Horizon 2020 Grant Agreement no: 814523

Tera**h**ertz end-to-end wireless systems supp**o**rting ultra-high data **R**ate applications

ThoR

Deliverable D2.2

Overall System Design

Coordinator (EU): Thomas Kürner
Organisation: Technische Universität Braunschweig

Coordinator (Japan): Tetsuya Kawansihi
Organisation: Waseda University

Start date of project: 01-Jul-2018

Date of issue: 24-Apr-2019
Due date: 28-Feb-2019
ThoR Ref: ThoR_SIKLU_190417_F_WP2

Leader in charge of deliverable: Yigal Leiba
Siklu Communication

Project co-funded by the European Commission within the Horizon 2020 programme and the National Institute of Information and Communications Technology in Japan (NICT)		
Dissemination level		
PU	**Public**	**X**
PP	**Restricted to other programme participants (including the Commission Services)**	
RE	**Restricted to a group specified by the consortium (including the Commission Services)**	
CO	**Confidential, only for members of the consortium (including the Commission Services)**	

Contents

Change register

Version	Date	Author	Organisation	Changes
A	01-Dec-2018	Yigal Leiba	Siklu Communication	TOC
B	24-Feb-2019	Petr Jurcik Ralf-Peter Braun Thomas Kuerner Yigal Leiba Ran Timar Eisaku Sasaki	DTAG DTAG TUBS Siklu Communication NEC	1st draft
C	21-Mar-2019	Petr Jurcik Ralf-Peter Braun	DTAG DTAG	Draft for review

		Thomas Kuerner Yigal Leiba Ran Timar Eisaku Sasaki Keitarou Kondou	TUBS Siklu Communication NEC HRCP	
D	4-April-2019	Petr Jurcik Ralf-Peter Braun Thomas Kuerner Yigal Leiba Ran Timar Eisaku Sasaki Keitarou Kondou	DTAG DTAG TUBS Siklu Communication NEC HRCP	Draft for fixes containing comments from Iulia Dan
E	17-April-2019	Petr Jurcik Ralf-Peter Braun Thomas Kuerner Bo Kum Jung Yigal Leiba Ran Timar Eisaku Sasaki Keitarou Kondou	DTAG DTAG TUBS Siklu Communication NEC HRCP	Comment fixes implemented
F	24April 2019	Thomas Kürner	TUBS	Small editorial changes

Reviewed by Iulia Dan USTUTT C & 3-April-2019

1. Statement of independence

The work described in this document is genuinely a result of efforts pertaining to the ThoR project. Any external source is properly referenced.

Confirmation by Authors:	Petr Jurcik	DTAG
	Ralf-Peter Braun	DTAG
	Thomas Kuerner	TUBS
	Bo Kum Jung	TUBS
	Yigal Leiba	Siklu Communication
	Ran Timar	Siklu Communication
	Eisaku Sasaki	NEC
	Keitarou Kondou	HRCP

2. Abbreviations

5G	5th generation of cellular mobile communication systems
ADC	Analogue to Digital Converter
AWGN	Additive White Gaussian Noise
B5G	Generation(s) Beyond 5G
BB	Baseband
BER	Bit Error Rate
BS	Base Station
BW	Bandwidth
CNR	Carrier to Noise Ratio
CU	Central Unit
DAC	Digital to Analogue Converter
DU	Distributed Unit
EIRP	Effective Isotropic Radiated Power
EVM	Error Vector Magnitude
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FSL	Free Space Loss
IF	Intermediate Frequency
IMT2020	International Mobile Communications 2020 standard
IOT	Internet of Things

LACP	Link Aggregation Control Protocol
LAG	Link Aggregation Protocol
LNA	Low Noise Amplifier
LO	Local Oscillator
LOS	Line Of Sight
LSI	Large Scale Integrated circuit
LTE	Long Term Evolution
MAC	Media Access Control
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
NF	Noise Figure
NRE	Non-Recurring Expense
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PHY	PHYsical layer
QAM	Quadrature Amplitude Modulation
QPSK	Quaternary Phase Shift Keying
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuit
RSL	Receive Signal Level
RU	Remote Unit
RX	Receive
SNR	Signal to Noise ratio
SFP	Small From-factor Pluggable
TDD	Time Division Duplex
TWTA	Traveling Wave Tube Amplifier
TX	Transmit
UE	User Equipment

3. Executive summary

The requirements for a wireless P2P link operating around 300 GHz are presented and defined in [1]. This document considers the overall system design, starting from the selection of the throughput requirements that may be satisfied by the technology and continuing with the implications on the modes (e.g. frequency channel bandwidth, modulations, antennas). The document also reviews the radio propagation characteristics of the 300 GHz spectrum and reviews the assumptions and models available for the analysis of this frequency band. Based on these models the maximum achievable link distances and data rates are calculated.

The document proceeds to review the system design concept where the 300 GHz P2P link is designed to be implemented using two different concepts. One implementation is operating in Time Division Duplex (TDD) mode modems based on IEEE 802.15.3e-2017 (60 GHz) compliant chips and the other is operating in Frequency Division Duplex (FDD) mode based on ETSI EN 302 217 (70/80 GHz). The TDD system is more flexible in terms of operating frequency and better transmit/receive channel consistency. Further, the TDD system is easier to implement on a chip as filters that cannot fit on the chip are not required. The FDD system has advantages such as better spectral efficiency and lower latency.

The document concludes with the system specification which details the block diagram and interfaces for the system. The frequencies channels scheme is discussed in detail and provides a comparison between the FDD and TDD operation modes, the targeted frequency conversion scheme and the associated expected spurious product. Based on this design the expected throughput and range details for the system design are estimated.

4. Introduction

Starting with historic cellular network generations, and ever growing since, the demand for high-speed connectivity to the cellular base stations has always been present. With the upcoming 5th generation of cellular wireless communication, ultra-high data rates are introduced and the use case of a fully connected society (e.g. Internet of Things-IOT, connected vehicles) all demand a massive increase in the volume of traffic to be carried by the cellular network and consequently, a similar increase to its underlying connectivity infrastructure. The traffic densities are envisioned by IMT2020 to be in the order of several 10Mbit/m^2 [1].

To achieve the growth in traffic density, it is not enough to increase the throughput available by the current base-stations, but also required to significantly densify the network, placing base-stations closer together. This increase in capacity in the cellular access layer must be reflected also to its underlying infrastructure which is the transport network connecting the base-stations to Internet backbone. This connection, has been in recent years a bottleneck to the realization of the full network capacity potential, where backhaul networks, could often not provide enough capacity for cellular base-stations in those case where fibre infrastructure was not sufficient [2].

Wireless systems can complement optical fibres by enabling easy extension of available fibre infrastructure without need for additional trenching, and hence quickly and at relative low cost. Such fibre extension can support various communication scenario such as backhaul/fronthaul feeding of cellular access base-stations, fixed communication scenarios, ad hoc networks for big events, natural disasters and more. Such deployments leverage on the capacity of the already existing optical fibres and extends their reach, and hence their usefulness and benefit. THz wireless communication is especially suitable for such fibre extension in dense urban and suburban applications due to the large capacity and a range than can extend between a few hundreds of meters to beyond one kilometre.

ThoR’s system design presented in this document targets serving the scenarios mentioned above, and especially the 5G backhauling/fronthauling application. The design targets the terahertz frequency spectrum between 252-325GHz, as a possible candidate band, while catering for the capacity and distance requirements of 5G and beyond 5G access systems. The system design leverages and exploits the new IEEE 802.15.3d standard which is expected to lead to economical solution based on deep Silicon integration. The design targets a parallelization of up to eight THz channels in the IEEE 802.15.3d frequency range from 252-325 GHz. To demonstrate this concept, aggregated sub-channels in the 60 or 70-80 GHz bands are utilized and converted to THz frequencies. This architecture can achieve data rates above 200 Gbps and enables a transparent, real-time, scalable solution for 5G and beyond compliant wireless fibre extension.

5. System Design Considerations

5.1. Throughput requirements

The volume of data traffic consumed by the 5G and beyond 5G (B5G) use-cases, services and applications is expected to significantly grow in comparison to today's 4G/LTE generation. A factor of approximately 5-10× is foreseen. The experienced 5G user data rate depends on the targeted application/use case, and ranges from few kbps in case of massive Internet of Things to hundreds of Mbps (up to a peak of several Gbps) in case of broadband access in dense urban areas and indoors [3]. These consumers' performance requirements should be also reflected and supported in access and transport networks.

Evolving from 4G/LTE to 5G network architecture, the main change is that the original single-node baseband functions in 4G/LTE are split between Central Unit (CU), Distributed Unit(s) (DU) and Radio Unit(s) (RU) resulting in a so-called **centralized network architecture with functional split** (Figure 1). This flexible and efficient architecture can deliver the different service requirements of a wide range of expected 5G use cases and applications [4].

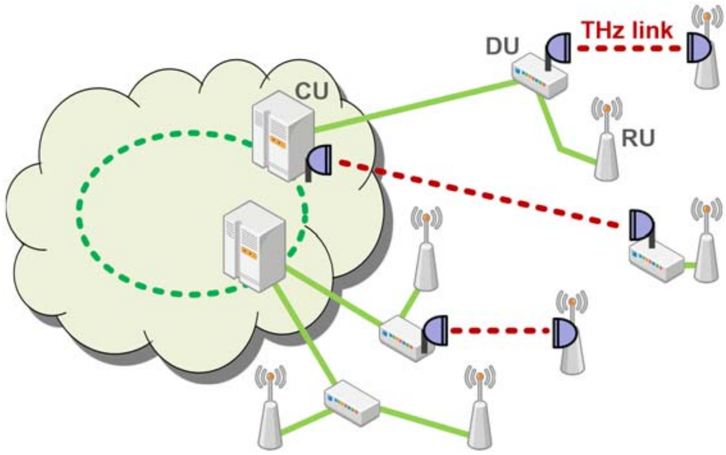

Figure 1 Centralized architecture with functional split

The choice of functional split points depends on the specific use case and application, and determines the performance requirements for the transport network and consequently the capability of the mobile access network and user experience. The specific performance requirements for the transport network due to a certain functional split option were elaborated in [4]. The base stations (BS) of cellular 5G networks can be deployed with variety of configurations and shall support up to 1 GHz bandwidth, base station antennas with up to 256 antenna ports and UE antennas with up to eight antenna ports [5]. The performance requirements of five representative configurations of base station, which are expected to be adopted in typical 5G network deployment, were studied in [4] and the resulting throughputs are summarized in Table 1. Each configuration is described by total aggregated bandwidth (in MHz), number of antenna ports (e.g. 32 transmitting/receiving antenna ports = 32T32R) and number of MIMO layers. The following parameters are common to all the configurations: modulation of 256QAM, 32 bits per I/Q sample, max FFT size of 4096, physical resource blocks ranging from 20 to 275 – the other details can be found in [4] Section 7. The required throughput of each split option is compared with the reference split option 8 (CPRI) and expressed as a percentage - for example, Option 7-2 usually requires less than 10 % of the throughput required by Option 8.

Table 1 Throughput requirements for the transport network due to a certain functional split option [4]

3GPP split option			2	6	7-3	7-2	8 (CPRI)
Throughput requirement between CU and DU	Configuration 1 20MHz, 4T4R, 4 MIMO layers	per sector/cell (micro BS)	0.42Gbps 11%	0.43Gbps 11%	0.54Gbps 14%	1.3Gbps 34%	3.9Gbps 100%
		per macro BS[1]	1.26Gbps	1.3Gbps	1.6Gbps	4Gbps	11.8Gbps
	Configuration 2 40MHz, 32T32R, 8 MIMO layers	per sector/cell (micro BS)	1.84Gbps 3%	1.9Gbps 3%	2.3Gbps 4%	5.8Gbps 9%	62.9Gbps 100%
		per macro BS	5.4Gbps	5.6Gbps	7Gbps	17.4Gbps	189Gbps
	Configuration 3 100MHz, 64T64R, 8 MIMO layers	per sector/cell (micro BS)	4.37Gbps 2%	4.5Gbps 2%	5.7Gbps 3%	14.2Gbps 6%	252Gbps 100%
		per macro BS	13.2Gbps	13.6Gbps	17Gbps	42.6Gbps	755Gbps
	Configuration 4 200MHz, 64T64R, 8 MIMO layers	per sector/cell (micro BS)	8.7Gbps 2%	9Gbps 2%	11.4Gbps 3%	28.4Gbps 6%	503Gbps 100%
		per macro BS	26.4Gbps	27.2Gbps	34.1Gbps	85.1Gbps	1510Gbps
	Configuration 5 400MHz, 128T128R, 8 MIMO layers	per sector/cell (micro BS)	17.5Gbps 0.9%	18Gbps 0.9%	22.8Gbps 1.1%	56.8Gbps 2.8%	2014Gbps 100%
		per macro BS	52.45Gbps	54Gbps	68.4Gbps	170Gbps	6042Gbps

The combinations which could be served by current E-band products are highlighted in orange. In addition to these combinations, those which could be served by future terahertz-based products targeting throughputs beyond 200 Gbps are highlighted in green. As can be observed the required throughput of the transport network (namely link between DU and CU) depends greatly on the particular split option. The lower the split point (towards Option 8) the higher the required throughput, and consequently the more difficult and costly the deployment in large-scale networks. At the lowest split point (Option 8), the typical configurations of 5G macro BS (with 3 sectors/cells) require hundreds to thousands of Gbps of throughout. In this case, the optical fibre will be the only transport solution. If the wireless transport connection is needed (e.g. to ensure fast, flexible, and low cost deployment), a lower layer split point requiring throughput of tens to hundreds of Gbps must be assumed. Nevertheless, even when assuming a lower layer split point, the current V- or E-band products providing maximum throughputs of 10 Gbps cannot serve most of the configurations of 5G macro base station. Such throughputs can be served by the future terahertz-based products targeting throughputs beyond 100Gbps (e.g. in focus of ThoR project).

5.2. Modem implications

Meeting the ultra-high throughput requirements targeted by ThoR is highly challenging from the modem perspective. The modem can utilize three kinds of resources, but each has some disadvantages, as will be discussed in subsequent sections. Specific choices for the system implementation will be available in the relevant WP3 deliverables [6], [7].

5.2.1. Wide frequency channel

The throughput possible from the modem is proportional to the spectrum resource available to it. In the low terahertz region, a wide bandwidth is available, around 50 GHz, between 275 GHz and 325 GHz. However, considerations such as segmentation of spectrum due to other uses of the

[1] Assuming a macro base station with 3 sectors/cells

spectrum, the wish to have more than one frequency channel, and the wish to use FDD type communication would often reduce the actually usable spectrum significantly. As an example, suppose we wish to have only two frequency channels, using FDD and allocated 20% of the band for other uses (besides P2P wireless communication). A reasonable segmentation of the 275 GHz to 325 GHz spectrum would be to allocate the range 295 GHz to 305 GHz to those other uses, and also to serve as a guard band between the lower part and the upper part of the band. We can then allocate two paired frequency channels, each with 10 GHz width, one with centre frequencies 280 GHz / 310 GHz and the other with 290 GHz / 320 GHz. In this example we end up with just 10 GHz of spectrum of the original 50 GHz band. The above being said, it is stressed the frequency is still considered the most important resource to determine the modem performance, however, relying on it alone will fail to deliver the desired throughputs.

5.2.2. High modulation

The use of high modulation order is a significant factor in improving the throughput that can be delivered by the modem. In order accommodate different incompatible modulations, the use of various forward error correction (FEC) schemes and other inefficiencies related to spectral masks and physical layer overheads, we use a term called spectral efficiency. The spectral efficiency is measured in bit per second per Hertz (b/s/Hz) unit and defines how many bits of information a modem can deliver using 1 Hz of spectrum. The use of high modulations has a drawback due to the fact that higher modulations require higher signal to noise (S/N) ratio. This increase in S/N quickly generates diminishing returns, as for example, transition from QPSK modulation to 16QAM modulation doubles the throughput at a cost of roughly 6dB, but transition from 16QAM to 64QAM adds only 50% for the same (roughly) 6dB. Further transition from 64QAM to 256QAM contributes only 30% additional throughput for the same (roughly) 6dB, and so on. The S/N for the wireless link is ultimately determined by the transmission power, antenna gains, receiver noise figure, thermal noise floor and the path loss. Since all the above factors except the last one (path loss) are practically limited by size, or technological feasibility, the S/N requirement determines the maximum supported path loss and thus the usable link distance. The targeted spectral efficiency would therefore be a compromise between the desired throughput and the desired range for the wireless link.

5.2.3. Multiple antennas

The use of multiple antennas for receive and transmit (MIMO) has the potential to increase the available link throughput. The concept is similar to multiplying the capacity that may be carried by a certain wire by placing more wires in parallel. However, in order for the capacity gain to be realized, the communication paths between the antenna must conform to some criterion of independence, such as for example, the channel matrix defining the channel between the transmit antennas and the receive antennas must be invertible [8]. MIMO can be realized also for pure line-of-sight (LOS) propagation scenarios [9], by placing antennas in cross polarization and further by placing antennas in such a distance that the propagation induces phase difference between them is an integer (non-zero) multiple of π/2. The obvious drawback of using MIMO related method is the associated increase in cost and dimension of the equipment, as multiple transmit and receive chains are required, and distance separation between antennas increases the overall sight footprint.

5.2.4. Modem parameters further practical considerations

The required bandwidth to achieve the throughputs which are green-coloured in Table 1 using a single carrier modem type of implementation is shown in Figure 2. The assumptions for this calculation are listed in Table 2.

From the conditions in Table 2, the CNR at the receiver can be calculated. The baud rate is 1/1.2 times of bandwidth assuming 20% of roll-of-factor. Also, assuming around 4 dB coding gain of FEC, the best modulation scheme (efficiency) can be selected. The throughputs are calculated from the baud rate, the payload rate, and modulation scheme (efficiency). The throughput is not proportional to the bandwidth since the bandwidth expansion causes SNR degradation. According to Figure 2, around 30 GHz bandwidth is necessary for over 100 Gbps. The 30 GHz bandwidth is available in 300 GHz-band. In the following discussion, 30 GHz bandwidth is assumed.

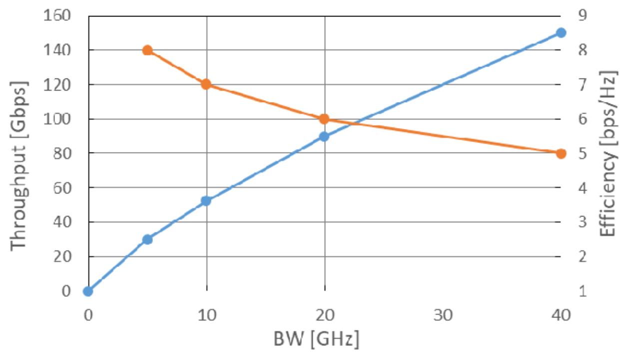

Figure 2 Bandwidth vs. Throughput for the best efficiency (single carrier modem)

Table 2 Assumptions for Throughput Calculation

Parameter	Value	Remarks
RF Frequency [GHz]	300	
Baud Rate [Gbaud]	BW/1.2	due to 20% roll-off, BW in GHz units
NF [dB]	10	T=300 K
TX Power [dBm]	10	
Link Distance [m]	1000	
Antenna Gain [dBi]	50	Common for both TX and RX
Payload Rate	0.9	Payload/Frame length

Currently, such a wide-band modem as described in Table 2 is not available since it requires ultra-high speed data converters (DAC, ADC) and a digital signal processor. A multi-carrier configuration, a combination of multiple current V or E-band modems can be applied to ThoR project by combining them together as an FDMA signal.

The total throughput is calculated as a summation of all of the individual single carrier modem throughputs. As a result, in the terahertz band, over 100 Gbps throughput can be achieved using available modems. For the scenario of identical TX-power, multi-carrier configuration combined via a single amplifier, the peak factor, i.e. ratio of peak power and average power (PAPR) increases. This increase is in the worst case (i.e. at a point where all the carriers have similar phase) proportional to the number of carriers. For example, in case of two carriers, the average power increases 3 dB, however the peak power increases 6 dB when the maximum amplitude appears for the both carriers at the same time. Therefore, the peak factor increases by 3 dB. This is the mathematical worst case. The time rate of the worst state is extremely small due to the randomness of the transmitted data. The TX power may have to be decreased as much as increase of the peak factor to maintain the same PAPR. The total throughput decreases as the TX power decreases. The results regarding this effect are shown in Figure 3. For all number of carriers, the total bandwidth of multi-carrier is equal to the one of a single carrier.

The decrease in throughput may seem counter-intuitive, but as we are considering a multi-carrier system which has single amplifier, and the bandwidth is fixed. The increase of number of carriers can reduce the digital circuit operational speed and the noise power in the receiver. This forces reducing the TX power which causes the throughput degradation.

The following is an example of calculation step in Figure 3 for 4 carriers.

i) To determine baud rate 6.25 GHz and TX power 4.0dBm (6 dB down from single carrier) from 30 GHz bandwidth and number of carriers 4.

ii) To calculate the CNR at the receiver by using link budget formulas. The conditions are listed in Table 7. The CNR = 21.8 dB.

iii) To select an appropriate modulation scheme for the CNR. Assuming an FEC with around 6 dB gain, 32QAM is suitable.

iv) To calculate the total throughput from the baud rate, efficiency, payload rate and the number of carrier. In this case, 67.5 Gbps can be obtained.

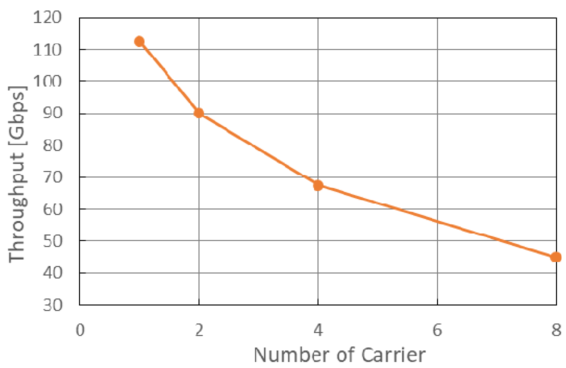

Figure 3 Number of Carrier vs. Throughput in Multi-carrier configuration

Moreover, the effects of the large phase noise of the LO signal on the BER are to be taken into account. The LO phase noise level in terahertz band is estimated around 10 dB larger phase noise than in E-band[2]. The modems have to suppress this phase noise sufficiently.

5.3. Radio propagation and antenna

At the frequency range around 300 GHz several 10s of GHz of bandwidth are available. This fact has been also the foundation for the development of IEEE Std. 802.15.3d [10], which addresses the spectrum between 252 GHz and 325 GHz. In the process of the development of [10] a channel model for backhaul/fronthaul has been proposed (TG3d Channel Model) [11], which has been used to evaluate the performance of the standard [12]. In this section we describe the approach from [12] with updated numbers corresponding to the approach we follow in ThoR. The section is organized as follows: In the following sub-section 5.3.1 the assumptions and models with respect to radio propagation and antennas made in [11] and [12] are described. Section 5.3.2 provides calculations of maximum achievable link distances and data rates for the possible transmission modes of IEEE Std. 802.15.3d.

[2] 20·log of the ratio between the frequencies

5.3.1. Assumptions and Models

For the development of the TG3d Channel model the following assumptions have been made:

- The mitigation of the high path loss at 300 GHz requires high gain antennas in the order of 40 dBi at both sides of the link
- Backhaul/fronthaul links require a LOS connection.
- The high gain antennas mentioned above are spatial filters, which suppress multi path propagation at large. Based on an evaluation in [13] on the minimum distance of objects to the line-of-sight link, the TG3d channel model assumes that a simple path loss model, which does not take into account any multi path propagation, is sufficient to evaluate the link budget[3]. According to [11] the overall path loss at a distance d and a carrier frequency f can be modelled as:

$$L/dB = 92.4 + 20\log d/km + 20\log f/GHz + (\gamma_0 + \gamma_w + \gamma_R + +\gamma_c)d/km \quad \textbf{(1)}$$

Where

γ_0: specific attenuation due to dry air (acc. to ITU − R P. 676 − 11)
γ_w: specific attenuation due to water vapour (acc. to ITU − R P. 676 − 11)
γ_R: specific attenuation due to rain (acc. to ITU − R P. 838 − 3)
γ_C: specific attenuation due to clouds and fog (acc. to ITU − R P. 840 − 6)

as defined in [14], [15] and [16].

For the description of the influence of weather conditions the TG3d Channel Modelling Document [11] contains seven models for Backhaul/Fronthaul as contained in Table 3. For each of these models a total specific attenuation at 300 GHz has been derived. According to Table 3 worst case values are in the order of 30 to 50 dB/km are achieved for situations, where the THz link crosses clouds or/and heavy rainfall.[4]

Table 3 Channel models taking into account weather conditions [11]

Channel Model Name	Description in *M.Rosker, Progress towards a THz imager, IMS 2007, Workshop WFE, „THz Device Characterization and security applications“, 8 June 2007, slide 5.*	Water vapour density $[g/m^3]$	Rain rate $[mm/h]$	Liquid water density in fog $[g/m^3]$	Liquid Water content of a cloud $[g/m^3]$	Total Specific Attenuation At 300 GHz $[dB/km]$
CM-BFH 1	Bangkok, temperature 35°C, relative humidity 90%	37.5	n/a	n/a	n/a	32,1
CM-BFH 2	Basra, temperature 43°C, relative humidity 30%, dust (10 m visibility)	28.2	n/a	0.5	n/a	27,8
CM-BFH 3	Berkeley, temperature 20°C, relative humidity 60%, fog (100m visibility)	10.5	n/a	0.14	n/a	9,5
CM-BFH 4	Bellingham, temperature 22°C, relative humidity 50%, rain ($4mm/h$)	9.8	4	n/a	n/a	10,5

[3] A key assumption for this is, that the applied antennas are required to have no side lobes which are attenuated by less than 30 dB compared to the main antenna lobe. The fulfilment of this and the conditions mentioned in [14] have to be checked during the planning process. ThoR will investigate this in WP5

[4] Please note, that the calculation for the specific attenuation due to dry air and water vapour is based on the most recent version of ITU-R 676-11 [14] different from the one in [11], which is based on the previous version ITU-R 676-10.

CM-BFH 5	Boulder, temperature 20°C, relative humidity 44%	8.6	n/a	n/a	n/a	5,8
CM-BFH 6	Buffalo, temperature -10°C, relative humidity 30%	0.5	n/a	n/a	n/a	0,4
CM-BFH 7	Boulder including clouds (100m of large cumulus clouds), temperature 20°C, relative humidity 44%	8.6	n/a	n/a	2.5	44,7
CM-BFH 1 with 50 mm/h rain	Bangkok, temperature 35°C, relative humidity 90%	37.5	50	n/a	n/a	51,1

5.3.2. Maximum Achievable Link Distances and Data Rates

The calculation of the maximum achievable link distance with IEEE Std. 802.15.3d is based on a transmit power of 65 dBm EIRP[5] , an Rx antenna gain of 55 dBi and the receiver sensitivity values listed in Table 4. The latter values have been derived by link level simulations and the SNR requirements for a BER of 10^{-12}.

Table 4 Receiver Sensitivity depending on MCS and bandwidth ([10], [12]); the values in bold mark those configurations, where 100 Gb/s are possible

MCS Identifier	Modulation	FEC Rate	Receiver Sensitivity / dBm depending on the bandwidth							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	-67	-64	-61	-59	-58	-56	-53	-52
1	BPSK	14/15	-63	-60	-57	-55	-54	-52	-49	-48
2	QPSK	11/15	-64	-61	-58	-56	-55	-53	-50	-49
3	QPSK	14/15	-60	-57	-54	-52	-51	-49	-46	-45
4	8-PSK	11/15	-59	-56	-53	-51	-50	-48	-45	**-44**
5	8-PSK	14/15	-57	-54	-51	-49	-48	-46	**-43**	**-42**
6	8-APSK	11/15	-59	-56	-53	-51	-50	-48	-45	**-44**
7	8-APSK	14/15	-57	-54	-51	-49	-48	-46	**-43**	**-42**
8	16-QAM	11/15	-57	-54	-51	-49	-48	-46	**-43**	**-42**
9	16-QAM	14/15	-53	-50	-47	-45	-44	-42	**-39**	**-38**
10	64-QAM	11/15	-52	-49	-46	-44	-43	-41	**-38**	**-36**
11	64-QAM	14/15	-47	-44	-41	-40	-38	**-36**	**-33**	**-32**

Under the further assumption of a 20 dB margin[6] for atmospheric attenuation due to weather conditions of 20 dB the maximum achievable link distances and data rates can be derived. The total path loss is assumed to be 20 dB higher compared to free space loss. The results are listed in Table 5.

[5] Achieved for example by 10 dBm output power of the transmitter and an antenna gain of 55 dBi

[6] The 20 dB margin

Table 5 Maximum achievable link distances; the values in bold mark those configurations, where 100 Gb/s are possible

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	5343	3778	2671	2181	1889	1542	1091	944
1	BPSK	14/15	3646	2578	1823	1488	1289	1052	744	644
2	QPSK	11/15	3796	2684	1898	1550	1342	1096	775	671
3	QPSK	14/15	2563	1812	1282	1046	906	740	523	**453**
4	8-PSK	11/15	2157	1525	1078	880	762	623	440	**381**
5	8-PSK	14/15	1725	1220	862	704	610	498	**352**	**305**
6	8-APSK	11/15	2157	1525	1078	880	762	623	440	**381**
7	8-APSK	14/15	1729	1223	864	706	611	499	**353**	**306**
8	16-QAM	11/15	1709	1209	855	698	604	493	**349**	**302**
9	16-QAM	14/15	1152	814	576	470	407	332	**235**	**204**
10	64-QAM	11/15	949	671	475	387	336	274	**194**	**168**
11	64-QAM	14/15	581	411	291	237	205	**168**	**119**	**103**

From the link distances the maximum allowed total specific attenuation to keep the total atmospheric attenuation within the 20 dB margin as assumed for the calculations in Table 5 can be calculated, see Table 6. The values in Table 6 can be compared with the values listed in Table 4Table 4. For example, to achieve a maximum distance of 581m with 64-QAM, a code rate of 14/15 and a bandwidth of 2.16 GHz a maximum specific attenuation of 34 dB/km is allowed, which roughly corresponds to the channel model CM-BFH 1 as defined in Table 3.

Table 6 Maximum allowable total attenuation ; the values in bold mark those configurations, where 100 Gb/s are possible

MCS Identifier	Modulation	FEC Rate	Maximum allowable specific attenuation due to weather conditions in dB/km							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	4	5	7	9	11	13	18	21
1	BPSK	14/15	5	8	11	13	16	19	27	31
2	QPSK	11/15	5	7	11	13	15	18	26	30
3	QPSK	14/15	8	11	16	19	22	27	38	**44**
4	8-PSK	11/15	9	13	19	23	26	32	45	**52**
5	8-PSK	14/15	12	16	23	28	33	40	**57**	**66**
6	8-APSK	11/15	9	13	19	23	26	32	45	**52**
7	8-APSK	14/15	12	16	23	28	33	40	**57**	**65**
8	16-QAM	11/15	12	17	23	29	33	41	**57**	**66**

MCS Identifier	Modulation	FEC Rate	Maximum allowable specific attenuation due to weather conditions in dB/km							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
9	16-QAM	14/15	17	25	35	43	49	60	**85**	**98**
10	64-QAM	11/15	21	30	42	52	60	73	**103**	**119**
11	64-QAM	14/15	34	49	69	84	97	**119**	**169**	**195**

5.4. Overall system view

To realize a wireless link with a carrier frequency of around 300 GHz, at least three types of functional blocks are required: data interface, baseband modem, and 300-GHz RF.

As discussed in 5.2.4. in this project, multiple modems, which operate in E-band or V-band, are employed for achieving a bandwidth of 30 GHz around carrier frequency of 300 GHz. The system makes use not of the modem, but the entire E-Band or V-band system as a part of terahertz system, as shown in Figure 4 below.

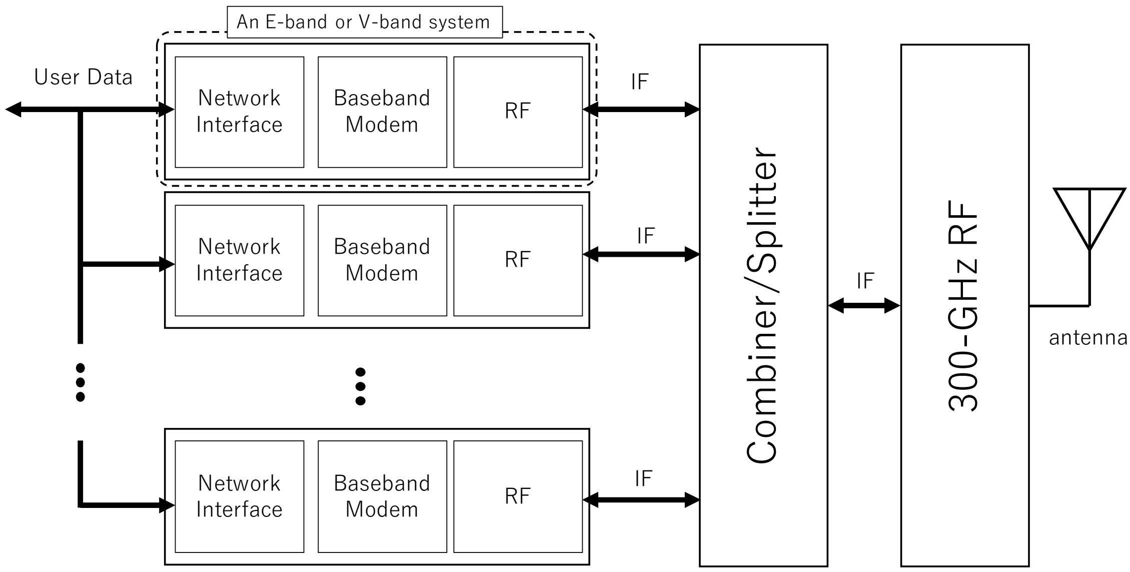

Figure 4 Functional System block diagram

RF output from the E-band or V- band system is treated as an intermediate frequency signal, then the signal is up-converted to the 300 GHz in the RF part. There exists a combiner and a splitter between E-band or V-band system and 300 GHz RF for combining multiple output from the modems. The strategy for changing frequency or controlling timing is discussed in the subsequent sections. Each of the E-band and V-band systems already have an industrial standard interface, such as 10G Ethernet for receiving and sending user data, these interfaces are also used for the data interface of the terahertz system. A data combiner or switch may also be employed to aggregate the channels.

For the V-band system, as shown in Figure 5, an IEEE 802.15.e compliant PHY/MAC chip exits, which includes a baseband modem, a 60-GHz RF transceiver and a 10 gigabit Ethernet interface, all employed for converting user data to a data frame transferred at 60 GHz. The PHY/MAC frame format and MAC control scheme are compatible with those of IEEE 802.15.d except for the carrier frequency. With adequate up-conversion and down-conversion, a wireless system compatible with IEEE 802.15.3d is easily implemented.

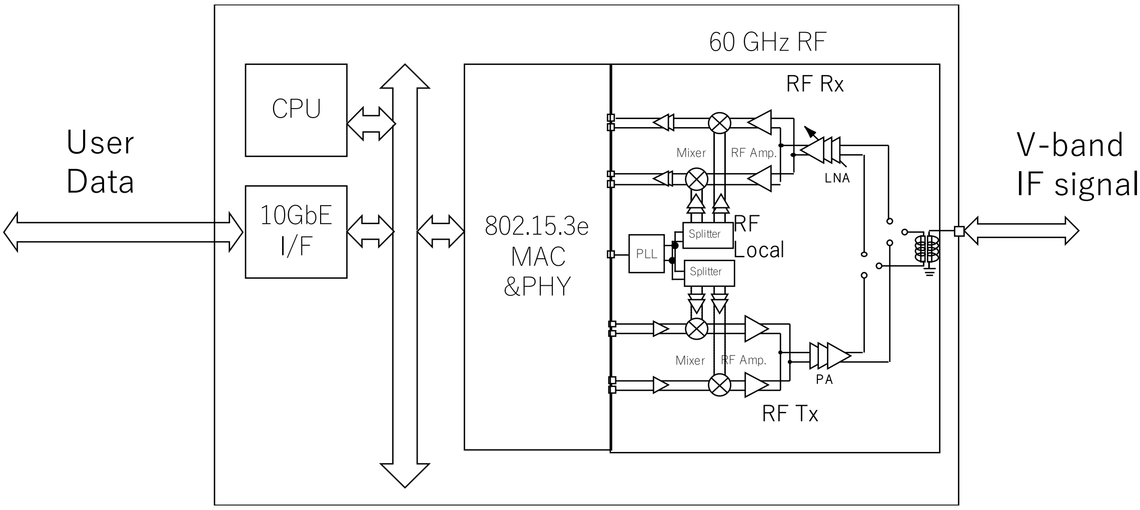

Figure 5 V-band system block diagram

6. System specifications

6.1. Interfaces and block diagram

Two variants of the system are proposed, one based on TDD operation, building on IEEE 802.15.3d compliant modem as described in 5.4, and another, based on FDD operation utilizing proprietary modems. The block diagrams for the systems based on both concepts are shown in Figure 6 and Figure 7.

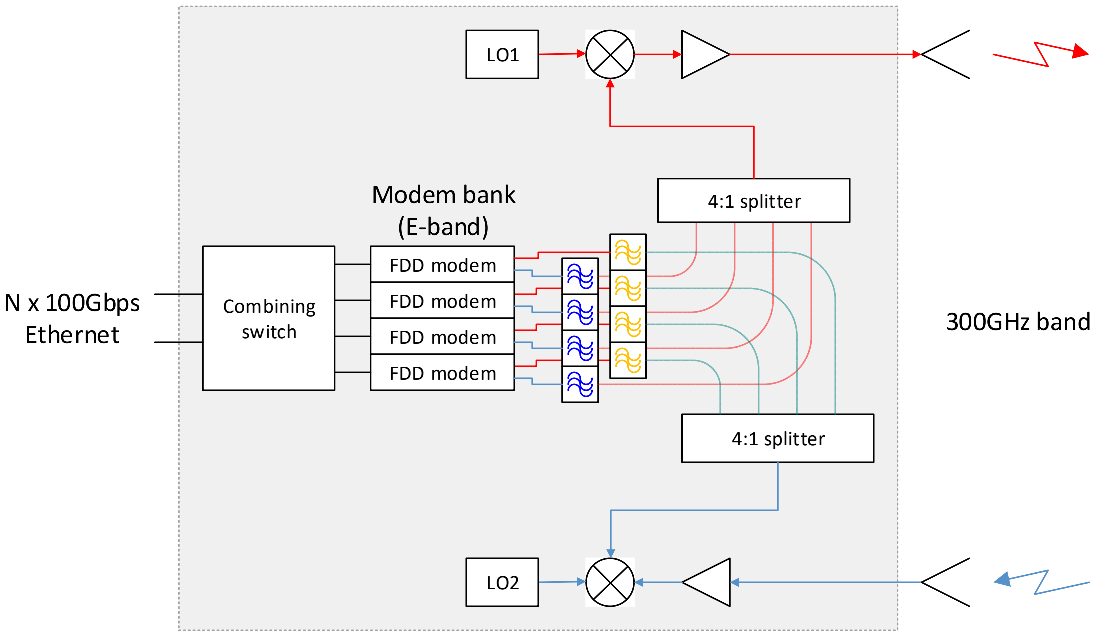

Figure 6 Block diagram of a system based on E-band FDD modem bank (4 channel example)

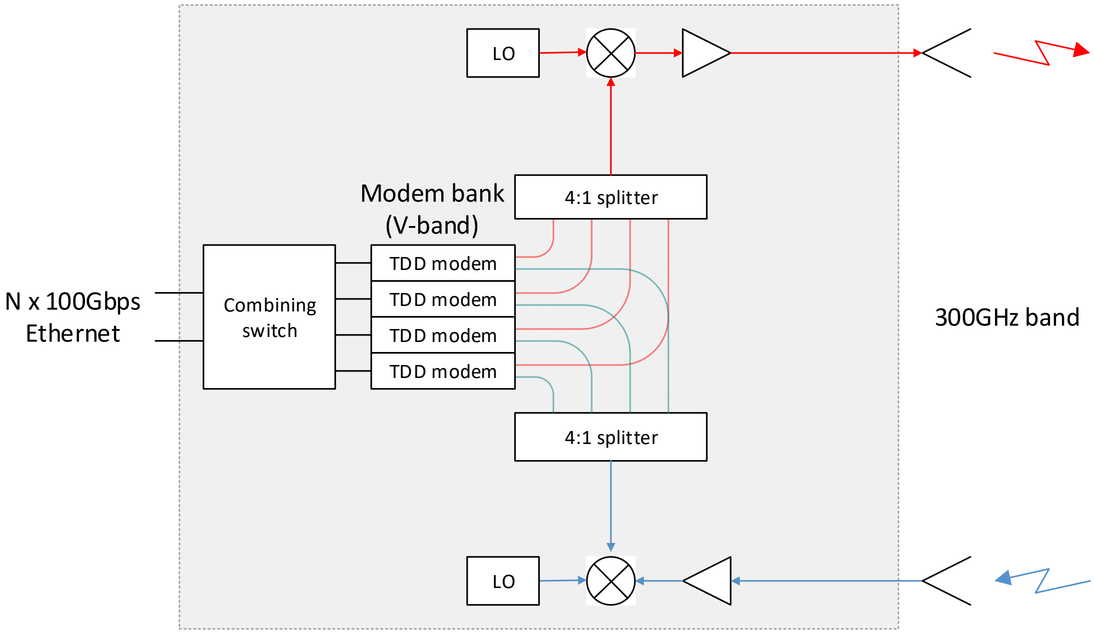

Figure 7 Block diagram of a system based on V-band TDD modem bank (4 channel example)

Both systems are based on the concept of multiplexing multiple narrow band channels together, and each is shown for the example of four parallel channels, but more channels could be aggregated if desired. The actual number of channels utilized for each system will be determined by the specification of V-band or E-band modem to be employed.

6.2. Frequencies scheme

The system modem devices typically work at baseband frequency where is easiest to sample wide band signals using available ADC/DAC devices. To utilize the system designated frequency band around 300 GHz a process of up-converting or down-converting the signal must be utilized. Such frequency translation is controlled by several considerations as summarized in the forthcoming subsections.

6.2.1. FDD vs. TDD operation

A bi-directional communication device typically contains a transmitter and a receiver in close proximity. The requirement from the transmitter and receiver are conflicting in the sense that the transmitter is typically required to produce as much RF power as possible, while the receiver is required to detect a very weak RF signal, close to the thermal noise floor. In such a scenario, the transmitter is likely to degrade the performance of the receiver. The typical remedy for this problem is to separate the transmitter and the receiver either in the time domain or in the frequency domain (or sometimes in both). For the purpose of defining the frequencies scheme, the time-division-duplex (TDD) mode of operation poses no constrains on the frequencies scheme, and typically, due to the consideration of efficient use of spectrum, the transmit and receive frequency will be set to be the same and all the isolation between transmitter and receiver is achieved by having them operate at different, non-overlapping periods. The frequency-division-duplex (FDD) mode of operation does pose constraints on the frequency scheme. The two main considerations are the amount of in-band power and amount of out-of-band power reaching the receiver, as illustrated in Figure 8.

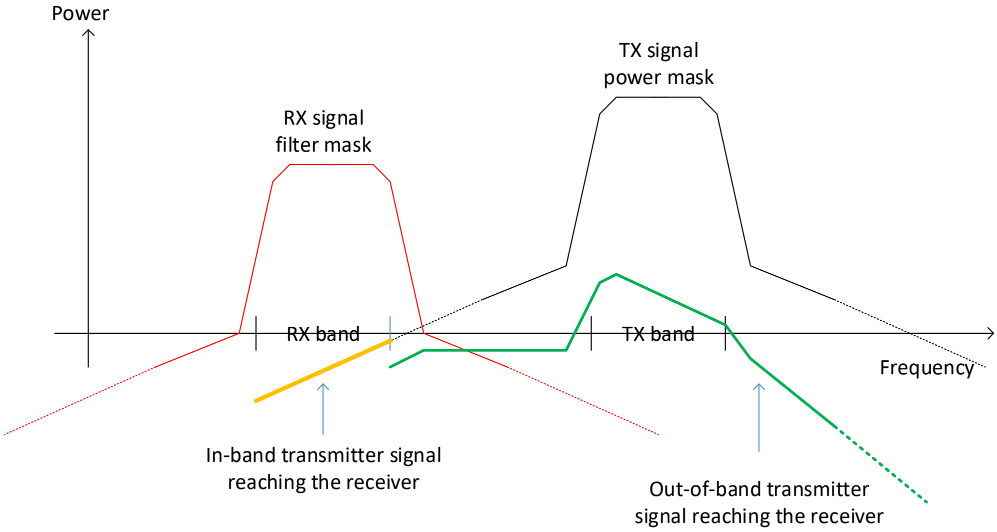

Figure 8 In-band and out-of-band power coupled from transmitter to receiver

The in-band power (depicted in orange) is a residue of the transmitter power (typically due to non-linearity) that falls under the receiver filter mask (and hence not rejected by the receiver) while out-of-band power (depicted in green) falls outside of the receiver filter mask (and hence rejected to a certain degree), but typically include the major component of the transmitter power. The consideration in FDD operation is therefore to keep sufficient separation between the transmit and receive band such that the suppression available by the receiver and transmitter filters is enough to prevent any degradation of the receiver operation due the transmitter. This consideration certainly applies to the designated RF band where the two signals couple via the antenna, but is often also relevant to any intermediate frequency band where coupling may exist due to leakages inside the radio hardware.

6.2.2. Conversion spurious products

A frequency conversion involves an input frequency band a desired output frequency band and an LO signal. However, the process of frequency conversion practically also produces spurious products. Such spurious products include the leakage of the LO to the output band and also the image band to the desired band [5]. In fact, not only these signals are present, but also a host of their harmonics and intermodulation signals. In the case of direct conversion from base-band to RF, the spurious products of the frequency translation process are usually of no concern and will be removed by front end filters, however, when the translation process involves on or more intermediate frequencies (IF), the selection of the frequencies to use during should take in account the position of these spurious products and ensure they are not conflicting or too close to the selected frequencies, and that there exists enough isolation between them.

6.2.3. Targeted frequency conversion scheme

For the purpose of the Thor project the indirect frequency conversion scheme is preferred (i.e. using an intermediate frequency) due to the lesser constraints it places on the 300 GHz RF components. Specifically, IF frequencies at V-band (57-66 GHz) and E-band (71-76 GHz to 81-86 GHz) are considered. The IF frequencies are preferred since there are commercially available components in these specific frequencies at reasonable cost. These frequency bands also offer relatively wide bandwidth and thus allow translation of a wide band signal through them. The V-band and E-band are used in a TDD and an FDD conversion scheme respectively, as each of the duplexing methods has its respective advantages. The target for the frequency scheme is also to simplify as possible the requirements of the RF components.

When using E-band as an IF frequency we may use the bands 71-76 GHz and 81-86 GHz each as TX and RX but preventing these channels from overlapping in the 300 GHz band. The frequency arrangement in Figure 9 is proposed. The figure depicts both ends of the wireless P2P link, one at the left side of the drawing and the other at the right side. In each side there are FDD modems using the band full band for TX and RX. The 71-76 GHz band and the 81-86 GHz band are combined/splitted in each side. The used frequency over the air consists of four sections with bandwidth of 5 GHz (highlighted in different colours). This arrangement is placed in the 300 GHz band (frequencies details are defined in [6]) and presents an efficient usage of the spectrum (no holes) and minimizes the flatness of response required from RF components.

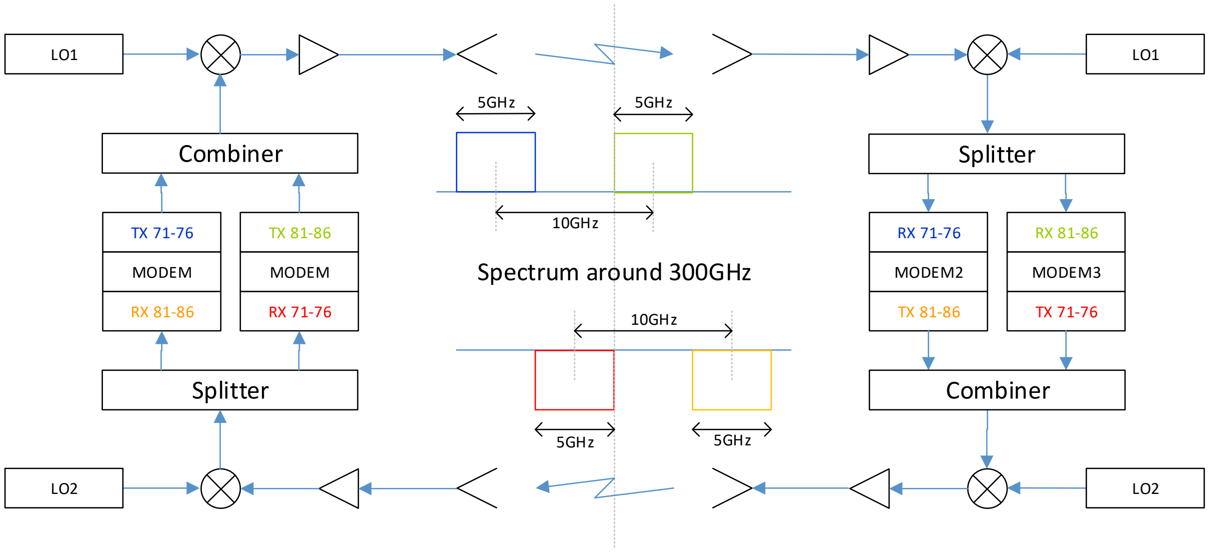

Figure 9 Frequency arrangement for E-band IF (FDD)

Figure 10 describes an example scheme using V-band as an IF frequency with a two V-band channel employed. Each V-band channel has 2.16 GHz of bandwidth and operates in TDD in within a channel. Required bandwidth in 300 GHz region shall be 4.32 GHz at least.

A gap between channels may be required for avoiding interference as these channels are not synchronized and because of the coupling in IF combiner or splitter as mentioned in 6.2.1.

In case more bandwidth is required, another set of V-band modem, Combiner and Splitter converted by LO with an offset of 4.32 GHz can be employed.

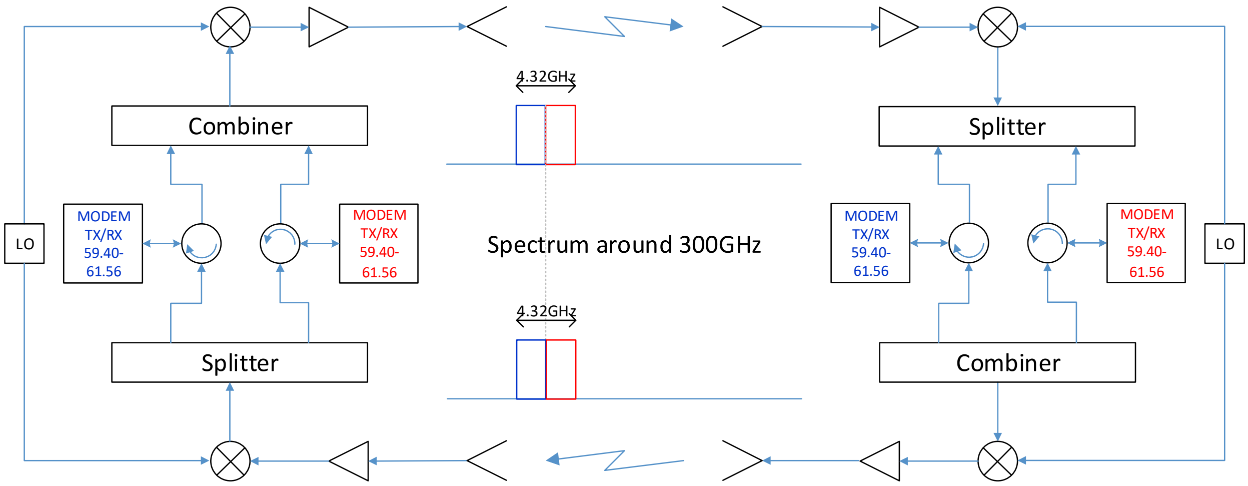

Figure 10 Frequency arrangement for V-band IF (TDD)

6.3. Throughput and range

The throughput and range of any terahertz system depends on many factors that are interacting with each other. As an example, given a certain transmit power budget, choosing to implement a wider band system will result in better throughput, but will also result in shorter distance, as the system will cope with higher receiver noise due to the larger bandwidth. Likewise, use of multiple narrow band carriers might improve the overall transmitted power (depends on implementation) but will also increase the signal PAPR which in turn will force reduced transmission power (again, depending on implementation). Therefore, in order to demonstrate the range of options, we shall specify the assumed operation parameters for various possible scenarios.

The conditions of the assumed system are shown in Table 7. We assume that all the implementations of the system use the same bandwidth, but the realization is done with a different number of sub-carriers (i.e. combined modem channels). We further assume that the combining is done prior to the PA, and thus needs to account for the increased signal PAPR. The throughput is calculated from the efficiency of appropriate modulation scheme for the realised CNR.

The calculation steps for the numbers in Table 8 are detailed as follows,

i) Determine TX power and noise power (N) at the receiver per carrier considering each bandwidth and peak factor. TX power is decreased 3dB for double number of carriers considering peak factor.

ii) Calculate the CNR at the receiver by using link budget formulas. The conditions are listed in Table 7. The CNR is (RSL – N) (in dB).

iii) Select an appropriate modulation scheme for the CNR assuming an FEC with around 6 dB gain. The criterion is theoretical CNR at BER = 1e-3 without FEC for each modulation scheme. RSL threshold can be determined from the required CNR for the selected modulation scheme. The system gain can be calculated as total TX power minus the RSL threshold (in dB).

iv) Calculate the total throughput from the spectral efficiency and total baud rate. The spectral efficiency in Table 8 includes modulation scheme, baud rate, and payload rate.

Table 7 Conditions for the throughput calculation

Item	Value	Remarks
RF Frequency [GHz]	300	
Total Bandwidth [GHz]	30	Occupied BW or Channel Separation
Total Baud Rate [Gbaud]	25	Assuming 20% BW expansion due to roll-off
Noise Power [dBm]	-59.8[7]	NF=10dB, T=300K
TX Power [dBm]	10	+30dBm with TWTA, TWTA gain assumed 20dB
Link Distance [m]	1000	
FSL [dB]	142.0	at 300GHz
Antenna Gain [dBi]	50	Common for both TX and RX
Payload Rate	0.9	Payload/Frame length
Number of Carrier	N	N=1 to 8

Table 8 Parameters for various numbers of carriers

Scenario	System gain (dB)	Backoff (dB)	RX C/N (dB)	Spectral efficiency (b/s/Hz)
1 sub-carrier, with TWTA	29.8	7	47.9	9.00
2 sub-carriers, with TWTA	32.9	10	44.9	8.25
4 sub-carriers, with TWTA	35.7	13	41.9	7.50
8 sub-carriers, with TWTA	38.7	16	38.9	6.75
1 sub-carrier, w/o TWTA	50.5	7	27.9	3.75
2 sub-carriers, w/o TWTA	53.4	10	24.9	3.00
4 sub-carriers, w/o TWTA	55.0	13	21.9	2.25
8 sub-carriers, w/o TWTA	60.1	16	18.9	1.50

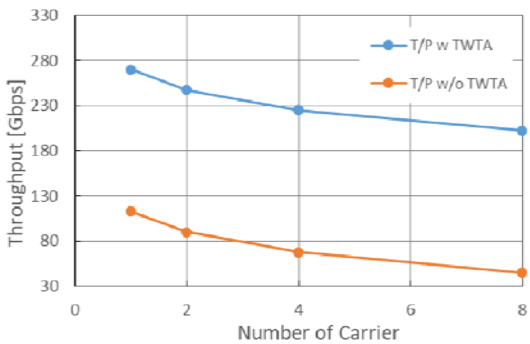

Figure 11 Calculation results of Throughput vs. Number of Carrier

The planned gain of TWTA is 20 dB. The calculated throughput increases due to this extra gain since SNR and consequently modulation order can be increased. However, this calculation assumes non-limited linearity and SNR in the receiver. Generally, it is difficult to achieve both more than 50 dB SNR and enough non-linearity for higher order QAM in the receiver. As a result, even with the TWTA, the total throughput does not increase since it would be limited by the SNR

[7] Calculated as per P_{Noise}(dB)=kTBF(dB) + NF(dB) with k=1.38e-23 [J/K], T=300 [K], B=25e9 [Hz], F=10 [dB]

in the receiver. On the other hand, TWTA has an effect to increase the RSL, and availability would be improved than a semiconductor amplifier. This is an important point considering rain-fall effect.

7. Summary and conclusions

In this document we have reviewed the expected increase in data traffic to support the requirement of 5G and beyond 5G cellular networks. We have further concluded that these modern cellular networks will also require densification, and thus multiple additional sites that will need to be connected to the network core. Fibre technology is capable of handling the traffic requirements of the application, but extending the fibre reach is a costly and a long endeavour.

We thus identified that there is a range of use cases that have throughput requirements ranging for several Gbps and up to close to 200 Gbps that can be catered by a wireless extension to the fibre infrastructure. Given that traditional wireless link using current V and E-band technology will not scale support the 5G and beyond requirements, we propose a new approach, utilizing the terahertz frequencies around 300GHz to realized such a wireless fibre extension.

The specification proceeds to define the conditions for realizing the wireless link in terms of the targeted spectrum and channel bandwidth and the propagation conditions. The targeted implementation is based on a modem bank combining approach with modems operating either in TDD fashion with IF at V-band spectrum or in FDD fashion with IF at E-band spectrum. The resulting multicarrier modulation is then analysed in terms of the throughput and range it may support based on the assumptions about the feasible radio components and propagation conditions known to exist in the target band.

8. References

[1] ITU-T/ITU-R, “5G roadmap challenges and opportunities ahead,” July 2017.

[2] A. H. Jafari, D. López-Pérez, H. Song, H. Claussen, L. Ho and J. Zhang, “Small cell backhaul: challenges and prospective solutions,” *EURASIP Journal on Wireless Communications and Networking,* December 2015.

[3] NGMN, “NGMN 5G Initiative White Paper v1.0,” 2015.

[4] P. Jurcik, Y. Leiba and R.-P. Braun, “Deliverable 2.1 Requirements for B5G backhaul/fronthaul,” 2018.

[5] D. M. K., Radio-frequency and microwave communication circuits analysis and design, Wiley, 2001.

[6] Y. Leiba and R. Timar, “Deliverable 3.2 Specifications for the 70-80 GHz TRX modules,” 2018.

[7] K. Kondou, “Deliverable 3.1 Specifications for the 60 GHz TRX modules,” 2018.

[8] A. J. PAULRAJ, D. A. GORE, R. U. NABAR and H. BÖLCSKEI, “An Overview of MIMO Communications — A Key to Gigabit Wireless,” *PROCEEDINGS OF THE IEEE,* pp. 198-218, FEBRUARY 2004.

[9] P. F. Driessen and G. Foschini, “On the capacity formula for multiple input-multiple,” *IEEE Trans. Commun.,* pp. 173-176, February 1999.

[10] IEEE, “Standard for High Data Rate Wireless Multi-Media Networks--Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer, " in IEEE Std 802.15.3d-2017 (Amendment to IEEE Std 802.15.3-2016 as amended by IEEE Std 802.15.3e-2017) , pp.1-55,” Oct. 18 2017.

[11] A. Fricke, I. Seto, K. Hiraga, T. Kürner, B. Peng, S. Rey, M. Yaita, H.-j. Song, A. Kasamatsu, I. Hosako, D. He, K. Guan, H. Ogawa, A. Bo, Z. Zhong, P. L. Bars and A. Mounir, “Channel Modeling Document (CMD),” [Online]. Available: https://mentor.ieee.org/802.15/dcn/14/15-14-0310-18-003d-channel-modeling-document.docx.

[12] T. Kürner, “Summary of Results from TG3d Link Level Simulations, doc. 802.15-17-0039-04-003d,” [Online]. Available: https://mentor.ieee.org/802.15/dcn/17/15-17-0039-04-003d-summary-of-results-from-tg3d-link-level-simulations.pdf.

[13] S. Rey, “Why/when is AWGN a suitable channel model for wireless front-/backhaul?, doc. 802.15-15-0681-01-003d,” [Online]. Available: https://mentor.ieee.org/802.15/dcn/15/15-15-0681-01-003d-why-when-is-awgn-a-suitable-channel-model-for-wireless-front-backhaul.pdf.

[14] ITU-R, “Rec. P.676-11, Attenuation by atmospheric gases,” 2016.

[15] ITU-R, “Rec. P.838-3, Specific attenuation for rain for use in prediction methods,” 2005.

[16] ITU-R, “Rec. P.840-6, Attenuation due to clouds and fog,” 2013.