Mmw readout for particle-physics detector WADAPT

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Wadapt

- Wadapt: "**Wireless Allowing Data And Power Transmission**"

- Objectives:
 - Precise definition of the needs of particle-physics detectors

  Topology, number of channels per detector, power required per channel, expected data rate per channel, local environment (implementation, radiated heat, radiation, magnetic field, reflections, attenuations, couplings, etc.), global environment (experimental setup, machine operation mode, etc.)

  - Evaluation of the present technologies for data and power transfer
  - The chosen technologies will be required to operate under harsh conditions with a high level of reliability, over 10 to 20 years

- Consortium
  - CERN, European Organisation for Nuclear Research, Genève, Switzerland
  - CEA/LETI/DRT/DACLE/LAIR, Grenoble, France
  - Argonne National Laboratory, Argonne, IL 60439, USA
  - Gangneung National University, Korea
  - CEA/DSM/IRFU/SPP, Gif-sur-Yvette, France
  - University of Heidelberg, Germany
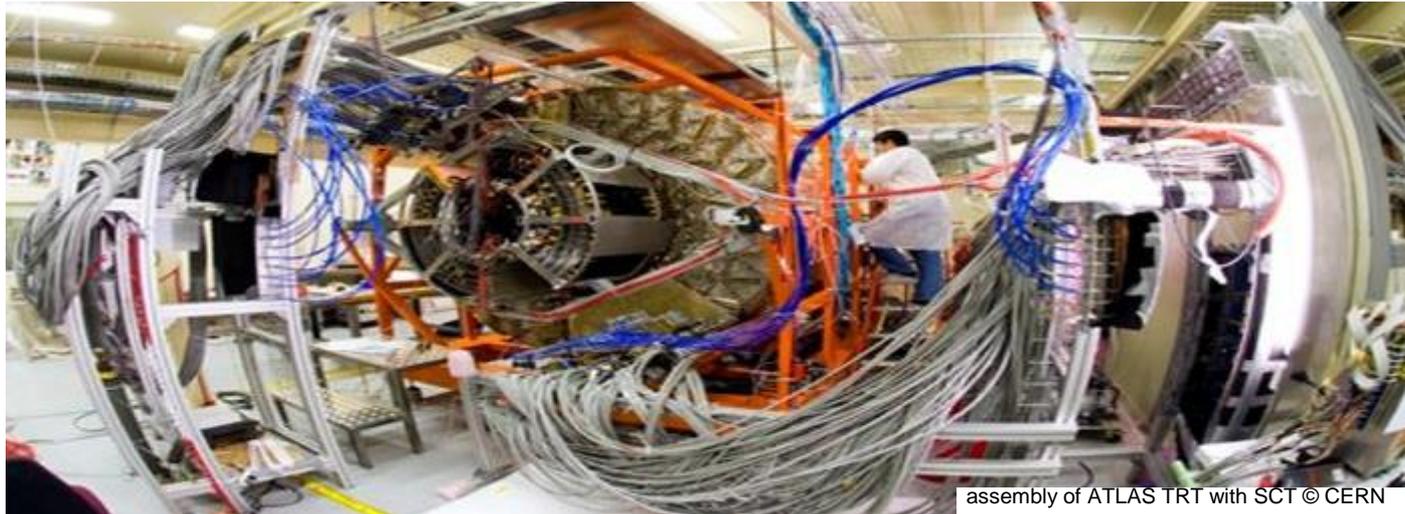
assembly of ATLAS TRT with SCT © CERN

- **<u>Impact on the measurements</u>**
  - Multiple scattering and nuclear interactions
  - Dead-zone areas
- **<u>Impact on the installation and the operation</u>**
  - Cables and connectors are fragile
  - Cable path is not so flexible
  - Design constraints
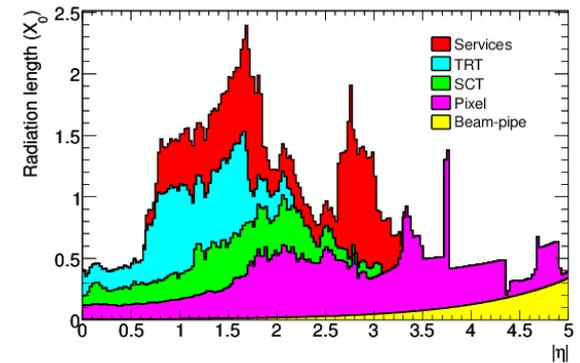
Leti mmw | 3

Why Wireless ?

- Minimize material budget of cables/connectors

Limited radiation length because of massive services in region between Barrel and Disks
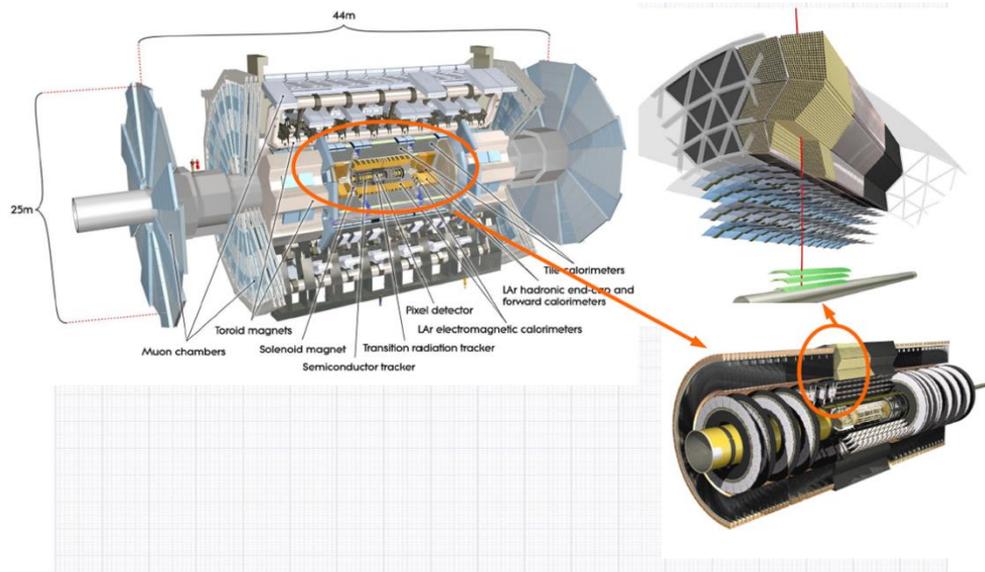
Atlas radiation length

Richard Brenner – Uppsala University   3/(22)   WADAPT June 12, 2015

- Axial readout induce important latencies
  Direct communication between layers (radial readout)
- More flexible transceiver placement
- Point-to-Multipoint links, interlayer intelligence
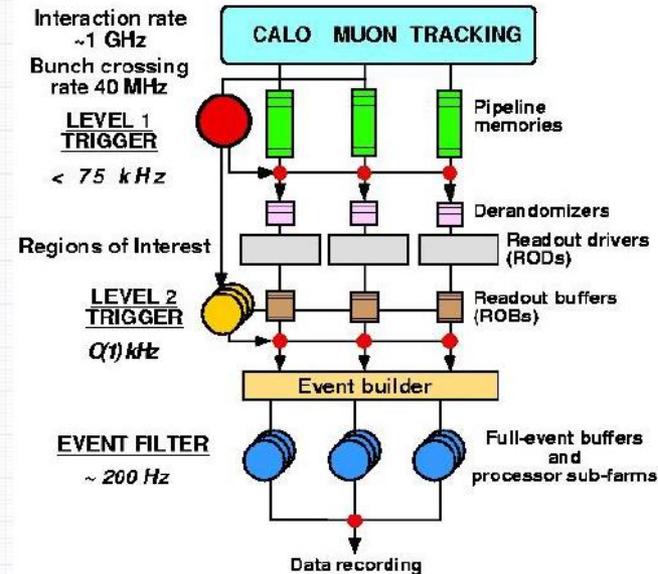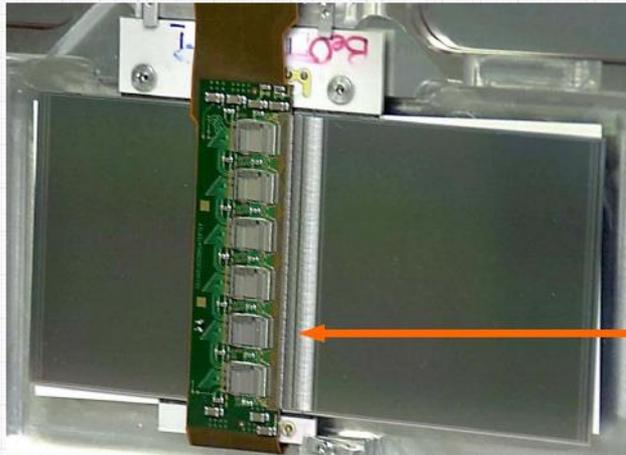- Data follows event topology enabling fast triggering

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Data flow

- Collisions in LHC at 40MHz
  - All data stored in detector front-end electronics for ~3µs
  - Decision based on muon and calorimeter information to readout data at ~100kHz

Front-end ASIC

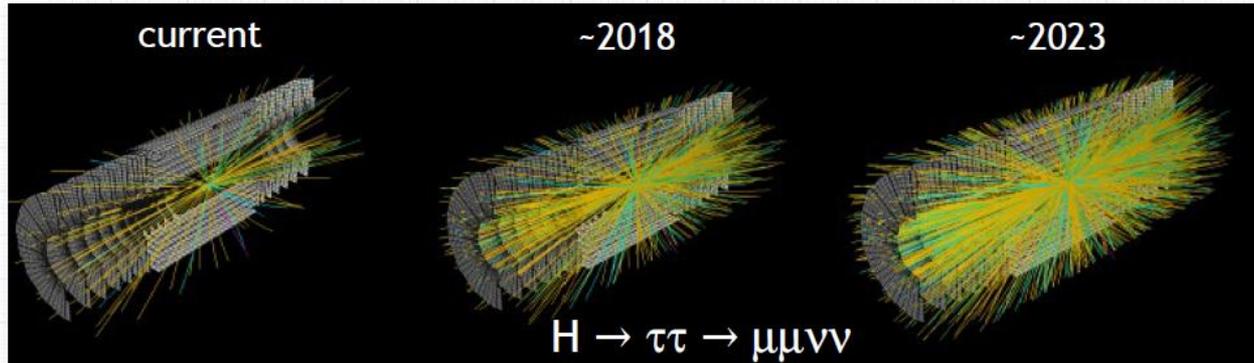Richard Brenner – Uppsala University   4/(22)   WADAPT June 12, 2015

E.g.: Large collider readout

Future data challenge

current   ~2018   ~2023

$$H \to \tau\tau \to \mu\mu\nu\nu$$

The only sub-detector currently not used for fast trigger are the tracking detectors.
To maintain current trigger thresholds at HL-LHC for maximum physics output
The tracking detectors (being the most granular) can make this possible.

This will however require

+ Fast data transfer for short latency
+ Matching with current trigger objects
+ High band-width transfer of large amount of data
+ Possible data reduction on detector

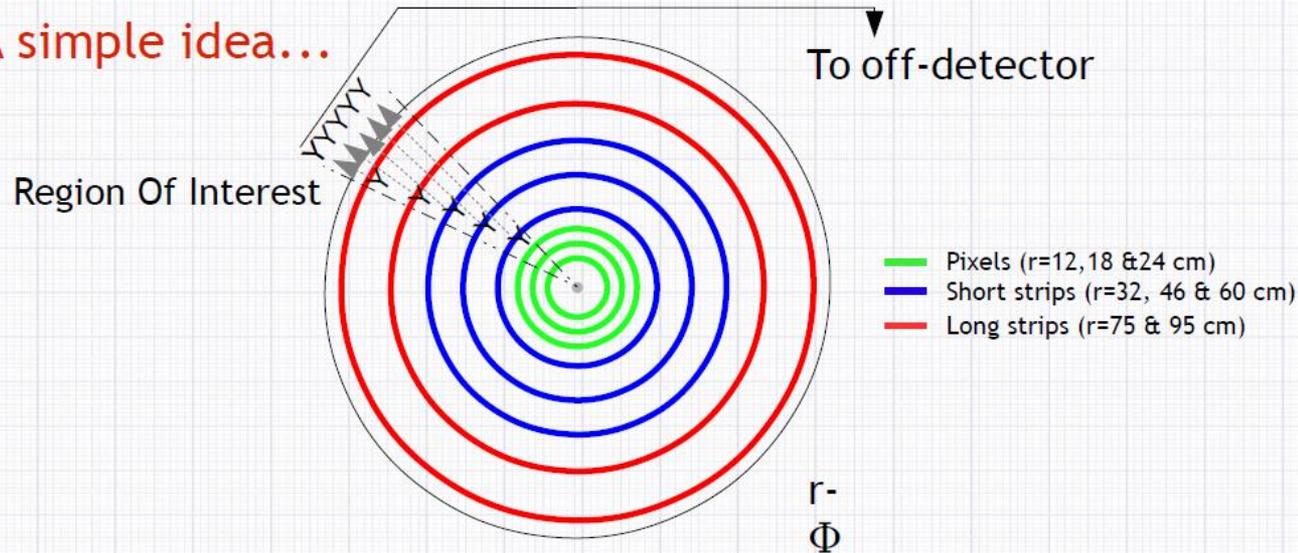Leti mmw | 6

Track trigger and data rate reduction

A simple idea...

Region Of Interest

To off-detector

- Pixels (r=12,18 &24 cm)
- Short strips (r=32, 46 & 60 cm)
- Long strips (r=75 & 95 cm)

r-Φ

...but not trivial to build on detector

→ If only 1-2 hit clusters from a few strip layers are read out for L1 trigger the required bandwidth is 50-100 Tb/s!

→ The detectors is fortunately divided into a 20-50k independent segments and if each is provided with a link then the bandwidth/link < 5 Gb/s Perhaps doable after all?

■ Heidelberg Univ.

Outer enclosure

Layer 3

Layer 2

~10cm

Layer 1

high p_T track
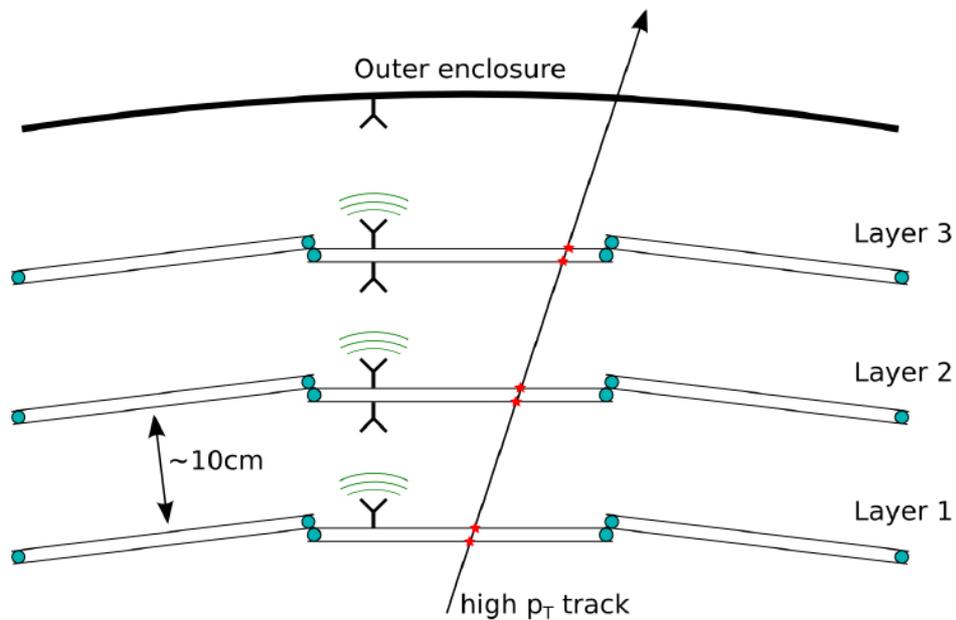
Idea by R. Brenner (Uppsala)

Wireless readout concept

- Radial data transfer
  → Communication between layers

- Signal cannot penetrate layers
  → Reuseability of frequency channels

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Millimeter-waves technology

- 30 to 300 GHz
- Wavelength (λ) of few mm (eg. 5mm @60GHz)
- Multiple Gbits/s (Several GHz of bandwidth)
- High "natural" signal attenuation (68dB@1m at 60Ghz)
- suitable for short range communication

60GHz transmitter © Universtität Heidelberg
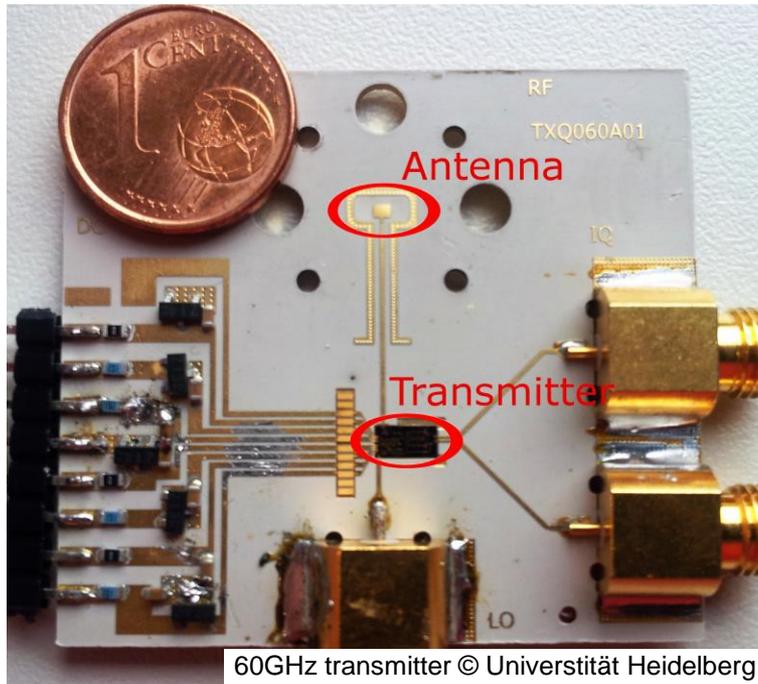
- Compact and low power system
- High integration
- High density
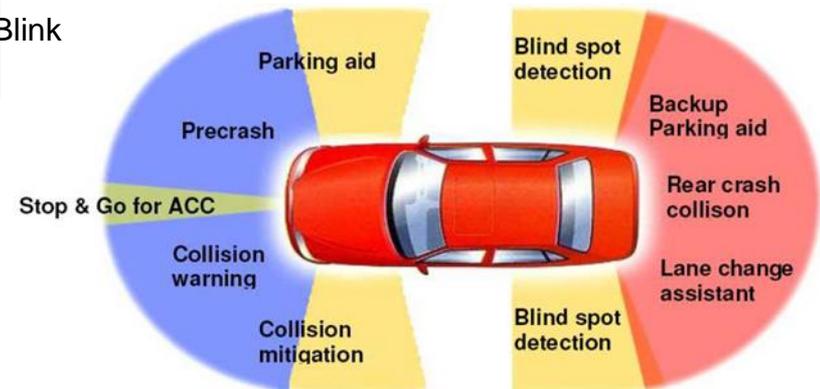
Wireless HD and WLAN 802.11ad (WiGig)

Backhaul and fronthaul

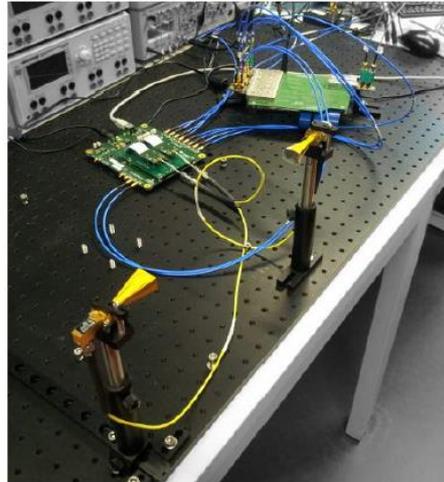EBlink

24 and 79GHz Automotive Radar

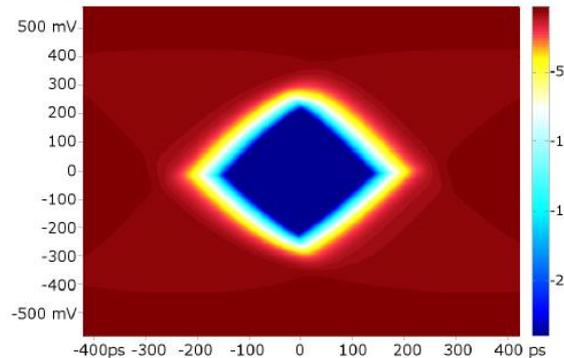## Tests in Heidelberg: line of sight transmission
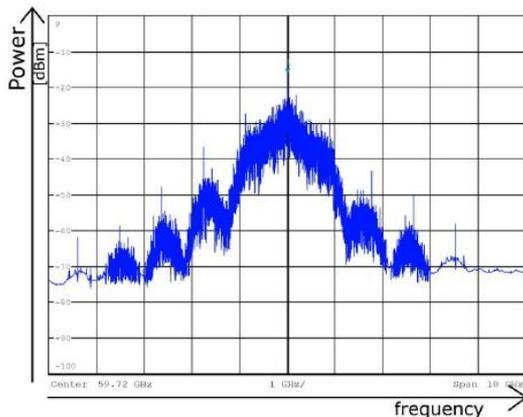
Setup in the lab

Distance: 22 cm
Horn antennas from
Kapton und aluminium

60 GHz spectrum

1.76 Gbps eye diagram

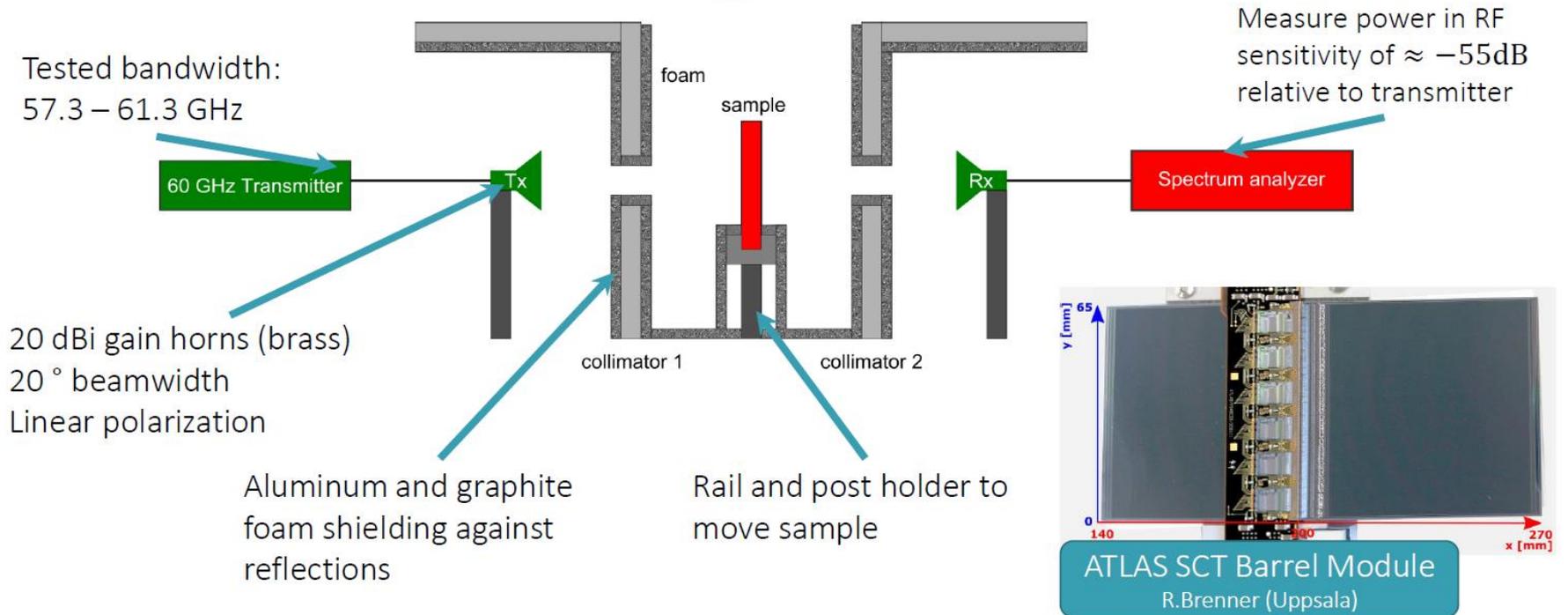## Data transmission studies

- 60 GHz Tx/Rx byHittite HMC 6000/6001
  - Bandwidth: 1.8 GHz

- Setup: Bit error rate test
  - Data rate: 1.76 Gbps
  - Minimum Shift Keying
    $BER < 10^{-14}$

- HD-SDI-Video transmission

Tests in Heidelberg: intra layer signal confinement

Transmission through detector modules

Tested bandwidth:
57.3 − 61.3 GHz

60 GHz Transmitter

20 dBi gain horns (brass)
20 ° beamwidth
Linear polarization

foam

sample

collimator 1   collimator 2

Aluminum and graphite
foam shielding against
reflections

Rail and post holder to
move sample

Measure power in RF
sensitivity of ≈ −55dB
relative to transmitter

Spectrum analyzer

ATLAS SCT Barrel Module
R.Brenner (Uppsala)

Tests in Heidelberg: intra layer signal confinement
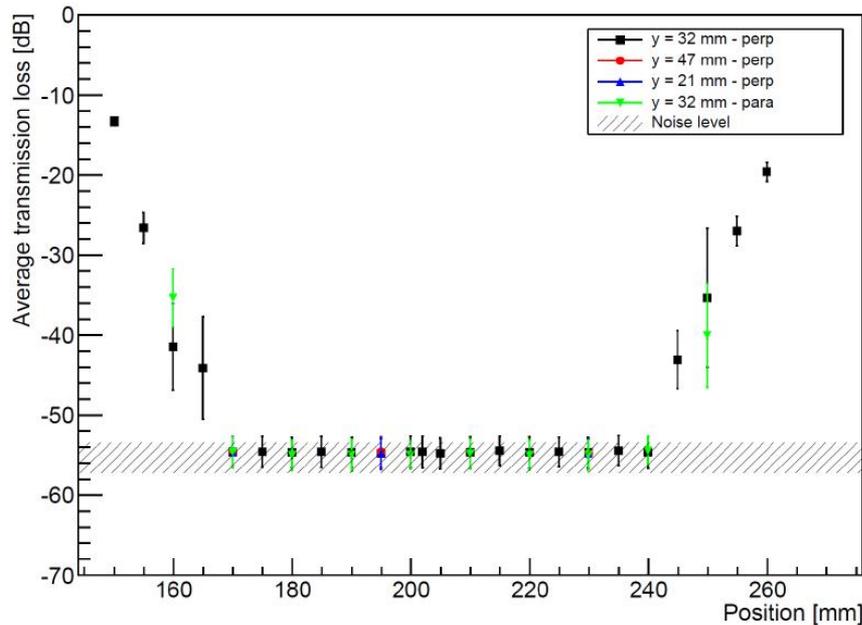
Transmission: SCT Barrel Module

- Transmission loss
  $$I_{loss} \geq 55 \text{ dB}$$

- **60 GHz signals are fully reflected**

- Diffraction leads to transmission near edges

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FROM RESEARCH TO INDUSTRY

CEA tech
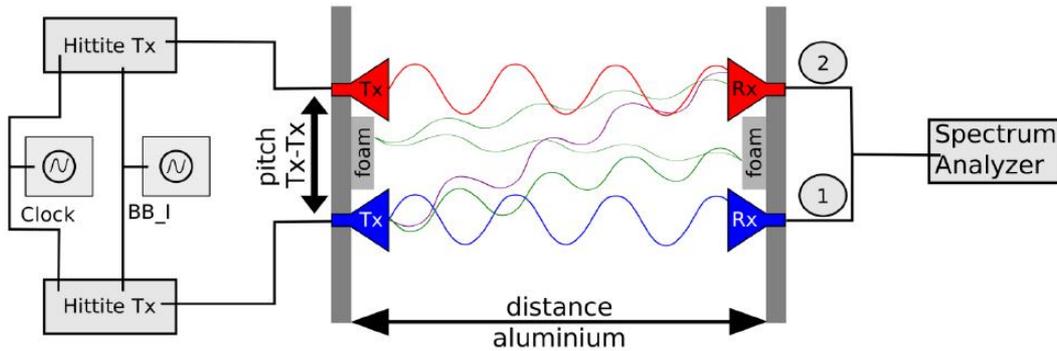
Ray tracing simulation: <u>crosstalk mitigation</u>

Approach:

- Directive horn antenna (12-17dBi gain), polarization diversity
- Graphite foam absorbing material (loss: 15-20dB transmission, 10dB reflection)

Antenna

Foam

A

B

Tracking Layer

Graphite foam cover

Example for high directivity: Aluminized Kapton horn antennas ~ 12-17 dBi
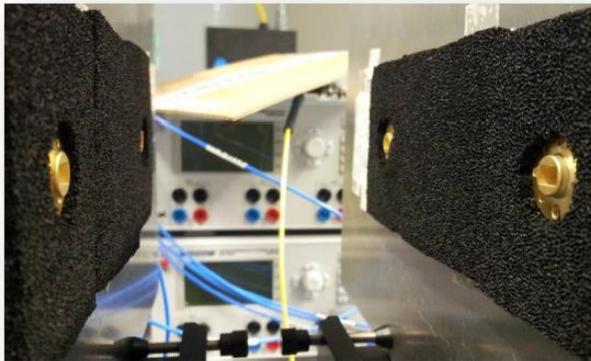
Crosstalk studies with reflections

- Aluminium plates $\triangleq$ reflective layers

- Under test:
  Directive antennas
  Linear polarisation
  Absorbing foam

- S/N = $\dfrac{Signal\ Tx1_{@Rx1}}{Signal\ Tx2_{@Rx1}}$

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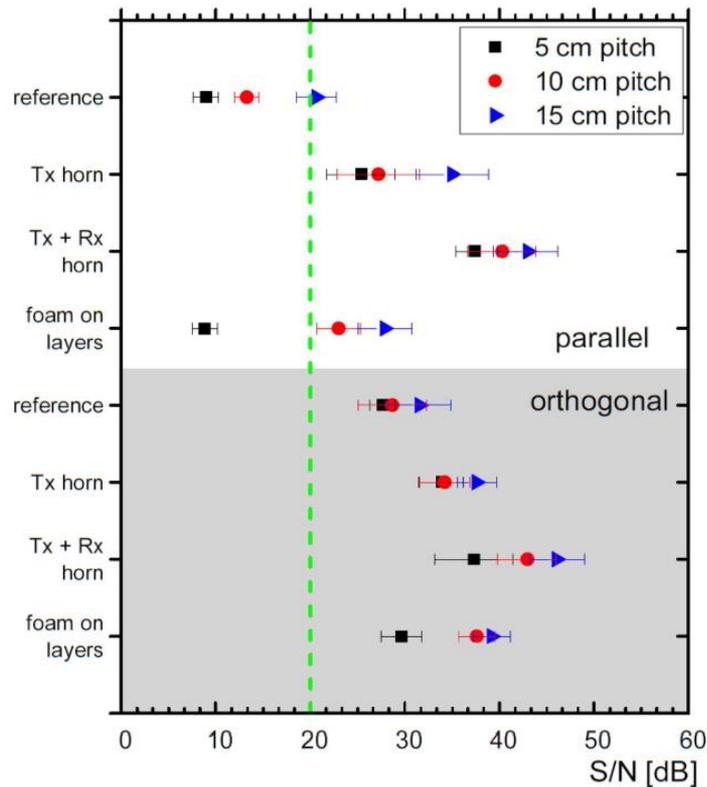
Distance between layers: 10 cm
Reference: without directive antennas and foam

Crosstalk studies with reflections

- Highly **directive antenans** increase S/N significantly

- Orthogonal linear **polarisation**: S/N > 20 dB

- **Foam on layers** can additionaly reduce crosstalk

- 5 cm pitch between channels is possible

Coexistence with detector

Setup

FPGA
1.76 Gbps BERT

CPU

data

baseband I/Q
data I/Q

60 GHz Transmitter — Tx

ABC-Next Hybrid
with short strips

Hits

Fit:
Gauss & Landau

width

threshold
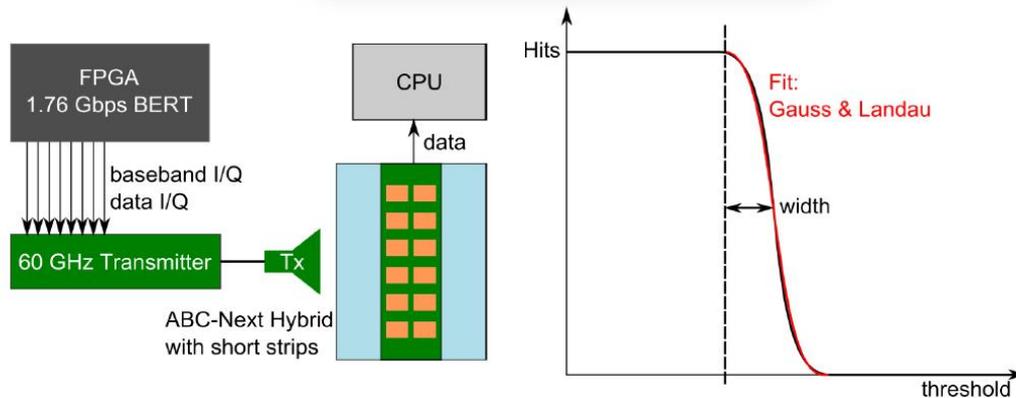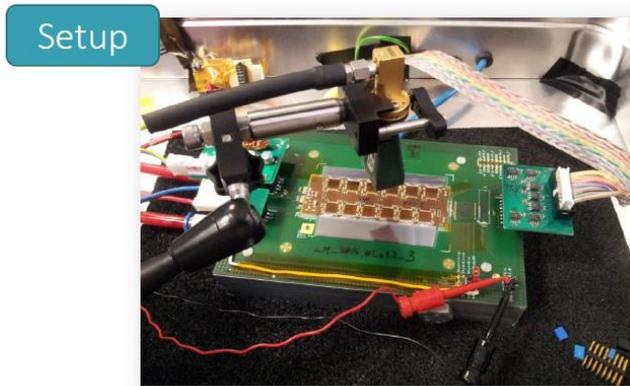
Detector performance under 60 GHz "irradiation"

- Tests done using ABC-Next Hybrid for the upgrade of ATLAS endcap detector
  (kindly supprted by U. Parzefall & S. Kühn, Uni Freiburg)

- Measurement: Compare noise in readout chips with and without wireless transmission

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Coexistence with detector

Hybrid without strips

Transmission turned on
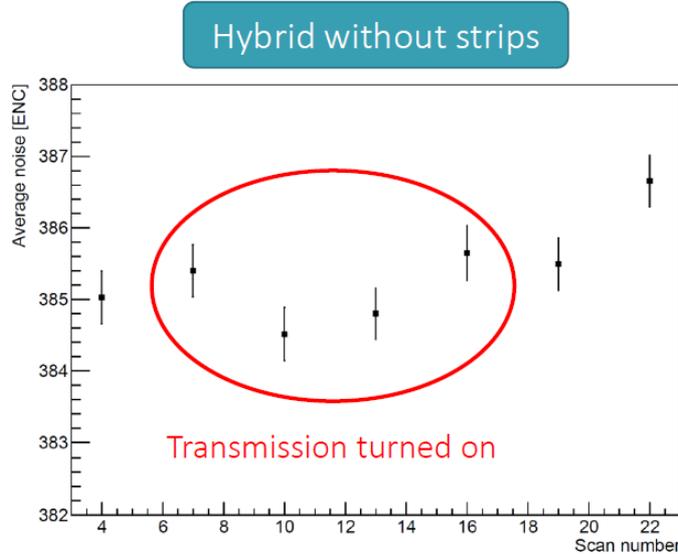
Hybrid

$$\delta_{noise} = \left(0.40 \pm 0.13_{stat} \pm 0.49_{sys}\right)\%$$
of average noise (385.0 ± 0.4) ENC

Hybrid + Strip sensor

$$\delta_{noise} = \left(0.60 \pm 0.11_{stat} \pm 0.93_{sys}\right)\%$$
of average noise (577.5 ± 0.5) ENC

No significant increase in noise!

Detector performance under 60 GHz "irradiation"

- No additional noise observed

- Hybrid + sensor: Temperature is dominating effect on noise per channel

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Summary

Stable data transmission of 1.76 Gbps with test setup: $$BER < 10^{-14}$$	By means of antennas, polarisation and graphite foam, a high link density can be achieved. Link pitch ≤ 5 cm @ S/N ≥ 20
SCT detector modules attenuate transmission of 60 GHz waves by ≥ **55 dB**	Performance of detector modules will not be degraded by 60 GHz waves

SRR	WiHD WIGIG/802.11ad UWB impulse	Backhaul	ACC	SRR	Backhaul	LRR
21,5-26,5GHz	57-66GHz	71-76GHz	77-81GHz		81-86GHz	94GHz

ISM	ISM	C2C Sub THz Imaging
122GHz	240GHz	275-300GHz
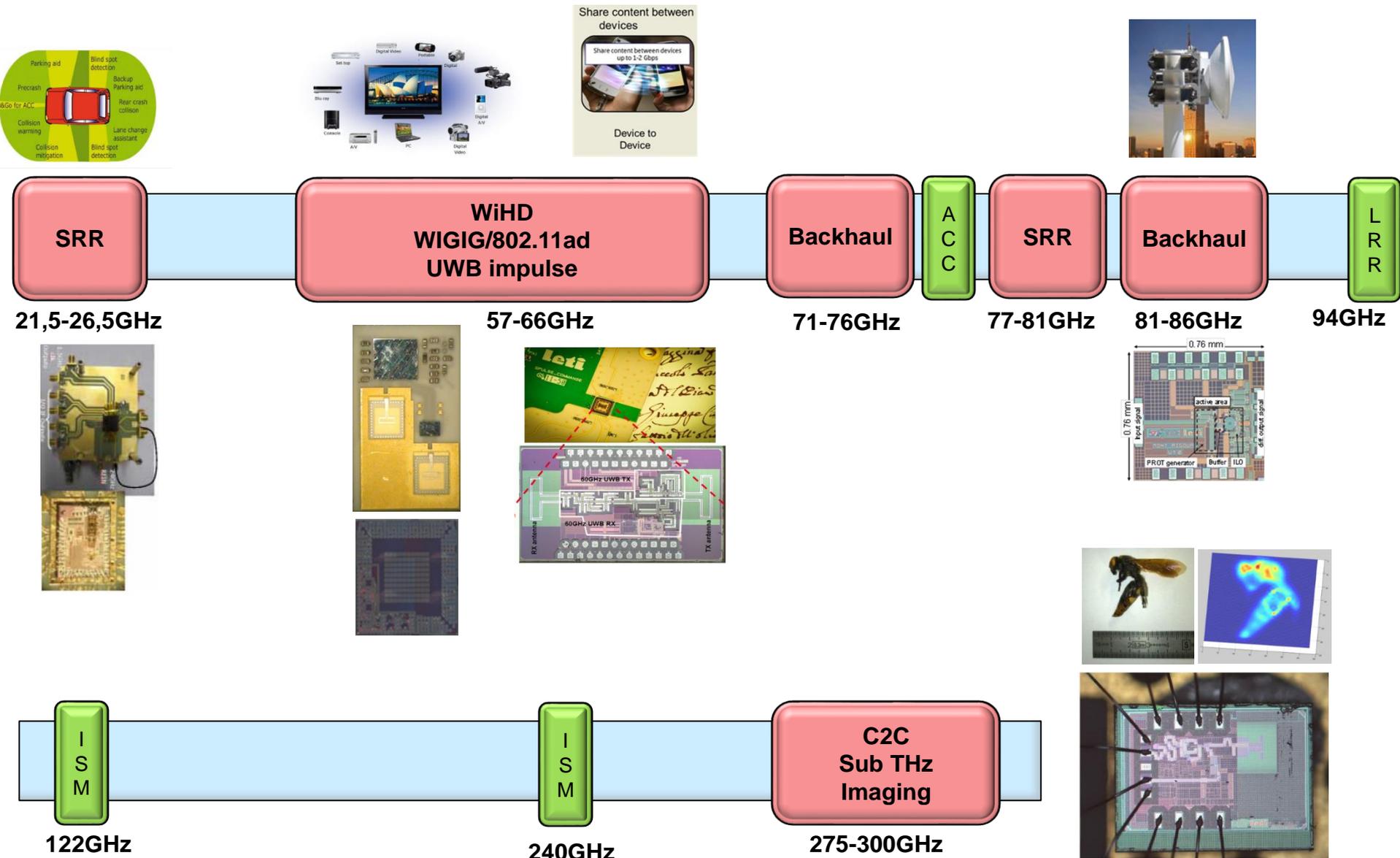
Chip	Standard	Range	Data rate	Power consumption	Maturity
Frequency domain 60GHz transceiver	802.11ad WiHD	0,5-2m	1-4Gbps	~400mW	prototype
Time domain 60GHz transceiver	No standard	5-20cm (2-5m with lens)	500Mbps-2Gbps	~70mW	prototype
E-band Backhaul	No standard	100-200m with lens	1-8Gbps	NA	Some IPs

- OFDM not relevant for low power transmission
- 1. Single carrier with analog/mixed signal processing
- 2. UWB impulse radio for short range

log(1/ (Power efficiency)) vs. Communication distance and data-rate (larger is better)
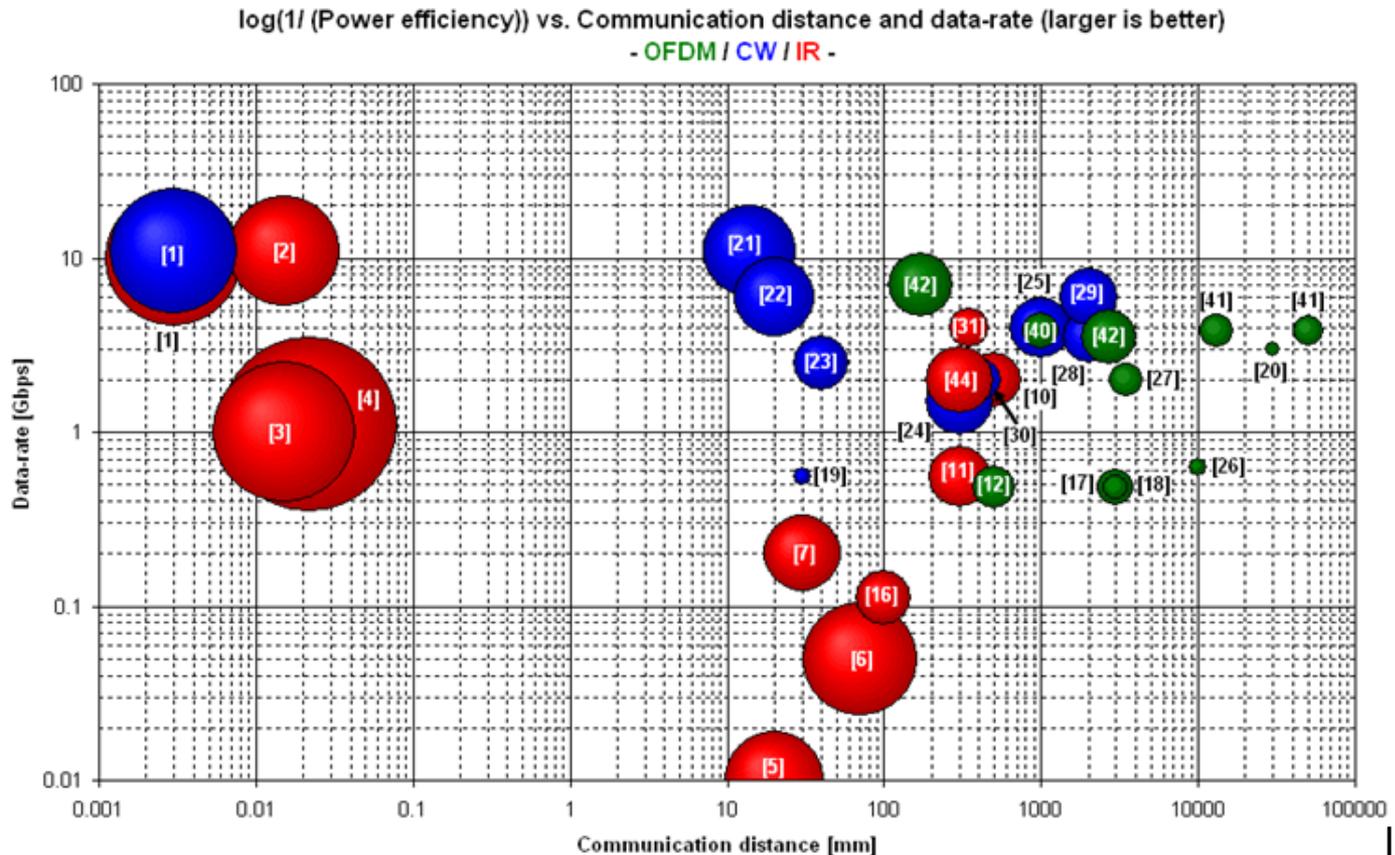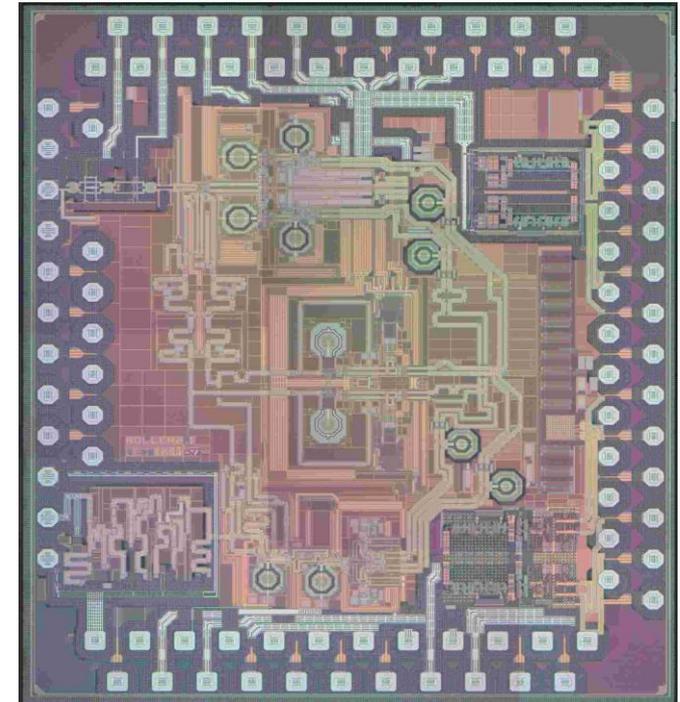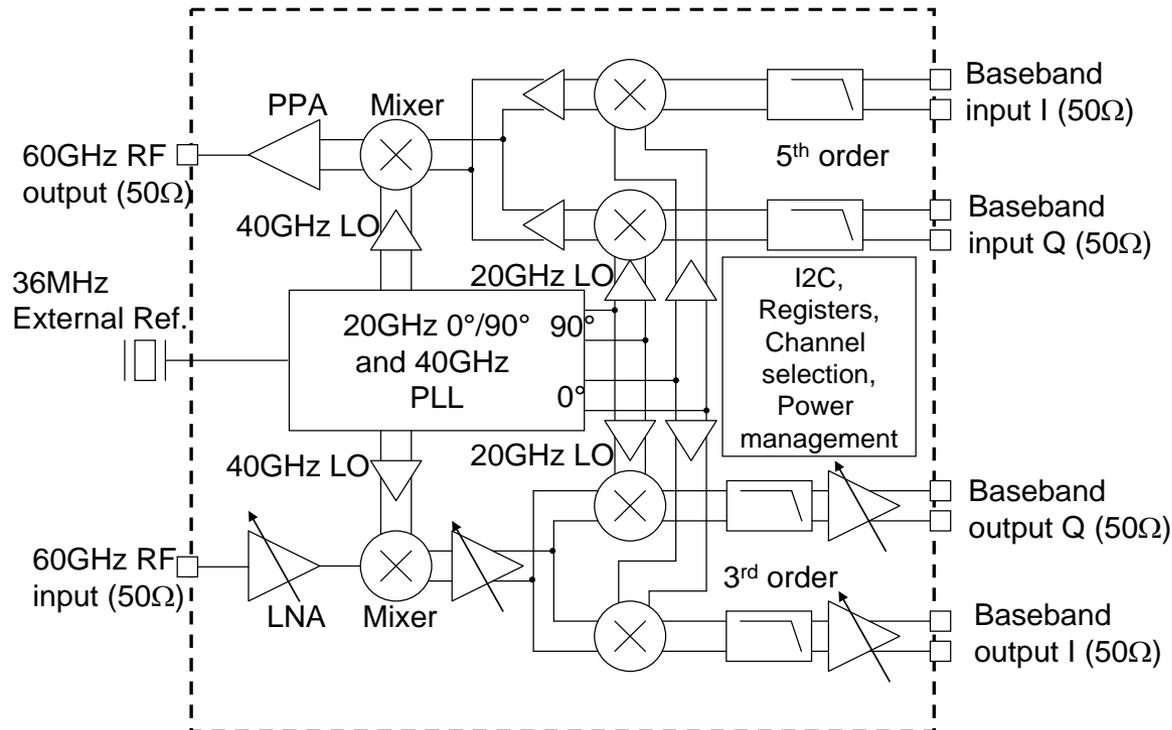- OFDM / CW / IR -

Figure 24 Inverse of the energy efficiency (size of balls in log. scale) as a function of the communication distance (x-axis), of the data-rate (y-axis) and of the radio mode (colors)

- Sliding IF architecture
- Cover the <u>4 IEEE channels</u>
- Compatible with WiHD/WiGig standards
- 3 ISSCC papers 2010 & 2011

- ## 13.5*8.5mm² mmW RFFE module on industrial HTCC
  - Covers the <u>4 IEEE channels</u> between 57 and 66GHz
  - 3.8Gbps OFDM 16QAM, 3 meters
  - Single IPD glass antenna
  - CMOS 65nm chips :
    - Front-end RF: TX: 357mW - RX: 454mW
    - PA CMOS: 0.7W
    - Digital Baseband: ~ 2W

2 ISSCC '10
ISSCC '11
JSSC '12
EuCAP '10

Transceiver chip
3.3x2.8mm²

CMOS PA
1.0X0.7mm²

TX PA
CMOS 65

60 GHz Tx
Wireless

RF Roller
CMOS65nm

60 GHz Rx
Wireless

ADC/DAC
Digital BB

Taille
Comparaison
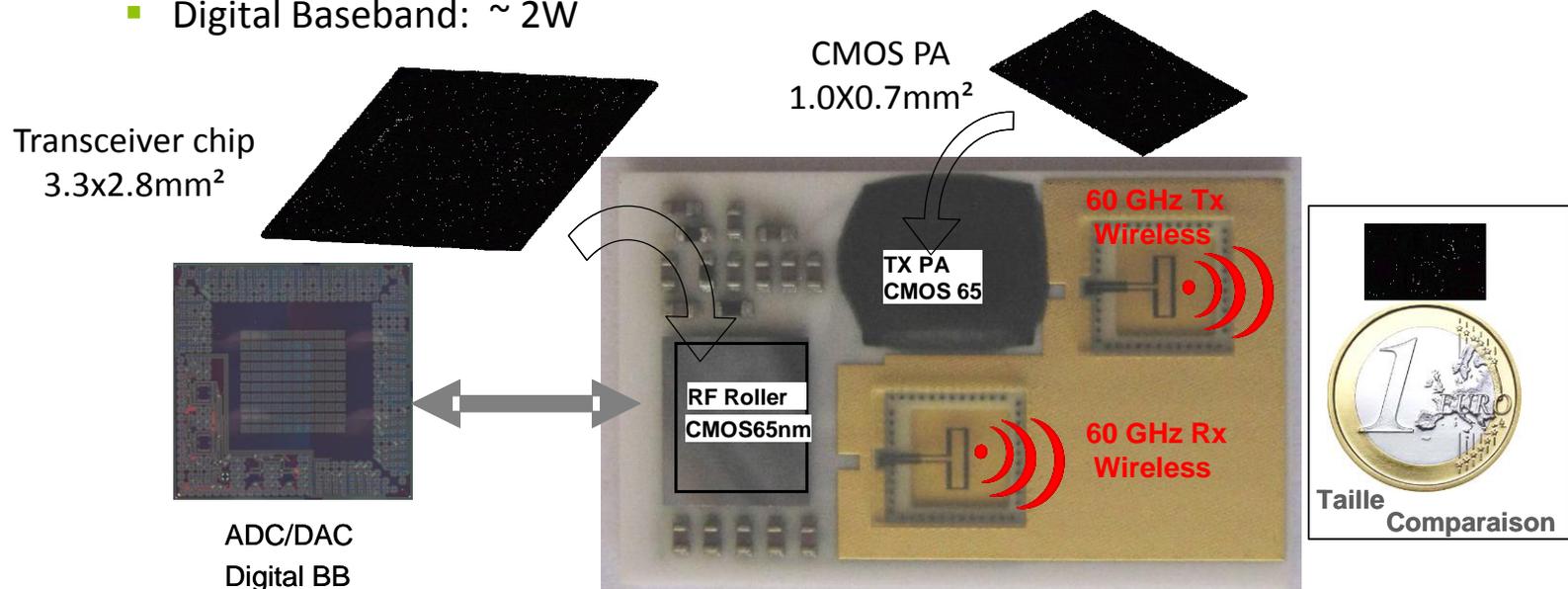
6,5*6,5mm² module with mmw transceiver and antennas

- 3.8Gbps OFDM 16QAM, 1 meter
- 120 µm HR-Si interposer
- 2-metal layer back-end: antennas, interconnects
- TSV for shielding and vertical interconnects
- T/R RFIC flip-chipped on the interposer
- BGA connection of the interposer on the PCB
- Polymer molding

ECTC'13
MTT'12
3DIC'13

RFIC

Interposer top view

Tx antenna

Rx antenna
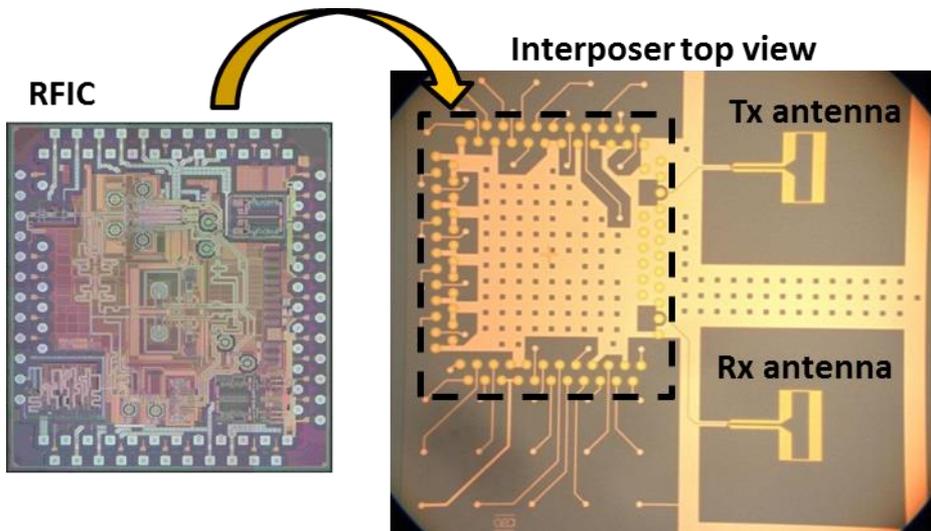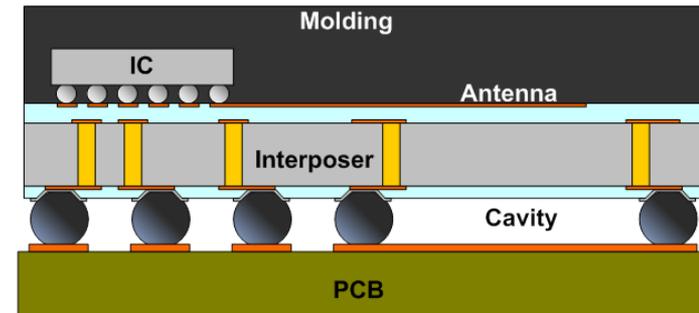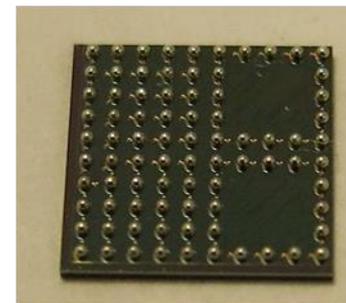
Balled interposer

Molded interposer
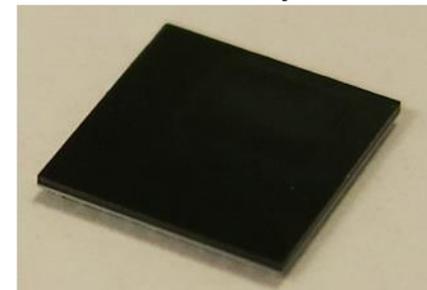
Data transmission tests

- Transmission of Wireless HD data frames at 4Gbps (OFDM 16QAM) over 80 cm, 2Gbps over 2m

- The system operates over the 4 IEEE channels between 57 and 66 GHz

- Low interconnection losses (~1dB)

- Good heat dissipation in the interposer substrate (max 42°C)

Experimental test bed

Thermal image of the interposer

Interposer on PCB

FROM RESEARCH TO INDUSTRY

CEA tech

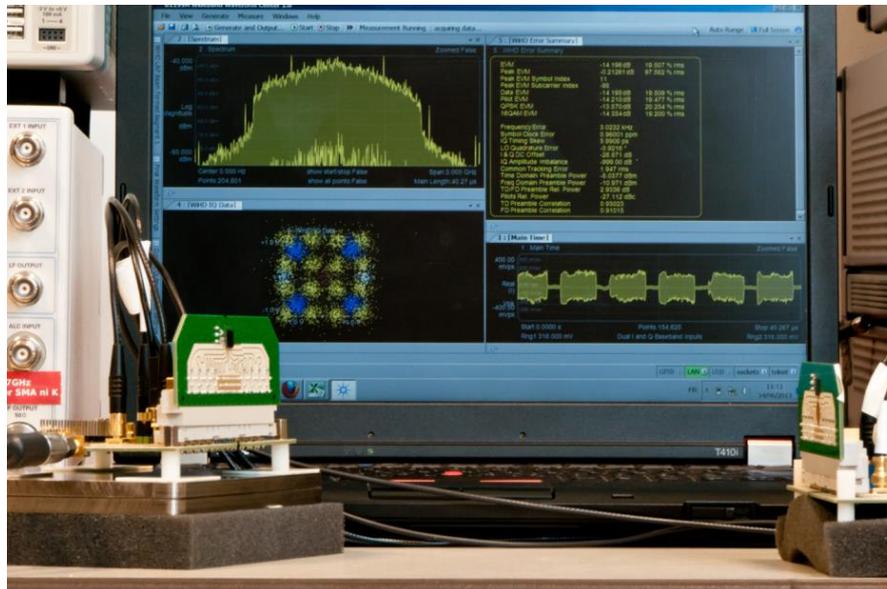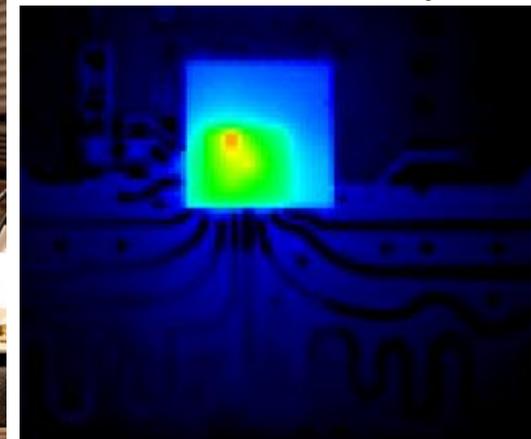IR UWB at 60GHz will offer new uses cases for device to device communication

- 100mW @ 2.5Gbps (RFFE +DBB): TX 30mW, RX 70mW
- Range 0.2m meter with single antenna
- Scalable data rate from 100Mbps to 2.5Gbps
- Integrated 4dBi 60GHz antenna (thanks to SOI 65nm HR process)
- Very low cost (standard QFN package)
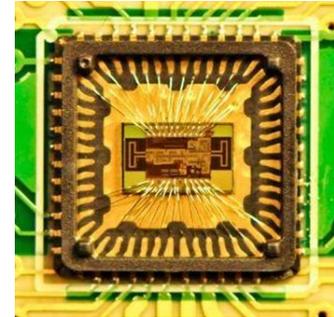
1,9mm x 3,1mm

JSSC '10
SIRF '11
ESSIRC '09
RFIC '09
RFIC'13

TX

Pulse Generator

Signal shaping — PA

Data input — RF output

Re-generation

RF input — LNA — Detection, analogue base band, digitization — Data output

Synchronization managment

RX

60GHz UWB TX

60GHz UWB RX

RX antenna

TX antenna

Leti & List
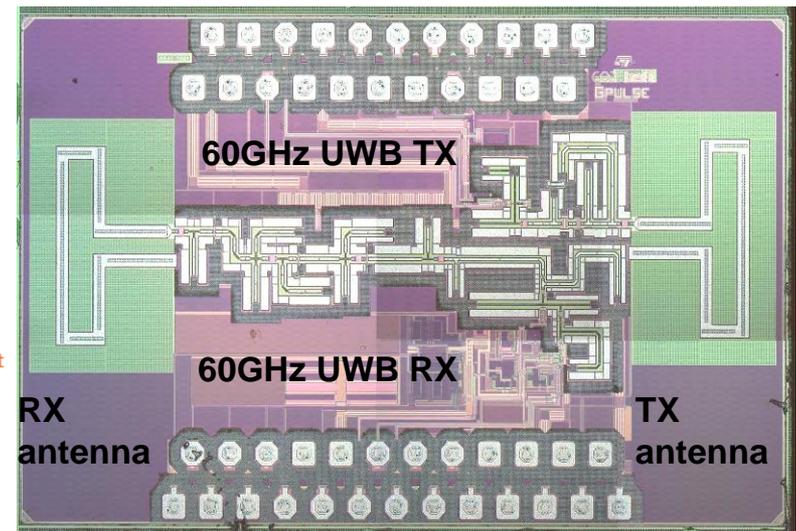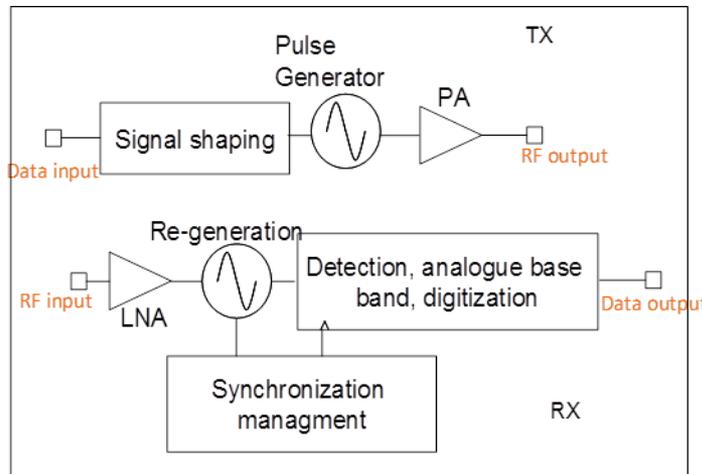
In-Package coupled antenna and focusing lens:

- No mmW interconnection; +15 dB antenna gain improvement
- Chip size: 2x3.3 mm²; package 7x7 mm²; lens 25x25 mm²

In-package antenna : ~5 dBi

Discrete lens: ~16 dBi

T/R chip

RFIC

PCB
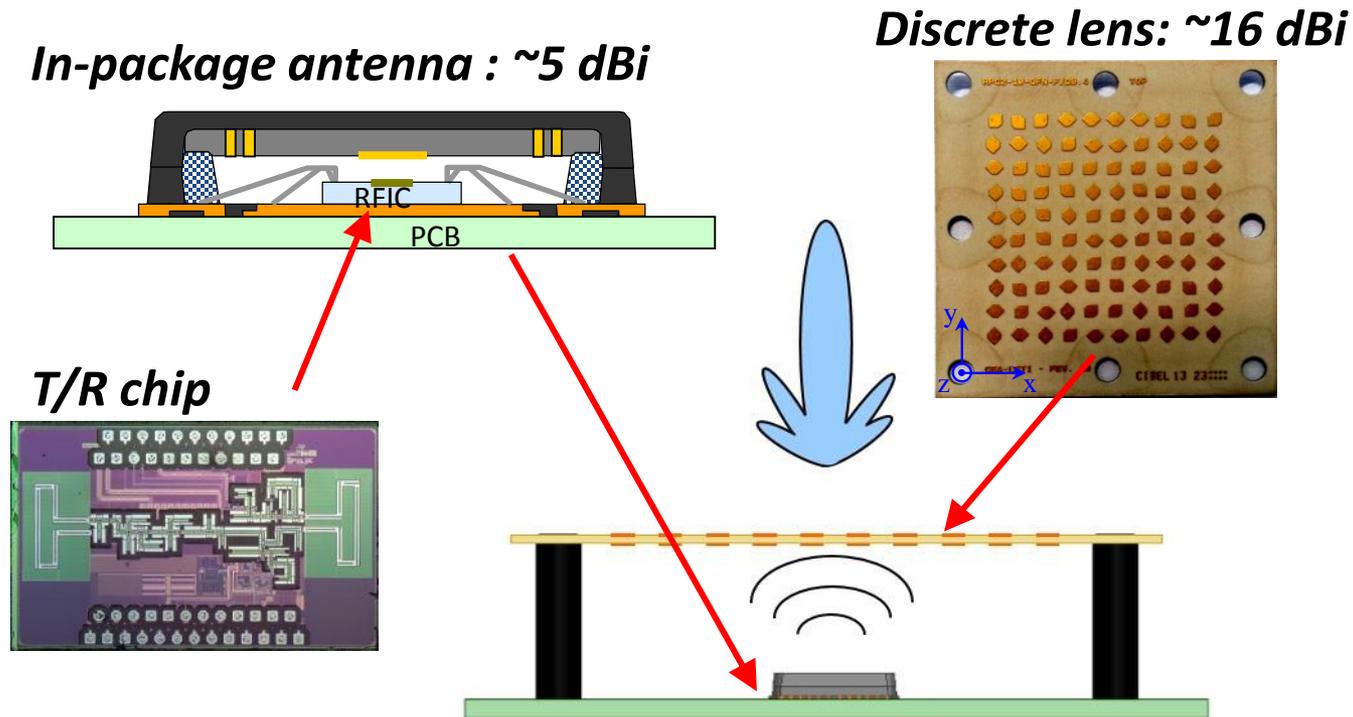
Data transmission tests

- Transmission of PRBS @10e-9 at :
  2Gbps over 5 cm, 0,5Gbps over 20cm

- Up to 5m range with discrete lens

Data Rate	Range
0.5 Gbps	530 cm
1 Gbps	400 cm
1.5 Gbps	353 cm
2 Gbps	190 cm
2.2 Gbps	175 cm

TX

RX

Chip-to-chip distance

2 Gbps (BER=10^{-5})

10^{-5} at 26 dB

BER

SNR (dB)
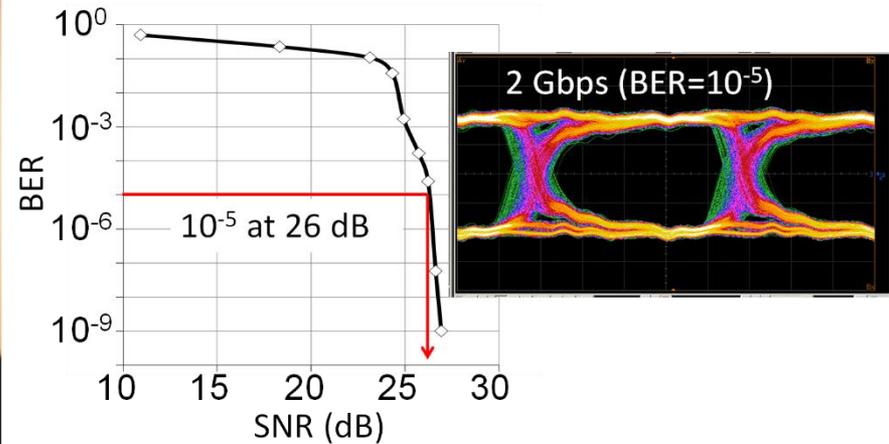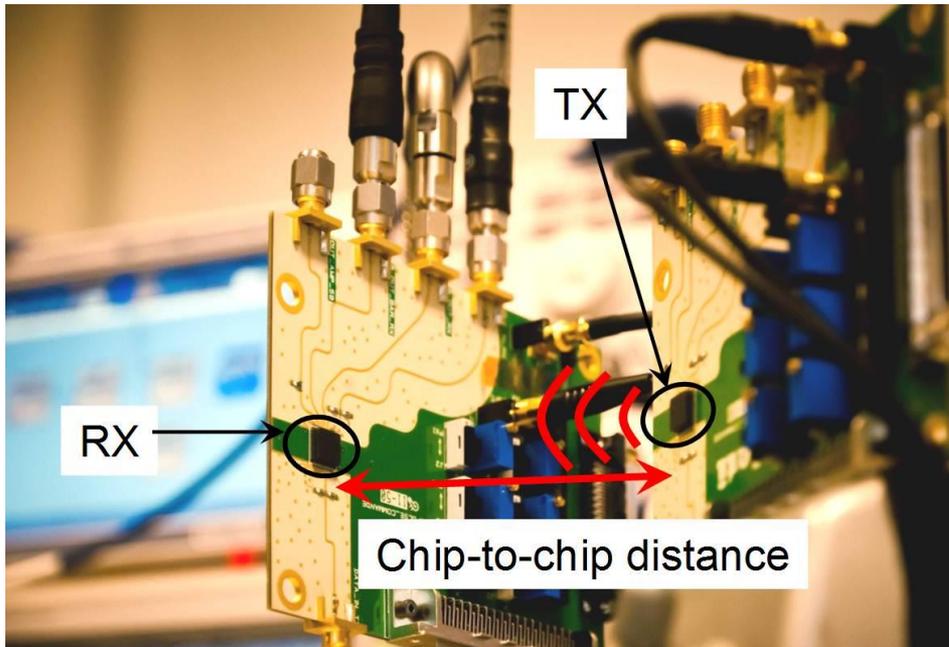
Frequency domain

5G mmw small cell
Access point and Backhauling
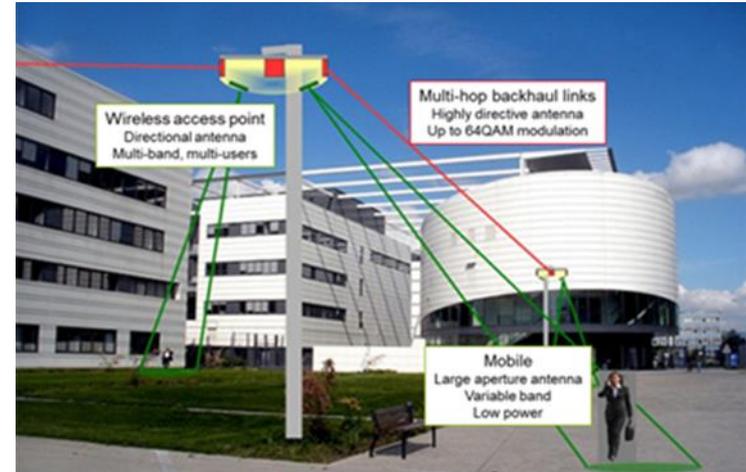
Time domain

Contactless Connectors
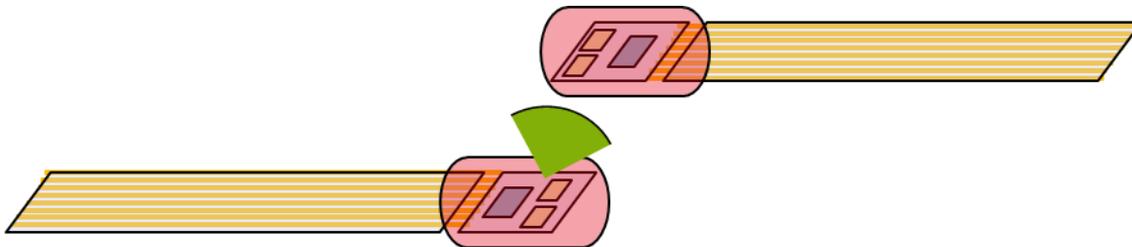
5G Heterogeneous Network with mmw small cells

Towards the **core network**

Multi-hop backhaul links
60GHz/E-band
Highly directive antenna
Up to 64QAM modulation

Wireless access point
WiFi/4G picocell/mmw
60GHz directional antenna
multi-band, multi-users

100-200m

10-50m

Mobile
Large aperture antenna
Scalable bandwidth
Low power

IMS WS'15
EUMW WS'15

3G/4G/5G/WiFi RAT
RRM
Service
GW
Service
EPC
Fiber
mmw Backhaul
mmW 3/4/5G Mobile Access
mmW WiFi
Mgmt
5G/WiFi User Equipement

Incremental approach to satisfy various applications

WiGig · 1-10m

Access Point · 10-50m

Backhaul · 50-200m

Control of antenna array

MAC, control — DBB — RFFE

Feeding Network

Active antenna unitary matrix

θ_{t1} — PA — SPDT Switch
θ_{r1} — LNA
θ_{t2} — PA — SPDT Switch
θ_{r2} — LNA
θ_{tn} — PA — SPDT Switch
θ_{rn} — LNA

Chip set available

Antenna array under development

Discrete LENS
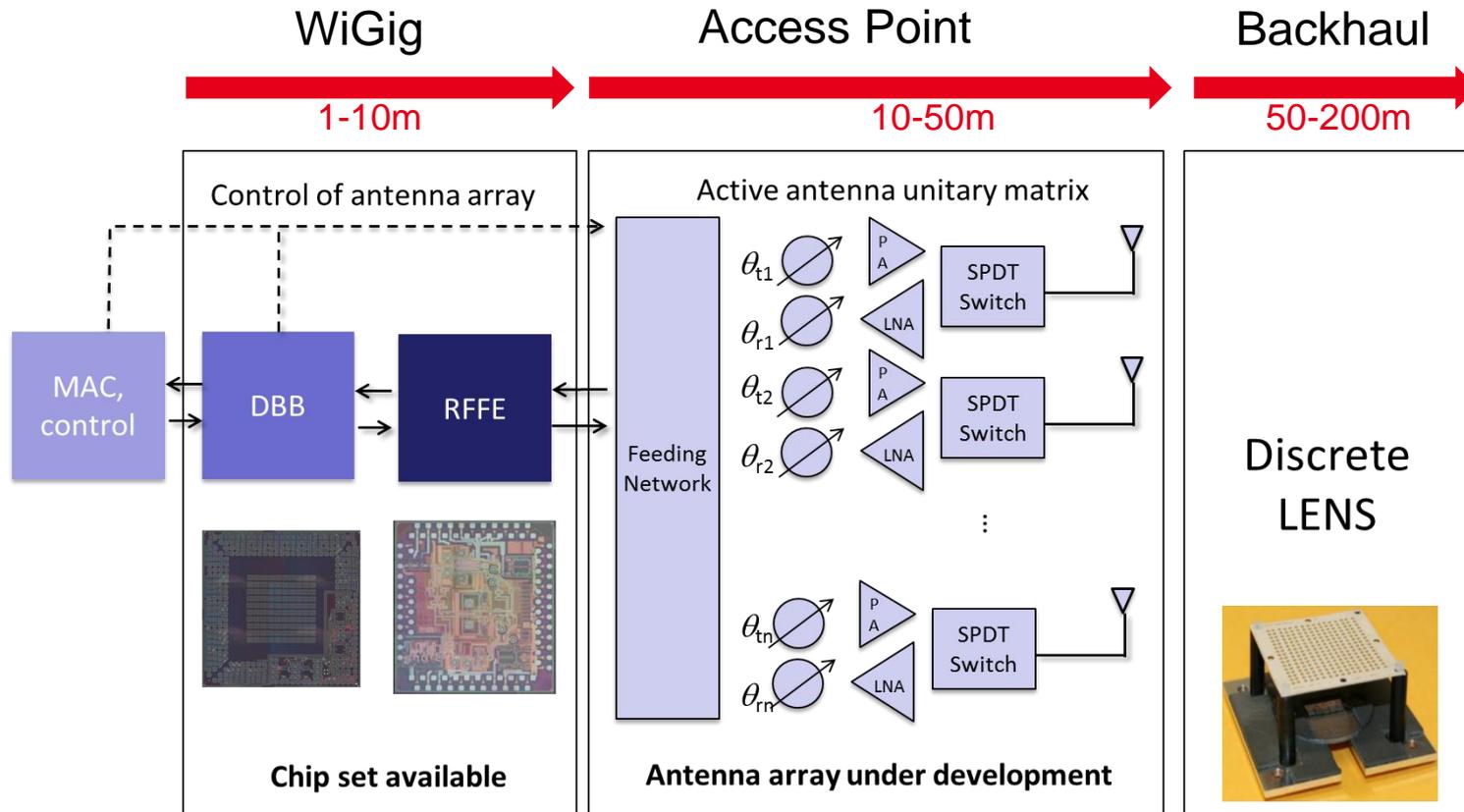
Access point scheme

- From available WiHD/Wigig transceiver
- Active phase shifted antenna array module
- Synchronization of modules
  to increase range/data rate
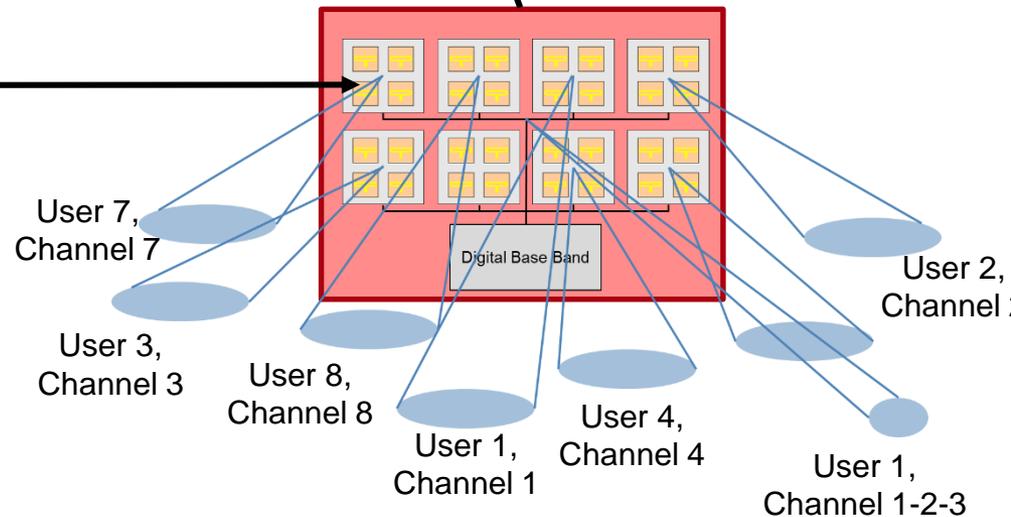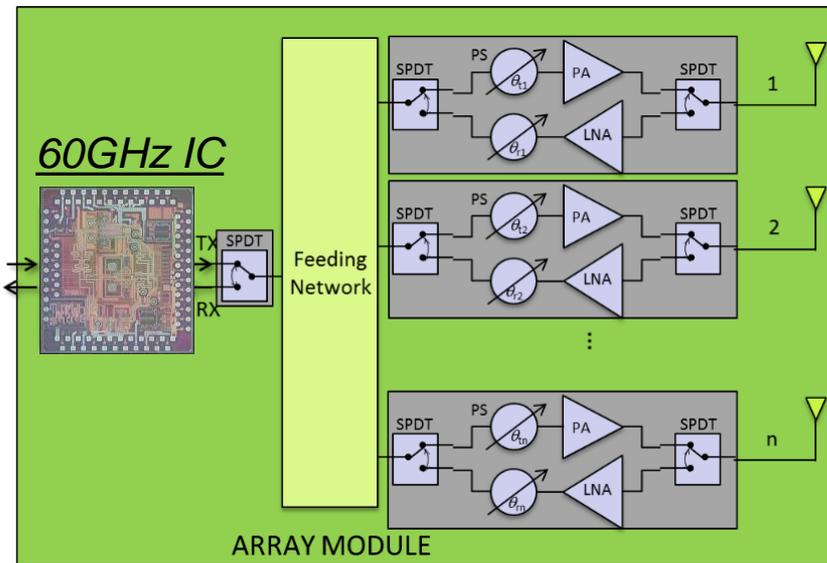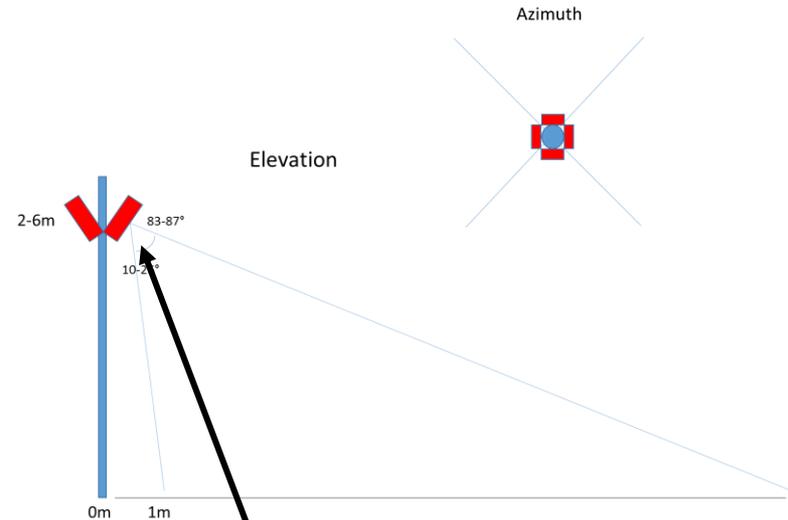
IEEE Com. Mag. Sept 14

60GHz switched-beam antenna for small cell backhauling
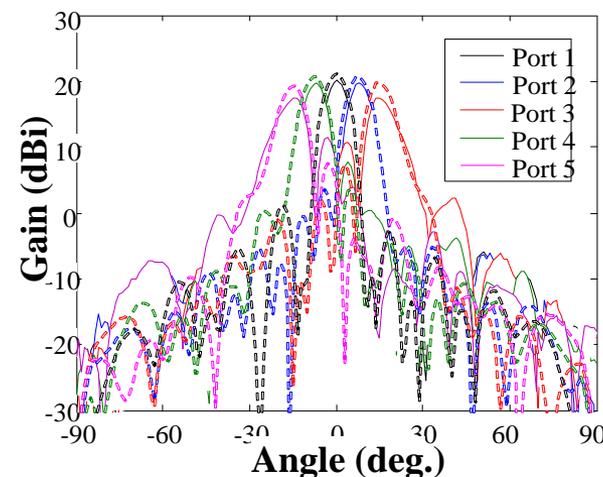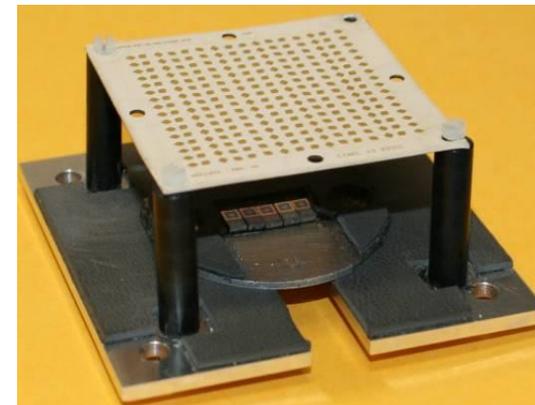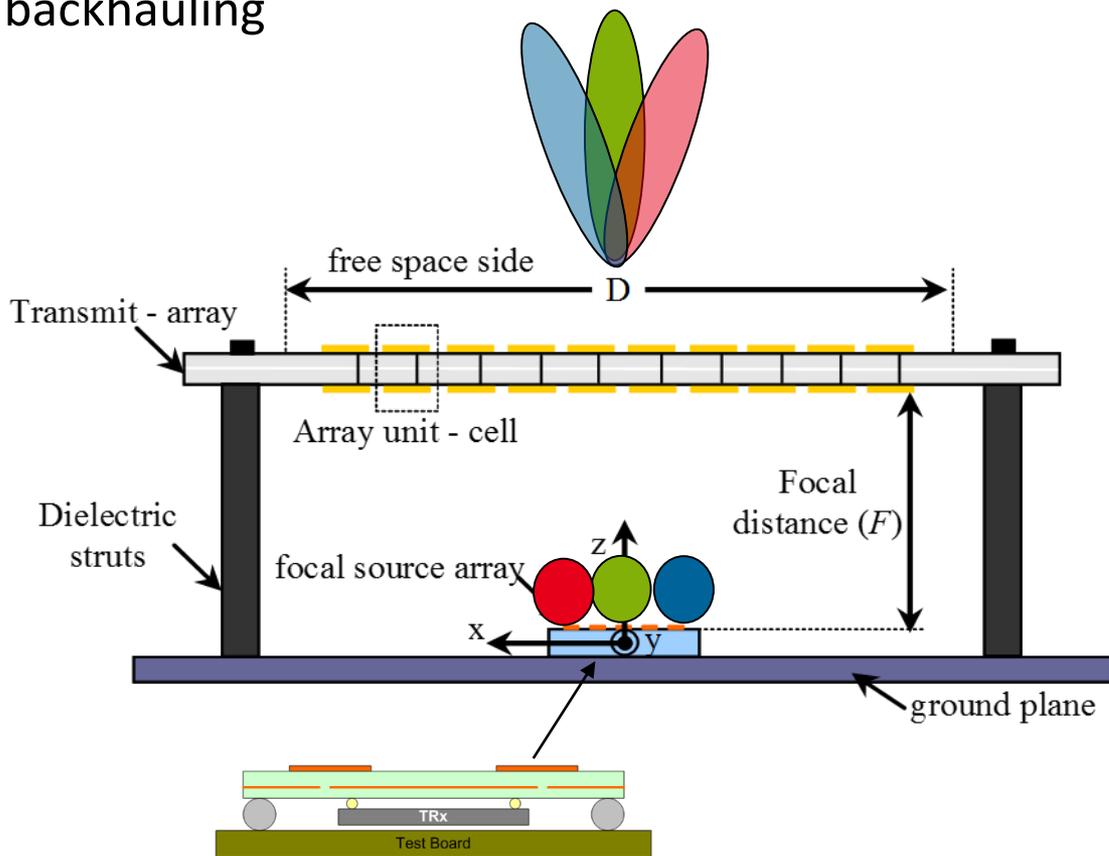
Reconfigurable antenna pattern for link adaption

- **Low cost**, wideband and compact form factor
- Passive transmit-array on standard PCB technology
- **Switchable** antenna source on silicon interposer

Contactless connector for consumer market
mm range high data rate applications

Wireless power and data transmission between mobile and docking station

Slim and waterproof connectorless mobile device

HD TV

Wireless USB or Ethernet

Features	Docking	Wireless USB
Frequency	60GHz	60GHz
Range	Few mm	Few cm
Data rate	2-5Gbps	5-10Gbps
Pdc	50mW	100mW

Keyssa

- Up to 6 Gbps data transfer
- Supports standard protocols like USB 3.0, DisplayPort, SATA, PCIe
- Software transparent. No programming overheard or software drivers required

Sibeam

- USB type A, B, C and micro USB, USB2.0, USB3.0
- HDMI type A, C, and D
- DisplayPort and Mini-Display Port
- I2C tunneling provides control, HID, and private communications
- No software needed
- Up to 12 Gbps

Wireless alternative to USB connections... SiBEAM Snap

CERN specifications

- Radial wireless transmission of detector data
- Remote power supply as a must

Technical issues

- Important aggregated data rate from detectors (Tbytes/s)
- Important number of detector modules (20000 for ATLAS)
- Crosstalks
- Signal confinement
- Liability in harsh environment (radiations)
- Low power consumption (for remote power supply)
- Efficiency of remote power transmission
- Etc.

-> Wifi not suitable: Limited data rate, low QoS, important power consumption

-> Optical links not suitable: Difficult implementation

1. Layer to layer transmission of data @60GHz

   - Proposed by Heidelberg Univ.
   - Low power short range transmission
   - Time domain transceiver
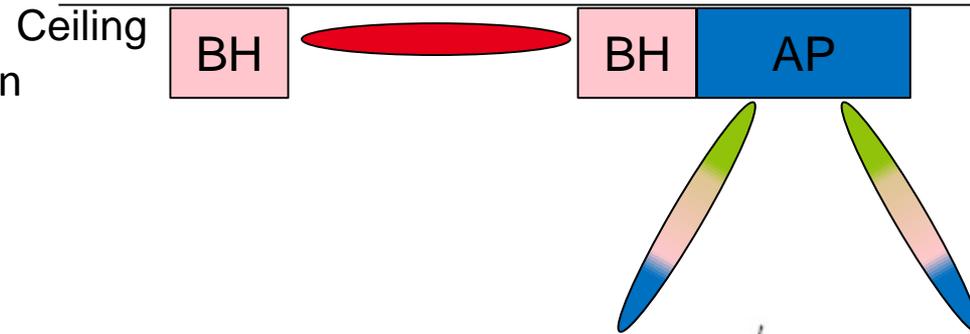
2. Gateway

   - Aggregation of data
   - Medium range high data rate transmission
   - Frequency domain transceiver
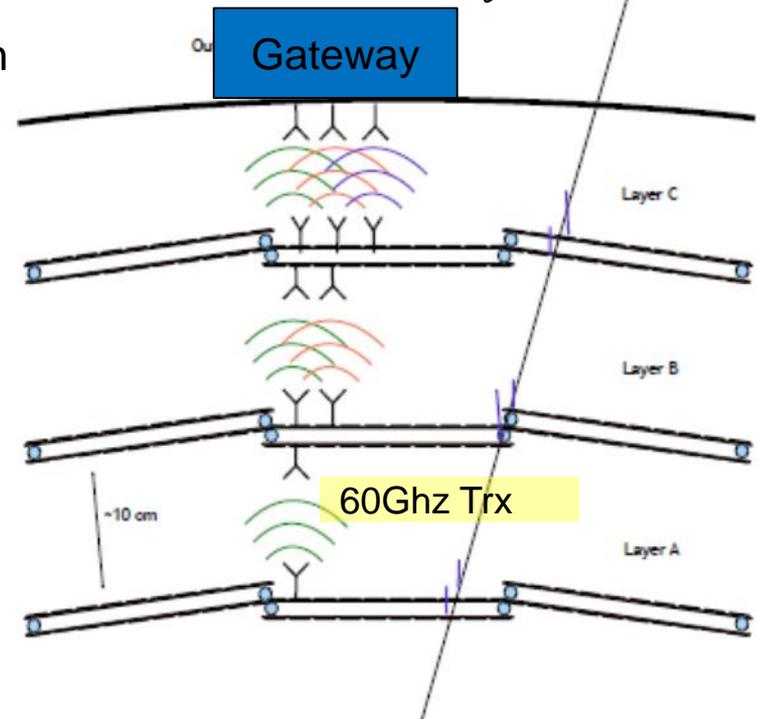
3. Wireless access point

   - Multi user access scheme
   - Very high data rate
   - Frequency domain transceiver

4. Data Backhauling

Ceiling

BH   BH   AP

Gateway

60Ghz Trx

Layer C

Layer B

~10 cm

Layer A

Possible radio schemes

Radio scheme	Typical Range	Data rate	Power consumption	Closest mass market application	Expected commercial availability
1. Cross layer data transmission	10cm	0.1-2Gbps	~50mW	Contacless connector	2 years
2. Gateway	5m	5-7Gbps	1W	802.11ad	Almost now
3. Access point	5m	20-25Gbps	5-10W	5G small cell AP	5 years
4. Backhaul	50-200m	20-40Gbps	5-10W	5G BH small cell	2 years

Questions related to CEA's time domain prototype and expected products

Question topic	Answer/comment
Full duplex mode	Prototype operates in half duplex mode Products shall be compatible with USB3 (full duplex)
Downlink broadcast mode	Possible assuming line of sight
Interference and crosstalks	5cm link pitch between devices demonstrated by Heidelberg Univ. assuming directive antennas, graphite foam FDD also possible
Tx/Rx Synchronization	Receiver synchronized on data (envelop detector) low latency, <4ps random jitter
Interface	Analog for prototype, interface with FPGA and SerDes validated M-Phy compatibility for products
QoS	1e-11 achieved with prototype 1e-12 targeted for products
Robustess in harsh env.	Not evaluated yet

- Mmw allows high data rate, low power communication at short range

- Commercial products at 60GHz should be available soon for test and customize for particle-physics detector

- Early prototypes available for test at CEA Leti

- Future developments above 100GHz should challenge optical links at short range

- Not solved issues: power transfer, clock synchronization

Leti

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List

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Architecture and system studies

- Characterization of the environment, propagation medium, channel modeling, interference
- Type modulation: SC QAM, FM, PM, UWB impulse, etc. Pros and cons.
- Choice of Carrier Frequency vs application : 60-300GHz (range, precision, material penetration, O_2/H_2O absorption peaks, etc)
- System study and budget link
- Strategy for data aggregation, data fusion and compression
- Crosstalks and coexistence issues
- System definition and specification
- Simulation chain for RF and digital specifications

Preliminary experimentation

- Build measurement set-up (from prototypes or commercial products)
- Propagation, channel sounding in realistic environment
- Data transmission for proof of concept

RF/mmw design

- Customization of existing 60GHz chips towards LHC requirements (from system studies)
  - Focusing on the cross layers data transmission
- Design of higher data rate transceiver
  - At higher frequencies (e.g. 300GHz), associated to wider bandwidth
  - Operating on multiple frequency channels (FDMA)
  - With multiple inputs multiple outputs (MIMO)

Antenna/package design

- Design of antenna/package with a directive pattern (antenna array or lens), and/or polarization diversity
- Mitigation of the crosstalk/coexistence issues

Prototyping

- Design and fabrication of prototype boards
- Experimentation of data transmission in a realistic environment

- CEA shall reuse transceiver and IPs from other projects and industrial collaborations

- Possible Carnot Label (French national research agency) project funding

- CEA Internship proposed for next year

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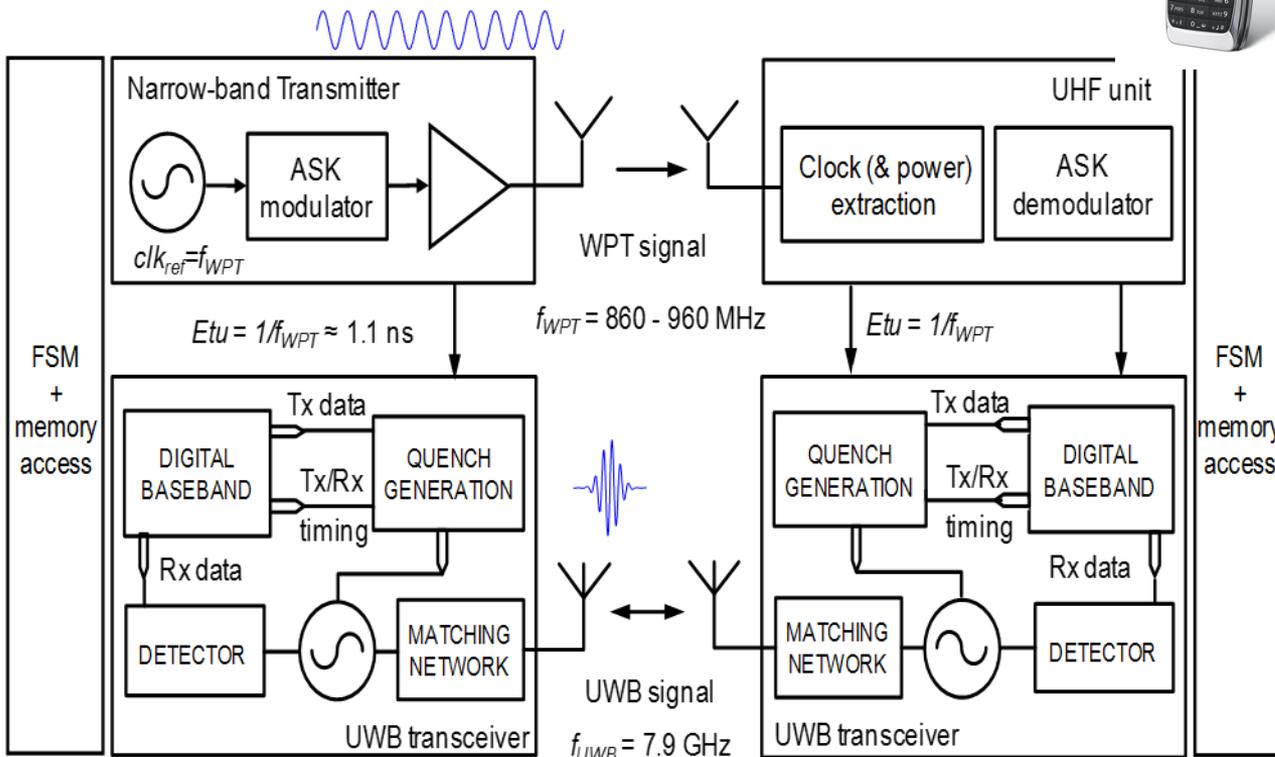# Example of UHF (900MHz) wireless power supplies of UWB memory tag

RF power supply, around 25% power efficiency (+path loss)

~5mW power supply at 30cm for 2W emitted power

| Variable distance 1cm-30cm | ⇔ | scalable bit rate 14/56/112 Mbit/s |

Battery-free system or Battery-assisted system with up to 1Gbits Memory

Technology	0.13μm
Remote powering	UHF
Clock Extraction	UHF
Downlink	UWB (7.25-8.5GHz)
Data rate	typ. 112Mb/s
Power consumption	5.4mW
FOM (energy/bit)	48pJ/b
Uplink	UWB (7.25-8.5GHz)
Data rate	typ. 112Mb/s
Power consumption	6.5mW
FOM (energy/bit)	58pJ/b

Example of RFID (13.56MHz)

Magnetic coupling, around 80% power efficiency at short range (<1cm)

>50mW power supply at 1-3cm range for 1W emitted power
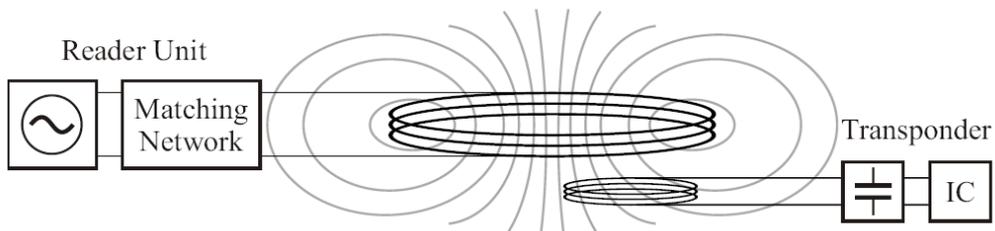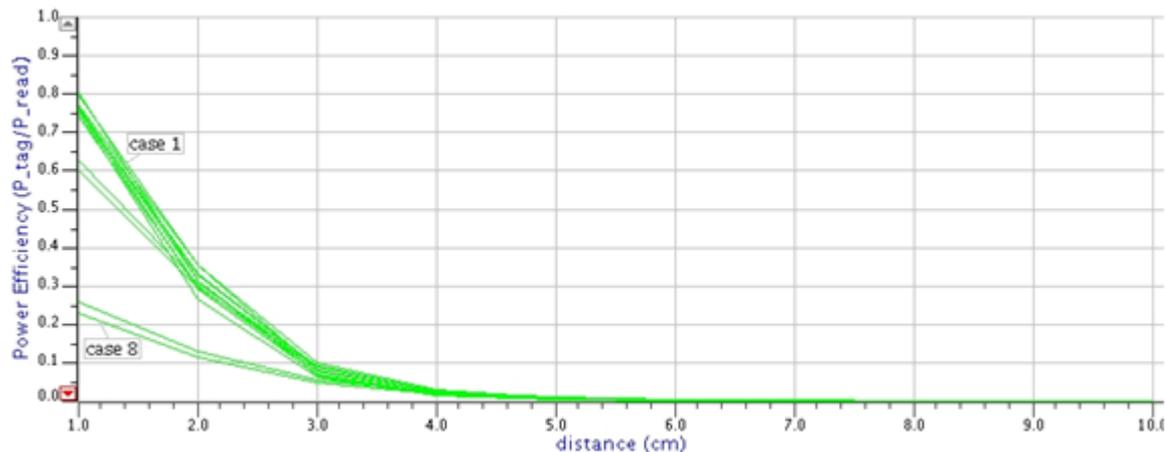
Efficiency rapidly drops with range

Figure 1: Basic setup of inductive coupled coils in a 13.56MHz RFID system

■ **RF power transfer**

50-100mW could be obtained assuming directive antennas, and high emitted power

e.g. Wireless power supply @ 900MHz

- -5dB power harvester efficiency (30%)
- 14dBi Tx / 11dBi Rx antenna gain
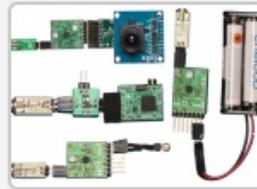- 44dBm output power (25W)
- → ~100mW maximum available @4m (Friis)

■ **Inductive coupling**

▬ Good efficiency but restricted to very short range 1-3cm at 13.56MHz

▬ Coupling at 125kHz to be evaluated (theoretical 1-3m range)

Technology News
Using Wi-Fi to power the IoT

June 08, 2015 | Rich Pell | 222909149

An article in the MIT Technology Review presents a power-over-Wi-Fi system that uses existing Wi-Fi chipsets in wireless routers to deliver far-field wireless power to various sensors as well as to recharge coin cell batteries at distances up to 28 feet.

The power-over-Wi-Fi system - or "PoWiFi" for short - is a University of Washington (Seattle, WA) research project aimed at powering the Internet of Things (IoT) using Wi-Fi signals. Its concept is that Wi-Fi receivers could, in addition to retrieving the information being transmitted over Wi-Fi, be designed to harvest the energy in these signals as well.

The biggest hurdle in achieving this is the discontinuous nature of normal Wi-Fi signals - data is often broadcast in bursts, on a single channel. Initial testing with a temperature sensor that had been fitted with a Wi-Fi antenna showed that while voltage across the sensor often came close to the 300 mV needed for the sensor to operate it was not enough.

To get around this, the researchers injected non-intrusive "power traffic" onto multiple 2.4-GHz Wi-Fi channels to increase channel occupancy - while minimally impacting network performance - so as to allow energy harvesting across multiple channels. They also designed a multi-channel harvester to retrieve the energy from the resulting transmissions, from both the artificial and normal traffic across three non-overlapping channels, and to allow for continuous power delivery.

Using this approach, the researchers found that the temperature sensor could operate at distances of about 6 meters from the router - a distance that increased to 9 meters when a rechargeable battery was added. A further test with a Wi-Fi antenna-enabled low-power camera equipped with a low-leakage storage capacitor showed that it could operate at up to about 5 meters without a battery, and about 7 meters with a battery.

Also demonstrated was the remote battery recharging of a Jawbone fitness tracker. Once equipped with the PoWiFi antenna and placed in the vicinity of a PoWiFi router, the device's coin cell battery was able to be brought to 41% charged from a no-charge state in 2.5 hours.

According to the researchers, the impact of the system on normal Wi-Fi traffic and performance was minimal to users on the networks tested. For more, see "Powering the Next Billion Devices with Wi-Fi" (PDF).