Distributed Digital Data Acquisition System with Network Time Synchronization

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Motivation

NP community => DOE => SBIR Solicitation for

“Software-Driven Network Architectures for Data Acquisition”

- Design for a distributed DAQ system
- Eliminate clock and trigger distribution networks
- Synchronize DAQ units via data network

Requirements for timing precision depends on experiment

- Background reduction by coincidence: Hundreds of nanoseconds
- Event building for detector arrays: Tens of nanoseconds
- Time of flight measurements: Sub-nanosecond
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Approach

Existing Technologies

- **IEEE 1588 Precision Time Protocol (PTP)**
  - Time Stamping Units (TSU) built into several Ethernet MACs, physical layers (PHY);
    also into a few routers
  - Open source software for managing time synchronization (LinuxPTP, ptpd)
  - Reported time resolutions: milliseconds (software TSU)
    low nanoseconds (hardware TSU)

- **CERN’s White Rabbit (WR)**
  - Extension of PTP standard with synchronized Ethernet
  - Open hardware project
  - Reported time resolution: sub-nanosecond, even tens of picoseconds

XIA SBIR Project

- Adapt existing solutions (PTP and/or WR) to detector DAQ modules
  (Sounds simple, but has not been done before)
- Stay within standards, use open HW/SW environment, no “black box” for purchase
- Collaborate with scientists, open for new ideas
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XIA SBIR Project Timeline

- Phase I (now)
  - Implement PTP
  - Test performance
  - Explore WR

- Phase II (2018)
  - Integrate WR
  - Software trigger scheme
  - Whatever you want
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R&D Platform: Pixie-Net

- Latest in a family of DAQ electronics for nuclear physics
  - ~2000: DGF-4C
    Developed with GRETA related SBIR
    Patented technology for processing segmented HPGe signals
    Still used in Miniball, AGATA detector testing
    100/500 MB/s data bandwidth with PCI/PCIe
    Used in many smaller lab systems <10 channels
  - ~2005: Pixie-16, 2016: Pixie-32
    Low cost, high density, extensive clock/trigger capabilities
    Used in SeGA, VANDLE, CANDOR …

- Based on Zynq SoC: FPGA + ARM

  pulse processing
  Linux OS
  pulse heights, waveforms
  USB SD Ethernet webserver
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- COTS Zynq board
- ARM runs Ubuntu 15
- SSH login to control DAQ
- Webserver displays results
- Data stored to USB drive, SD card, or network drive
- New for SBIR: Ethernet PHY with PTP TSU and clock output
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Measurements (PTP)

The PTP PHY clocks
- ADCs capturing coincident scintillator pulses
- FPGA logic for time stamping pulses

If perfectly synchronized clock => zero variation in arrival time difference of coincident 511 keV gammas
If not => time difference varies over time
But also broadened by clock jitter, light collection variations, PMT transit time, noise, etc.
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Preliminary Results (PTP)

2x LaBr with Na-22 source into 2x Pixie-Net synchronized over network (PTP)
XIA network
Direct connection (CFD)
P4e shared clock (CFD)

Not a SW report on network delay, or jitter of PPS reference signals, but measured time difference between coincident gammas

PTP
LaBr pair

FWHM Timing Resolution
- XIA Network: 251 ns
- Direct connection: 11.1 ns
- P4e shared clock: 0.78 ns
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Measurements (WR)

Using commercial WR “black box” for time synchronization, standard Ethernet for data.

(Phase II: integrate WR into Pixie-Net, use the WR data link instead of ARM controlled Ethernet)
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Preliminary Results: WR (with LaBr$_3$)

For LaBr, the WR synchronization matches timing resolution of P4e shared clock

(But need to improve detector, past P4e measurements were better)
Preliminary Results: WR (with Pulser)

For split pulser, timing resolution improves but WR not quite matching PN shared clock

=> Signal source matters!
Phase II Project

Phase I will result in a demo system with standard IEEE 1588 PTP, ~10ns resolution, White Rabbit compatible. Available with existing Pixie-Net. Suitable for less demanding applications.

In Phase II, aim for 10-100ps resolution by integrating White Rabbit into an upgraded Pixie-Net. Work with scientists to be compatible with HW and SW infrastructure developed locally. Collaborate in “open hardware” projects rather than trying to sell “black box” proprietary electronics.
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Summary

Explored PTP and WR network time synchronization for detector data acquisition electronics

Phase I is work in progress

<table>
<thead>
<tr>
<th>Month</th>
<th>Description</th>
<th>Time Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>February</td>
<td>ptpd software time stamping</td>
<td>17,966,000 ps</td>
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<tr>
<td>March</td>
<td>Zynq PTP hardware time stamping</td>
<td>1,310,000 ps</td>
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<td>April</td>
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<td>398,000 ps</td>
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<td>June</td>
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<td></td>
<td>PHY PTP hardware time stamping, PN-PN, CFD, LaBr</td>
<td>11,000 ps</td>
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<td>July</td>
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<td>900 ps*</td>
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<tr>
<td></td>
<td>WR clocking, sinc* pulser</td>
<td>600 ps*</td>
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<td>...</td>
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<tr>
<td></td>
<td>goal</td>
<td>shared clock equivalent</td>
</tr>
</tbody>
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Phase II plans

- Integrate WR
- Develop software for triggering and event building
- Collaborate with interested scientists

The ultimate goal is to reach the timing resolution of an optimized shared clock system (e.g. Pixie-500e: 7ps [1]) or what was reported for WR PPS measurements (6 ps [2]). Signal sources and timing algorithms need to be improved as well.

[1] WK Warburton et al, to be published
Questions?
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Traditional Synchronization
Traditionally, time synchronization between multiple channels of digital data acquisition is accomplished by sharing clocks, clock reset signals, and triggers. With suitable algorithms (CFD), timing resolutions can be ~20 ps for idealized signals and a few hundred ps for detector signals digitized with 100-5000 MSPS.
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### Traditional
Crate with data I/O to host PC and local clock distribution

### This Project
Independent modules with network data and derived clock
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**PTP synchronization**

If $d$ is the transit time for the Sync message, and $\tilde{\delta}$ is the constant offset between master and slave clocks, then

$$T1' - T1 = \tilde{\delta} + d \quad \text{and} \quad T2' - T2 = -\tilde{\delta} + d$$

Combining the above two equations, we find that

$$\tilde{\delta} = (T1' - T1 - T2' + T2)/2$$