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An overview of the Meteracom Project

(Metrology for THz Communications)

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***Abstract*—We overview the 3-year Meteracom project which will provide traceability to the SI for THz communication measurement parameters. The key objectives are to develop new metrological methods to characterize the measurement systems, system components and propagation channels. The final objective is to develop metrology for functionality and signal integrity of THz communication systems; particularly device discovery and beam tracking, determination of physical layer parameters for digital transmission and real-time performance evaluation.**

Keywords—THz Communications; Metrology; Beam discovery; Channel Sounding; Sampling Physical layer; Real-Time performance monitoring

I. INTRODUCTION

Applications such as wireless backhaul and fronthaul require data rates around 100 Gbps. Extrapolating [1] this to 2030 infers wireless data rates of 1 Tbit/s per data link. Although such rates can be achieved over optical fiber, in many scenarios access may not be feasible, and a wireless solution is required. Diversity schemes extend the effective bandwidth, but available spectrum and the practical fractional bandwidth will push the carrier to high mm-Wave/low THz frequency regime. Research to go beyond 5G, with >100 Gb/s capacity systems and carrier frequencies of > 200 GHz [2], are being addressed through Horizon 2020 [3]-[5] and national projects [6]. The feasibility of THz communications has been demonstrated and shown to have potential for future wireless transmission.

Metrology at THz frequencies is still at an early stage of development and currently only covers detector calibration, characterization of ultrafast devices and the analysis of measurement uncertainty analysis for different spectrometer types. An earlier intercomparison of THz absorption coefficient and refractive index measurements revealed significant discrepancies between the participant's results [7].

Communication system manufacture is a worldwide business, disciplined by specification standards. Traceability and confidence in the results is the basis for trust and essential for future trade. The lack of suitable SI-traceable metrological methods and reference measurement standards for THz communications is a persistent problem. The research unit FOR 2863 Meteracom (Metrology for THz Communications), a multi-disciplinary team, has been set up and funded by the German Research foundation, DFG [8], to address this issue.

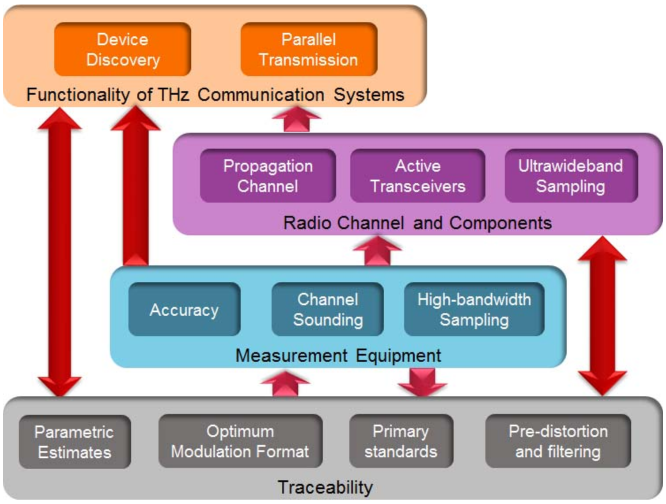

Fig. 1. Meteracom Project Structure

This paper outlines the objectives and program of this project and the paper is structured as follows: the next section overviews the challenges and project structure and sections III-

VI describe some of the planned work in more detail with an overall summary to conclude.

II. TECHNICAL CHALLENGES AND PROJECT STRUCTURE

A. *The challenges*

The four key metrological grand challenges identified for THz communication and addressed by this project, are:

1. Traceability to the International System of Units (SI)
2. Characterization of the measurement system itself
3. RF component and the propagation channel
4. Measurements of THz comms system functionality.

B. *Meteracom project structure*

The project has a duration of three years and the work is structured as traceability and three main project areas (see Figure 1). Each sub-project contains two to four tasks and there is a degree of overlap and dependency across the tasks. Traceability has been treated as a separate project to avoid duplication and to encourage interworking. It addresses both specific and common themes and has a high degree of overlap across the project areas. This is particularly true for the traceability sub-project. Overall, the project supports ten Doctoral candidates who will each contribute to one or more tasks.

III. TRACEABILITY

The three scientific objectives of this work are firstly, to determine the most appropriate parametric measures and uncertainty representation to assess the transmission quality of THz communication systems. These may be waveform and measurement-centric parameters, such as Error-Vector Magnitude (EVM), or data-centric measures such as Block Error-rate (BLER). Secondly to build on the knowledge gained of the propagation channel and limitations of the transmitter and receivers and to propose optimum modulation formats to maximize the system bit-efficiency. The final objective is to develop an Electro-Optic Sampling (EOS) technique traceable to waveform metrology standards to measure a repetitive THz waveform. The work program is divided into the four main tasks to realize these objectives

A. *Parametric estimates*

The first of these tasks builds on existing standards activity [9] and is focused on parametric quality estimates to characterize the system performance. Error-Vector Magnitude (EVM) and Block-Error Ratio (BLER), which are typically used to estimate the quality of the communication channel. The potential data rate in a THz communication system is 10 Gb/s and above which will limit the complexity of the real-time signal processing that can be applied without a significant energy penalty. A desired outcome of this sub-project the is to determine whether EVM or BLER is the most appropriate parametric measure to optimize the system performance. The impairments arising from the hardware and channel measurements need to be known in order to determine the best approach. Early transmission channel results from the sub-project tasks, outlined in IV.B and V.A, will be used to estimate possible scenarios including multi-path and dispersive effects. The distortion and dynamic range behavior of the transmitter will influence constellation design and predistortion options and this links to the second task.

B. *Optimum modulation format*

Waveform metrology is essential to determine the optimum modulation formats and constellations to maximize the system bit-efficiency. At lower carrier frequencies this optimization is often carried out at baseband but even at mm-wave frequencies error behavior can be highly correlated [10]. In this second task, noise is viewed as a limiting factor for THz systems. The path-loss is significant due to the high carrier frequency and phase-noise is anticipated to be a significant problem due to the high carrier-frequency. We will analyze the signal phase-behavior to determine if the carrier-phase can be tracked. There will be a residual random phase-noise component and other noise processes, so optimization of the constellation design is expected to yield a system budget gain of a few decibels. The results will be analyzed using the model developed in project V.B and we will also collaborate with V.C phase-tracking and sampling.

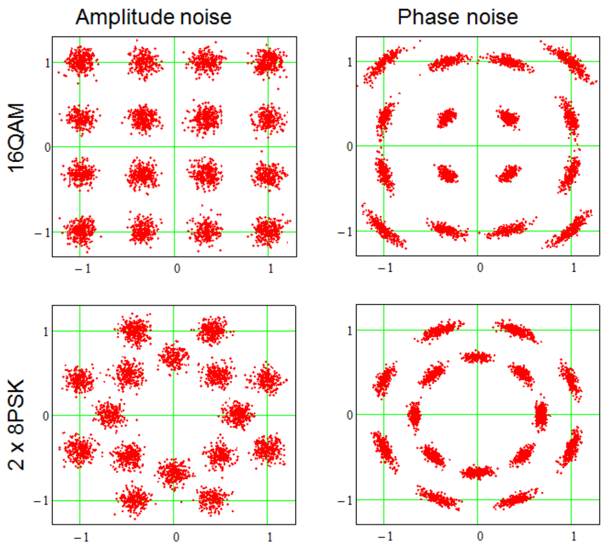

Fig. 2. Constellation designs showing immunity to amplitude and phase noise for 16 QAM and 2 x 8PSK signals (simulation)

To achieve a higher bit-efficiency than 2 (QPSK), it may be beneficial to tailor the constellation design to minimize its sensitivity to impairments [11], [12]. Figure 2 shows that 2 x 8QPSK will have improved phase-noise immunity, giving an angular separation of 0.78 radians compared with 0.64 radians but this constellation may be more difficult to decode.

C. *Primary standards*

The third area of work needed to establish primary standards traceability to the SI for the calibration of THz communications measurement systems is to develop a practical electro-optic sensor that can be made traceable to waveform standards. A typical EOS system comprises a Low Temperature GaAs photoconductive switch (<1 ps) and an electro-optic field probe, which can be the substrate [13] or an external probe. By adding a THz antenna to the system several sampling options are available. These include direct sampling of the waveform and demodulation using the photoconductive switch. For traceability of optical sampling techniques, direct detection of down-converted modulated THz signals using Electro-Optic Sampling (EOS) will be investigated in collaboration with IV.C. This could be realized using a fully synchronous or offset-locked EOS system. Direct detection in Low-temperature Growth (LT) GaAs is used for impulse generation for Electro-optic sampling. If the efficiency is low or if the source phase-noise dominates the results, then a proposed alternative strategy is to use direct waveform capture using a calibrated Real-Time Digital Oscilloscope.

The calibration of channel sounder (CS) components [14] has special requirements with respect to the connector systems, frequency, bandwidth and dynamic range. This links with the work to be done in IV.B. A goal of this task is to extend the modelling of VNA standards to meet the higher frequency measurements requirements Traceability based on well characterized standards for vector network analyzer system only available to 67 GHz (1.85 mm).

D. *Pre-distortion and filtering*

The final task is to perform a quantitative analysis, system level simulation and an experimental validation of baseband pre-distortion and filtering methods for wideband THz communication systems. There is expected to be a trade-off between computational speed and finite digital resolution. This will affect error parameters, such as EVM. This work will start by building a simulation test-bench in Keysight SystemVue CAD design environment. The object is to create a seamless model linking the key figures of merit on the digital to the analogue domains of THz communication systems and to determine the trade-off mapping the analogue impairments and correcting the results with a DSP. Waveform metrology plays an essential part in this task as the realization of the mathematical correction may be imperfect.

IV. METROLOGY FOR MEASUREMENT SYSTEM CHARCERIZATION

This work is divided into three parts, addressing the accuracy of THz communication measurement systems, metrology of multi-dimensional channel sounding (MD-CS) and the metrology of high-bandwidth sampling systems. We anticipate that the work on CS will be used widely across the project.

Measurement instruments such as channel sounders and high-bandwidth sampling systems are crucial to deliver the necessary measurements of parameters that are needed to plan, design, build and operate THz communication systems. THz communications has the capability to handle extremely high data-rates for a large number of users. To enable widespread adoption of this technology will require significant advances in system topology and integration, antenna array technology and new photonic components. None of these advances will be possible without the ability to perform reliable and traceable measurements and the correct evaluation of these measurements to facilitate advanced system planning and design. Also, such measurements allow more advanced fabrication techniques and ensure interoperability of systems and devices where specifications are much more critical and allowable tolerances are smaller. Reliable measurements of channel properties and system parameters will be essential for THz communications to reach its full potential.

Without the knowledge of the measurement uncertainty attributed to the respective parameter measurement, the measurement result is incomplete and useless when it comes to relying on the obtained information. The measurement uncertainty assigned is the result of a detailed modelling of the measurement process and of establishing an unbroken traceability chain of measurements to the representation of SI units. The uncertainty analysis comprises contributions from a statistical analysis of a series of observations and other scientific knowledge about the measurement process. Even in case of a small and often negligible contribution, a measurement uncertainty budget needs to be complete for the measurement process to be understood. Together with the best estimate of the measurand, the assigned overall standard measurement uncertainty specifies the interval in which the measurand can be expected.

A. *Accuracy of THz Communications Measurement Systems*

CS Systems [15], [16] are invaluable for characterizing the propagation channels. Whereas system evaluation of wired transmission systems and circuits follows very well-defined rules of metrology, this is not the case for wireless systems. The reason for this complexity is the stochastically time-variant interaction of multipath propagation and antennas that leads to a multidimensional system characterization. For practical applications this has to be broken down to useful performance measures such as the characterization of the propagation channel to derive channel models for system evaluation and standardization. The quality of these models has a major impact on the performance of the systems. While for frequencies below 6 GHz we have already achieved an acceptable level of best practice, this is by not the case at millimeter-wave or THz frequencies [16]. Establishing reliable quantitative measures for the THz transmission channel-properties is a key goal of this project.

Providing traceability for complex measurement quantities will involve characterization of channel sounder components and is strongly linked with III. Resolution and accuracy of the channel sounder in the joint delay-Doppler direction-of-arrival domain will be evaluated with waveguide-based propagation artefacts developed in this project. Calibration methods based on existing methods for mm-wave radar systems will be developed together with test scenarios where channel sounder measurements can be verified with well-established vector-network-analyzer-based channel characterization.

B. *Metrology of Multi-Dimensional Channel Sounding*

MD-CS allows an estimate of the geometrical structure of wave propagation in terms of direction, time-of-flight and Doppler shift. The object is to predict the performance of transmission systems-based knowledge of these parameters. The spread in the respective domain determines the measures to be taken in order to achieve a certain communication link performance and has a major influence for standardization decisions.

At high millimeter-wave and THz frequencies there is a shortage of experimental data for wave propagation. This is especially true for the multidimensional joint-statistics and for the impact of highly directive antennas in dynamic scenarios. This sub-project aims to develop measurement procedures for multidimensional channel sounding and the supporting metrological assessment so that channel sounding results can be used to evaluate system performance and design. The challenge lies in the multidimensional coupling of all parameters as these cannot currently be easily analyzed in dynamic scenarios. We need to develop new concepts for the sounder architecture and a high-resolution parameter estimator (HRPE) [16]. We aim to achieve estimates, bounded by measurement uncertainties, that are largely independent of the measurement device.

Different sounder architectures will be compared in dynamic environments to verify the stability of the approach. Ultra-wide band frequency response calibration and the impact of nonlinear distortion will present a measurement challenge. We will investigate both incoherent and coherent directional analysis processing schemes to determine the directivity of the array output. Non-coherent processing allows estimating statistical delay-Doppler-angular distributions within the antenna resolution limits. Coherent processing is more challenging in terms of hardware stability and calibration. However, high resolution of directional multipath parameter estimation can be achieved. Corresponding antenna architectures and calibration schemes will be proposed, and phased array receivers will be assessed in dynamic situations using wideband sounder signals.

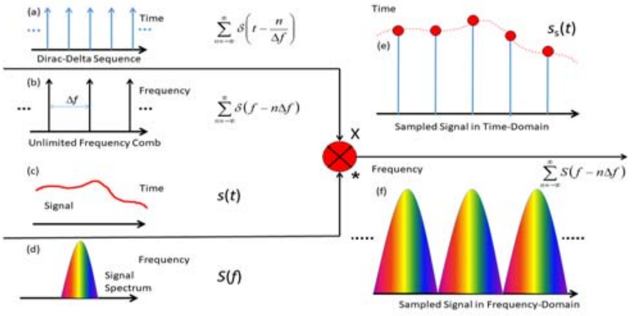

Fig. 3. Ideal sampling in the frequency and time domain.

C. *Metrology of High-bandwidth Sampling Systems*

All-optical sampling systems enable much higher sampling rates and can have a much lower jitter than electrical sampling and are therefore key components both for transmission systems and measurement equipment operating at >100 Gb/s [17][17]. Figure 3 shows the principle of ideal sampling and Figure 4 the approach taken with optical sampling that comes as close as possible. However, optical sampling systems can just sample optical signals. The transfer from the THz to the optical domain might distort the signal. Additionally, the sampling itself leads to distortion and adds noise to the signal. Thus, an important evolving metrological task which is in the focus of this project is the characterization of all of these effects and the comparison between these pure-optical, opto-electronical and pure electronic sampling [18].

The metrology of optical sampling systems will include the modification of methods from waveform metrology in such a way that they can be used to evaluate new optical sampling techniques. New optical sampling techniques will be compared to existing electrical sampling methods quantitatively. Furthermore, the main properties of optical sampling such as transfer function, effective number of bits, jitter, linearity and effective bandwidth will be calibrated.

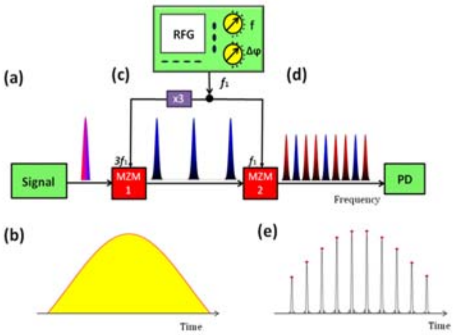

Fig. 4. Basic principle of the convolution based optical sampling (MZM: Mach-Zehnder modulator, PD: photodiode, RFG: radio frequency generator).

V. METROLOGY OF THZ COMPONENTS INCLUDING THE PROPAGATION CHANNEL

This project theme deals with the characterization of propagation measurement and modelling, active THz transceiver components and ultrawideband sampling. There is overlap between this work, III and IV.

A. *Characterization of propagation channels*

Whenever a wireless communication system is going to be operated in (i) either a new frequency band, (ii) higher bandwidths or (iii) in a new application environment, where wireless communication has not been applied for, this triggers activities in channel modeling. In the case of THz communications with carrier frequencies beyond 100GHz, channel bandwidths of several 10s of GHz and new applications like wireless links in data centers [19] or in devices like computers [20] cameras or video projectors, all three conditions (i) - (iii) apply. Channel models are relevant in such cases since profound knowledge of the propagation channel is essential for the design of the radio system. Furthermore, channel models are key elements in the process of developing wireless standards. On the path to develop these channel models, channel measurements are always the first step, which require that adequate measurement equipment and measurement procedures are available.

For THz channel measurements, mature measurement equipment like Terahertz Time-Domain Spectroscopy (TDS) and Vector Network Analyzers (VNA) are commercially available. Although these types of equipment can be applied to work on a couple of research questions, they have restrictions in terms of their applicability to all the measurement tasks required to fully understand the propagation channel. An example for such a challenge is the measurement of the ultra-wideband characteristics of a time-variant channel, influenced by the presence of people who are either blocking or scattering the signal. Such scenarios cannot be measured by a VNA [21] and a time-domain CS, is required because of its much shorter measurement times.

The four objectives in this sub-project to characterize the propagation channels are:

(i) THz-TDS will be used to systematically determine numbers for basic propagation phenomena such as reflection and scattering properties of materials relevant to THz communications.

(ii) The atmospheric attenuation systematically measured under real weather conditions. This also includes a repetition of parts of the measurements using a CS and a comparison of the results.

(iii) New methods to determine the geometrical properties of time-varying propagation channels using the CS will be investigated.

(iv) The measured CS data will be used to derive metrics for the ultra-wideband system performance predictions in time-varying channels.

These results will provide Meteracom with a sound metrological basis to development of channel models for THz communications.

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B. *Active THz Transceiver Components*

Compared to radios operating at purely optical or RF/microwave frequencies, the combination of extremely high absolute bandwidths and high relative bandwidths in the THz frequency regime, paired with the severe performance limitations of technologies operating in the so-called “THz-gap”, imposes unique challenges on modern digital transmission schemes relying on high signal integrity. Since no direct DSP is yet possible at THz frequencies, signals need to be frequency-shifted into and from the THz range. This frequency-shifting is performed by the transceiver, which can be implemented based either on fully electronic, fully photonic or mixed electronic-photonic technologies [22] - [24]. The latter approach is viewed as the most promising way forward since it allows to combine the unique advantages of both domains, namely the low receiver noise, high transmit power and high functional integration density of electronics-based THz transceivers, with the high spectral purity and high-quality phase and frequency control of photonics-based THz signal generation.

The work in this section aims to develop a theoretical and experimental understanding of the design of THz transceivers based on electronic and photonic technologies, as well as circuit design and simulation methods of optimizing their application-specific characteristics, in view of pushing their data rate capability, modulation format versatility and system gain. The project will also provide a technology platform for the experimental validation of the Terahertz metrology concepts investigated in the frame of the other projects.

Electronic THz transceiver circuits operating within the WR3 frequency range from 220 GHz to 325 GHz will be investigated, with a particular focus on ultra-wideband (> 60 GHz) channel bandwidths, which are encountered in THz communication, radar and metrology applications. In an application-oriented top-down design approach based on theoretical analysis and system-level CAD simulations we will study and experimentally evaluate the sensitivity of the vector-signal degradation of communication signals and the impairments of heterodyne, quadrature electronic THz transmit-receive frontends. This information will allow us to design an optimized transceiver circuit design.

We will investigate active THz transceivers using highly-stable and spectrally-pure mode-locked laser-based signal generation, as a the tunable THz local oscillator [25] and electronic transceivers using opto-electronically phase-locked microwave oscillators [26].

Experimental validation in this project will comprise the time and frequency domain characterization of the individual electronic and photonic transceiver components, as well as complete data transmission experiments using combined photonic-electronic transceivers in a back-to-back configuration, as well as existing THz transceivers.

C. *Ultra-Wideband Sampling*

The metrology of wireless communication has to properly represent the complex interaction of the digital and analog signal domains. The high bandwidth at THz frequencies allows for extreme radio frequency (RF) bandwidth and hence also very large baseband bandwidth. In the baseband the broadband analog signals are digitized by broadband analog-to-digital-converters (ADC). In an ADC the signal is first sampled and then the stream of analog samples is converted to a stream of digital data words. Typically, it is the precision of the sampling which determines the precision of the ADC. The high bandwidths of the analog input signals require extreme fast samplers and insufficient sampler bandwidth will be a cause for signal degradation. Besides bandwidth, another major performance bottleneck of broadband samplers is aperture jitter rsp. clock jitter of the electronic clock. As an alternative, optical clocks based on pulse-trains from mode-locked lasers (MLL) have demonstrated to achieve much lower jitter than electronic clocks. This has led to the development of photonic samplers and ADCs using ultra-low-jitter optical clocks. So far most of the photonic sampling techniques use discrete optical devices and large, complex laboratory setups. Recently photonics integration technology such as indium phosphide technology and silicon photonics have made significant progress and allow to integrate photonic sampling circuits (except the MLL) in a similar way as electronic samplers. This will allow for mechanically stable, miniaturized, and cost-efficient photonic sampling devices. In this section different variants of ultra-broadband electronic and photonic sampling techniques with bandwidth up to 40 GHz, suitable for THz wireless communication, and the possibility of integrating these devices will be investigated.

The three goals of this work are:

1) to investigate different photonic sampling techniques for the sampling of THz waveforms both theoretically and experimentally

2) to implement a novel ultrabroadband photonic sampling technique (frequency-time-coherent sampling) for the first time in a silicon photonic chip and

3) to model and compare electronic and photonic sampling techniques and find the ultra-broadband sampling technique which is best suited for integration.

Investigations will be carried out by means of mathematical analysis, numerical modeling and simulation, as well as measurements of different sampling devices.

VI. METROLOGY FOR SYSTEM FUNCTIONALITY

Functionality and signal integrity of the THz communication systems requires the real-time monitoring and measurements required during the operation. The aim is to address how to shape measurement and testing to enable the functionality of THz communication systems.

A. Device discovery and beam tracking

In order to set-up a wireless link between two terminals, the very first step is that both terminals detect each other. In the literature this process often called "device discovery" or "initial access". We will use the term *device discovery* in this proposal. Device discovery in wireless systems usually works by a transmitter is sending a beacon that identifies the transmitter and is detected by a receiving terminal. The receiving terminal is then able to transmit a signal back to the originally transmitting terminal. The pre-requisite for a straight-forward set-up of such a protocol is an omni-directional transmission of radio signals. At 100 GHz and higher typically high-gain antennas with so-called pencil beams are required to increase the antenna gain and mitigate the high path-loss, which makes it difficult for the two terminals to set-up a communication link without knowing each other's position. At millimeter-wave frequencies, such as 60 GHz [27], the typical approach is to use antennas with wider beams for the initial low-data rate link set-up and then subsequently narrowing the beam for the transmission of higher user data rates. This approach is possible since the lower data-rate transmission used during the discovery phase allows a lower signal-to-noise (SNR) ratio, which can be achieved even by antennas with a lower gain and larger beam width, whereas for high data-rate transmission high gain antennas with a narrower beam is required. The link budget, at the carrier frequencies used in this proposal, does not allow such an approach, which means that even for the discovery phase high-gain antennas at 300 GHz are required. Instead two principal approaches are possible to handle this:

1) Brute-force scanning using high-gain antennas at both ends of the radio link;

2) Using a lower carrier frequency for a quick and rough first estimation of the terminals position and then refine the search with high-gain antennas at the higher carrier frequency.

Approach 1) is to time-consuming, which leaves approach 2) as the only viable solution [28].

Device discovery is only the first steps in the life-time of a wireless communication link. In order to keep the communication link active, particularly in the context of moving terminals, moving obstacles and scatters, which will occur in a real environment (e.g. people located in the same room), further measures have to be taken in order to track the selected pencil beam. This has to take into account multi-path propagation, which either needs to be mitigated or can be even exploited to set-up alternative – reflected or scattered – paths. The problem we are facing here has similarities to radar, where the operation is split into a target acquisition phase (device discovery) and target tracking (corresponding to beam tracking in this proposal).

These dynamics of the channel – caused by moving terminal, moving scattering elements or moving obstacles - need to be accounted for using suitable methods to guarantee a robust communication link while maintaining a low power consumption. Situational awareness hence is key to maintain such robustness, requiring sustained signal monitoring and evaluation. Furthermore, the combination of situational awareness with machine-learning approaches has proven useful for solving the resulting complex control tasks. Since the methods have to be applied during operation of the system, signal acquisition and evaluation has to be done within short time-periods, which are in the order of magnitudes of the relevant changes. The signal decrease in a shadowing process, for example caused by people blocking the line of sight, is in the order of 100 ms [20]. Therefore, a highly time-efficient real-time implementation is needed. Consequently, a suitable accelerator architecture is required to provide the necessary computing power in an overall low-power environment.

The two research questions that have to be resolved to enable device discovery and beam tracking are:

1) Measurement procedures and algorithms have to be developed, evaluated and assessed taking into account the geometrical properties of time-variant propagation channels investigated in V.A.

2) Methods have to be derived that allow the real-time implementation of these procedures and algorithms.

B. Metrology for Parallel THz Communication Channels

Terahertz (THz) transmission is considered a promising solution to meet the Quality of Service (QoS) of future ultra-high-speed services and bandwidth-intensive wireless applications. One of the major challenges is our ability to assessing the measurements of the relevant system performance parameters, including bit error rate (BER), packet error rate (PER), and latency. This sub-project sets to goal of addressing the system measurement challenges using a parallel space-division multiplexed THz system as a means to overcome the intrinsic system complexity, high transmission speed, device impairments and use time-varying outdoor channel models developed in V. Parallelization generates multiple parallel beams at sub-terahertz frequencies (e.g., 300 GHz), while achieving the Terabit/s throughput, akin to the multiple input and multiple-output (MIMO) systems. We propose to use various methods and tools to improve the measurements, and evaluating measurands as accurately as possible, including machine learning algorithms and erasure coding to determine the influence and correlation of the system performance parameters with the time varying spatial multiplexed parallel channels.

As part of this work we propose to experimentally study the physical security of the THz channels against passive and active attacks. The possibility of eavesdropping – a passive attack - will be measured by placing small sized reflectors in the line of sight of THz communication channels. To address the active jamming and integrity attacks we measure differentiating physical channel distortions under an attack scenario using machine learning techniques, as well as coding methods. Finally, this sub-project focuses on the challenging aspects of hardware system design needed to implement the algorithms and methods proposed and proposes a proof of concept experiment with real-time measurements of the performance parameters studied. With the choice of algorithms having a strong influence on hardware complexity, finding a suitable architecture requires a thorough hardware design-space exploration. A special framework will be created that allows for fast and accurate architecture design parameter estimation like size and speed without the need for a full hardware implementation. This information can be fed back into algorithm design enabling an algorithm-architecture co-design with extensive design-space exploration.

VII. CONCLUSION

In this contribution we have outlined the main aims and activities of the collaborative Meteracom project. The project aims to develop new metrological methods for THz communications, comprising the characterization of the measurement systems itself, the system components and propagation channels. Furthermore, the project will include also the development of metrology for functionality and signal integrity of THz communication systems; particularly device discovery and beam tracking, determination of physical layer parameters for digital transmission and real-time performance evaluation. The capability to perform measurements and to evaluate these measurements in a proper way are crucial for the advance of THz communication systems. Meteracom will work towards the provision of these capabilities.

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REFERENCES

[1] S. Cherry, "Edholm's law of bandwidth," in *IEEE Spectrum*, vol. 41, no. 7, pp. 58-60, July 2004.M. Lattva-aho, K. Lappänen; Key drivers and research challenges for 6G ubiquitous wireless intelligence, http://urn.fi/urn:isbn:9789526223544

[2] C. Paoloni et. al. ICT Beyond 5G Cluster: Seven H2020 for Future 5G, Proc. European Conference on Networks and Communications *18-21 Jun-2019; Valencia, Spain; [online] https://doi.org/10.24355/dbbs.084-201908211514-0*

[3] Davy, A.; Renaud, C.; Wasige, E.; Naftaly, M.; Kürner, T.; George, G.; Pessoa, L.; Cojocariy, O.; O’Mahonny, N.; Porcel, M.: Building an End User focused THz based Ultra High Bandwidth Wireless Access Network: The TERAPOD Approach. In Proc. 2nd Workshop on THz Communications (THZCOM), electronic publication (6 pages), München, November 2017.

[4] A. A. Boulogeorgos *et al*., "Terahertz Technologies to Deliver Optical Network Quality of Experience in Wireless Systems Beyond 5G," in *IEEE Communications Magazine*, vol. 56, no. 6, pp. 144-151, June 2018

[5] “ThoR: TeraHertz end-to-end wireless systems supporting ultra high data Rate applications,” EU-Horizon 2020, Ref. 814523.Available at: www.thorproject.eu

[6] “Wireless 100 GB/s and beyond,” DFG SPP1655. Available at : https://www.wireless100gb.de/

[7] M. Naftaly: An International Intercomparison of THz Time-domain Spectrometers, 41st International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz 2016), Copenhagen, Denmark, Sept. 2016.

[8] DFG “Deutsche Forschungsgemeinschaft” Project details for research unit 2863 “ Metrology for THz Communications.” Available at: https://www.dfg.de/en/funded_projects/current_projects_programmes/list/projectdetails/index.jsp?id=403579441

[9] P1765 - Trial-Use Recommended Practice for Estimating the Uncertainty in Error Vector Magnitude of Measured Digitally Modulated Signals for Wireless Communications, “Modulated Signal Meas. Uncertainty” Working Group MTT/SCC, Approval date 8th March 2018. Available at: https://standards.ieee.org/project/1765.html

[10] K. A. Remley, D. F. Williams, P. D. Hale, C. Wang, J. Jargon and Y. Park, "Millimeter-Wave Modulated-Signal and Error-Vector-Magnitude Measurement With Uncertainty," in IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 5, pp. 1710-1720, May 2015.

[11] Y. Li, S. Xu, H. Yang, “Design of Signal Constellations in the Presence of Phase Noise,” IEEE 68th Vehicular Technology Conference (Calgary), 21-24 Sept. 2008.

[12] T. Liu, I. B. Djordjevic, T. Wang, “Optimal signal constellation design for ultra-high-speed optical transport in the presence of phase noise, “Conference on Lasers and Electro-Optics (CLEO), San Jose, 8-13 June 2014.

[13] M. Bieler, H. Füser and K. Pierz, "Time-Domain Optoelectronic Vector Network Analysis on Coplanar Waveguides," in IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 11, pp. 3775-3784, Nov. 2015.

[14] M. A. Salhi, A. Kazemipour, G. Gentille, M. Spirito, T. Kleine-Ostmann, and T. Schrader, Near- and Far-Field Characterization of Planar mm-Wave Antenna Arrays with Waveguide-to-Microstrip Transition, J Infrared Milli Terahz Waves 37, 857-873 (2016).

[15] Rey, S.; Eckhardt, J.; Peng, B.; Guan, K.; Kürner, T.: Channel Sounding Techniques for Applications in THz Communications. In Proc. 2nd Workshop on THz Communications (THZCOM), electronic publication (5 pages), München, November 2017.

[16] M. Landmann, M. Käske, and R.S. Thomä, “Impact of Incomplete and Inaccurate Data Model on High Resolution Parameter Estimation in Multidimensional Channel Sounding,” IEEE Trans. AP, vol. 60, no 2, February 2012, pp. 557-573.

[17] M. A. Soto, M. Alem, M. A. Shoaie, A. Vedadi, C. S. Brès, L. Thévenaz, and T. Schneider, Optical sinc-shaped Nyquist pulses of exceptional quality, Nature Commun. 4:2898 doi: 10.1038/ncomms3898 (2013).

[18] S. Preussler, G. Raoof Mehrpoor and T. Schneider, “Frequency-time coherence for all-optical sampling without optical pulse source,” Scientific Reports 6, 34500, 2016. doi:10.1038/srep34500

[19] Eckhardt, J. M.; Doeker, T.; Kürner, T.: 300 GHz Channel Measurements in a Real Data Center – First Results. Proc. 19th European Conference on Antennas and Propagation (EuCAP), Krakow/Poland, April 2019, electronic publication (5 pages)

[20] S. Kim and A. Zajić, "Characterization of 300-GHz Wireless Channel on a Computer Motherboard," in IEEE Transactions on Antennas and Propagation, vol. 64, no. 12, pp. 5411-5423, Dec. 2016.

[21] M. Jacob, The 60 GHz Indoor Radio Channel – Overcoming the Challenges of Human Blockage, Ph. D. Thesis, TU Braunschweig, 2013 [online]:https://publikationsserver.tu-braunschweig.de/servlets/MCRFileNodeServlet/dbbs_derivate_00034174/Dissertation_Jacob_Shaker_v2_25_03.pdf

[22] I. Kallfass, F. Boes et al. “64 Gbit/s Transmission over 850 m fixed wireless link at 240 GHz carrier frequency,” J. Infrared Milli. Terahz Waves 36, pp. 221-233 (2015).

[23] T. Nagatsuma, G. Ducournau, “Advances in terahertz communications accelerated by photonics,” Nature Photonics, 10, pp. 371 379 (2016)

[24] I.Kallfass et. al., “300 GHz Wireless Communication Systems Exploiting the Benefits of Combining Photonic and Electronic Transceiver Components” , Proc. IRmmWTHz 2019, Paris, September 2019.

[25] S. Preußler et al., “Generation of ultra-narrow, stable and tunable millimeter- and terahertz- waves with very low phase noise,” Opt. Express, vol. 21, no. 20, pp. 23950–23962, 2013.

[26] M. Bahmanian, J. Tiedau, C. Silberhorn, and J. C. Scheytt, “Octave-Band Microwave Frequency Synthesizer Using Mode-Locked Laser as a Reference,” in 2019 International Topical Meeting on Microwave Photonics (MWP), 2019, pp. 1–4.

[27] 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) , vol., no., pp.1-55, Oct. 18 2017.

[28] B. Peng, K. Guan, S. Rey and T. Kürner, "Power-Angular Spectra Correlation Based Two Step Angle of Arrival Estimation for Future Indoor Terahertz Communications," in *IEEE Transactions on Antennas and Propagation*. doi: 10.1109/TAP.2019.2927892 (Early Access).