Towards Energy-Efficient High-Speed THz Communications Links

N. Llombart[1], M. Alonso-delPino[1], A. Bechrakis Triantafyllos[1], H. Zhang[1], D. Cavallo[1], M. Spirito[1], M. Dörpinghaus[2], D. Swist[2], H. Zirath[3], F. Strömbeck[3], Y. Yan[3], V. Vassilev[3], M. Mollaalipouramiri[3], G. Lasser[3], F. Dielacher[4], K. Aufinger[4], K. Konstantinos[5], P. Aghdam[6], W.-C. Liao[6], S. An[6]

[1]Delft University of Technology, The Netherlands
[2]Technische Universität Dresden, Germany
[3]Chalmers University of Technology, Sweden
[4]Infineon Technologies, Germany
[5]OTE, Greece
[6]Ericsson, Sweden

***Abstract* — The THz spectrum is being explored due to its inherent large bandwidth to fulfill the throughput requirements for future wireless systems. However, there are intrinsic challenges for the exploitation of this spectrum for wireless communications, particularly concerning current technological capabilities. Moreover, it remains a big question if THz systems can be made efficient. In this contribution, we present a system analysis to show the potential of overcoming these challenges using quasi-optical antennas integrated with wideband SiGe-BiCMOS electronics and a suitable baseband design that can lead to the Tbit/sec and energy-efficient wireless transmission.**

***Keywords* — communications, THz technology, BiCMOS, antennas, signal processing, wireless backhaul, wireless link.**

I. INTRODUCTION

THz communications are becoming increasingly attractive [1] due to several driving factors: growing demand for higher data rates and bandwidth driven by applications like high-definition video streaming, virtual reality, and the Internet of Things, and the spectrum congestion at low frequency bands. THz communications can support ultra-high-speed data transfer rates, which are essential for future applications such as real-time data processing and the support of future advanced 6G applications and services. In particular, THz communications can enable wireless fronthaul and backhaul, reducing the need for expensive fiber-optic infrastructure. In addition, THz-based wireless links can be set up much faster than fiber-optic links, enabling faster expansion of existing 5G networks and faster rollout of future 6G networks, particularly in areas where existing fiber is sparse or too costly to install. Moreover, the development of future 6G networks will benefit from technological solutions that are energy efficient.

In recent years, significant research effort has been directed towards the area of THz communications and several system demonstrations have been realized. Two main research directions have been pursued in these demonstrations, employing either all-electronics or photonic-assisted front ends. Compared to the photonic-assisted systems, electronic-based systems can fulfill all the required signal-handling processes in electronic circuits and are more suitable in terms of monolithic integrability and the potential for mass production. Table 1 summarizes the most relevant key demonstrations of THz wireless links available in the literature showing the potential of 100 Gbps data rate using far-field links. Photonic-based demonstrations [2], [3] show overall larger capacity and bandwidth compared to the electronic-based ones [4]-[6]. The most recent work even achieved 220 Gbps capacity at a medium range [3]. However, all demonstrations present low/moderate radiated energy efficiencies. Larger radiated energy efficiencies were achieved in [6], but the distance is only 3 m.

In this contribution, we present the results of simulated link performance using key emerging technologies: new 90 nm SiGe-BiCMOS processes capable of cut-off frequencies reaching 500 GHz, quasi-optical (QO) antennas for radiative near-field links enabling high power transfers for medium range links [7], and wide-band zero-crossing modulation enabling energy-efficient communication [8]. The estimated link performance is compared to the state of the art in Table 1.

Table 1. State-of-the-art THz link performance at H-band.

Cap. [Gbps]	Dist. [m]	B [GHz]	Spec. eff. [Bit/s/Hz]	Rad. eff. [Tbit/J]	[Ref]
125	104	30	4.2	627	[2] Pho.
220	214	47	4.7	2200	[3] Pho.
128	500	40	3.2	322	[4] GaAs
110	1	26	4.2	13	[5] Si.
120	3	20	6	5000	[6] GaAs
230	280	50	4.6	5100	This work (Si.)

II. MAIN USE CASES FOR THZ LOS LINKS

The journey from 5G to 6G represents a significant leap in mobile communication technology, building on the foundational advancements of 5G while addressing new and emerging demands for connectivity. The path to 6G will be marked by the exploration of new spectrum ranges, including the use of THz frequencies, which can enable unprecedented bandwidth and communication capacity [9]. In particular, THz LoS wireless systems can serve as a complete fronthaul-backhaul solution for small-cell dense urban networks and for purpose-built fixed wireless access applications where backhaul capacity will be in the range of 200-1000 Gbps.

However, future 6G networks will prioritize sustainability with energy-efficient solutions. Therefore, in this effort, we are aiming to develop energy-efficient technologies, to enable the densification of cells in a cost-effective, power-friendly and eco-friendly manner. As a first step, we outlined four identified use cases:

Fronthaul in ultra-dense small cell networks: The main critical challenge is providing energy-efficient and high-capacity fronthaul solutions. Small cells are essential for delivering high data rates and low latency in 6G networks, especially in dense urban environments. However, the fronthaul links must handle massive amounts of data traffic. THz-based solutions offer ultra-high bandwidth for these fronthaul links, ensuring seamless communication while significantly reducing energy consumption. The targeted distances here are 50-200m, with peak data rates reaching terabit-per-second (Tbps).

High throughput fixed wireless access (FWA): The goal here focuses on delivering ultra-fast, energy-efficient internet connectivity to homes, businesses, and remote areas. By leveraging THz spectrum, we aim at multi-Gbps data rates, allowing users to experience fibre-like speeds wirelessly without the need for costly deployment. The targeted distances here are 50-1000m, with peak data rates reaching Tbps.

Live immersive XR in large-scale events: The goal here focuses on delivering seamless, high-bandwidth backhaul solutions that enable participants to interact in real-time with virtual elements, no matter the scale of the audience. Using THz communication, ultra-low latency, ultra-high capacity , and high data rates that are required to support immersive technologies such as augmented reality and virtual reality at events like concerts, sports events, or conferences can be achieved wirelessly. The targeted distances are up to 100m with peak data rates reaching Tbps.

Wireless data centres: With increasing demands of cloud computing, AI, and big data analytics, traditional wired infrastructure can become a bottleneck in speed, flexibility, and energy consumption. THz spectrum offers ultra-high throughput, low-latency wireless links that can replace fibre-optic connections within data centres, enabling faster data transmission between servers, storage units, and other critical components. The targeted distances here are up to 10m with peak data rates reaching Tbps.

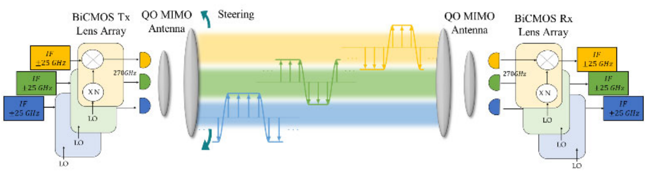

Fig. 1. Conceptual drawing of the proposed THz wireless LoS system.

III. Proposed System Architecture and Key Technologies

In this work, we aim at developing energy-efficient THz systems for point-to-point wireless links with capacities of 200 Gbps to 1 Tbps that will pave the way for even higher data rates. The proposed system architecture is shown in Fig. 1. The system converts information into modulated signals spanning large bandwidths (50 GHz) using energy-efficient modulation schemes. These signals are then transmitted through a QO link with minimal over-the-air energy spreading and are up- and down-converted by low-power consumption silicon transceivers. To reach even higher data rates, polarization and MIMO multiplexing techniques are introduced. In the following, these key technologies are detailed together with the simulated performances.

A. Low Power Silicon-Based Front-end Circuits at H-band

The block diagrams of the proposed THz transmitter and receiver architectures for each channel are shown in Fig. 2, similar to those in [10]. The key components to be integrated on chip are a low-noise amplifier, a frequency mixer i.e. I-Q modulator and demodulator, frequency multipliers for the local oscillator signal, and a power amplifier. The LO-multiplication factor is chosen to be $\times 8$ as the main target. The LO-input frequency at the chip is then of the order 25-33 GHz. The targeted baseband bandwidth for the I and Q-channel is of the order 25-30 GHz. This translates to an instantaneous RF-bandwidth of 50-60 GHz. The simulated noise figure is F=10-15 dB in the H-band and the output power can be tuned from -26.5 dBm to 3 dBm. The low output power levels are targeted in order to reach high radiated energy efficiency when transmitting data, while the high power levels are targeted to enable the link alignment and give a link budget margin for potential negative effects on the SNR. The estimated DC consumption for the amplifiers in these transceivers is in the order of 30-150 mW depending on the architecture, gain, and output power.

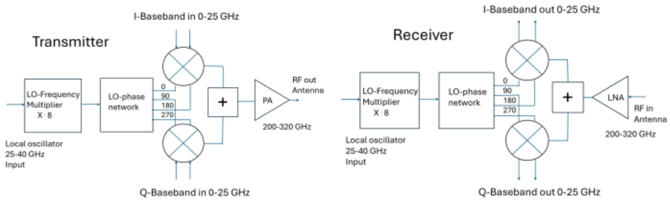

Fig. 2. Transmitter and receiver circuit architecture

B. Energy-Efficient Radiative Near-Field Links

We aim at using QO links [7] that minimize energy spread in free space, enabling reduction of radiated energy levels by a factor of 1000 compared to existing 5G solutions. These links are based on QO antennas with ultra-high gain and precise alignment capabilities to mitigate the high free-space path loss inherent in THz frequencies. As an illustrative case, the link coupling at 290 GHz is presented in Fig. 3(a) versus link distance for different diameters. On top of these coupling curves, the coefficients derived directly from the Friis equation are also plotted. As illustrated, operating a wireless link in the radiative near-field can lead to power spreading loss of only a few dBs for distances in the hundreds of meters, enabling wireless systems with low levels of transmitted power. To achieve this, depending on the link distance and the examined frequency, a sufficiently electrically large primary aperture is required.

One crucial aspect in the operation of point-to-point links refers to maintaining good alignment between the transmitting and receiving antennas. This is especially important for cases that employ electrically large and thus directive antennas. Indicatively, a 0.5 m radiating aperture corresponds to roughly 480 λ_0 at 290 GHz and features a half-power beamwidth of 0.12^o (λ_0/D) for a uniform aperture field distribution. This implies that even very small angular misalignments can lead to a significant degradation in the power transfer over the link.

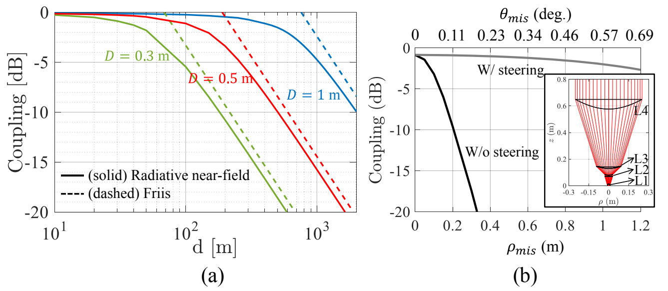

Fig. 3. (a) Power transfer efficiency vs. link distance and aperture diameter. (b) Simulated coupling efficiency (290 GHz) at 100 m versus misalignment distance/angle. Inset is the geometry of the proposed multi-lens QO system.

C. Energy-Efficient Modulation

High bandwidth at the baseband typically calls for high-speed high-resolution ADCs. However, studies have shown that ADC power dissipation strongly surges with increasing sampling frequency required for analog-to-digital conversion of high-bandwidth signals [11], especially when high amplitude resolution is desired. In contrast to low sampling rates, the power dissipation grows quadratically with the sampling frequency above approximately 300 MHz. Moreover, the power consumption grows exponentially with the amplitude resolution in terms of the number of bits, posing a severe energy bottleneck obstructing wide deployment and implementation of very high bandwidth systems. To mitigate the problem of excessively high power consumption of high-resolution ADCs at high sampling frequencies, a promising approach is to use 1-bit quantization with temporal oversampling w.r.t. the signal bandwidth at the receiver. As such a receiver based on temporally oversampled 1-bit quantization can only resolve the sign of the received signal, the information has to be encoded in the temporal distances of the zero-crossings. In this regard we consider a novel modulation scheme denoted as zero-crossing modulation (ZXM) [8] which can be realized by using a combination of runlength coding and faster-than-Nyquist (FTN) signalling [12]. The achievable rate of ZXM strongly depends on the FTN signalling factor M_{tx}. With increasing M_{tx} the resolution of the time grid on which the zero-crossings can be placed increases enabling increasing achievable data rates. To resolve these zero-crossing time instants the sampling rate of the 1-bit ADC at the receiver side has to be chosen accordingly, requiring an oversampling factor $M_{rx} > M_{tx}$ w.r.t. Nyquist rate sampling. For such a zero-crossing modulation a finite state machine based runlength coding scheme has been proposed and the achievable spectral efficiency depending on the FTN signalling rate M_{tx} and the SNR at the receiver input has been evaluated in [13].

To achieve a desired data rate given a fixed bandwidth, the conditions for a certain spectral efficiency need to be met. Let us consider a 200 Gbps link at a 50 GHz RF signal bandwidth. Considering two available spatial channels (e.g. polarization), the required goodput is 2 bit/s/Hz per polarization domain, which can be achieved using an FTN signalling factor M_{tx}=2 [13]. Considering a 5G NR LDPC code with a code rate R_{FEC} =8/9 the minimum required receive SNR can be determined to be 14 dB [13]. Choosing other code rates could reduce SNR requirements. However, as no losses due to imperfect implementation, synchronization or other distortions like phase noise etc. are considered here, the choice of R_{FEC}=8/9 leaves a margin for practical realization.

Using literature-based power consumption models for the DAC and the ADC [14] for the desired system parameters M_{tx}=M_{rx}=2, bADC=1, and B=50 GHz the estimated power consumption of a single DAC and a single ADC are P_{DAC}=0.9W and P_{ADC}=12 mW, respectively.

D. Quasi-Optical Antennas

To realize even higher data rates, we can use polarization multiplexing and MIMO techniques. For radiative near-field wireless links, the statistical impact of the channel can be neglected. The multiplexing can therefore be realized directly via dual-polarized antennas and lens arrays. The main challenge in THz antenna designs is maintaining high radiation efficiency over a wide bandwidth. To adhere to this requirement, highly integrated solutions are favoured at these frequencies that minimize the loss associated with transitions in and out of the silicon chip. The challenges are even more stringent when aiming at dual polarized designs and arrays. Indeed, little work has been reported on dual polarized on-chip antennas at 300 GHz [5]. To benefit from the multiple metal layers available in BiCMOS technology, we have designed a dual-polarized antenna on-chip and integrate it with two Tx and two Rx front-ends. The proposed antenna is shown in Fig. 4 and was described in detail in [15]. Simulations indicate low levels of cross-polarization (<-24dB), high polarization isolation (<-50 dB), good matching (<-15 dB) and reasonable radiation efficiency (>53%) in the 250-320 GHz band.

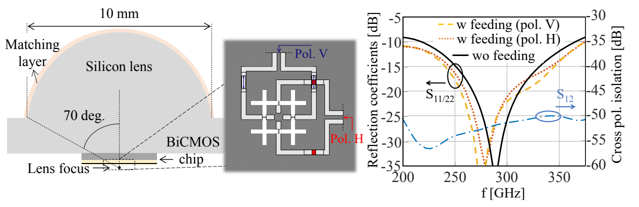

Fig. 4. Proposed dual-polarized lens antenna with simulated performance.

To realize a radiative near-field link at 100 m, we can couple the lens antenna of Fig. 4 to a QO system with an aperture of 50 cm [see Fig. 3(b)]. The considered QO system (50 cm × 65 cm) features three lenses [16] to realize high coupling efficiency with steering capabilities due to the need for tight alignment. The estimated loss of the complete QO system (including the loss of the lens antenna in Fig. 4) is

$L_{ant} \leq$ 5.5 dB. Fig. 3(b) shows the simulated coupling efficiency versus misalignment distance/angle. By introducing the steering capability, the system becomes more robust against misalignment. The proposed antenna architecture can be extended with focal plane arrays of lenses, as in Fig. 1, for realizing QO MIMO [7].

IV. LINK BUDGET ESTIMATION

In this section, we provide the estimation of the link budget and expected capacity for a single spatial channel using the simulations of the different parts of the system described before. The capacity estimation is done using the previously described zero-crossing modulation where FTN signalling is used at the transmitter and temporal oversampling at the receiver. This means that the signalling rate of the DAC is increased beyond the limits of the Nyquist rate f_N, constituted by the double-sided transceiver RF bandwidth B, by a factor of M_{tx}. The resulting signalling rate f_{Tx} (output sample rate) of the DAC is then f_{Tx}=$M_{tx} \cdot f_N$. Likewise, the oversampling factor at the receiver M_{rx} determines the actual sampling rate at the receiver ($M_{rx} \geq M_{tx}$required) f_{rx}=$M_{rx} \cdot f_N$. The achievable spectral efficiency of the link in a ZXM system and the hardware requirements are greatly affected by the achievable SNR. The achievable data rate R is determined by R=S·B where S is the spectral efficiency. Table 2 shows the simulated achievable data rate based across a range of parameters.

Table 2. Achievable data rate and required sampling rate f_{tx} for different values of M_{tx} and bandwidth $\boldsymbol{B}$.

B GHz	M_{tx}	f_{tx} GSa/s	SNR_{TH} dB	Spec. eff bit/s/Hz	Cap. Gbps
40	2	80	14	2.3	92
50	2	100	14	2.3	115
40	3	120	18.5	2.75	110
50	3	150	18.5	2.75	137.5
40	4	160	25	3.2	128
50	4	200	25	3.2	160

We estimate the link budget using the following equation:

$$SNR = P_{in} - 2L_{ant} + E_{ant} - N - L_{atm} - L \qquad (1)$$

where P_{in} is the input power to the antenna, L_{ant} is the loss of the complete QO antenna in Fig. 3(b), E_{ant} is the power transfer efficiency in Fig. 3(b) for no misalignment, N is the receiver noise level, L_{atm} is the atmospheric absorption loss, and $L = 3$ dB is other additional loss in the link that could be misalignment in the connection or other unexpected loss. Here we assume an RF bandwidth B of 50 GHz, a noise temperature T of 290 K, and as a result $N = k_b TBF = -53dBm$.

Table 3. Link budget for several parameters

Dist (m)	D (cm)	E_{ant} (dB)	L_{atm} (dB)	P_{in} (dBm)	SNR_{TH}/ Margin (dB)	Cap. (Gbps)	Rad.eff (Tbit/J)
60	50	-1	0.25	-18	18.5/1.3	137.5	8700
60	50	-1	0.25	3	25/15.8	160	80
280	50	-7	1.5	-16.5	14/0	115	5100
280	50	-7	1.5	3	25/8.5	160	80

A summary of the link performance estimation is shown in Table 3 for different parameters. The radiated energy efficiency is calculated as $C(Tbs)/P_{in}(W) = Tbit/J$. From Table 3 we can see the link budget that could be achieved under perfect antenna alignment and the described simulations. For 3 dBm as the input power, we have 80 Tbit/Joule for a capacity of 160 Gbps. Since we still have some SNR margin, if we consider a perfect alignment case, no SNR degradation due to phase noise, interference and non-linear distortion, the transmitted power can be backed off to reach a higher radiated energy efficiency.

To conclude, the proposed THz system has the potential to reach capacities beyond 100 Gbps for a single channel. If multiplexing techniques such as polarization and MIMO arrays are added, the expected capacities can go beyond Tbps. Moreover, the system is energy-efficient in terms of levels of radiated energy and potentially low DC consumption. The simulated results are promising in terms of state-of-the-art THz demonstrations as highlighted in Table 1.

ACKNOWLEDGMENT

This work is part of the TeraGreen project which received funding from the Smart Networks and Services Joint Undertaking (SNS JU) under the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101139117.

REFERENCES

[1] T. S. Rappaport *et al.*, "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond," *IEEE Access*, 2019.

[2] J. Ding *et al.*, "124.8-Gbit/s PS-256QAM Signal Wireless Delivery Over 104 m in a Photonics-Aided Terahertz-Wave System," *IEEE TTST*, 2022.

[3] K. Maekawa *et al.*, "Single-carrier 220-Gbit/s sub-THz wireless transmission over 214 m using a photonics-based system," *Opt. Lett.*, 2024.

[4] C. Castro *et al.*, "Experimental Demonstrations of High-Capacity THz-Wireless Transmission Systems for Beyond 5G," *IEEE Commun. Mag.*, 2020.

[5] P. R.-Vazquez *et al.*, "A QPSK 110-Gb/s Polarization-Diversity MIMO Wireless Link With a 220–255GHz Tunable LO in a SiGe HBT Technology," *IEEE TMTT*, 2020.

[6] I. Fatadin *et al.*, "Demonstration of 120 Gbit/s 64-QAM Wireless Link Operating in the 300 GHz Band," *IEEE Access*, 2024.

[7] N. Llombart *et al.*, "Feasibility Study of Quasi-Optical MIMO Antennas for Radiative Near-Field Links," *IEEE TAP*, 2022.

[8] G. Fettweis, *et al.*, "Zero crossing modulation for communication with temporally oversampled 1-bit quantization," *in ACSSC*, 2019.

[9] ETSI GR THz 001 V1.1.1 (2024-01). TeraHertz modeling (THz); Identification of use cases for THz communication systems.

[10] F. Strömbeck, *et al.*, "A Beyond 100-Gbps Polymer Microwave Fiber Communication Link at D-Band," *in IEEE TCS I*, 2023.

[11] B. Murmann, "ADC Performance Survey 1997-2024," [Online]. Available: https://github.com/bmurmann/ADC-survey.

[12] L. Landau, *et al.*, "1-bit quantization and oversampling at the receiver: Sequence-based communication," *EURASIP JWCN*, 2018.

[13] P. Neuhaus, *et al.*, "Zero-Crossing Modulation for Wideband Systems Employing 1-Bit Quantization and Temporal Oversampling: Transceiver Design and Performance Evaluation," *IEEE OJCS*, 2021.

[14] F. Gast, *et al.*, "Energy Optimization using Joint Modulation Scheme and Front End Adaptation - the Gearbox-PHY," *ISWCS*, Brazil, 2024.

[15] A. Bechrakis Triantafyllos *et al.*, "Dual-Polarized Double-Slot Lens Antenna with Low Cross-Polarization at 300GHz in 90nm SiGe BiCMOS," *in EuCAP*, Sweden, 2025.

[16] H. Zhang *et al.*, "Design of a Scanning Quasi-Optical Lens System for Radiative Near-Field Communication Links," *EuCAP*, Sweden, 2025.