FROM RESEARCH TO INDUSTRY

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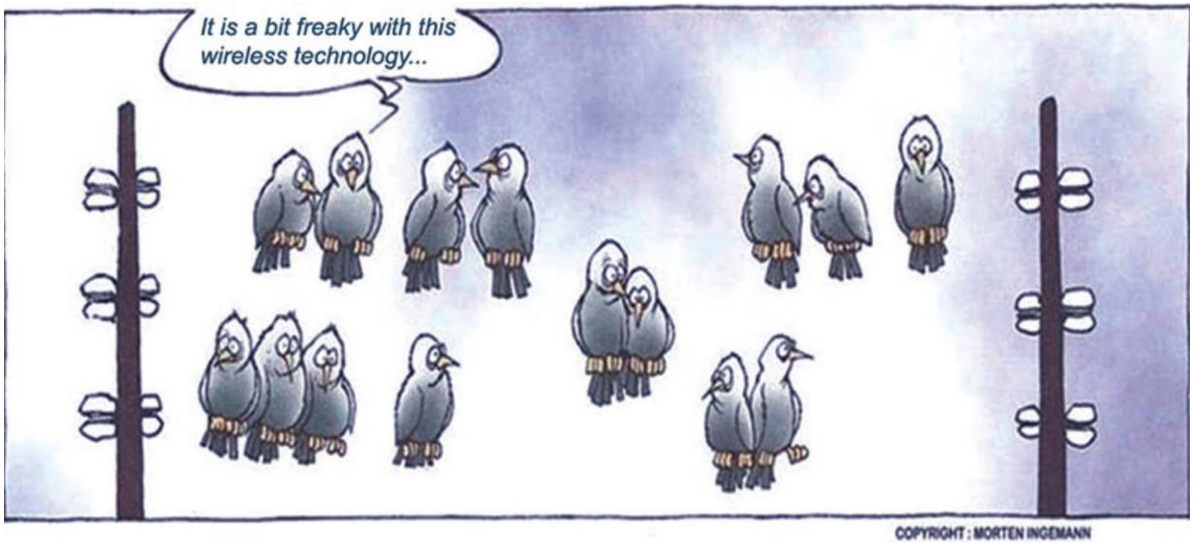
Multi-Gigabit Wireless Data Transfer for High Energy Physics Applications



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leti & list

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Outline

- Wireless readout: context and motivation, principle of integration in HEP
- Introduction to millimeter wave, focus on 60GHz
- RFIC architecture and design
- Antenna requirement, design and integration
- Feasibility tests

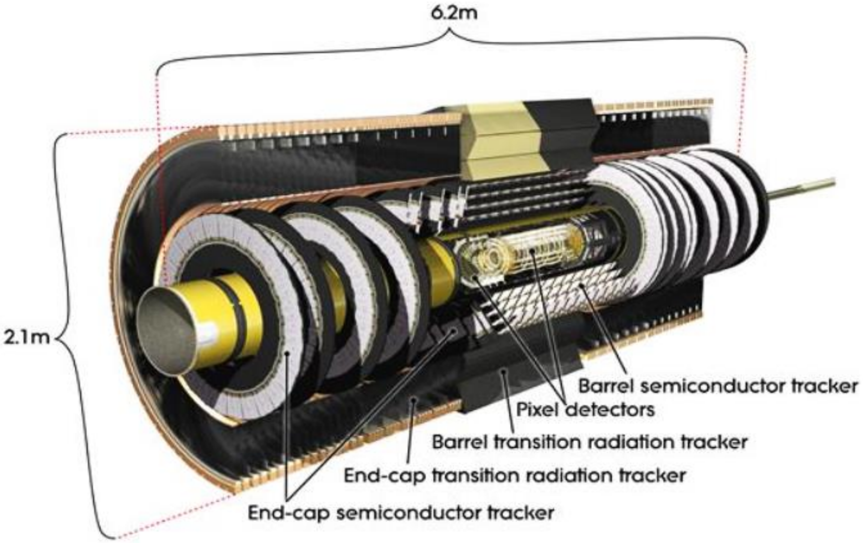
WADAPT Collaboration

- Wadapt: "**Wireless Allowing Data And Power Transmission**"
- Objectives:
  - Definition of the needs of data connectivity for particle-physics detectors
  - Evaluation of the wireless technologies for data and power transfer
  - Hardening, specific design and prototyping
- Consortium
  - **CERN**, European Organisation for Nuclear Research, Geneva, Switzerland
  - **CEA/DSM/IRFU**, Gif-sur-Yvette, France
  - **CEA/LETI**, Grenoble, France
  - **University of Heidelberg**, Germany
  - **University of Uppsala**, Sweden
  - **University of Bergen**, Norway
  - **Argonne National Laboratory**, Argonne, USA
  - **Gangneung National University**, Korea

Context: large data readout

The **inner detector** is the first part of ATLAS to see the decay products of the collisions, so it is very compact and highly sensitive. It consists of three different systems of sensors all immersed in a magnetic field parallel to the beam axis. The Inner Detector measures the direction, momentum, and charge of electrically-charged particles produced in each proton-proton collision.

The main components of the Inner Detector are: **Pixel Detector**, **Semiconductor Tracker** (SCT), and **Transition Radiation Tracker** (TRT).



Pixel Detector

- 80 million pixels (80 million channels). Area 1.7m^2. 15 kW power consumption
- Barrel has 1,744 modules (10cm^2) with 46,080 readout channels per module
- Pixel size 50 x 400µm^2 . Resolution 14 x 115µm^2
- Three Pixel disks (in each endcap) have 6.6 million channels
- 3 barrel layers: 1,456 modules (i.e. 67M)
- 3 disks in each end-cap: 288 modules (i.e. 13M)

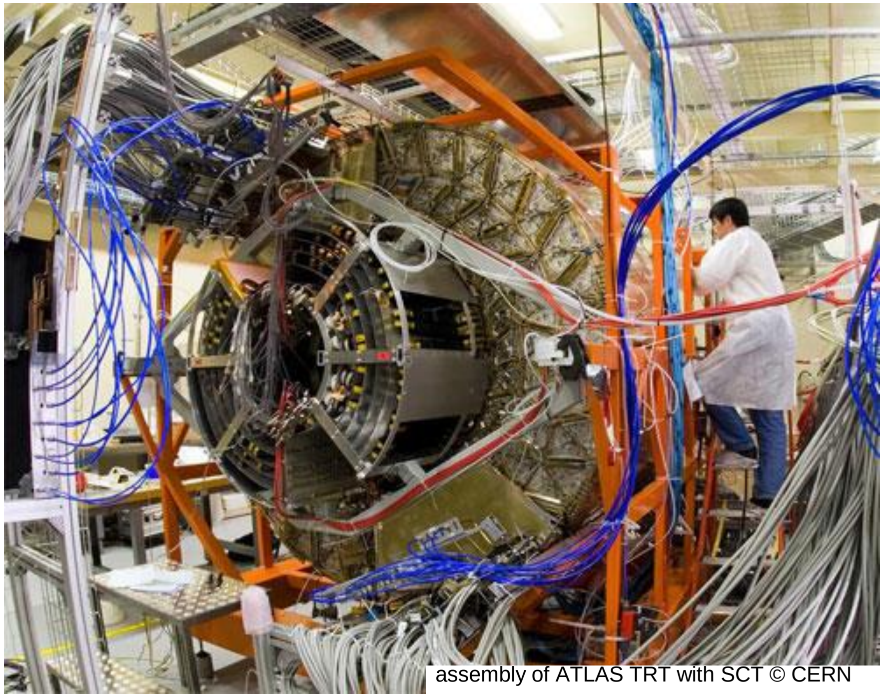
Semiconductor Tracker

- A silicon microstrip tracker consisting of 4,088 two-sided modules and over 6 million implanted readout strips (6 million channels)
- 60m^2 of silicon distributed over 4 cylindrical barrel layers and 18 planar endcap discs
- Readout strips every 80µm on the silicon, allowing the positions of charged particles to be recorded to an accuracy of 17µm per layer (in the direction transverse to the strips)

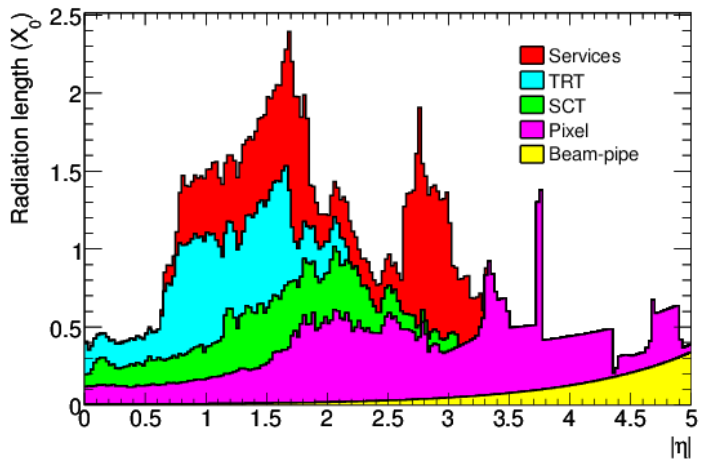
Transition Radiation Tracker

- 350,000 read-out channels
- Volume 12m^3
- Basic detector element: straw tube with 4mm diameter, in the centre a 0.03mm diameter gold-plated tungsten wire
- 50,000 straws in Barrel, each straw 144 cm long. The ends of a straw are read out separately
- 250,000 straws in both endcaps, each straw 39 cm long
- Precision measurement of 0.17 mm (particle track to wire)
- Provides additional information on the particle type that flew through the detector, i.e. if it is an electron or pion

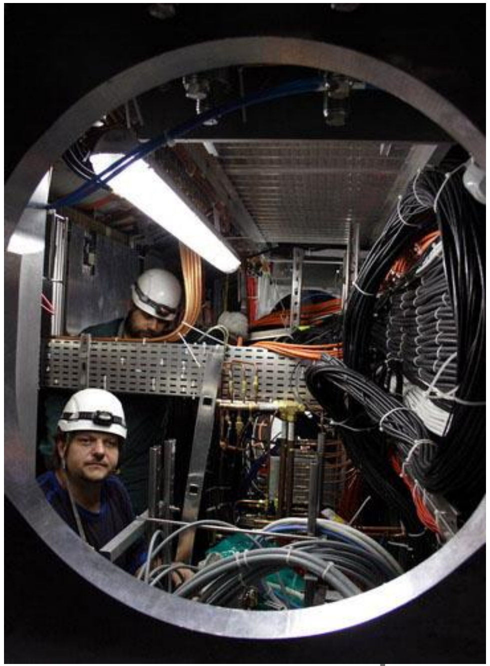
Context: massive cable plant


assembly of ATLAS TRT with SCT © CERN

Atlas radiation length

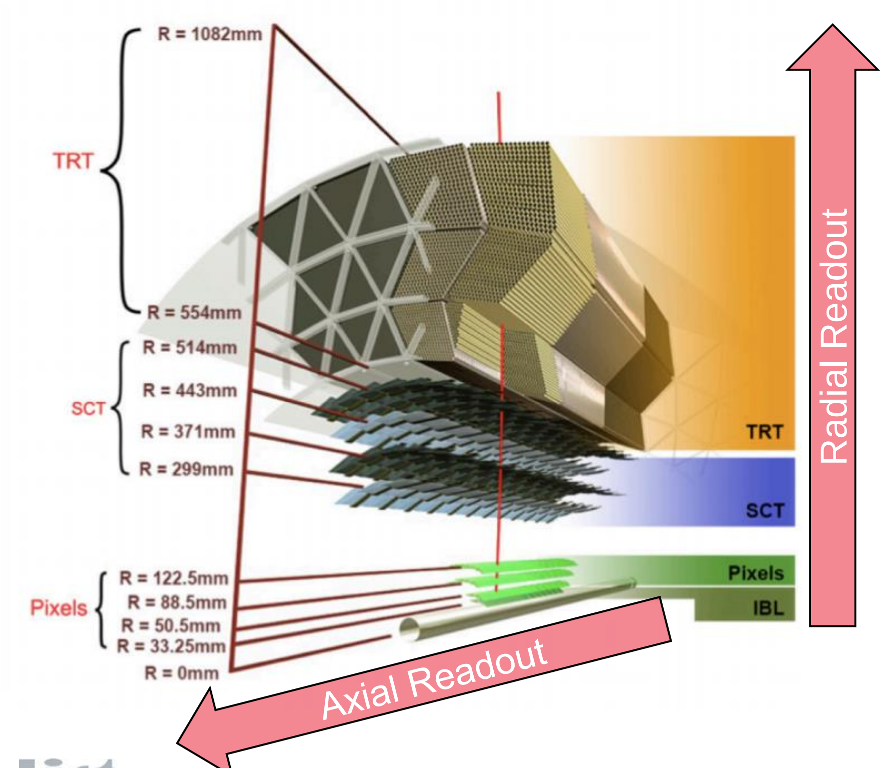


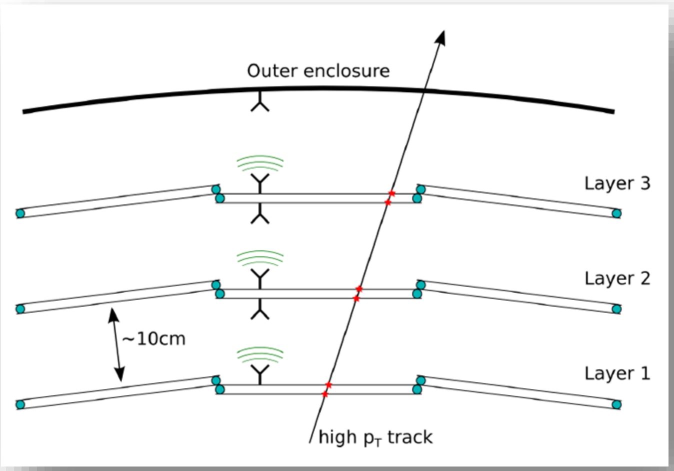
- **Impact on the measurements**
  - Multiple scattering and nuclear interactions
  - Dead-zone areas
- **Impact on the installation and the operation**
  - Cables and connectors are fragile
  - Cable path is not so flexible
  - Design constraints



Why Wireless ?

- Minimize material budget of cables/connectors
  Limited radiation length because of massive services in region between Barrel and Disks
- 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





Wireless readout principle
(R. Brenner, Uppsala Univ)

E.g.: Large collider readout

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

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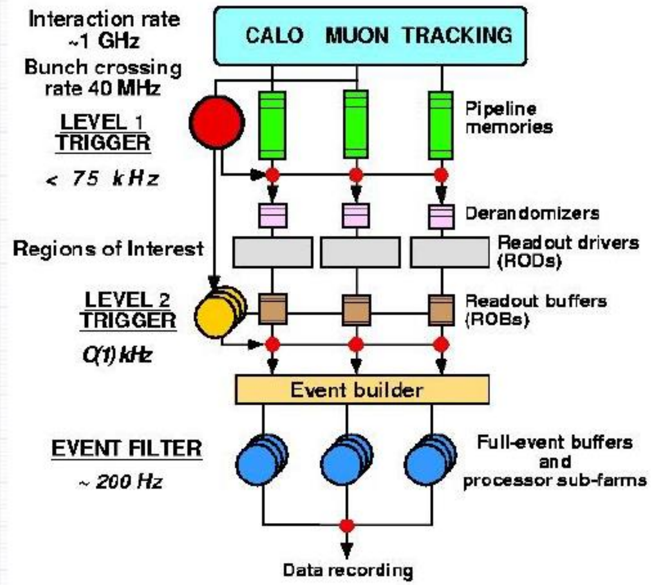

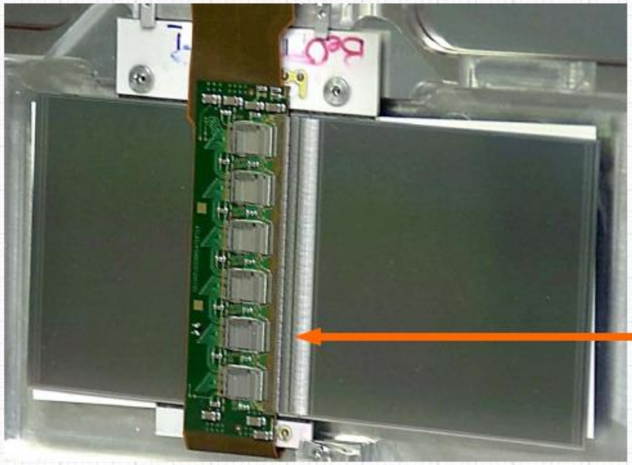

Front-end ASIC

E.g.: Large collider readout

Future data challenge

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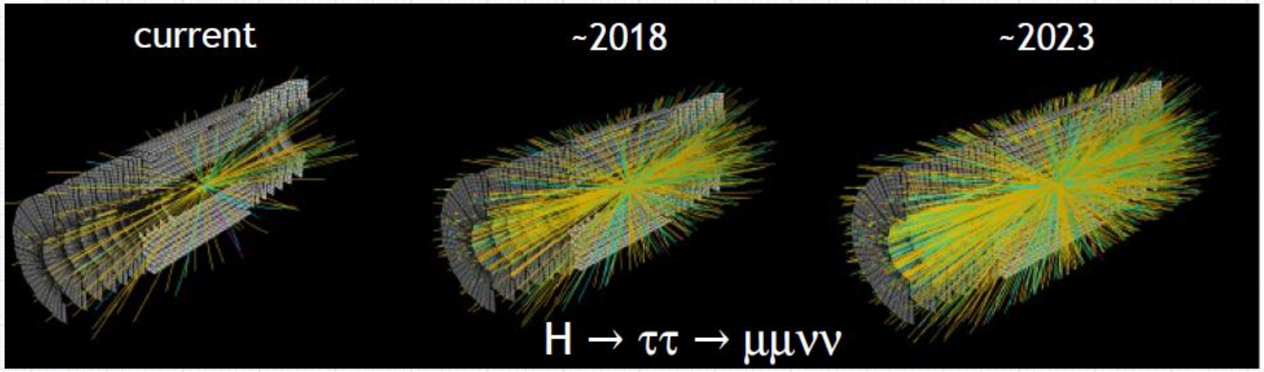

The only sub-detector currently not used for fast trigger are the tracking detectors.
To maintain current trigger thresholds at HL-LHC for maximum physics output
The tracking detectors (being the most granular) can make this possible.

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

Proposed approach

Track trigger and data rate reduction

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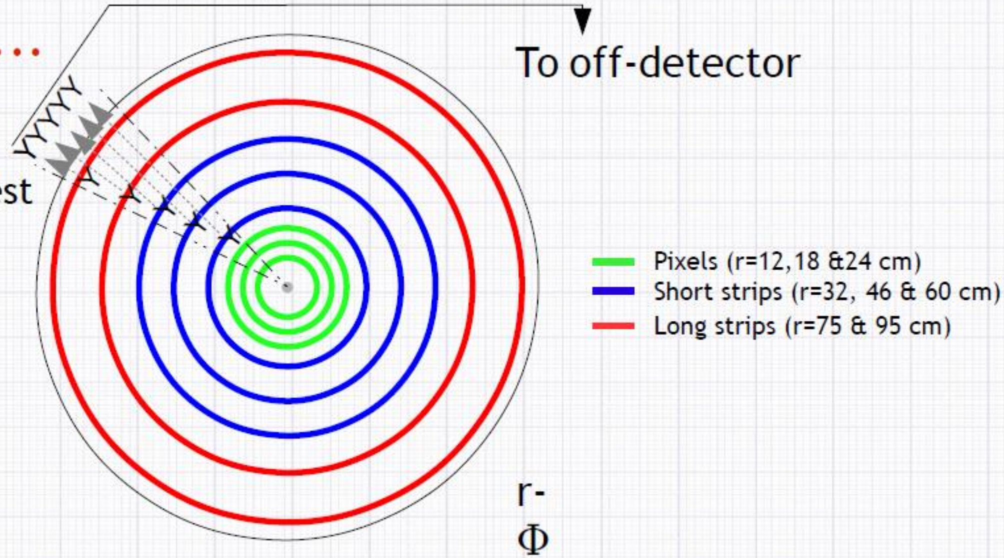
A simple idea…



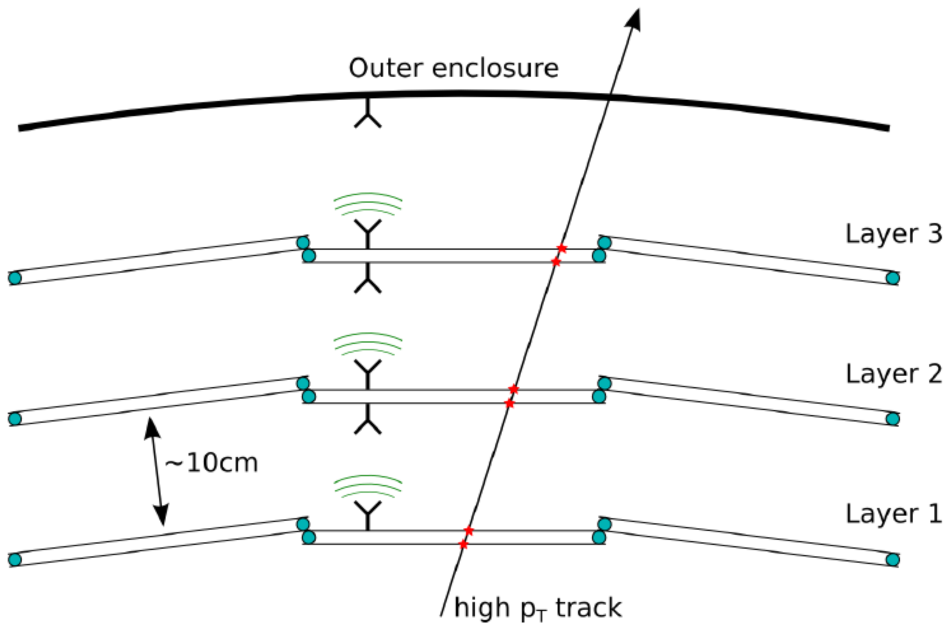
…but not trivial to build on detector

- 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?

Proposed wireless approach

- Heidelberg Univ.



Wireless readout concept

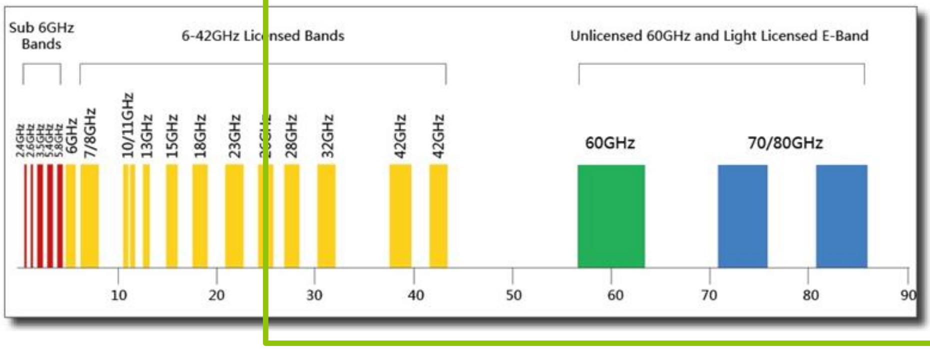
- Radial data transfer
  ⟶ Communciation between layers
- Signal cannot penetrate layers
  ⟶ Reuseability of frequency channels

Idea by R. Brenner (Uppsala)

Introduction to millimeter wave

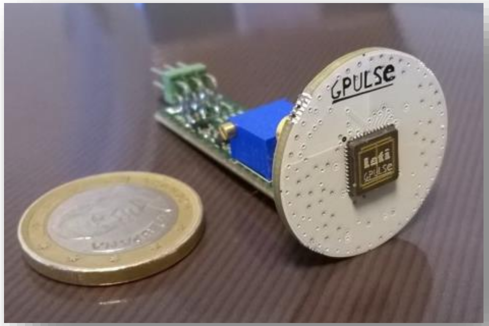
Definition

- 30-300GHz carrier frequency



MmW Rationale

- Short wavelength
  - High level of integration, compact antenna scheme
- High free path loss
  - Suitable for short range
  - High frequency reuse
- Huge available bandwidths for high data rate communication
- Natural immunity to interference



60GHz system in package
with integrated antenna

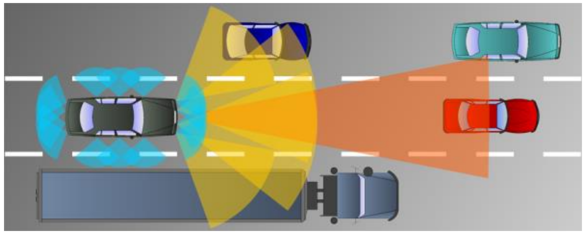
Introduction to millimeter wave

Millimeter wave current applications

R A N G E

- Radio astronomy
- Military and space
- Cellular Infrastructure, 5G small cell
- Automotive Radar
- Wireless HD
- WLAN 802.11ad
- Imaging and security
- **Short range, chip to chip, contactless connectivity**

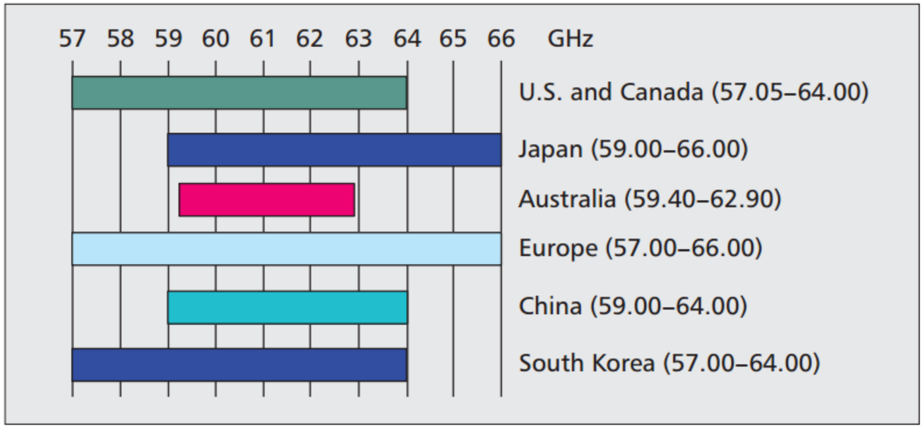





Features of the 60GHz band

- Huge worldwide unlicensed channels

US: Recent FCC extension 64-71GHz



- Favorable regulations for short range device
  - Maximum transmit power : 10dBm (Europe-Japan)
  - FCC :
    - emission limit for UWB systems: -51.3 dBm for indoor at 3m
    - 40-200GHz spurious emissions: -10 dBm EIRP max at 3m
  - ETSI:
    - Unwanted emissions (frequencies beyond the limit of 250 % of the necessary bandwidth) in the spurious domain: -30dBm (in operating mode) and -47dBm (in standbye mode)

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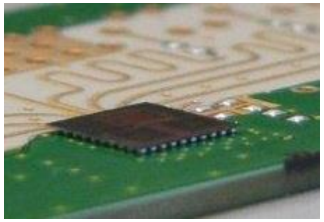
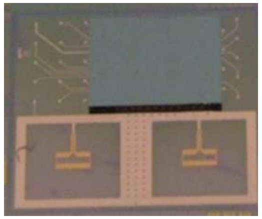
Features of the 60GHz band

- Short (5mm) wave length
  - High free space loss:
    28dB@1cm; 48dB@10cm; 68dB@1m
  - Small antenna size
  - System in package integration

60GHz Si SiP



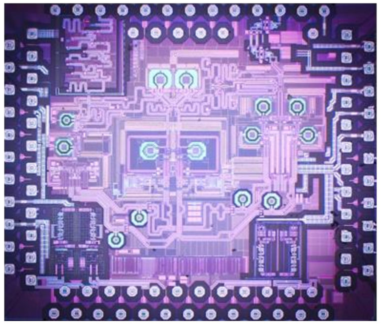


60GHz patch antenna
2.5mm

60GHz transmit array antenna

- Compatible with low cost CMOS
  - Design at <Fmax/3, <90nm node
  - Passives in Back End Of Line
    High quality factor >40nm node

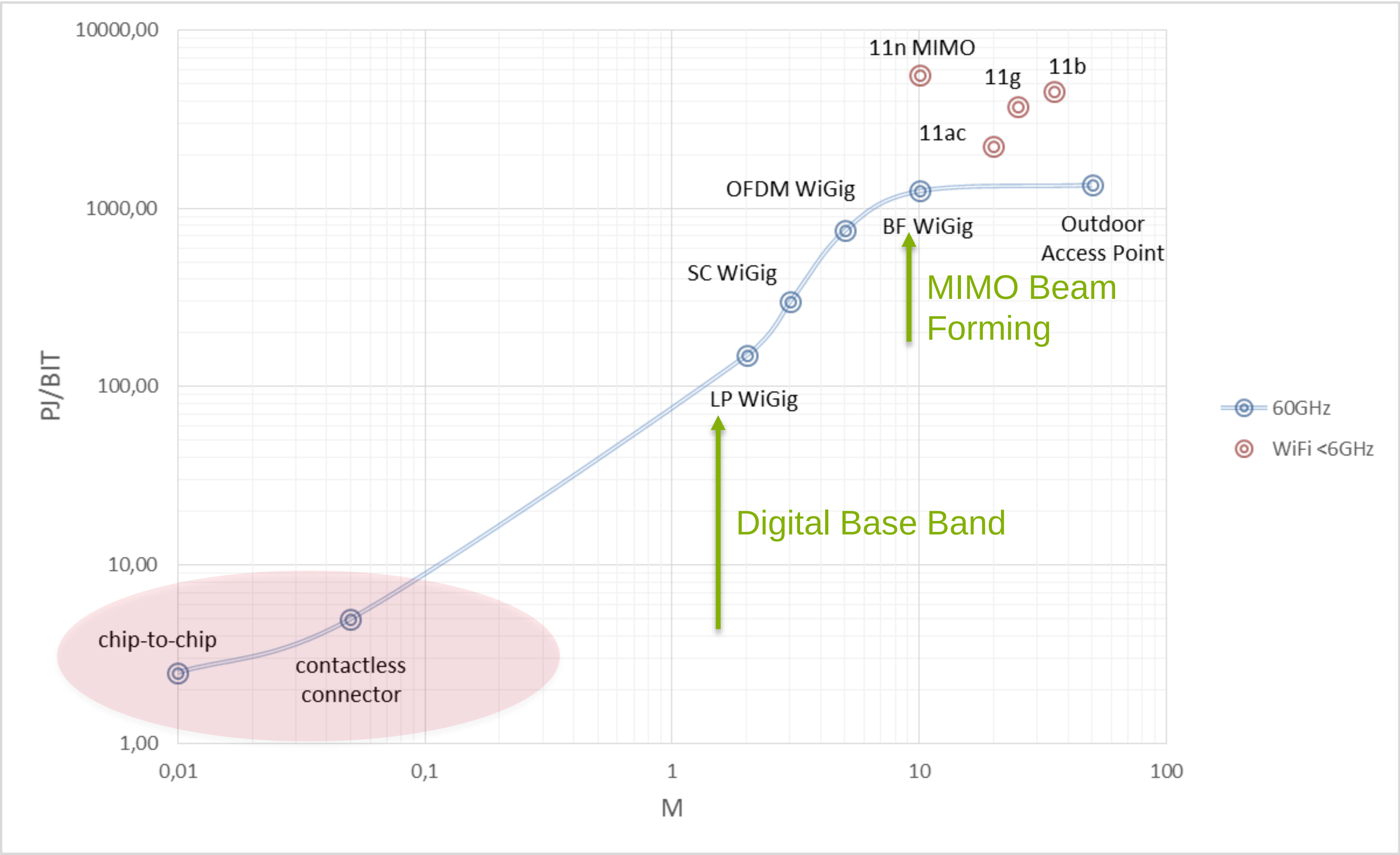
WiHD/802.11ad
60GHz TRx, CMOS65nm



Zigbee

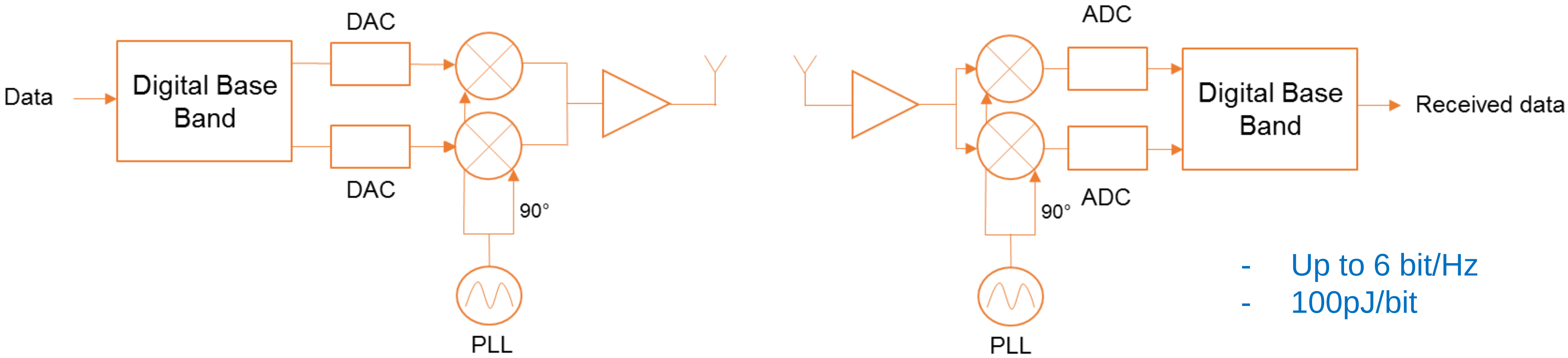
Bluetooth LE

Is mmw low power ?



RFIC architectures

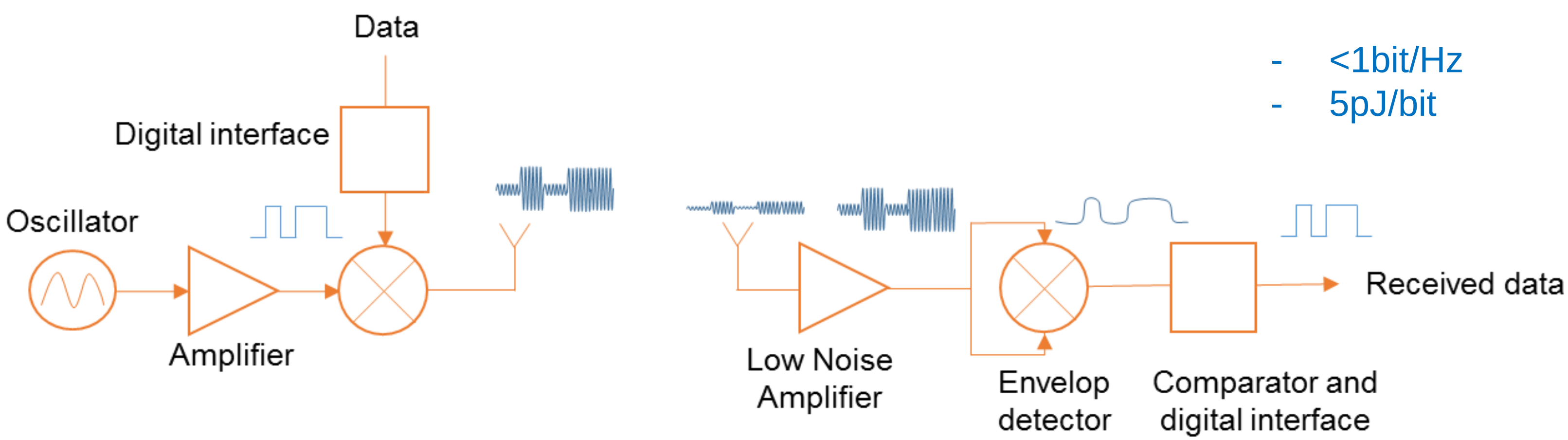
Coherent architecture



- Up to 6 bit/Hz
- 100pJ/bit

Non coherent architecture (On/Off keying)

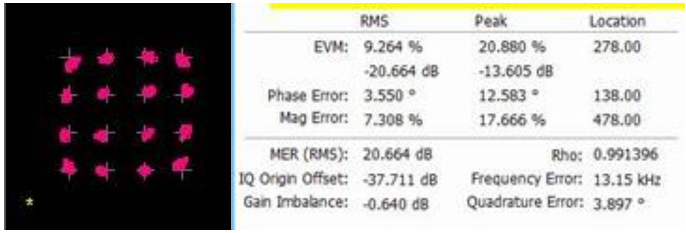
- <1bit/Hz
- 5pJ/bit



RFIC architectures

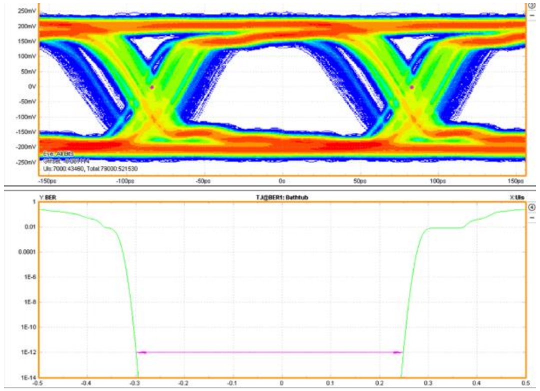
Coherent architecture

- Widely used today as the most efficient (range, robustness, and spectral efficiency)
- Need power hungry PLL and digital base band processor
- Signal processing latencies
- Performance metrics: EVM, SNR, BER, PER

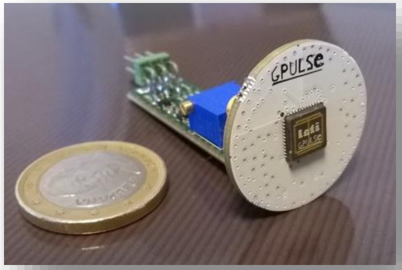


Non coherent architecture (On/Off Keying)

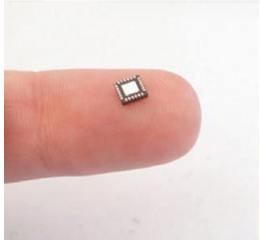
- Former and simple analog technology
- Very low power, almost no latency
- Ideal for cable replacement at short range
- Weak sensitivity (short range) and spectral efficiency
- Sensitive to multi paths, interferers
- Performance metrics: eye diagram, jitter, BER, PER



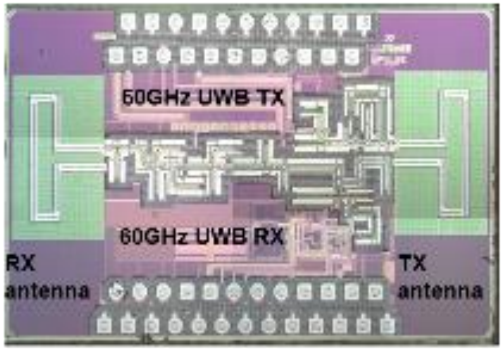
60GHz RFIC design



60GHz contactless connector (2011-2015)



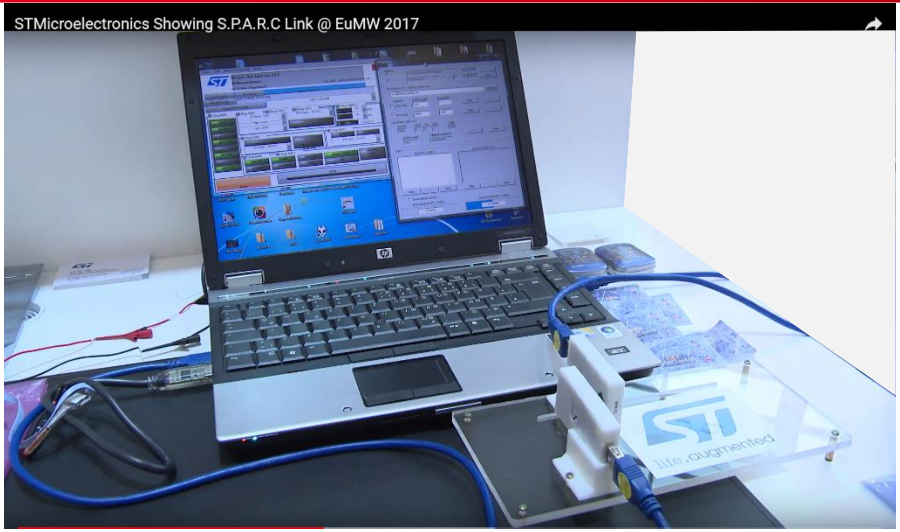
1,9mm x 3,1mm



<u>Technology</u>:
- 60GHz OOK transceiver in CMOS SOI 65nm
- Super-regeneration receiver
- Integrated antennas

<u>Demonstrated performances</u>:
- HD Video streaming
- Data rate: up to 2.5Gbps
- Range: 10cm
- Power consumption: 50mW (20pJ/bit)

60GHz RFIC design



60GHz contactless connector (2015-2017)

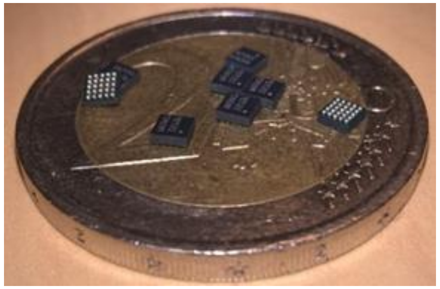
Technology:
- 60GHz ASK transceiver in CMOS 65nm
- Non coherent receiver (envelop detector)
- BGA package
- External antennas

Demonstrated performances:
- HD Video streaming (2Gbps FPGA limited)
- Data rate: up to 6Gbps
- Range: 3cm with 4dB gain antenna
- Power consumption: 35mW (<6pJ/bit)

60GHz RFIC design

Technical features (from datasheet)

- 60GHz V-Band transceiver for short range contactless connectivity **up to 6Gb/s**
- Compact solution integrating full RF transceiver operating in **half-duplex mode** with ASK modulation
- SLVS serial IO to host processor supporting 1Mb/s up to 6Gb/s with MIPI m-phy compatibility
- 60GHz TX/RX single-ended 50Ω RF ports for antenna on PCB
- Supply voltage : Dual 1.8V and 1.45V *or* single 1.8V
- RFIC control through I2C or asynchronous control pin for TX/RX mode
- Very Low power consumption: **40mW** in transmit mode, **25mW** in receive mode @ 5Gbps
- Dedicated RF Wake-Up idle mode with 10µW average battery consumption
- 1uW in off mode
- Package:
  VFBGA 2.2mm x 2.2mm x 1.0mm, 25 balls, F5x5, 0.4mm pitch



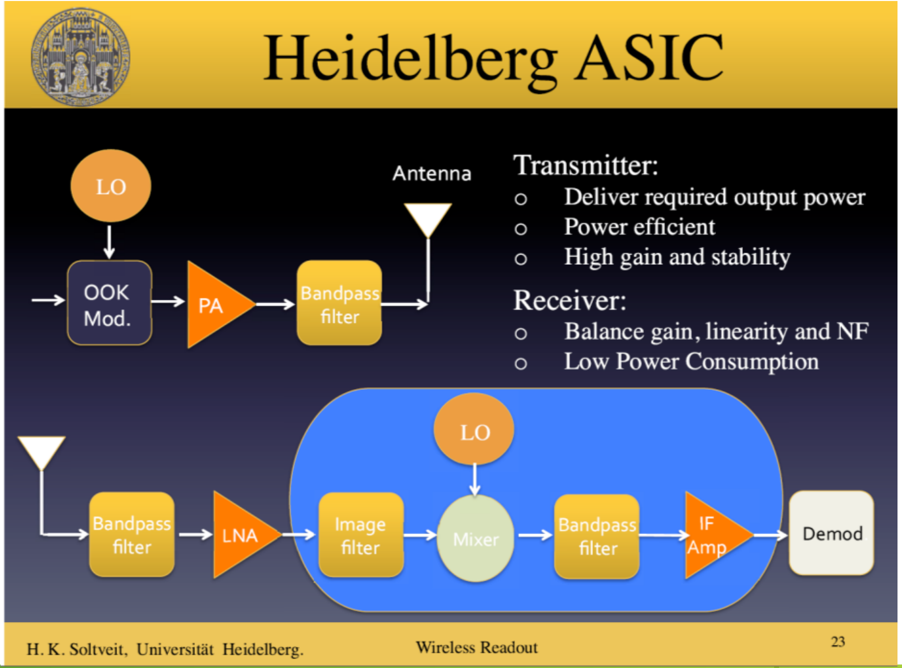
60GHz RFIC design (Heidelberg)

60GHz transceiver design ongoing, <u>dedicated to wireless readout</u>

- Specifications in line with the HEP applications
- Technology and architecture chosen from in-depth studies

  SiGe HBT BiCMOS technology
- Comprehensive simulations on the RF blocks over PVT, mismatchs and coupling effects
- Strong attention paid to robustness and reliability
- Chip under development, timeline through 2019

Specifications	Value
Frequency band	57-66 GHz
Bandwidth	**9 GHz**
Data Rate	**4.5 Gbps**
Modulation	OOK
Minimum sensitivity $S_{rx(min)}$	- 49 dBm
Bit Error Rate (BER)	10^{-12}
Target Power consumption	**250 - 150 mW**
Transmission Range	20 cm (1m)



RFIC design: perspectives

Towards 20-40Gbps, challenging the optical links

Challenges: limited range, gain,
emitted power

High frequency
High bandwidth > 100GHz

Multiple channels
Spatial and/or frequency multiplexing

Multiple levels modulation
QAM, M-ASK

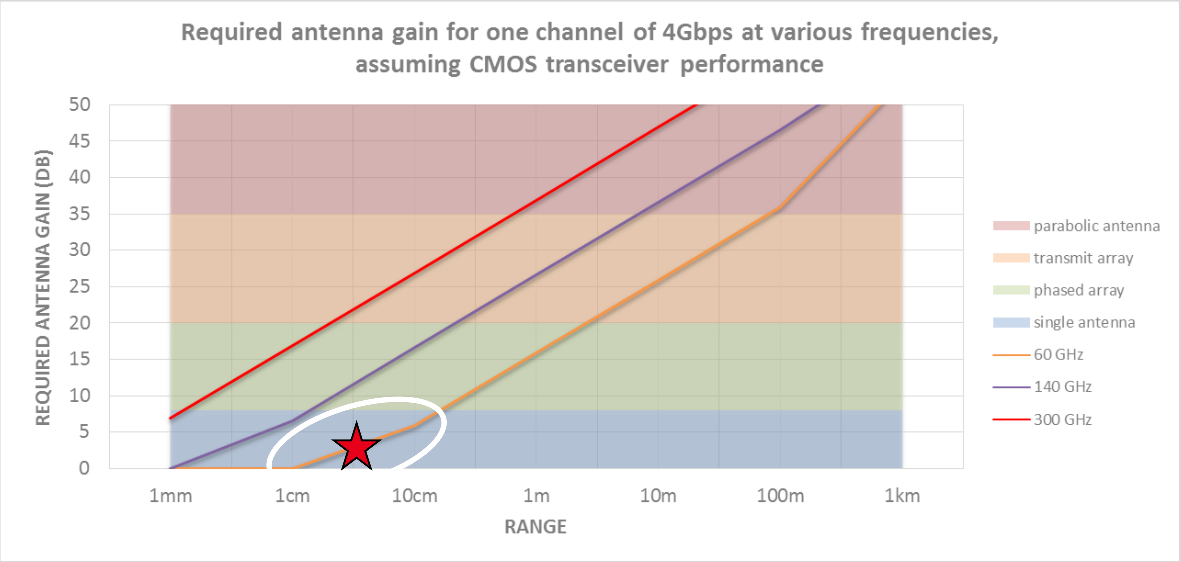
Challenges: RF architecture, bandwidth, channel filtering, multi tone frequency synthesis, antenna coupling, silicon area and antenna form factor

20-40Gbps, 5pJ/bit

Challenges: RF architecture, linearity, carrier synchronization (phase & frequency)

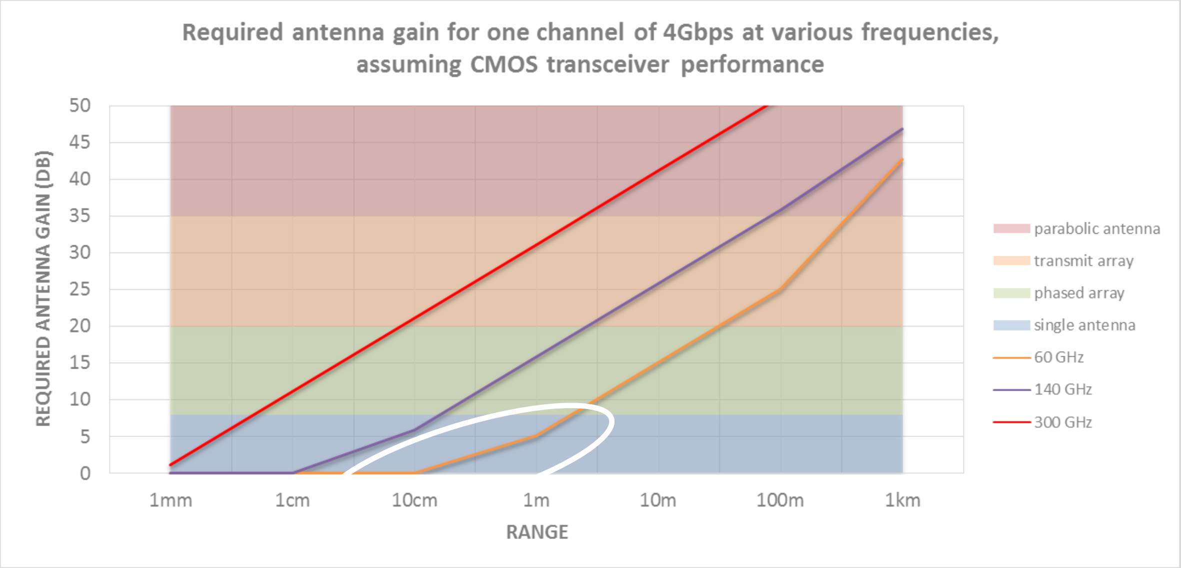
Advanced technology

Antenna requirement (e. g.)



Non-coherent architecture

<75ps total jitter



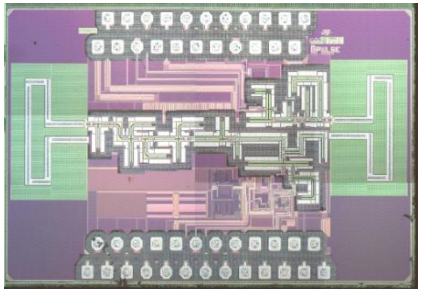
Coherent architecture

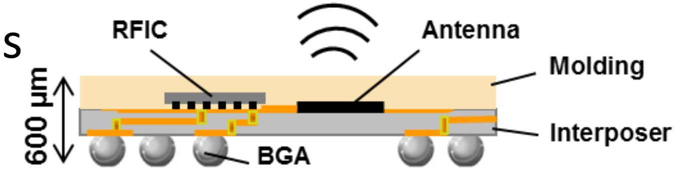
BER<1e-5 before decoding

Antenna design

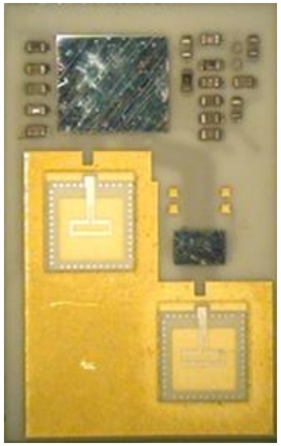
- On High Resistivity Silicon (SOI HR) antenna
  - 5dB antenna gain
  - 20% bandwidth
  - Sensitive to wire bonding
- System in Package with antennas
  - Transceiver flip-chipped close to the antennas
  - Ceramic, silicon or organic interposer
  - 2D or 3D interconnections
  - 5-8dB gain

HR SOI 65nm OOK TRX
1,9*3,1mm²



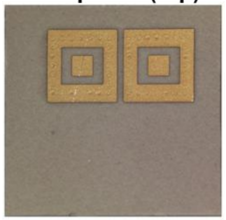


HTCC
13.5*8.5mm²

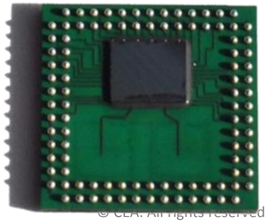


LCP
10*10mm²

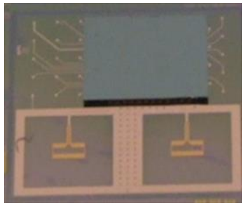
Interposer (top)

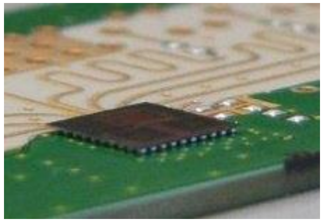


Interposer (bottom)



Si
6.5*6.5mm²





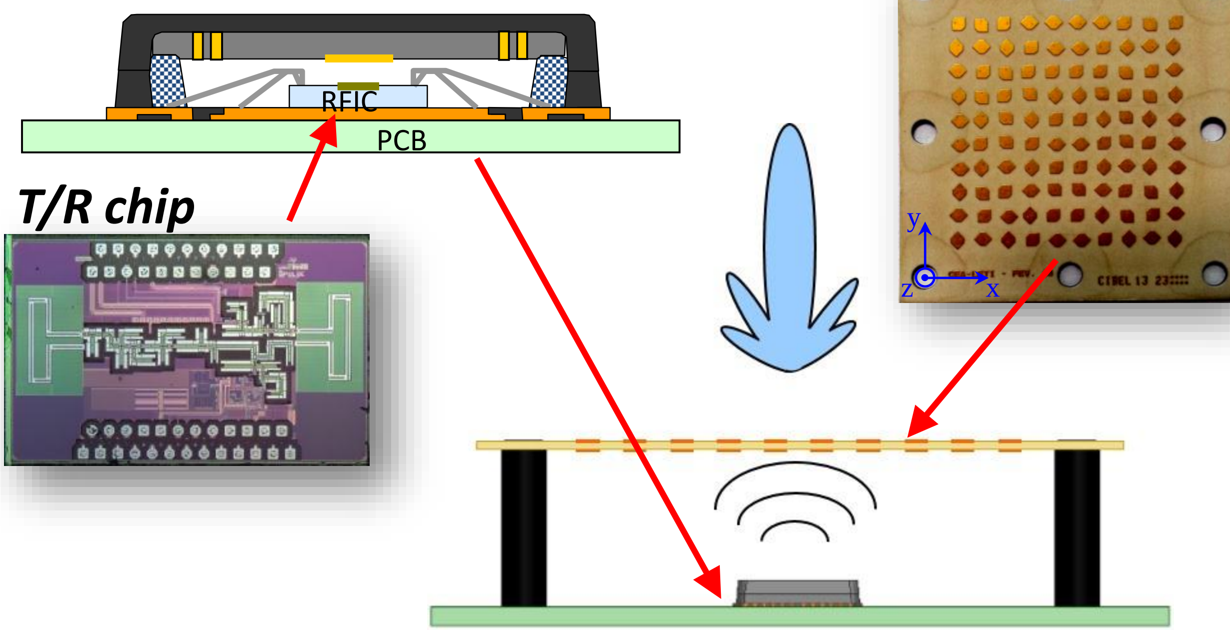
Antenna design

In-Package coupled antenna and focusing lens:

- Transmit array quasi-optical lens
- No mmW interconnection; **+15 dB** antenna gain improvement; fixed beam
- At 2Gbps: from 6cm range to 190cm range using an external lens
- Chip size: 2x3.3 mm^2; package 7x7 mm^2; lens 25x25 mm^2

In-package antenna : ~5 dBi

Discrete lens: ~16 dBi



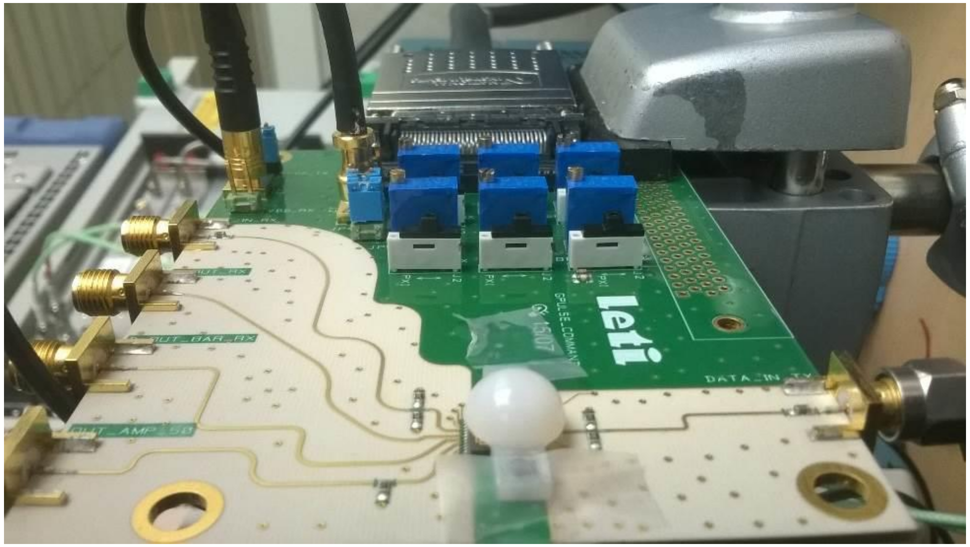
OTA Measurement

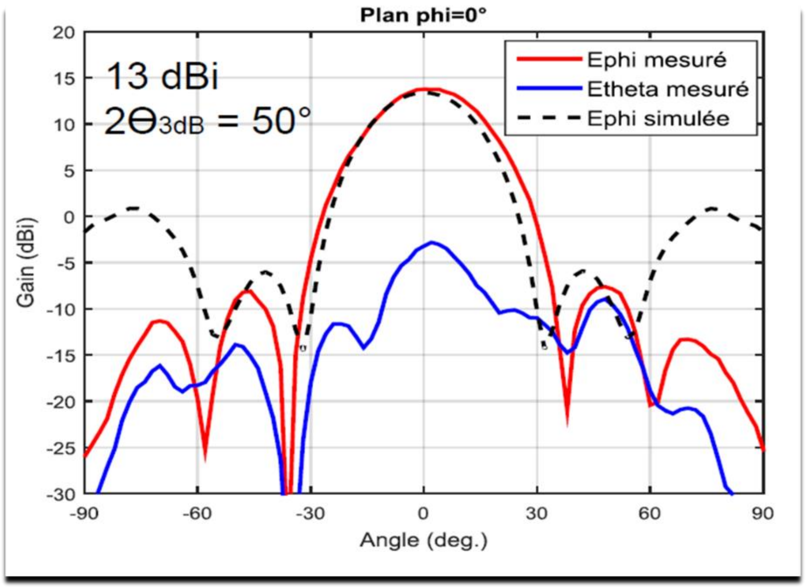
Data Rate	Range
0.5 Gbps	530 cm
1 Gbps	400 cm
1.5 Gbps	353 cm
2 Gbps	190 cm
2.2 Gbps	175 cm

Antenna design

In-Package coupled antenna and dielectric lens:

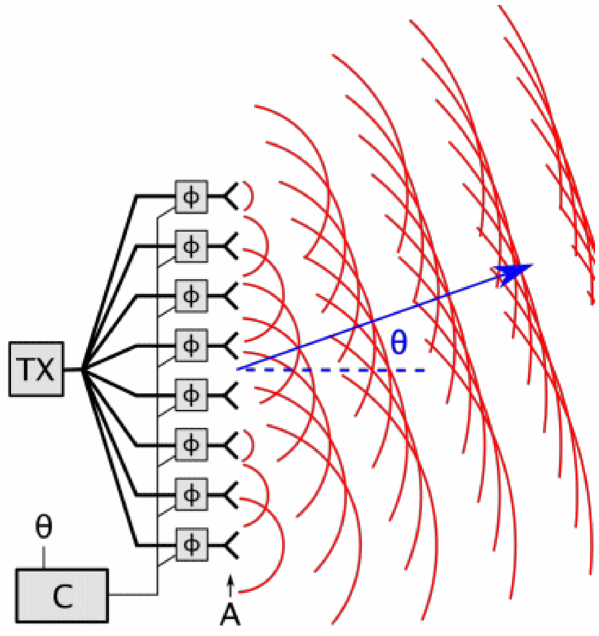
- Polyimide dielectric lens
- +8 dB antenna gain improvement
- At 2Gbps: from 6cm range to 40cm range using an external lens
- Chip size: 2x3.3 mm^2; package 7x7 mm^2; lens ∅ 10 mm

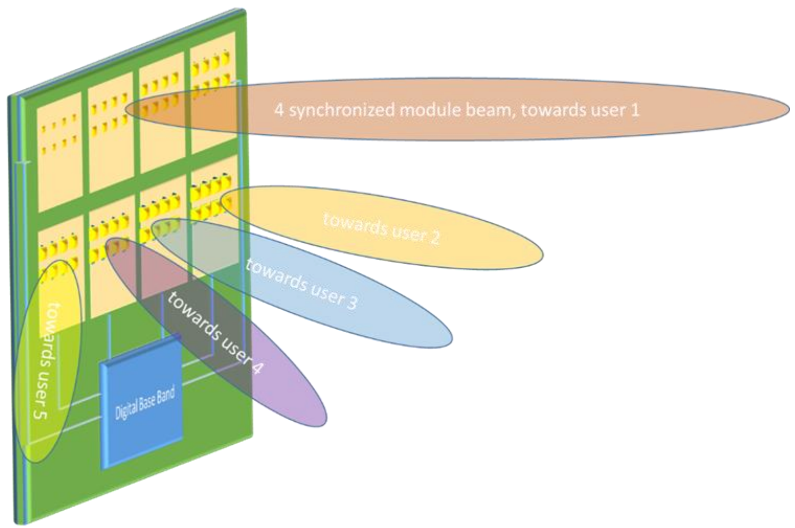




Antenna design

- Phased array antenna with beamforming capability
  - Require controllable phase shifters to steer the beam
  - Single beam or multi-beams

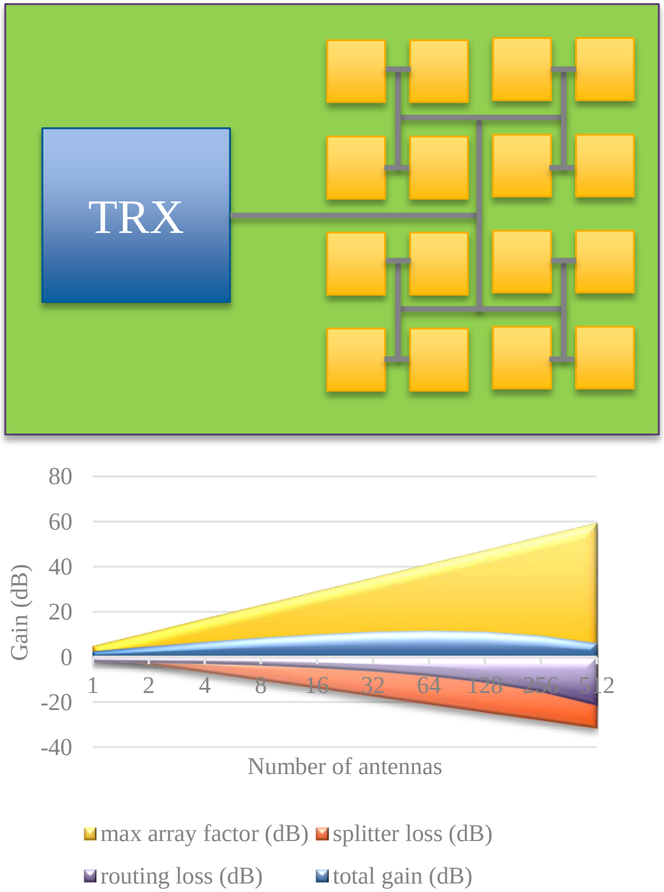




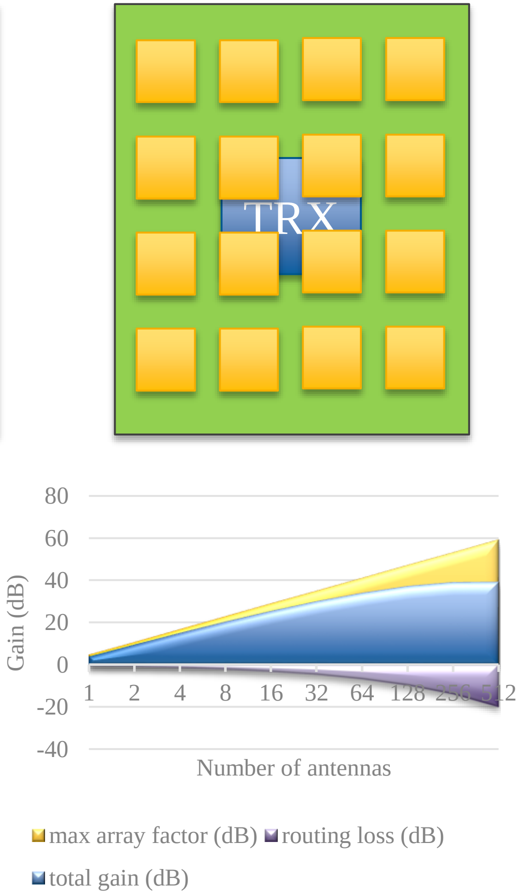
Antenna design

RF Beamforming approaches

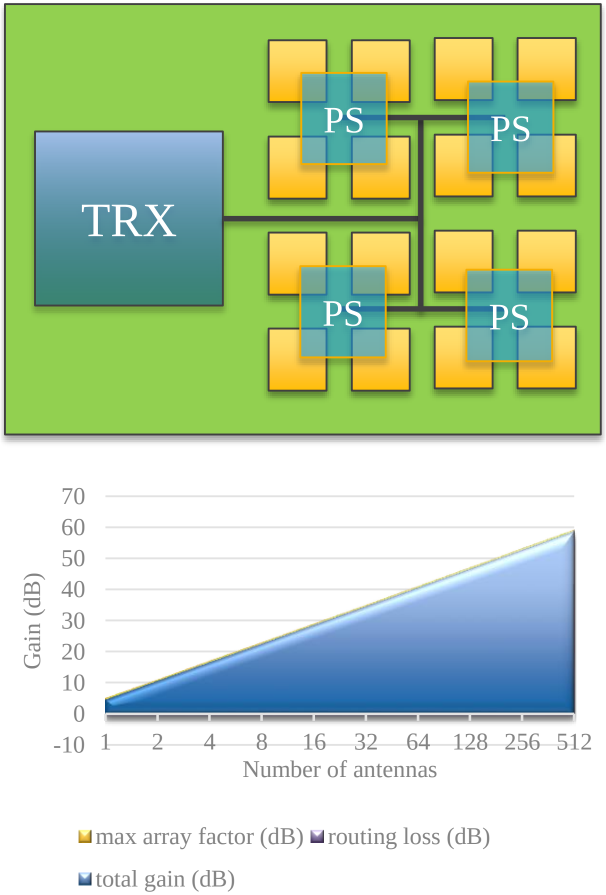
Fixed beam antenna array



Compact monochip TRX and phase shifters



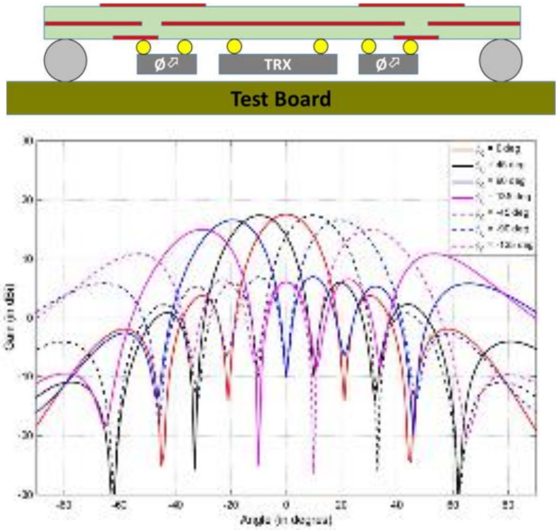
Satellite phase shifters



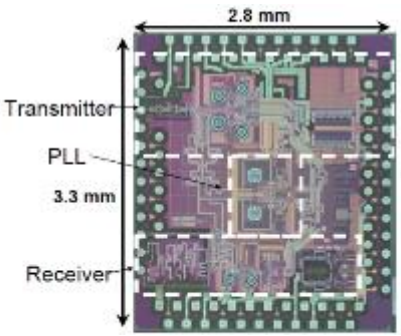
Antenna design

Beamforming with satellite phase shifter (2015)

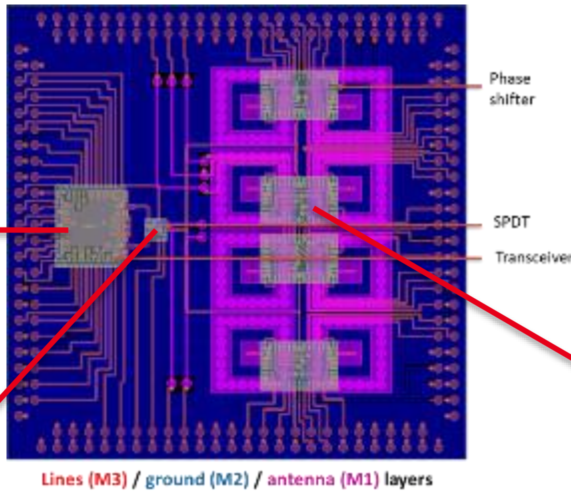
- 2*4 antenna array, 17dBi gain, 36dBm EIRP
- {PA, LNA, phase shifter} circuit in BICMOS55nm
  - Compensation of the power splitter and phase shifter losses
  - Vector modulator phase shifter
- 3D multi-layer organic module (LCP), 20*20mm²

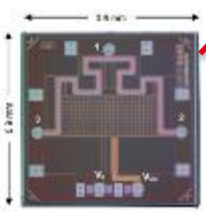


60GHz transceiver
4 channels 57-66GHz

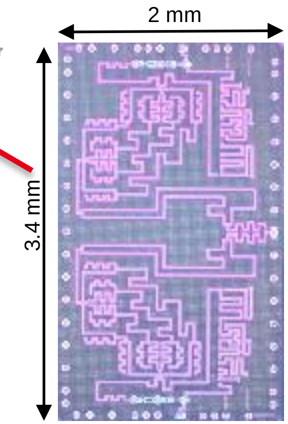


LCP interposer module layout





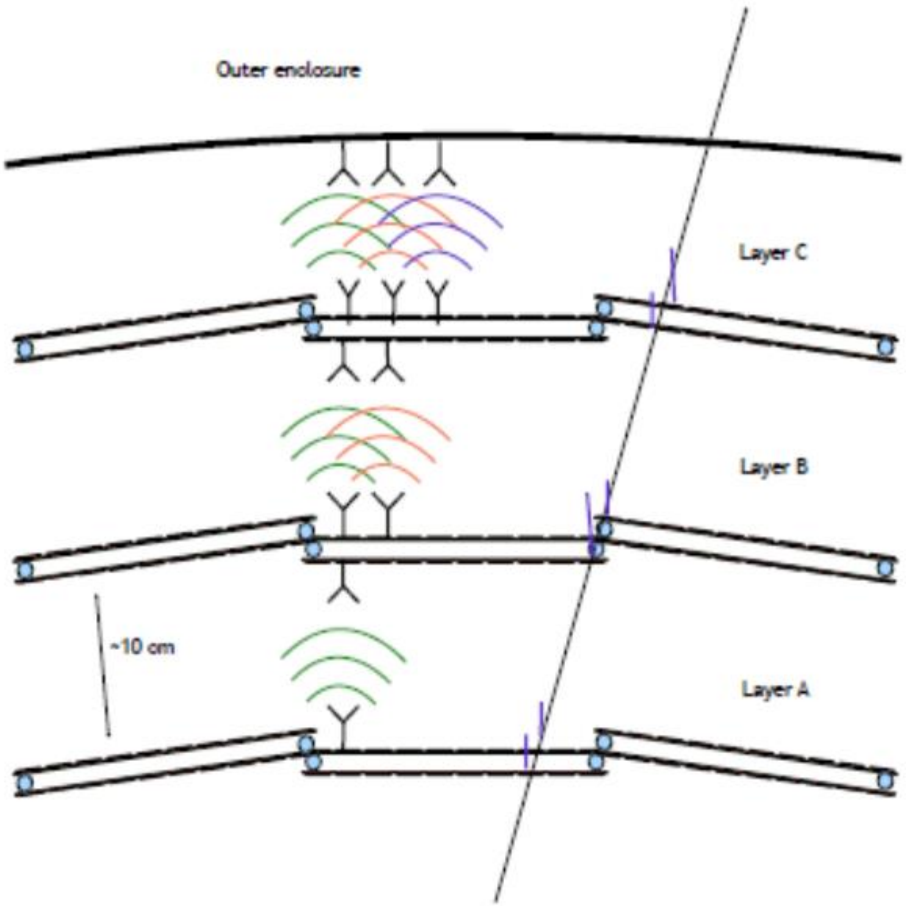
Tx/Rx switch



PA, LNA, phase shifter IC

Proposed approach

- Heidelberg Univ.



Wireless readout concept

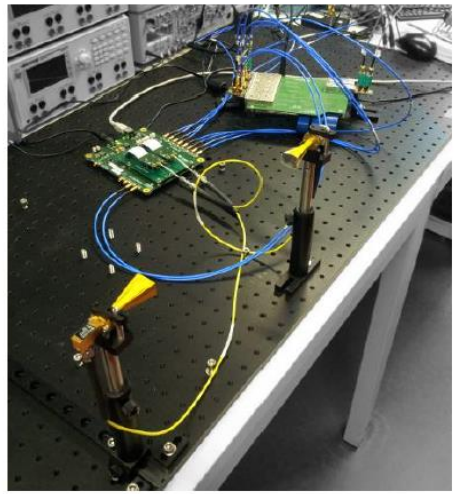
- Radial data transfer
  ⟶ Communciation between layers
- Signal cannot penetrate layers
  ⟶ Reuseability of frequency channels

Feasibility studies, Heidelberg Univ.

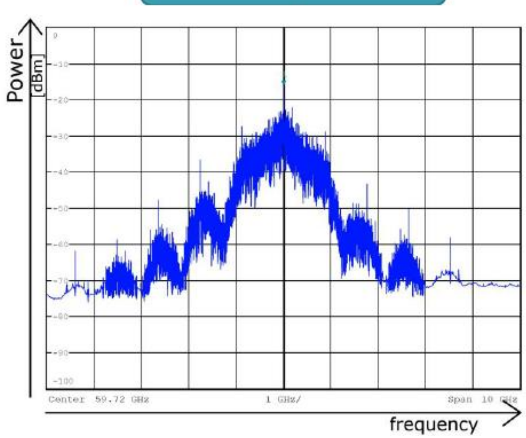
Tests in Heidelberg: line of sight transmission

Setup in the lab

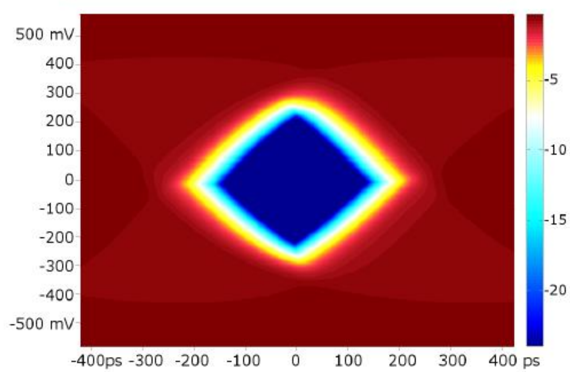
Distance: 22 cm
Horn antennas from Kapton und aluminium



60 GHz spectrum



1.76 Gbps eye diagram

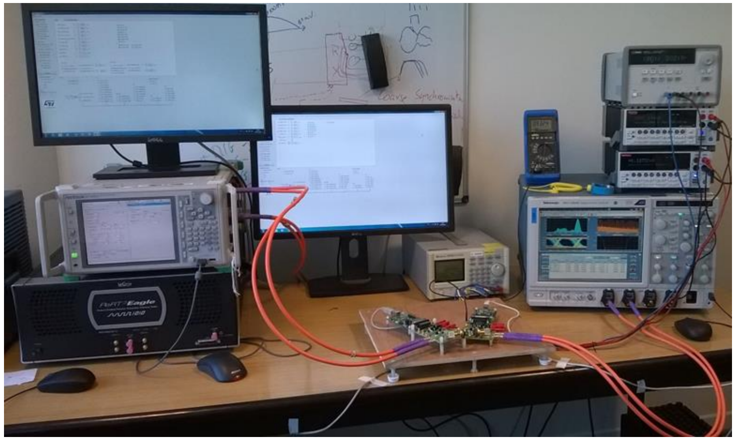


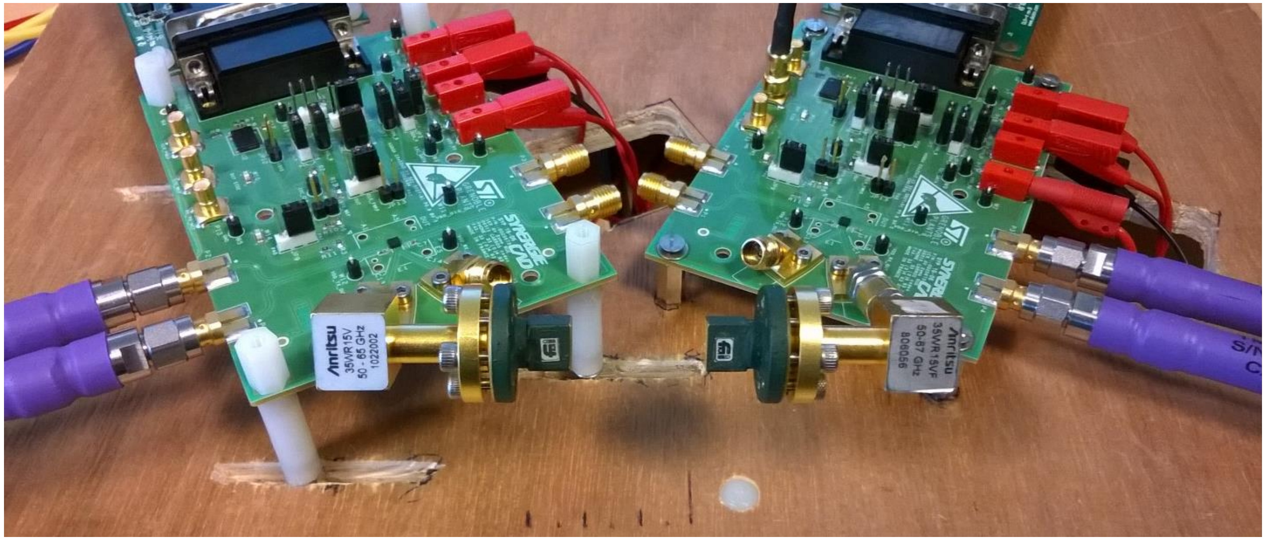
Data transmission studies

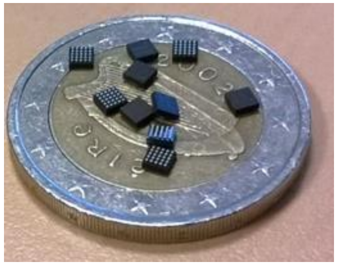
- 60 GHz Tx/Rx byHittite HMC 6000/6001
  - Bandwidth: 1.8 GHz
- Setup: Bit error rate test
  - Data rate: 1.76 Gbps
  - Minimum Shift Keying $\boldsymbol{BER < 10^{-14}}$
- HD-SDI-Video transmission

Feasibility studies, CEA Leti

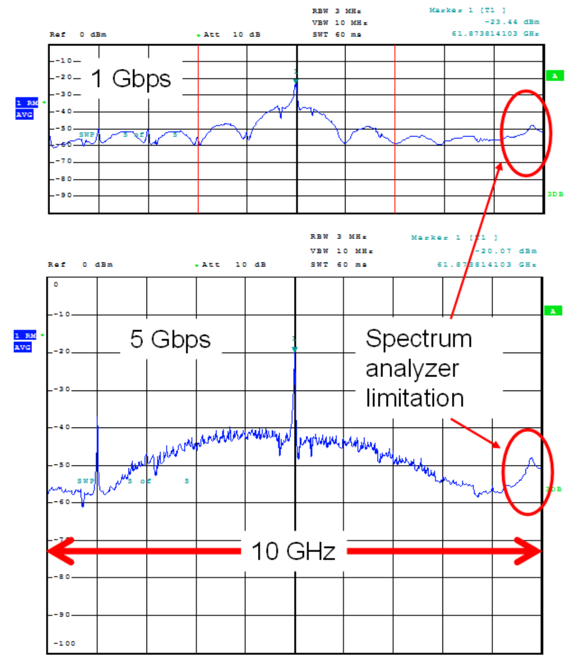
- PRBS 8b/10b
- 60GHz TRX package on test board
- 9dB horn antennas
- 3cm range
- Oscilloscope eye and jitter analysis



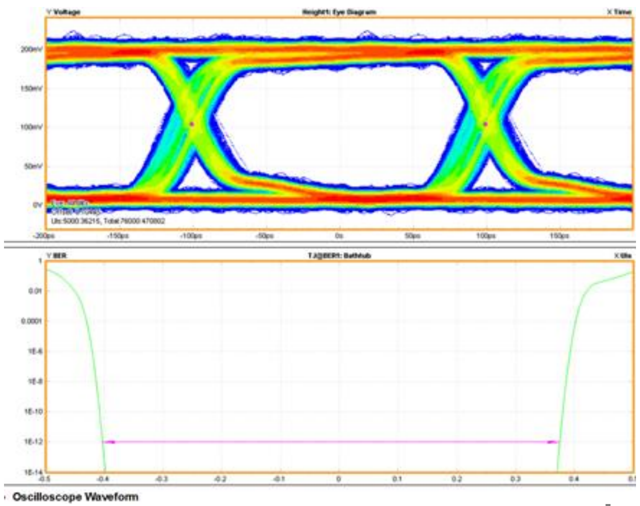




- Emitted wave form (60GHz)



- Receiver eye diagram (5Gbps)
  - 400mV peak-peak differential
  - 35ps 20-80% fall/rise time



Cable replacement compatibility (USB, M-PHY)

Budget

Jitter budget @5Gbps for BER = 10e-12

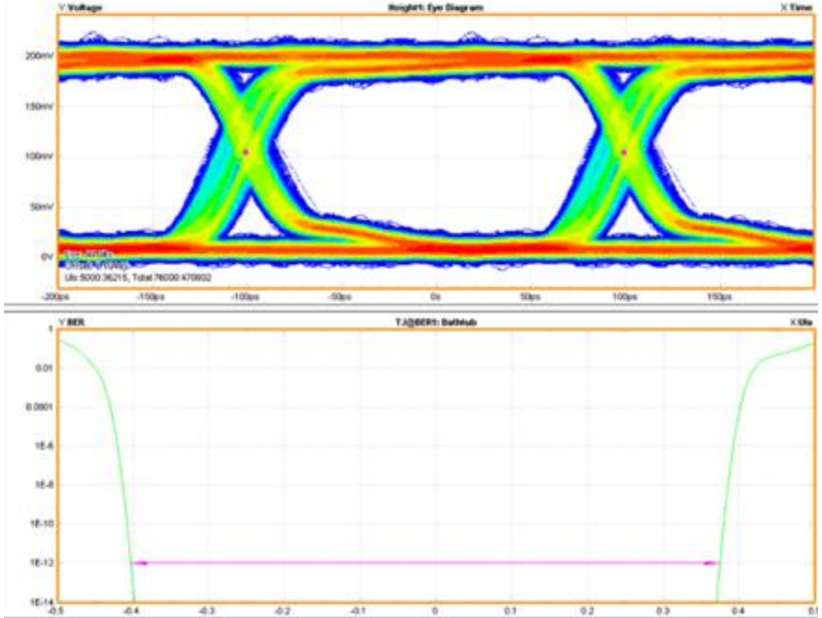
	Random Jitter (ps)	Deterministic Jitter (ps)	Total Jitter (ps)
mipi jitter budget	**Rj**	**Dj**	**Tj (ps)**
Tx	2,42	30,00	64,04
Media	2,13	45,00	74,96
Rx	2,42	40,00	74,04
Total	4,03	115,00	171,71
			200 max

M-PHY standard:
75ps total jitter allowed for cable

Tj = Dj+14.07*Rj

Example of measurement @ 5Gbps

Description	Mean	Std Dev	Max	Min
TIE1, Ch1	-1.1483fs	6.5838ps	19.456ps	-20.614ps
Current Acquisition	2.8881fs	6.6011ps	17.545ps	-19.785ps
Height1, Ch1	150.47mV	2.6951mV	155.04mV	146.04mV
Current Acquisition	149.81mV	0.0000V	149.81mV	149.81mV
TJ@BER1, Ch1	45.070ps	1.3558ps	47.132ps	43.128ps
Current Acquisition	46.657ps	0.0000s	46.657ps	46.657ps
RJ–δδ1, Ch1	1.4268ps	71.681fs	1.5120ps	1.3044ps
Current Acquisition	1.5075ps	0.0000s	1.5075ps	1.5075ps
DJ–δδ1, Ch1	25.094ps	641.34fs	26.207ps	24.165ps
Current Acquisition	25.552ps	0.0000s	25.552ps	25.552ps
Width@BER1, Ch1	154.93ps	1.3558ps	156.87ps	152.87ps
Current Acquisition	153.34ps	0.0000s	153.34ps	153.34ps

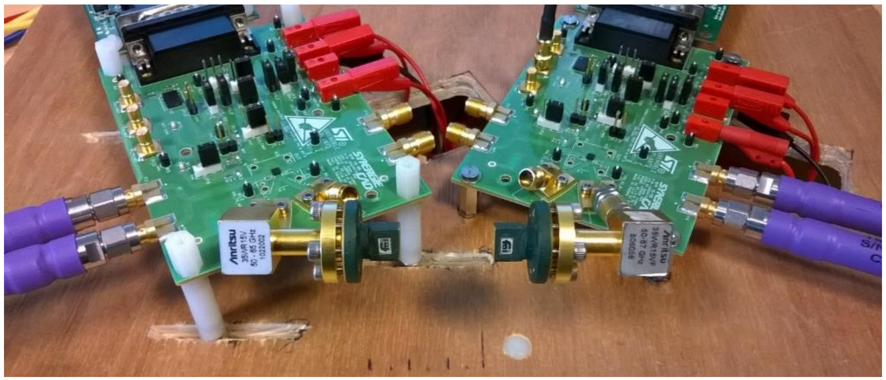


Oscilloscope Waveform

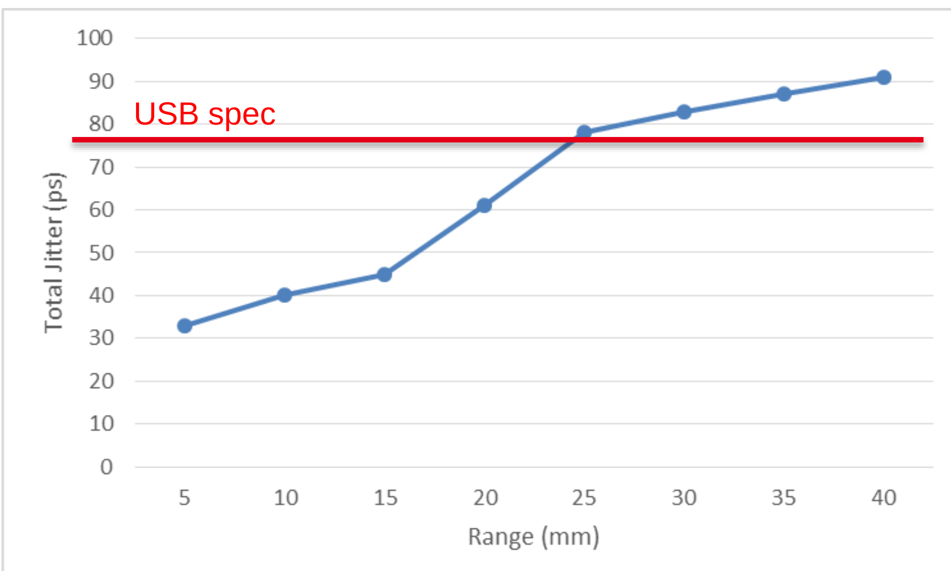
Feasibility studies, CEA Leti

Cable replacement compatibility (USB, M-PHY)

- Example of measured jitter @5Gbps with test boards



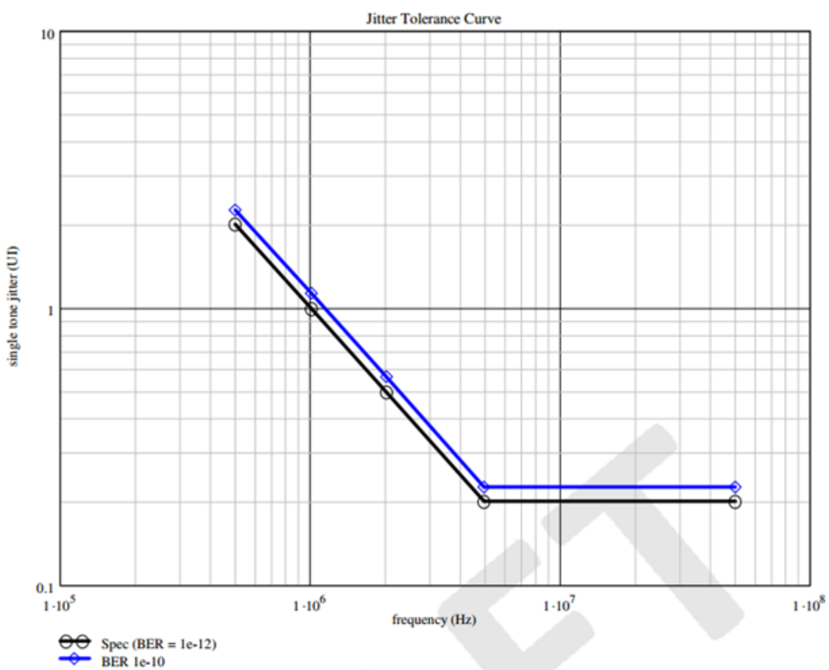
9dB horn antenna
– 3dB interconnection loss



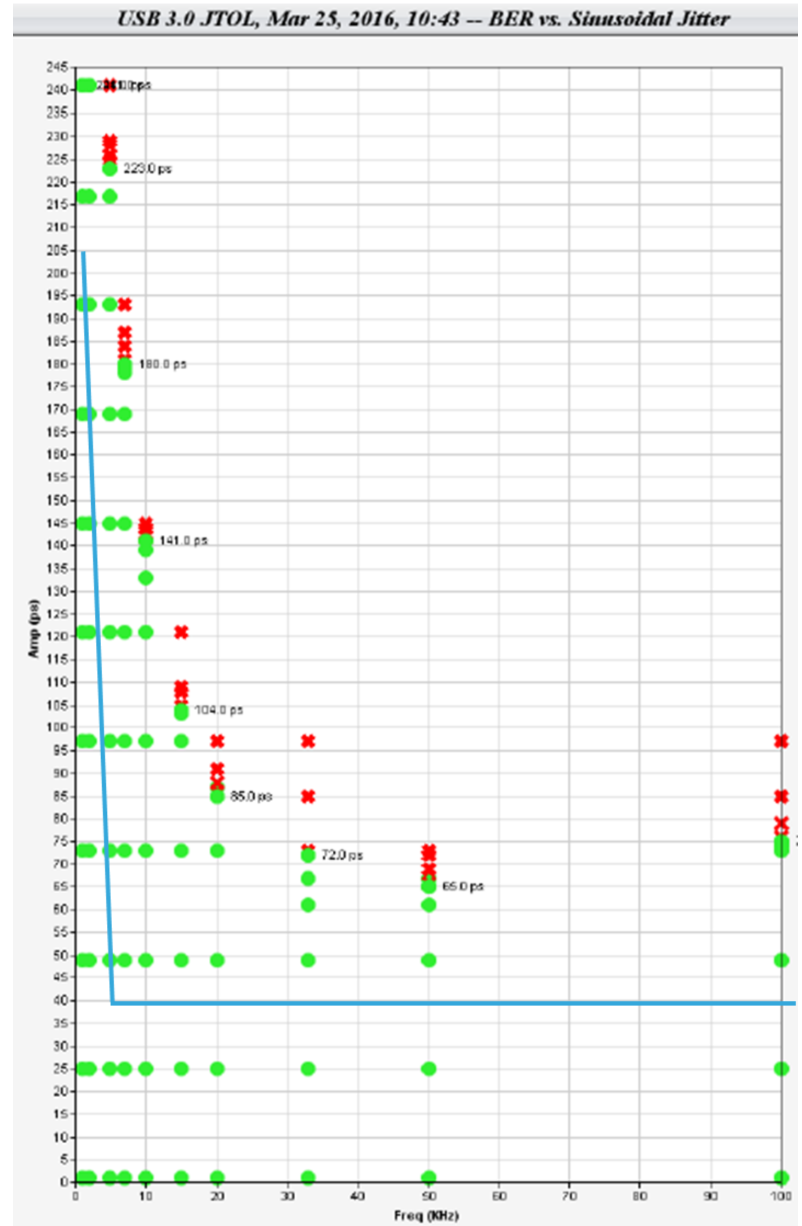
Feasibility studies, CEA Leti

Cable replacement compatibility

USB3 Jitter tolerance test

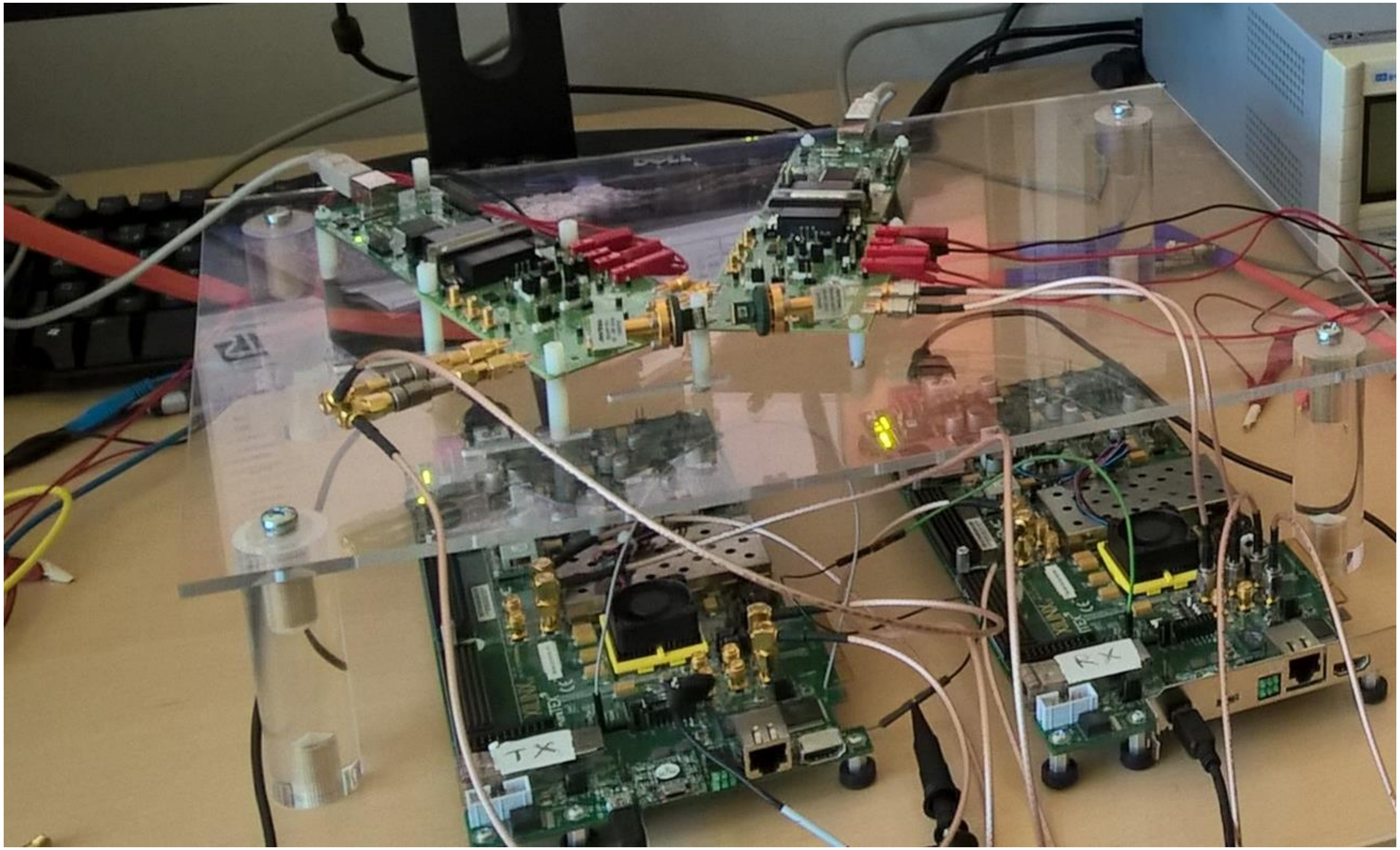


Frequency (Hz)	Jitter (UI)		Jitter (ps)	
	BER=10^{-12}	BER=10^{-10}	BER=10^{-12}	BER=10^{-10}
5×10^5	2	2.265	400	453
1×10^6	1	1.132	200	226.4
2×10^6	0.5	0.566	100	113.2
4.9×10^6	0.205	0.232	41	46.4
5×10^7	0.205	0.232	41	46.4



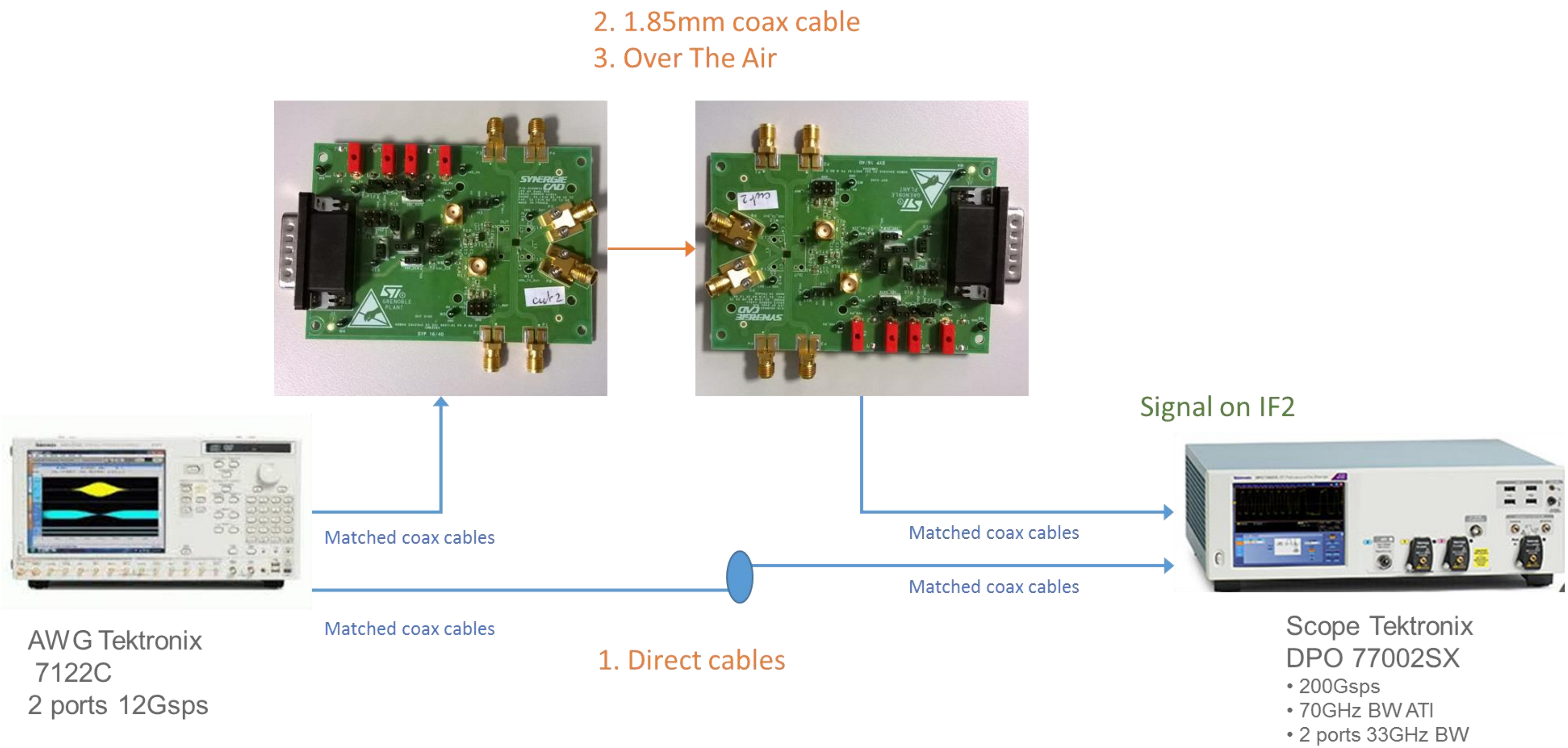
Interfacing with FPGAs

Error free transmission of 8b/10b video stream at 2Gbps during a full day

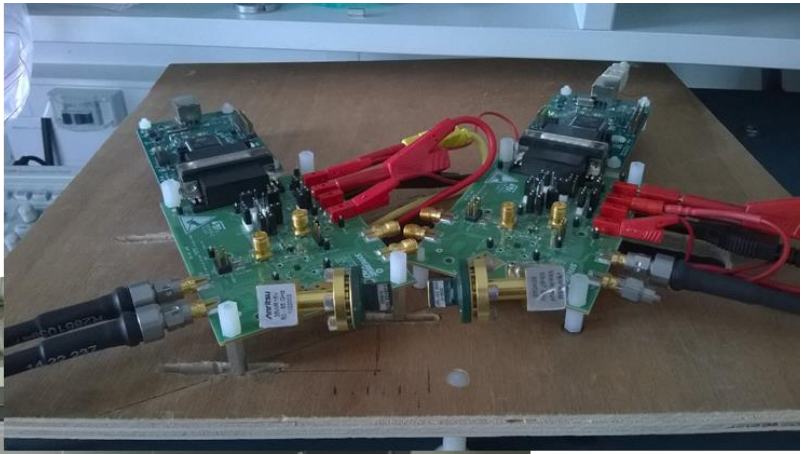


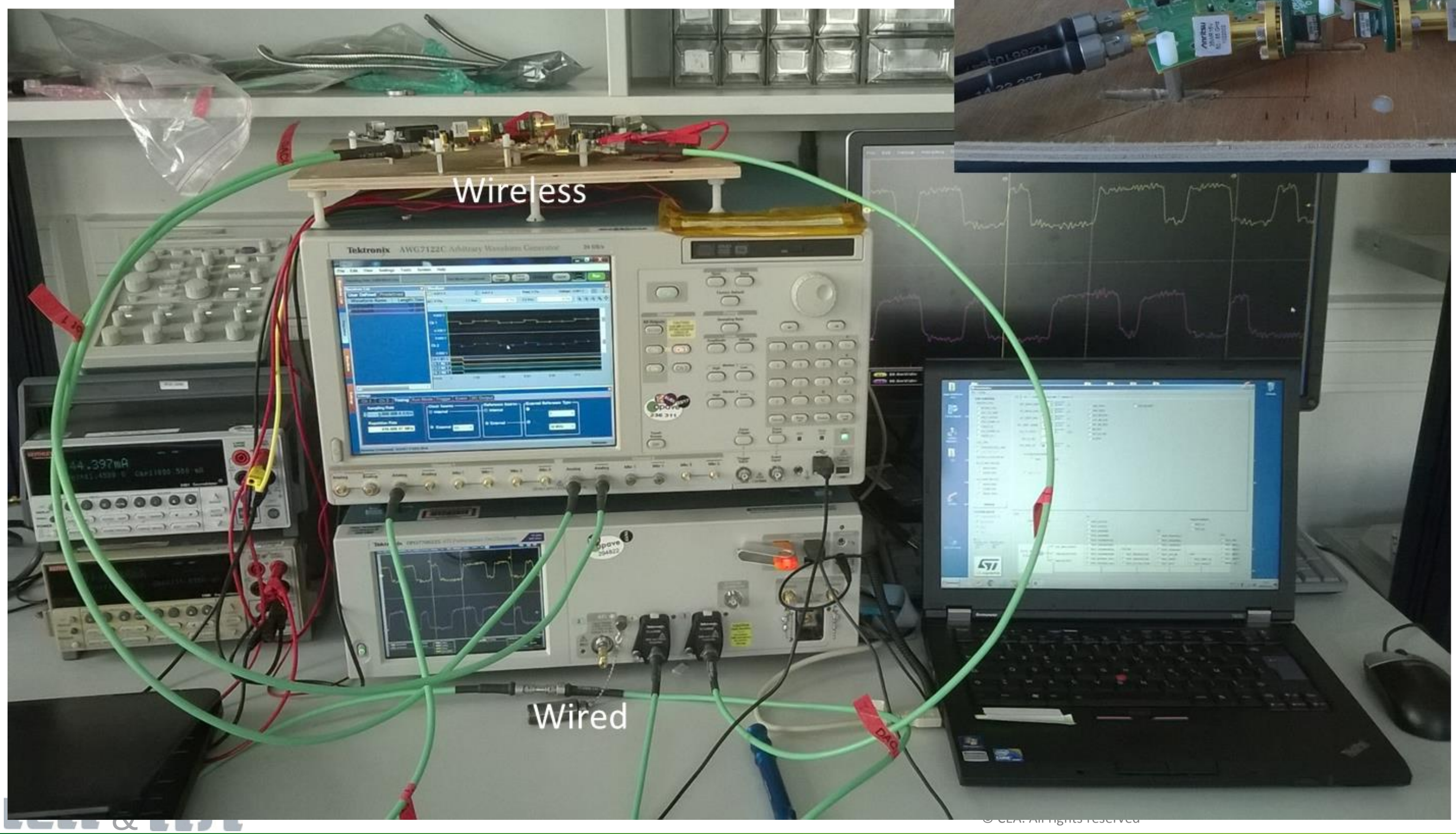
Non-coherent RFIC delay measurement: test bed

Comparison of delays from wired/wireless paths



Non-coherent RFIC delay measurement: test bed

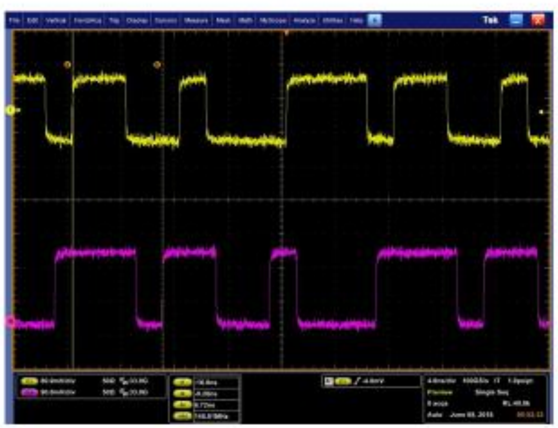




Non-coherent RFIC delay measurement: methodology

- Measurement of relative delays in coaxial cables
- Evaluation of delays in PCB µstrip lines and connectors
- Comparison of delays between the 3 paths:

Path 1: direct transmission with 2 coaxial cables (ref. delay)
Path 2: signal experiencing emitter and receiver boards delays
+ 60GHz transmission in 1.85mm coaxial cable
Path 3: signal experiencing emitter and receiver boards delays
+ 60GHz over the air transmission (2cm range)



Wireless path

Reference wired path

Non-coherent RFIC delay measurement: results and evaluation of delays

~400ps delay in RFIC
~280ps delay in µstrip lines
~2.7ns in 60cm 1.85mm cables @60GHz
~70ps over the air

	Eval.	Path 2 – Path 1 1 coax cable	Path 2 – Path 1 2 coax cables	Path 3 – Path 1 Over the air
$\tau1$ (x2)	202	x	x	x
$\tau2$ (x2)	?	388	401	394
$\tau3$ (x2)	77	x	x	x
$\tau4$	2730	x		
$\tau5$	5340		x	
$\tau6$	67			x
$\tau7$	500			x
Total		4.09ns	6.70ns	1.98ns
Measured		4.09ns	6.70ns	1.98ns

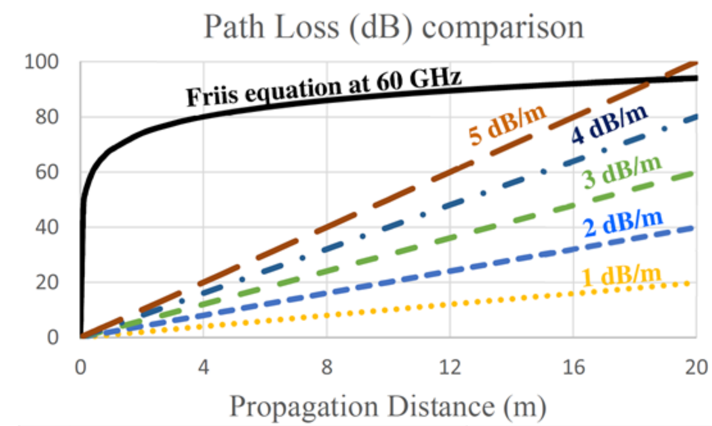
Evaluation for the three configurations

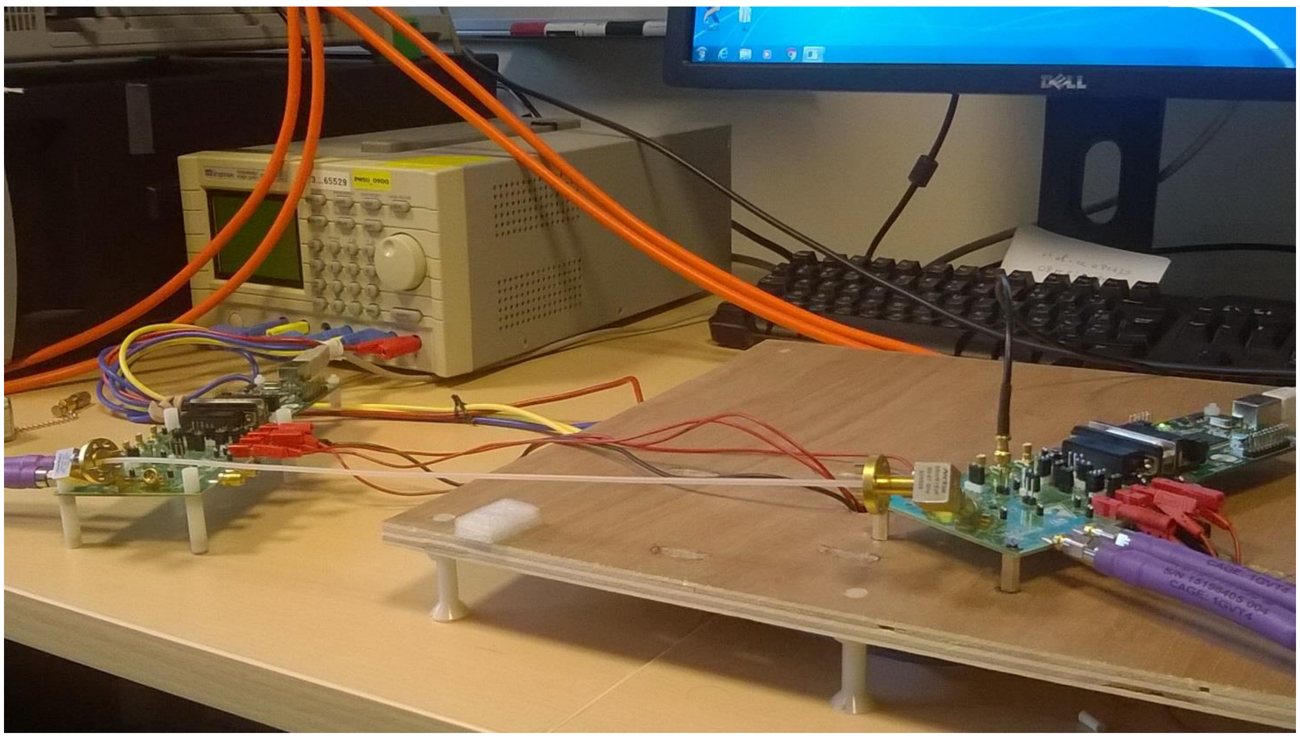
De-embedding of transceiver delay:
~800ps for both emitter and receiver

Feasibility studies, CEA Leti

Interfacing with plastic waveguide

Extension of the range to few meters





Path loss comparison (in dB) for free-space propagation at 60 GHz and waveguides with attenuation constants in the range of 1 to 5 dB/m

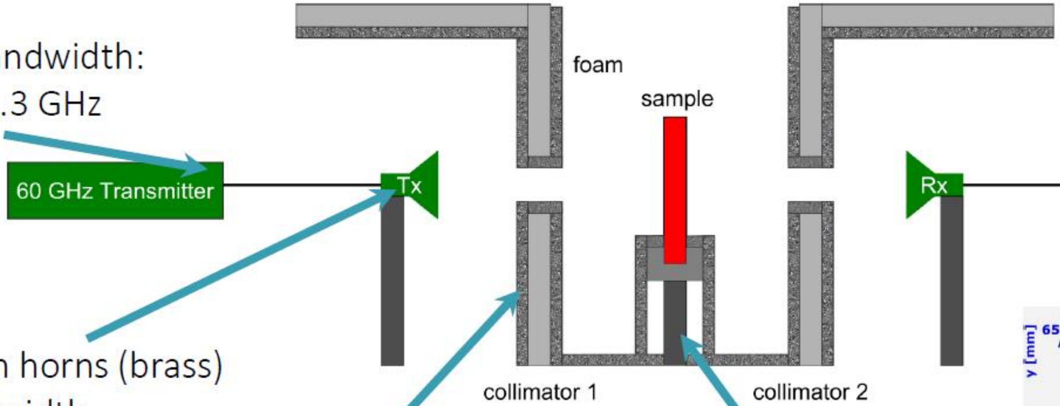
"A 12 Gb/s 64QAM and OFDM Compatible Millimeter-Wave Communication Link Using a Novel Plastic Waveguide Design"
F. Voineau et. al. RWS 2018

Tests in Heidelberg: **intra layer signal confinement**

Transmission through detector modules

Tested bandwidth:
57.3 – 61.3 GHz

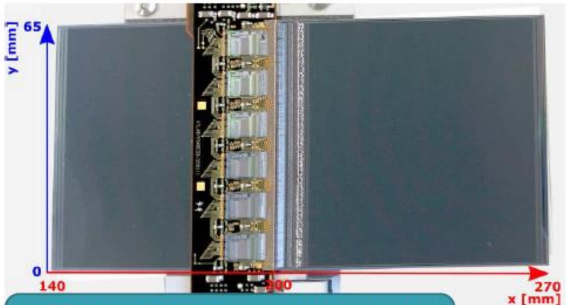
Measure power in RF sensitivity of $\approx -55\text{dB}$ relative to transmitter



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

Aluminum and graphite foam shielding against reflections

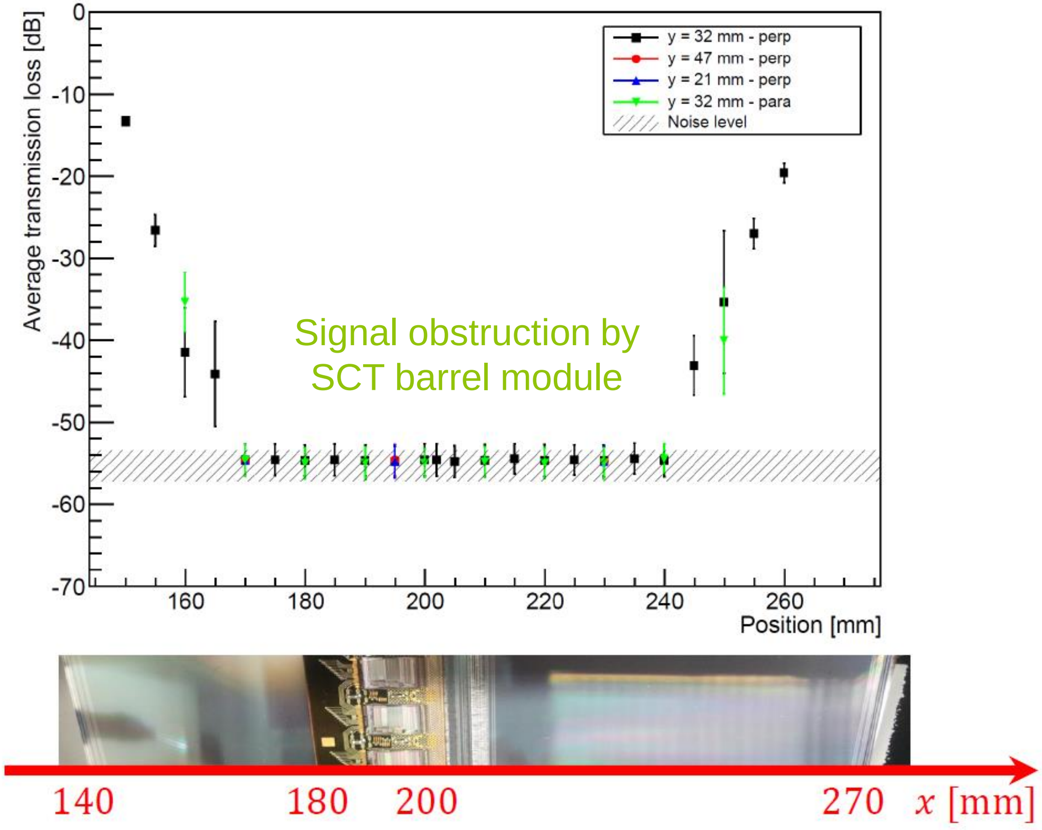
Rail and post holder to move sample



ATLAS SCT Barrel Module
R.Brenner (Uppsala)

Feasibility studies, Heidelberg Univ.

Tests in Heidelberg: intra layer signal confinement



Transmission:
SCT Barrel Module

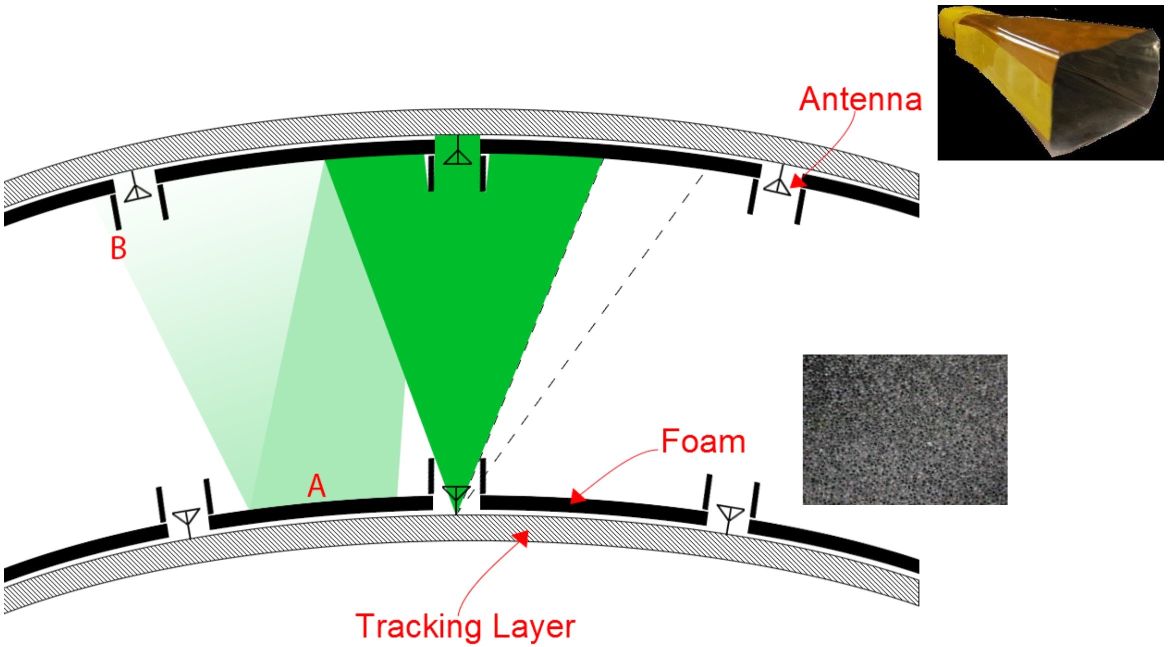
- Transmission loss
  $I_{loss} \geq 55$ dB
- **60 GHz signals are fully reflected**
- Diffraction leads to transmission near edges

Feasibility studies, Heidelberg Univ.

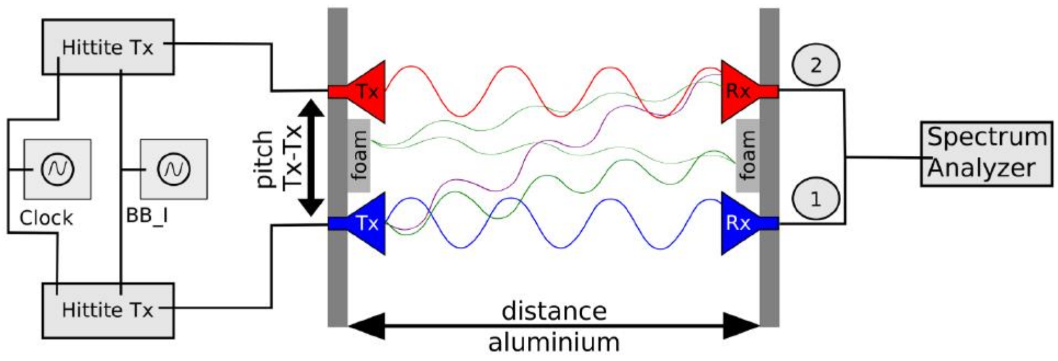
Ray tracing simulation: crosstalk mitigation

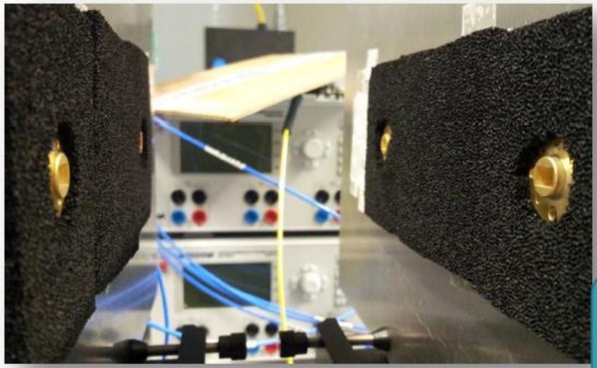
Approach:

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

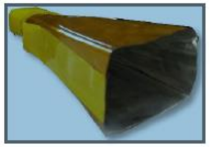


Feasibility studies, Heidelberg Univ.





Graphite foam cover



Example for high directivity: Aluminized Kapton horn antennas ~ 12-17 dBi

Crosstalk studies with reflections

- Aluminium plates ≙ reflective layers
- Under test:
  Directive antennas
  Linear polarisation
  Absorbing foam
- S/N = $\frac{Signal\ Tx1_{@Rx1}}{Signal\ Tx2_{@Rx1}}$

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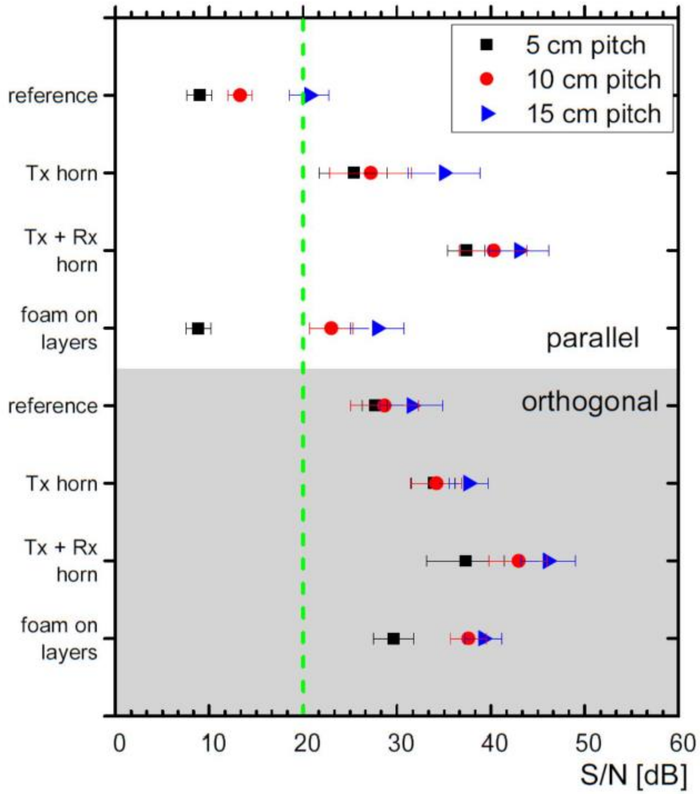
leti & list

Feasibility studies, Heidelberg Univ.



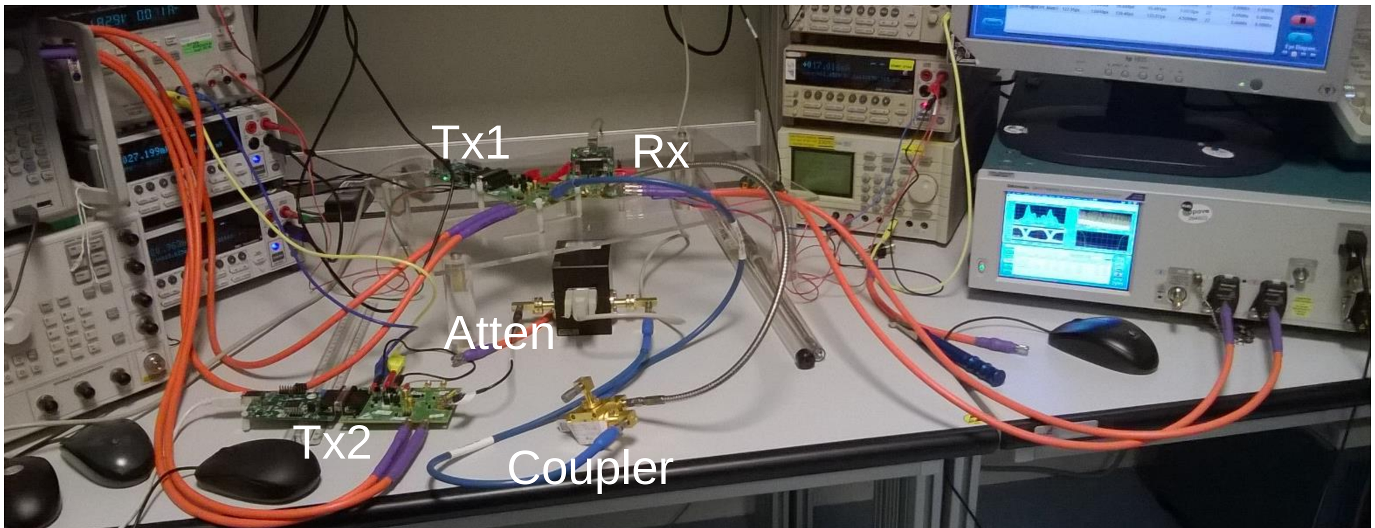
Distance between layers: 10 cm
Reference: without directive antennas and foam

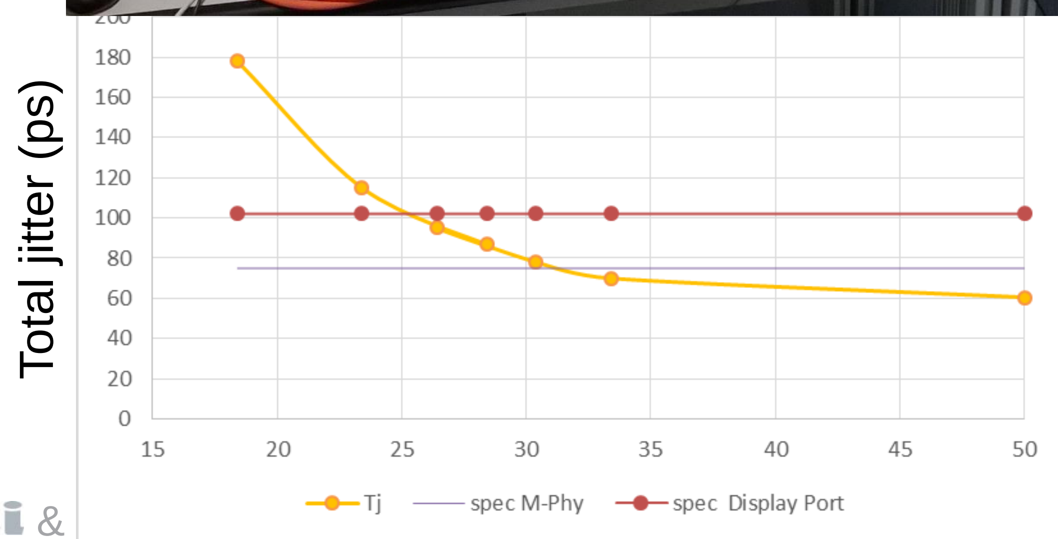
Crosstalk studies with reflections

- 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**

Feasibility studies

- Crosstalk: Evaluation of the required Channel/Interferer power ratio for OOK modulation





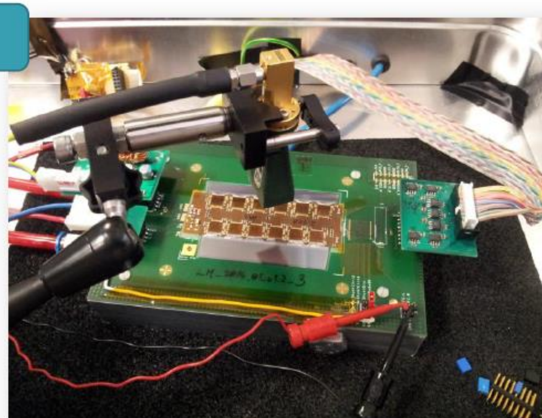
Tx1: Emitter → Rx
Tx2: Interferer

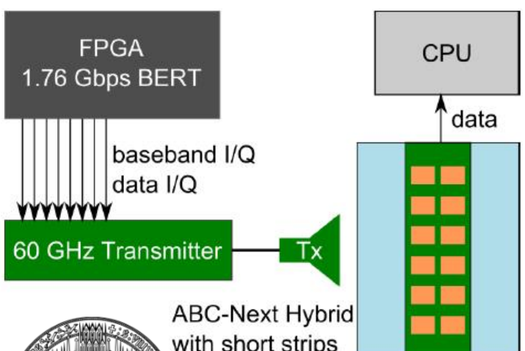
>25dB C/I required @ 5Gbps

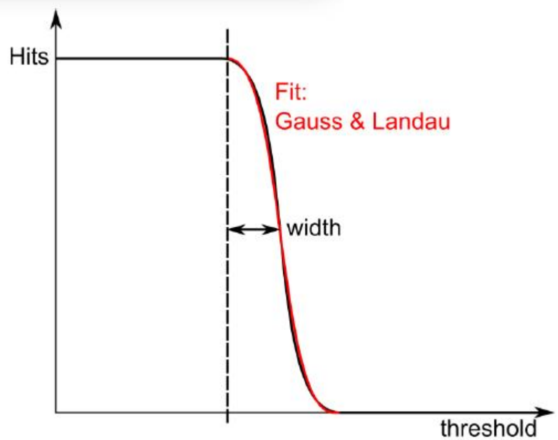
Feasibility studies, Heidelberg Univ.

Coexistence with detector

Setup







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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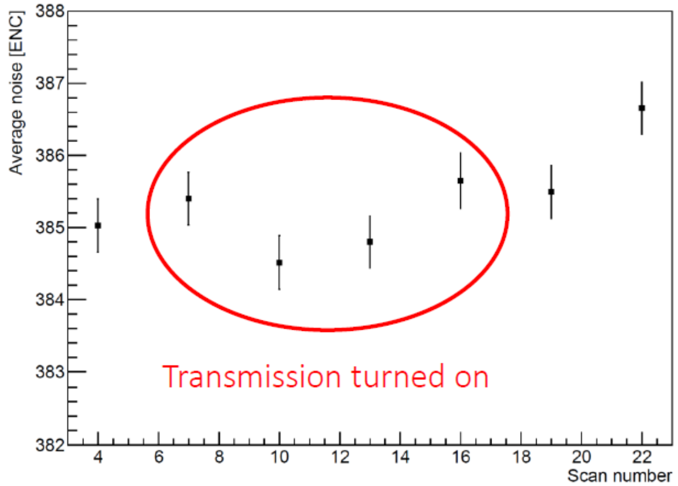
Coexistence with detector

Hybrid without strips



Hybrid

$$\delta_{noise} = (0.40 \pm 0.13_{stat} \pm 0.49_{sys})\%$$

of average noise (385.0 ± 0.4) ENC

Hybrid + Strip sensor

$$\delta_{noise} = (0.60 \pm 0.11_{stat} \pm 0.93_{sys})\%$$

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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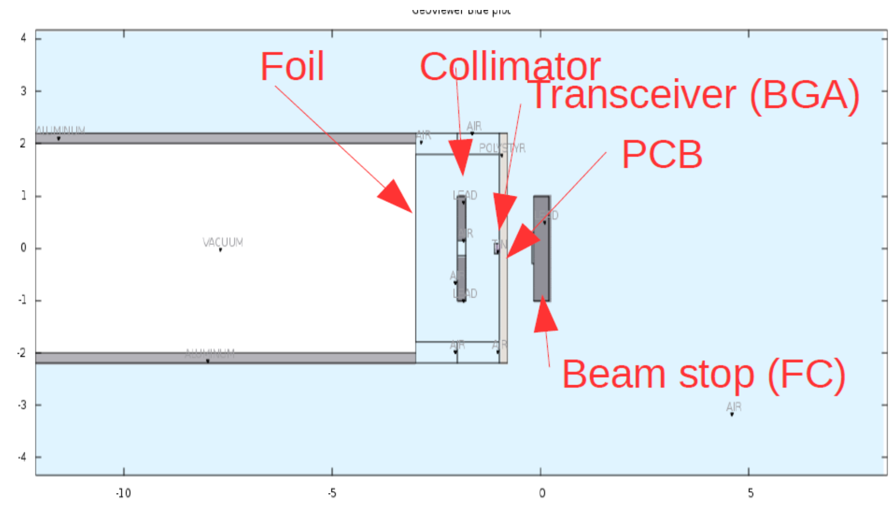
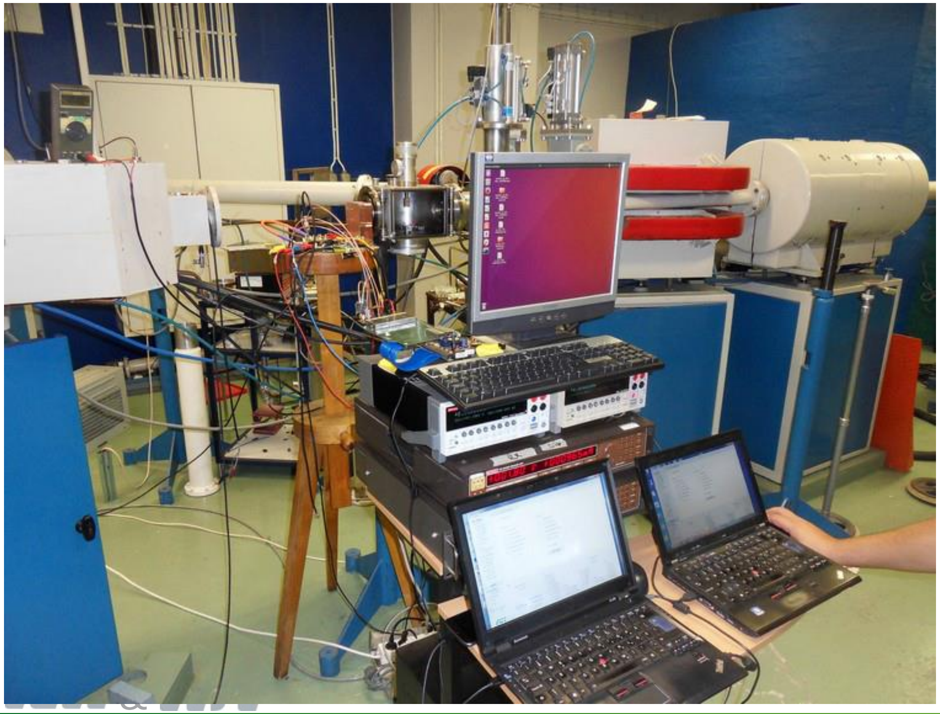
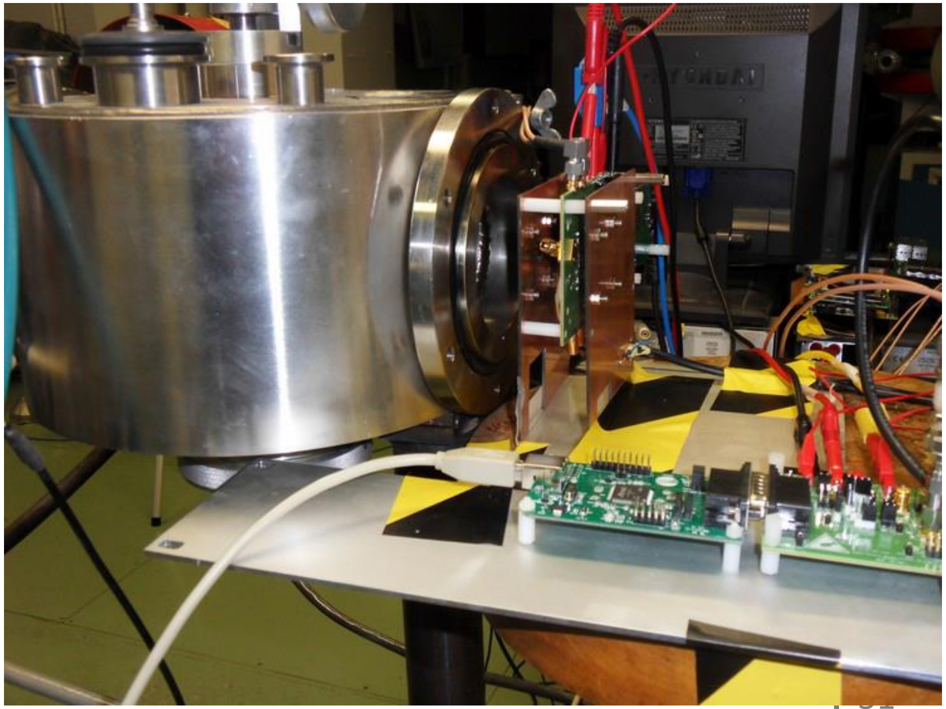
Irradiation test, Uppsala & Heidelberg univ.

- Turku Cyclotron set-up with 17 MeV proton beam
- Target fluence: ~1e14 protons/cm2
- Sim. energy dose: 192 kGy (19 Mrad)
- Continuous performance assessment of the CMOS65nm transceiver under irradiation







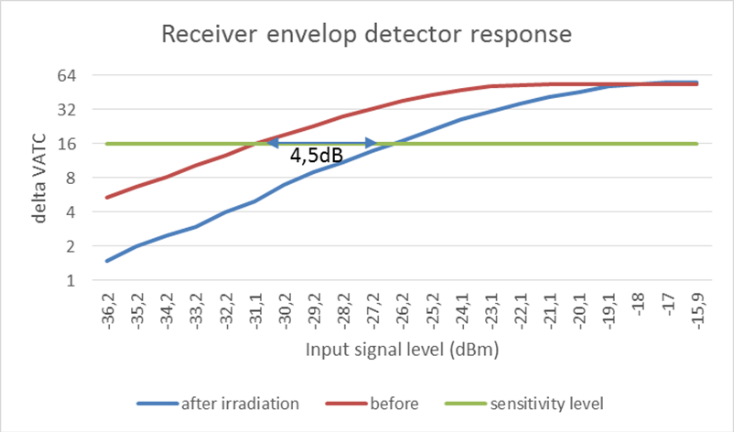
Irradiation test, Uppsala & Heidelberg univ.

Performance during irradiation

- No impact observed on the emitter frequency/amplitude
- Impact on the receiver low noise amplifier
- Errors obtained on the transmission
- No more errors after 3 weeks in freezer for the activity to decay

Irradiation tests results

- Emitter: weak alteration of the performance
  - less than 1dB output power degradation
  - no influence on frequency or data rate
- Receiver: alteration of the sensitivity
  - -4,5dB LNA gain
  - Identical envelop detector response



New test campaign ongoing at CERN CLEAR

- Neutron flux, 50Mrad cumulative dose

Feasibility studies, conclusions

- Reliable data transmission at 60GHz using both coherent 802.11ad or non coherent transceiver
- Cable replacement with no loss in Quality of Service
- Non coherent transmission allows low latency data export
- Good intra layer signal confinement
- Crosstalk studies. Antenna directivity and polarization diversity may be used for high density of RF links.
- Coexistence. No degradation of detector module performance observed due to 60GHz wave
- Good robustness of CMOS technology to proton and neutron radiations

Conclusions

- MmW allows high data rate, low power communication at short range.
- Early feasibility studies show no deadlock for their use in HEP.
- Commercial products at 60GHz should be available soon for test and can be customized for particle-physics detector.
- Early prototypes available for test.
- Future developments should challenge optical links at short range.

leti

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list

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91191 Gif sur Yvette
Cedex

Thanks for your attention

Questions ?

Main publications

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