# Multi-Gigabit Wireless Data Transfer for High Energy Physics Applications

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On behalf of the WADAPT Working Group

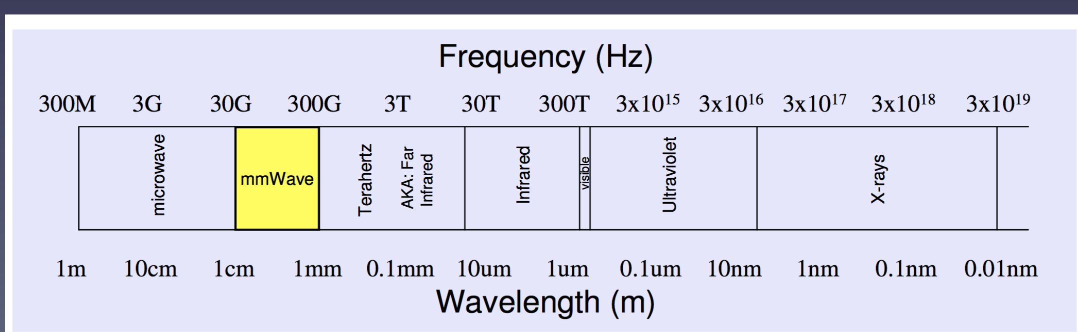
Wireless Allowing Data And Power Transmission

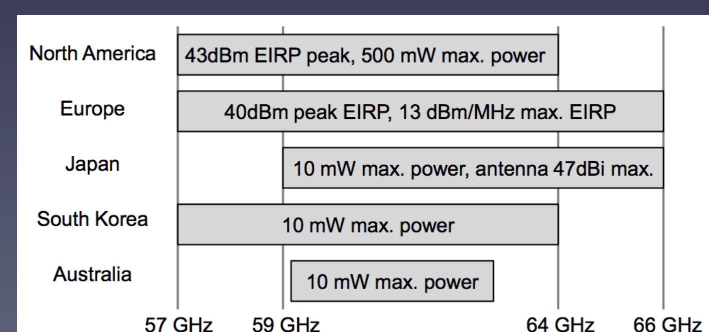
# OUTLINE

- ✧ Introduction to millimeter Wave
- ✧ Features of the 60 GHz Band
- ✧ Practical Opportunities
- ✧ Application in HEP
- ✧ Proposed Readout Concept
- ✧ Heidelberg ASIC
- ✧ Other developments
  - ✧ Antenna design
  - ✧ Leti ASIC
  - ✧ Heidelberg tests
- ✧ Summary and Outlook

# millimeter - Wave

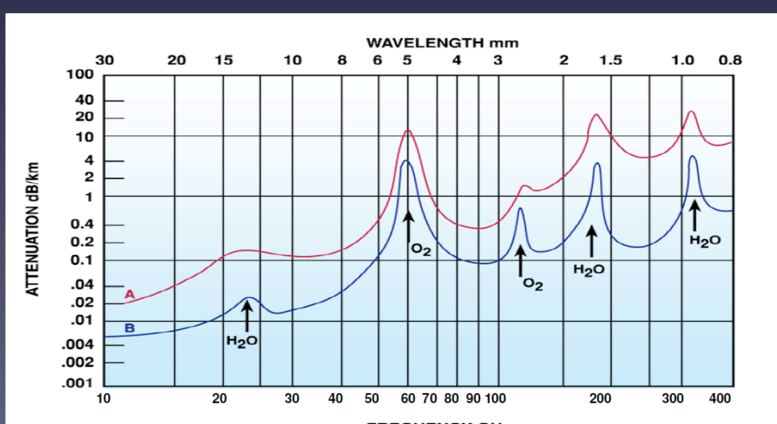
- The mm-Wave is defined as the band between 30 GHz (10mm) to 300 GHz (1mm)
- In 2001, the Federal Communication Commission (FCC) opened up the 57 - 66 GHz band. In 2003 several other bands followed (Automotive 77 GHz Radar, 94 GHz imaging, THz spectroscopy > 100 GHz and so on….).
- This due to the "technological advance" and in order to "facilitate the commercialization of the Millimeter Wave Band"
- Triggered huge interest from Industry and Research center/Universities etc.
- Energy propagation in the 60 GHz band has some unique characteristic that makes some interesting features.
- This allows a higher Effective Isotropic Radiated Power (EIRP)

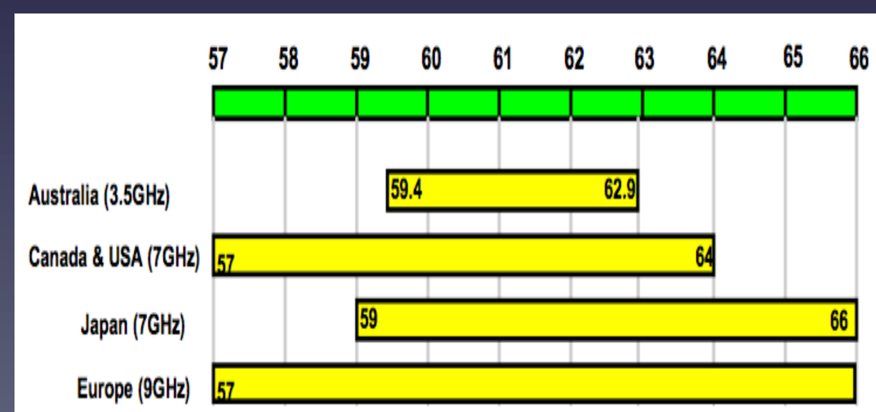


# Features of the 60 GHz Band

- Unlicensed Spectrum: 4-9 GHz bandwidth available world-wide
- Can send Gigabits/s of data over short distance (0.01-100 m)
- Highly secure and low interference probability: Short transmission distance, oxygen absorption, narrow beam width and attenuation through materials.
  - Reuse of frequency
- Placement: High flexibility, reduced complexity of cabling, material budget.
- High frequency: Small form factor.
- High transmit power: 40 dBm EIRP (Equivalent Isotropically Radiated Power)
- Mature techniques: Long history in being used for secure communication.

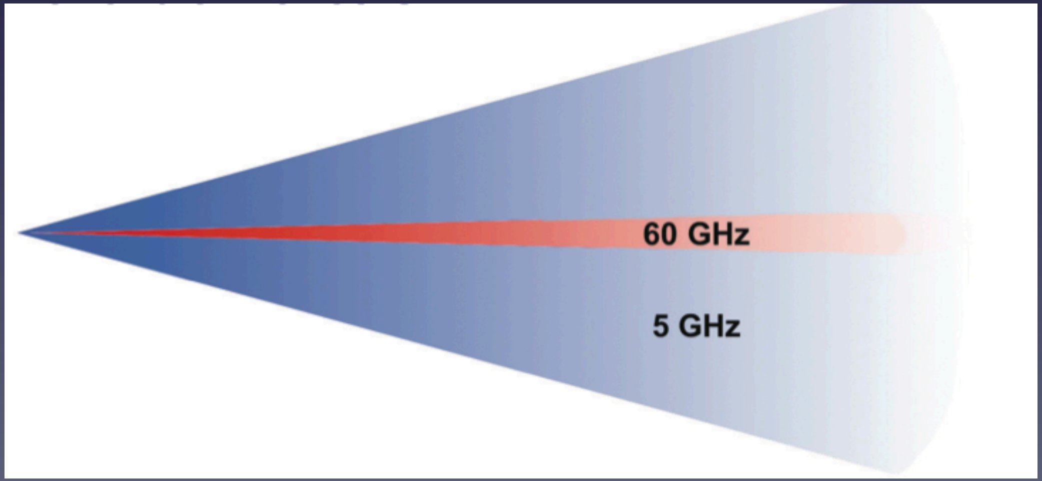


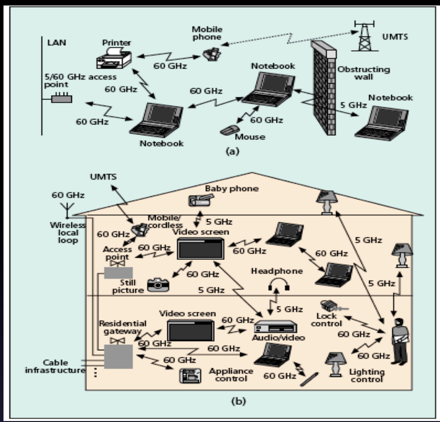
# Features of the 60 GHz Band

## These Features:

Narrow beam-width, high bandwidth, high interference immunity, high security, high frequency reuse, high density of users, high penetration loss, ultra low latency and low material budget makes the 60 GHz band an **excellent choice** for high data transfer in a closed short range environment as the **detector environment**.



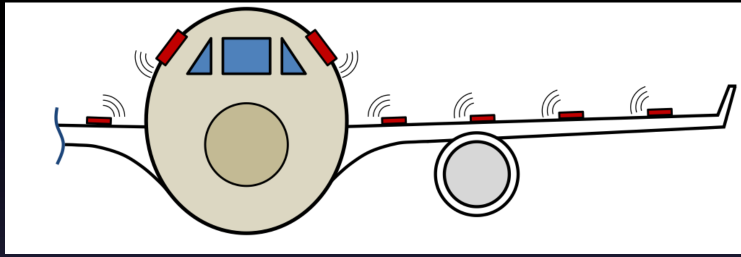
# Practical Opportunities




- Fast file transfer, data rates
- Interconnectivity of media devices
- Streaming of uncompressed HD Content

## In-flight Entertainment:

- Do not interfere with other aircraft communications/flight navigation

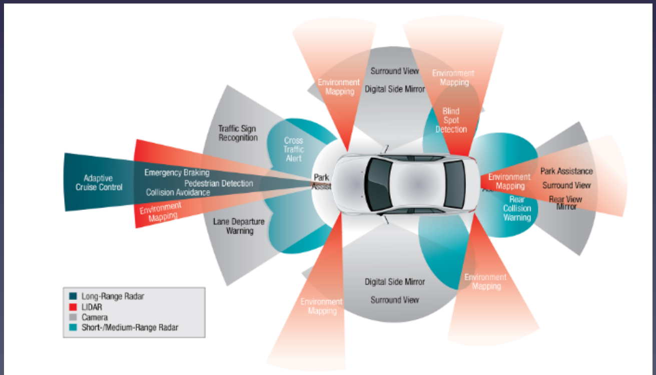


## Replace Gigabit Ethernet

- Cables reduce/stop airflow
  - Energy savings in cooling


- ✧ Copper resistance increase
- ✧ Easy reconfiguration
- ✧ Lower power
- ✧ Reduction in cable number
- ✧ Cooling requirement

## Vehicles will need Gbps data rates




## Internet of Things (IoT)

# The *FUTURE* of connectivity

# is

# *WIRELESS*

# The HEP community is not

# an exception

# Applications in HEP

## ATLAS Silicon Micro-strip Tracker upgrade would require:

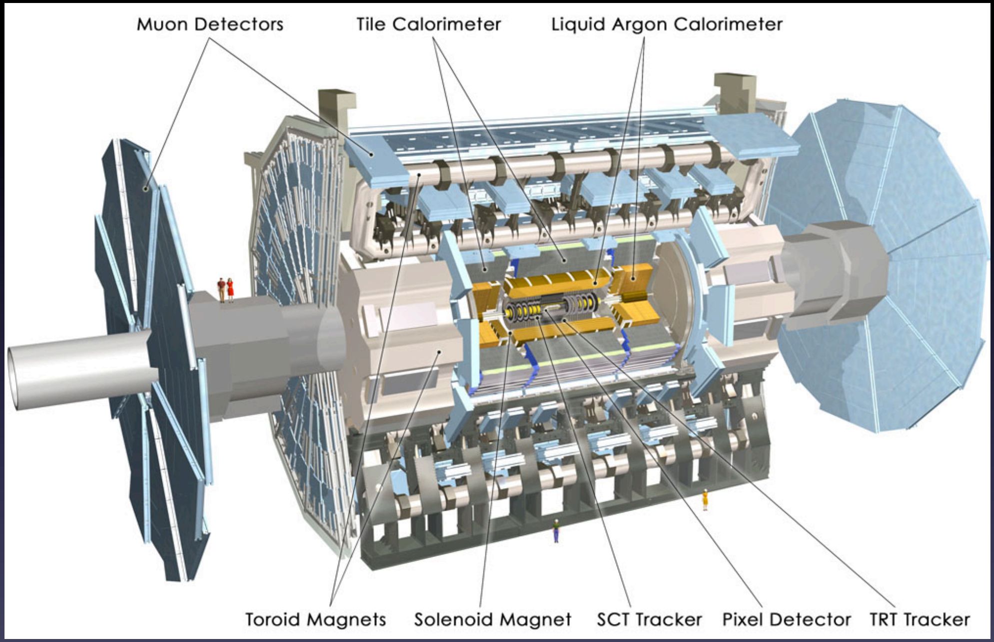
- ✧ Bandwidth of 100 Tb/s
- ✧ 20 000 links at 5 Gb/s

without increasing the

- ✧ Material budget
- ✧ Power consumption
- ✧ Space for services

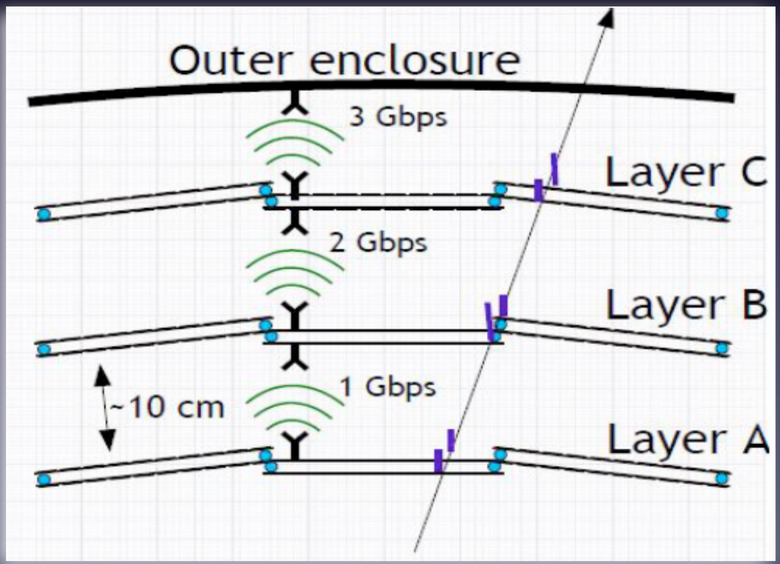
and in addition

- ✧ Contribute to the fast trigger decision



# Applications in HEP

- Today the data are readout perpendicular to the particle path.
- Static System with Line-of-Sight (LOS) data transfer Communication
- One Approach among many: Readout radially by sending the data through the layers by wire/via connection, with an antenna on both sides.




## Detector Improvements

- ✓ Reduced Material budget
- ✓ Cutting edge Low Latency
  - ✓ upto 50% faster than fiber
  - ✓ Fixed mmwave wireless is able to work faster than fiber (refraction in the fibre).
- ✓ mmwave links can overcome topographical obstacles, and faster Inst.
  - ✓ Optical systems has to go around/follow existing path.

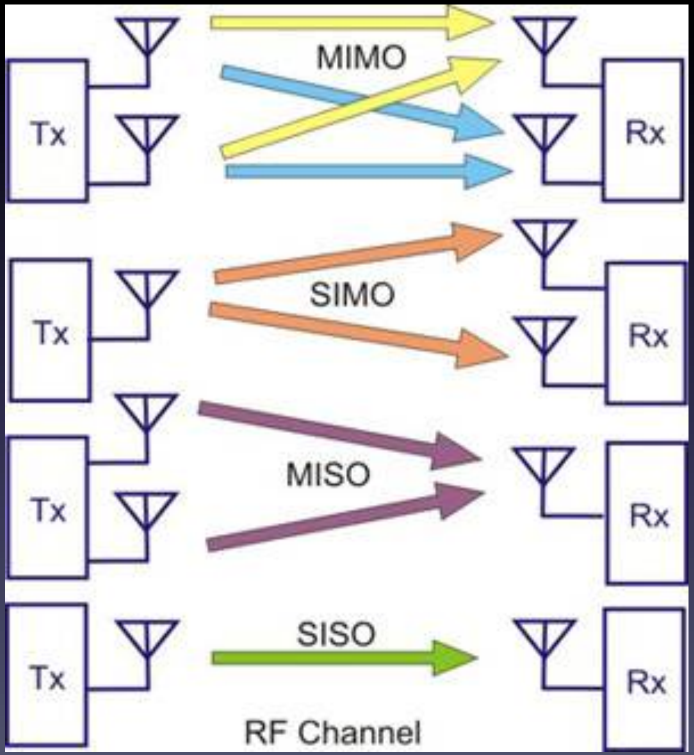
**For sure applications for the next decade will be extremely sensitive to latency.**

# Application in HEP

## Steering and Control of complex detector systems

Create topologies which are much more challenging to be realized by using wires

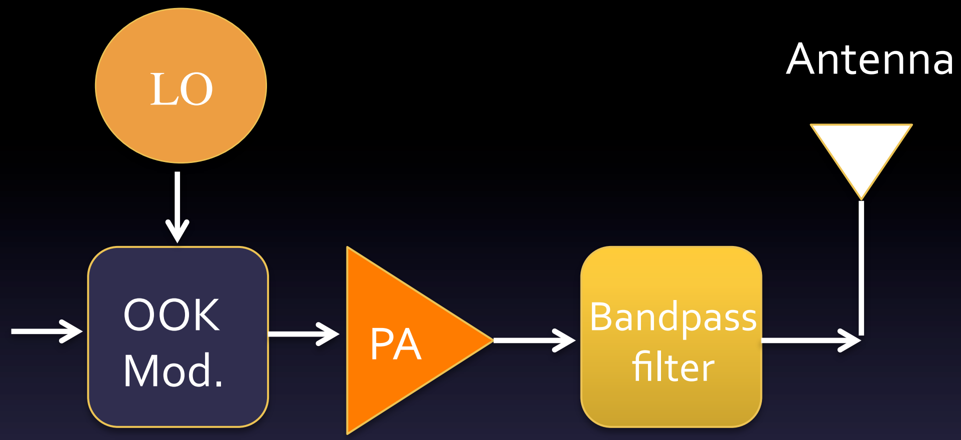
Super-fast speed and very low latency opens up a lot of opportunities for real time applications




- MIMO uses multiple antennas to transmit multiple parallel signals
- Data from one single transmitter can be sent to several receivers.
- Data from several transmitters send to one receiver
- Data from single transmitter to single receiver

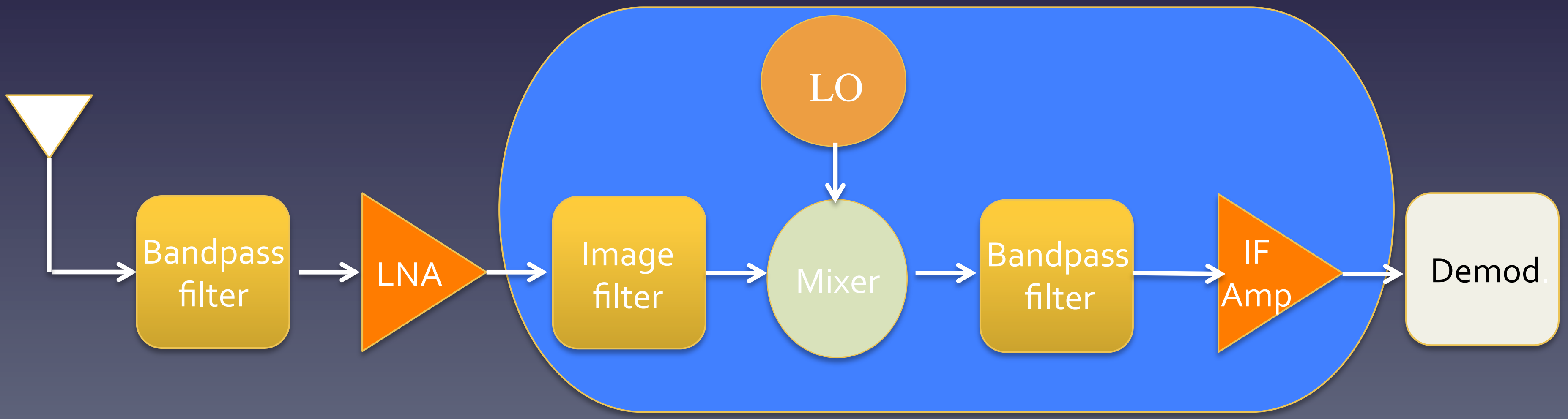
This can totally or even partially remove cables and connectors that will/can result in cost reduction, simplified installation, repair and reduction in detector dead material.

# Heidelberg ASIC




Transmitter:
- Deliver required output power
- Power efficient
- High gain and stability

Receiver:
- Balance gain, linearity and NF
- Low Power Consumption



# System Specifications

System $SNR_{min}$ is determined by the Bit-Error-Rate (BER) of a given Modulation scheme.

For OOK: $BER = 10^{-12} \rightarrow SNR_{min} \approx 17dB$

$$Noisefloor = -174dBm + 10\log_{10}(9G) = -75\ dBm$$

$NF_{tot}$ chosen to be 9 dB

$$S_{RX} = \text{Noisefloor} + SNR_{min} + NF_{tot} = -49\ \text{dBm}$$

Minimum power level that the system can detect producing an acceptable signal SNR at the output.

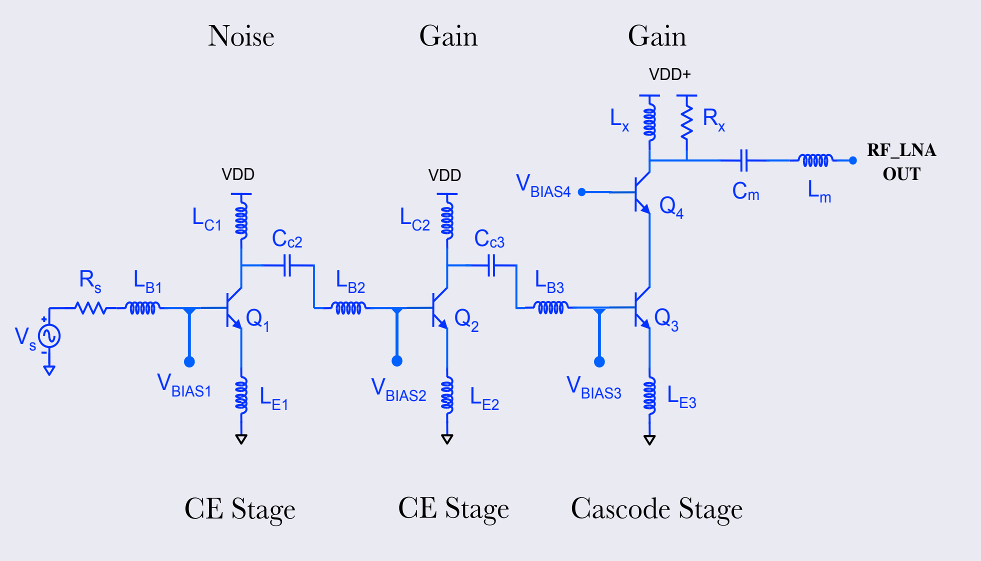
| Specifications | Value |
|---|---|
| Frequency band | 57-66 GHz |
| Bandwidth | **9 GHz** |
| Data Rate | **4.5 Gbps** |
| Modulation | OOK |
| Minimum sensitivity $S_{rx(min)}$ | - 49 dBm |
| Bit Error Rate (BER) | $10^{-12}$ |
| Target Power consumption | **150 mW** |
| Transmission Range | 20 cm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

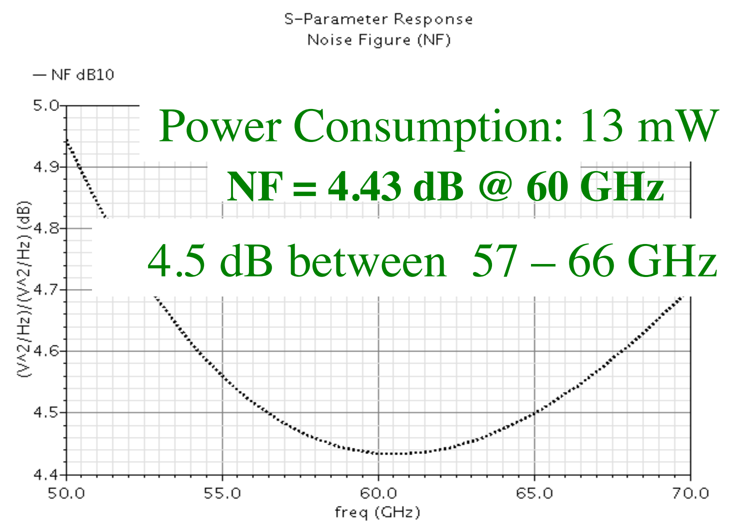
# 60 GHz LNA Simulations

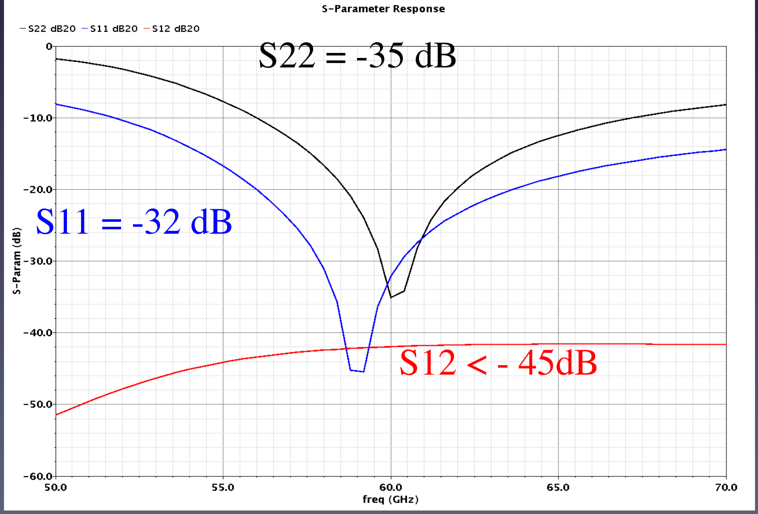
## S-Parameter Response all @ 60 GHz

$$NF_{IN} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \frac{NF_4 - 1}{G_1 G_2 G_3} + .... + \frac{NF_n - 1}{G_1 G_2 ... G_{n-1}}$$

S11 - Forward reflection (input match)
S22 – Reverse reflection (output match)
S12 - Reverse Transmission (leakage)



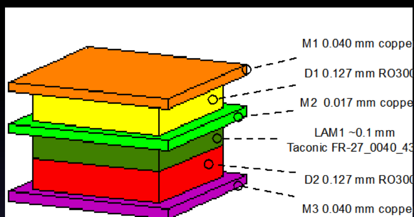



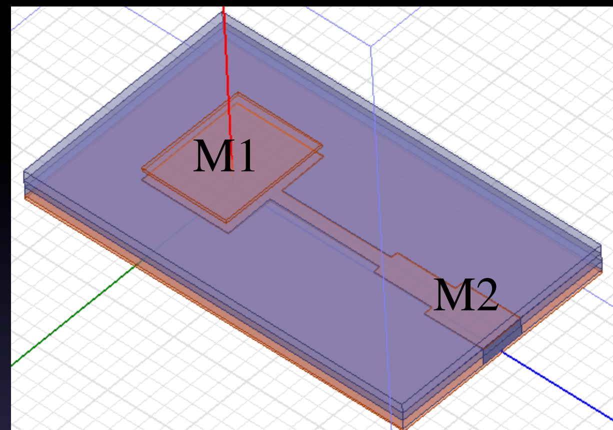



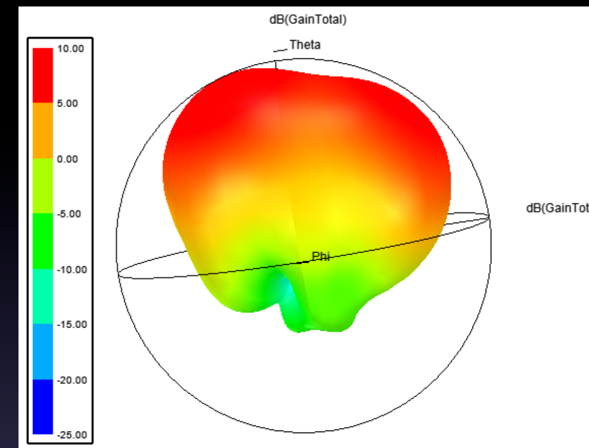
# 60 GHz broadband Antenna

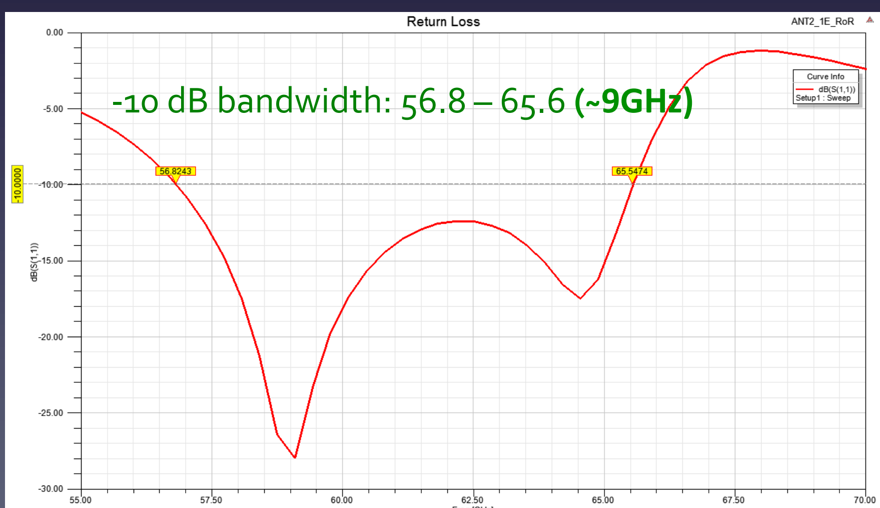
## Uppsala University

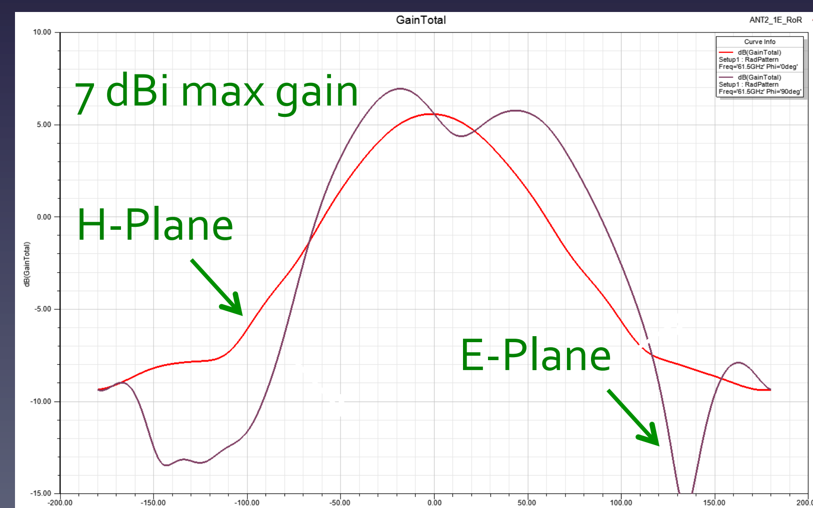
Multilayer Structure



# Time Domain 60GHz transceiver

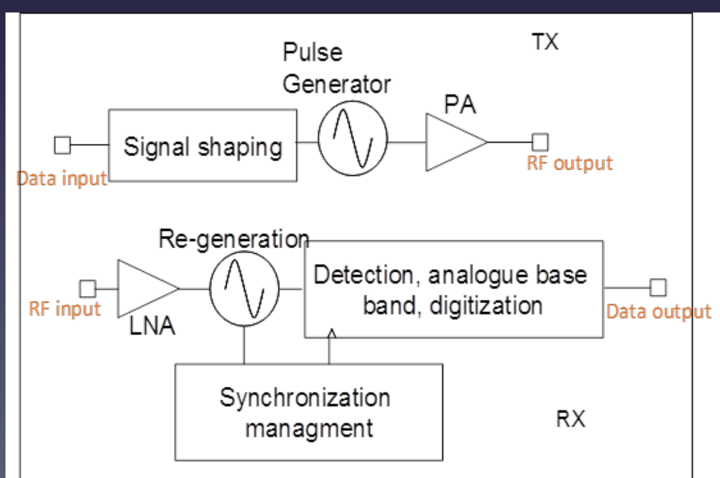
**Power consumption @ 2.5Gbps** (RFFE +DBB): TX 30mW, RX 70mW

**Range 0.2m meter with single antenna**

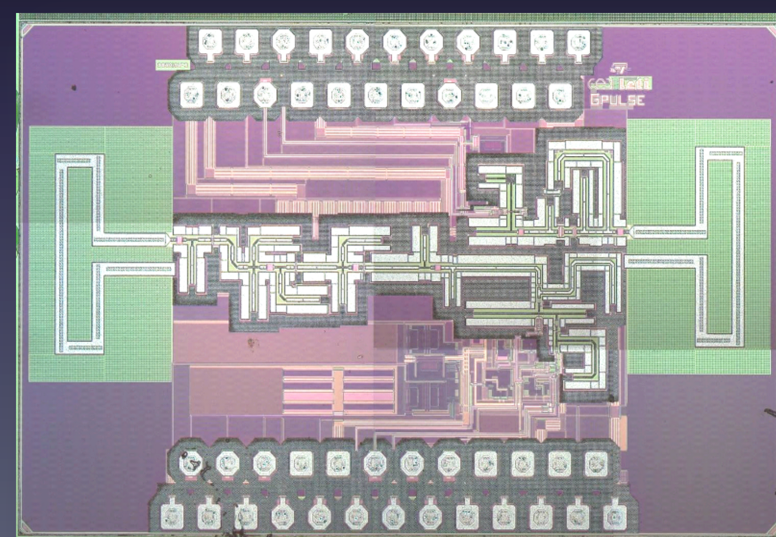
**Scalable data rate from 100Mbps to 2.5Gbps**

Integrated 4dBi 60GHz antenna (thanks to SOI 65nm HR process)

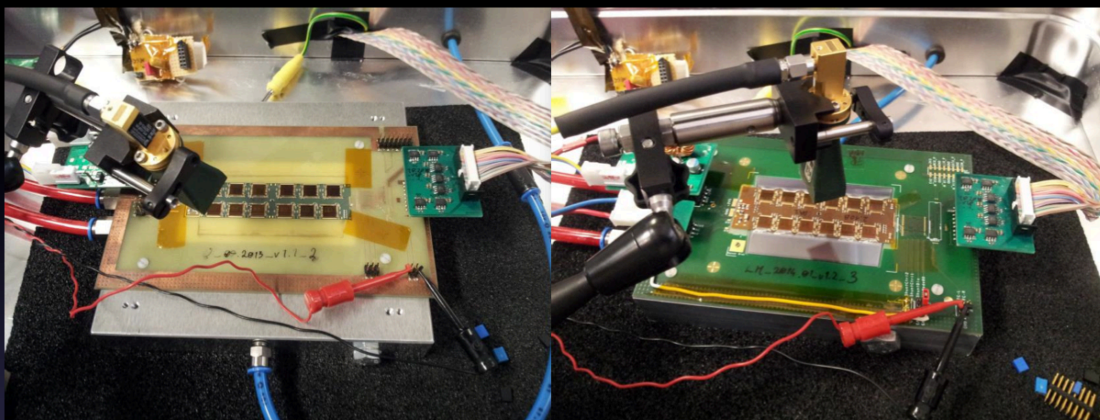
Very low cost (standard QFN package)



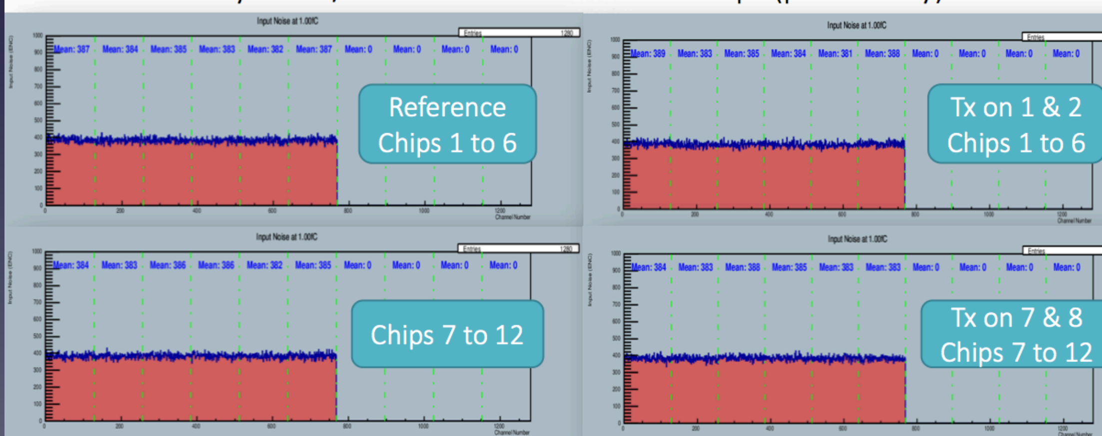

1,9mm x 3,1mm



# Heidelberg Test
## 60 GHz Irradiation



Hybrid w/o silicon – no influence on chips (preliminary)




✧ Tests done using ABC-next Hybrid for the upgrade of ATLAS endcap detector

✓ No influence of noise was measured

✓ Performance of detector **will not be degraded** by 60 GHz waves

No influence on transceiver chips working in the 60 GHz band from other chips in the vicinity are expected.

# Summary

- ✓ A third option (**Wireless**, Optical and Wire) readout are described.
- ✓ MmWave technology presented as a possible solution for current bandwidth limitations of LHC and maybe other detector facilities

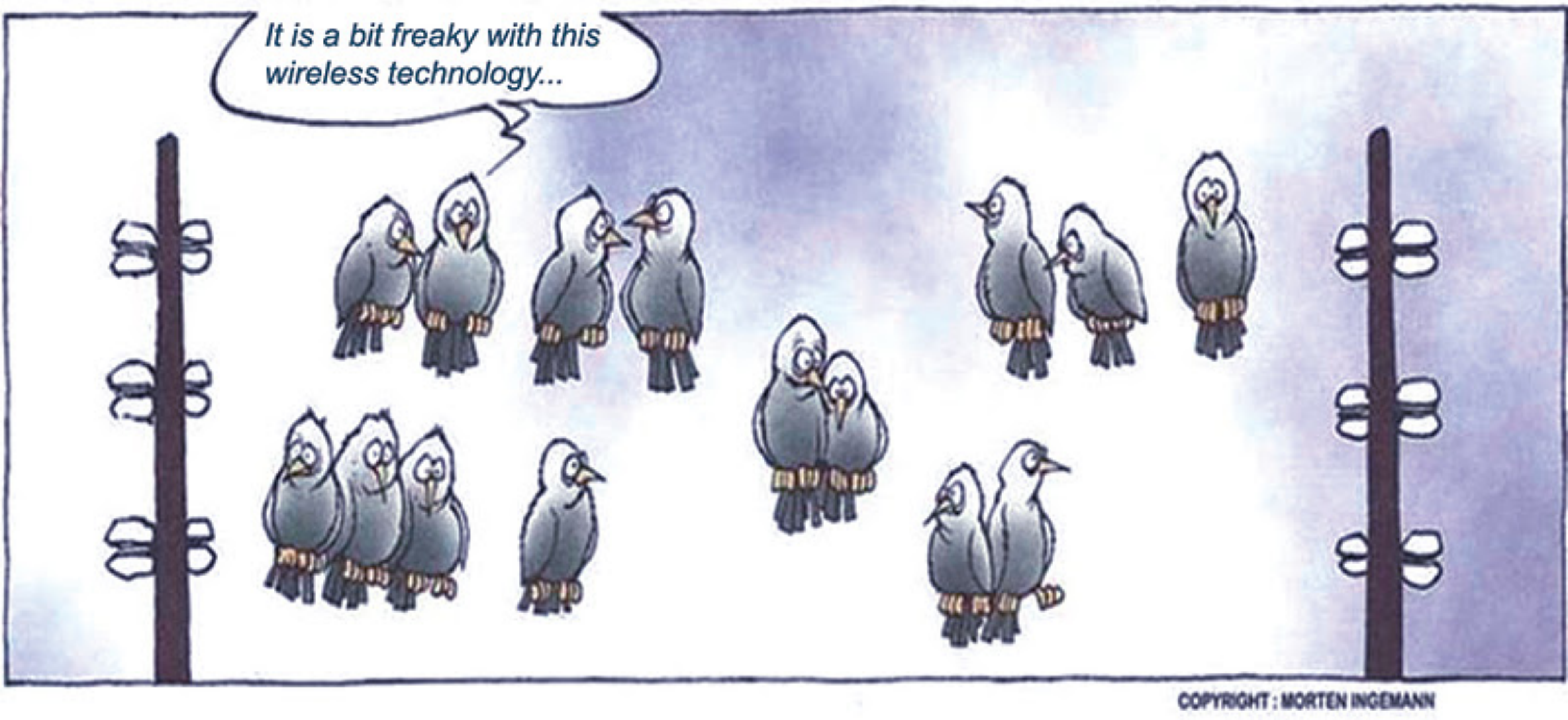
There is a lot and increasing interest for this development on different levels

**Technical Paper sent and evaluated by CERN Scientific Committee**

**LHCC Committee meeting Closed session May 11 2017**

**Final outcome/approval expected September/December 2017**

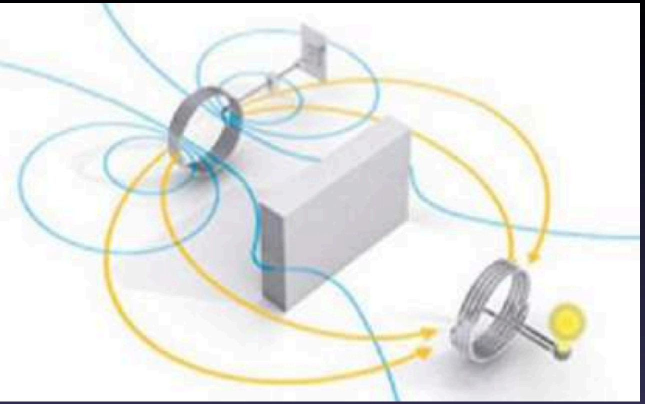
# Questions!


It is a bit freaky with this wireless technology...
COPYRIGHT : MORTEN INGEMANN

# Backup

# Wireless Electricity
## (WITRICITY)

Wireless power transmission is needed where instantaneous or continuous energy transfer but interconnecting cables are inconvenient (limited space), dangerous or impossible



### Magnetic resonant coupling:

Reduce cable pollution, such as cable number, material performance and power efficiency

- ✧ Medium range (room/detector size) 2-3 m

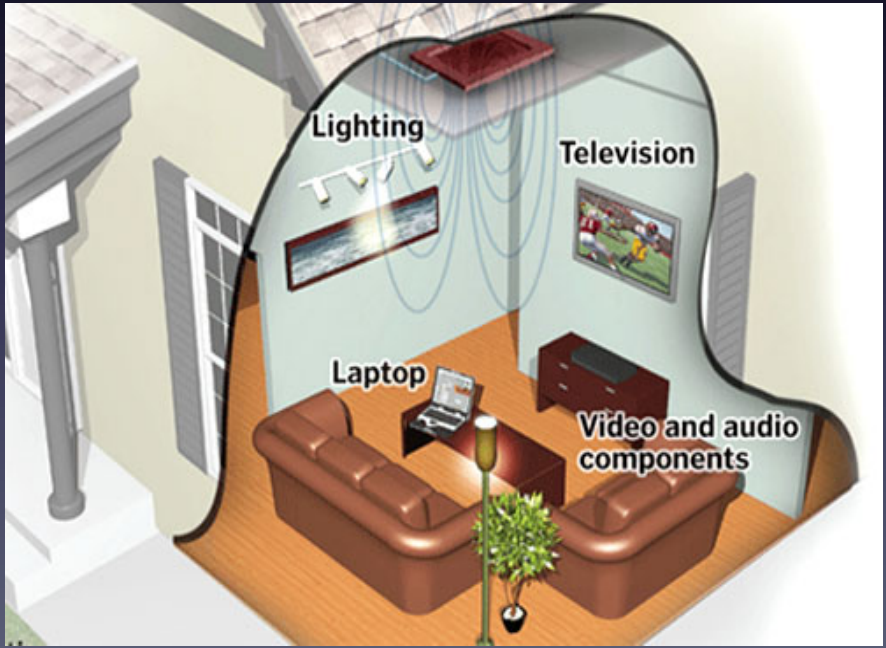
  Power robots, computers electronics
- ✧ No Realignment between source and device necessary
- ✧ One coil can recharge any device in that is in range, as long as the coils have the same resonance frequency
- ✧ Transfer power only when needed
- ✧ Efficiency in the 45 - 95 %


https://arxiv.org/vc/physics/papers/0611/0611063v1.pdf

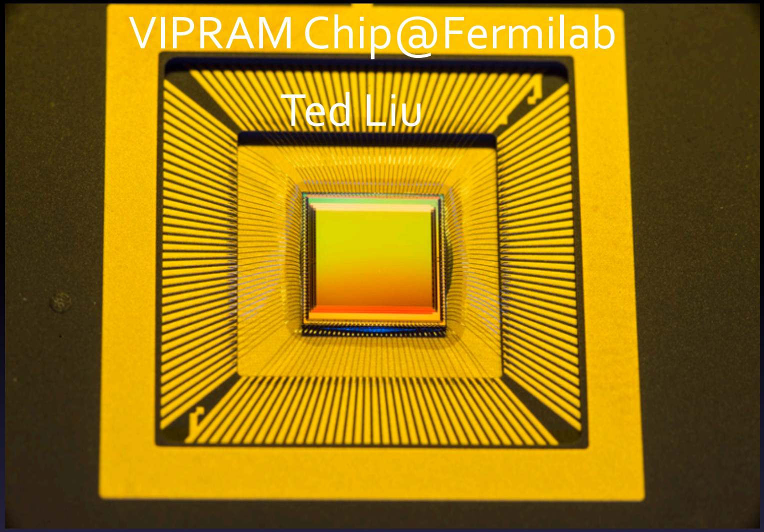
# Wireless Electricity
## (WITRICITY)

Applications:

- **Consumer electronics** – mobile device charge, wireless batteries, retail packaging….
- **Automotive** – In-vehicle mobile device charging
- **Industrial** – Wireless charging for robotics, direct powering of sensors
- **Medical** – through-the-skin charging for implantable devices



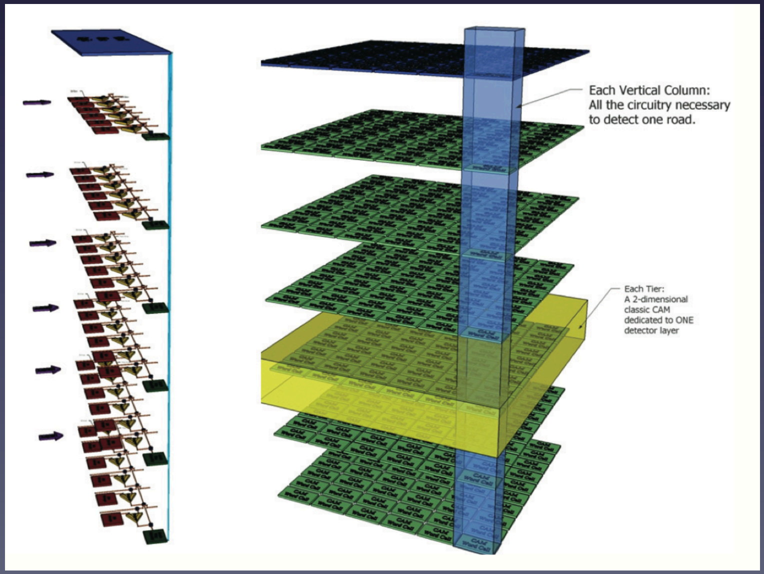
# Vertically Integrated Pattern Recognition Associative Memory (VIPRAM)



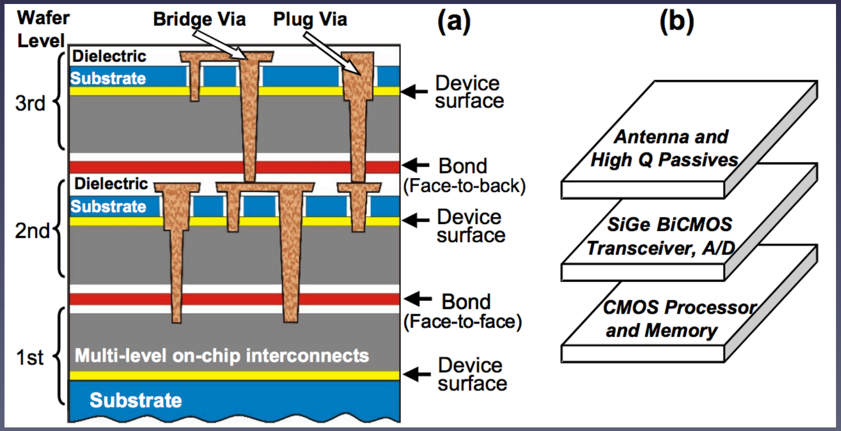

As Moore law is approaching is limits, it is expected that 3D will be the next scaling engine.

## Associative memory chip:

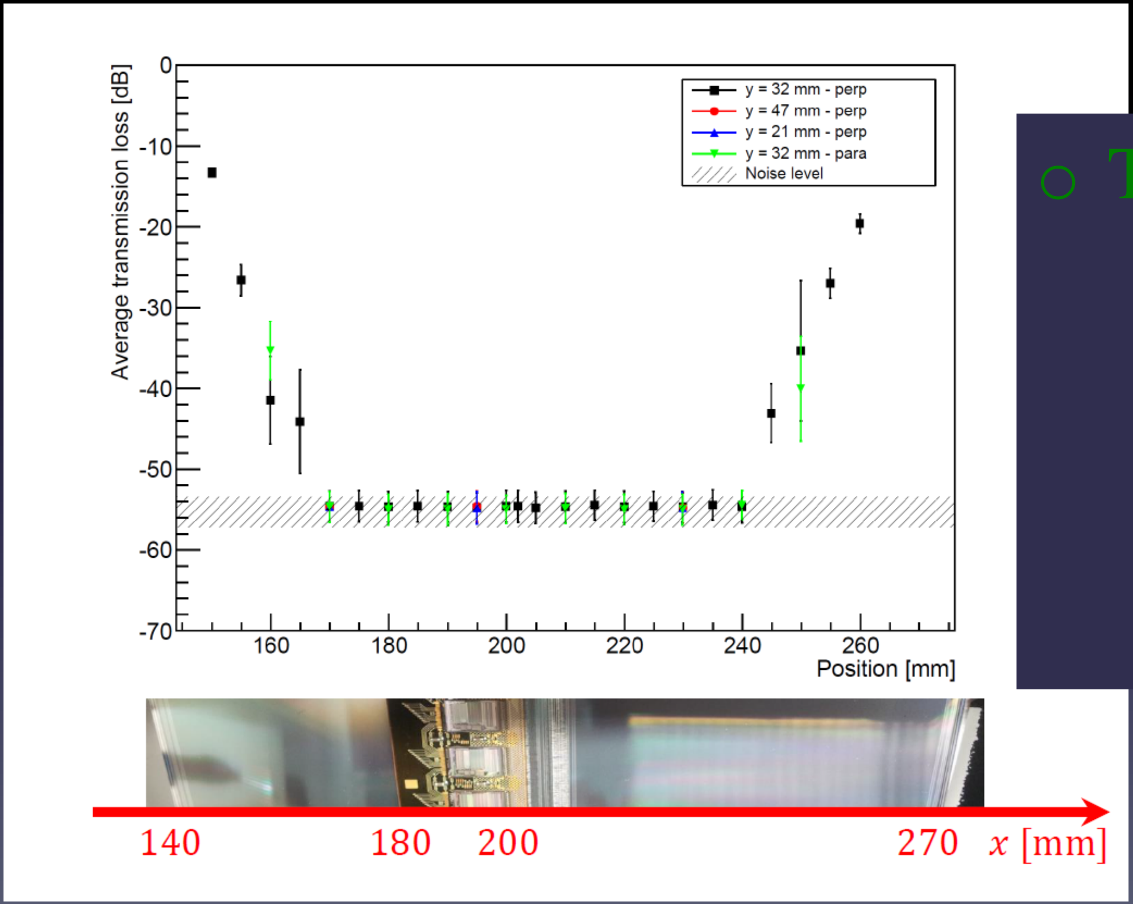
- Fast pattern recognition for fast track triggering at ATLAS and CMS




### Through Silicon Vias between VIPRAM and the Heidelberg Transceiver



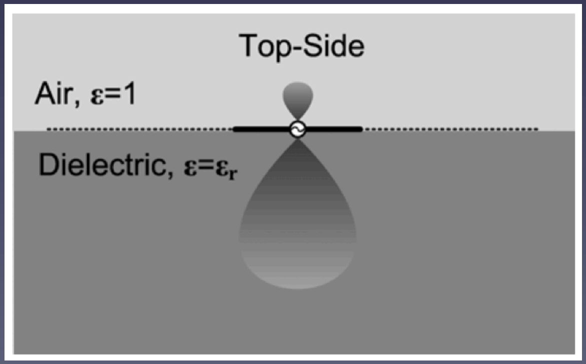
# Transmission: SCT Barrel Module

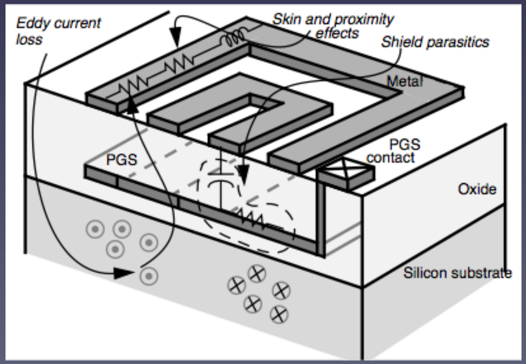


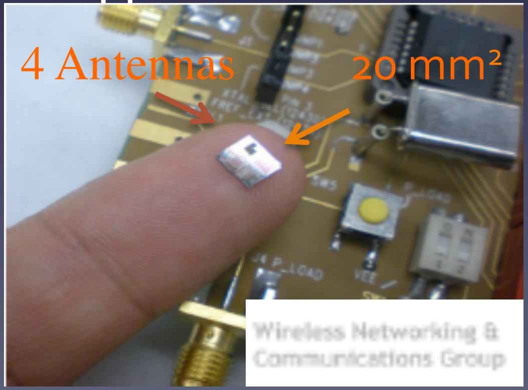

- Transmission Loss
  - $I_{loss} > 50$ dB
  - 60 GHz signals are fully reflected
  - Diffraction leads to transmission near edges.

# On-chip Antenna

- Small wavelengths at 60 GHz (5mm  λ/4=1.25 mm)
- Possible to integrate receive and transmit antenna(s) on chip.
- Multiple metal layers on ICs available
  - Can be used to fabricate mm-wave antennas.
- Eliminate cable/connectors loss and the need for ESD protection
- Cost effective compared to a packaged solution with off-chip antenna
- Issue: On-chip antenna in silicon has a very low radiation efficiency
  - High dielectric constant (11.7) and low substrate resistivity (10 Ohm-cm)
  - Energy loss due to magnetically induced current
  - Ohmic loss can be high, small skin depth (300nm) of copper at 60 GHz.



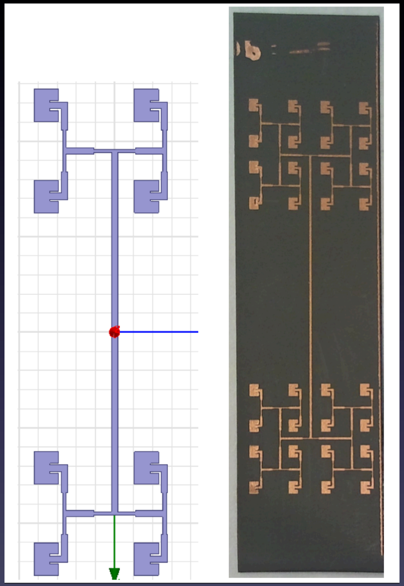



# Antenna Design

## Uppsala University

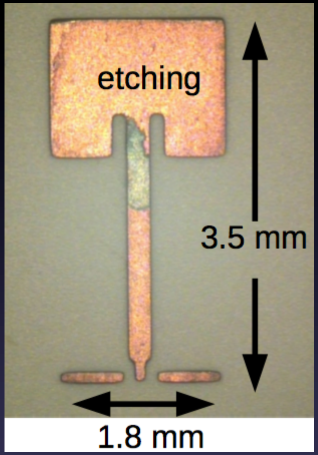
## Started to design and produce patch antennas



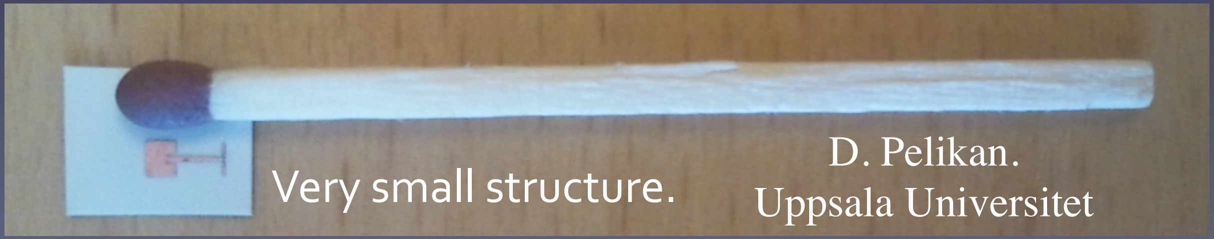
- Single and antenna arrays
- Can be produced on PCB material
  - Etching and milling.
  - Rogers, Dupont PCB material

## 1, 4 and 16 patch design

- Patches are connected by micro-strip transformations (Imp. Matching)
- Antenna arrays are connected by micro-strip







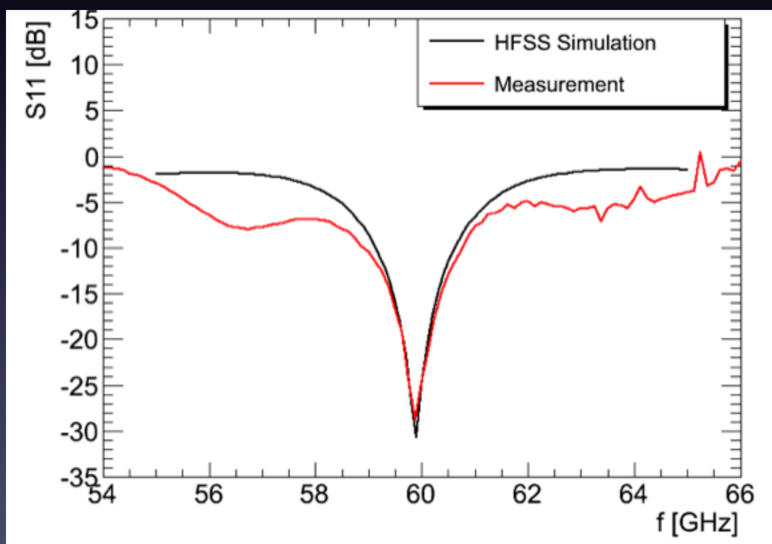
# Antenna Design

## Uppsala University

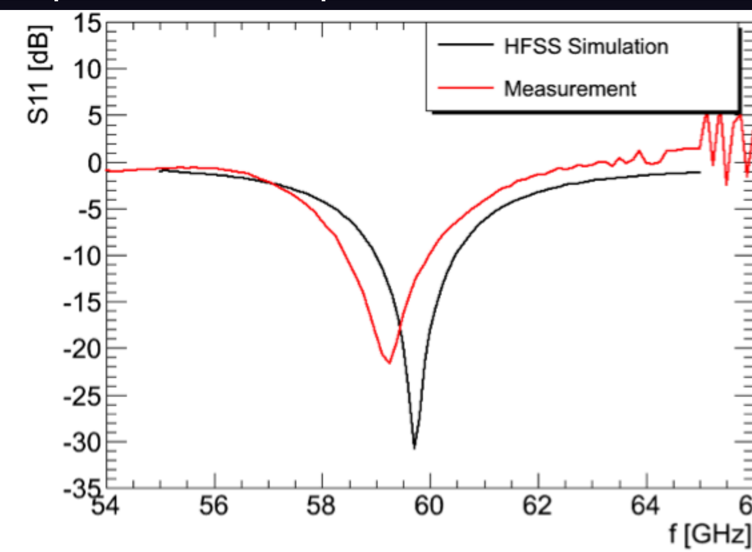
## Etched antennas were used (PCB etching process)

4 Patch Antenna array: Very good agreement with simulation
1 Patch Antenna: A shift of 500 MHz seen

Good results:  It shows that antenna production is possible




4 Patch design



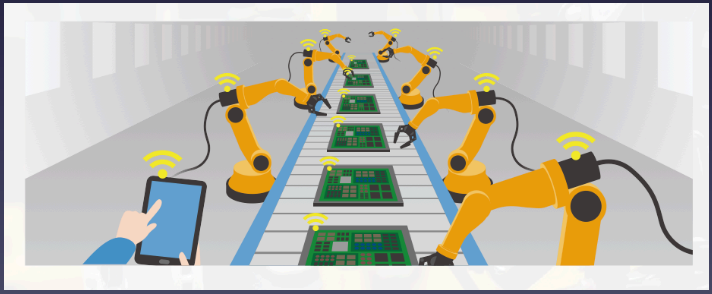

single patch design

Antennas that cover a broader bandwidth 9 GHz is under development

# Internet of Things/5G

Key drivers very Briefly summarized: mmwave band the frequency

- Mobile video traffic increases rapidly:
  - Virtual realilty
    - Virtual games, live sporting events, remote presentation…etc.
- Smart driving:
  - Internet of Vehicles
    - Reduce traffic accidents, save energy and reduce pollution
- Smart Manufacturing:
  - Industry revolution 4.0
  - Complete manufacturing chain connected
  - Production efficiency will drastically improve



- Health:
  - Latency – Remote surgery is very latency intolerant

Large bandwidth and low latency are required for real time, high quality image processing and spatial location. More than 20-50 Billion devices expected to be connected by 2020.

# System Specifications

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{TX} - PL(R) - L_{RX} - FM$$

$P_{RX}$ = RX Power (dBm)
$P_{TX}$ = TX Power (5 dBm)
$G_{TX}$ = Transmitter antenna gain (10 dBi)
$G_{RX}$ = Receiver antenna gain (10 dBi)
$L_{TX}$ = Transmitter losses (4 dB)
$L_{RX}$ = Receiver losses (4 dB)
FM = Fading Margin (3 dBm)
$PL(R)$ = Free space loss@20 cm(1m)= 48 (68 dB)

System operating margin:
15 dB