FROM RESEARCH TO INDUSTRY

cea tech

Mmw readout for particle-physics detector WADAPT

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leti & list

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

Wadapt

- Wadapt: “**Wireless Allowing Data And Power Transmission**”

- 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

Outline

- Context: why mmW wireless links?
- Proposed approach for wireless data read-out in HEP detectors
- mmW Integrated Circuits at CEA-Leti
- Conclusions & Discussion

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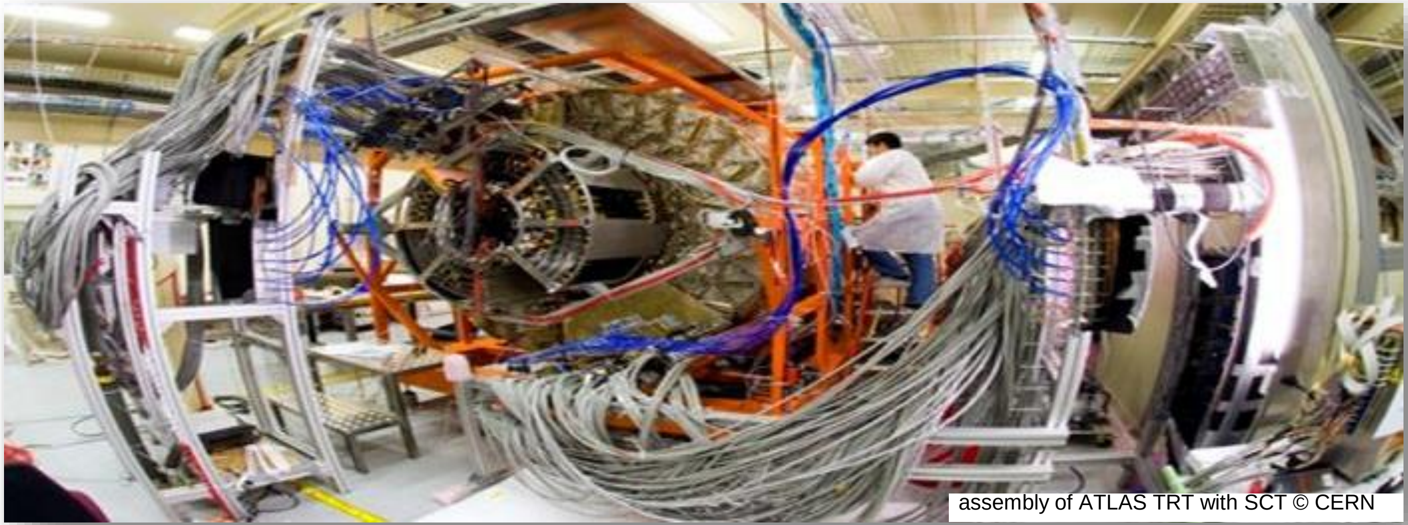
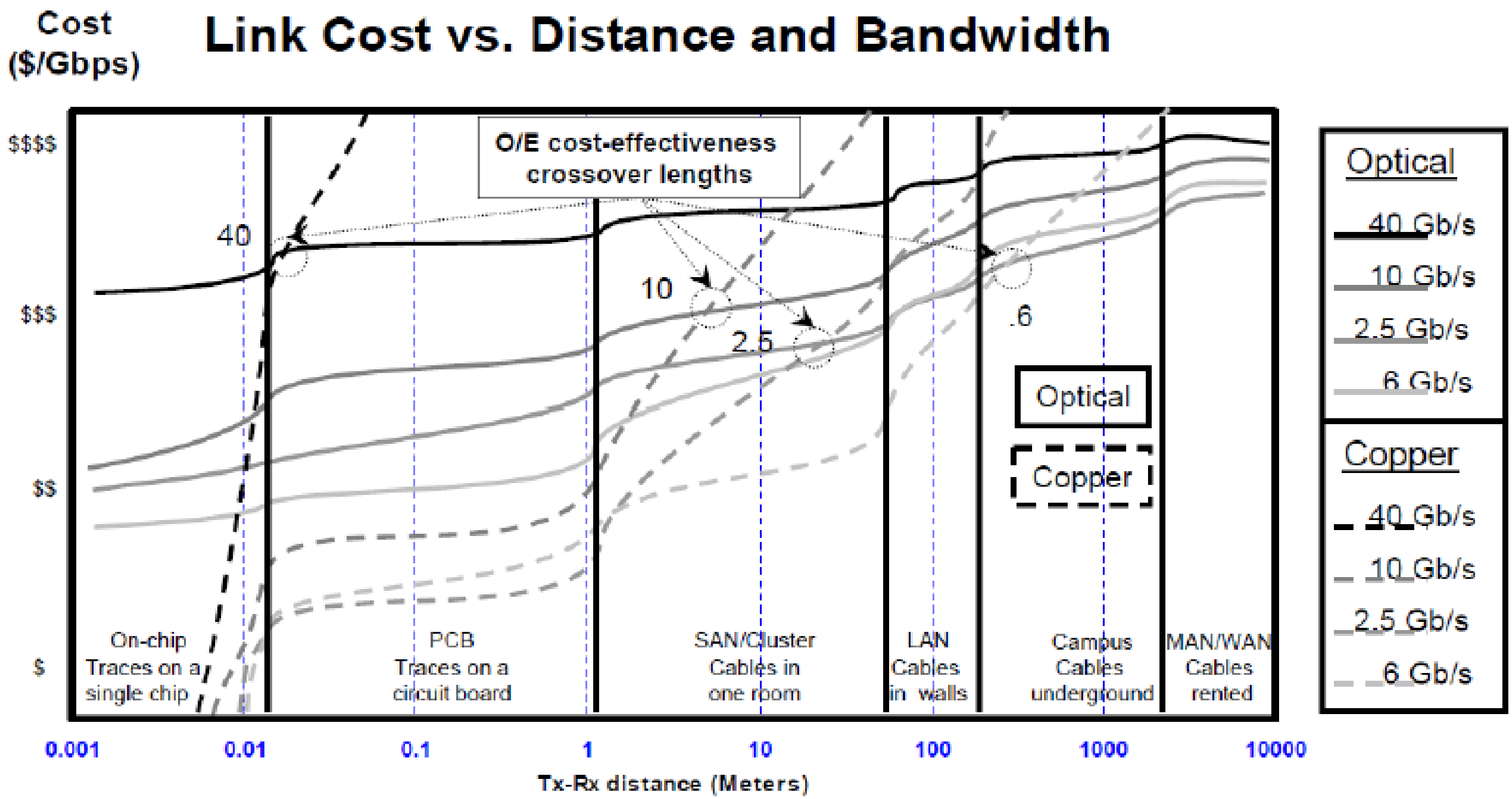
Context: massive cable plant



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

Context: optical vs electrical wires

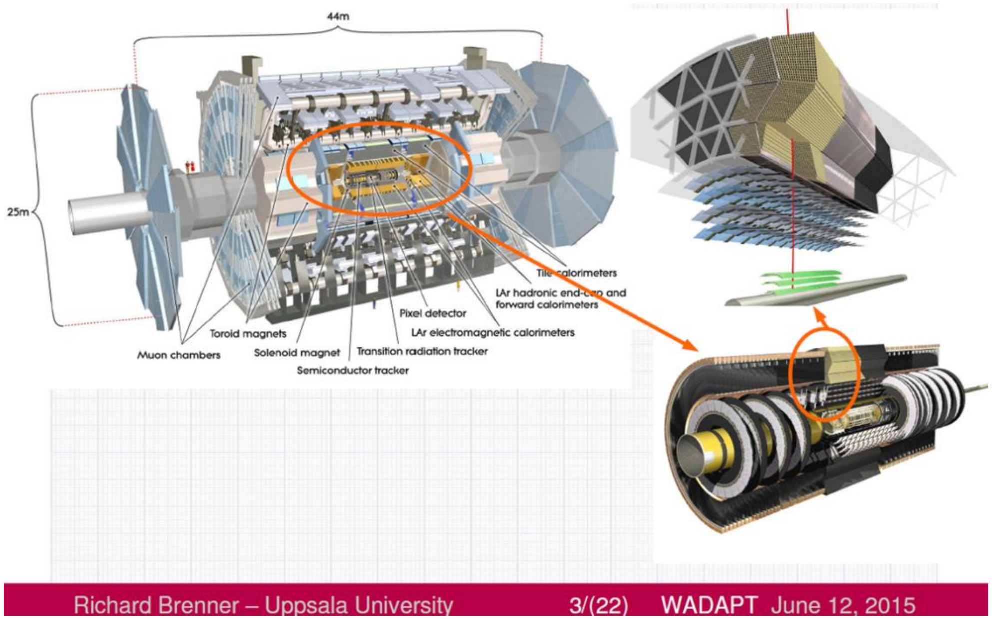


A. Benner, "Optical interconnect opportunities in supercomputers and high end computing," OFC 2012

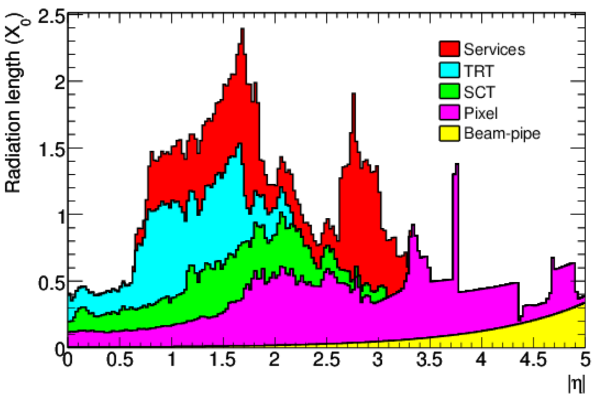
Why Wireless ?

- Minimize material budget of cables/connectors

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



Atlas radiation length



- 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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Why mmW?

- mmW operation allows to access larger bandwidth
- High-throughput (Gbps) using simple modulations
- Lower power consumption (~pJ/bit)
- Much lower latency (~ns): good for fast triggering and easy synchronization

E.g.: Large collider readout

Data flow

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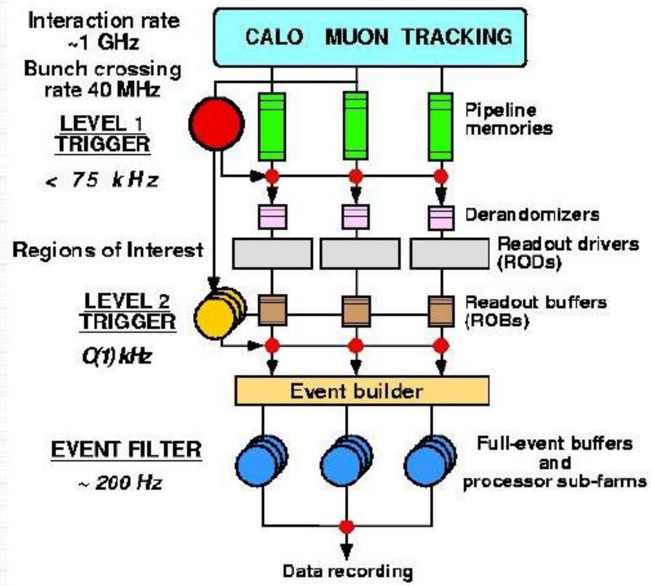
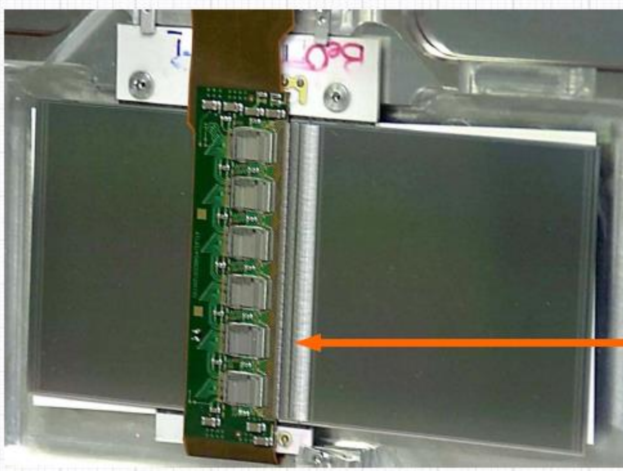
- Collisions in LHC at 40MHz
  - All data stored in detector front-end electronics for ~3µs
  - Decision based on muon and calorimeter information to readout data at ~100kHz





Front-end ASIC

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

E.g.: Large collider readout

Future data challenge

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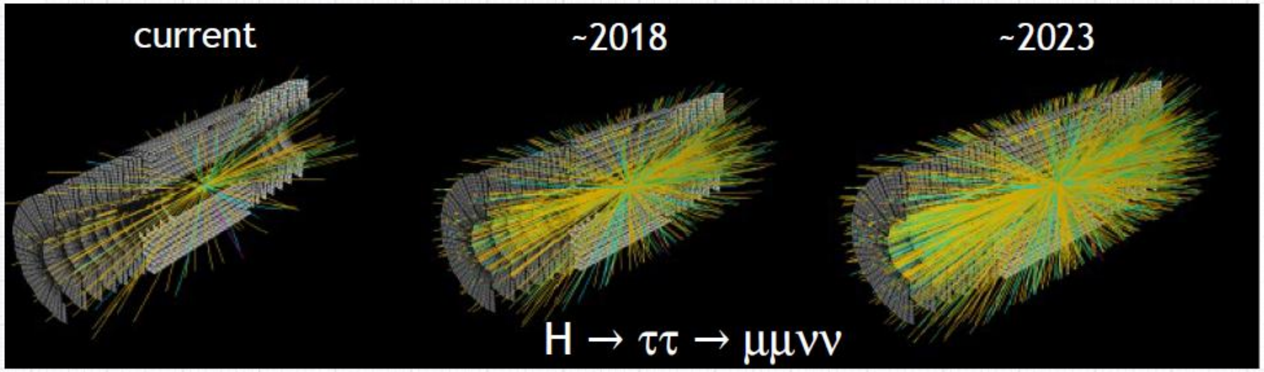

The only sub-detector currently not used for fast trigger are the tracking detectors.
To maintain current trigger thresholds at HL-LHC for maximum physics output
The tracking detectors (being the most granular) can make this possible.

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

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CERN requirements

- 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

Proposed approach

Track trigger and data rate reduction

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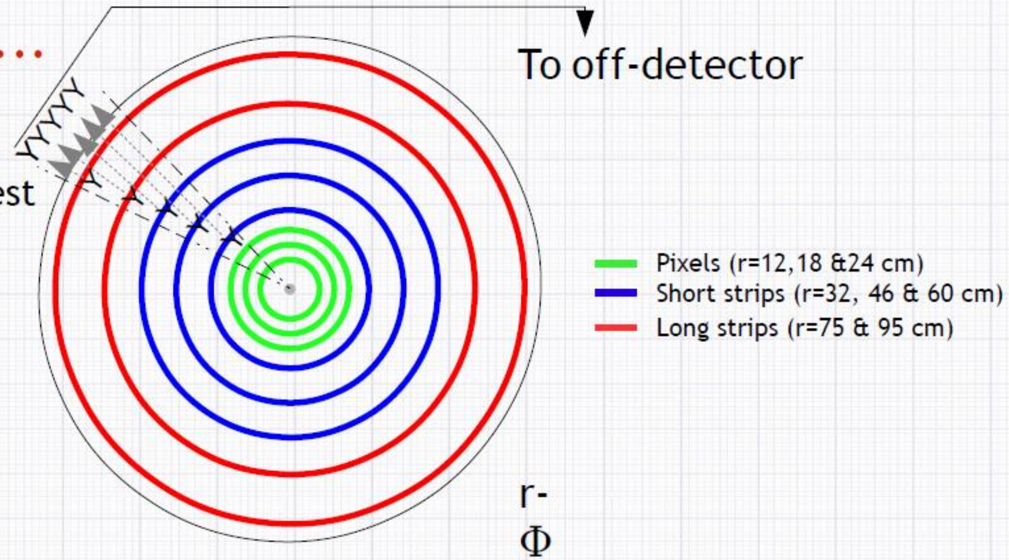
A simple idea…



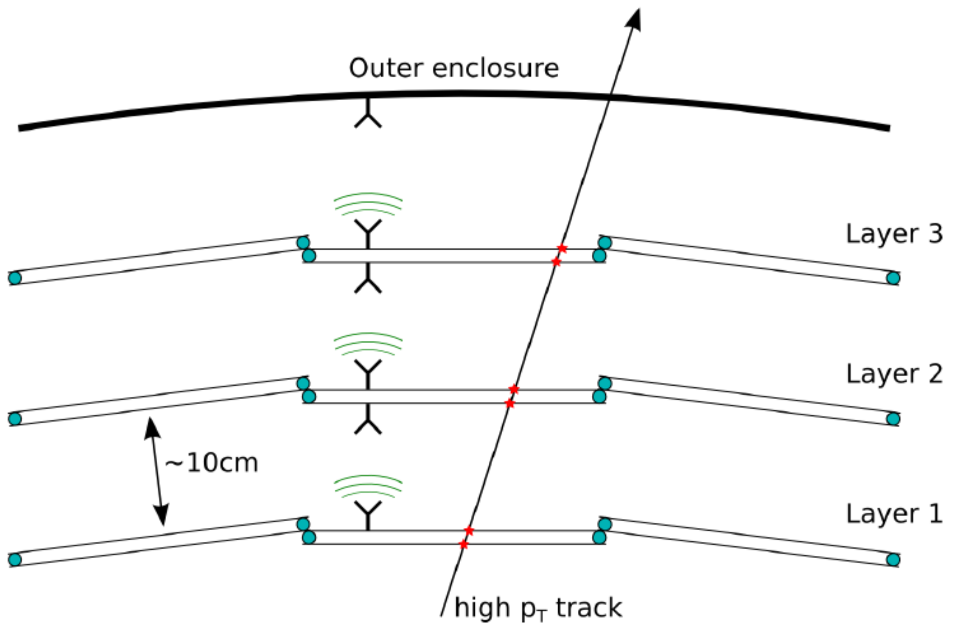
…but not trivial to build on detector

- 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 approach

Heidelberg Univ.



Idea by R. Brenner (Uppsala)

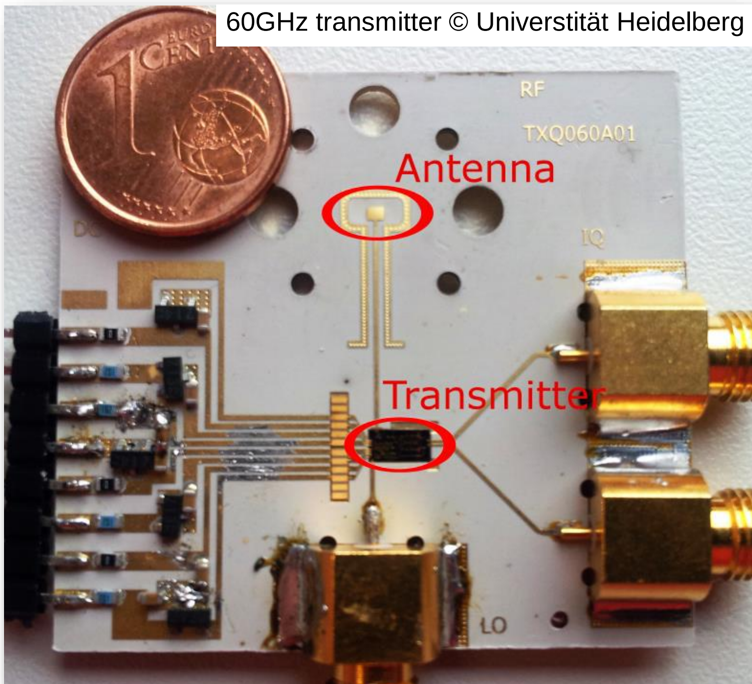
Wireless readout concept

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

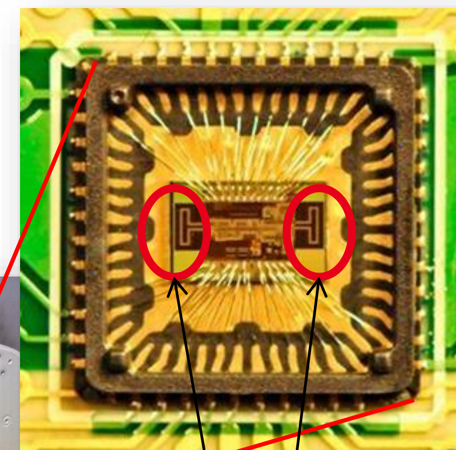
Millimeter-waves technology

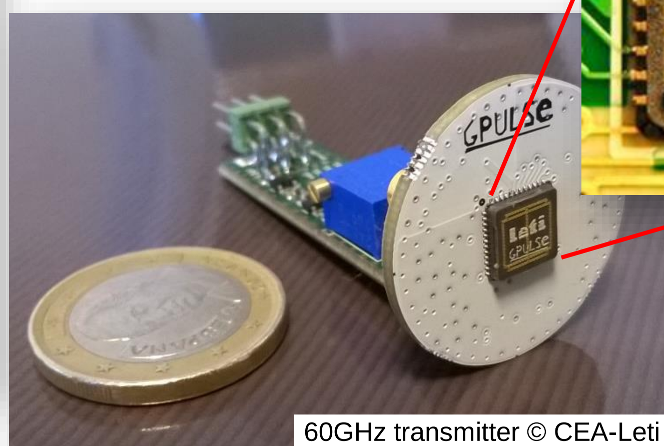
- 30 to 300 GHz
- Wavelength (λ) of few mm (eg. 5mm @60GHz)
- Multiple Gbits/s (Several GHz of bandwidth)
- High “natural” signal attenuation (68dB@1m at 60Ghz)
- suitable for short range communication

60GHz transmitter © Universtität Heidelberg



- Compact and low power system
- High integration
- High density

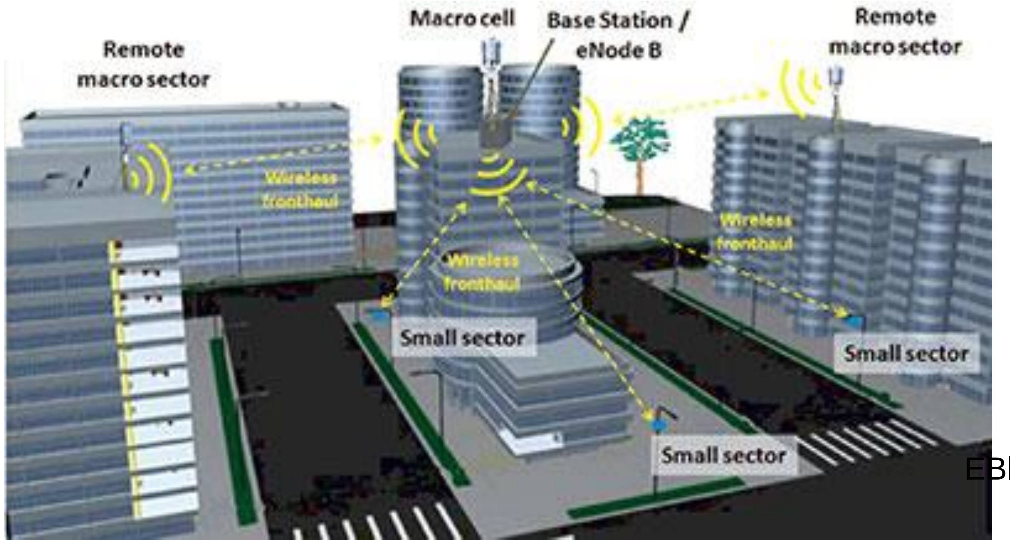




60GHz transmitter © CEA-Leti

Millimeter wave current key applications

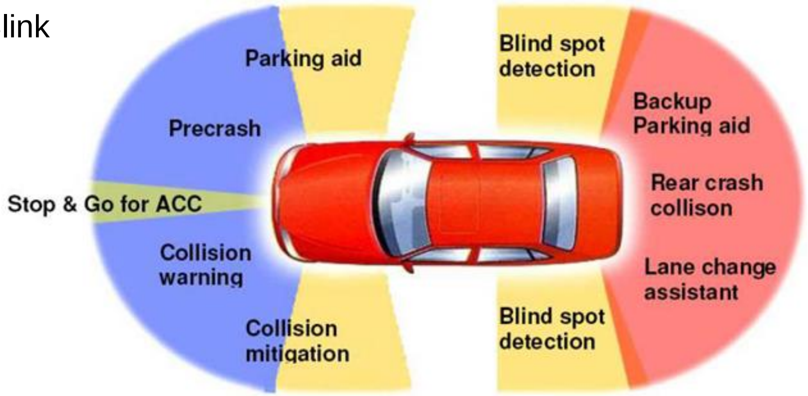
Wireless HD and WLAN 802.11ad (WiGig)



Backhaul and fronthaul

EBlink

24 and 79GHz Automotive Radar

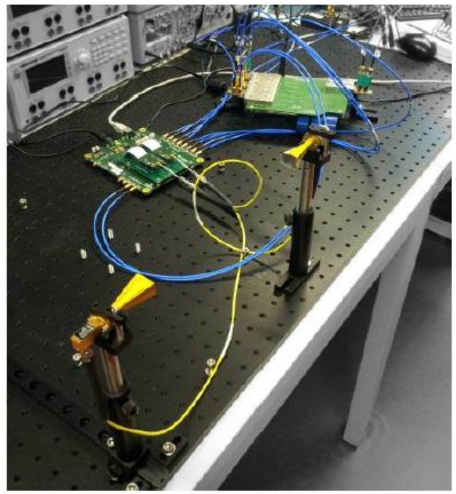


Feasibility studies, Heidelberg Univ.

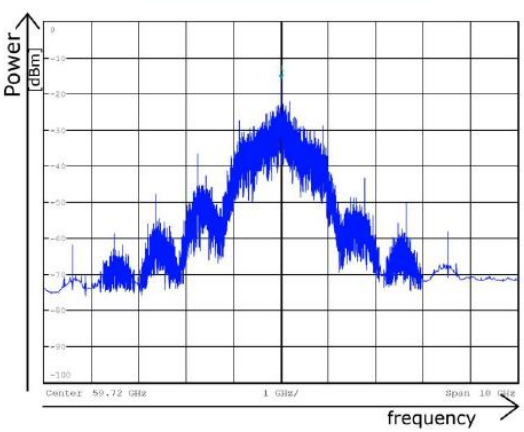
Tests in Heidelberg: line of sight transmission

Setup in the lab

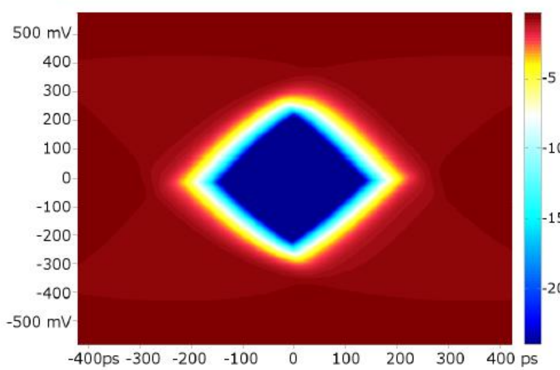
Distance: 22 cm
Horn antennas from Kapton und aluminium



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 $BER < 10^{-14}$
- HD-SDI-Video transmission

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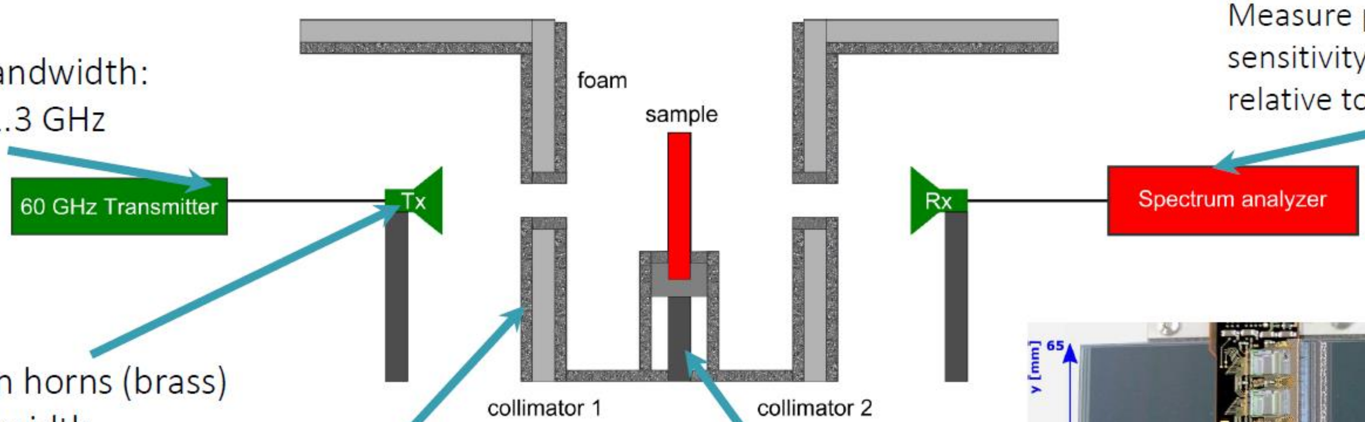
Feasibility studies, Heidelberg Univ.

Tests in Heidelberg: intra layer signal confinement

Transmission through detector modules

Tested bandwidth:
57.3 – 61.3 GHz

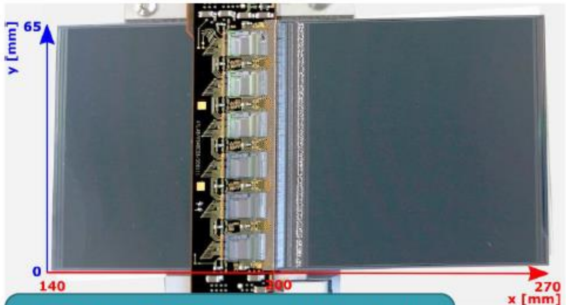
Measure power in RF sensitivity of ≈ -55dB relative to transmitter



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

Aluminum and graphite foam shielding against reflections

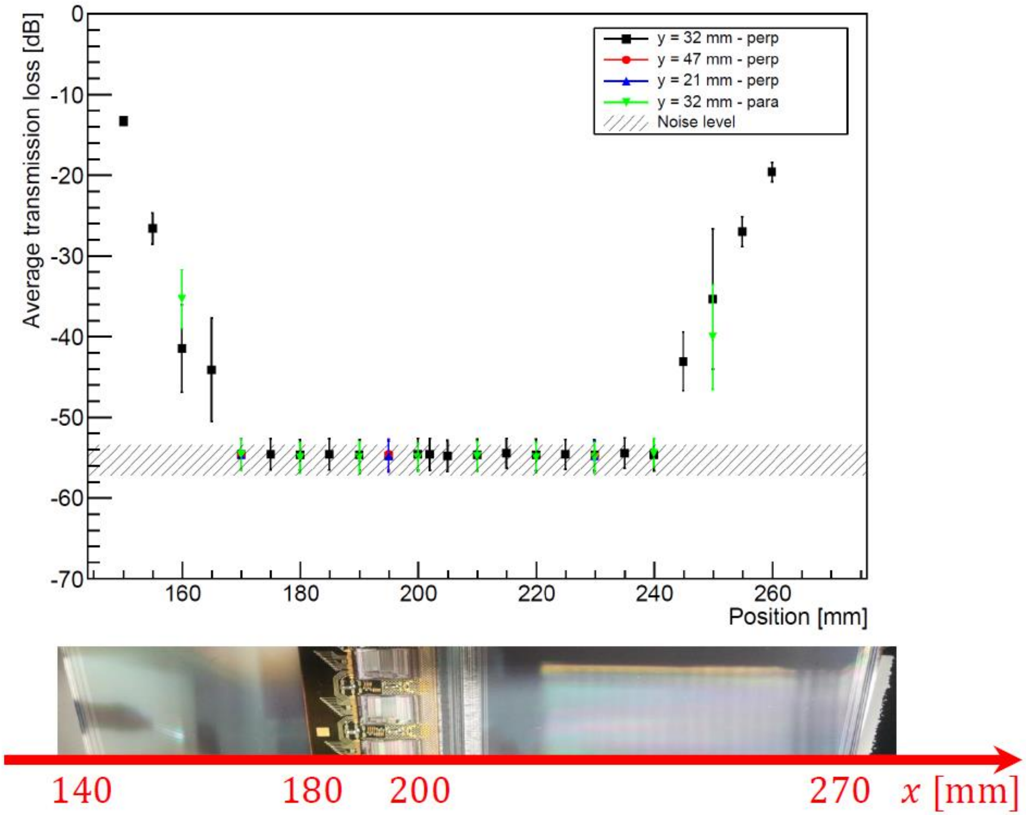
Rail and post holder to move sample



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

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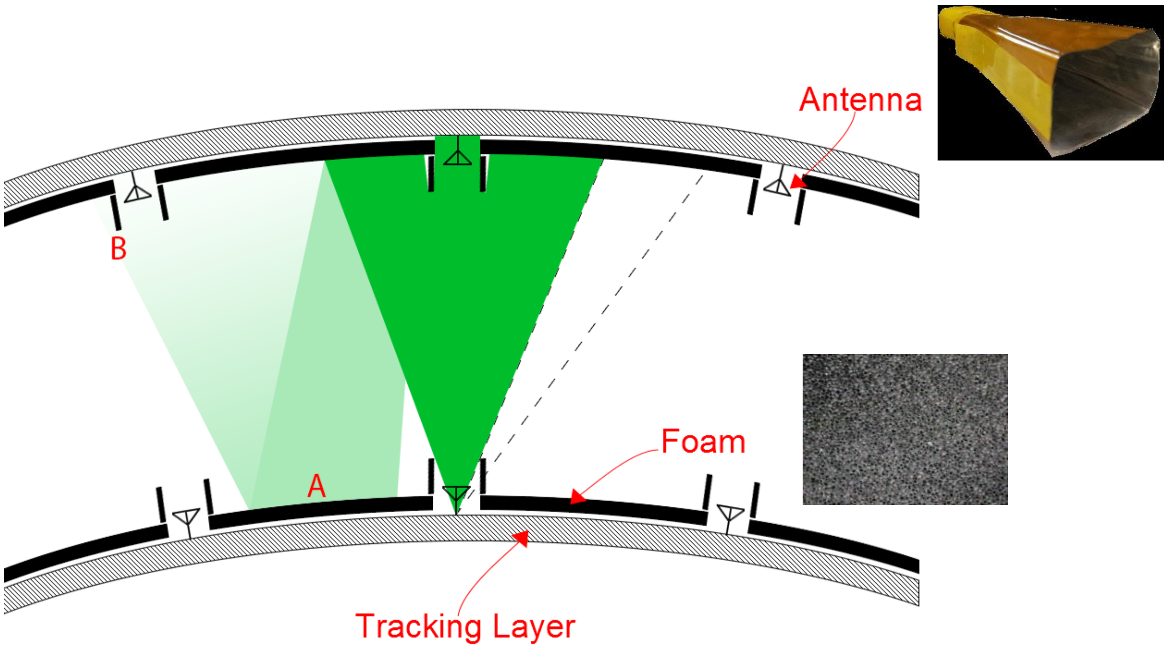
Feasibility studies, Heidelberg Univ.

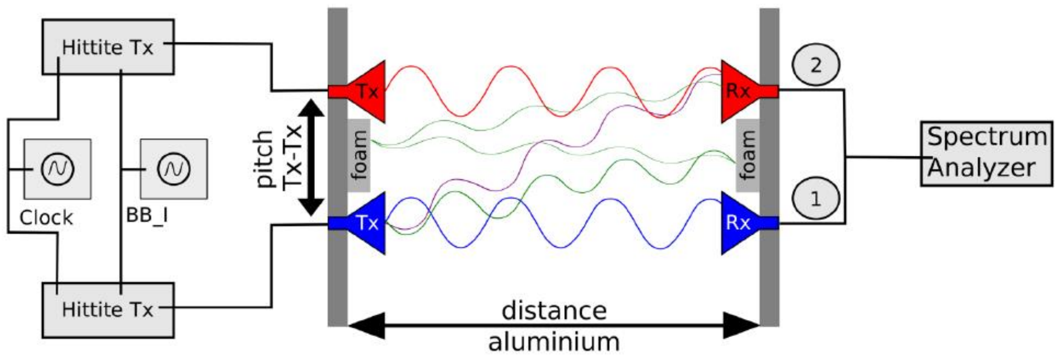
Ray tracing simulation: <u>crosstalk mitigation</u>

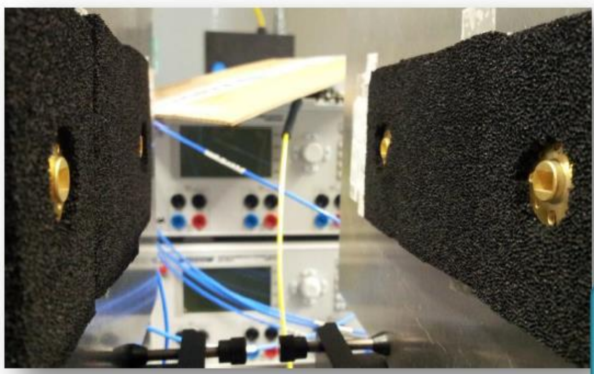
Approach:

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

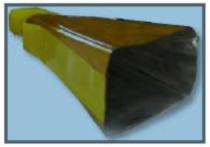


Feasibility studies, Heidelberg Univ.





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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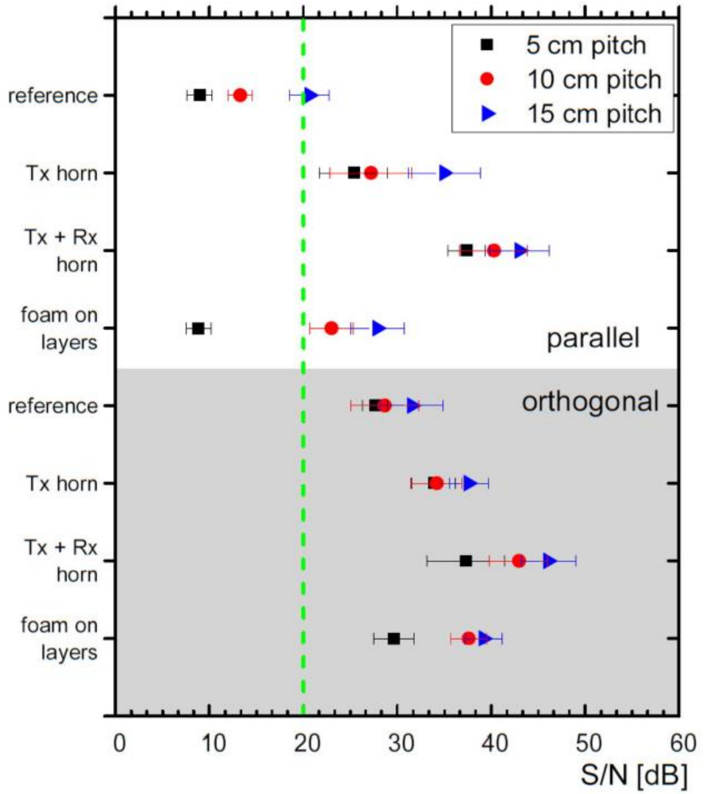
Feasibility studies, Heidelberg Univ.



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

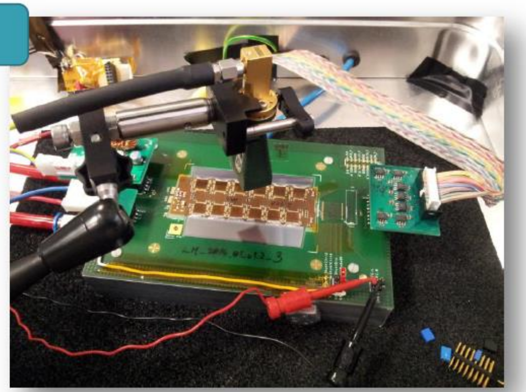
Crosstalk studies with reflections

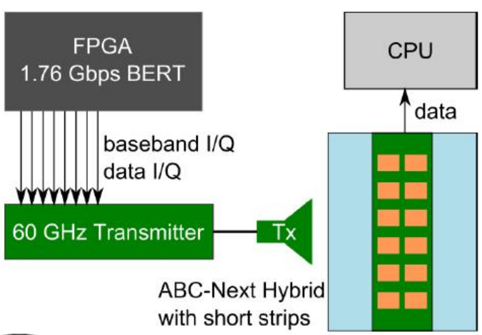
- Highly **directive antenans** increase S/N significantly
- Orthogonal linear **polarisation:** S/N > 20 dB
- **Foam on layers** can additionaly reduce crosstalk
- **5 cm pitch between channels is possible**

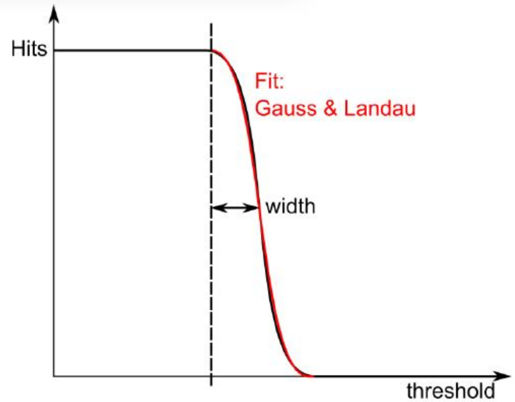
Feasibility studies, Heidelberg Univ.

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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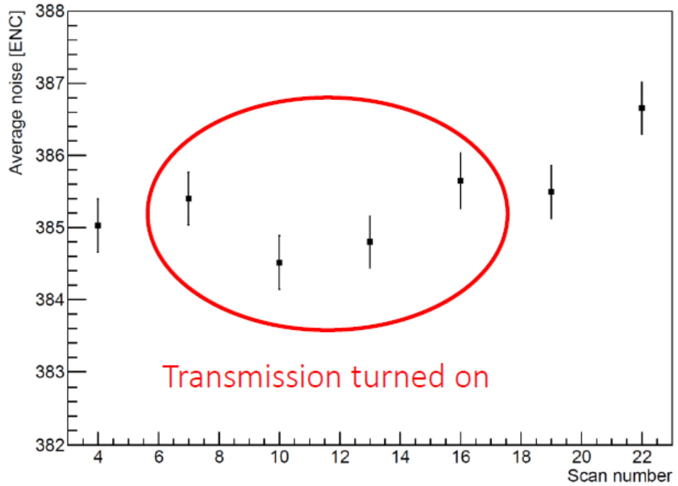
Feasibility studies, Heidelberg Univ.

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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Feasibility studies, Heidelberg Univ.

Summary

Stable data transmission of 1.76 Gbps with test setup:
$\boldsymbol{BER < 10^{-14}}$

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

Leti & List

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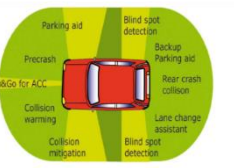
mmW integrated circuits, CEA Leti



SRR — 21,5-26,5GHz

WiHD
WIGIG/802.11ad
UWB impulse — 57-66GHz

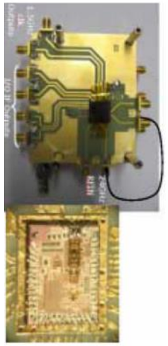
Backhaul — 71-76GHz

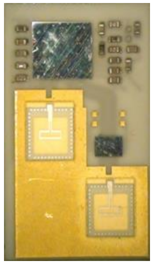
ACC

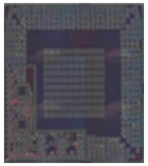
SRR — 77-81GHz

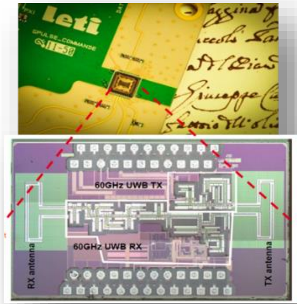
Backhaul — 81-86GHz

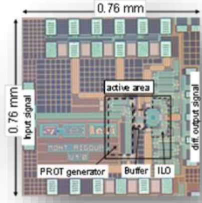
LRR — 94GHz

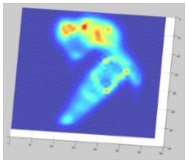


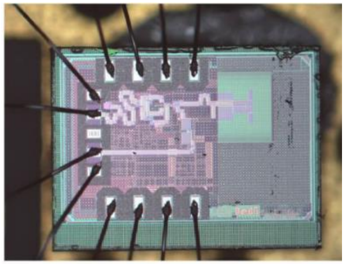












ISM — 122GHz

ISM — 240GHz

C2C
Sub THz
Imaging — 275-300GHz

CEA Leti mmW developments

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

Modulation vs. range & power consumption

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

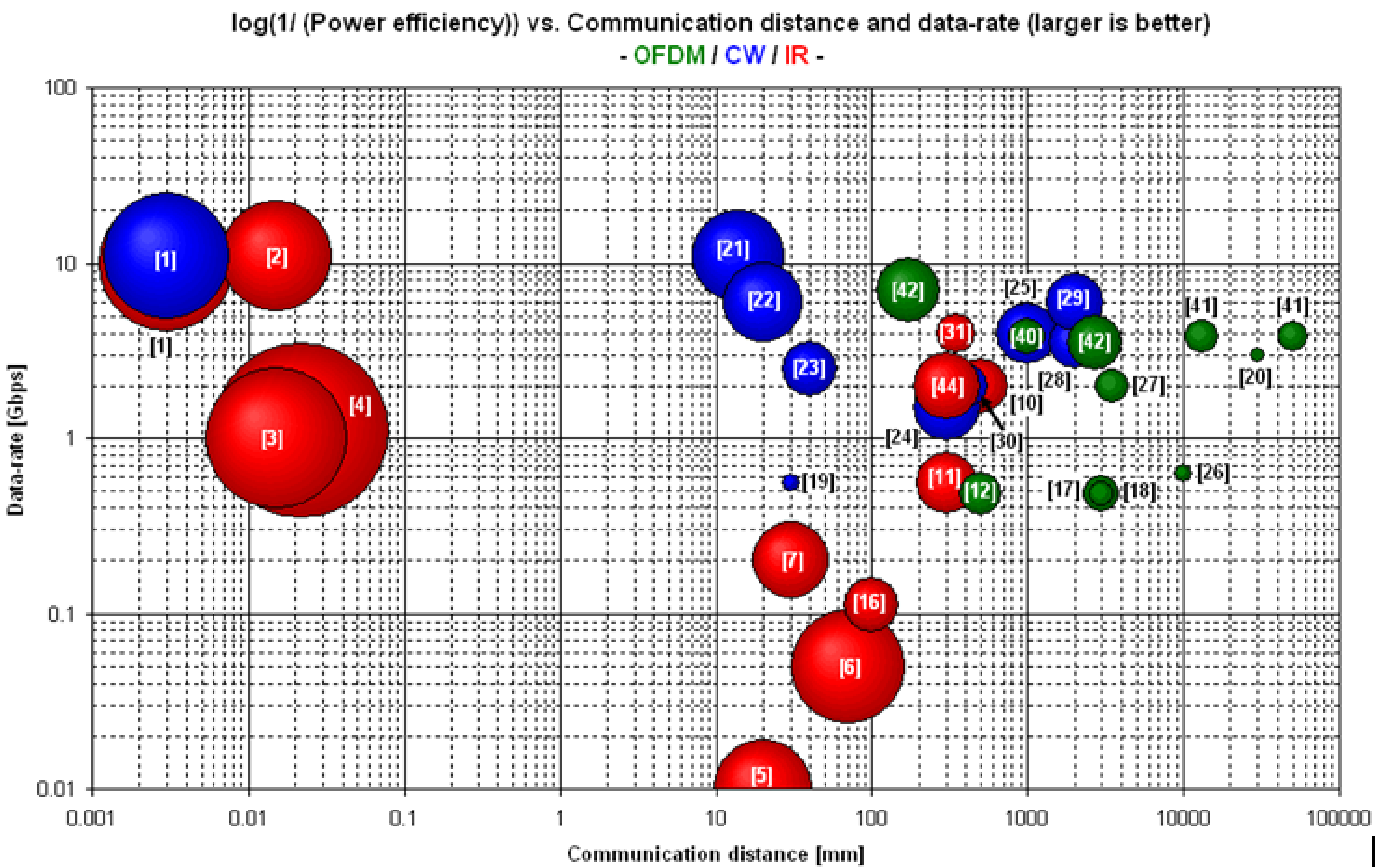
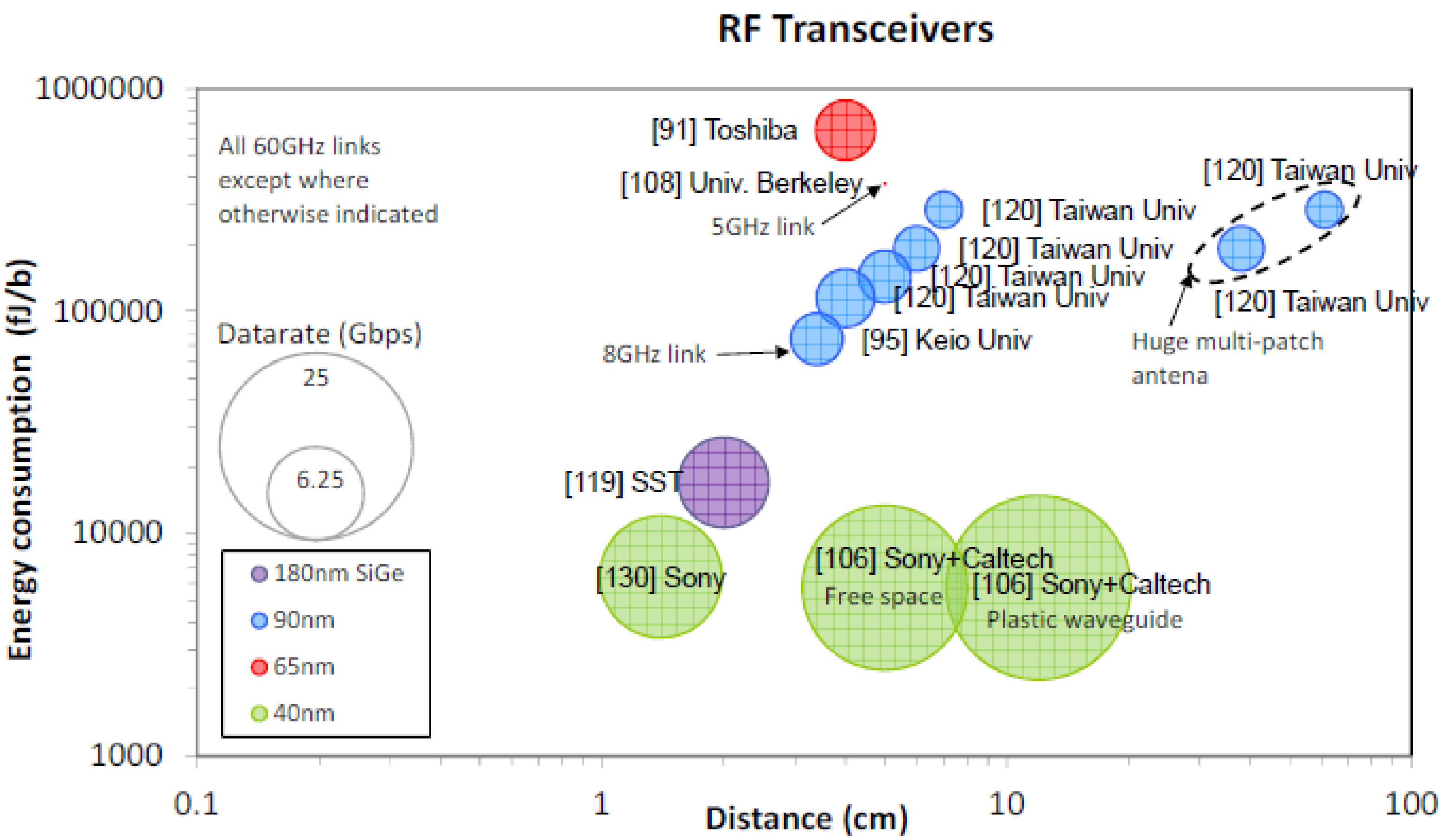


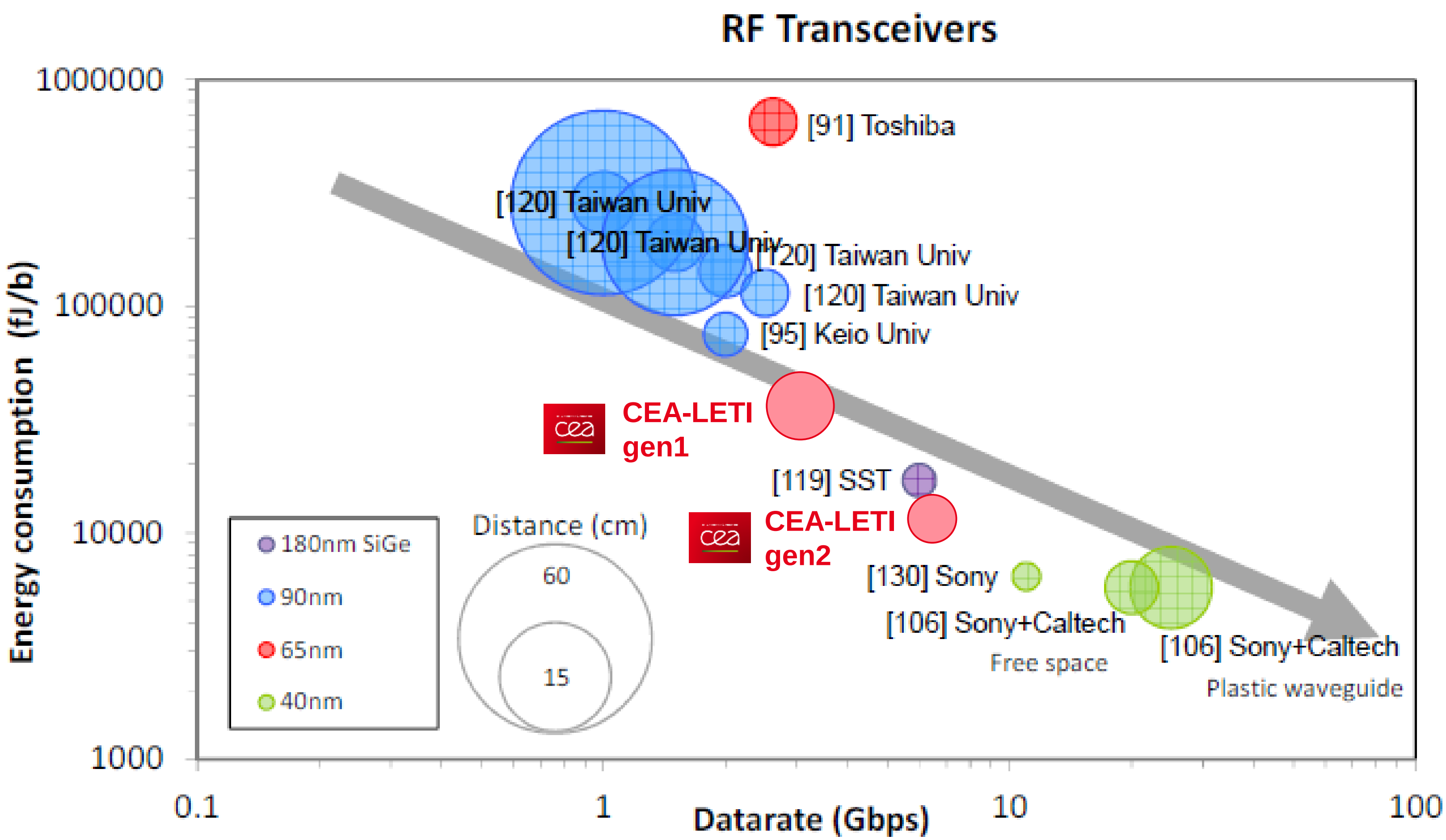
Figure 24 Inverse of the energy efficiency (size of balls in log. scale) as a function of the communication distance (x-axis), of the data-rate (y-axis) and of the radio mode (colors)

Energy consumption vs. link range

Energy efficiency trend of RF links

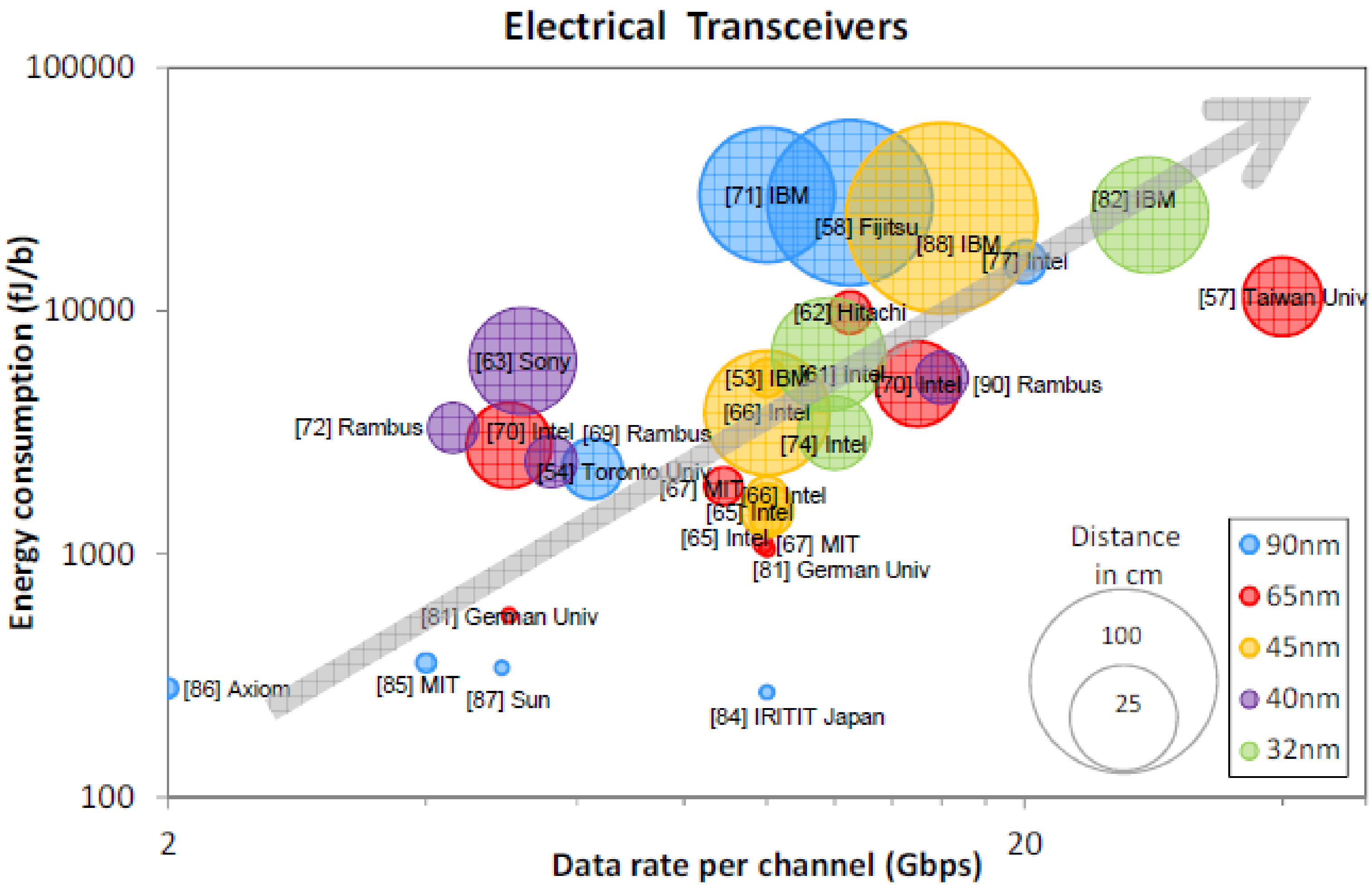


Energy efficiency trend of RF links



Energy consumption vs. data rate

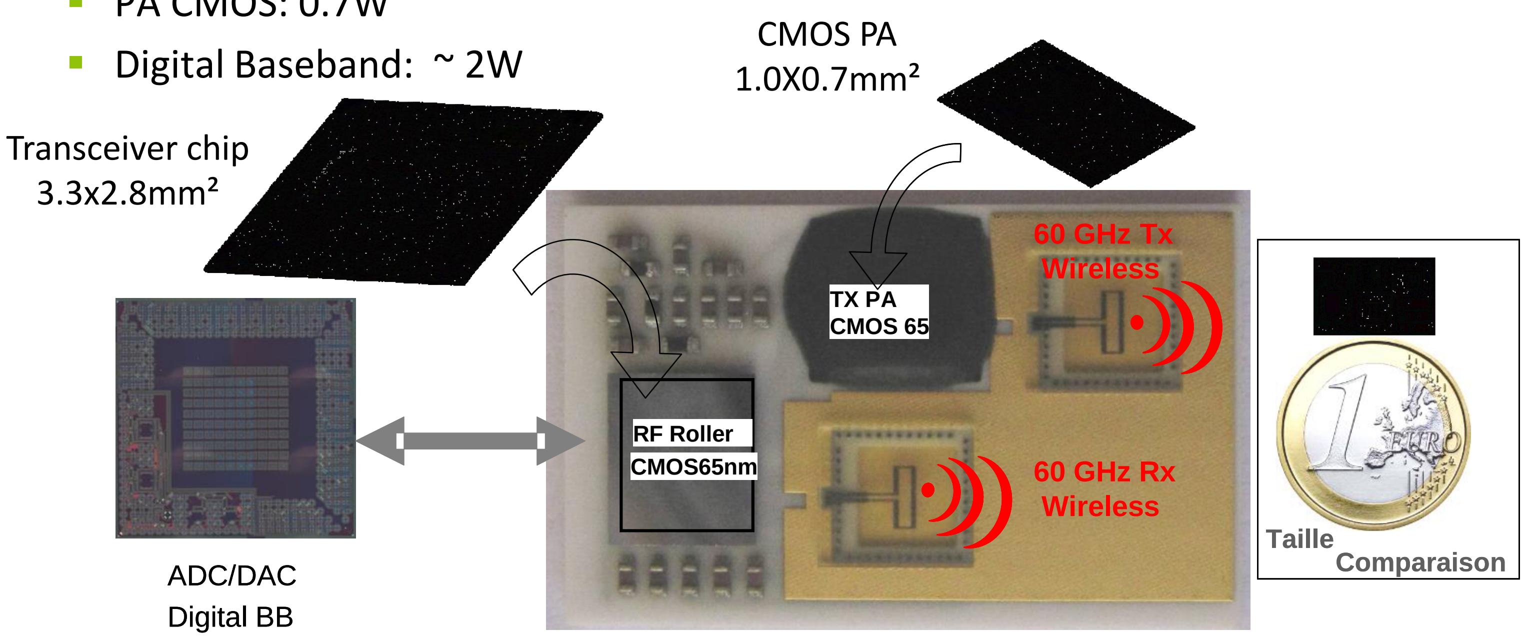
Energy efficiency trend of electrical links



Frequency domain 60GHz SiP1

- 13.5*8.5mm² mmW RFFE module on industrial HTCC
  - Transceiver with integrated PLL.
  - Covers the 4 IEEE channels 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

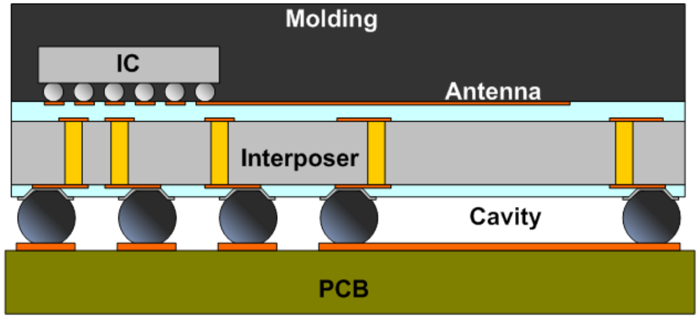


Frequency domain 60GHz SiP2

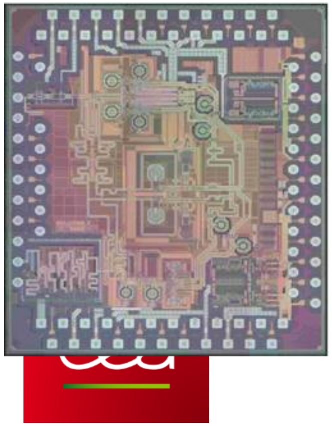
6,5*6,5mm² module with mmw transceiver and antennas

- 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

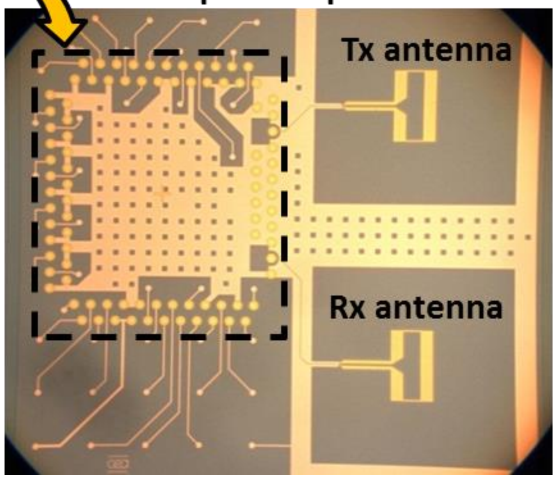
ECTC'13
MTT'12
3DIC'13



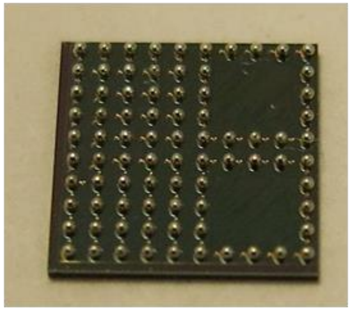
RFIC



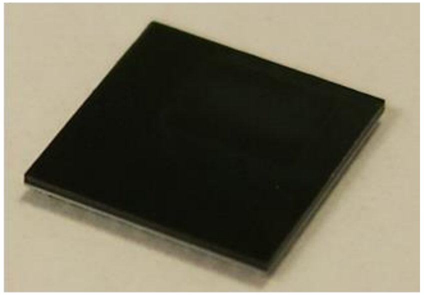
Interposer top view



Balled interposer



Molded interposer

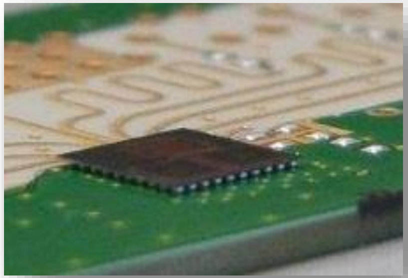


Frequency domain 60GHz demo

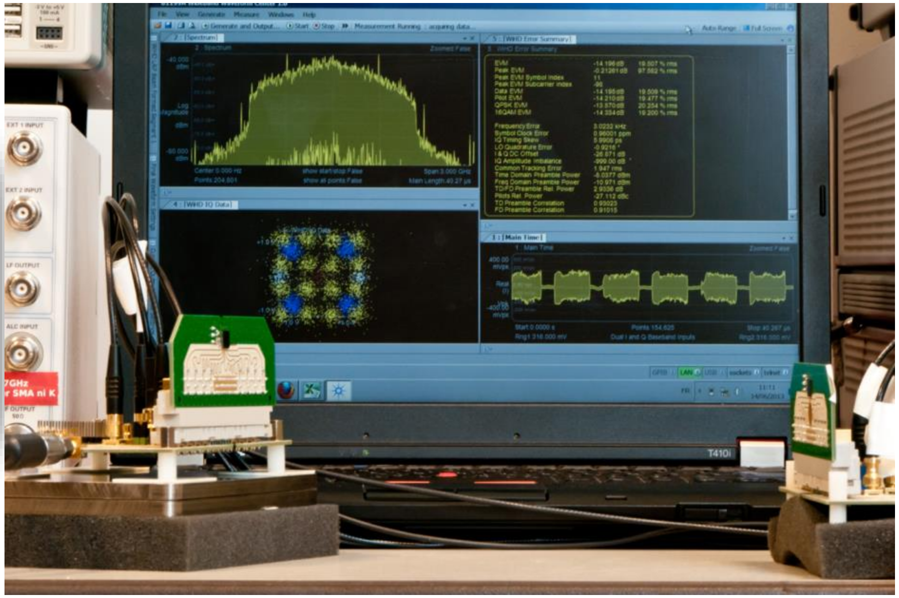
Data transmission tests

- 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). **Power consumption ~400mW**
- Good heat dissipation in the interposer substrate (max 42°C)

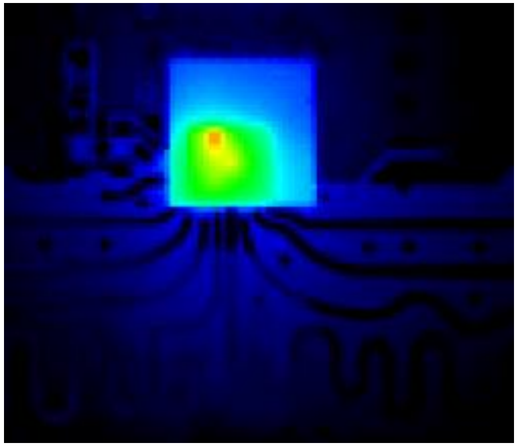
Interposer on PCB



Experimental test bed



Thermal image of the interposer

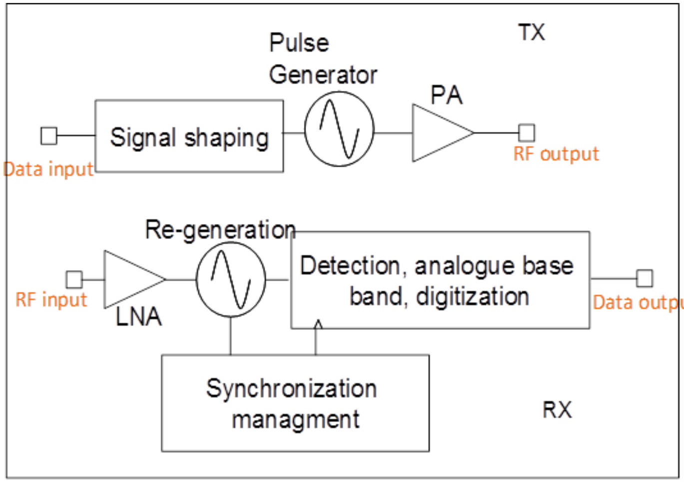


Time Domain 60GHz transceiver

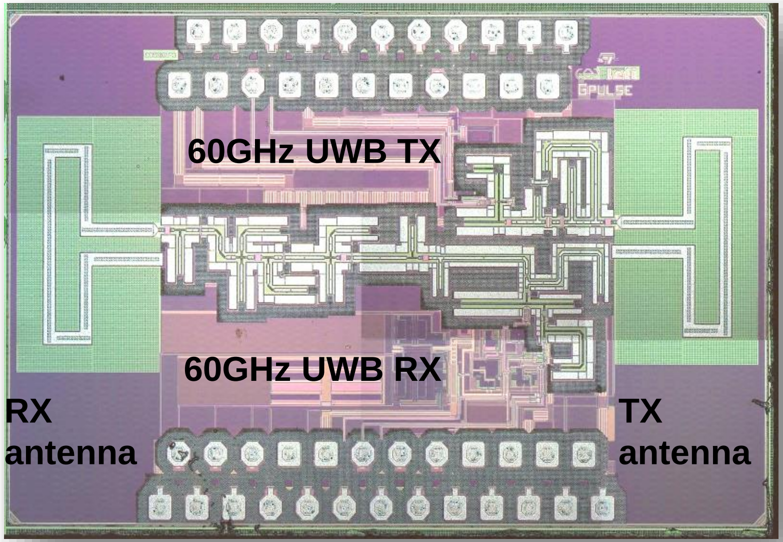
IR UWB at 60GHz will offer new uses cases for device to device communication

- **Power consumption @ 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)

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



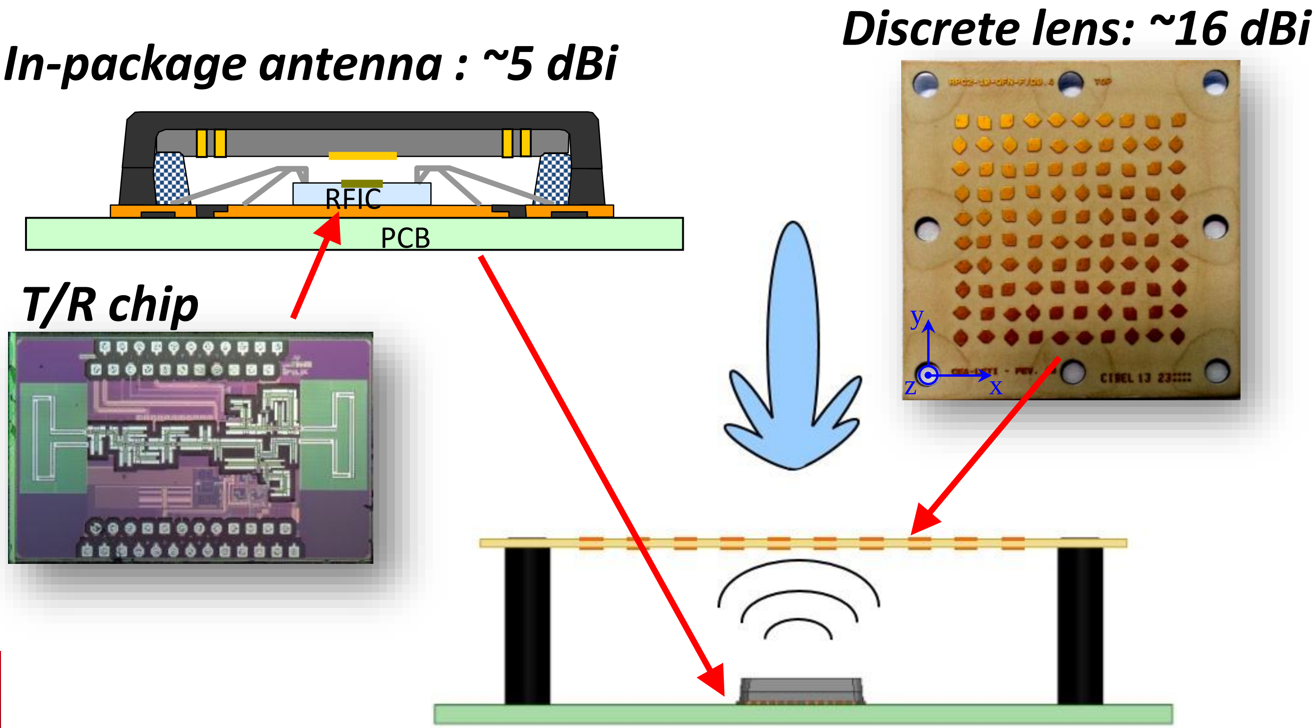
1,9mm x 3,1mm



Time Domain 60GHz transceiver

In-Package coupled antenna and focusing lens:

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

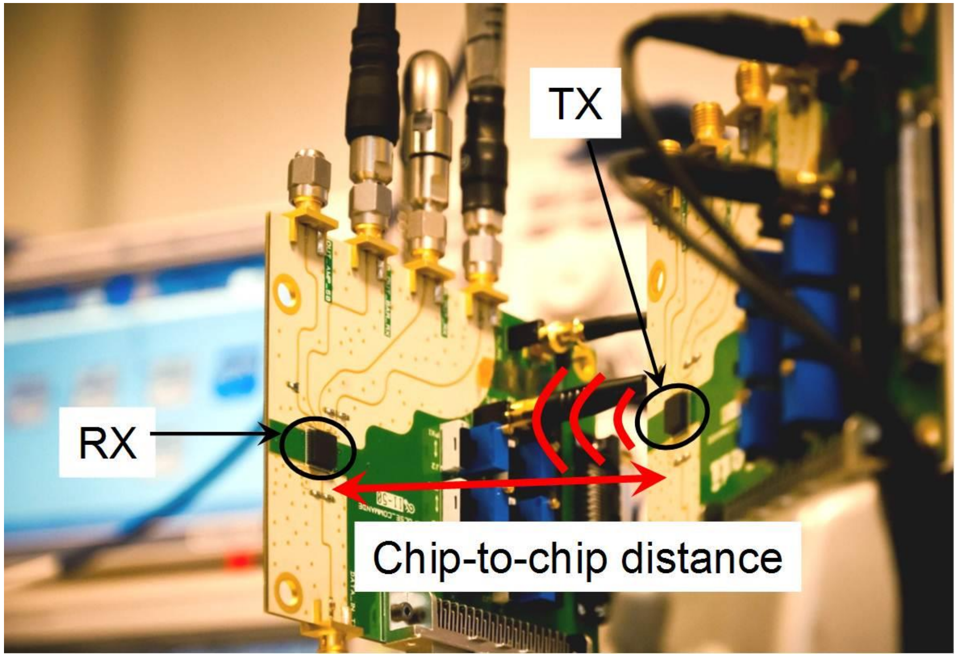


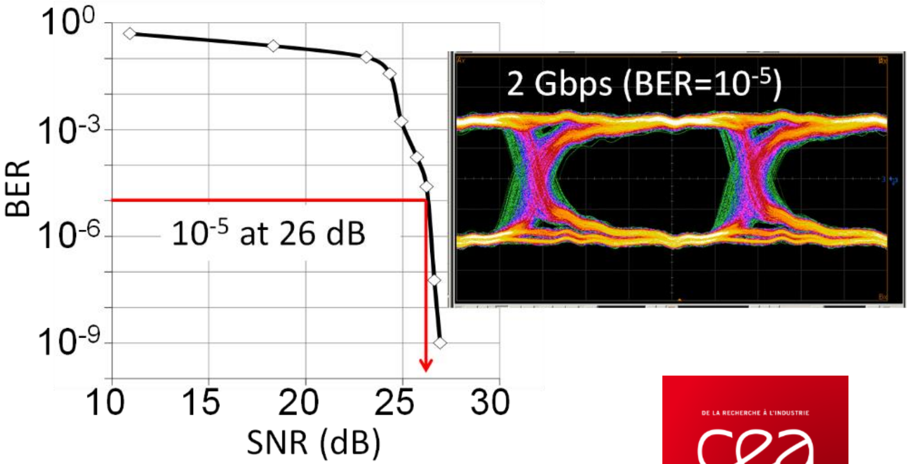
Time domain 60GHz demo

Data transmission tests

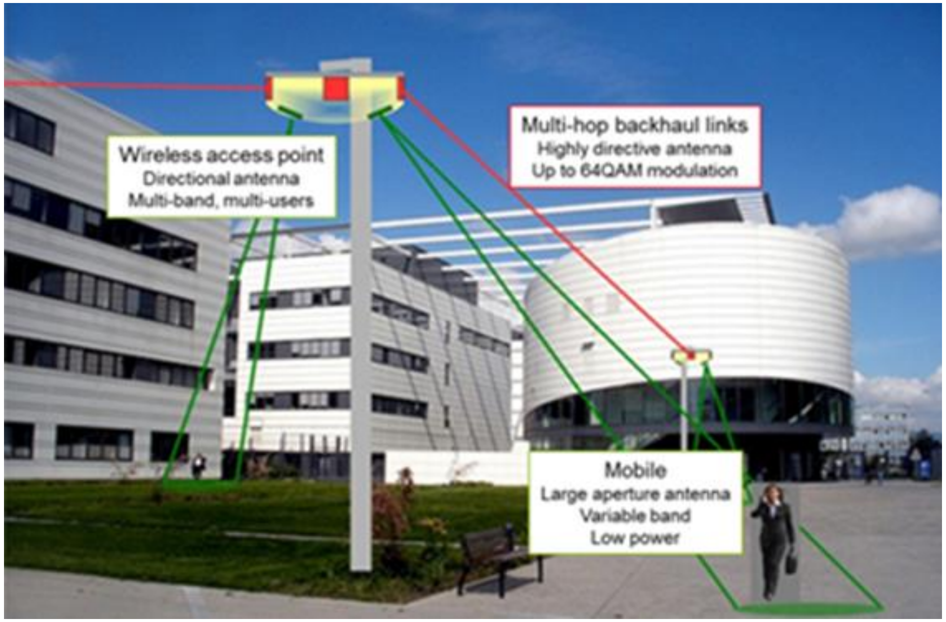
- Transmission of PRBS @10e-9 at : 2Gbps over 5 cm, 0,5Gbps over 20cm
- Up to 5m range with discrete lens

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





Ongoing developments



Frequency domain

5G mmw small cell

Access point and Backhauling

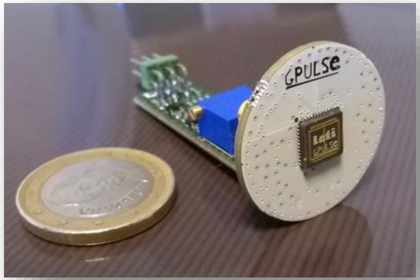
SEVENTH FRAMEWORK PROGRAMME

MiWaveS

E3NETWORK

Time domain

Contactless Connectors

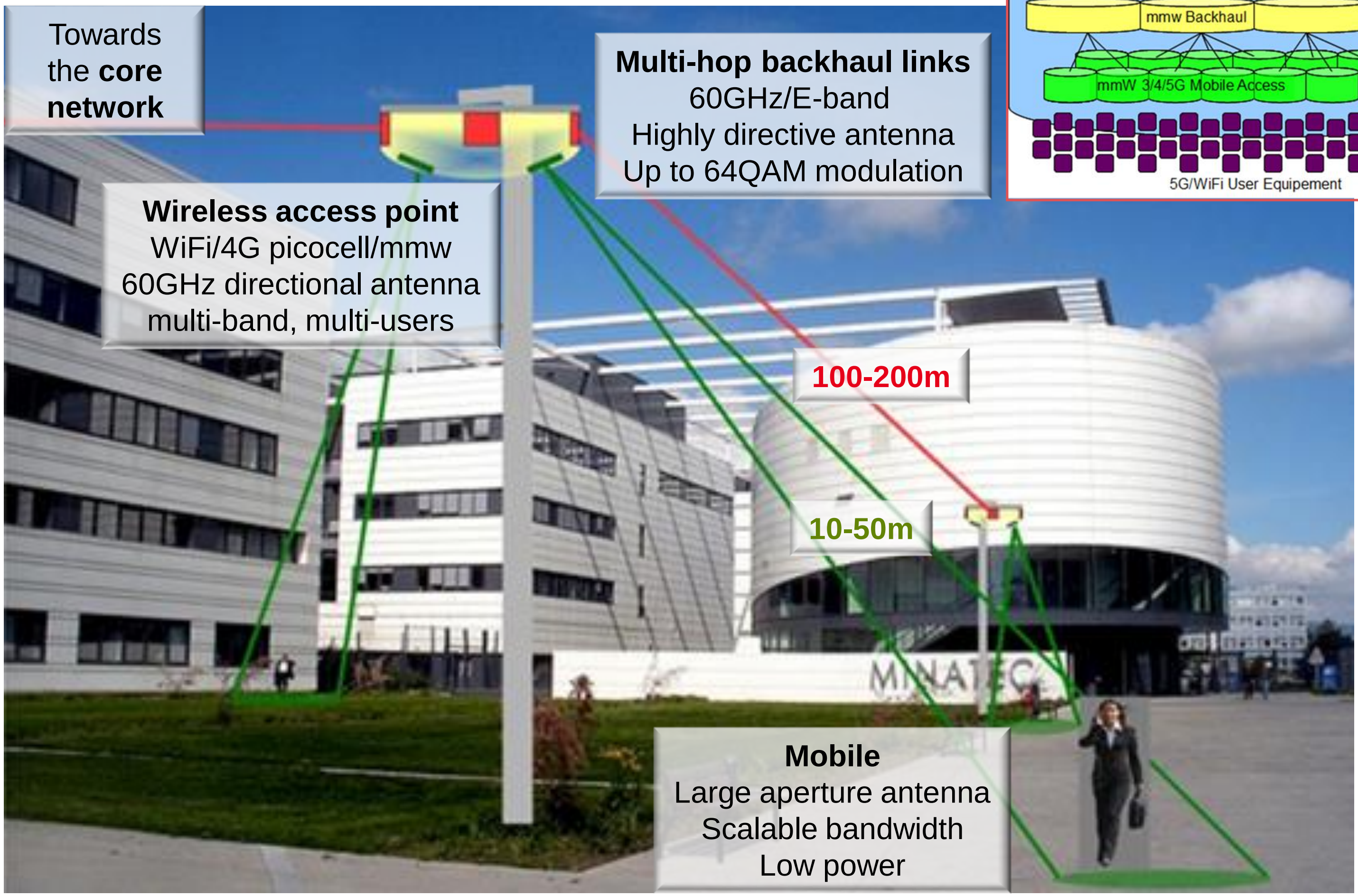


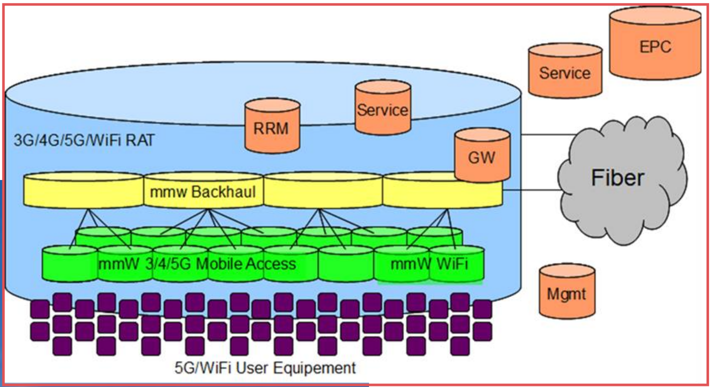
2016 International CES

leti & list

Ongoing developments - Frequency domain

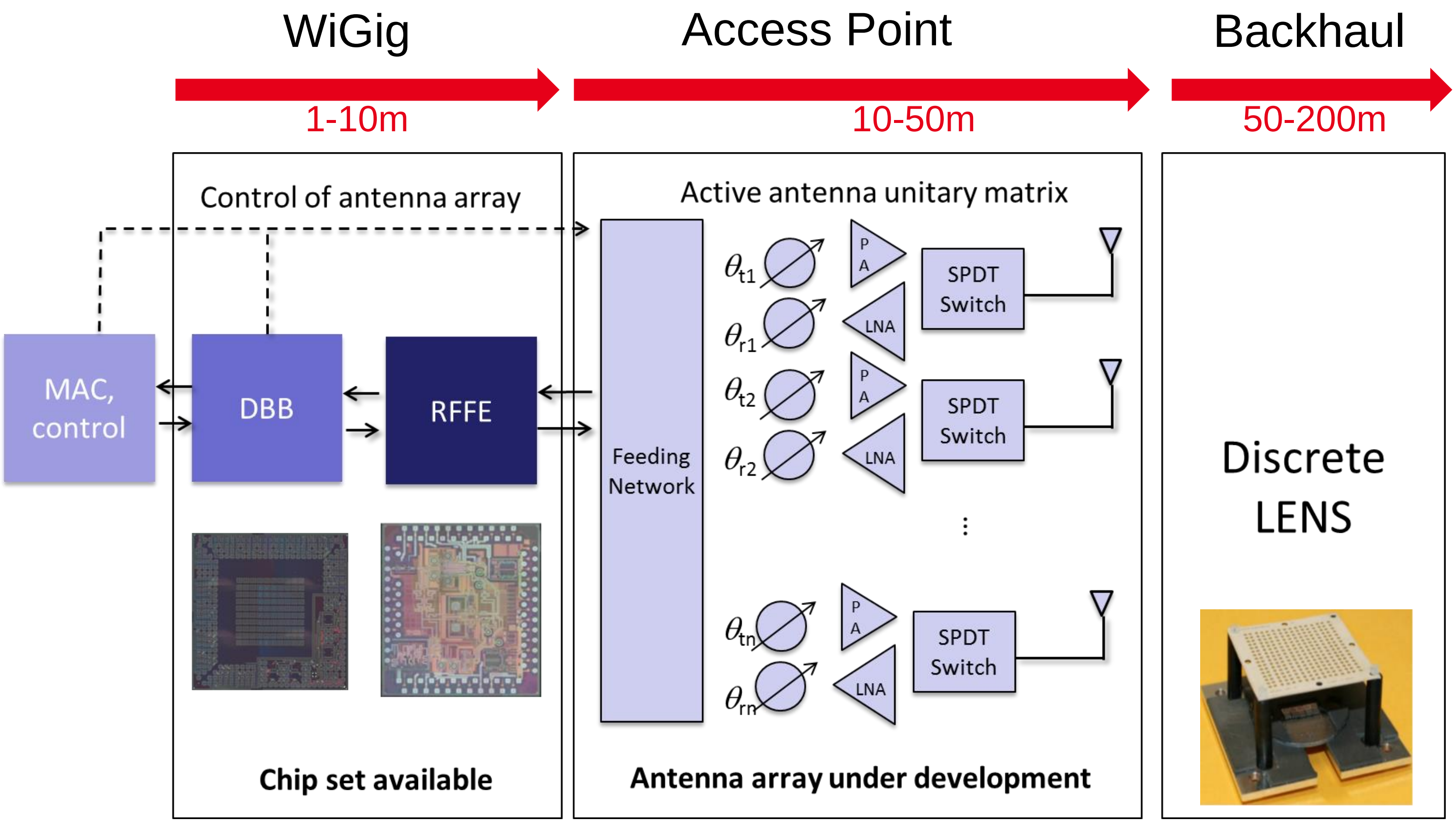
5G Heterogeneous Network with mmw small cells





Ongoing developments - Frequency domain

Incremental approach to satisfy various applications

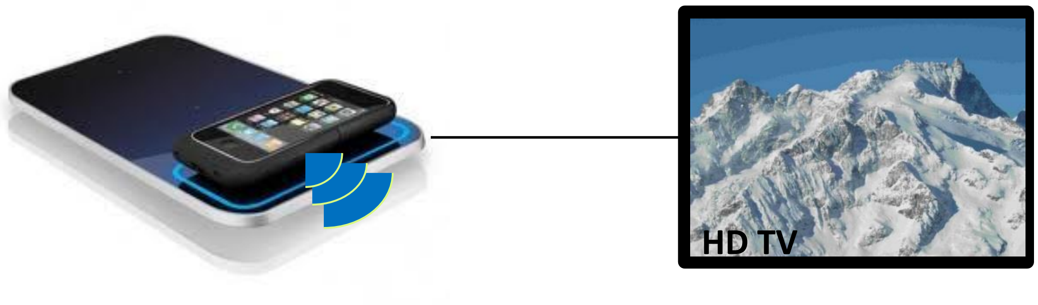


Ongoing developments – Time domain

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



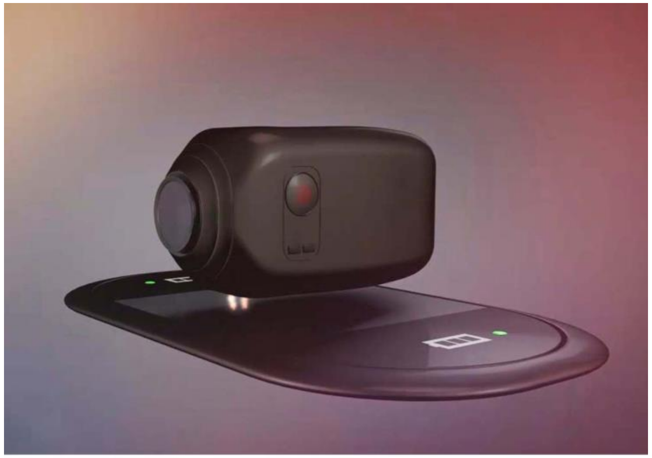
Wireless USB or Ethernet

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

Other products on the market

- 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

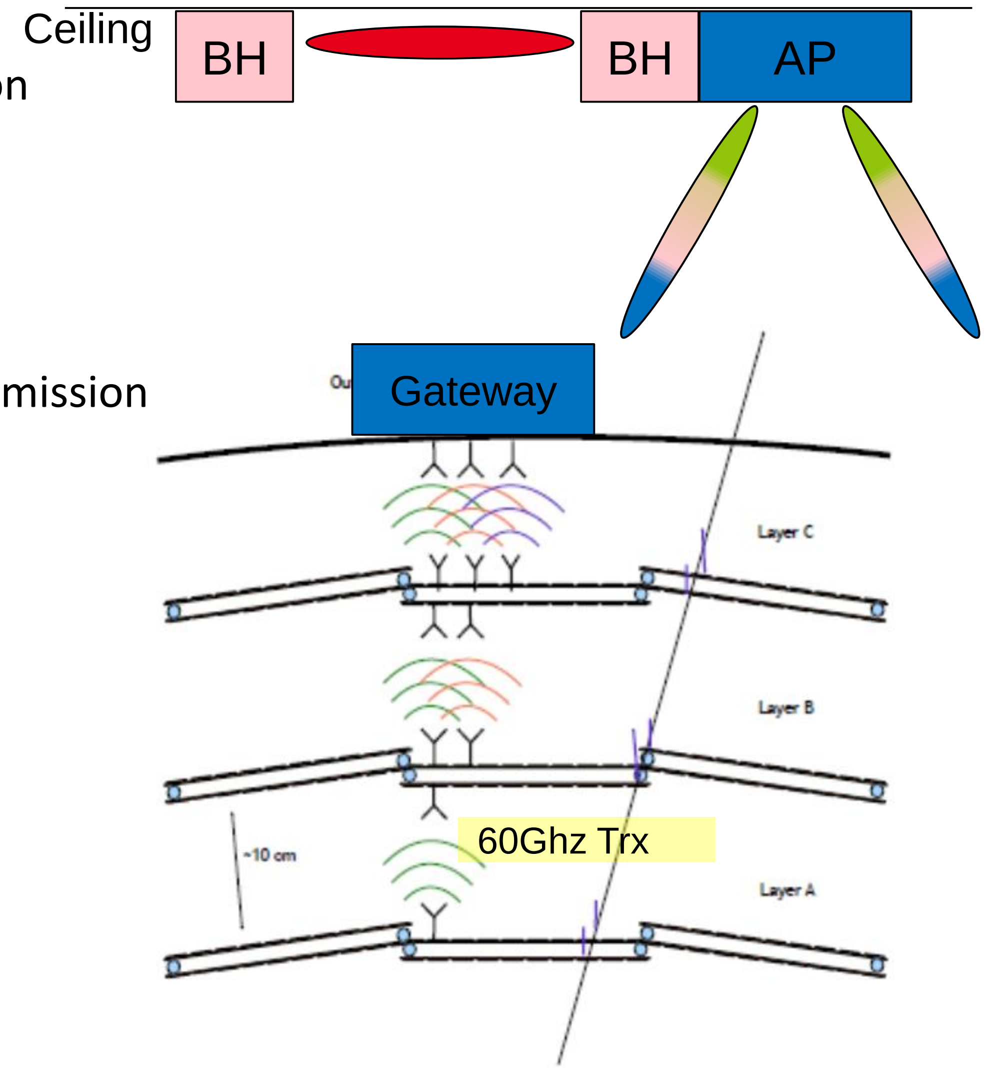
- Sibeam
  - USB type A, B, C and micro USB, USB2.0, USB3.0
  - HDMI type A, C, and D
  - DisplayPort and Mini-Display Port
  - I2C tunneling provides control, HID, and private communications
  - No software needed
  - Up to 12 Gbps



Wireless alternative to USB connections... SiBEAM Snap

Possible radio schemes

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

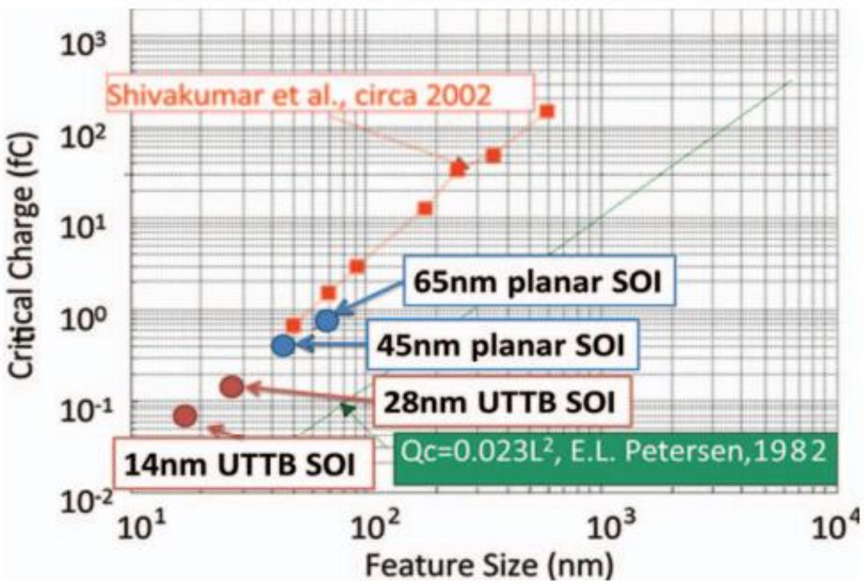


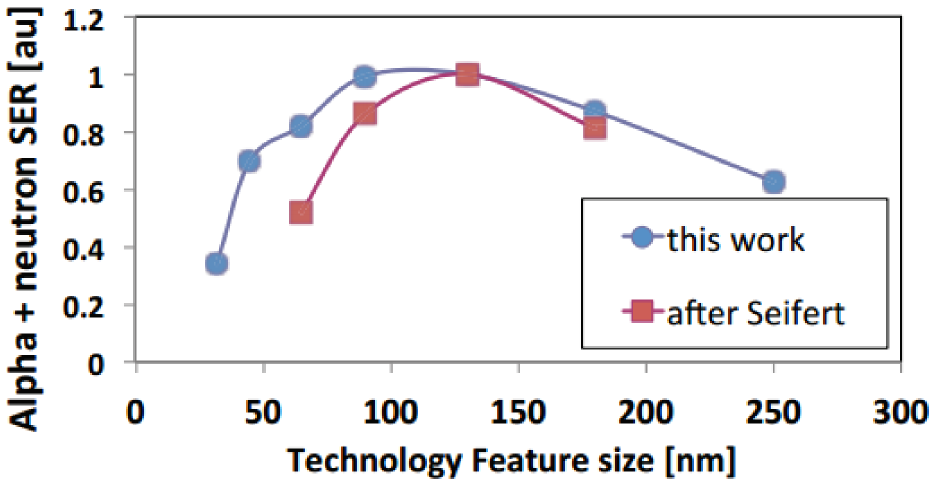
Possible radio schemes

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	Contactless 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

mmW ICs in harsh environments

- mmW ICs required advanced technology nodes
- Radiation effects have been investigated mainly for digital operation

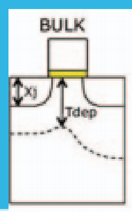


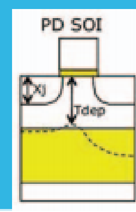


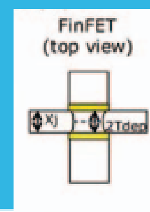
P. Roche, et al, "Technology Downscaling Worsening Radiation Effects in Bulk: SOI to the Rescue ," IEDM 2013

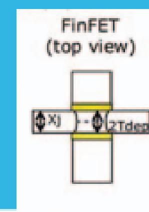
mmW ICs in harsh environments

- SOI and FinFet/FDSOI advanced nodes shift radiation paradigms.









	PD-SOI	Bulk FinFET	SOI FinFET	UTBB-FDSOI
Critical charge min. charge to upset	0.1fC	<0.1fC	<0.1fC	<0.1fC
Sensitive depth charge collection	**Gate** thicker body Gate area	**Drain** drain volume substrate extension	**Gate** fin height gate area	**Gate** very thin body gate area
Parasitic bipolar charge amplification	**Significant** without ties >10	**Very limited** substrate tied to gate	**Low Bipolar** simulated ~2-8	**Very low Bipolar** simulated ~2-3
Neutron-SER	**÷5 to ÷20**	**÷2.5 to ÷3.5**	**÷10**	**÷50 to ÷110**
Muon-SER	**New (1000x) SER risk** under evaluation			
Thermal-SER	**New (2x) SER risk** under evaluation			
Low-energy proton-SER	**New SER risk** under evaluation			
SEL ion-induced LU	**Immune** by construct	no data yet from literature	**Immune** by construct	**Immune** including hybrid devices
TID Gamma and X-rays	**Mrad** with body ties/taps	**100's krad** with large fins	**Mrad** with narrow fins	**100's krad** under full evaluation

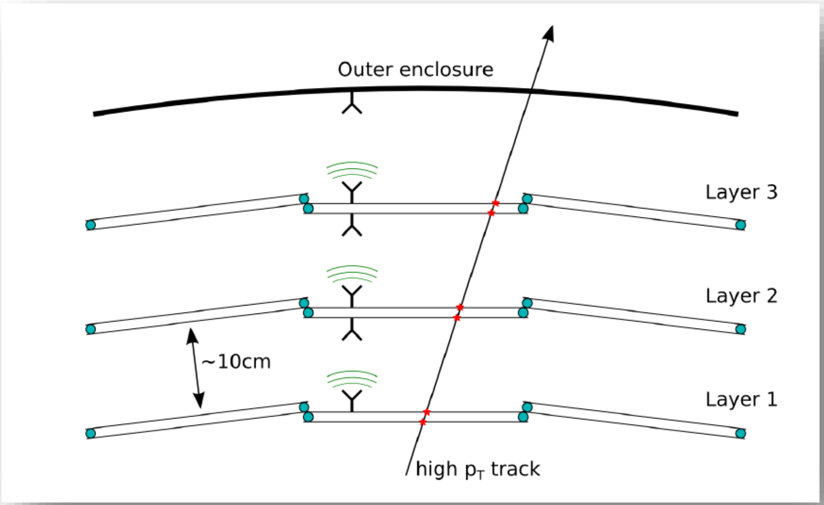
P. Roche, et al, "Technology Downscaling Worsening Radiation Effects in Bulk: SOI to the Rescue ," IEDM 2013

Outline

- Context: why mmW wireless links?
- Proposed approach for wireless data read-out in HEP detectors
- mmW Integrated Circuits at CEA-Leti
- **Conclusions & Discussion**

Conclusions

- 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.
- On-going investigations about radiation and high-magnetic fields impact should be extended to RF functions.



Thanks for your attention

Questions ?

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Major publications

- Richard, O et. al. "A 17.5-to-20.94GHz and 35-to-41.88GHz PLL in 65nm CMOS for wireless HD applications," Solid-State Circuits Conference Digest of Technical Papers (**ISSCC**), 2010 IEEE International , vol., no., pp.252,253, 7-11 Feb. 2010
- Siligaris, A et. al."A 60 GHz Power Amplifier With 14.5 dBm Saturation Power and 25% Peak PAE in CMOS 65 nm SOI," IEEE Journal of Solid-State Circuits (**JSSC**), vol.45, no.7, pp.1286,1294, July 2010
- A. Siligaris et al., "A 65 nm CMOS fully integrated transceiver module for 60 GHz Wireless HD applications," International Solid-State Circuits Conference (**ISSCC**), San Francisco, 20-24 February 2011.
- A. Siligaris et al., "A 65-nm CMOS fully integrated transceiver module for 60-GHz Wireless HD applications," IEEE Journal of Solid-State Circuits (**JSSC**) , Dec. 2011.
- Y. Fu et al., "Characterization of integrated antennas at millimeter-wave frequencies," Int**. Journal of Microwave** and Wireless Technologies, pp. 1-8, 2011.
- H. Kaouach et al., "Wideband low-loss linear and circular polarization transmit-arrays in V-band," **IEEE Trans**. Antennas and Prop., July 2011.
- A. Siligaris et al., "A 60 GHz UWB impulse radio transmitter with integrated antenna in CMOS 65 nm SOI technology," 11th IEEE Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems, Phoenix, 17-19 January 2011.
- L. Dussopt, "Integrated antennas and antenna arrays for millimetre-wave high data-rate communications," 2011 Loughborough Ant. and Propag. Conf. (**LAPC** 2011), 14-15 Nov. 2011, Loughborough, UK.
- L. Dussopt, et al., "Silicon Interposer with Integrated Antenna Array for Millimeter-Wave Short-Range Communications," IEEE **MTT-S** Int. Microwave Symp., 17-22 jun. 2012, Montreal, Canada.
- J.A. Zevallos Luna et al., "Hybrid on-chip/in-package integrated antennas for millimeter-wave short-range communications," **IEEE Trans.** on Antennas and Propagation, vol. 61, no. 11, November 2013, pp. 5377-5384.
- A. Siligaris, et al., "A low power 60-GHz 2.2-Gbps UWB transceiver with integrated antennas for short range communications," 2013 IEEE **RFIC** conference, June 2-4, 2013, Seattle, Washington, USA.
- Guerra, J.M et. al., "A 283 GHz low power heterodyne receiver with on-chip local oscillator in 65 nm CMOS process," Radio Frequency Integrated Circuits Symposium (**RFIC**), 2013 IEEE , vol., no., pp.301,304, 2-4 June 2013
- Y. Lamy, et al., "A compact 3D silicon interposer package with integrated antenna for 60 GHz wireless applications," IEEE Int. 3D Systems Integration Conference (**3DIC**), Oct. 2-4, 2013, San Francisco, CA, USA.
- Luna, J.A.Z. et. al."A packaged 60 GHz low-power transceiver with integrated antennas for short-range communications," Radio and Wireless Symposium (**RWS**), 2013 IEEE , vol., no., pp.355,357, 20-23 Jan. 2013
- J.A. Zevallos Luna et al., "A V-band Switched-Beam Transmit-array antenna," to appear in Int. **Journal on Microwave** and Wireless Technology, 2014.
- Dehos, C. et. al., "Millimeter-wave access and backhauling: the solution to the exponential data traffic increase in 5G mobile communications systems?," **IEEE Communications Magazine**, vol.52, no.9, pp.88,95, September 2014

FROM RESEARCH TO INDUSTRY

Additional material

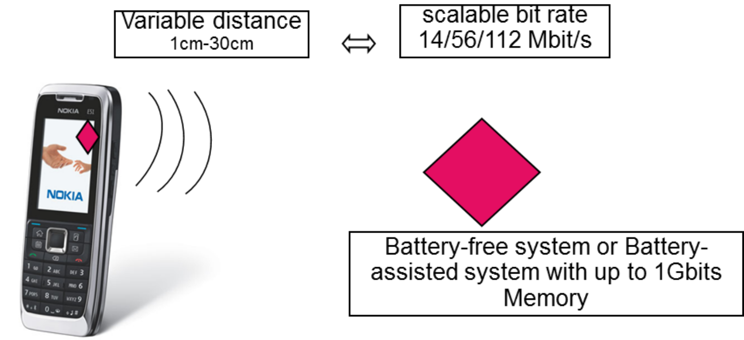
www.cea.fr

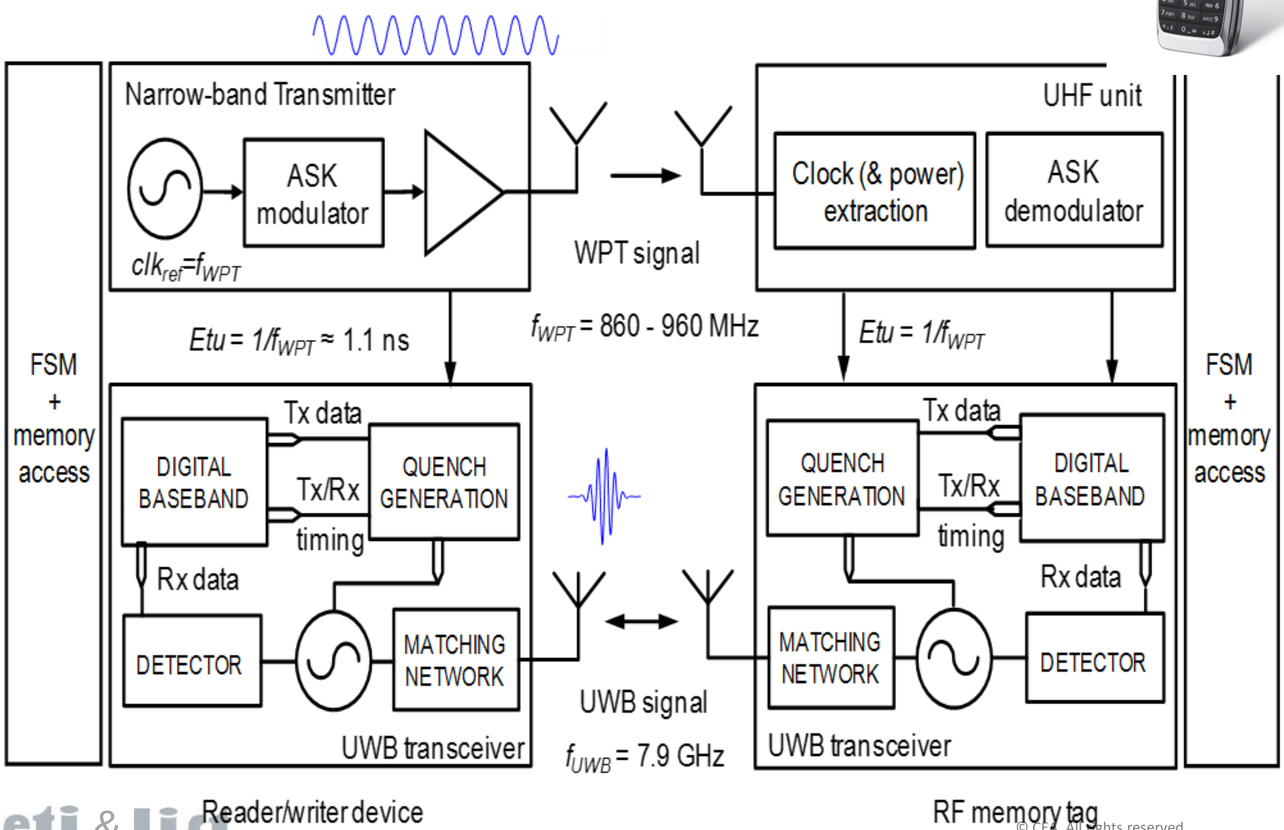
Wireless Power Supply

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





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

Wireless Power Supply

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

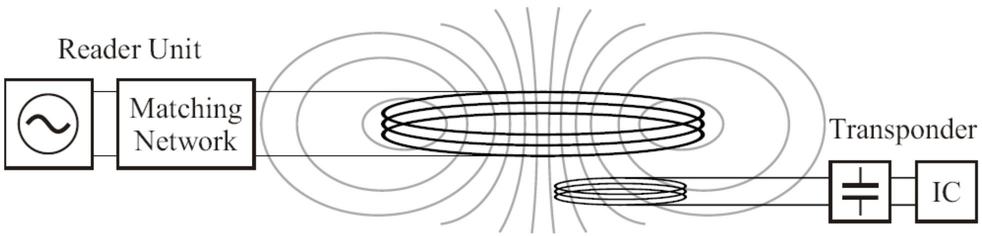
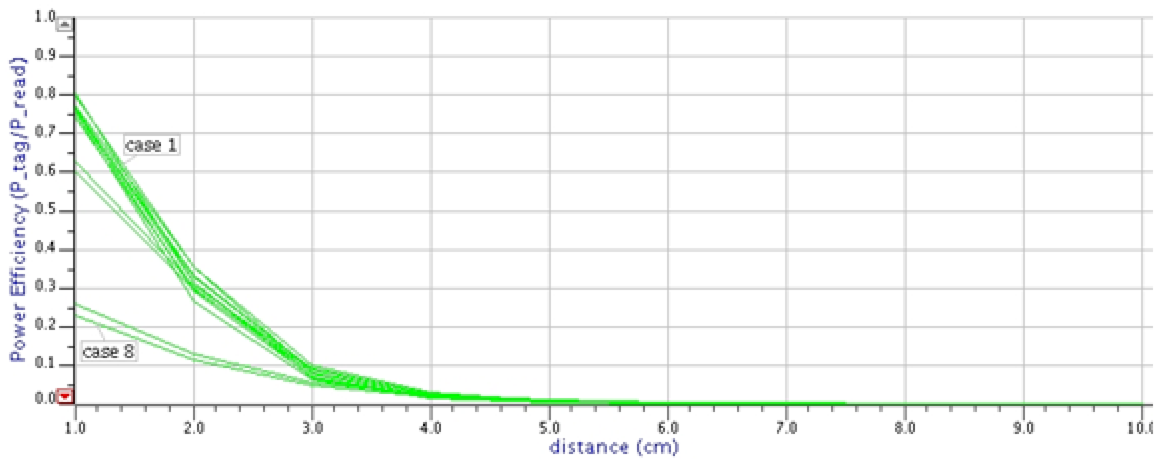


Figure 1: Basic setup of inductive coupled coils in a 13.56MHz RFID system



Wireless Power Supply

- 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)

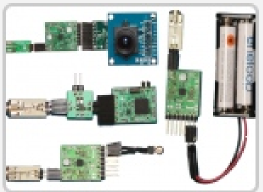
- Inductive coupling
  - Good efficiency but restricted to very short range 1-3cm at 13.56MHz
  - Coupling at 125kHz to be evaluated (theoretical 1-3m range)

Wireless Power Supply

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.

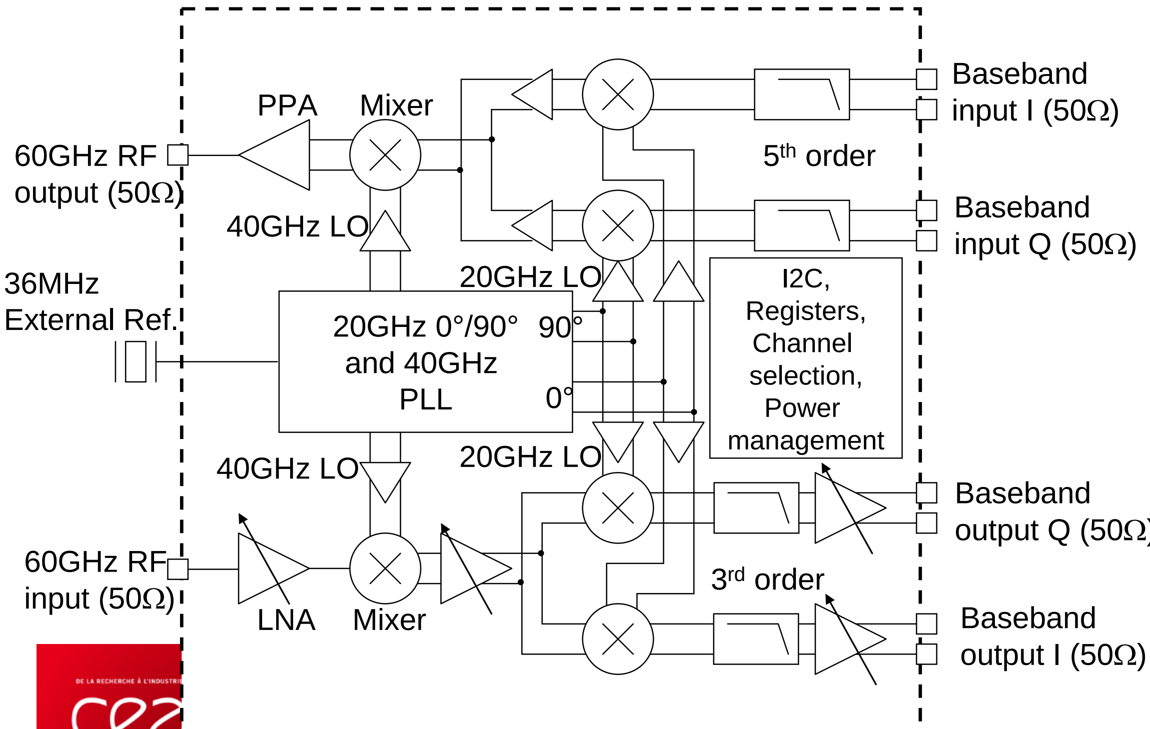
Using this approach, the researchers found that the temperature sensor could operate at distances of about 6 meters from the router - a distance that increased to 9 meters when a rechargeable battery was added. A further test with a Wi-Fi antenna-enabled low-power camera equipped with a low-leakage storage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

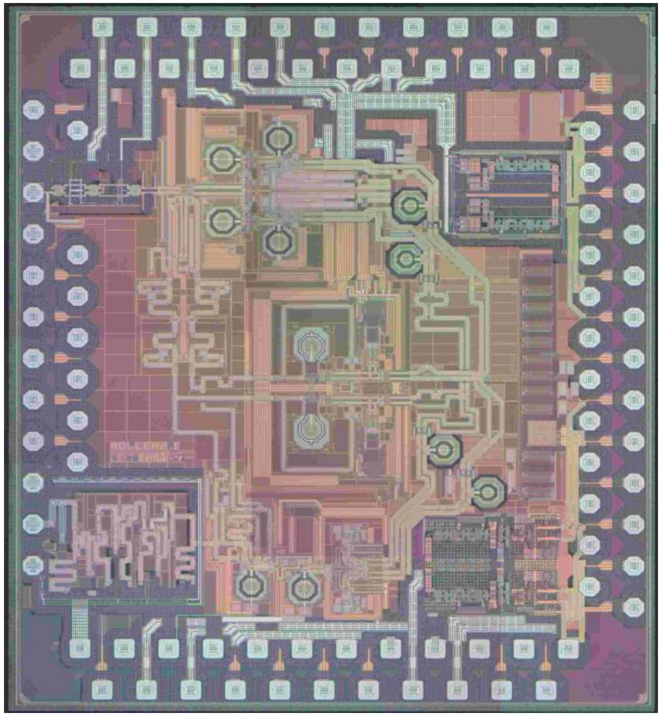
Also demonstrated was the remote battery recharging of a Jawbone fitness tracker. Once equipped with the PoWiFi antenna and placed in the vicinity of a PoWiFi router, the device's coin cell battery was able to be brought to 41% charged from a no-charge state in 2.5 hours.

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).

60GHz frequency domain transceiver

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

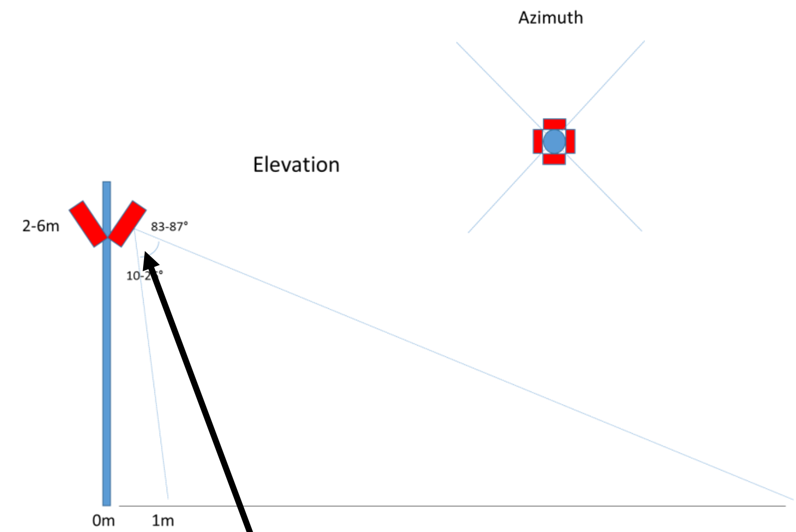


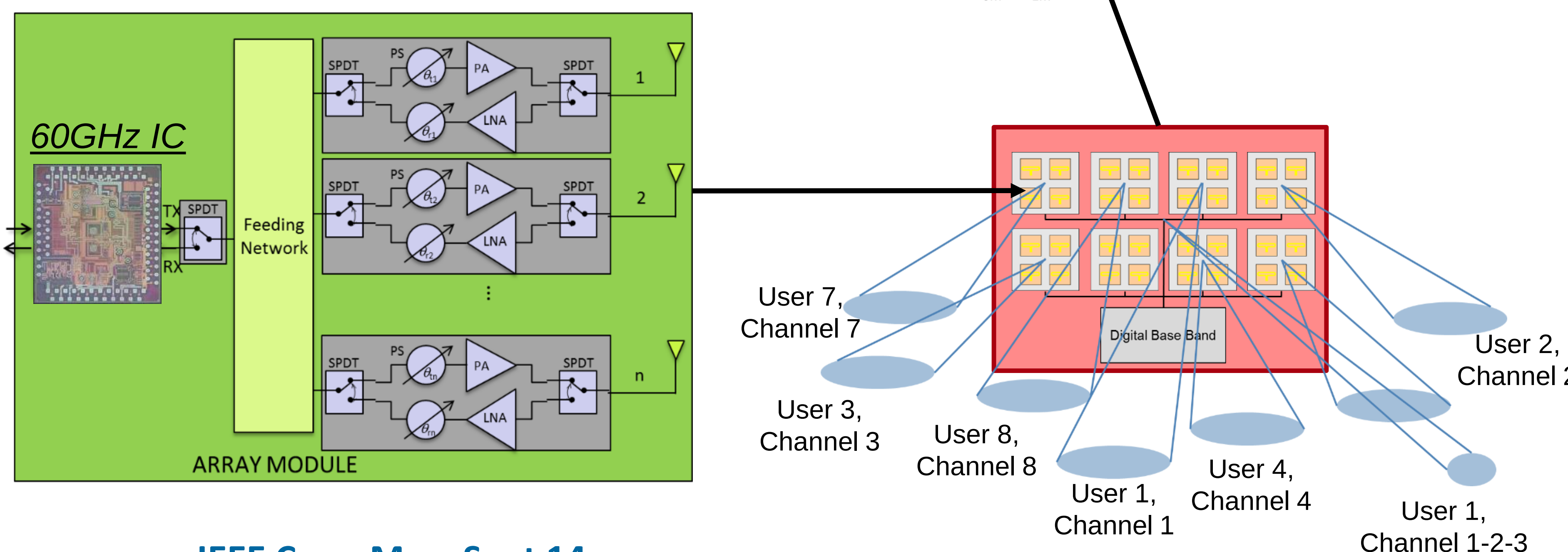


Ongoing developments - Frequency domain

Access point scheme

- From available WiHD/Wigig transceiver
- Active phase shifted antenna array module
- Synchronization of modules
  to increase range/data rate

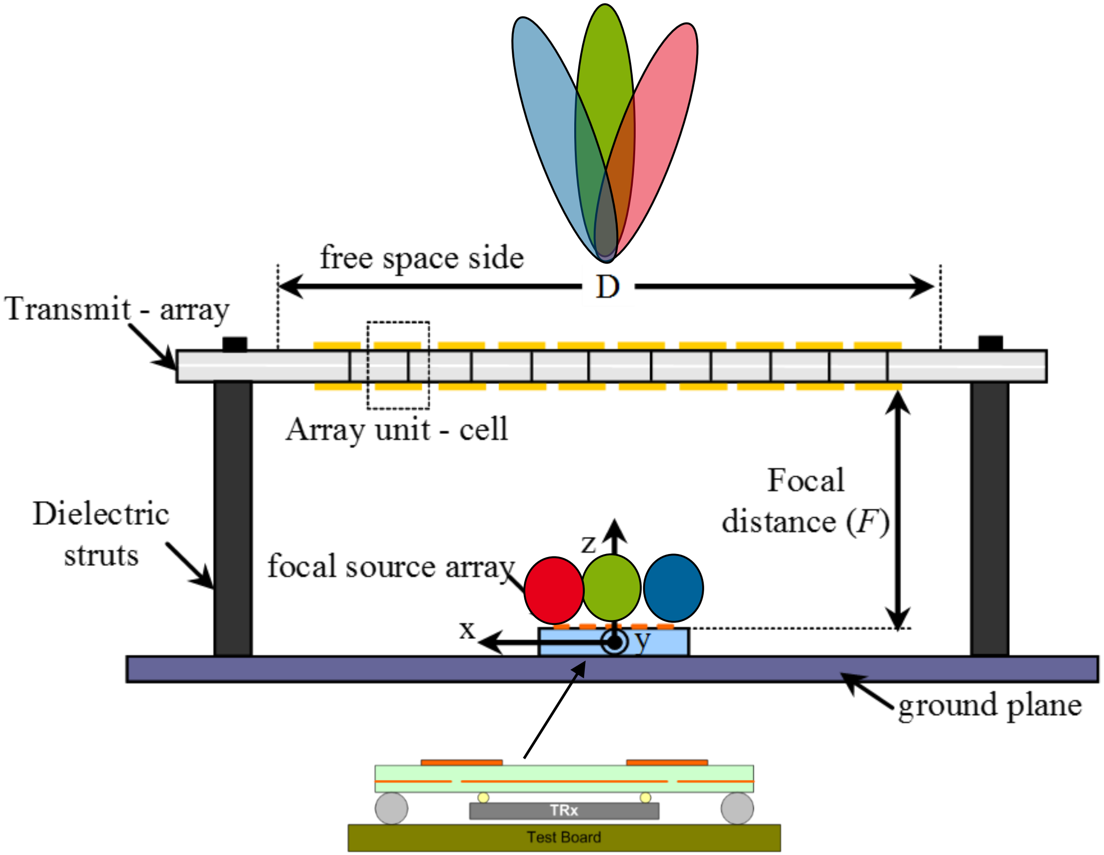


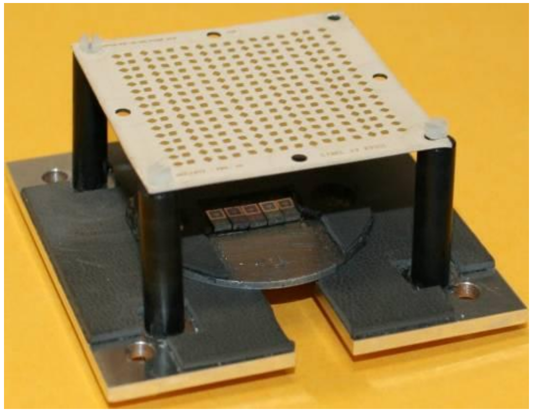


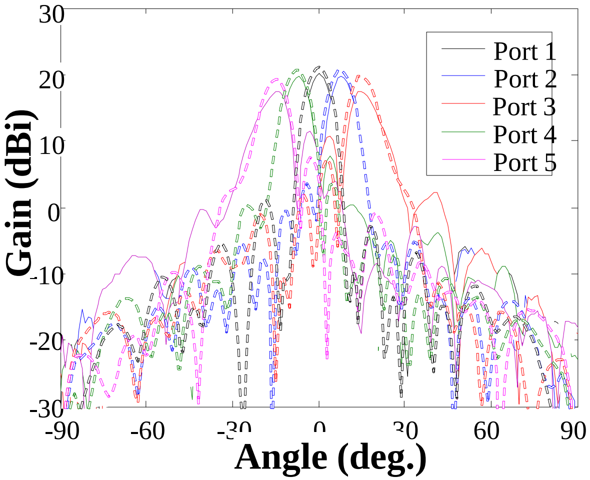
IEEE Com. Mag. Sept 14

Ongoing developments - Frequency domain

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
- Gain >30 dBi, with switchable beam over 20°