MULTI-GIGABIT WIRELESS DATA TRANSFER USING THE 60 GHZ BAND

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On behave of the WADAPT Working Group

Wireless Allowing Data And Power Transmission

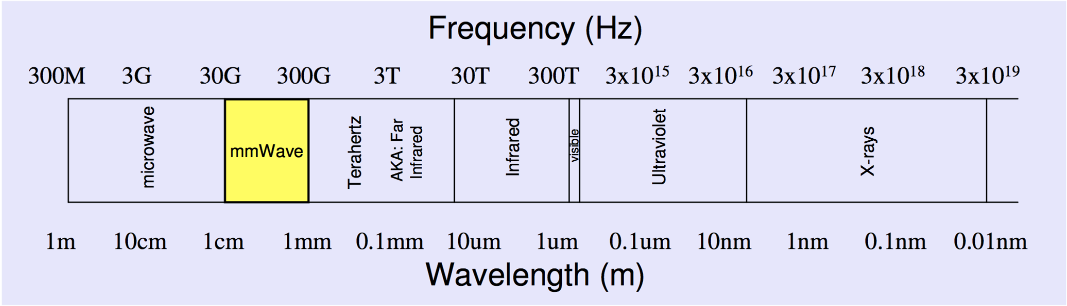
FCC-Week Rome 14-04-2016

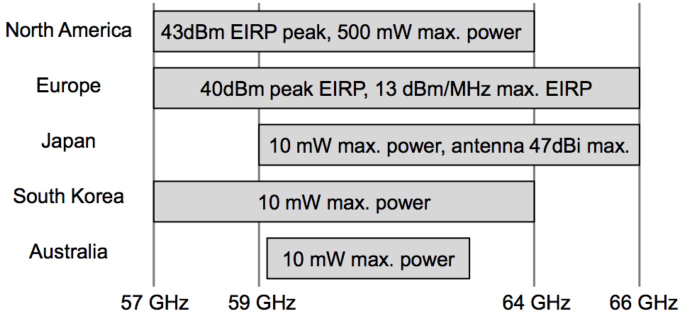
OUTLINE

- ✧ Introduction to millimeter Wave
- ✧ Features of the 60 GHz Band
- ✧ Practical Opportunities
- ✧ Application in HEP
- ✧ Proposed Readout Concept
- ✧ Current Development
- ✧ Summary and Outlook

The mm-Waveband

- 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)

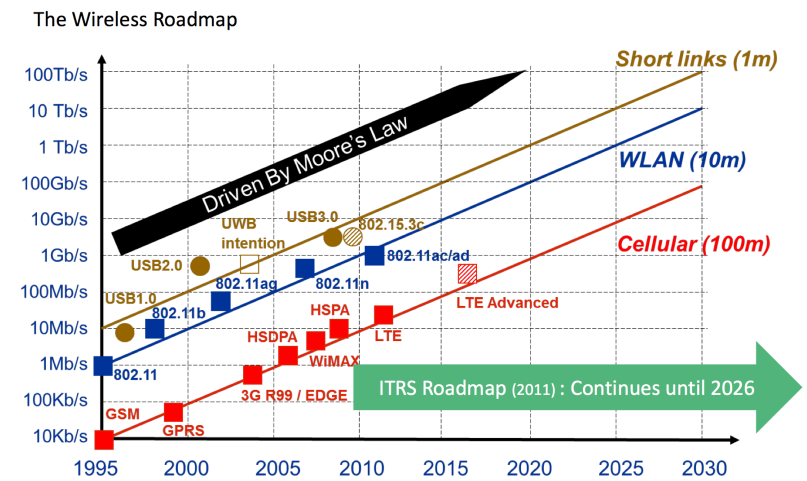




The mm-Waveband

✧ Demand for high capacity continues to increase with an incredible speed.

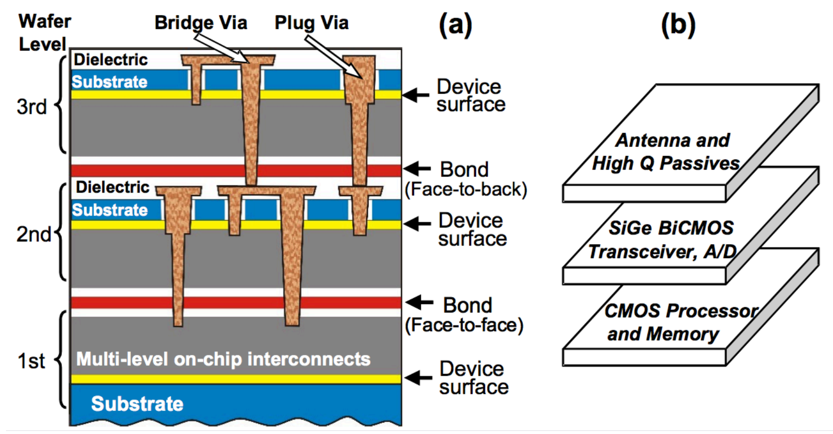
✧ An ongoing race: technology and application developers have pushed into higher and higher bandwidth.



Performance driven applications and high level of integration:

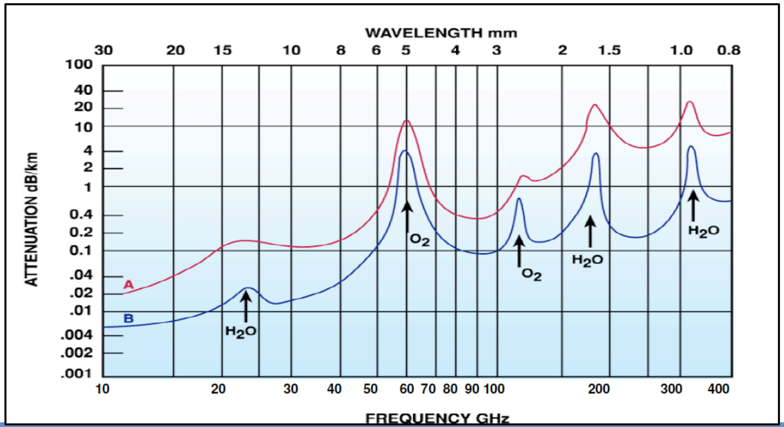
✧Heterogeneous Integration advantage

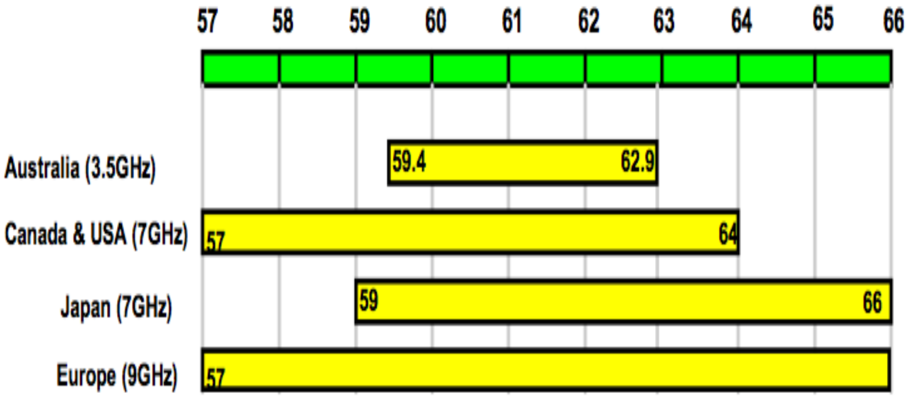
✧ Allow to use technology optimized according to their function



Features of the 60 GHz Band

- ✧ Unlicensed Spectrum: 4-9 GHz bandwidth available world-wide
- ✧ Can send Gigabits/s of data over short distance (0-10m)
- ✧ 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
- ✧ Mature techniques: Long history in being used for secure communication.





Features of the 60 GHz Band

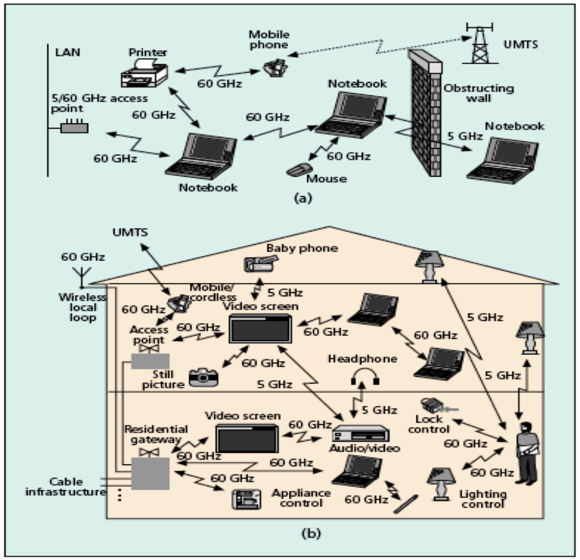
- Unlicensed Spectrum: 4-9 GHz bandwidth available world-wide
- Can send Gigabits/s of data over short distance (0-100m)
- Highly secure and low interference probability: Short transmission distance, oxygen absorption, narrow beam width and attenuation through materials.
  - Reuse of frequency
- Placement: High flexibility, reduced complexity of cabling, material budget.
- High frequency: Small form factor.
- High transmit power: 40 dBm EIRP
- Mature techniques: Long history in being used for secure communication.

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, low material budget and radiation hardness

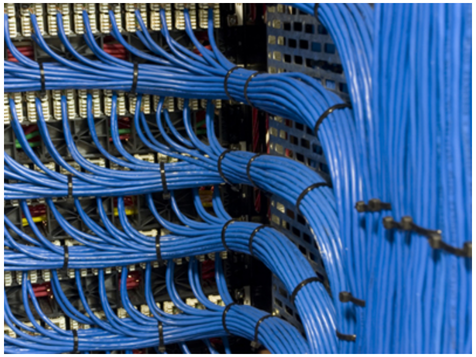
makes the 60 GHz band an **excellent choice** for high data transfer in a closed short range environment as the **detector environment**.

Practical Opportunities

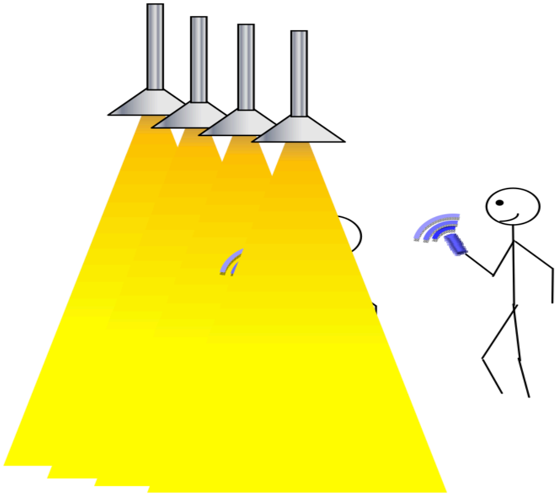


- ✧ Interconnectivity of media devices
- ✧ High data rates, fast file transfers
- ✧ Streaming uncompressed HD content

Replace Gigabit Ethernet Cables



“Showered” with information

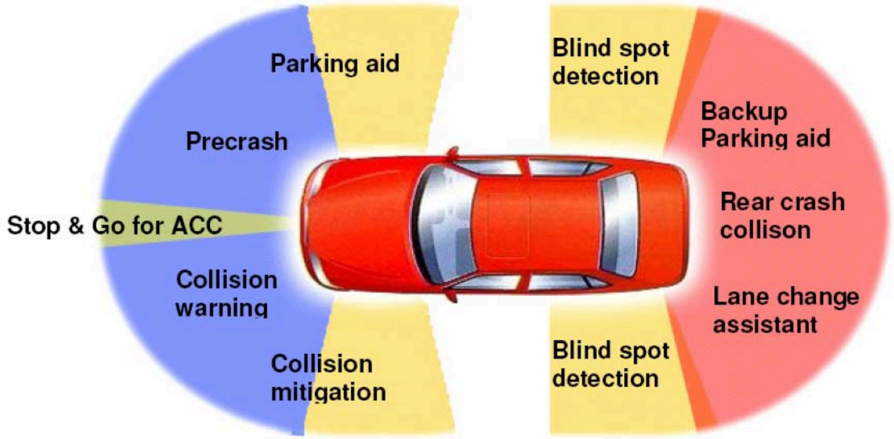


- ✧ Access points could be mounted on ceilings, walls, doorways, vehicles
- ✧ Massive Gbps data transfer while moving through a small area

Practical Opportunities

Automotive and the medicine industry plays a more and more important role for this kind of development

Automotive radar: 77 GHz



In-flight Entertainment:

- Do not interfere with other aircraft communications

Satellite communication:

- Outside atmosphere
  - No free space path loss
  - Line-Of-Sight

Intra vehicle communication:

- Inability to penetrate and interfere with other vehicle networks

Vehicle to Vehicle:

Applications in HEP

ATLAS Silicon Micro-strip Tracker upgrade would require:

✧ Bandwidth of 50 -100 Tb/s

✧ 20 000 links at 5 Gb/s

without increasing the

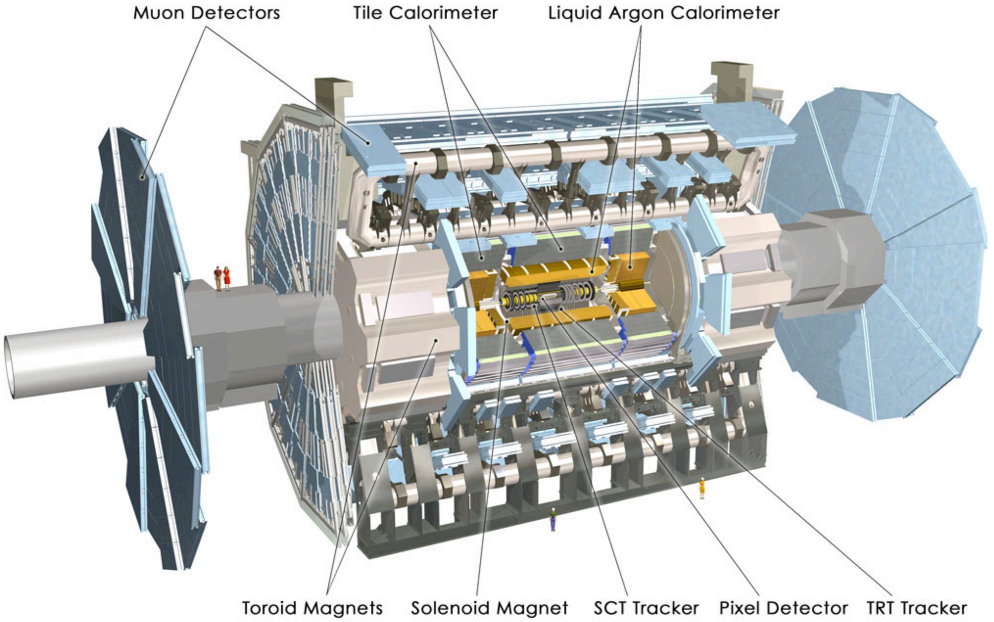
✧ Material budget

✧ Power consumption

✧ Space for services

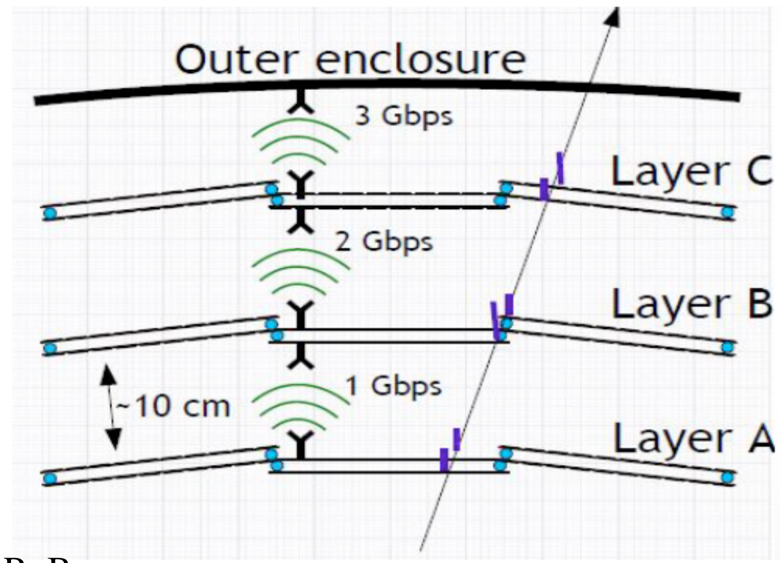
and in addition

✧ Contribute to the fast trigger decision



Applications in HEP

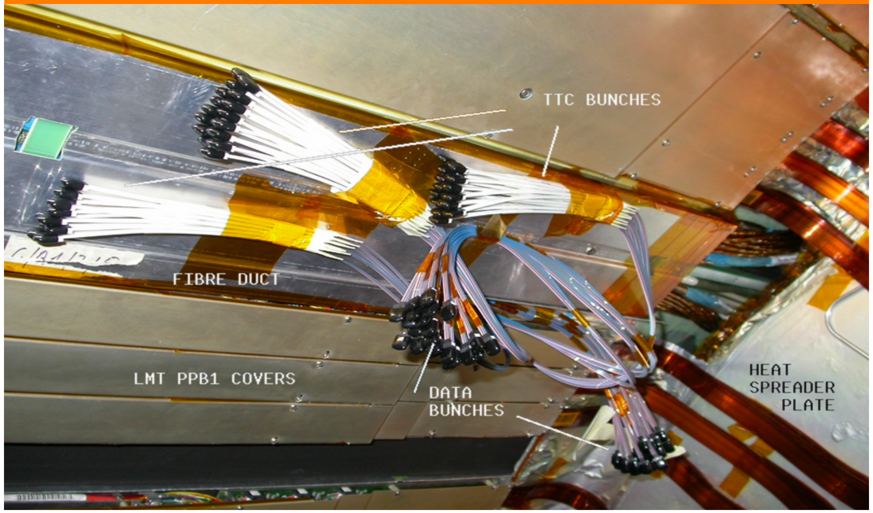
- Today the data are readout perpendicular to the particle path.
- Static system with Line-of-Sight (LOS) data transfer communication
- Approach: Readout radially by sending the data through the layer(s) by wire/via connection, with an antenna on both sides.



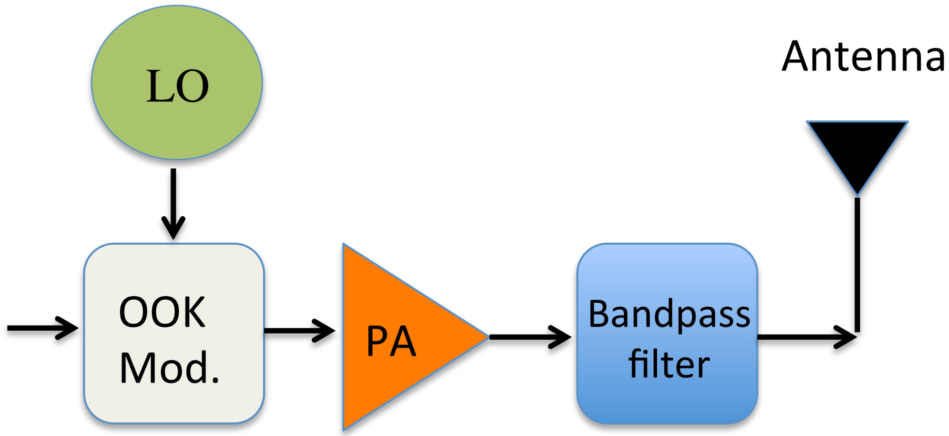
R. Brenner

Less cables and Connectors

Reduce Material Budget



Heidelberg Chip

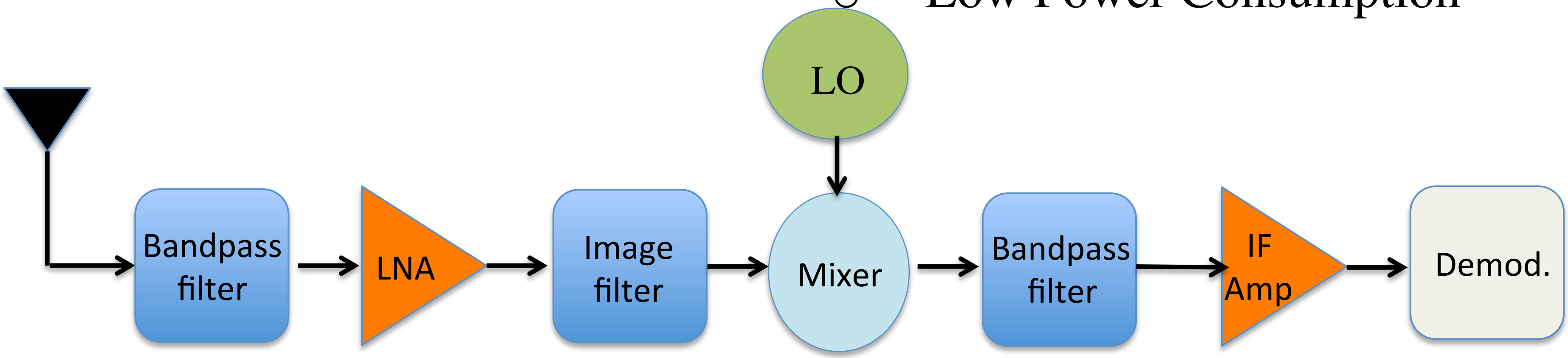


Transmitter:

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

Receiver:

- Balance gain, linearity and NF
- Low Power Consumption



Technology

- 130 nm SiGe-Bi-CMOS
- SiGe NPNs, We = 120 nm, ft = 200 GHz, BVceo = 1.8V
- 130 nm CMOS FETs 1.5/2.5V

High Integration level

- Fully-characterized Millimeter Wave Passive Elements
    - Resistors, Varactors, MOS, MIM-caps, inductors, Transmissions lines, etc.
- Silicon On Insulator (SOI)
    - Isolation in the gigahertz range

For the future development and final choice of technology will depend on given specifications

Fundamental Data Capacity

Shannon's Theorem

Shannon's theorem gives an upper bound to the capacity of a link, in bps, as a function of the available bandwidth and the SNR

Increase data rate:

- ✧Spectral Efficiency
  - Complexity, Power consumption
- ✧Bandwidth (B)
- ✧Signal-to-Noise-Ratio (SNR)

$$C = B \cdot \log_2\left(1 + \frac{S}{N}\right)$$

C = Channel capacity in b/s

B = Bandwidth in Hz

S = Signal in Watts

N = Noise power in watts

High Bandwidth:

Spectral efficiency not a dominant factor

Can trade bandwidth for complexity

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.

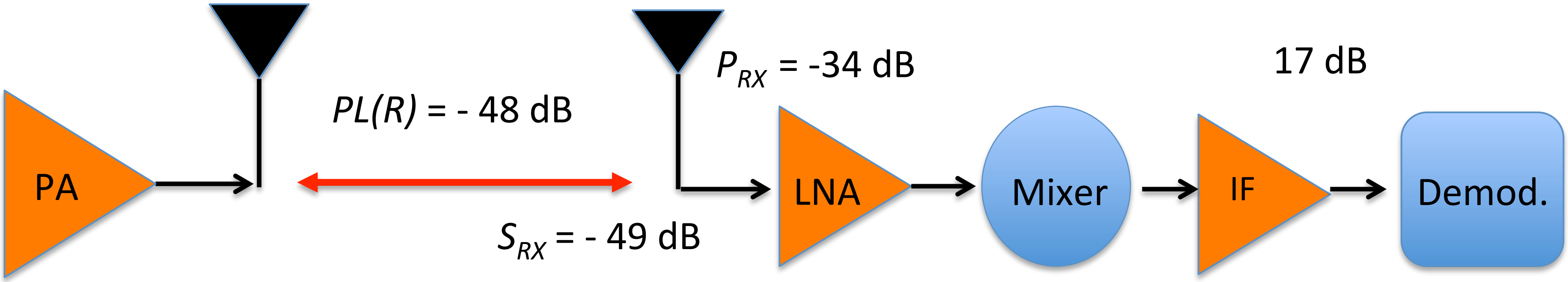
Specifications	Value
Frequency band	57-66 GHz
Bandwidth	**9 GHz**
Data Rate	**4.5 Gbps**
Modulation	OOK
Minimum sensitivity $S_{rx(min)}$	- 49 dBm
Bit Error Rate (BER)	10^{-12}
Target Power consumption	**150 mW**
Transmission Range	20 cm (1m)

Link-Budget

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

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

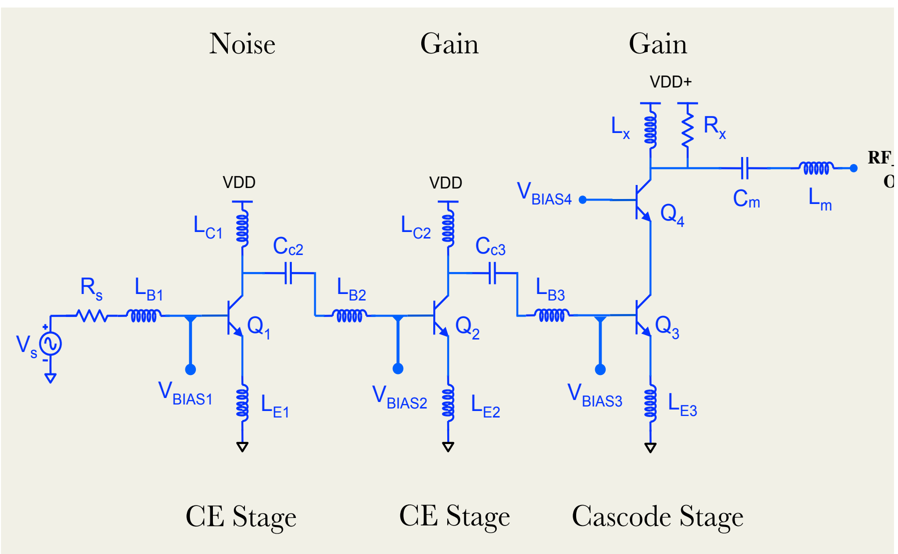


Low noise Amplifier

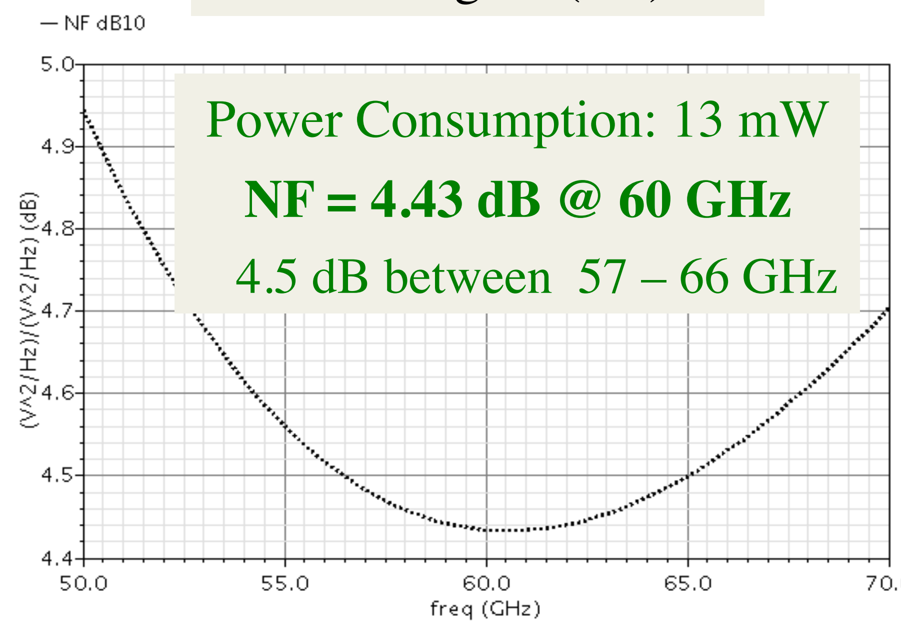
H.K. Soltveit

- Sets the lower limit of the system
- Optimized for NF and Gain

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



S-Parameter Response
Noise figure (NF)



Power Consumption: 13 mW

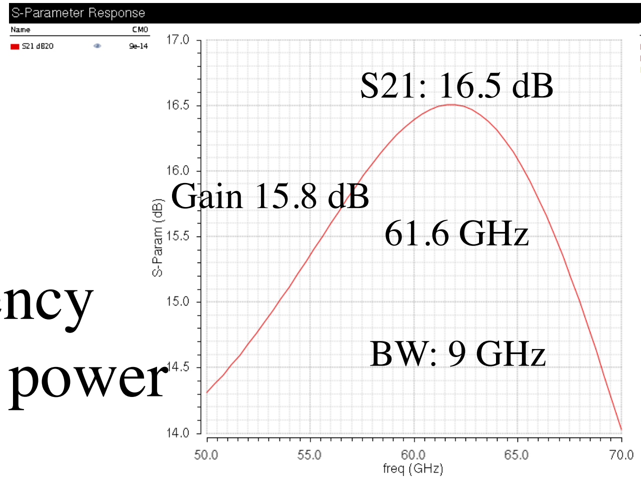
NF = 4.43 dB @ 60 GHz

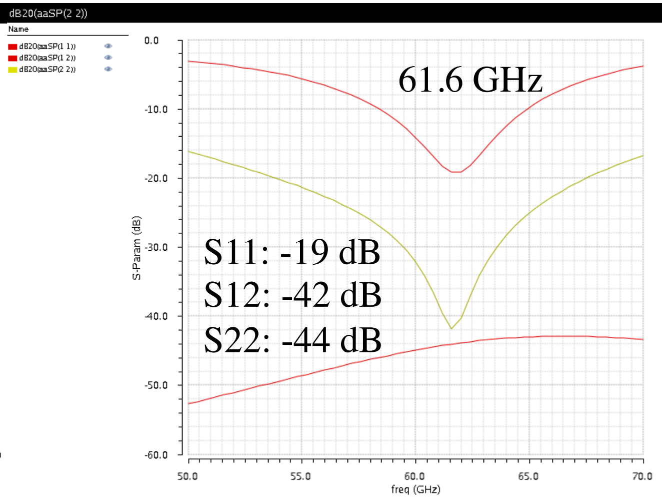
4.5 dB between 57 – 66 GHz

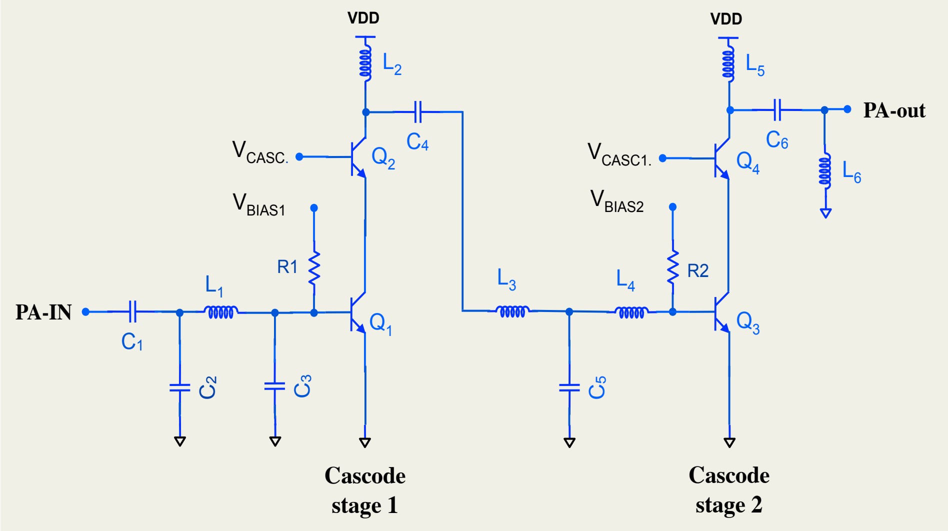
Power Amplifier

H.K. Soltveit

- Drives the antenna
- Isolation
- Power Added Efficiency
- Provide the required power level







Peak Frequency: 61.6 GHz

- ✓ S12 and S22 << -10 dB (57 – 66 GHz)
- ✓ S11 = - 8 dB
- ✓ S21 = 16.5 dB with +- 0.8 dB
- ✓ P1dB = 5 dBm
- ✓ Power consumption 60 mW

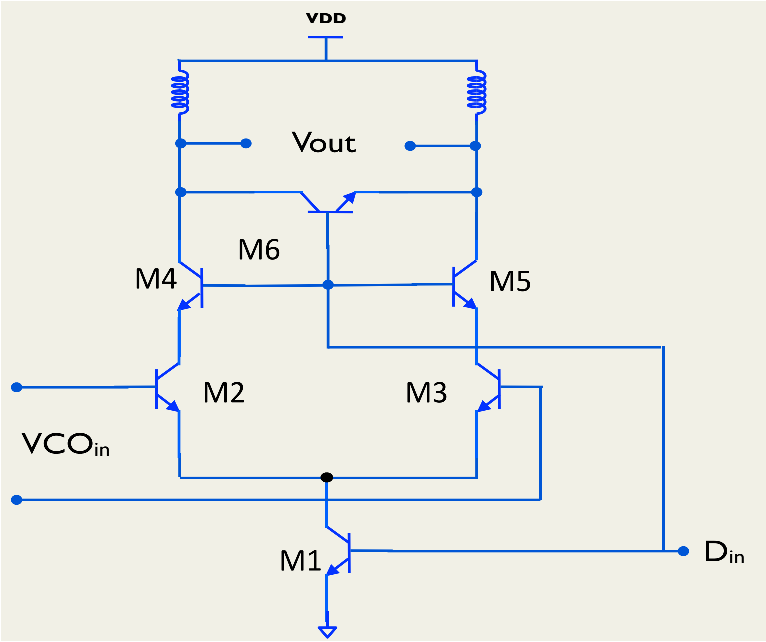
On-Off keying Modulation

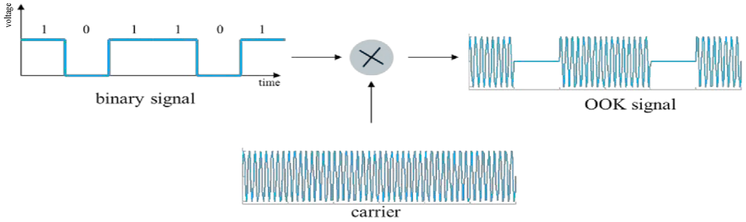
- ✧ System bandwidth
- ✧ Sensitivity
- ✧ Spectral efficiency
- ✧ Complexity

Spectral efficiency: 0.5 bps/Hz

But

- ✧ Non-coherent demodulation
- ✧ Simple implementation
- ✧ Use non-linear PA
- ✧ Little power consumption
  - Constant envelope (no Amplitude Var.)





Preliminary Power Estimate

More blocks under development, too early to show their characteristic behavior.

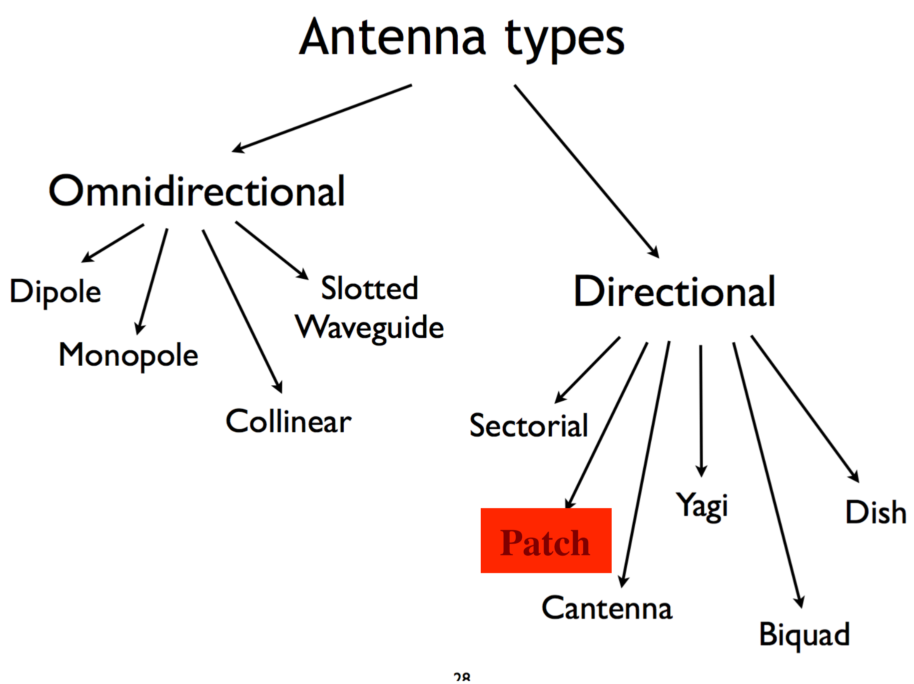
Low Noise Amplifier:	13 mW
Gilbert Mixer:	7 mW
Local Oscillator:	20 mW
Intermediate Amplifier:	10 mW
Modulation Scheme:	20 mW
Demodulation Scheme:	20 mW
Power Amplifier:	60 mW
Total Power Consumption:	**150 mW**

Data rate:	4.5 Gbps
BER:	10^{-12}
Bandwidth:	9 GHz
Distance:	20 cm (1m)

Still room for Power Consumption optimization

Antenna Design

- ✧ Passive component and do not generate power
- ✧ Rely on antenna gain to close the link budget
- ✧ Largest part of the transceiver



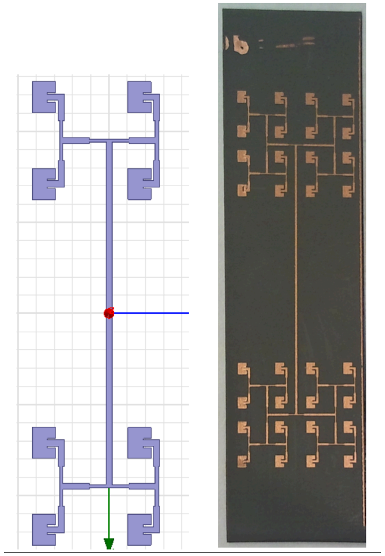
Antenna requirement:

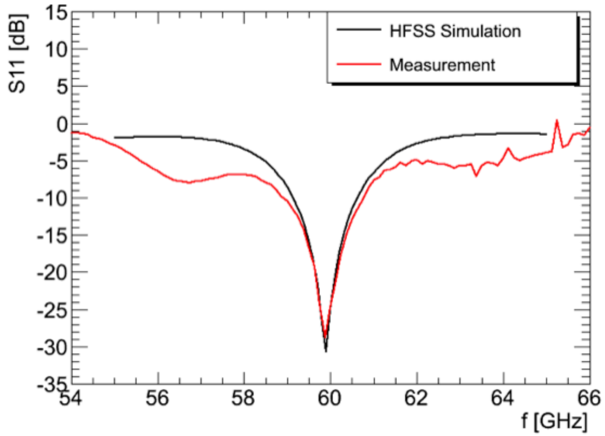
- ✧ Light weight
- ✧ Compact
- ✧ Reproducibility
- ✧ Easy to fabricate
- ✧ Cost

Antenna Design

Started to design and produce patch antennas

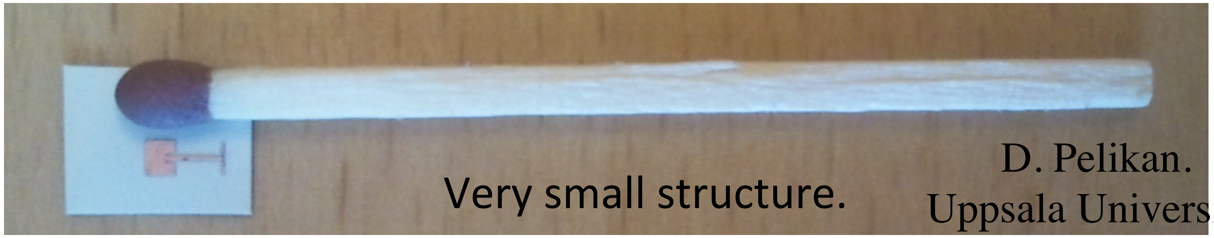
- Single and antenna arrays
- Can be produced on PCB material
  - Etching and milling.
  - Rogers, Dupont PCB material

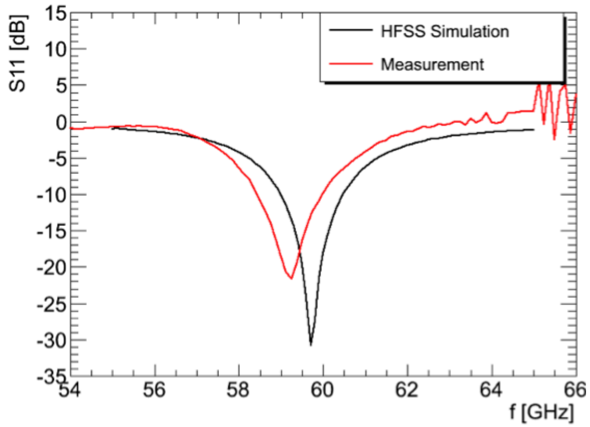




1, 4 and 16 patch design

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

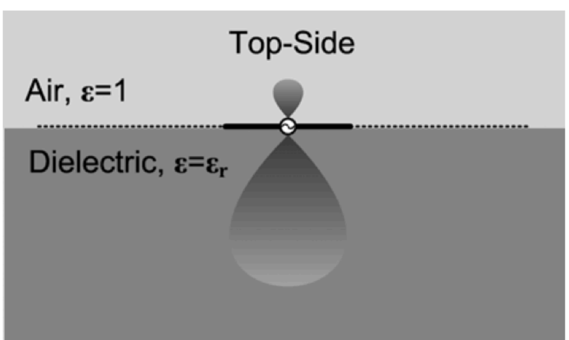


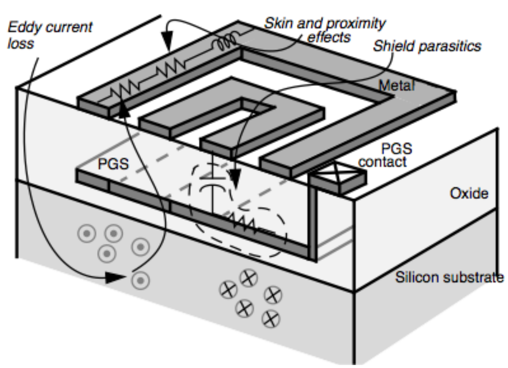


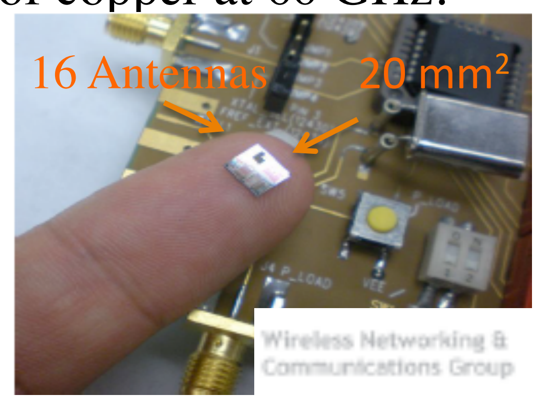
single patch design

On-chip Antenna

- Small wavelengths at 60 GHz (5mm $\lambda/4=1.25$ 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.







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-2 Gbps	~70-100mW	prototype
E-band Backhaul	No standard	100-200m with lens	1-8Gbps	NA	Some IPs

Time Domain 60GHz transceiver

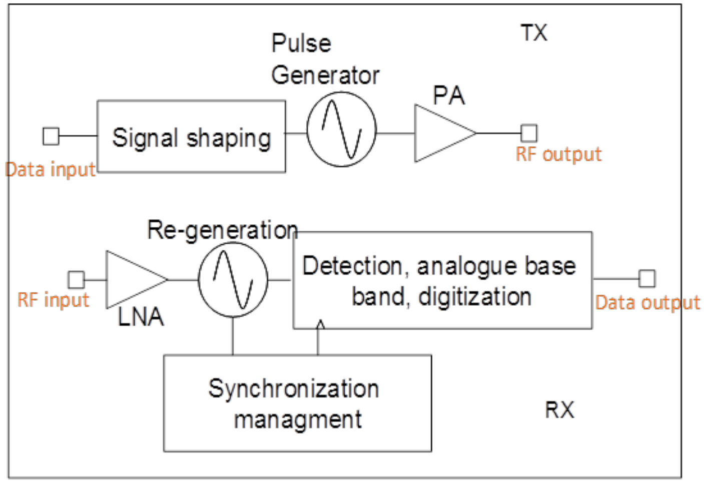
Power consumption @ 2.5Gbps (RFFE +DBB): TX 30mW, RX 70mW

Range 0.2m meter with single antenna

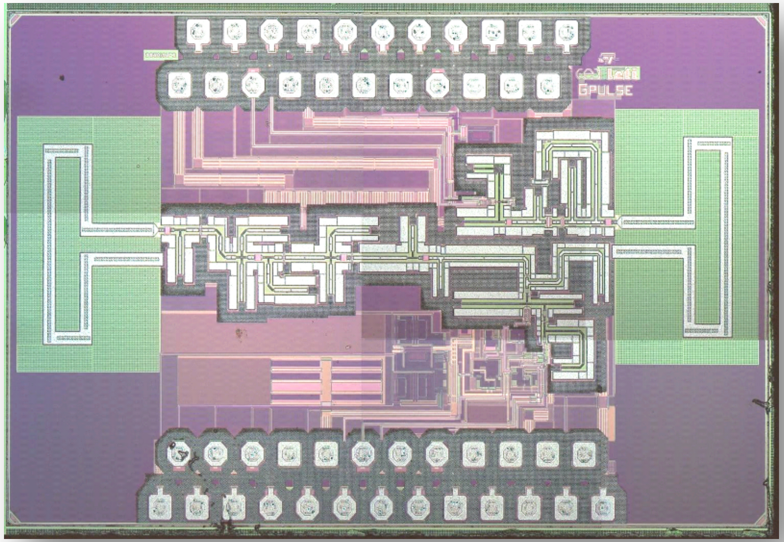
Scalable data rate from 100Mbps to 2.5Gbps

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

Very low cost (standard QFN package)

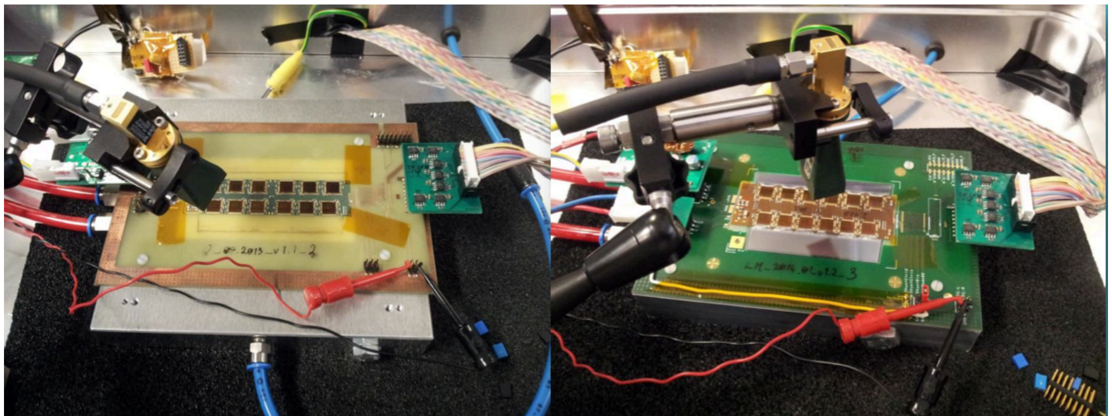


1,9mm x 3,1mm

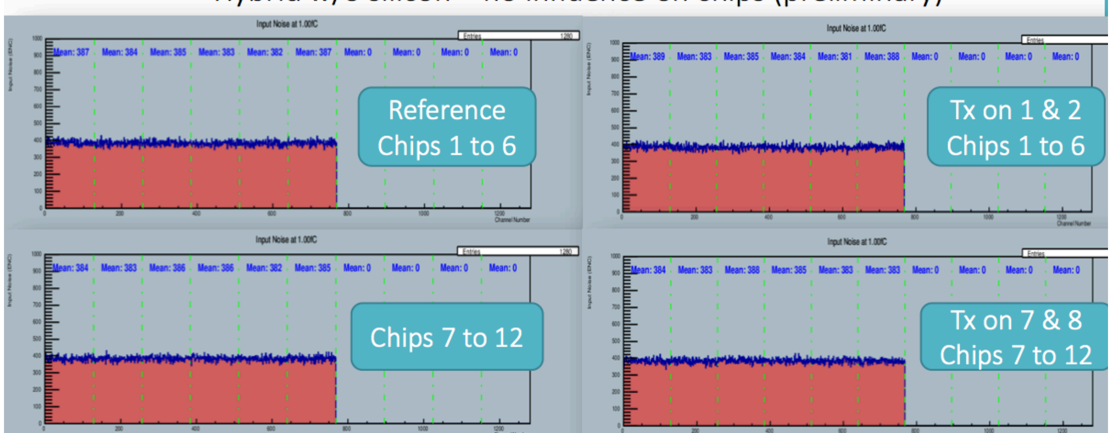


Feasibility studies
@
University of Heidelberg

Detector performance under 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 degrade** by 60 GHz waves

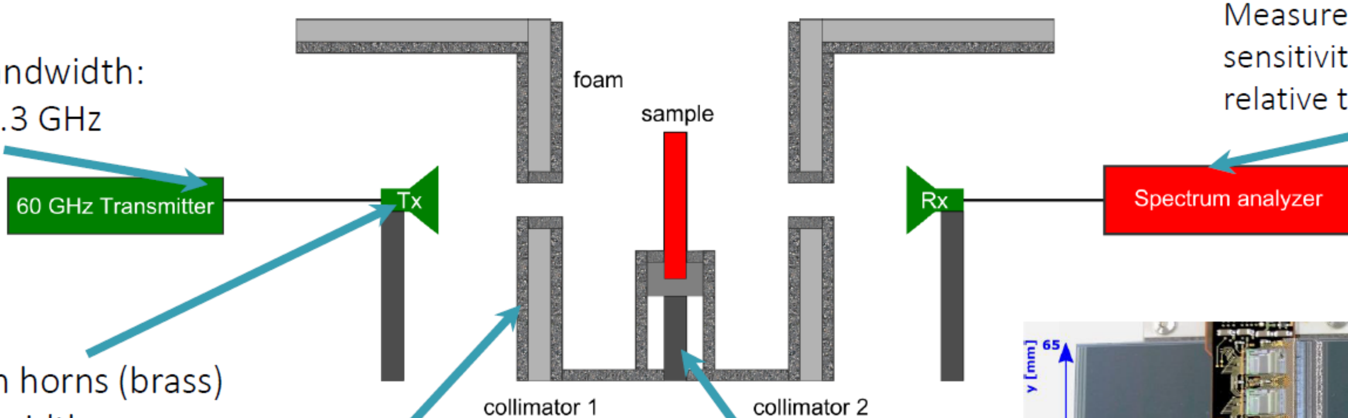
S. Dittmeier

Transmission:
SCT Barrel Module

Transmission through detector modules

Tested bandwidth:
57.3 – 61.3 GHz

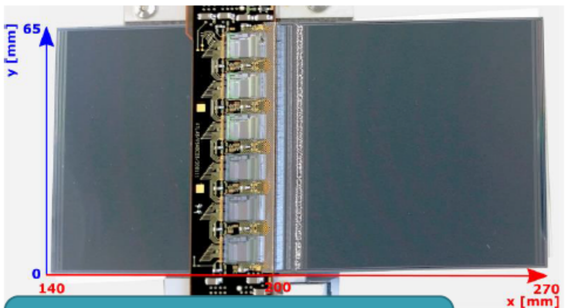
Measure power in RF sensitivity of $\approx -55\text{dB}$ relative to transmitter



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

Aluminum and graphite foam shielding against reflections

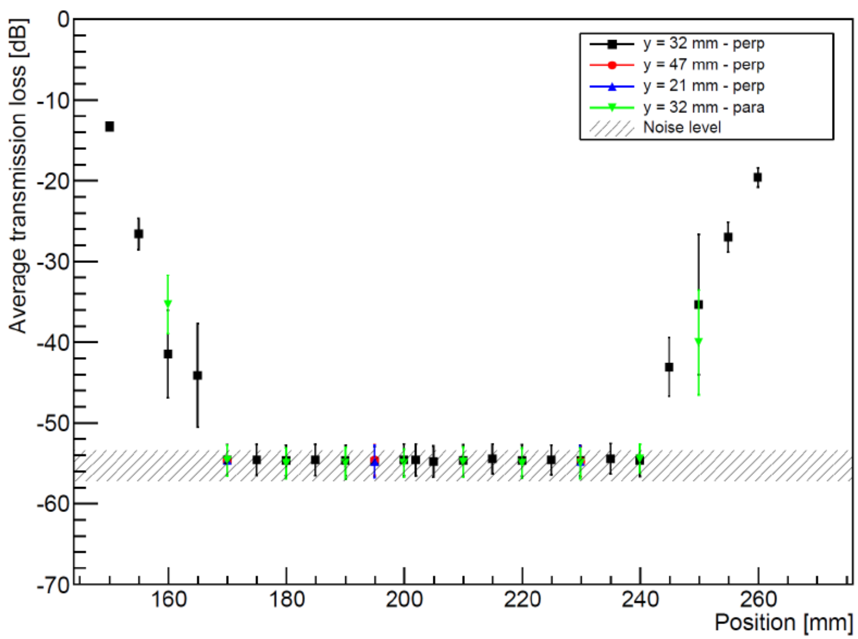
Rail and post holder to move sample



ATLAS SCT Barrel Module
R.Brenner (Uppsala)

S. Dittmeier

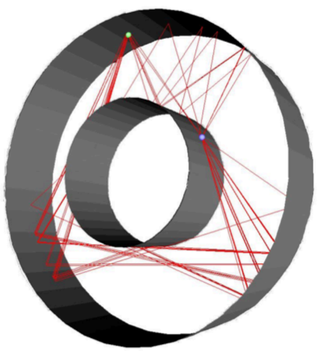
Transmission: SCT Barrel Module



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

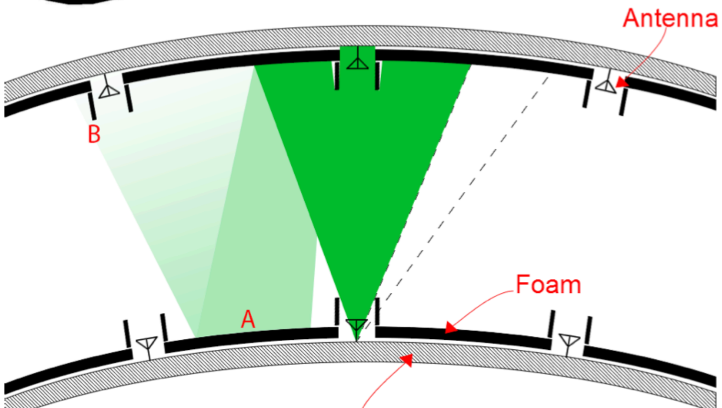
S. Dittmeier

Crosstalk



Simulations with a ray tracer have shown
(B.Sc. Thesis by Thomas Hugle)

In a highly reflective environment, directing and / or shielding the signal is essential

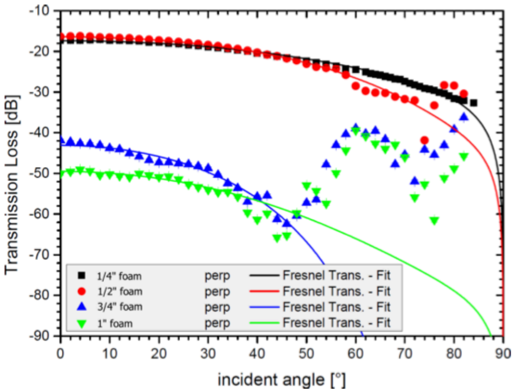


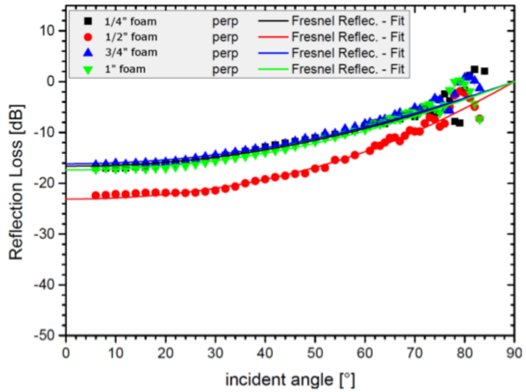
- ✧ How to avoid crosstalk?
  - ✧ Absorption of reflections
  - ✧ Directive antennas
  - ✧ Linear polarization
  - ✧ Frequency channeling
- ✧ Signal pickup:
  - ✧ Detector electronics
  - ✧ Transceiver

S. Dittmeier

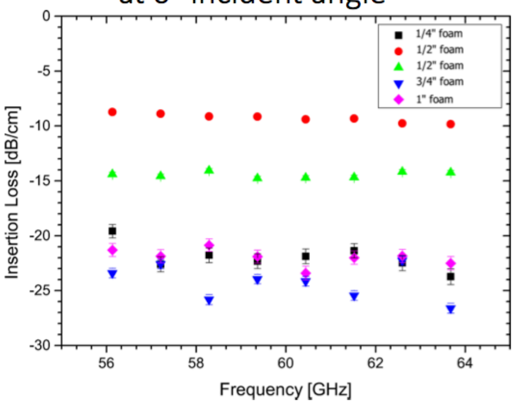
Graphite Foam

fixed frequency: f = 60.721 GHz





Frequency dependence
at 0° incident angle



Foam sample

- ✓ Transmission reduced by > 15-20 dB
- ✓ Reflections reduced by > 10 dB up to large angles
- ✓ Absorption (20 dB/cm) to reduce transmitted intensity, stable over frequency
- ✓ Low density material: p = 50 – 70 mg/cm³

S. Dittmeier

Summary and Outlook

- ✓ mmWave technology presented as a possible solution for current bandwidth limitations of LHC and other detector facilities

- ✓ Feasibility studies has shown that the **Performance** of detector modules will **not** be degraded by 60 GHz waves

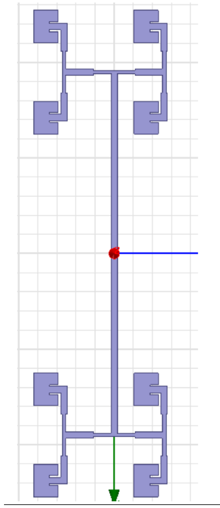
- ✓ Readout options: Wire, optical and **Wireless**

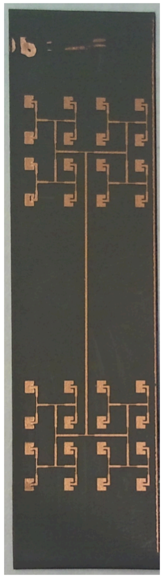
Heidelberg Wireless 60 GHz Chip submission is forseen Nov. 2016

Back-Up

Antenna Design

Started to design and produce patch antennas

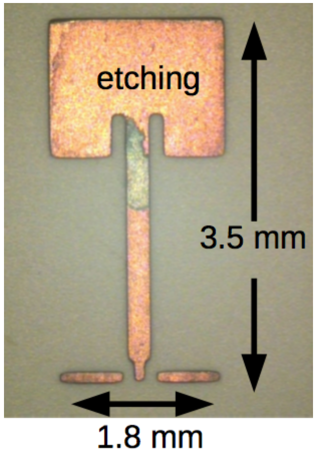


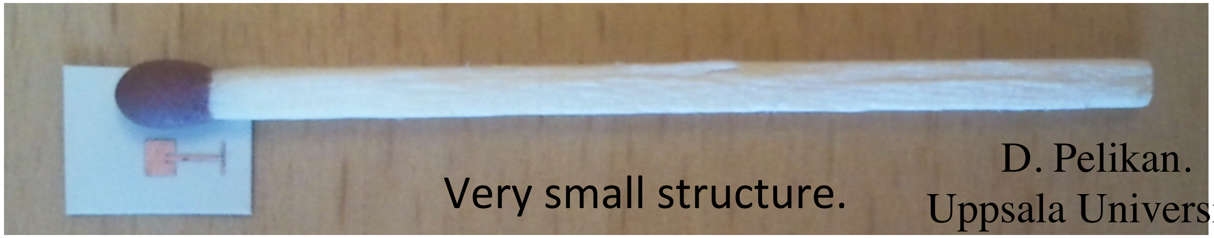


- Single and antenna arrays
- Can be produced on PCB material
  - Etching and milling.
  - Rogers, Dupont PCB material

1, 4 and 16 patch design

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





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Why Modulation?

The basic principle of pass-band modulation is to encode information into a carrier signal (60 GHz) suitable for transmission

Motivation:

Simplify radiation of the signal

- ✧ Couple EM into space – antenna size a function of wavelength

$$\lambda = \frac{c}{f} = \frac{3.0 * 10^8}{60 * 10^9} = 5mm$$

$$\lambda = \frac{c_0}{f\sqrt{\varepsilon_r}} \text{ (dielectric)}$$

- ✧ Frequency assignment:
  Allows multiple radio channels to broadcast simultaneously at different carrier or translate different frequencies to different spectral locations.

Factors influencing choice of Modulation

- ✧ Spectral efficiency
  - How effectively the allocated bandwidth is used (B/s/Hz)
- ✧ Bit Error Rate (BER)
- ✧ Signal-to-Noise Ratio (SNR)
- ✧ Power Efficiency
  - The power efficiency expresses the " signal energy over the noise energy" ratio (Eb/No) required at the receiver to guaranty a certain BER
- ✧ Performance in multipath environment
  - Envelope fluctuations and channel non-linearity
- ✧ Implementation cost and complexity

No modulation scheme possess all the above characteristics, so trade-offs are made when selecting modulation/demodulation schemes.

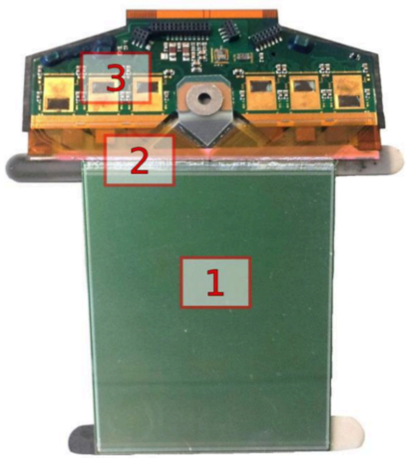
Modulation Schemes

Several modulation techniques are available, most of them fall into one of following categories :

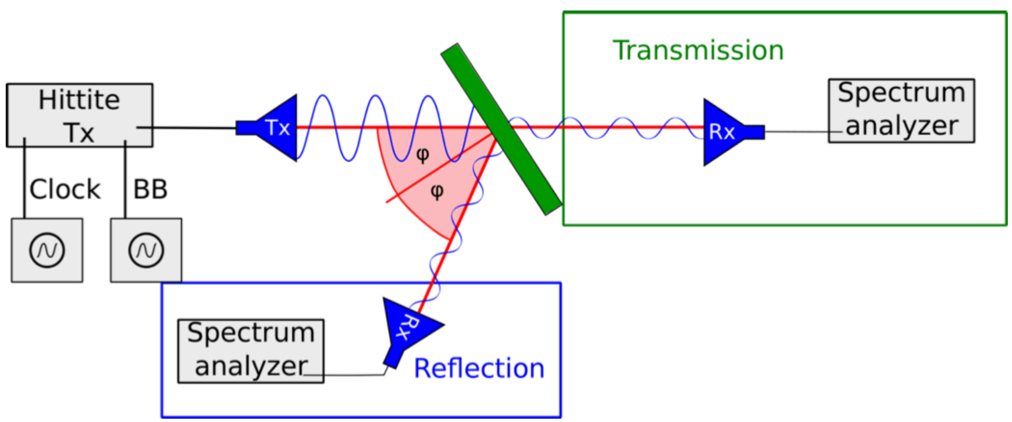
1. Spectral efficiency
2. Cost efficiency
3. System complexity
4. Power efficiency

	Modulation circuit Complexity	Demodulation circuit Complexity	IF Circuitry Complexity	Clock Recovery	Spectral efficiency B/s/Hz
OOK	**Low**	**Lowest**	**Lowest**	**No**	**0.5**
FSK (Coherent)	Medium	High	Lowest	Yes	1
MSK	High	High	Low	Yes	1
OFDM	Highest	Highest	Low	Yes	3

Electromagn. Properties



Unpowered spare ATLAS SCT end cap module w/o ABC-chips (provided by Uni Freiburg)



Tested Properties:

- Transmission loss
- Reflection loss

Tested homogeneity of transmission depending on

- Position
- Frequency

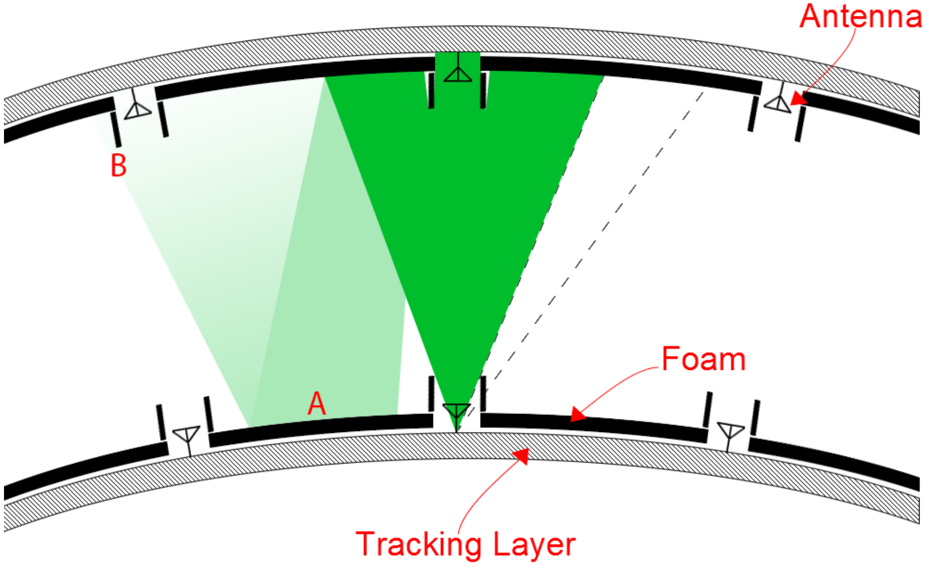
S. Dittmeier

Crosstalk

Ray tracing simulation: crosstalk mitigation

Approach:

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



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