering the spacing of the UL and DL channel pairs at modem level of 10 GHz in contrast to the channel spacing of 2.16 GHz in the IEEE802.15.3d standard, two different LO frequencies are required for the H-band up- (ULH) and down-link (DLH) respectively. The ULH and DLH channels are chosen to be separated six channels apart resulting in a pairwise addressing of the channels starting at channel 15 together with channel 21 and stopping at channel 22 in combination with channel 28. Considering the superheterodyne architecture of the link, the required LO frequencies at the Tx and Rx module inputs are calculated to

$$f_{\mathrm{LO}} = \frac{f_{\mathrm{RF,center}} - f_{\mathrm{IF,center}}}{3} \tag{1}$$

with $f_{\mathrm{RF,center}}$ being the center frequency of the selected IEEE802.15.3d channel and $f_{\mathrm{IF,center}}$ being the center frequency of used modem channel.

D. Link Setup

Each modem is combined with a set of H-band Tx and Rx as shown in Fig. 1. Variable WR-12 attenuators are inserted at the Tx for adjustment of the modem transmit power of around -5 dBm down to -10 dBm in order to enable optimum operation as well as prevent damage of the Tx modules during modem start-up. Due to the high small-signal gain of the SSPA of up to 28 dB, additional WR-3 variable attenuators are added to account for a back-off from the $\mathrm{IP}_{\mathrm{1dB}}$, resulting in an RF transmit power of 0 dBm. This ensures sufficient linear operation and allows for use of higher order modulation schemes with increasing peak-to-average power ratio (PAPR) such as 64-QAM. The air interface is realized by WR-3.4 horn antennas with an antenna gain of 20 to 25 dBi. The generation of the injected LO signals, which is not shown specifically in the block diagram, is performed by two electronic frequency synthesizers in conjunction with frequency multipliers. In order to test the link embedded into a real-world application scenario each modem is connected to a PC via a 10G Ethernet network card, theoretically allowing for up to 10 Gbps simplex troughput. However, a measurement of the two PCs in back-to-back configuration revealed a maximum simplex throughput of 8.73 Gbps. Both PCs run open source traffic generation tools serving as server and client in a standard Transmission Control Protocol / Internet Protocol (TCP/IP) communication scenario. DC power is supplied to the modems by Power over Ethernet (PoE).

III. Measurement Results

The modems are combined with the H-band hardware and transmission experiments over a distance of 0.5 m are conducted. A picture of the laboratory setup is shown in Fig. 3. All following traffic measurements are conducted using the maximum available channel bandwidth of the modems and the alignment of the antennas being performed by optical inspection.

A. Maximum Channel Throughput

At first the achievable maximum throughput per channel is determined based on 60 second recordings of sequential traffic generation at PC 1 and logging of the successfully received data at PC 2 and vice versa. The shown numbers represent mean values over this time period.

The maximum throughput of around 7 Gbps achieved with 64-QAM using modem channels 72.125 and 82.125 GHz as shown in Fig.4 is reached in channels 19 trough 22 which are paired with 25 through 28. Higher data rates which would be achieved using 128-QAM are not reached because the carrier-to-interferer-noise ratio (CINR) does not sufficiently exceed the 23.6 dB threshold required by the modems.

The increasingly reduced performance in channel 16, 17 and 18 is explained by strong in-band interferers at 285.43 GHz, 288.31 GHz and 291.19 GHz respectively which correspond to the fourth harmonic of the frequency multiplier in the LO path leaking into the RF domain. The correspondingly limited throughput in channels 22, 23 and 24 is related to the modems not being able to apply different modulation schemes in the

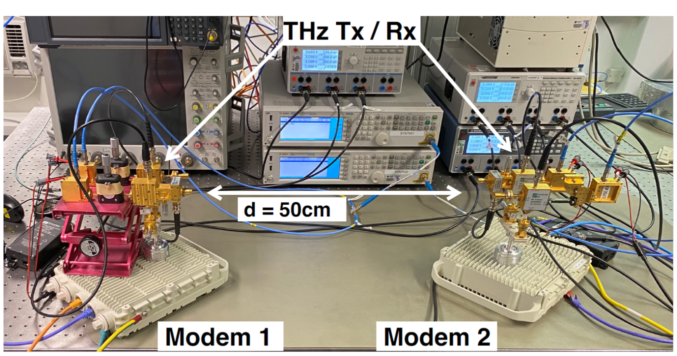

Fig. 3. Photograph of the link setup in the laboratory.

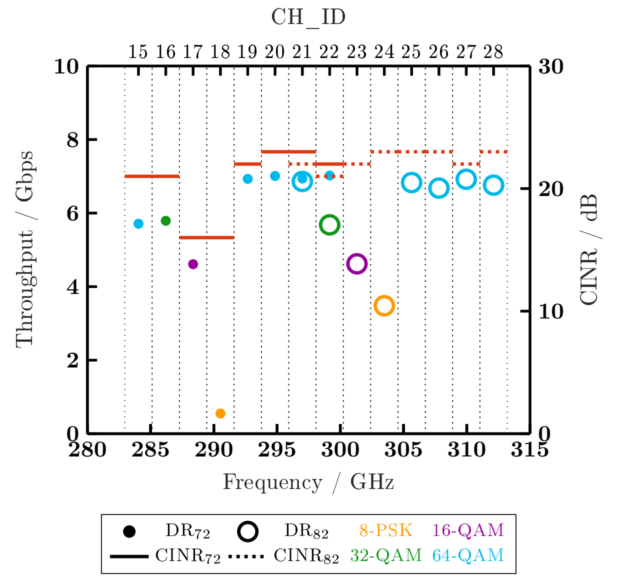

Fig. 4. Achieved throughput and corresponding received CINR values for a transmission distance of 0.5 meter using different RF channels with the 72.125 GHz as IF DL and 82.125 GHz as IF UL channel.

UL and DL at the same time. However, still the maximum possible throughput with respect to applied modulation scheme is achieved here. Considering the CINR values of 22 dB and 23 dB in channels 23 and 24 it is assumed that 64-QAM transmissions are feasable as well if operated in combination with other ULH channels than 17 and 18.

B. Full-Duplex Transmission

The maximum simultaneous throughput over the full-duplex link in contrast to the predominantly sequential sending of data via the up- or down-link channel, as done in III-A, is evaluated using channels 21 and 27 in combination with 64-QAM modulation. The traffic generation is at first initiated only for down-link channel 27. After 15 seconds traffic generation for up-link channel 21 is added which results in a drop of the throughput in channel 27 by about 1.4 Gbps as shown in fig. 5. The combined throughput of both channels reaches 11.09 Gbps with almost equal rates of about 5.5 Gbps being transfered over up- and down-link simulatenously. After 45 seconds the traffic generation for channel 21 is stopped which enables channel 27 to increase its throughput again to the initial rate of 7 Gbps. This proves that the simplex throughput is limited by the THz link in terms of signal quality while the full-duplex throughput is limited by the network connection and modem capabilities.

C. Long Term Full-Duplex Transmission

In order to demonstrate long-term link stability the testbed is operated for a continuous ten-hour period using channels 21 and 27 as up- and down link. As depicted in Fig. 6 the link stays established over the full period. Mean throughputs of 5.62 Gbps and 5.47 Gbps are achieved in channel 27 and 21 respectively which leads to a combined throughput of

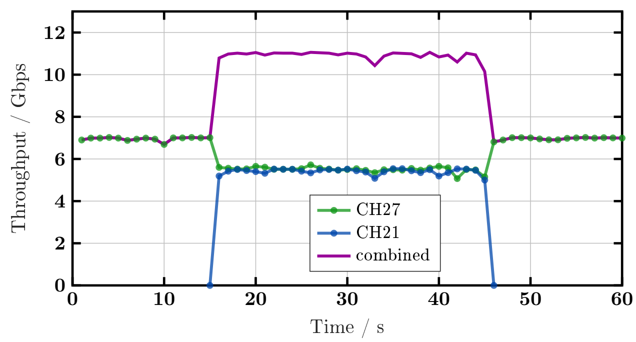

Fig. 5. Dependency of the channel throughput with respect to separate or combined up- and down-link traffic generation.

11.09 Gbps. This way 45.37 TB of accumulated net data have been transferred over the link during the 10 hour period.

IV. State of the Art

Table I lists transmission experiments implementing short-range THz wireless links comparable to this work. Even though all experiments listed report on real-time transmission scenarios only this work reports on a full-duplex operation. With [6] reporting on the highest throughput of 100 Gbps it has to be noted that this was achieved using significantly larger RF channel bandwidths of 45.9 GHz in conjunction with QPSK modulation as well as spatial multiplexing. While [7] and [8] use QPSK and 16-QAM respectively, this work makes use of spectrally more efficient modulation schemes, such as 64-QAM.

V. Conclusion

We successfully demonstrated the operation of a short-range THz wireless testbed achieving up to 11.09 Gbps of data throughput and stable long-term operation. To the best of the author's knowledge this is the first demonstration of a real-time full-duplex wireless link at THz frequencies compliant with the IEEE802.15.3d standard. Future work will include the aggregation of multiple modems at each terminal in order to increase the total data rate.

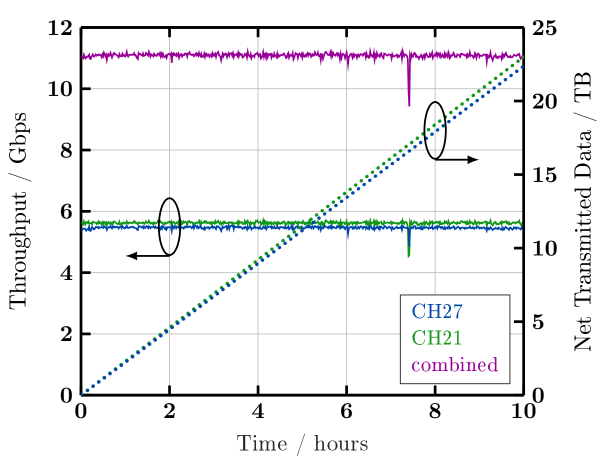

Fig. 6. Throughput and accumulated traffic of a continuous ten-hour transmission using channel 21 and 27 for parallel up- and down-link operation.

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

	$f_{\mathrm{RF,center}}$ / GHz	Throughput / Gbps	Direction	Distance / m
This Work	282 - 313	11.09	full duplex	0.5
[6]	300	100	simplex	0.5
[7]	300	1.228	simplex	0.6
[8]	294	1.68	simplex	10

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