The RIS Potential for THz Wireless Applications: Feasibility Study and Open Challenges

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TERRAMETA's Technical Coordinator

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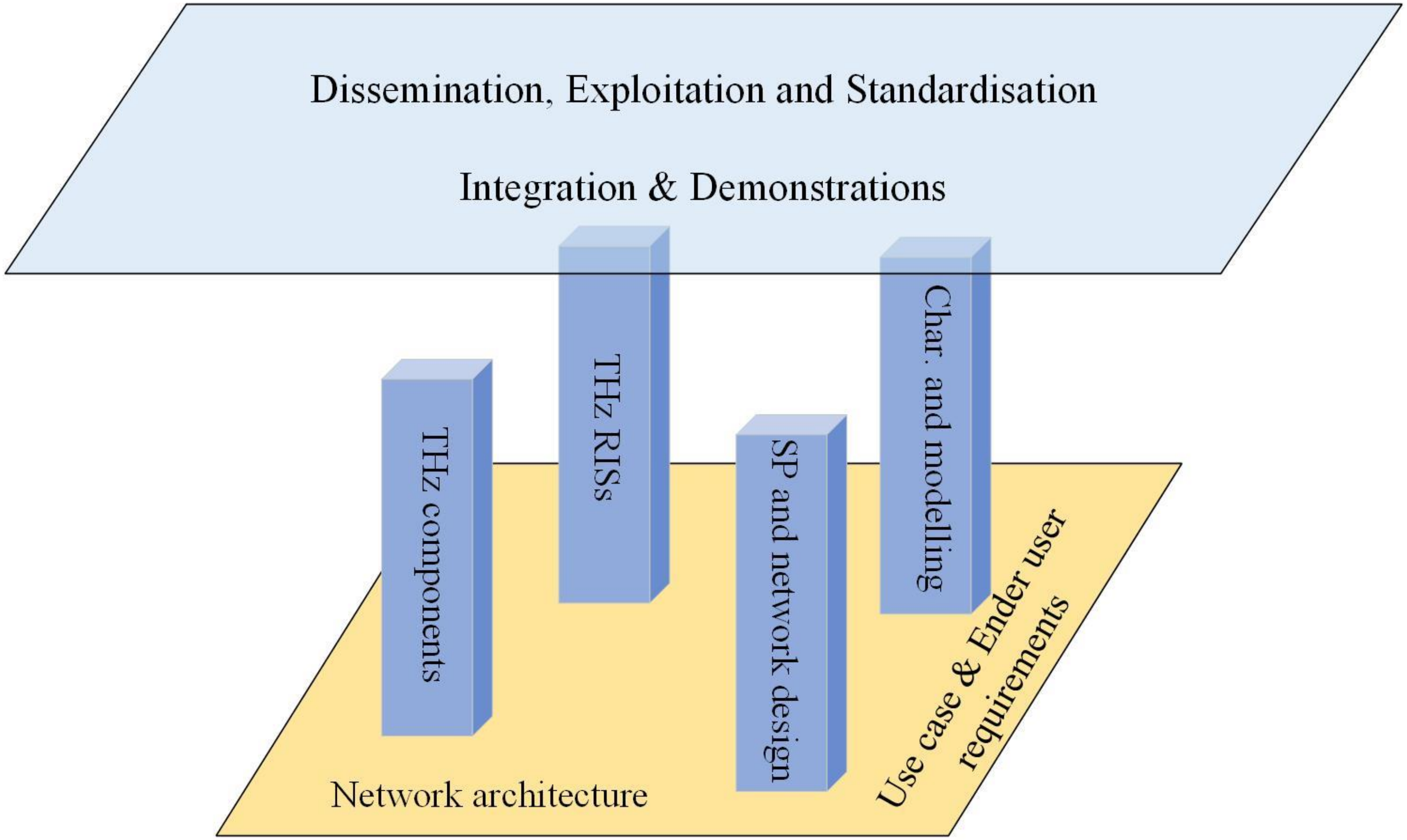
TERRAMETA in a Nutshell

- Investigation of ground-breaking technologies for 6G, demonstrating the feasibility of ultra-high data rate wireless communications leveraging THz metasurfaces.
  - Novel high-performance THz hardware will be developed, including low-power consumption wideband switches, RISs, and TXs/RXs.
  - Using the designed THz components, advanced network analysis/optimisation techniques will be investigated.

- The TERRAMETA THz network will be driven by 6G usage scenario requirements.
- Indoor, outdoor, and indoor-to-outdoor scenarios will be demonstrated in a real factory setting and a telecom testing field.

<u>TERRAMETA's definition of frequency bands:</u> *mmWave (30GHz - 100GHz) and THz (100GHz – 1 THz)*

TERRAMETA’s Pillars



TERRAMETA's Consortium

Sector	Partner	Expertise	Role inTERRAMETA
Research Center	INESC	THz antennas; switch modelling; IC design.	**Project coordinator**, Task leader
University	NKUA	Signal processing; multi-element transceiver hardware architectures; reconfigurable metasurfaces.	**Technical coordinator**, WP leader
University	UH	Reflectarrays and transmitarrays; beam-forming algorithm; localization and sensing.	Task leader
University	UOULU	THz antennas and measurement; IC design.	Task leader
Research Center	IT	Reflectarrays and transmitarrays; antenna characterization.	WP leader
Large Industrial	ICOM	Baseband unit; signal processing.	Task leader
Research Center	CEA-Leti	Reflectarrays and transmitarrays; array and metasurface modelling, design and characterization; IC design.	WP leader
University	UniLu	Network design and optimization; metasurfaces.	Task leader
Large Industrial	DER	Industrial operations and management.	WP leader
University	TUBS	THz characterization and propagation modelling; standardization.	WP leader
SME	ACST	THz transmitter and receiver.	Task leader
University	UNL	Memristor design and fabrication.	Task leader
Large Industrial	BT	System architecture; Exploitation of application scenarios.	WP leader

Outline

- RIS THz Use Cases and Applications
- Hardware Developments
- Channel Modeling
- Signal Processing
- Planning of Proofs of Concept
- Standardization Impact

RIS THz Use Cases and Applications (1/2)

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Application Type	Use case	Indoor / Outdoor	Near-Field / Far-Field	RIS Types and Operation Modes	Key use case and network aspects
Coverage Extension	Blind spot coverage	Both	Both	Reflective	Blocked LOS
	Hybrid indoor/outdoor repeater	Indoor-to-Outdoor	Both	Reflective, Transmissive, Reconfigurable	Either static or reconfigurable repeater
Network interoperation	Multi-carrier/multi-RIS operation	Outdoor	Far-Field	Reflective, Reconfigurable	Multiple network operators
	Infrastructure sharing	Outdoor	Far-Field	Reflective, Reconfigurable	Multiple network operators
Backhaul Planning	Backhaul and integrated access	Outdoor	Far-Field	Reflective	Backhaul topologies
High-Capacity connectivity	Direct short-range links	Indoor	Near Field (mainly) / Both	Reflective, Reconfigurable	Multiple user terminals
	Ultra-directive short-haul and mid-haul	Both	Both	Transmissive, Reconfigurable	Even fixed beam antennas may be used
Localisation and Sensing	THz RIS-aided backhaul link sensing and localisation	Outdoor	Both	Reflective, Reconfigurable, Receiving	Inter-base station, NLOS
	THz RIS-aided multi-access sensing	Both	Both	Reflective, Reconfigurable, Receiving	Multiple targets
	THz RIS-aided outdoor-to-indoor Sensing	Outdoor-to-Indoor	Both	Reflective, Reconfigurable, Receiving, STAR RIS	Can be integrated to existing WLAN infrastructure

RIS THz Use Cases and Applications (2/2)

Application Type	Use case	Indoor / Outdoor	Near-Field / Far-Field	RIS Types and Operation Modes	Key use case and network aspects
RF Sensing	JCAS with Dynamic Metasurface Antennas (DMAs)	Both	Near Field	Receiving, DMA	Can serve multiple users
	Environmental mapping and imaging (RF mapping)	Both	Near Field	Receiving, DMA	3D reconstruction of targets
	Large-scale distributed sensing in factory	Indoor	Near Field	Receiving	Detection of passive objects
	Enhancing throughput, localisation, and mapping in factory settings	Indoor	Near Field	Reflective, Reconfigurable, Receiving, Transmissive	Mobility and blockage scenarios
Network resilience / Multiple Access	Software-defined networking enhancement in data centers	Indoor	Both	Reflective, Reconfigurable, Transmissive	Dynamic management of multiple server nodes

KPI Definitions and TERRAMETA Requirements

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- Generic 6G requirements (speculations); 6G requirements are still under discussion within standardisation bodies. The TERRAMETA Consortium is an active participant via its pre-standardisation and standardisation efforts.

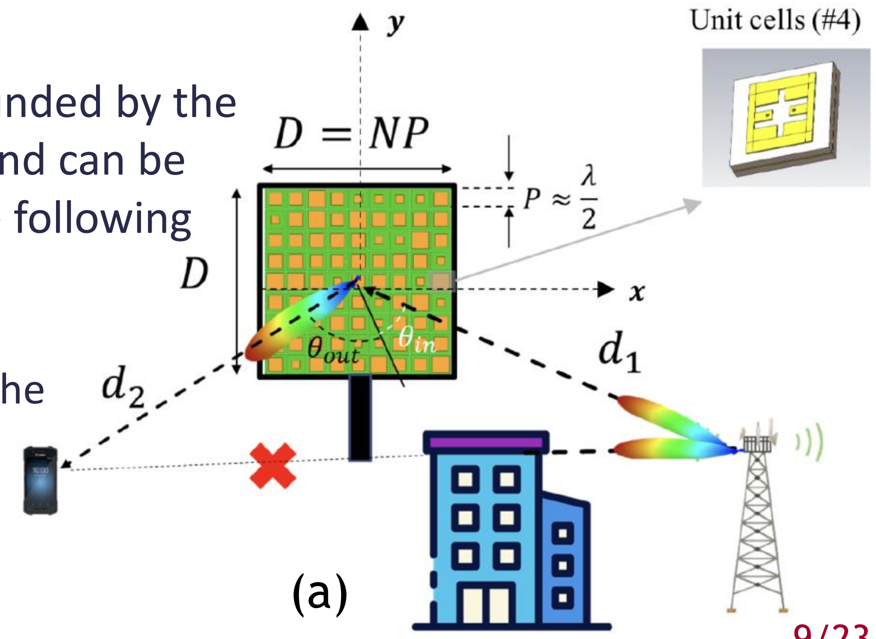
KPI	6G requirement
Peak data rate	1 Tbps
User experienced data rate	1 Gbps
Peak spectral efficiency	60 bps/Hz
User experienced spectral efficiency	3 bps/Hz
End-to-End latency	1 ms
Radio-only latency	100 microseconds
Block Error Rate (BLER)	10e^-9
Connection density	10e^7 devices/km^2
Network energy efficiency	1 pJ/b
Position accuracy	0.1 m
Maximum frequency	10 THz
Maximum bandwidth	100 GHz

- Various manufacturing use cases may require additional KPIs even higher requirements. Below, indicative values for manufacturing use cases are presented. It should be noted that these are not final and are expected to be updated throughout the lifetime of the project.

KPIs/Requirements	Description
Minimum Bitrate	3 Gbps
Minimum Range	10 m
Signal-to-Noise Ratio (SNR)	5 dB
Bandwidth Utilization	2 GHz (approximately)
Frequency Band	140-300 GHz
Modulation & Coding Schemes	Based on IEEE 802.15.3d (300 GHz), OOK, BPSK, QPSK, 8-PSK, 8-APSK, 16-QAM, 64-QAM, FEC 14/15, 11/15 LDPC
Bit Error Rate	Less than 10e^-9
Packet Loss	Less than 1%
Throughput	Approx. 2.8 Gbps
Latency	Less than 10 ms (end-to-end)
Jitter	Less than 2ms

Feasibility Study- RIS Design Example at THz (1/2)

- Consider a scenario with blocked LOS between the transmitter (BS) and the receiver (UE). Both the BS and UE are assumed to be in the far-field of the RIS (a).
- Assume a distance link of 100 meters @140GHz with an RIS placed at equal distances between the UE and the BS (d_1 = d_2 = 50 meters in (a)). Furthermore, it is considered that the minimum detectable power P_{rx} at the UE is -60 dBm.
- The link budget is given as: $\left(\frac{P_{rx}}{P_{tx}}\right)_{dB} = G_{BS}^{dB} + G_{T}^{dB} + (\sigma_{RIS})_{dB} + 10\log_{10}\left(\frac{1}{(4\,\pi)^3}\left(\frac{\lambda}{d_1 d_2}\right)^2\right)$ (1), where the antenna gain and transmit power of the BS are G_{BS}^{dB} = 46dBi and P_{tx} = 20 dBm, respectively, the RIS incident and output angles are considered as θ_{in} =0 and θ_{out} = 45 degrees, respectively, and the antenna gain of the UE is assumed as G_{T}^{dB} = 10 dBi.
- The unknown variable in (1) is the RIS's Radar Cross Section (RCS), σ_{RIS}, which is bounded by the specular reflection limit (ideal reflection) in a perfect electric conductor surface, and can be estimated as a function of the aperture efficiency of the RIS, η_{ap}, according to the following expression: $\sigma_{RIS} = \frac{\eta_{ap} 4\pi}{\lambda^2} D^4 \cos(\theta_{in}) \cos(\theta_{out})$ (2).
- To meet the requirements set by the minimum detectable P_{rx}, we need to determine the aperture efficiency η_{ap}, and then, the RIS's aperture via D.



(a)

Feasibility Study- RIS Design Example at THz (2/2)

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- The RIS aperture efficiency depends on many factors, including the phase quantisation error and the unit-cell insertion losses of the RIS. For passive structures, it is expected that a reflect-array can provide 50% aperture efficiency.
- Additionally, the integration of the reconfigurable technology will further degrade the performance of the metasurface. Based on previous works on reconfigurable technologies, at least 3 dB of insertion losses are expected, therefore an aperture efficiency of 25% can be considered.
- From (1), it can be concluded that a gain of 18.32 dB is missing, which the RIS is tasked to compensate.
- By solving $(\sigma_{RIS})_{dB} = 18.32$ with respect to D we get 110 mm, which corresponds to **10540** elements for the considered frequency.
- These numbers provide a more vivid picture on the scalability required for the RIS technology.

G. C. Alexandropoulos, A. Clemente, S. Matos, R. Husbands, S. Ahearne, Q. Luo, V. Lain-Rubio, T. Kürner, and L. M. Pessoa, "Reconfigurable intelligent surfaces for THz: Signal processing and hardware design challenges," *European Conference on Antennas and Propagation*, Glasgow, Scotland, 17–22 March 2024, to be presented.

TERRAMETA's Hardware Development

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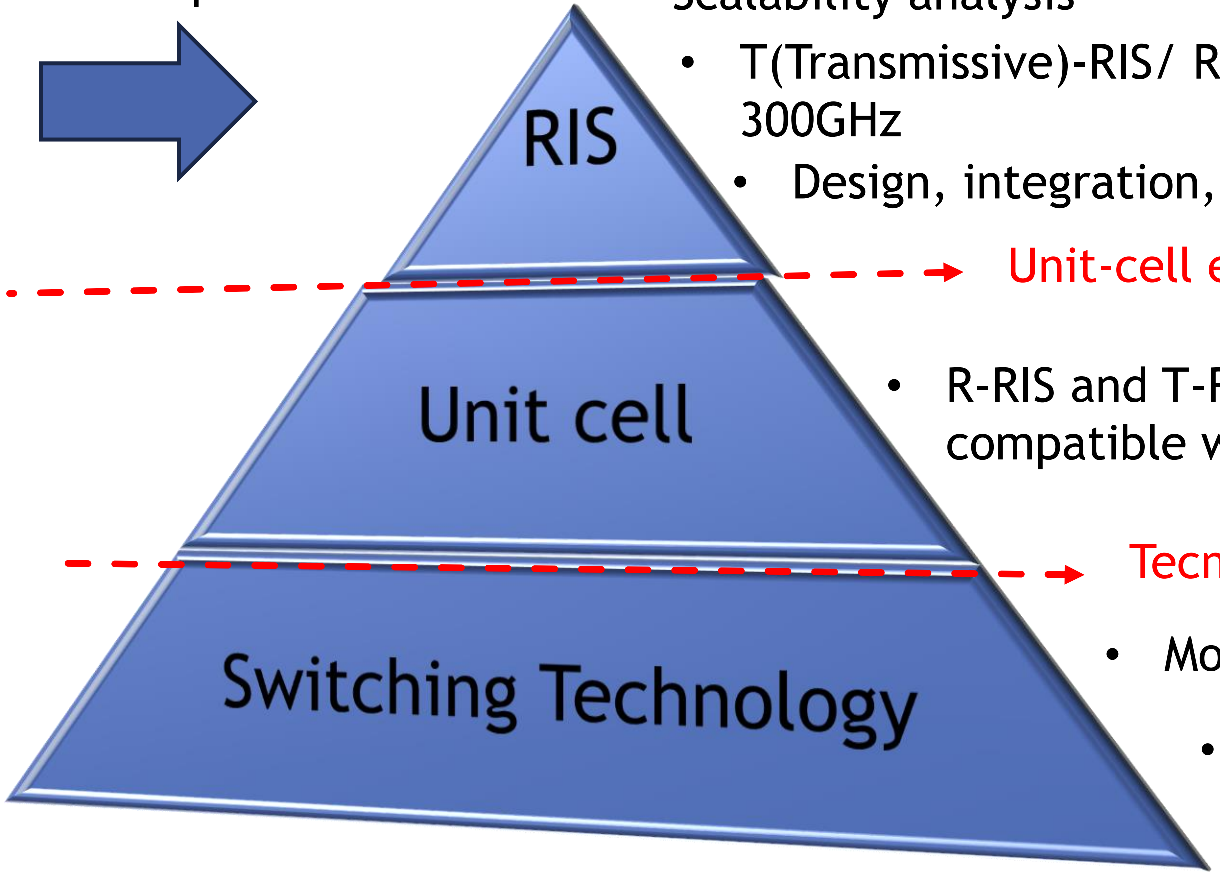
RIS deployment for channel sounding and demonstrators

High-power THz sources development



- Scalability analysis
  - T(Transmissive)-RIS/ R (Reflective)-RIS implementation at 140GHz and 300GHz
    - Design, integration, and characterisation of the controlling circuits

Unit-cell element selection for R-RIS/T-RIS

- R-RIS and T-RIS unit cell designs for 140GHz and 300GHz compatible with different switching tecnologies

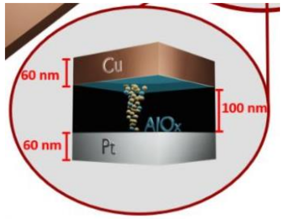
Tecnhology definition for TERRAMETA

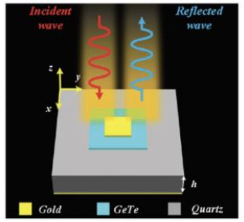
- Modelling and characterisation
  - Development of new fabrication processes
    - Benchmark of different technologies

TERRAMETA's Hardware Development - Switching Technologies

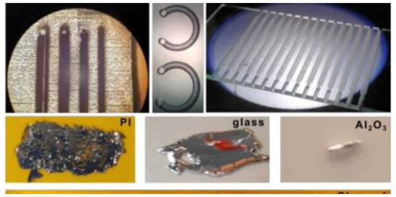
Types of Technologies

Memristors and PCM

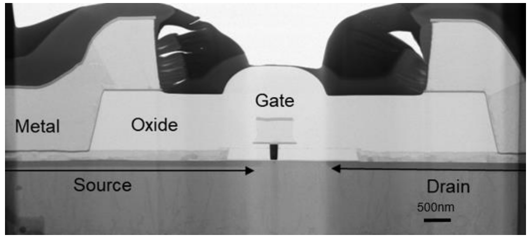




Microfluid



CMOS/wafer based switches



Advantages

Memristors and PCM:
- Miniaturized switch
- Non-volatile switching (retains its state when power is turned off)

Microfluid:
- Continuous phase control
- Lower power consumption

CMOS/wafer based switches:
- More mature technologies
- Easier integration

Challenges

Memristors and PCM:
- Technology development (low TRL)
- Integration issues with unit cell

Microfluid:
- Microfabrication
- Actuation mechanism (this technology is still immature and an actuation mechanism has not yet been established)

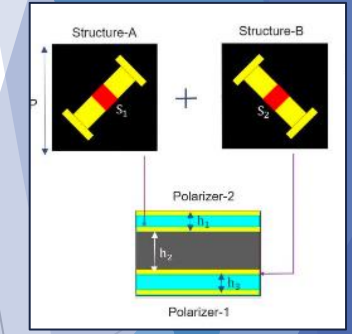
CMOS/wafer based switches:
- Optimisation for RIS applications
- Low-bit phase states
- Fabrication cost

TERRAMETA's Hardware Development – Unit Cell

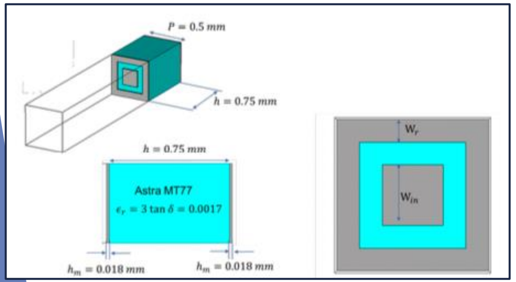
Technology Demonstration (TRL>4)
Research to Prove Feasibility with preliminary experimental tests (TRL 3-4)
Basic Technology Research (TRL 1-2)

- Unit-cell design for R-RIS:
  - Microfluid R-RIS @D-band: tunability by manipulating the movement of liquid in space (continuous phase shift).
  - Passive R-RIS : single-layer patch-based unit cells, different patterns of the top layer provide the required discrete set of phase states (design for 1, 2, and 3 bit tunability).
- Unit-cell design for T-RIS:
  - Passive T-RIS @D-band: three metallic layers printed on low-cost substrates, 4-bit tunability.
  - T-RIS @300GHz: a via-less 3-bit reconfigurable unit cell.

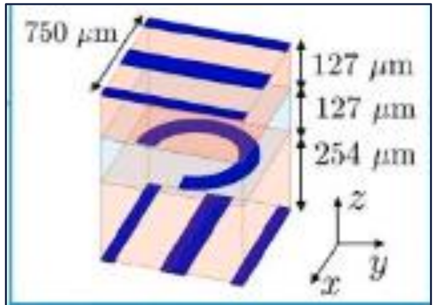
T-RIS @D-band



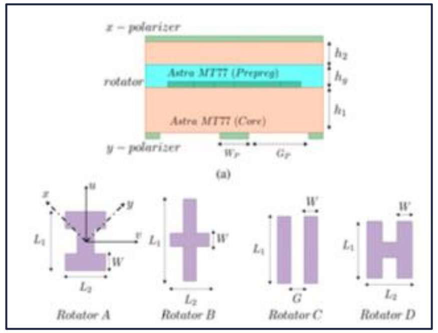
Passive R-RIS @300GHz



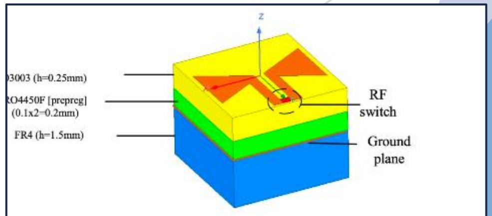
Passive T-RIS @D-band



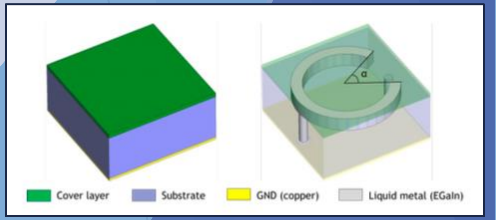
Passive T-RIS @300GHz



R-RIS @D-band

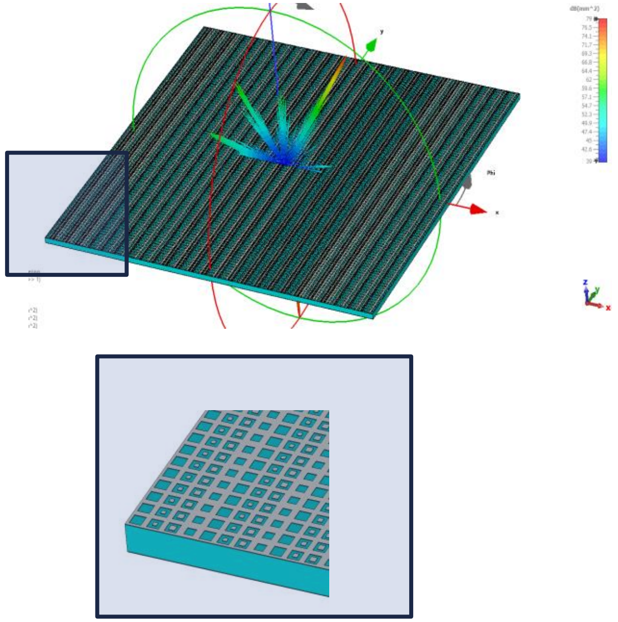


Microfluid R-RIS @D-band

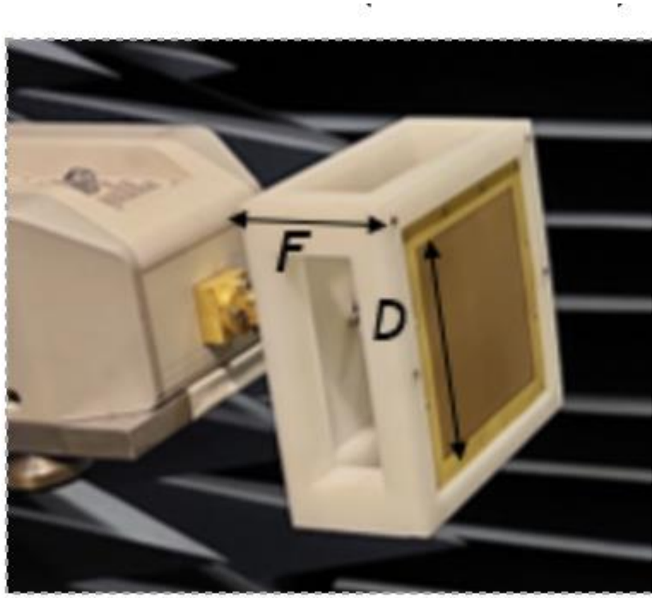


TERRAMETA's Hardware Development – RIS Panel

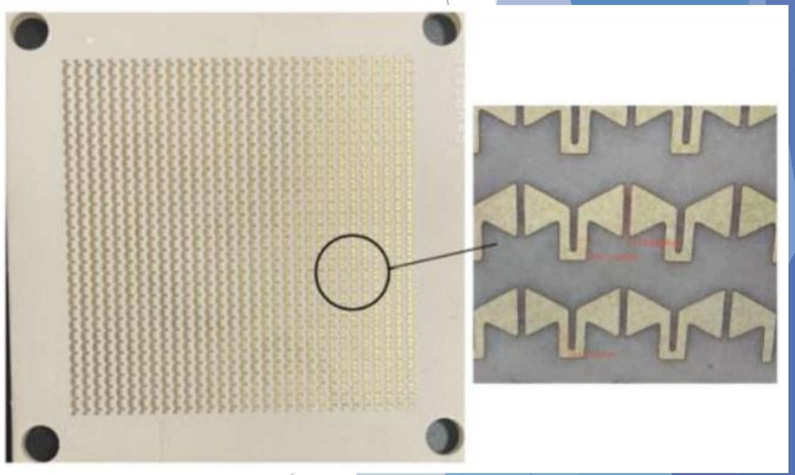
- Passive hardware is being used for preliminary validation of fabrication process, testing, and modelling; development of characterisation techniques.
- Manufactured a T-RIS @300GHz with 47dBi directivity.
- Wideband (50-150 GHz) 1-bit tunable R-RIS based on tightly coupled dipoles.



Passive R-RIS @300 GHz of 5 cm^2 (10k elements)



43 dBi passive T-RIS @300GHz of 7 cm^2



Wideband sub-THz RIS consisting of 31 × 31 tightly coupled dipole elements

THz Design Challenges in TERRAMETA

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- Design of multi-bit phase resolution RIS (2-bits or more) in limited physical space is extremely challenging.
- Mitigation of the high cost for RIS implementations.
- Prove that the main KPIs for RIS use cases can be met when realistic hardware impairments are accounted.
- High power sources with advanced modulation schemes in the THz regime.
- The intrinsic phase wrapping used in the RIS design implies the occurrence of the beam squint, which, for very narrow beams, can have significant impact on the system performance

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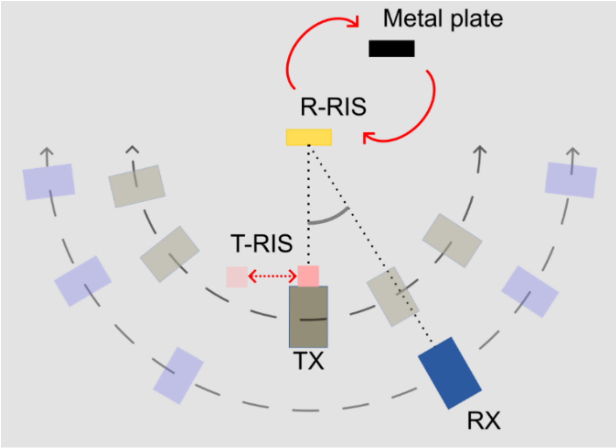
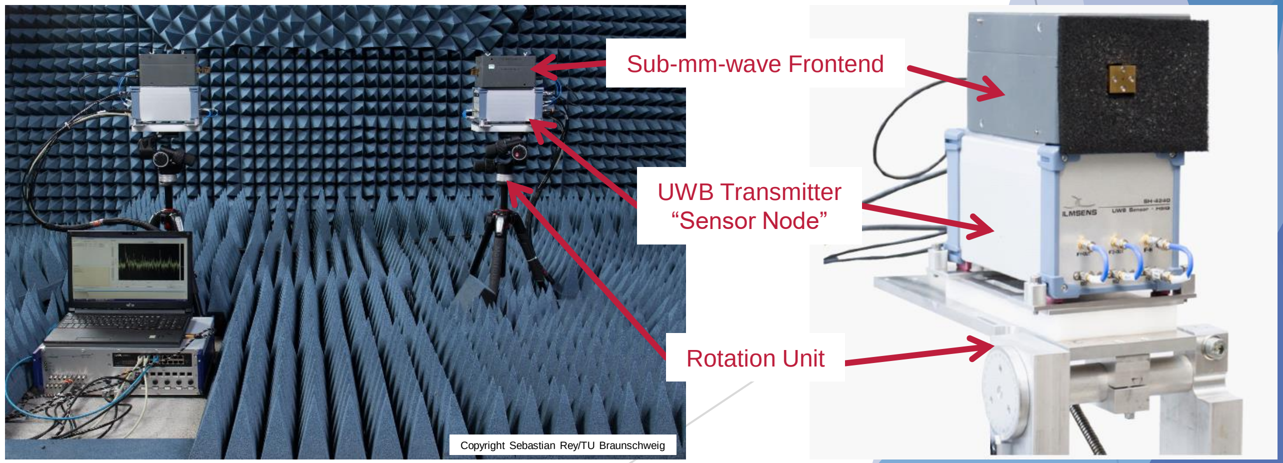
Channel Modelling – TERRAMETA's 1st Measurement Campaign

- THz channel measurement campaign with different RIS types
  - TERRAMETA's first measurement campaign will be performed using a 300GHz channel sounder to characterise both fabricated RISs (T-RIS/R-RIS), and the wireless channel including the RISs, as well as a metal plate as a dummy reflector. Lastly, both far- and near-field regimes will be tested.
- The channel sounding results will be used as a basis for developing new THz channel models. Furthermore, we aim to design innovative algorithms at THz for channel estimation and beamforming, novel strategies for near- and far-field beam management, and novel localisation, and joint communications and sensing schemes for RIS-empowered and ultra-massive MIMO systems.



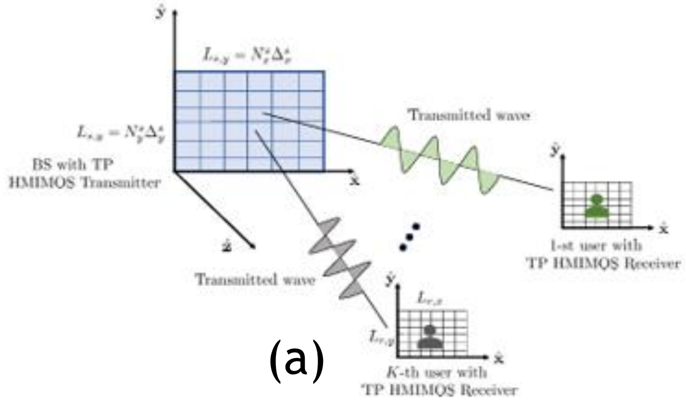
TERRAMETA's channel sounding plan for far- and near-field T/R-RIS-enabled wireless links @300GHz



THz channel sounding equipment from TUBS

Channel Modelling – TERRAMETA's Contributions

- Unit-cell and end-to-end RIS-parametrised channel modelling.
  - Novel multi-user near-field channel modelling with holographic MIMO transceivers (e.g., metasurface-based antenna panels) and triple polarization, using the dyadic Green's function (a).
  - Unit-cell wideband frequency response modelling parametrised in terms circuital hardware parameter, extending the coupled mode theory (b). ***(ongoing)***
  - Channel characterisation from physics-inspired models, categorised mainly as scattering parameter analysis, mutual impedance modeling and coupled dipole formalism (PhysFad channel model). Testing and comparison of the preceding models both regarding to experimental measurement-fitting and signal processing applicability (e.g., for ISAC). ***(ongoing)***
  - Electromagnetics-consistent modelling based on the scattering matrix representation (S-parameters) to model mutual coupling; engineered mutual coupling (non-diagonal entries of the RIS phase configuration matrix) to optimise active and passive beamforming for downlink communications. ***(ongoing)***



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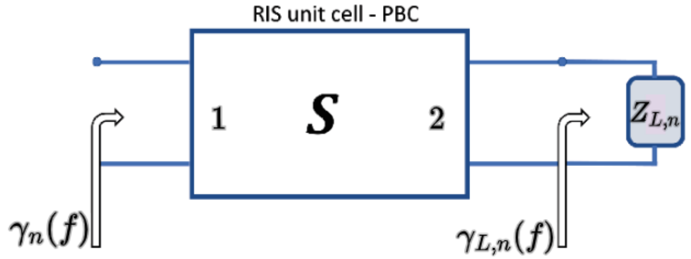

(b)

Signal Processing- TERRAMETA's Contributions (1/2)

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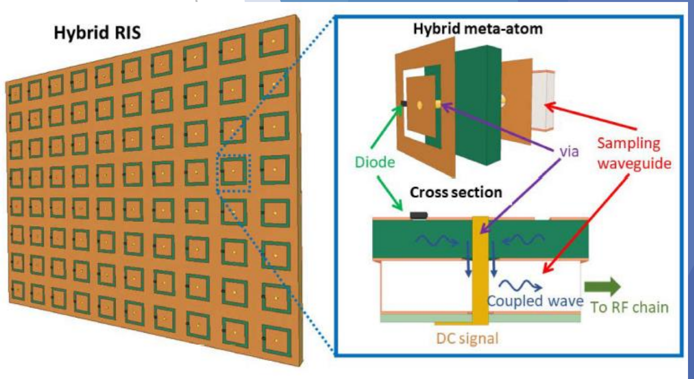
- Estimation algorithms for ultra-massive MIMO THz systems:
  - Time-domain channel estimation for extremely large MIMO THz communications, considering the presence of propagation delays across the entire array apertures, which leads to frequency selectivity (*beam squint*).
  - Channel estimation with metasurface-based (DMA) receivers for low-bit resolution ADCs. ***(ongoing)***
- Beam codebooks for RISs:
  - Near-field hierarchical beam management for RIS-enabled MIMO systems. Design of reflective beam codebooks starting from wider to increasingly narrow beams, which can be used for low over-head localisation and beamforming.
  - Near-field dynamic codebook for directional beamforming using metasurface-based (DMA) transmitters. Design of a dynamic beam focusing codebook for beam-tracking to serve a moving user.
  - Low-complexity neural-network-based beam training for THz Beamforming. Hierarchical codebook search assisted by a neural network to establish the relationship between the codewords in the angle domain to speed up the beam search.

Signal Processing- TERRAMETA's Contributions (2/2)

- Beamforming strategies for ultra massive MIMO (umMIMO) THz systems:
  - Optimal design of RIS-assisted high-rank umMIMO THz channels.
  - Hybrid umMIMO beamforming with DMAs for wideband THz systems.
  - Low-complexity fully digital beamforming transceivers aided by stacked transmissive RISs that realise wave-based analog beamforming (a).
  - A metasurface-based (DMA) receiver architecture with low-bit resolution ADCs (b).
- Localisation and RF mapping schemes:
  - RIS-enabled and access-point-free simultaneous radio localisation and mapping (c).
  - Joint 3D user and 6D hybrid RIS localisation (both rotation and position) (d).
  - Full-duplex metasurface-based (DMA) transceivers for ISAC.



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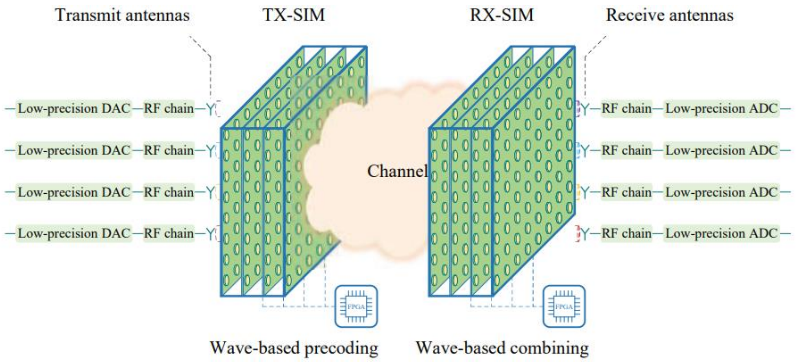
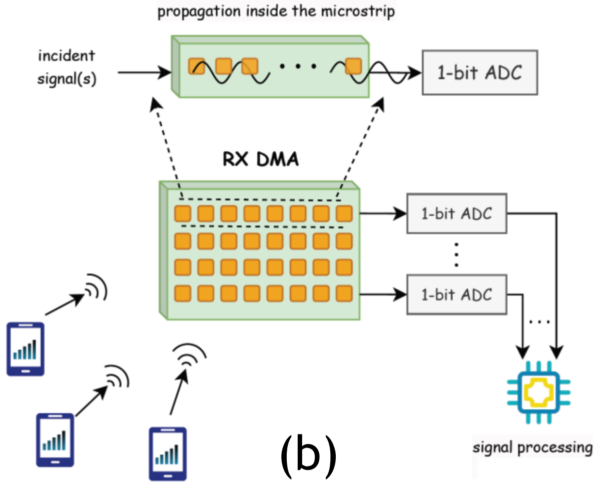


(a)



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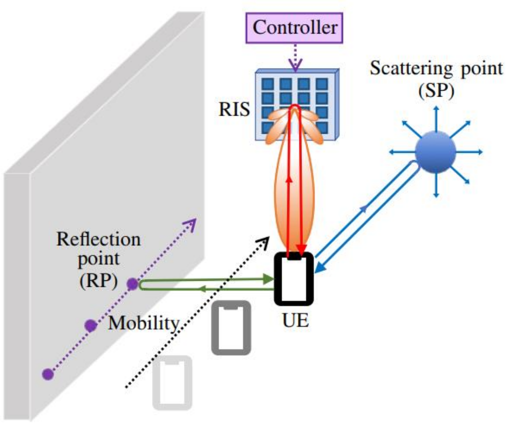


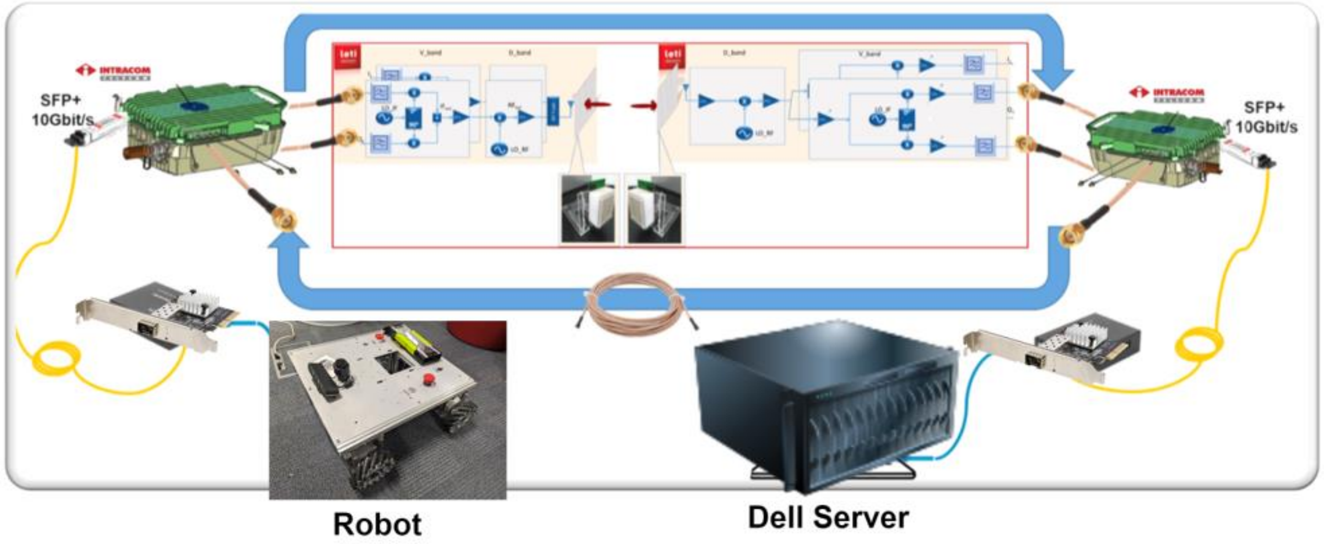
(c)

Signal Processing- TERRAMETA’s Planned Work

- Protocols for cascade channel estimation.
- Hardware limitations on channel estimation algorithms.
- Including RISs into THz backhaul links.
- Sharing of RISs for multiple access points.
- NLOS localisation and sensing for THz.
- Interference management with the aid of RISs.
- RF mapping with receiving and hybrid RISs.
- Potential of RISs with respect to wireless activity monitoring (e.g., presence, number and/or mobility of people or objects in the environment).
- and others…

TERRAMETA's Proof-of-Concept Activities

- Simulation demonstrator
  - Using SiMONE to realize THz communications including an RIS for a complete vision of the project's indoor and outdoor use cases.
- Lab-based demonstrator
  - Testing of the integrated THz devices and the RIS under ideal conditions, to represent the best possible performance of the hardware produced in the project.
- Use-case demonstrator
  - Testing of the final THz and RIS system(s) in the use-case environment: outdoor at BT facilities and in-factory at DELL.



Standardisation

- TERRAMETA has been actively contributing to two standardisation groups at IEEE 802 (IEEE 802.15 SC THz) and ETSI (ISG THz), which are both working towards pre-standardisation of THz communication systems.
  - 2 Contributions to IEEE 802.15 SC THz (plus one on 16 January 2024)
    - There are ongoing opportunities in 2024 (two more meetings are planned).
  - 5 Contributions to ETSI ISG THz to WI#1: Identification of use cases for THz communication systems
    - Targeting contributions in 2024:
      - WI#3: Channel measurements and modelling in THz bands.
      - WI#4: RF Hardware Modelling.

- In addition, NKUA, INESC TEC, and TUBS are also actively participating in ETSI ISG RIS and on the new ETSI ISG on ISAC.

Thank you Hexa-X II for the invitation!
Thank you all for your attention!

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https://terrameta-project.eu/