Draft : 25/11/2016

- Letter of Intent -

DEVELOPMENT OF WIRELESS TECHNIQUES IN DATA AND POWER TRANSMISSION APPLICATION FOR PARTICLE-PHYSICS DETECTORS

- WADAPT - Wireless Allowing Data And Power Transmission

R. Brenner[a], D. Dancila[a], C. Dehos[b], P. De Lurgio[c], Z. Djurcic[c], G. Drake[c], J.L. Gonzalez Gimenez[b], L. Gustafsson[a], D.W. Kim[d], E. Locci[*e], U. Pfeiffer[f], D. Röhrich[g], D. Rydberg[a], A. Schöning[h], A. Siligaris[b], H.K. Soltveit[h], K. Ullaland[g], P. Vincent[b], P.R. Vasquez[f], D. Wiedner[h], S. Yang[g]

[a] *Uppsala University, Sweden*
[b] *CEA/LETI/DRT/DACLE/LAIR, Grenoble, France*
[c] *Argonne National Laboratory, Argonne, IL 60439, USA*
[d] *Gangneung National University, Korea*
[e] *CEA/DRF/IRFU/SPP, Gif-sur-Yvette, France*
[f] *University of Wuppertal, Germany*
[g] *University of Bergen, Norway*
[h] *University of Heidelberg, Germany*

CERN-LHCC-2017-002 / LHCC-I-028
31/01/2017

Abstract

In the WADAPT project described in this Letter of Intent, we propose to develop wireless techniques for data and power transmission in particle-physics detectors.
Wireless techniques have developed extremely fast over the last decade and are now mature for being considered as a promising alternative to cables and optical links that would revolutionize the detector design.
The WADAPT consortium has been formed to identify the specific needs of different projects that might benefit from wireless techniques with the objective of providing a common platform for research and development in order to optimize effectiveness and cost. The proposed R&D will aim at designing and testing wireless demonstrators for large instrumentation systems.

* Contact: elizabeth.locci@cern.ch

1. Introduction

Today, millimeter-wave (mm-wave) is a well-developed field of electronics. Advanced silicon-integration technologies, which provide production level transistors with fT/fmax of more than 200 GHz are the key part for wireless applications in the mm-wave frequency band. The mm-wave band covers the electromagnetic spectrum between 30 and 300 GHz. This band is further divided into smaller bands based on user applications. At this stage the consortium has decided to focus on the 60 GHz band due to its extraordinary features for short-range data transfer and the availability of development tools and testbeds. Our developments are mainly driven by the demand of higher bandwidth that keeps on increasing at a significant rate. This is due to the incredible number of users and applications, which has largely increased during the last years. This includes the vehicular, mobile phone, consumer electronics and aerospace applications to mention a few.

The International Roadmap for Semiconductors (ITRS) has identified the interconnect delays as the most critical phenomenon affecting high-performance products (ITRS09). The copper interconnects are an issue, since the bandwidth is decreased due to increased resistance at higher frequency. An on-chip or in-package antenna may mitigate this because it would reduce the total wire length seen by the signal.

Also the development of wireless power is a natural evolution and is thought to be useful in many ways as transmission of power, where instantaneous or continuous transfer is needed, but where interconnected cables are inconvenient (limited space as in a detector environment), dangerous or impossible.

As many of the applications mentioned above will benefit from this increased bandwidth, the time has now come to introduce this to the HEP community.

The envisioned R&D has two parts: wireless data transmission and power transmission. The present small consortium has started focusing on wireless data transmission, but this consortium is expected to grow and to further investigate power transmission as well. The following sections will mainly concentrate on data transmission. More information, particularly in the domain of power transmission, can be found in reference [1].

2. Motivation

The motivation for wireless power and data transmission is manifold in particle physics detectors:

- Wireless technologies offer a unique and very elegant opportunity to send broadcasts. This is particularly interesting for steering and control of a complex detector system and might save a lot of cables if one single signal is sent to many receivers.
- The total or even partial removal of cables and connectors will result in cost reductions, simplified installation and repair, and reductions in detector dead material. These two last aspects are especially important in tracking detectors and they may become particularly important in case of limited access or/and hostile environment.
- Wireless data transfer offers the possibility to realize topologies which are much more difficult to be realized using wires, as data from one single point can be sent to several receivers or several transceivers send to one receiver.

These features may become of particular importance for future HEP detectors.

- The increasing demand for high data transfer rates from highly granular detectors in HEP that is limited today by the available bandwidth of electrical and optical links. In this context, we propose a wireless link, since this in many occasions might be a good alternative to electrical and optical links. The proposed wireless data transmission, using the 60 GHz or higher band, offers in this context the required bandwidth, high space efficiency, security and form factor.

Minimizing the amount of material in the region of the tracking detectors will reduce multiple scattering and nuclear interactions that degrade the precision on the measurement of track momentum and interaction vertices, and in addition will reduce the number of fake hits arising from secondaries. Well-chosen detector technology and geometry, combined with wireless techniques might help in reducing the amount of cables and optimizing their path, and thus minimizing the geometrical inefficiency. Fast triggering, as exemplified in section 4, using all information from the tracker, and possibly from other detectors, is essential for hadron colliders at high luminosity. Although less mandatory for lepton colliders, introducing wireless-links providing communication between sections (tracking layers, for instance) of a detector within a region of interest might be useful [2-8].

3. Wireless Technology

There has been a huge development in wireless standards since the original version of the standard IEEE 802.11, well known as Wi-Fi, which was released in 1997 and could deliver about 1 Mbps of payload traffic. During the last decade performances in terms of data rate have constantly increased and the standarization activities related to high rate transmission and communication in the 60 GHz band has generated an extraordinary interest during the last years. WiGig 60 GHz wireless standard (also known as IEEE 802.11ad) completed in 2010 supports data rates up to 7 Gbps. WirelessHD is another standard in this band that can support data transmission rates in the range of 10-28 Gbps and permits concurrent transmission of uncompressed HD video and multi-channel audio and data.

Significant improvements were also made in radio link reliability, medium access, power consumption and system cost.

For years, radio communication technology had tried to reach the channel capacity limit as defined by the Shannon-Hartley theorem without exceeding it. The theoretical physical data rate at which information can be transmitted over a communication channel is a function of the bandwidth and the signal-to-noise ratio[1]. The recent development of the MIMO (Multiple-Input, Multiple-Output) radio systems has enabled to overtake this limit. Making use of the spatial dimension of a communication link, the maximum channel capacity is still a function of bandwidth and signal-to-noise ratio but it is increased by a factor n of the number of spatial streams.

The fast development of the wireless technologies is linked to the improvements made in the electronics, especially the semiconductor devices and the new simulation capacity [9-15]. Some of the main strategies to improve the performance of radio

[1] here the signal to noise ratio is defined as the average received signal over the bandwith, and the noise is defined as the average noise or interference power over the bandwidth

communication systems are the following:

- Over the last decade the spectral efficiency, meaning the data rate of the physical layer that could be transmitted in a given radio frequency bandwidth, has been increased by a factor 10. The use of these advanced techniques requires intensive signal processing, increasing the complexity of the chipset design, the size as well as the power consumption. These constraints are now properly tackled by the industry, which has been able to increase the embedded computing power in the radio chipset while containing the power consumption, heat dissipation and manufacturing cost.
- According to the Shannon-Hartley theorem, another strategy to increase the throughput is to increase the spectrum bandwidth. However, larger bandwidths require transmission at higher frequency, which became feasible, once again, with the progresses made on the electronics.
- According to the Free Space Path Loss equation, the attenuation of a 60 GHz transmission at 1 meter is about 68 dB, which is 21.6 dB higher than a 5 GHz transmission. Consequently at constant transmit power and using a given modulation scheme, the communication range will be 12 times shorter. This shorter signal range could be either a challenge to setup high throughput links over several meters or a benefit to mitigate co-channel interference making a high-density channel-reuse design possible.
- The higher frequencies lead to smaller sizes of the RF components, including antennae, which can be easily integrated into electronic systems. The application-related antenna must be carefully chosen according to many parameters such as directionality, bandwidth, gain, etc. A wide range of antennae can be produced with standard methods used for electronics and printed circuits boards. The use of RF lenses to increase the gain and the directivity of the antenna is also a possibility at this frequency.
- Improvements lie in carefully selecting the communication protocol. For a radio communication channel to work, a large amount of the transmission time is devoted to transmitter and receiver synchronisation, medium access, medium sensing, legacy standard-protection mechanism or transmission error compensation. The distribution of a system clock in particle physics detectors will facilitate the transmitter-receiver synchronisation.

Wireless technology for consumer devices is also believed to use the 60 GHz spectrum, and it is anticipated that the band will be the first step towards unwired houses. The opening of the unlicensed band has initiated a lot of new opportunities for high data rates applications. Existing applications include wireless high quality video transfer such as HDTV signals, video/music transfer from/to portable devices and so on, which all provides speeds in the Gbps range. This is an on-going race, where technology and application developers push into higher and higher bandwidths, and it is clearly seen in prediction of the wireless ITRS roadmap for future wireless bandwidth requirements up to 2026 (figure 1) and beyond. Another feature is the flexible design of data centers, this could be placement of servers, reduction of cables that would result in less requirements when it comes to cooling and power requirements. Wires could be replaced with high-speed wireless interconnect. For example chip-to-chip, shelf-to-shelf and rack-to-rack could be an option. This would then reduce the electrical copper connection that is one of the future issues with the foreseen increasing data transfer.

Developments are also ongoing in the smart antenna field [16-24] promising a better control on the radio link quality and sharing. The 240 GHz [25] or 280 GHz [26] technologies for high data rate (40 to 100 Gbps) are on the rails as prototypes, and might become industrialised within three to five years.

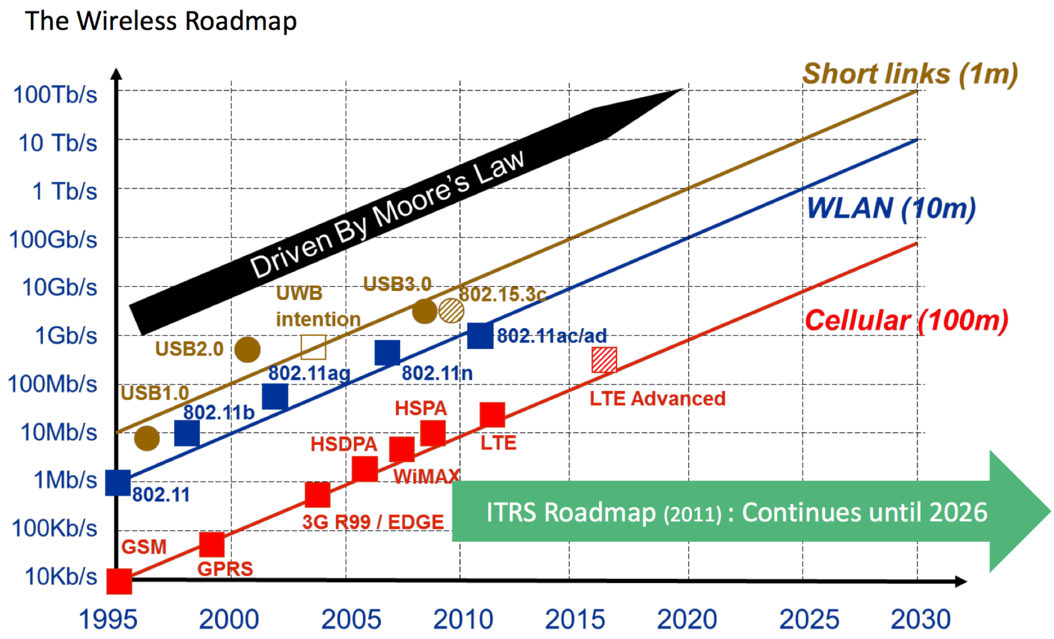

Figure 1: ITRS Wireless Roadmap [27-29]

To conclude, the latest research performed on Orbital Angular Momentum (OAM) multiplexing technique [30] seems very promising and could be the next breakthrough to reach Terabit wireless transmission.

4. Experimental Context

The application of wireless techniques for data transmission has been studied in two different contexts:

- **Neutrino experiments**

  Some examples include monitoring of the neutrino flux at a nuclear reactor, large mobile neutron detectors for detection of radioactive materials in security applications, and detectors operating in high radiation areas. In the following we will concentrate on the context of LHC experiments and future HEP Large detectors, but more details about neutrino experiments are given in reference [1].

- **LHC experiments**

  In the last decade there has been tremendous advances in silicon technologies that have made it possible to build high performance transceivers operating in the millimetre-wave band, where the 57-66 GHz band is situated. This license free 9 GHz band is very attractive in order to achieve high data rate transfer that has triggered the use in the HEP environment.
  In addition to the high data rates, which are possible using the 60 GHz spectrum, the energy propagation characteristic of this band is unique. It has a free space

path loss of 68 dB over a distance of 1 m, a high material penetration loss, that in our case is measured to be about -50 dB (preliminary value) for a fully equipped ATLAS Semiconductor-Tracker detector module, and a oxygen absorption of about 15 dB/km. The last effect is of less importance for us, since a typical data transmission distance in HEP detectors is from a few cm to about 1 m for which an attenuation of about 0.1 dB is expected.

Antennae operating at such high frequency are typically very directional, unlike those operating at 2 or 5 GHz. Directivity is a measure of how well an antenna focuses its energy in an intended direction, thus operating at 60 GHz frequency results in a more focused antenna with a narrower beam width for a fixed size antenna, that minimizes the possibility of interference and the risk that the transmission will be intercepted. These features, the high path loss, high material penetration loss, narrow beam-width, Line-Of-Sight (LOS), and operation in a controlled environment, makes the 60 GHz band optimal for short range operation. Also the use of the high carrier frequency provides small form factor, which will reduce the material budget. This provides an extremely desirable frequency re-use that can handle a large number of transceivers in a small area as in the HEP detectors and other detector systems.

The work described in reference [2,8] aims at demonstrating the feasibility of wireless readout of the Silicon inner-tracker for the ATLAS silicon strip detector with use of the 60 GHz band (Figure 2).

The 60 GHz band is very suitable for high data rate and short distance applications, which can provide wireless Multi Gigabit per second radial data transmission inside the ATLAS silicon strip detector, making a first level track trigger processing all hit data feasible.

An example of a complete readout is the silicon micro-strip tracker, where a bandwidth of about 50-100 Tbps is required. So with 20,000 links, a bandwidth of 5 Gbps per link would be required. The use of the 60 GHz band associated to a large spectral bandwidth (9 GHz) would make a few 10's of Gbps achievable. The block diagram of the proposed 60 GHz transceiver chain is illustrated in Figure 3.

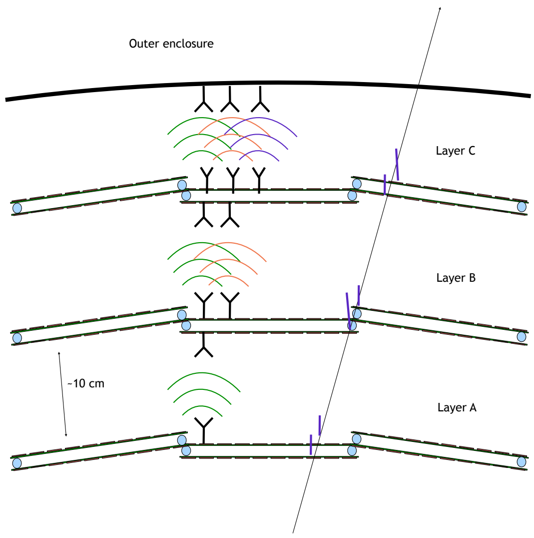

Figure 2: Proposal of a radial readout for the tracking detector of the ATLAS experiment [2].

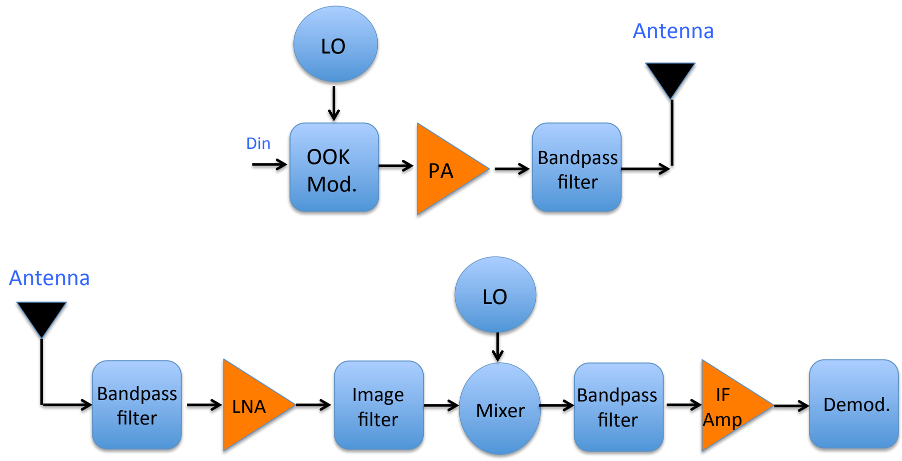

Figure 3: Block diagram of the transceiver. The transmitter is shown at the top and the receiver at the bottom [8]

The first prototype is designed to handle a data rate of 4.5 Gbps over a link distance of 1 m. Estimated power consumption for a first full prototype readout is about 150 mW. The chosen technology must be able to fulfil requirements addressing noise and linearity, radiation hardness, and at the same time have a high production yield at a reasonable cost. The 130 nm SiGe Bi-CMOS HBT 8HP technology has been chosen for the first prototype. Radiation hardness at increased radiation level as expected for the ATLAS upgrade, for instance, needs to be tested, and a radiation hard layout for such conditions may be necessary.

The On-Off Keying (OOK) modulation chosen for the first prototype has the benefit of simplicity but the drawback of low spectral efficiency (0.5 bps/Hz) and high noise sensitivity. This will not be an issue in our case, since we are working in a static and well-controlled environment where reflection should be of less concern. More advanced modulation and transmission techniques like OFDM and MIMO could be investigated. For example, the spectral efficiency of 802.11ad wireless standard is about 3 bps/Hz for the highest modulation (OFDM 64QAM 13/16). The throughput at the hardware layer would be increased by a factor six. In addition, the use of antenna diversity or MIMO techniques as mentioned above could enhance the link reliability. These techniques are commonly used in wireless communication to mitigate the impact of wave reflections. Although these techniques are today mature technologies, the design would be more complex and the power consumption will increase.

5. R&D status and perspectives

The present R&D is based on three main components: the wireless technology, the transceiver, and the antenna. Laboratory tests have also been performed to demonstrate the feasibility of wireless data transmission in the considered experimental context. This section describes the progress that has been made in these areas.

5.1. **Wireless technology**

The CEA group has recently developed a 60 GHz chip [17-24] able to reach 5 Gbps and 10 Gbps occasionally over a short distance (a few centimeters) with a BER < 10^{-12} at 5 Gps and a power consumption of 40 mW in transmission and 20 mW in reception. This chip is now functional and available for testing and prototyping. A second version of the chip, which is expected to provide stronger emitted output power and better receiver sensitivity over an extended range, is now under measurement.

The CEA group envisages to complement the 60 GHz developments with studies at higher frequencies in the 240-280 GHz range [25-26], which are of a great interest for their larger bandwidth and for the smaller size of the electronic circuits and antennae which scales with frequency/wavelength. Future developments above 100 GHz should challenge optical links at short range.

5.2. **Transceiver**

The ATLAS group at the University of Heidelberg is mainly focused on the development of a transceiver chip [8] and on the building of a demonstrator. The ALICE group at the University of Bergen has shown great interest in the project for the LS3 upgrade; four students are already assigned for the project development.

An extensive simulation of the device described in section 4 has been carried out. The scattering parameters and power consumption have been estimated. With the present design a total power consumption of about 150 mW is expected, out of which 60 mW is the consumption of the power amplifier, but there is room for improvement. The schematic design and layout of the chip is fully ongoing in Heidelberg. Bergen will collaborate in the test-board development.

5.3. **Antenna**

The work of the ATLAS group in Uppsala encompasses the design and simulation of various antenna types suitable for usage in tracking detectors, their fabrication and characterization, preliminary radiation studies, their interconnection to transceivers with wire bonding, and the design of a demonstrator. The first irradiations with electrons of 5 MeV (100 krad dose), 120 MeV (100 krad and 10 Mrad) have shown no effect on capacitance for Dupont, whilst a small but sizeable effect has been observed with Rogers antennae. The first step of a demonstrator circuit has been achieved by attaching an antenna to a LNA, and in a second step an antenna will be attached to the transceiver developed in Heidelberg.

A study of antennae for 60 GHz data transfer in tracking detectors has been presented in a thesis [31]. In Uppsala the group collaborates on mm-wave technologies with the division of Solid State Electronics.

5.4. **Transmission tests**

To evaluate the influence and other potential issues that could appear under operation of the 60 GHz RF signal on electronics and material used for the ATLAS tracker readout, a 60 GHz Evaluation Kit from Hittite was installed and the following measurements were completed in Heidelberg [3]: data transmission, material properties, antenna characterization, cross-talk and link density and noise pickup in a detector module. The detector module attenuates transmission of 60 GHz waves by more than 55 dB. 60 GHz signals were fully reflected, although diffraction lead to transmission near the edges of the tested module. Ray tracing simulations were done and are reported in a thesis [32]. Crosstalk can be avoided using directive antennae, polarized antennae, absorbers of reflections, frequency channelling. A high link density can be achieved with a link pitch smaller than 5 cm at a signal to noise ratio larger than 20. The question of interference of the 60 GHz wireless with other detectors electronics was addressed by comparing the measured noise in readout chips with and without wireless transmission, and no significant effect was observed.

Some transmission studies were also performed at 240 GHz using a binary phase-shift keying (BPSK) in collaboration with the university of Wuppertal. Up to 10 Gbps very stable data transmission was achieved with a BER of 3.10^{-4}.

6. Objectives and Strategy

The global R&D project would integrate both data and power transmission, this would cover the next decade and might be extended depending on the time scale of the future experiments.

However on a shorter time scale of 3 to 5 years, the consortium plans to build a demonstrator that could be a full sector of a vertex detector. This sector could be tested in a beam facility at CERN. After a successful test, one would propose equipping a sector of the ATLAS (or CMS) vertex detector in situ for the HL-LHC run. Different steps are necessary to reach this goal:

- Prototyping the transceiver designed in Heidelberg;
- Attaching antennae to the transceiver developed in Heidelberg ;
- Transmission tests with this device;
- Environmental tests of the prototype and of commercial products: radiation, magnetic field, temperature and humidity, EMI/EMC immunity;
- Elaboration of a design that can be mass produced;
- Equipment of a vertex detector sector.

7. Expertise and resources

All groups are formed from experienced senior physicists and engineers who gained expertise from their work on large experiments such as UA1 at the SPS, H1 at HERA, ALEPH, DELPHI, OPAL at LEP, CMS, ATLAS, ALICE and LHCb at LHC as well as in R&D collaborations such as RD20 or CALICE. All have expertise in the building and operation of large detectors as well as in electronic engineering.

The CEA engineers have top expertise in all wireless techniques. The CEA-Leti possesses complete CAD design environment and test facilities for test and characterization of chips and antennae. They can offer early access to wireless technologies, and are able to address manufacturability. They have all competencies to adapt wireless techniques for the HEP requirements and to solve technical issues attached to this context, to realise prototypes, and ultimately produce all specifications for mass production at the best cost.

The physicists and engineers are heavily involved in current running and upgrade of ALICE, ATLAS and CMS experiments, and are presently spending a fraction of their time in the WADAPT project. The work is nevertheless supported by the institutes and a physicist is working full-time on the transceiver chip. One PhD student specialized in wireless technology is working full time on the project supported by supervisors from solid-state electronics division. The present size of the Collaboration does not require a formal management. Reference [1] describes how we propose to organize working groups and responsibilities. The Collaboration regularly holds meetings to discuss the progress in the various areas.

The consortium intends to combine the R&D efforts of the institutions, the equipment, the facilities and the available resources to work on this common project. The R&D collaboration is open and welcomes new collaborators. Additional institutes will be contacted and invited to join.

8. Demands to CERN

In order to facilitate the accomplishment of the project, the consortium presents the following demands to CERN:

- Approval from the LHCC as a CERN R&D project;
- Access to CERN facilities: space for the prototype, test time in beam and in magnetic field.
- Access to computing resources.

9. Benefits

The WADAPT project would be beneficial for the HEP community by providing technologies and solutions for the wireless transmission of data and power. In many cases wireless techniques would bring an elegant answer to the need of our ever-growing detectors (section 2):

- Reduction of the number of cables/connectors resulting in the reduction of dead material, of geometrical efficiency, cost.
- High data transfer rates from highly granular detectors.
- Complex topologies for fast triggering.

The public presentations of the project have triggered an interest outside of the HEP community that might indicate a possible societal impact.

The approval of WADAPT as a CERN R&D project would give it more visibility and credit. In this R&D project people could be gathered in an organized manner that would allow a more efficient use of time, efforts, by exploiting human and financial resources in a rational way. Furthermore non-HEP groups developing wireless technology may be attracted to the project, having a platform where they can demonstrate their technology for our applications and similar applications outside our field, e.g. for medical applications. This approval would be invaluable in seeking formal approval from the involved institutes.

10. Conclusions

In the last decade, there has been a growing interest for wireless techniques and the domain is advancing faster and faster. Considerable efforts are deployed in terms of performance (spectral efficiency, link reliability), miniaturisation, electric power consumption and manufacturing cost. Therefore we believe that these techniques will be widely used in the future, and would be of benefit to particle physics in the medium to long-term future. Furthermore, these developments could also provide a benefit to other industrial, medical and scientific applications. Thus in this context we propose a R&D supported by CERN to make the necessary step to deploy these techniques in the particle-physics field by defining a common platform for R&D to optimize effectiveness and cost, with the aim of designing and testing wireless demonstrators for large instrumentation systems.

Definition of Acronyms

3GPP	3rd Generation Partnership Project
BiCMOS	Integration of Bipolar junction transistor and Complementary Metal-Oxide-semiconductor in a single circuit
CA	Channel Access
CAD	Computer-Aided Design
CSMA	Carrier Sense Multiple Access
EMC	Electromagnetic Compatibility
EMI	ElectroMagnetic Interference
FTE	Full Time Equivalent
HBT	Heterojunction Bipolar Transistor
ISM	Industrial Scientific Medical
LOS	Line-Of-Sight
LTE	Long Term Evolution (4G, LTE-B refers to 5G)
MIMO	Multiple Input – Multiple Output
MPW	Multi Project Wafer
OAM	Orbital Angular Momentum
OFDM	Orthogonal Frequency Division Multiplex
OOK	On-Off Keying
OSI	Open Systems Interconnection
PMT	Photo-Multiplier Tube
QAM	Quadrature Amplitude Modulation (2^NQAM refers to Nb of Information/symbol, then 4096QAM refers to 12 b)
RF	Radio Frequency
SCT	Semi-Conductor Tracker (ATLAS)
SDMA	Space-Division Multiple Access
SHARP	Stationary High Altitude Relay Platform
SPS	Solar Power generating Satellites
SWIPT	Simultaneous Wireless Information and Power Transfer
UMTS	Universal Mobile Telecommunication System
UNII	Unlicensed National Information Infrastructure
UWB	Ultra Wide Band
WiMAX	Worldwide Interoperability for Microwave Access
WIT	Wireless Information Transmission
WLAN	Wireless Local Area Network
WPT	Wireless Power Transmission

WSN	Wireless Sensor Network

References

[1] R. Brenner et al., “Development of Wireless Techniques in Data and Power Transmission - Application for Particle Physics Detectors, arXiv:1511.05807 .
[2] R. Brenner and S. Cheng, Multigigabit wireless transfer of trigger data through millimeter wave technology, Workshop on Intelligent Trackers 2010.
[3] S. Dittmeier, A. Schoening, H.K. Soltveit, D. Wiedner, Nucl.Instrum.Meth. A830 (2016) 417-426
[4] R. Brenner and S. Cheng, “Multigigabit wireless transfer of trigger data through millimetre wave technology”, 2010 *JINST* 5 C07002.
[5] D. Pelikan et al., “Wireless data transfer with mm-waves for future tracking detectors”, 2014 *JINST* **9** C11008.
[6] H.K. Soltveit et al., “Multi-gigabit wireless data transfer at 60 GHz”, 2012 *JINST* **7** C12016.
[7] S. Dittmeier *et al.*, “60 GHz wireless data transfer for tracker readout systems—first studies and results”, 2014 *JINST* **9** C11002.
[8] H. K. Soltveit et.al., “Towards Multi-Gigabit readout for the ATLAS silicon microstrip detector”, Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2013 IEEE.
[9] T.S. Rappaport et al., “State of the Art in 60-GHz Integrated Circuits and Systems for Wireless Communications”, Proceedings of the IEEE, Vol. 99, No. 8, August 2011.
[10] A. Siligaris 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, p.1286-1294, July 2010.
[11] 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.
[12] 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) , December 2011.
[13] H. Kaouach et al., "Wideband low-loss linear and circular polarization transmit-arrays in V-band,” IEEE Transactions on Antennae and Propagation, July 2011.
[14] U.R. Pfeiffer and D. Goren, “A 20 dBm fully-integrated 60 GHz SiGe power amplifier with automatic level control”, IEEE Journal of Solid-State Circuits, vol. 42, no. 7, p. 1455-1463, 2007.
[15] S. Reynolds et al., “A silicon 60-GHz receiver and transmitter chipset for broadband communications”, IEEE Journal of Solid-State Circuits, vol. 41, p. 2820-2831, December 2006.
[16] Y. Fu et al., "Characterization of integrated antennae at millimeter-wave frequencies”, International Journal of Microwave and Wireless Technologies, p. 1-8, 2011.
[17] 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.
[18] L. Dussopt, "Integrated antennae and antenna arrays for millimetre-wave high data-rate communications", 2011 Loughborough Antennae and Propagation Conference (LAPC 2011), 14-15 November 2011, Loughborough, UK.
[19] L. Dussopt, et al., "Silicon Interposer with Integrated Antenna Array for Millimeter-Wave Short-Range Communications", IEEE MTT-S International Microwave Symposium, 17-22 June 2012, Montreal, Canada.

[20] J.A. Zevallos Luna et al., "Hybrid on-chip/in-package integrated antennae for millimeter-wave short-range communications", IEEE Transactions on Antennae and Propagation, vol. 61, no. 11, p. 5377-5384, November 2013.
[21] A. Siligaris, et al., "A low power 60-GHz 2.2-Gbps UWB transceiver with integrated antennae for short range communications", 2013 IEEE RFIC conference, 2-4 June 2013, Seattle, Washington, USA.
[22] Y. Lamy et al., "A compact 3D silicon interposer package with integrated antenna for 60 GHz wireless applications," IEEE International 3D Systems Integration Conference (3DIC), 2-4 October 2013, San Francisco, CA, USA.
[23] J.A.Z. Luna et. al., "A packaged 60 GHz low-power transceiver with integrated antennae for short-range communications", Radio and Wireless Symposium (RWS), 2013 IEEE , p. 355-357, 20-23 January 2013.
[24] J.A.Z. Luna et al., "A V-band Switched-Beam Transmit-array antenna," International Journal on Microwave and Wireless Technology , 2014, 6(1), 51-56.
[25] J. Antes et al., "System concept and implementation of a mmW wireless link providing data rates up to 25 Gb/s" , presented at the IEEE COMCAS, Tel Aviv, Israel, 2011.
[26] J.M. Guerra 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, p. 301-304, 2-4 June 2013.
[27] G. Fettweis et al., "Entering the Path Towards Terabit/s Wireless Links", Proceedings of the IEEE European Conference on Antennae and Propagation (EUCAP), 2011.
[28] "ISSCC 2013 Trends", International Solid State Conference 2013.
[29] "ISSCC 2014 Trends", International Solid State Conference 2014.
[30] Yan Yan et al., "High-capacity millimetre-wave communications with orbital angular momentum multiplexing" Nature Communications 5, Article number: 4876, doi:10.1038/ncomms5876, Published 16 September 2014.
2014.
[31] Daniel Pelikan, Searches for a Charged Higgs Boson in ATLAS and Development of Novel Technology for Future Particle Detector Systems, Acta Universitatis Upsaliensis, 2015, ISBN: 978-91-554-9153-6 (http://uu.diva-portal.org/smash/get/diva2:784537/FULLTEXT01.pdf).
[32] T. Hugle. 2013. Simulation von Datenü. Bertragung und Beugung mit einem Raytracer, BSc Thesis , University of Heidelberg, Physikalisches Institut.