Partners:
IMEC, LMF, SEQ, NDE, WIN, ORA, SAT, OUL, EAB, AAU, QLC, SON, TUD, BI

HEXA-X-II D5.3 Deliverable

Initial design and validation of technologies and architecture of 6G devices and infrastructure

Hexa-X-II

hexa-x-ii.eu

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Deliverable structure

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  - 2.1 Dimensioning of sub-THz architectures
  - 2.2 Reviewing models of hardware non-idealities
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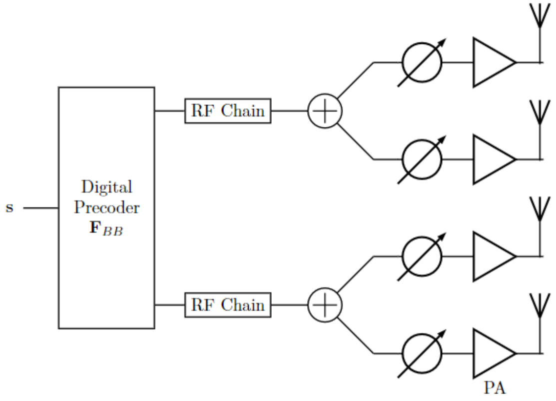
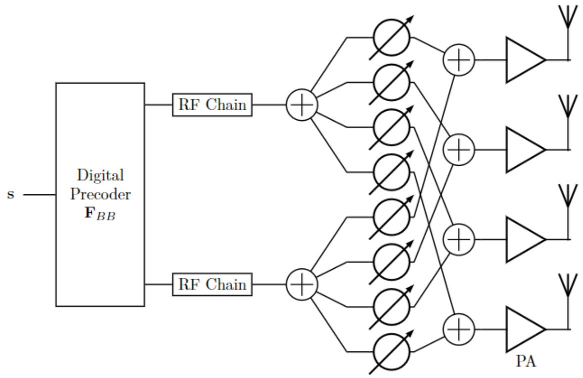
2. Sub-THz transceiver design

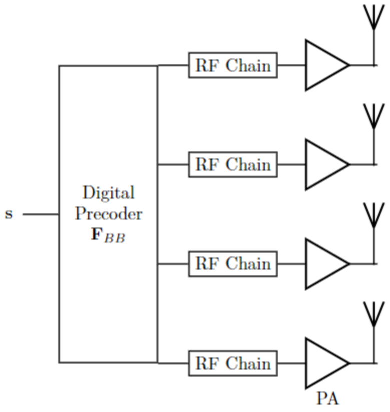
- Architecture dimensioning for maximum energy efficiency
  - Hybrid partially and fully-connected architectures vs. full-digital
  - Power modeling and dimensioning for selected hotspot scenarios
- HW non-idealities
  - Overview of models and recommendation towards sub-THz bands (PA models with memory, frequency-selective I/Q imbalance, per-antenna model correlation)
  - Role of LO distribution on phase noise impact (asymmetries in the different antenna paths)
- Alternative architectures
  - Resonant Tunneling Diodes for simpler architectures at frequencies > 100 GHz
  - Switched beam antenna lenses as lower-power alternative to phased arrays

2.1 - Dimensioning of sub-THz architectures

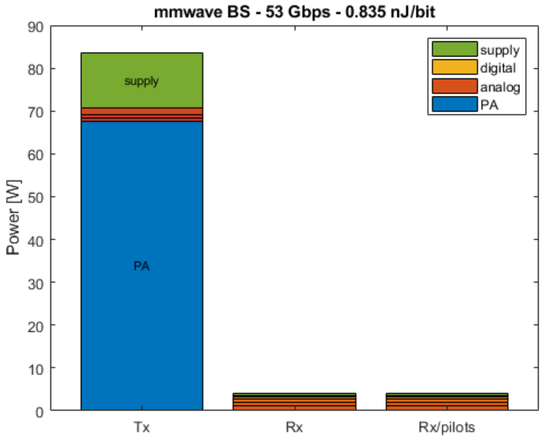
- Hybrid partially-connected / hybrid fully-connected / full-digital
  - Each architecture has benefits for specific scenarios



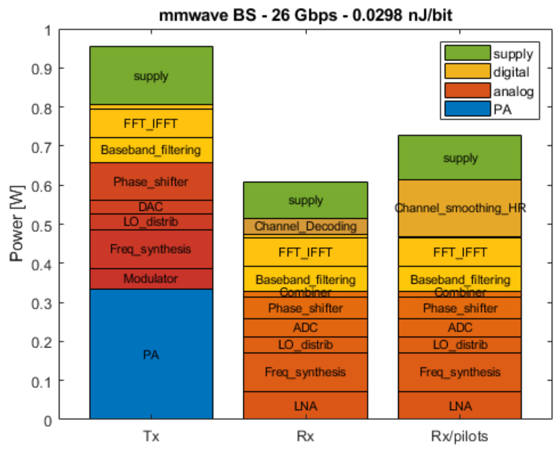




- Key dimensioning for lowest energy/bit (PA output level, number of antennas, MCS, ...)
  - 10x to 50x savings from baseline
  - Simulated for hotspot use cases
    - Small: 10 m, 2x MU-MIMO
    - Medium: 30 m, 4x MU-MIMO
    - Large: 100 m, 8x MU-MIMO/sector
  - Average of Tx and Rx power



0.84 nJ/bit



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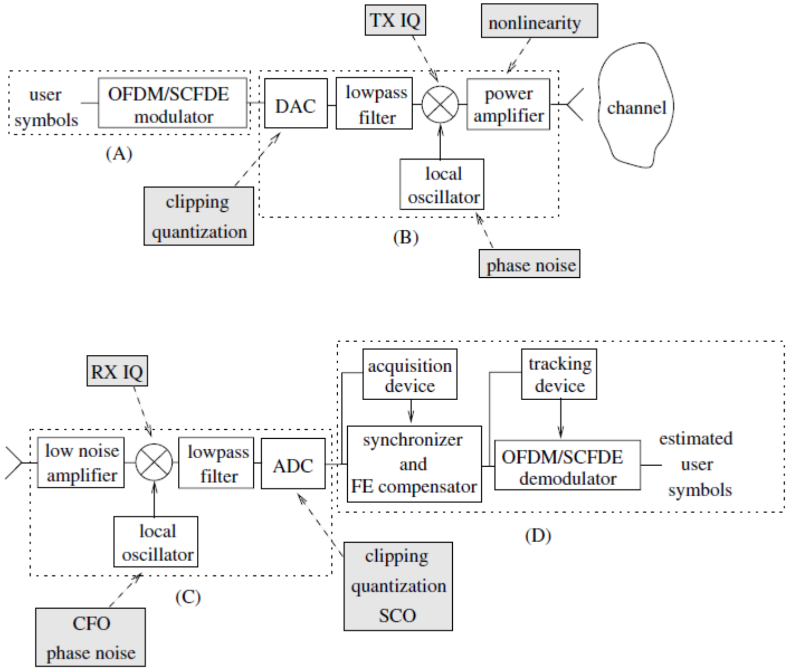
2.2 - Reviewing models of HW non-idealities

- Overview of main HW non-ideality models

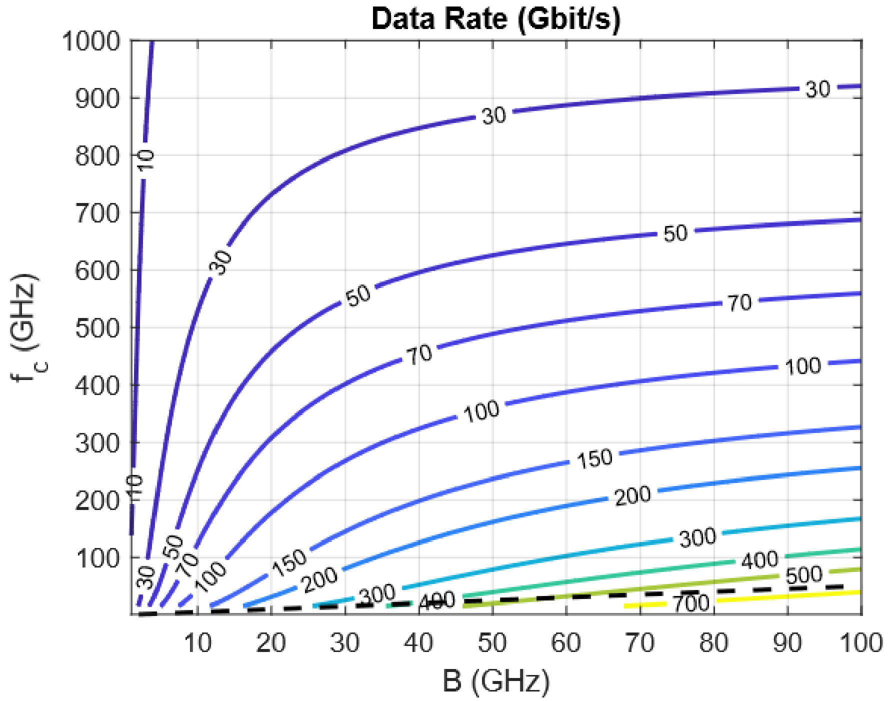
Non-idealities	RF component (main)
PA non-linearity	Power Amplifier/LNA
Phase noise	Local Oscillator
IQ imbalance	Mixer, Low-Pass Filter
DC Offset	Mixer, Local Oscillator
Sampling Frequency Offset	ADC/DAC
Carrier Frequency Offset	Local Oscillator
DAC/ADC non-idealities, clipping/quantization	DAC/ADC
Phase shift error	Phase shifters

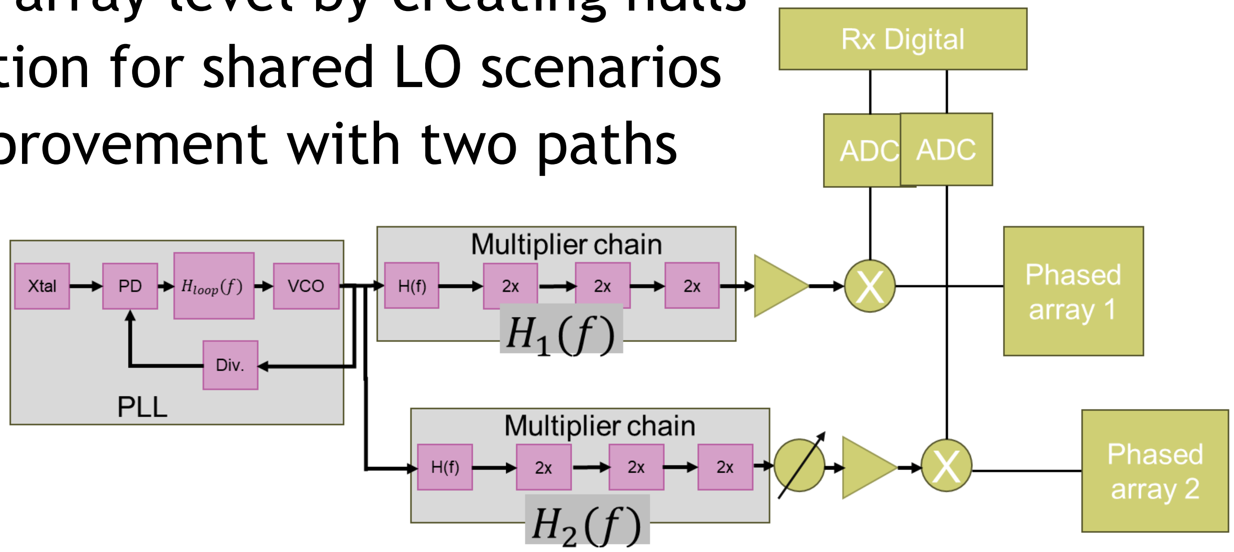


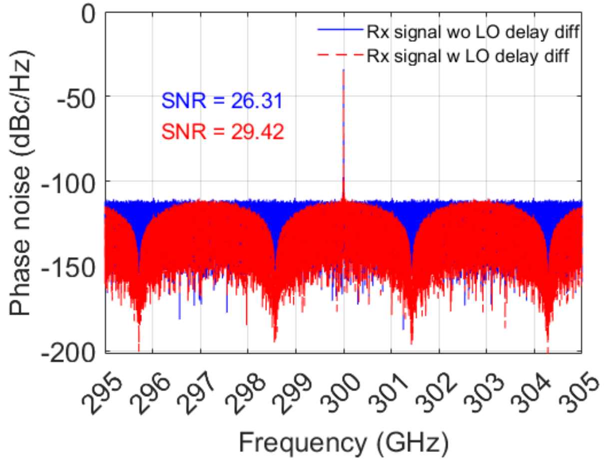
- Expected model updates for sub-THz bands
  - Specificities: higher carrier freq., wider bandwidth, more antennas, different arch.
    - PA models with memory
    - Larger phase noise and wider noise floor integration
    - Frequency-selective I/Q imbalance
    - Increased jitter and noise impact on ADC
    - Per-antenna random fluctuations (PA, LO distribution, I/Q)

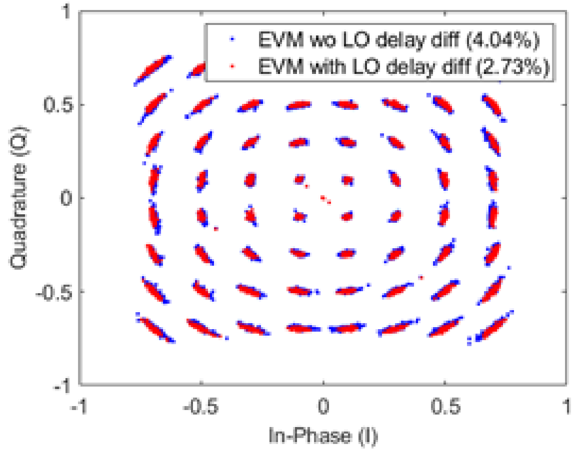
2.3 - Wideband array phase noise analysis and role of LO routing

- Wideband phase noise vs. achievable data-rate
  - ➢Relevant with very wide bandwidths
  - ➢Techniques needed to mitigate wideband phase noise
- Impact of analog delays in LO routing studied
  - ➢Delay difference helps to reduce combined phase noise spectrum at array level by creating nulls
  - ➢Noise reduction for shared LO scenarios
  - ➢3dB EVM improvement with two paths



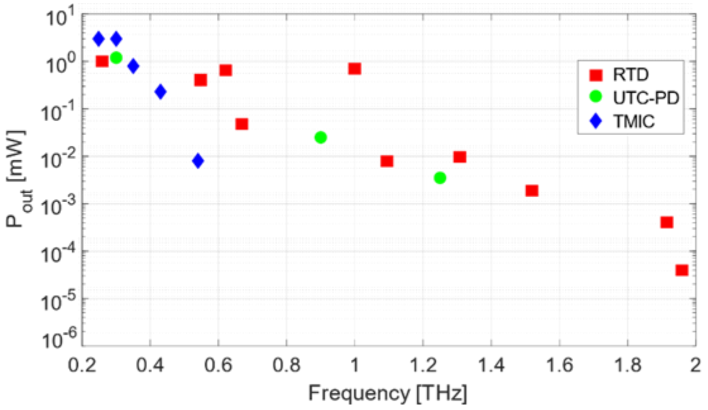


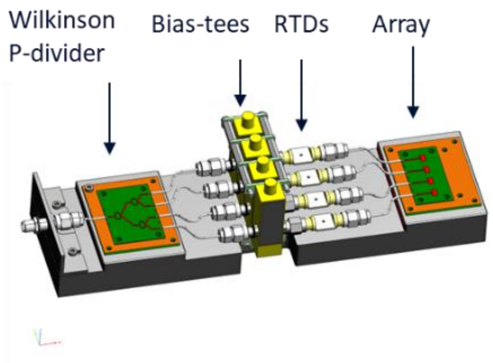


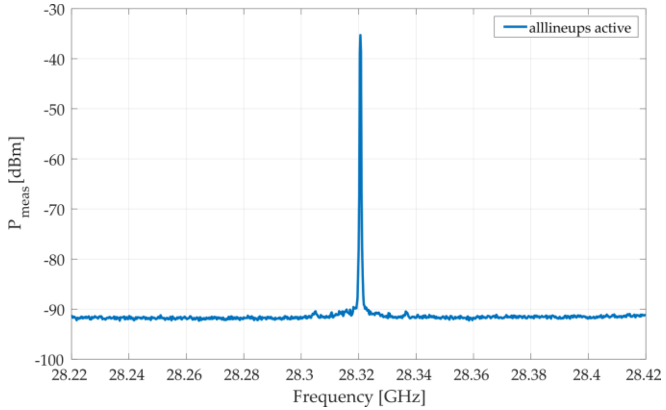


2.4 - Transceiver architectures building on RTD devices

- RTD (resonant tunneling diode)-based architectures represent a promising candidate for future 6G communications, especially for sub-THz/THz frequencies
  - Simpler architecture compared to more conventional transistor-based technologies
  - Easy circuit realization, increased versatility, and energy-efficient implementation
  - Output power limitations of single-based devices can be compensated by means of RTD-based array configurations operating coherently (28 GHz prototype)



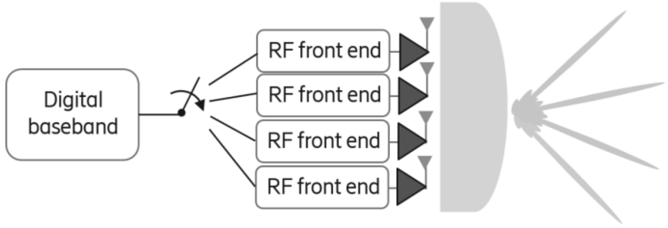




- Antenna integration challenges and solutions (e.g. slot-antenna, patch, bow-tie) are discussed
- Possible modulations supported on such architectures are explored (e.g. OOK, ASK)

2.5 - Switched beam antenna lenses

- Lenses collimate the electromagnetic waves, thus providing a beamforming gain
  - Alternative to phased arrays for sub-THz communication



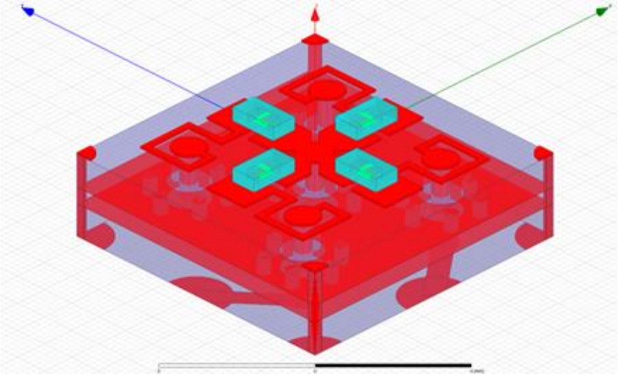
- Advantages
  - Enables beam switching by dynamic antenna port selection
  - Lack of beam squint due to the absence of phase shifters
  - One transceiver chain per polarization is active at any given time
    - Single active PA per direction and polarization
- Example results
  - Power consumption of the lens-based architecture is smaller than phased arrays
  - Achieving EIRP > 50 dBm in UEs is unrealistic by phased arrays
    - Consumed power > 20 W for phased arrays vs. 1-2 W for lens-based
  - Lenses could be considered for both devices and network radios at sub-THz
    - Significantly lower power consumption
    - Physical size of lenses will limit achievable device EIRP, hence UL link budget

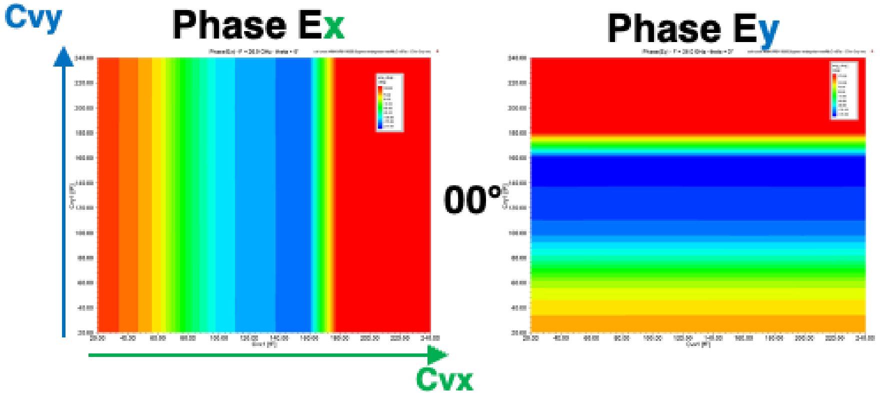
3. Reflective Intelligent Surfaces design

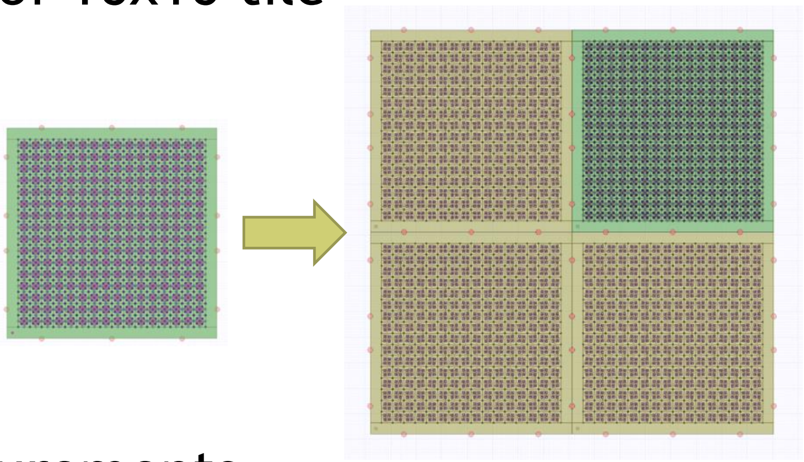
- RIS solutions for range extension
  - 3D radiation pattern modeling and reflection coefficients
  - Cross-validation between models and prototype measurements
  - Scalable architecture tiles
- RIS system integration
  - Different control options in the network
  - Main properties, control functions and protocols

3.1 - RIS models at mmWave

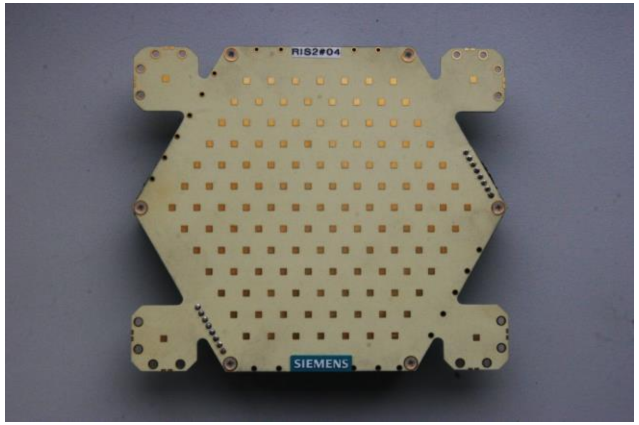
- Dual Polarization Unit cell at mmWave frequencies (24.25 - 27.5 GHz)
  - Continuous reflected phase control with at least 300° thanks to varactor diodes
  - Stable and independent phase controls - Modular design of 16x16 tile

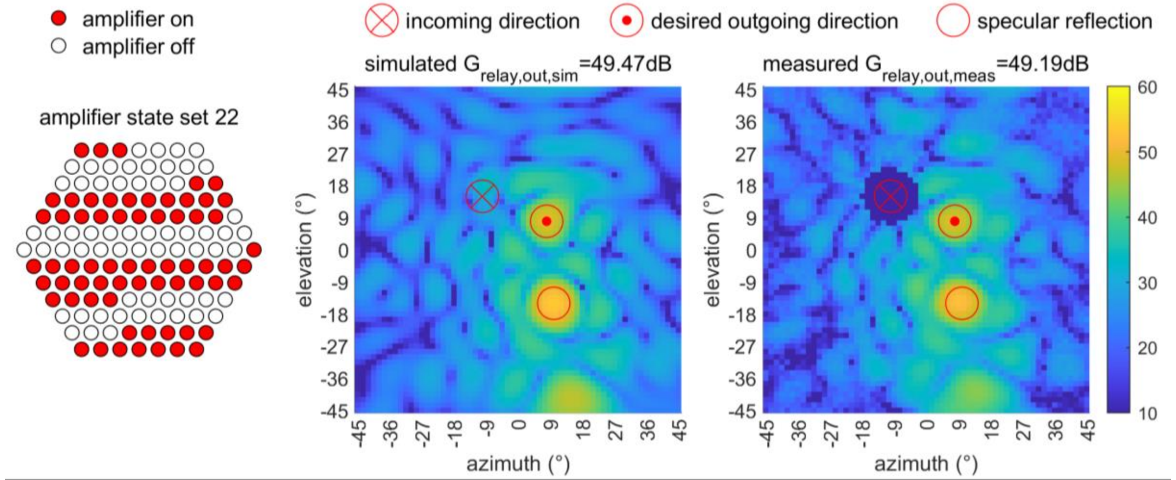






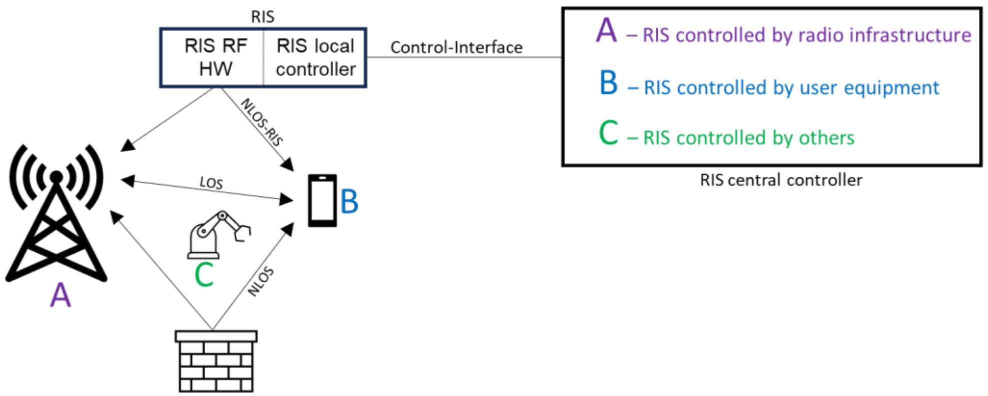
- Validated angular reflections between simulations and measurements





3.2 - RIS system integration

- Three possible control options



- Controller specs clarified
  - RIS properties
  - Local controller functions
  - Interfaces and protocols

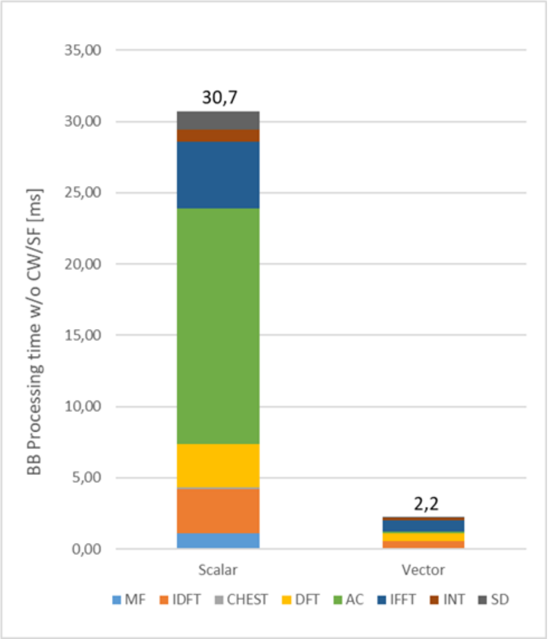
Property	Base unit	Typical value range	Comment
frequency range	GHz	for FR1, FR2, FR3	specifies for which frequency range the RIS is functioning
typical relay gain	dB	>40 dB	Typical relay gain that can be expected from the RIS during operation. It is defined as the gain of a fictional amplifier between a 0 dBi isotropic receive antenna and a 0 dBi isotropic transmit antenna located at the RIS centre position that produces the same field strength as the RIS in the desired target direction.
accepted incoming polarisation	-	H&V, H, LHCP, V, -45°, ±45°, …	Polarizations that the RIS can accept
produced outgoing polarization	-	H&V, H, LHCP, V, -45°, ±45°, …	Polarizations that the RIS can produce
polarization reciprocity	-	Yes Yes, with up/downlink awareness No	Polarization reciprocity defines whether signals can go in both directions without a change in polarization. Most passive RIS will be reciprocal. An active RIS might change the polarization and need direction switching dependent on up/downlink slots.
boresight alignment	dimensional axis	x	Boresight (center) direction of beam steering range with respect to the RIS construction / mounting instructions
polarization alignment	dimensional axis	e.g. vertical polarization aligned with z-axis	Alignment of polarization mode(s) with respect to the RIS construction / mounting instructions
typical beam width	degree (°)	from few degrees to some 10 degrees	Typical beam-with of the main beam when trained on the receiver.
beam control range	degree (°)	from few 10 degrees up to 150 degrees	Angular range in which the main beam can be steered.
switching time	µs	from µs to seconds	Transient time it takes to switch from one RIS configuration to the next (beam switching)
timing accuracy	µs	> a few µs	Accuracy of the time instant at which a pre-scheduled change of a RIS configuration (e.g., beam switching) takes place.
power consumption	W	> a few W	Power consumption of the RIS in operation.
maximum incoming signal power density	W/m²	from few W/m² to several 10 W/m²	Intended maximum power level at the RIS where it conforms to radio regulations regarding linearity.
dimensions	x, y, z	around 15 cm or larger	RIS size depends on operation frequency and typical relay gain
weight	kg	from below 1 kg to several 10 kg	

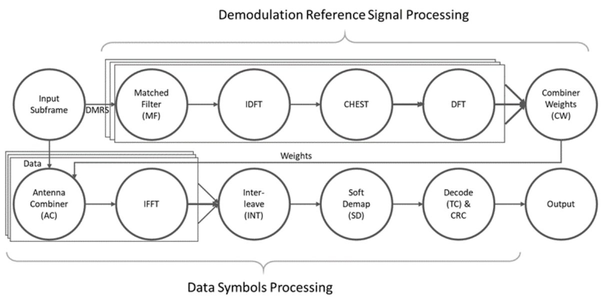
4. 6G System-on-Chip architecture

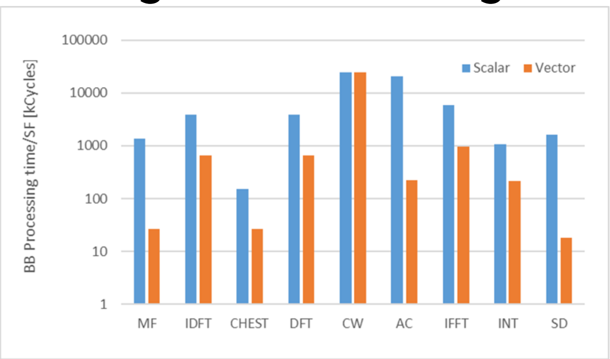
- Advanced DSP and AI capabilities
  - RISC-V based platform and specific accelerators
  - AI for resource allocation and network management
  - MIMO benchmark performance assessment
- Scalable design approach including security aspects
  - Integration of the different cores and accelerators, including high-throughput memory data transfers
  - Isolation of components and trustworthy connections
- Energy harvesting and power management
  - Combination of different energy sources
  - Monitoring and management of energy storage

4.1 - DSP and AI SoC components

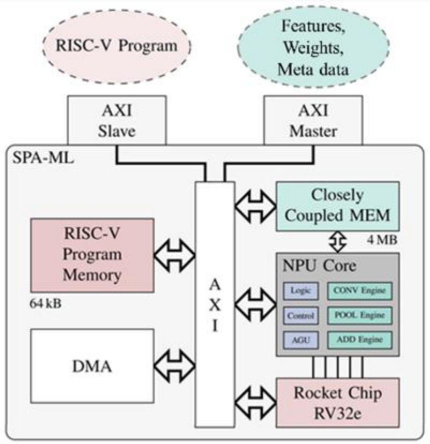
- Investigated RISC-V and its RVV for baseband signal processing
  - Selected scalable MIMO baseband benchmark algorithm commonly used in HW performance evdaluation (PhyBench)
  - Profiling and vectorization of baseband kernels on RISC-V
  - Speedup factor 14 achieved for subframe processing w/o MIMO combiner weight computation -> open problem: MIMO precoding/combiner weight computation







- Proposed AI Accelerator for signal processing:
  - RISC-V Control Processor
  - Scalable network processing unit (NPU)
  - Multi-bank TCM
  - AXI interface

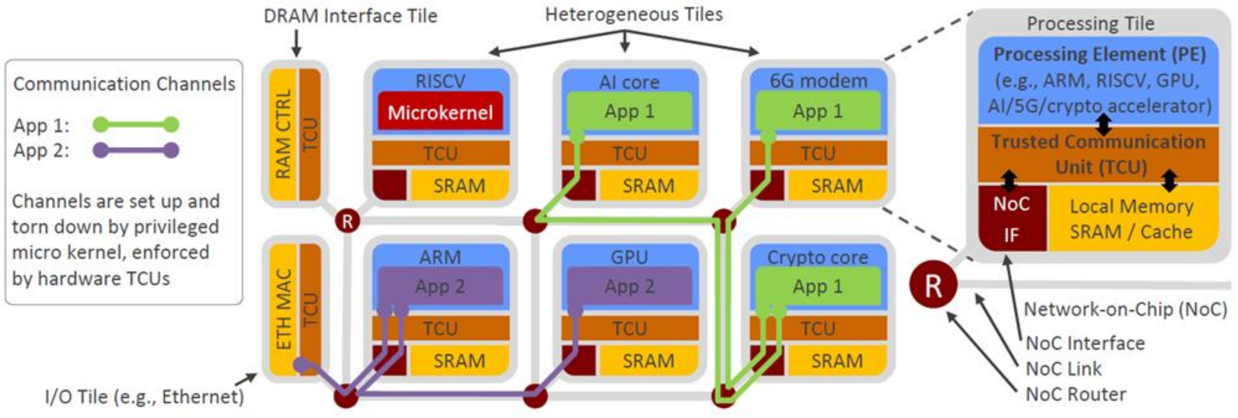


Selected features:
- Tensor DNNs, CNNs, FCNN operations
- Piecewise linear activation approximation
- Bit-serial processing for mixed-precision computations

4.2 - Secure and scalable 6G SoC design

Goals:

- Investigate secure connectivity of SoC HW/SW components by providing hardware-supported application isolation
- Isolate untrustworthy components to prevent their ability to attack other components
- Improve SoC trustworthiness while minimizing the impact of security overhead



General architectural concept of a secure and scalable SoC architecture

Started secure integration of hardware accelerators into SoC architecture

- Goal: Meet application-specific performance requirements
- Challenges:
  - Accelerator requires high throughputs to memory and data transfers
  - Integration with operating system, e.g., process communication, file system access
- Proposed and presented solution (in progress):
  - Add accelerator support module (ASM) into tile to configure the accelerator, load data from/to external memory to/from the local accelerator memory, support features of the OS

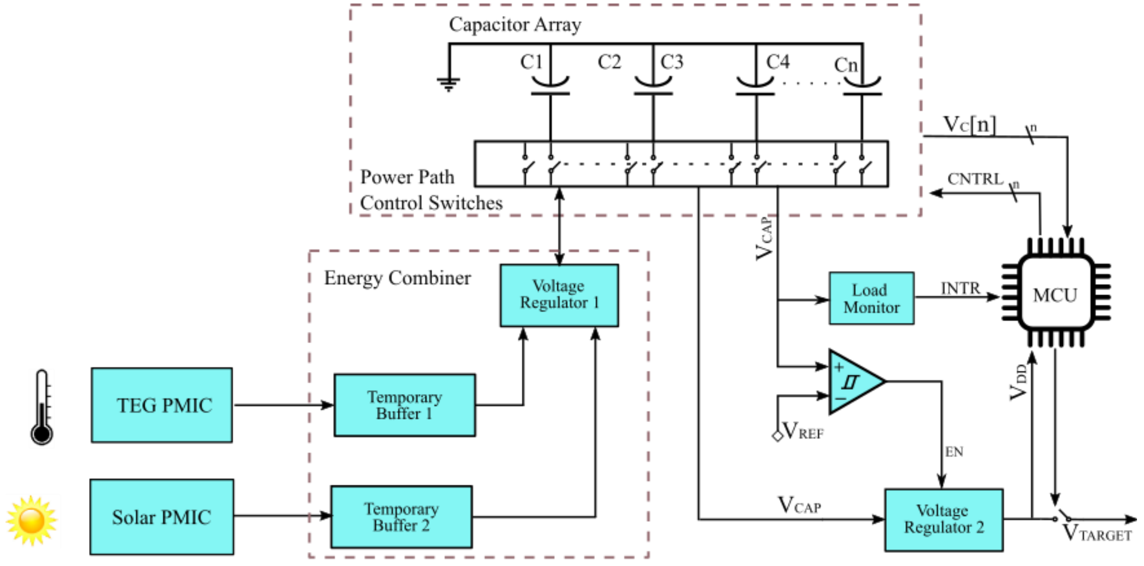
4.3 - Multi-source EH and power management

Requirements:

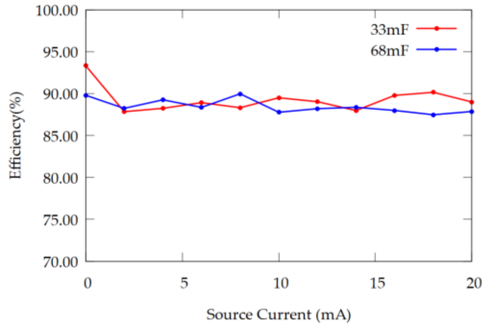
- To achieve simultaneous multi-source energy harvesting
- To collect energy-context data in real time to enable energy-aware applications on energy neutral devices

InfiniteEn

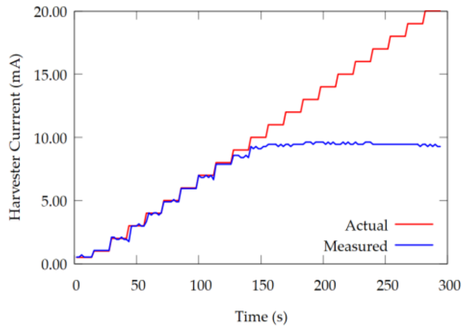
- A multisource energy harvesting power management unit (PMU) that incorporates:
    - An energy combiner: 88% nominal efficiency
    - An energy harvesting rate sensor for sensing harvesting rate in real time
    - A novel load monitoring module (LMM) for monitoring the energy state of the load
    - A reconfigurable storage, enabling on-the-run optimization of energy storage



A high-level block diagram of InfiniteEn.



Efficiency of the energy combiner incorporated into InfiniteEn.



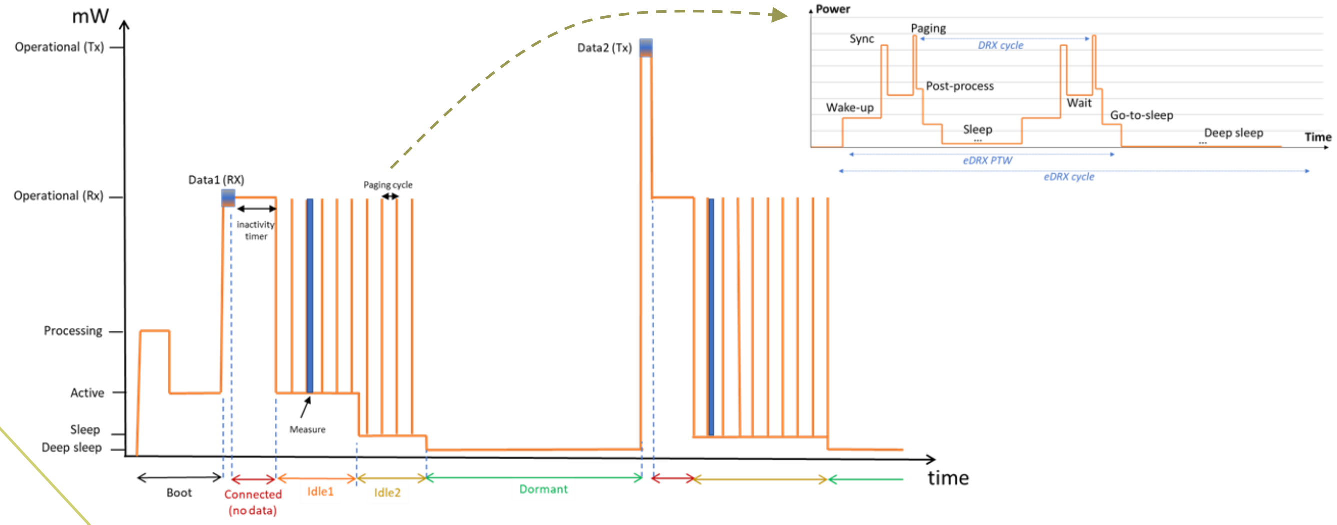
Comparison of actual harvest rate and that sensed by InfiniteEn.

5. Ultra-low cost/power devices

- Low-power operation of battery-operated and energy-neutral IoT devices
  - Analysis of power consumption traces
  - Duty-cycling and power saving modes
- Channel coding gain vs. complexity optimization
- Specific enabling technologies
  - Energy harvesting
  - Energy-aware protocols
  - Tiny ML
  - Wake-up radios
  - Connectionless 6G modes
- Zero-Energy PoC progress in lab and field trials
  - Communication via backscattering of reference signals

5.1 - Energy, cost, and performance trade-offs

- Power consumption analysis for 6G IoT modem
  - Insight for evolution of power saving mechanisms
  - Battery lifetime KPI assessment
  - Current progress:
    - Identify legacy and future potential features/mechanisms
    - Setup evaluation methodology
    - Realistic power model for legacy (NB-IoT) modem according to 3GPP technology configuration and lab measurements
  - Ongoing: generalised model parameterisation
  - Future plan: Generalised parameterization for flexible analysis of future EmMTC/ZE devices



- adaptive low-power sleep modes and duty-cycling at both Tx and Rx
- adaptive energy-aware configuration for uplink and downlink transmission
- energy-aware channel access, synchronization, signaling, scheduling
- wake-up radio implementation
- advanced battery technologies, e.g., rechargeable battery storage of low self-discharge
- EH forecasting/management mechanisms
- lightweight security mechanisms
- low complexity sensing
- tiny ML for ZED targeting higher-end applications
- …

- Channel coding
  - Significant performance gain over uncoded transmissions
  - Requires additional complexity
  - Specific for ultra-low power devices

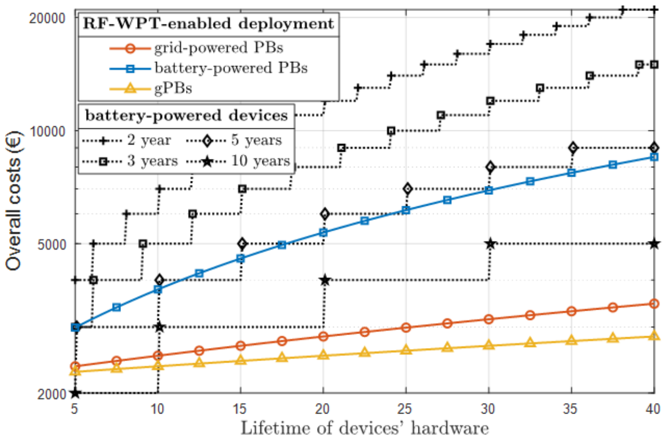
Code	Relative encoding complexity[3]	Performance gain over uncoded[4]
Tail Biting Convolutional Code[1]	1	5.5 dB
Turbo Code[1]	2	6.5 dB
Systematic Polar Code[2]	>10	7.2 dB

Notes: 1 [36.212]
2 [VHV16]
3 Extrapolated from [DF03] and [VHV16], Polar Code complexity depend on block length.
4 Eb/N0 gain with respect to uncoded transmission, for BPSK over AWGN channel, 112 bits payloads, 1/3 code rate

5.2 - Enabling technologies

- EH technologies
  - Suitable sources (light, heat, microbial fuel cells, vibration, RF) depend on the availability, energy demands and constraints
  - KPIs: power density, conversion eff., dynamic range
  - Performance boosters: array of transducers; widening frequency and spatial response; multi-source EH

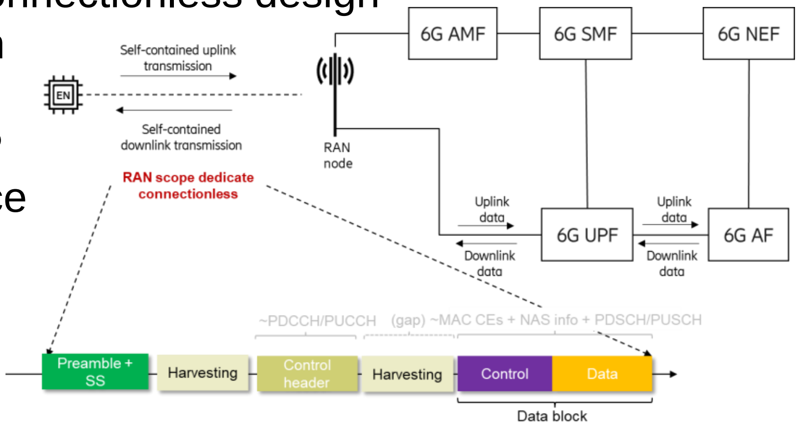
- RF-WPT
  - The deployment of PBs for RF-WTP can be cost-effective for charging massive IoT deployments



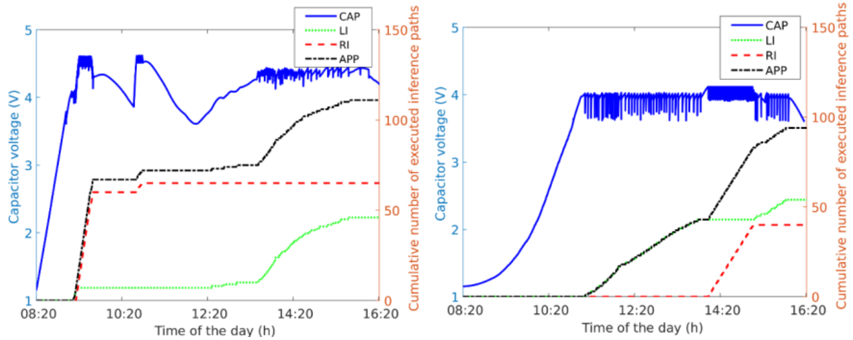
- Intelligent wake-up & duty cycling
  - Advanced (network side) or lightweight (device side) ML-based scheduling algorithms considering the sleep patterns of devices
  - Energy/ambient-awareness

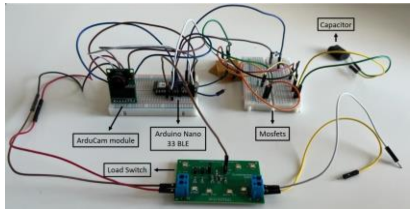
- Energy-aware protocols for communication and sensing
  - Adaptive and manage energy resources
  - Select and adapt uplink and downlink transmission and scheduling based on availability of energy source
  - Assistance information on device status provided to the network

- RAN scope dedicated connectionless design
  - Lightweight connection with 6G RAN
  - Improved NAS and UP security between device and 6G core network



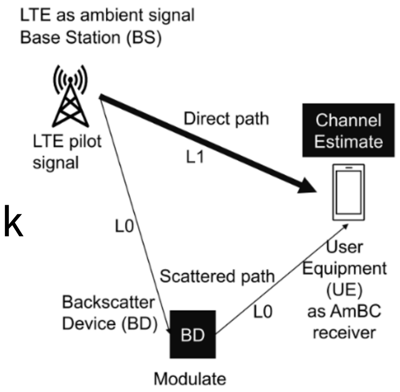
- TinyML

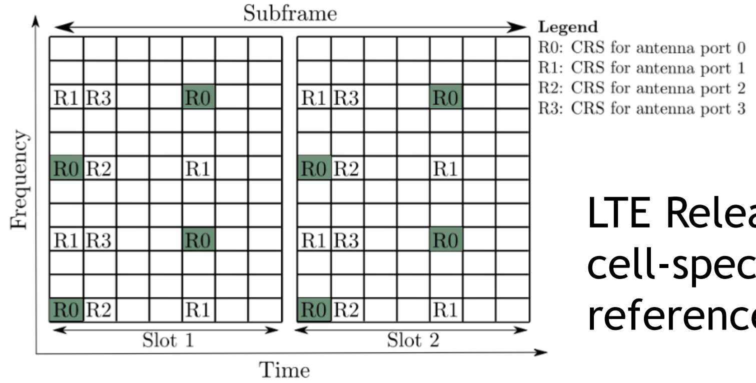




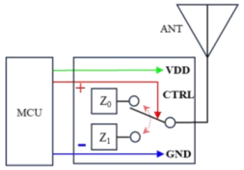
5.3 - ZE PoC

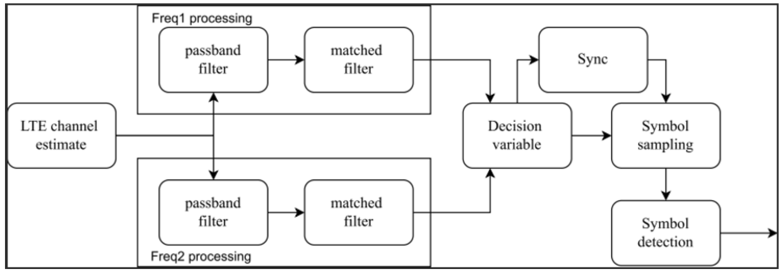
Downlink setup



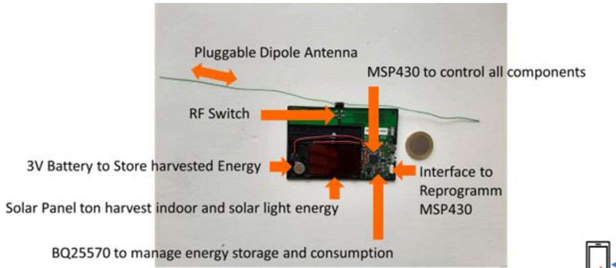


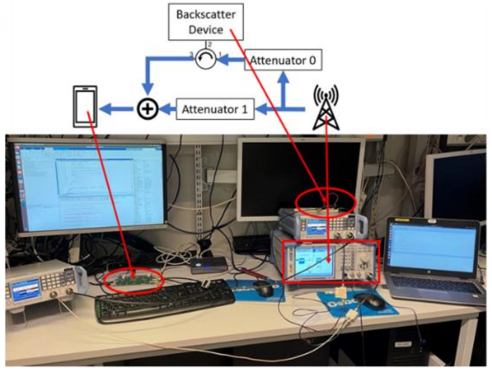
LTE Release 8 cell-specific reference signal



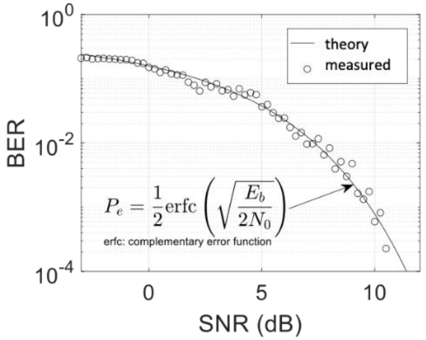


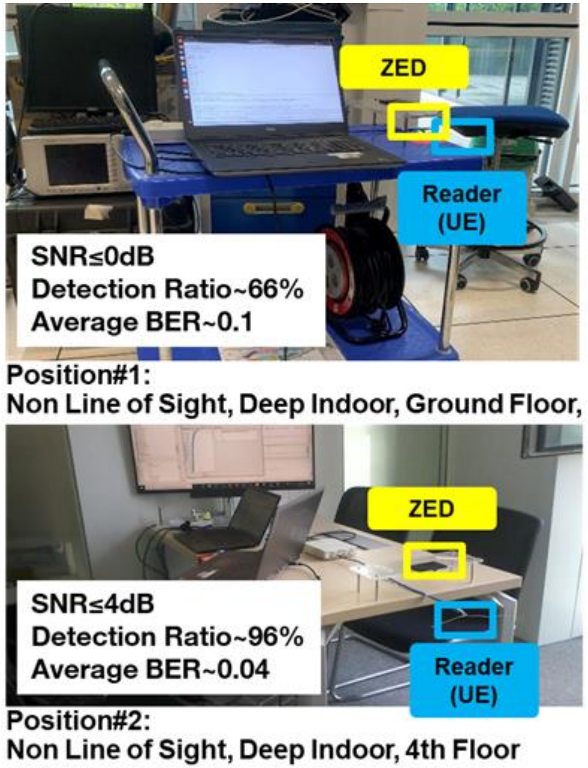
Flow chart of the proposed backscatter receiver





Laboratory tests





Field trial

6. Conclusions

- Hybrid partially-, fully-connected and full-digital architectures are relevant for sub-THz
  - Proper dimensioning (antennas and output power) has huge impact on energy eff.
- Analogue HW non-idealities need proper models for sub-THz performance assessment
  - Impact from higher carrier, wider bandwidth, more antennas and specific arch.
  - LO distribution in wideband arrays has strong impact on phase noise
- Resonant Tunneling Diodes and switched-beam antenna lenses offer alternative options
- RIS-based solutions are modeled from matching simulations and measurements
  - Proper control integration based on listed properties can enhance connectivity
- Flexible and energy-efficient SoC solutions integrate DSP and AI cores on RISC-V platform
  - Security aspects can be implemented using trusted communication between tiles
  - Multi-source energy harvesting and management of energy buffers are demonstrated
- Ultra-low power/cost IoT devices build on many technology enablers
  - Performance/longevity dynamics investigation, low-power channel coding, energy harvesting, wireless power transfer, tinyML, intelligent wake-up
  - A zero-energy PoC demonstrates backscattering using ambient cellular RF signals

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