Open Hardware Opportunities and Innovative Electronics at CERN

Erik van der Bij

CERN, Geneva, Switzerland

Electronics Design Show
Coventry, UK
22 - 23 October 2014
Outline

1. CERN
2. Why Open Hardware
3. OH designs
4. White Rabbit
5. What makes OH work
6. Is it for you?
7. Conclusions
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Basic research
Higgs Boson
Antimatter
Dark Matter
Standard Model
Neutrinos

Technology Transfer
World Wide Web
Hadron Therapy
Positron Emission Tomography (PET)
Evacuable Solar Collectors
CERN Accelerator Complex
CERN Accelerator Complex
CERN Accelerator Complex

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Open Hardware Opportunities and Innovative Electronics
Beams – Controls – Hardware & Timing

ADC, DAC, TDC, Fine Delay Generator, ...

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Open Hardware Opportunities and Innovative Electronics
Beams – Controls – Hardware & Timing

ADC, DAC, TDC, Fine Delay Generator, ...

4.3 km

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Why we use Open Hardware

Get a design just the way we want it
- We specify fully the design.

Peer review
- Get your design reviewed by experts all around the world.

Healthier relationship with companies
- No vendor-locked situations. Companies selected solely on the basis of technical excellence, good support and price.
Why we use Open Hardware

Spend money where you or your funding agencies want
- Makes life easier for public institutions.
- Opens the door to smaller companies with good local support.

Design re-use
- When it’s Open, people are more likely to re-use it.

Dissemination of knowledge
- One of CERN’s key missions!
Dispelling the commercial vs open myth

<table>
<thead>
<tr>
<th>Open</th>
<th>Commercial</th>
<th>Non-commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winning combination. Best of both worlds.</td>
<td>Whole support burden falls on developers. Not scalable.</td>
<td></td>
</tr>
<tr>
<td>Vendor lock-in.</td>
<td>Dedicated non-reusable projects.</td>
<td></td>
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</tbody>
</table>
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Open products are real products™
SPEC: Simple PCI Express FMC carrier
Made in Spain, The Netherlands & Poland

PCB with only 6-layers
SVEC - Simple VME FMC Carrier
Made in Germany
FMC mezzanine: 5-channel 1ns TDC
Made in Spain and Germany.
FMC mezzanine: 100 MSPS 14-bit 4-channel ADC
Made in The Netherlands & Poland
# Commercially available CERN OH designs

**October 2014**

<table>
<thead>
<tr>
<th>Project</th>
<th>Producers</th>
<th>Users</th>
<th>Produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEC carrier - PCIe</td>
<td>3</td>
<td>30</td>
<td>354</td>
</tr>
<tr>
<td>SVEC carrier - VME</td>
<td>2</td>
<td>6</td>
<td>265</td>
</tr>
<tr>
<td>SPEXI carrier - PXIe</td>
<td>1</td>
<td>3</td>
<td>42</td>
</tr>
<tr>
<td>ADC 100M 14b 4ch</td>
<td>2</td>
<td>17</td>
<td>112</td>
</tr>
<tr>
<td>TDC 1ns 5cha</td>
<td>2</td>
<td>3</td>
<td>63</td>
</tr>
<tr>
<td>FMC DEL 1ns 4cha</td>
<td>3</td>
<td>9</td>
<td>112</td>
</tr>
<tr>
<td>FMC DIO 5ch</td>
<td>3</td>
<td>16</td>
<td>122</td>
</tr>
<tr>
<td>WR switch 18 ports</td>
<td>2</td>
<td>23</td>
<td>127</td>
</tr>
</tbody>
</table>

**Table:** eight CERN OH designs found producers and users
Re-use of work

Examples of re-use of work

- Companies modified the SPEC carrier design.
  - larger FPGA (for software radio)
  - minimised versions
  - AMC, PXIe and CompactRIO bus versions

- A company modified the ADC100M design.
  - other input filter
  - high-voltage front-end

- A company re-used nanoFIP code for renovating trains.
SPLEXI board: a modified SPEC board uses the PXI Express bus instead of PCIe
White Rabbit – Innovation with Open approach

- Hardcore innovation.
- An enabling technology.
- Started at CERN and GSI high-energy physics labs.
- Everything Open: hardware, gateware, software.
- Made extensive use of small companies to develop.
- Companies develop and sell products based on it.
White Rabbit – is Ethernet...

- Bandwidth: 1 Gbps
- Single fiber medium
- Up to 10 km links
- WR Switch: 18 ports
- Allows non-WR Devices
- Ethernet features (VLAN) & protocols (SNMP)
White Rabbit – is enhanced Ethernet!

Two separate services (enhancements to Ethernet) provided by WR:

1. **Synchronization:**
   - accuracy better than 1 ns
   - precision (tens of ps sdev skew max)

2. **Deterministic, reliable and low-latency Control Data delivery**
White Rabbit applications

- Particle accelerators
- Cosmic ray & neutrinos detectors
- Metrology laboratories

All users: www.ohwr.org/projects/white-rabbit/wiki/WRUUsers
White Rabbit applications

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  - CERN (Switzerland/France)
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The Large High Altitude Air Shower Observation
White Rabbit applications

- Particle accelerators
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  - GSI (Germany)
- Cosmic ray & neutrinos detectors
  - LHAASO (China)
  - HiSCORE (Siberia)
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  - KM3NET (Mediterranean)
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European deep-sea research infrastructure

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- Metrology laboratories
  - MIKES (Finland)

Centre for metrology and accreditation

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  - VSL (Netherlands)

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Precision Time Protocol (IEEE 1588)

- Packet-based synchronization protocol.
- Synchronizes local clock with the master clock.
- Link delay evaluated by measuring and exchanging packets tx/rx timestamps.
Layer 1 Syntonization

**Common clock for the entire network**

- All network devices use the same physical layer clock.
- Clock is encoded in the Ethernet carrier and recovered by the receiver chip.
- Phase detection allows sub-ns delay measurement.
WR time transfer performance

Stable oscillator

Cesium beam clock

10 MHz

WR Switch (master)
WR time transfer performance

Stable oscillator

Cesium beam clock

WR Switch (master)

10 MHz

5 km

WR Switch (slave 1)
WR time transfer performance

Stable oscillator
Cesium beam clock

WR Switch (master)

5 km

WR Switch (slave 1)

5 km

WR Switch (slave 2)

5 km

WR Switch (slave 3)
WR time transfer performance

Stable oscillator

- Cesium beam clock

Oscilloscope

- CH1
- CH2
- CH3
- CH4

WR Switch (master)

- 10 MHz
- 1 PPS
- 5 km

WR Switch (slave 1)

- 5 km

WR Switch (slave 2)

- 5 km

WR Switch (slave 3)

- 1 PPS

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WR Switch (slave 1)

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WR Switch (slave 3)
WR time transfer performance

Histogram of offsets between master and each slave

Master (CH1)
WR time transfer performance

Histogram of offsets between master and each slave

Master (CH1)

Slave 1 (CH2)
mean = 161.86 ps
sdev = 5.45 ps
WR time transfer performance

Histogram of offsets between master and each slave

Master (CH1)

Slave 2 (CH3)
mean = 24.67 ps
sdev = 5.30 ps

Slave 1 (CH2)
mean = 161.86 ps
sdev = 5.45 ps
WR time transfer performance

Histogram of offsets between master and each slave

- **Master (CH1)**
- **Slave 1 (CH2)**
  - mean = 161.86 ps
  - sdev = 5.45 ps
- **Slave 2 (CH3)**
  - mean = 24.67 ps
  - sdev = 5.30 ps
- **Slave 3 (CH4)**
  - mean = -135.25 ps
  - sdev = 6.14 ps
White Rabbit Switch

- Central element of WR network
- Original design optimized for timing, designed from scratch
- 18 1000BASE-BX10 ports
- Open design (H/W and S/W)
- Commercially available from two companies
White Rabbit Node

- Ethernet MAC with White Rabbit
  - Open IP Core
  - Easily integrated into custom FPGA-based designs
White Rabbit Node

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- Mezzanines can use the accurate clock and TAI time
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FMC & CompactRIO  
PCI Express  
PXI Express  
VME
Common clock in entire network: no skew between ADCs.
Ability to sample with different clocks via Distributed DDS.
External triggers can be time tagged with a TDC and used to reconstruct the original time base in the operator’s PC.
LHC Instability Trigger Distribution System (LIST)

Purpose of LIST
Distribute triggers, with a low and fixed latency, despite distance differences.

In layman terms
The LIST is like a fixed latency coaxial cable linking every possible pair of trigger inputs and outputs.
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A web-based collaborative tool for electronics designers

- Wiki, News
- File repository
- Issues management
- Mailing list

Fully open access

- All information readable by everyone, without registration.
Example of an OHR project

FMC PROJECTS » SIMPLE PCIE FMC CARRIER (SPEC)

License
CERN OHL v1.1

A simple 4-lane PCIe carrier for a low pin count FPGA Mezzanine Card (VITA 57). It has memory and clocking resources and supports the White Rabbit timing and control network. Commercially available.

More info at the Wiki page

- Subprojects: Software support for the SPEC board
- Status: Release

Latest news
OHR Current Status

Projects
- 123 projects
  - 70 initiated by CERN groups, 53 by other institutes
- 165 active developers, many more users

Types of designs
- Around 60 hardware designs
- Around 20 re-usable HDL cores
- General tools like
  - Production test environment (Python based)
  - ADC performance test
CERN Open Hardware License – ohwr.org/cernohl

### Provides a solid legal basis
- Developed by Knowledge and Technology Transfer Group at CERN.
- Open Software licences not usable (GNU, GPL, ...).

### Practical: makes it easier to work with others
- Upfront clear: anything you give is available to everyone.
- Everyone can use it for free.
- No strings attached. *Really!*
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Same principles as Open Software

- Anyone can see the source (design documentation).
- Anyone is free to study, modify and share.
- Any modification and distribution under same licence.
- Persistence makes everyone profit from improvements.

Hardware production

- When produce: licensee is invited to inform the licensor.
Be Open

Use OHR to the fullest

- Document everything on OHR: schematics, status.
- Discuss over mailing list.
- Document design review results.
- Track Issues and detected bugs.

Don’t be afraid to show mistakes!

- E.g. SPEC: 86 Issues documented, 40 still ’Open’.
- Issues may help others when adapting a design.
- OHR becomes a teaching tool.
Make design general enough

General functions find more users

- General purpose carrier boards
- Analog to digital converters, Digital I/O
- Time to digital converter, Fine Delay
- White Rabbit timing and control network

Tips

- Some functions are more generic than you think e.g. White Rabbit network and WorldFIP interface.
- Keep as simple as possible. Stay cheap.
- People can modify or extend the design later if needed.
Use standards

Standards stimulate re-use and fit in systems

- Bus standards: VME, PCI express, PXI express
- FMC Mezzanine card (VITA 57.1)
- Wishbone internal bus, OpenCores IP, Plain VHDL
- Linux drivers
Wishbone-based System-on-Chip architecture (ADC)
If a standard does not exist, contribute to one

Contributions to standards

- White Rabbit: will be in IEEE 1588 High Accuracy profile.
- Linux driver structure called FMC bus: in Linux v3.11.
- ZIO Linux framework for DAQ and CTL hardware: RFC made to Linux Kernel list.
Be complete: from design to production test and driver

It’s not only about schematics and PCB

- Quality - design reviews; reduced BOM; DFM
- Professional production documentation, incl. quality norms
- Production test system
- Firmware and its documentation
- Linux drivers

Save yourself time

- Reuse a lot: document templates, IP cores, HW designs.
  - allows engineers to help each other.
- Make Design Tools.
  - hdlmake: generates makefiles for FPGA projects.
  - wbgen: wishbone register and documentation generator.
  - ZIO, SDB and FMC bus tools for driver development.

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Open Hardware Opportunities and Innovative Electronics
Work intensively with industry

Types of work we’ve outsourced

- Hardware: development, production.
- Software: VHDL firmware, drivers.
- Usually small projects (<2 months work).
- Speeds up projects.
- Gets in specialist knowledge.
- Small companies can play a large role.
- Production: follows CERN purchasing rules (competition).

Via OHR and companies the products find their own way

- The fun starts here: more users, more feedback.
Work intensively with industry

Industry and the OH concept

- Open Hardware is new and not always understood.
- Need to explain companies the opportunities and risks.
- Companies think they compete with *assembly companies*. We ask only *engineering companies* that can also give support (guarantee, repair, improve)!
- Needs time from us and guts from companies.
- Companies always found new clients.
Future work – tearing down the last wall

Improve re-usability with free electronics design tools
- Tools are expensive and do not interoperate.
- Existing free tools are not usable to make complex designs.
- Therefore we stimulate the development of free tools:
  - VHDL simulator (extension of Icarus Verilog simulator)
  - Schematics & PCB editor (catalysing KiCAD development)
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Is Open Hardware for you, as a company?

Some ‘personal’ prerequisites

- You don’t want to re-invent everything on your own.
- You’re ready to use work of others and build on top of that.
- You love to work with other open and clever engineers.
- You’re ready to document and publish everything. You’ll get so much back in return!
- You want to be at the cutting edge where you need the power of collaboration.
- Y’a wanna have fun!
Is it for you, as a company?

Be prepared for surprises

- Being Open makes you so much more accessible.
- You’ll get interested customers ’out of the blue’.
- Open community likely complements current customers.
- Customers will pay for adaptations of designs.
- You may even find your competitors helping you.

Basically together you make a big pie. And then split it. That’s better than everyone making his own, small pie.
Open Hardware creates Opportunities

- There are free, professional designs out there!
- Clients may help to make improvements or pay you for that.
- Opportunities for small companies to work differently
  - Produce and sell existing designs.
  - Adapt and extend these to create great products.
  - Get ’advertising by community’.
- You may ’Open’ your own products to get new clients.
Open Hardware and Innovation

- Open Hardware stimulates Innovation
  - The White Rabbit network is a great example.
  - Not only hardware, also drivers, firmware, design ideas.
- OH is an enabler to use the power of collaboration.
- ohwr.org is practical for engineers to collaborate.
- You can take part in a stimulating, learning environment.
- An opportunity to innovate your business model!
Conclusions – the bottom line

Open Hardware, the bottom line

- Likely not for every company or all designs.
- Eight CERN designs are already commercialised.
- Many other designs are available.
- Four SME’s in Europe profit from selling Open Hardware.
  - They sell new products and services.
  - They have improved in quality and technology level.
  - They have adapted their business model.
- Five years of experience show it works for all parties.
- The companies who join are in for a great adventure!

ohwr.org
Open products are real products™