Wireless Communication Systems in the 240 GHz Band: Applications, Feasibility and Challenges

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***Abstract*— The increasing demand for high data rates and the emergence of new data-hungry applications motivate the exploration of higher frequency bands for the beyond fifth generation (5G) wireless systems. The frequencies above 100 GHz, so-called terahertz (THz) spectrum, offer abundant communication bandwidth, hence enabling, in theory, terabit throughputs using small transceivers and, potentially, high energy efficiency. In this paper, we describe prospective applications and discuss challenges related to short-to-mid-range communication at these frequencies. Moreover, we present some initial results on the 240 GHz system and radio-frequency (RF) transceiver design, envisioned within the WORTECS project. We show that, for applications requiring short-range high-throughput data links, highly integrated THz wireless transceivers with low efficiency on-chip beam steering antennas can be used. These fully integrated transceivers set considerable limitations in terms of achievable data rate and communication distance. To overcome these limitations, in this paper, we propose different approaches, especially for short-range applications.**

Keywords—Terahertz, virtual reality (VR), beam steering, terabit, 240 GHz, WORTECS

I. Introduction

During past decades we are witnessing ever-growing demands for user data traffic. A 100 times increase in data traffic is projected over the next 10 years [1]. This increase in capacity can be achieved through network densification (i.e. small cell deployment, especially in urban areas), high spectral efficiency and more communication bandwidth (allocation of new spectrum bands). It is argued that low frequencies (Sub-6 GHz) are unlikely to deliver the demanded capacity increase due to interference and spectrum limitations. On the other hand, millimeter wave frequencies (30-300 GHz) allow the integration of beamforming techniques (i.e. phased arrays) in a smaller form-factor and offer wider, multi-GHz channel bandwidths, hence gigabit per second data rates. In 5G networks, 26 and 28 GHz bands are allocated for mobile access, whereas V-Band and E-Band are to be used for backhaul links. For beyond-5G and 6G systems, it is expected that new frequency bands need to be explored. More communication bandwidth is found at frequencies above 100 GHz, i.e. in the THz spectrum (0.1-10 THz). A plethora of applications has been already identified and new ones will certainly emerge demanding 100+ Gbps or even Tbps data rates [2]. Therefore, research community is advocating frequencies above 100 GHz to achieve such throughputs.

Similar to 5G networks, *wireless backhaul* is expected to be a potential bottleneck in beyond-5G networks. Since additional unutilized radio bandwidth is found at the frequencies above 100 GHz (i.e. 275+ GHz bands), THz link are deemed as a viable solution. Projects like ThoR [3], TERRANOVA [4] or ULTRAWAVE [5] are investigating the use of 300 GHz band for backhaul to support 100 Gbps throughputs, mainly because this spectrum is still unallocated. *THz hotspots*, also known as data showers, refers to deployment of THz access points (APs) in crowded areas. In these areas, users will be able to receive big chunks of data seamlessly. The project Fast Spot [6] is focusing on designing THz hotspots in trains. Another potential application for THz wireless links is in big data centers. Current data centers use dense and fixed wired fiber links between servers, which would become impractical beyond a certain scale and it is expected to be replaced with terabit wireless links in the future. *Wireless THz data centers* is the use case in the TERAPOD project [7]. In *board-to-board communication* or *chip-to-chip communication*, where very high data rates are to be expected, the board routing and mechanical connectors are seen as a bottleneck. For these reasons, THz wireless links have been proposed as a solution to communicate wirelessly between chips or boards directly, across a short range. *Kiosk downloading*, a data transfer system where a mobile device is connected to a fixed station, offering ultra-high speed downloads of multimedia-content, e.g. a movie, aims for use of THz band [8]. *Virtual* or *Augmented Reality* (VR or AR) is a scenario where high quality video should be projected in front of the user's eye with the help of a head-mounted display (HMD). The VR requires very high data rates (order of 20 Gbps and more) and very low latency (15 ms or less). Because of large communication bandwidth, THz links can be used. This application is a use case in the WORTECS project [9].

The rest of the paper is organized as follows: In Section II the WORTECS virtual reality use case with system overview is described. The related technical challenges are addressed in

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Section III, whereas envisioned approach, feasibility and initial results are presented in Section IV. Section V concludes the paper with the future work.

II. The WORTECS Project Virtual Reality Use Case

The WORTECS project focuses on a VR use case. In this use case, a number of users are gathered together in an empty room within the same VR scenario. The users are carrying VR HMDs, which are connected on a central VR system using a high throughput, low latency wireless connection. In this project this connection is triplicated, i.e. there is a THz connection, an optical wireless connection and a fiber wireless fiber connection. The optical wireless connection cannot achieve the required throughput, but it can be used as a redundant link in cases when the THz link is blocked or not available due to other reasons. An inter-Media Access Control (Inter-MAC) Layer2.5 is used to decide which link is going to be used for data transfer, based on the link quality [10].

To obtain excellent user experience, a high video resolution and high refresh rates (up to 120 Hz) are needed in the HMDs [11]. Video compression is usually employed, but it adds additional latency to the video, which introduces, so called, motion sickness. In WORTECS the overall latency (data transmission and data compression) is constrained to 3 ms. The low latency constraint requires low video compression ratios which, on the other hand, does not significantly reduce the required wireless throughput. These requirements were investigated within the WORTECS project, leading to wireless throughputs of 120 Gb/s [11].

A block diagram of the VR use case is shown in Fig. 1. The HMDs can be connected to the VR system using the three available wireless technologies. The Inter-MAC Layer2.5 (HetNet in Fig. 1), based on a link quality indicator (LQI), decides which technology is going to be used for a given user, when multiple connections are available. There is additional device, called LightHouse (see Fig. 1), which uses infrared lasers for estimation of the VR users' positions [12].

The current system requires the user to carry a laptop in a backpack introducing additional discomfort. To address this, the WORTECS project proposes a lightweight communication and positioning system that can be mounted on the HMD. This system should support high throughputs (up to Tbps) and high precision positioning, while at the same time being power efficient.

III. Challenges and Feasibility

In this section we address several challenges related to design of THz transceivers for high-speed data communication and user positioning in the context of VR.

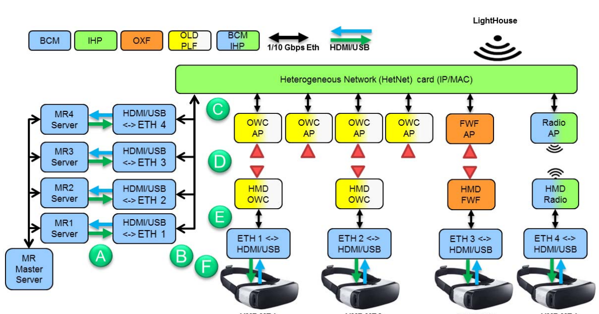


Fig. 1. The WORTECS VR system architecture.

The available *semiconductor technology* and the design of the transceiver determine the suitable frequency of operation. The current Complementary Metal-Oxide Semiconductor (CMOS) technology has limited f_t and f_{max} and, therefore, obtaining high output power is challenging. On the other hand, a high performance SiGe technology (e.g. IHP's 130 nm [13]) is able to deliver a higher output power at frequencies above 100 GHz, by sacrificing the transceiver efficiency. The IHP's SG13G2 technology has a reported f_t/f_{max} of 300/500 GHz. To have minimum current and power gain from the Heterojunction Bipolar Transistor (HBT), the frequency range 210-250 GHz is a suitable choice for the frequency of operation. With future enhancements in the SiGe technology [14], the frequency band 255-325 GHz standardized by IEEE.802.15.3d could be targeted as well. Further increase in the output power and improved transceiver power efficiency would be also possible.

THz links face several difficulties and challenges stemming from *propagation phenomena*. For indoor scenarios, like the VR scenario considered here, the main propagation phenomena is the free-space path loss (FSPL). For example, the FSPL is 94 dB at 5 meter distance at 240 GHz. The atmospheric attenuation at these frequencies can be up to a few dB/km, making it negligible compared to the FSPL. If no direct path is available, i.e. a Non-Line-of-Sight (NLoS) scenario, a reflected path can be used. In this case, additional attenuation can be expected due to scattering [15].

Given the aforementioned propagation phenomena, to achieve meaningful communication distances *high gain antennas* must be used. For instance, 25 dBi transmit and receive antenna gain is required to achieve a distance of 2 meters [16]. These solutions are bulky and only possible using, for instance, external high-gain horn antennas. Nevertheless, in this case, special attention should be paid when designing the interconnections between the RF electronics and antenna to reduce possible losses. A second solution is to use on-chip antennas integrated with RF electronics, which is possible thanks to the advances in silicon technologies. Such solution are interesting for applications requiring low to moderate distances. However, the design of on-chip antennas poses several challenges, such as low gains, low radiation efficiency, layout constrains due to metal density rules, on-wafer characterization, etc [17]. Typical on-chip antennas include dipole, loop, Yagi-Uda, slot antennas and their variations [17]. For example, an on-chip folded dipole at 240 GHz has 7.5 dBi gain and radiation efficiency of 75% [18], [19]. The small antenna gain constraints the system to short-range applications. The on-chip antennas are typically combined with lens antenna to boost the gain and increase communication distance [19], [20]. To further increase distance at THz frequencies, one can build an on-chip antenna array and, in this way, obtain the necessary beamforming gain.

Having a high gain antenna leads to a narrow antenna radiation pattern, or pencil beam, which makes the alignment of the beams between a transmitter and a receiver challenging. Alignment of narrow beams of two transceivers in two directions (azimuth and elevation) would require testing of high amount of possible combinations, which is a time consuming process. An alternative would be to perform a hierarchical *beam search*, but this would require changing of beam width, hence antenna gain, which would significantly reduce the useful communication distance.

TABLE I. LINK BUDGET, SNR AND POSSIBLE MODULATION FORMATS

No. elements in antenna array (azimuth × elevation)	16×2	16×1	8×2	8×1
TX Power [dBm]	22.5	19.5	19.5	16.5
TX antenna gain [dBi]	18	15	15	12
RX antenna gain [dBi]	18	15	15	12
FSPL @ 5m [dB]	94	94	94	94
RX power (10 GHz BW) [dBm]	-35.5	-44.5	-44.5	-53.5
Noise floor [dBm]	-74	-74	-74	-74
Receiver Noise Figure [dB]	15	15	15	15
Implementation loss [dB]	5	5	5	5
SNR [dB]	18.5	9.5	9.5	0.5
Possible modulations (@BER = 10^{-3})	16QAM QPSK BPSK	QPSK BPSK	QPSK BPSK	/

Regarding the *baseband (BB) processing*, the first issue one can encounter is associated with the signal generation and acquisition. Generation and acquisition of signals having bandwidths larger than a few GHz is challenging, especially if it should be low power. There are a few data converters on the market supporting these bandwidths, but not fulfilling the low power requirement. The second issue is the processing speed of the BB processor. Nevertheless, there are already available parallel approaches for achieving multi-gigabit throughputs.

One important parameter to bear in mind is the *energy consumption*. The THz systems or devices are to be used in battery-powered devices too. Such systems should be operating within a predefined energy limits. A typical mobile device should consume about 1 W of power, i.e. an energy per bit of around 10-100 pJ/bit for data rates of tens to one-hundred Gbps. This energy consumption refers to a full transceiver, meaning an RF transceiver, BB and MAC processors. If the power is divided equally among these parts, an RF transceiver would consume around 333 mW. This is considerably less than currently available RF front-ends reported in the literature. For example, the RF transceiver in [21] consumes 1.2 W with -4 dBm output power. In [19], the transmitter consumes 0.375 W while the receiver consumes 575 mW corresponding to 15 pJ/bit and 23 pJ/bit, respectively, without taking the BB and MAC processors into account.

Finally, *precise localization* of the user is also a challenge in the WORTECS project. At the moment, a special laser system is usually used for precise positioning. Using the Sub-6 GHz bands for precise positioning is not possible due to the limited bandwidth, which limits the positioning precision to more than 1 meter. On the other hand, the THz band offers huge bandwidth, opening new opportunities for high, sub-centimeter, precision positioning.

IV. APPROACH, SOLUTIONS AND INITIAL RESULTS

In the WORTECS project, many of the mentioned challenges are addressed. The main limitation was imposed by the limited output power as well as the high FSPL. Starting from the link budget and considering the current technology constraints, a few different configurations were chosen as favorable. In Table I, the available link budget and signal-to-noise (SNR) ratios are shown. The maximum expected bandwidth of the developed analog front-end (AFE), according to the performed simulations is about 17 GHz.

A. Analog Front-End for 240 GHz

The AFE developed in the WORTECS project can be divided into several sections, starting with carrier signal generation, the up and down converters, power amplification and phase shifting (or beam steering), completing the overall beam steering chip set.

Sub-THz carrier generation: The sub-THz carrier signal is generated on chip to avoid interfaces at such high frequencies. The frequency multiplier-by-N chains promise broadband operation allowing the utilization of a commercial of-the-shelf frequency source. A 40 GHz multiplier-by-8 LO chain was developed, multiplying a 30 GHz signal to generate the 240 GHz carrier. A 0 dBm of output power with drain efficiency of 0.4% is achieved [22].

Single phase transmitter and receiver: A direct conversion architecture promises wideband operation and reduced power consumption. Hence, a direct conversion transmitter and receiver were designed utilizing a single mixer as a first step to demonstrate BPSK modulation transmission. The transmitter and the receiver are integrated with the LO chain and on-chip antenna in a single chip, realizing a fully integrated transceiver (see Fig. 2). Data rates up to 25 Gb/s are demonstrated across 15 cm link distance, as an initial step toward the targeted system [19].

Power amplification: To achieve the required system specification the transmitted power per element needs to be increased. Therefore, a 4-way power amplifier was designed with zero-degree power combining. The PA achieves an output 1-dB compression point of 10.5 dBm across 55 GHz of 3-dB bandwidth [23].

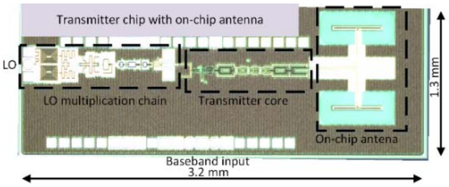
Vector modulator: To perform beam steering, the phase of each element needs to be controlled. The vector modulator allows for a more flexible resolution when compared to a digital phase shifter. In this work, a wideband vector modulator is utilized with a simulated root-mean-square phase error of less than 3 degrees.

Beam steering chip: By integrating several vector modulators on the same chip and several chips on the same board, a large-scale phased-array system can be built, using a modular approach. The routing of the LO to the different chips must be symmetric to assure the synchronization of the different antenna elements.

B. Phased Antenna Array

As discussed previously, high gain antennas are needed to achieve the necessary link budget. Since the user is moving, usually a few antennas pointing to different directions would be required. Lightweight on-chip antennas can be positioned on different sides of the HMD. With this approach, the user would always have a high-speed THz link, independently of the direction in which the HMD is pointing. The multiple antennas on the HMD can be used to gain diversity, using a single modem, or for each of them, a separate modem making multiple redundant links can be deployed. The envisioned Inter-MAC Layer2.5 can select one of these links based on the LQI.

In WORTECS, an on-chip phased antenna array is being developed. The configurations being investigated are 8×1, 16×1, 8×2 and 16×2 (see Table 1) antenna elements. The main approach would be to produce chips with, for example, 4 antennas and to mount them on a carrier in order to build the required arrays. According to Fig. 3 all of the elements would be connected to independent phase shifters. This would enable two dimensional (elevation and azimuth) steering for the 8×2 and 16×2 antenna configurations.



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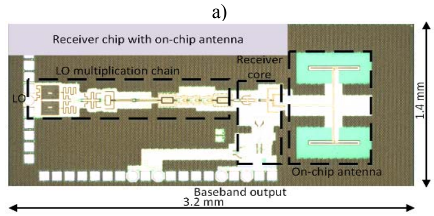
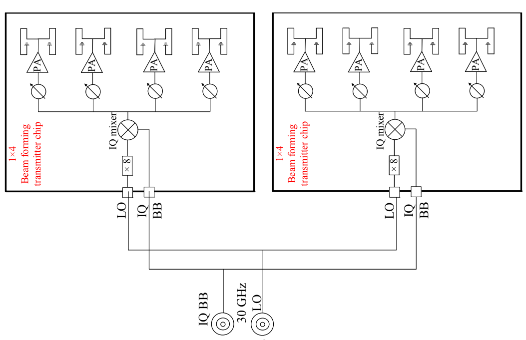


b)

Fig. 2. Die photo of a) transmitter, and b) receiver with an on-chip antenna [19].

The radiation patterns and the antenna gains were approximately estimated in MATLAB. A toolbox called ArrayCalc [24] was used for this purpose. This toolbox uses ideal antenna elements and calculates the phased antenna array gain as well as the radiation pattern. It does not take into account the feeding structures as well as the non-idealities of a real antenna.

In Table I, the available link budget and the possible modulation formats for different antenna arrays are given. The preferred solution would be the 16×1 array, since it has a 3 dB beam width of approximately 60 degrees in the elevation plane. This would cover all the needed elevations in the VR scenario. The antenna array has a 3 dB beam width of approximately 6 degrees in the azimuth plane. The radiation pattern is shown in Fig. 4. The beam steering would be performed only in the azimuth plane. The array with 16×2 elements allows using 16QAM, but due to the narrower radiation pattern in the elevation plane, two-dimensional beam steering must be performed.



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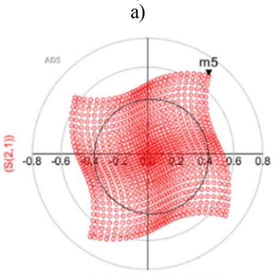

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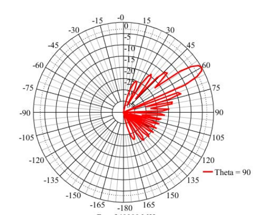
Fig. 3. a) Beamforming phased array transmitter, b) simulated phase plot of the vector modulator at 240 GHz.

C. Modulation Coding Schemes and BB Processing

Typical wireless communication systems designed to operate at THz frequencies use on-off keying (OOK) modulation. The use of OOK simplifies the BB processing as well the interface to the RF front-end. With the OOK it is sufficient to use 1-bit analog-to-digital converters (ADC), hence supporting the large signal bandwidth. However, the OOK has low spectral efficiency of 0.5 b/s/Hz, making it difficult to achieve more than 10 Gb/s over a 10 GHz bandwidth. For that reason, it is necessary to use modulation schemes with higher spectral efficiency (for instance BPSK – 1 b/s/Hz, QPSK – 2 b/s/Hz, 16QAM – 4 b/s/Hz).

As given in Table I, the maximum communication distance is 5 meter for the VR scenario. The FSPL equals 94 dB at the carrier frequency of 240 GHz. With the phased array system (16×1), the realized SNR is 9.5 dB accounting for an implementation loss of 5 dB and a noise figure of the receiver of 15 dB. Targeting an uncoded bit-error-rate (BER) of 10^{-3}, the required SNR is 7 dB for BPSK and QPSK. With strong forward error correction (FEC), such as turbo or LDPC code, it is possible to reach a coded BER of 10^{-6}. However, complex modulation formats as the one mentioned above require high-bit resolution digital-to-analog converters (DACs) and ADCs with large signal bandwidths. This makes the transceiver design extremely challenging, when ADCs with more than 10 GHz bandwidth are required. Although use of time-interleaved solutions (e.g. 6-bit ADC with 20 GSps [25]) makes single transceiver solution viable, its main limitation is the high power consumption and the low bit resolution (limiting the usable modulation schemes). This can be resolved by using frequency-interleaved (FI) transmitter and receiver, as the one reported in [26]. One can build a large bandwidth signal by combining several smaller bandwidth (2-3 GHz) signals by frequency division multiplexing (FDM). Therefore, with 4 sets of data converters supporting 3 GHz each, a bandwidth of more than 10 GHz can be covered. This is realistic since the newest RF System-on-Chip (RFSoC) solutions from Xilinx [27] have multiple data converters (up to 8) with these specifications. Furthermore, each small bandwidth signal can be processed by independent BB core, making the effective noise floor per FDM channel 10 dB lower than the one given in Table I.



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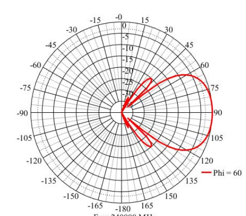

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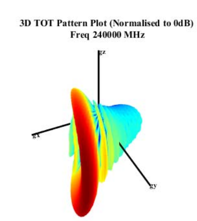

c)

Fig. 4. Radiation patterns of a 16×1 antenna array in a) azimuth and b) elevation. c) 3D radiation plot.

D. *Precise User Positioning using THz Frequencies*

In VR scenarios, it is of paramount importance to know the position and the orientation of the users. The VR system must know the positions of the users to render the scene as well as to process the user interactions.

The LightHouse is a typical solution, which gives excellent precision, but also introduces additional complexity in the system. To reduce the complexity of the overall system, in the WORTECS project, the same radio interface used for the high throughput data transmission is used for positioning. The system would use a two-way-ranging (TWR) procedure to measure the distances from the access points to the users. A TWR system achieving a ranging precision of less than 5 mm has been developed and reported in [28]. This system utilized a bandwidth of 1 GHz and was tested in the 60 GHz band. The same approach will be used in the THz band when the THz AFE chips become available. A higher precision is expected to be reached in the THz band given the larger bandwidths available, according to the Cramér-Rao lower bound [29].

V. Conclusion and Future Work

In this paper we presented part of the tasks in the WORTECS project that are in the domain of the THz communications. Within the project, a THz wireless transceiver is being developed and the first measurements of the building blocks are already finished. The used SiGe-BiCMOS technology shows that significant output power can be achieved. Combined with the simulated phased array antennas, the system would fit perfectly for the VR scenario.

The further work would be mainly focused on finalizing the complete AFE, building the modular phased antenna array, finishing the baseband processor, as well as, integration of the overall system.

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