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
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)

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>300M</th>
<th>3G</th>
<th>30G</th>
<th>300G</th>
<th>3T</th>
<th>30T</th>
<th>300T</th>
<th>$3 \times 10^{15}$</th>
<th>$3 \times 10^{16}$</th>
<th>$3 \times 10^{17}$</th>
<th>$3 \times 10^{18}$</th>
<th>$3 \times 10^{19}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mmWave</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength (m)</td>
<td>1m</td>
<td>10cm</td>
<td>1cm</td>
<td>1mm</td>
<td>0.1mm</td>
<td>10um</td>
<td>1um</td>
<td>0.1um</td>
<td>10nm</td>
<td>1nm</td>
<td>0.1nm</td>
<td>0.01nm</td>
</tr>
</tbody>
</table>

North America
- 43dBm EIRP peak, 500 mW max. power

Europe
- 40dBm peak EIRP, 13 dBm/MHz max. EIRP

Japan
- 10 mW max. power, antenna 47dBi max.

South Korea
- 10 mW max. power

Australia
- 10 mW max. power
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

- Cables reduce/stop airflow
- Energy savings in cooling

Replace Gigabit Ethernet
- Cables reduce/stop airflow
- Energy savings in cooling

- 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

Vehicles will need Gbps data rates

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

Internet of Things (IoT)
The **FUTURE** of connectivity is **WIRELESS**

The HEP community is not an exception

H. K. Soltveit, Universität Heidelberg.

Wireless Readout

EPS-HEP 2017
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.

H. K. Soltveit, Universität Heidelberg.

Wireless Readout

EPS-HEP 2017
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.

H. K. Soltveit, Universität Heidelberg.
Transmitter:
- Deliver required output power
- Power efficient
- High gain and stability

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

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

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

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

$\text{NF}_{\text{tot}}$ chosen to be 9 dB

$\text{S}_{\text{Rx}} = \text{Noisefloor} + \text{SNR}_{\text{min}} + \text{NF}_{\text{tot}} = -49 \text{ dBm}$

Minimum power level that the system can detect producing an acceptable signal $\text{SNR}$ at the output.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td>57-66 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>9 GHz</td>
</tr>
<tr>
<td>Data Rate</td>
<td>4.5 Gbps</td>
</tr>
<tr>
<td>Modulation</td>
<td>OOK</td>
</tr>
<tr>
<td>Minimum sensitivity</td>
<td>- 49 dBm</td>
</tr>
<tr>
<td>$\text{S}_{\text{rx(min)}}$</td>
<td>- 49 dBm</td>
</tr>
<tr>
<td>Bit Error Rate (BER)</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>Target Power consumption</td>
<td>150 mW</td>
</tr>
<tr>
<td>Transmission Range</td>
<td>20 cm (1m)</td>
</tr>
</tbody>
</table>
60 GHz LNA Simulations

S-Parameter Response all @ 60 GHz

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

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

Power Consumption: 13 mW

\[
NF = 4.43 \text{ dB @ 60 GHz}
\]

4.5 dB between 57 – 66 GHz

S22 = -35 dB

S11 = -32 dB

S12 < -45 dB
60 GHz broadband Antenna
Uppsala University

Multilayer Structure

-10 dB bandwidth: 56.8 – 65.6 (~9GHz)

7 dBi max gain
H-Plane
E-Plane
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)
Heidelberg Test
60 GHz Irradiation

✧ 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.
✔️ 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...
Backup
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 %

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 its 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 $\lambda/4=1.25$ 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
  o High dielectric constant (11.7) and low substrate resistivity (10 Ohm-cm)
  o Energy loss due to magnetically induced current
  o 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

Very small structure.

D. Pelikan.
Uppsala Universitet
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

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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 reality
    • 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

\[ P_{RX} = -34 \text{ dB} \]
\[ PL(R) = -48 \text{ dB} \]
\[ S_{RX} = -49 \text{ dB} \]

PA \[\rightarrow\] LNA \[\rightarrow\] Mixer \[\rightarrow\] IF \[\rightarrow\] Demod.

17 dB