

Applicability of Ethernet-Based Synchronization Mechanisms to Muography Detection Systems

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Introduction

Timing as an emerging dimension in muography

Muography today

Muon imaging has evolved from static density measurements to:

- Time-dependent applications
- Large-area and distributed detectors
- High-rate acquisition systems

Beyond imaging

Recent work [1] highlights muography as a potential tool for:

- Directional triggering
- Time-of-Flight (ToF) observables
- PNT-related and cryptography applications

Precise timestamping across detector planes enables:

- Robust coincidence identification
- Rejection of accidental triggers
- New time-based observables

Time-of-Flight in muography

Concepts and experimental considerations

ToF in muography literature

Several setups explore ToF-related observables:

- Direction discrimination (upward vs downward)
- Background suppression
- Event validation across planes

Typically using vertical or inclined multi-plane configurations.

- Muon velocity $\approx c$
- Plane separation: 0.5–5 m
- Expected Δt : few ns

Key challenge

Detector intrinsic resolution (< 1 ns) is insufficient without:

- Inter-plane synchronization
- Deterministic latency
- Clock frequency alignment

Implication

ToF-based muography is fundamentally a **system-level timing problem.**

Synchronization in current systems

Typical approaches

- Independent local clocks
- Simple trigger windows
- GPS PPS references

Limitations

- Drift between modules
- Large coincidence windows
- Poor scalability

Impact on data

- High accidental rate
- Increased data volume
- Reduced reconstruction quality

Opportunity

Ethernet-based synchronization merges timing and data transport. Particularly relevant for new large-surface or ToF measurement detectors.

Precision Time Protocol (IEEE 1588) [2] (sub- μ s)

Principle

Packet-based clock synchronization over Ethernet:

- Master–slave architecture
- Hardware timestamping support
- Widely adopted in industry: 5G, Smart Grids, Finance

Performance

- Software timestamping: $\sim 1\text{--}10\ \mu\text{s}$
- Hardware timestamping: $\sim 50\text{--}100\ \text{ns}$

For muography

- Viable for compact detector arrays
- Limits high-resolution Time-of-Flight
- Insufficient for strict ns-scale coincidence

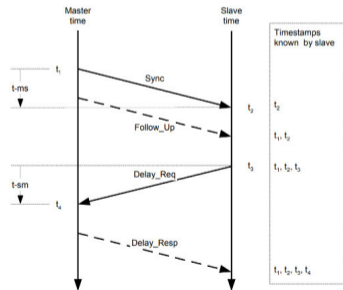


Figure from [3]. No changes. <https://creativecommons.org/licenses/by/4.0/>

White Rabbit [4] (sub-ns)

PTP extension for sub-nanosecond synchronization

Key features

- Extension of IEEE 1588 (PTP)
- **Layer 1 syntonization** via Synchronous Ethernet
- Dynamic phase tracking (DDMTD)
- Deterministic latency and routing

Performance

- Accuracy: < 1 ns (over tens of km)
- Proven in large HEP installations (e.g., CERN)

Why interesting for muography

- Sub-ns Time-of-Flight resolution
- Strict coincidence for background rejection
- Enables large-scale distributed arrays
- Unified timing and data over long fibers

Timing technology comparison

Synchronization options

Technology	Accuracy	Determinism	Sync Basis	Limitations
GPS PPS	10–30 ns	Non-deterministic	Satellite Signal	Outdoor only
PTP (HW)	50–100 ns	Variable	Packet-based Exchange	Network conditions
White Rabbit	<1 ns	Deterministic	PTP + SyncE + Phase Tracking	Specific HW

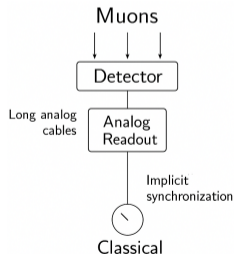
Take-away

White Rabbit provides the strict sub-nanosecond determinism essential for large-scale, distributed muography systems.

Classical vs Distributed Readout Architectures

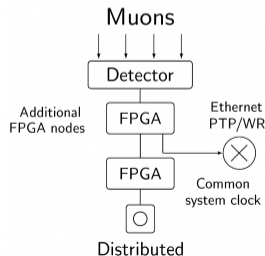
Classic (Centralized):

- Long analog cables (meters)
- Signal and timing degradation
- Implicit synchronization
- Limited scalability
- Lower initial cost



Distributed (FPGA + PTP/WR):

- Early digitization near detector
- Short analog paths → better signal integrity
- Explicit time synchronization (PTP / WR)
- Modular and scalable architecture
- Higher initial cost and complexity



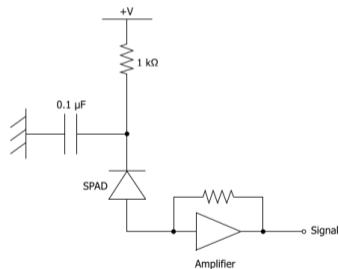
Working with Single Photon Avalanche Diodes (SPADs)

Key feature:

Capable of detecting individual photons with high temporal resolution, enabling precise light detection for scientific and industrial applications.

Applications:

- Optical satellite communications.
- Geolocation (optical TDOA and triangulation).
- Photon correlation/Quantum communications.
- **Scintillator signal detection in muography.**



Working with Single Photon Avalanche Diodes (SPADs)

Architecture for synchronized distributed capture

The proposal enables:

- Distribution: Deploy the acquisition hardware on a synchronized Ethernet network.
- Modularity: expansion of the number of sensors by adding new capture nodes to the network.
- Scalability: Adapt the overall detector size by proportionally expanding the network.

Significant advantages:

- Adapting to the specific requirements of the target to be detected.
- Allowing all distributed capture devices to operate as a single system using a common time base synchronized with sub-nanosecond precision (White Rabbit protocol).

Ongoing work

Proposal: PTP architecture for large scattering detectors

Detector Characteristics:

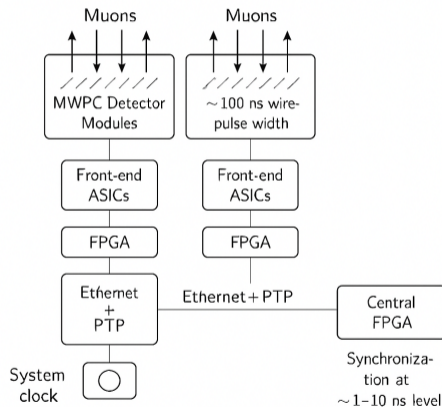
- MWPC-based cargo scanning portal
- 9 m^2 , $> 18 \text{ k}$ wires (4 mm separation)
- No need of ToF ($\sim 100 \text{ ns}$ wire-pulse width)

Proposed Architecture:

- Front-end ASICs
- FPGA per one-track 3 m^2 (coincidence)
- Ethernet + PTP synchronization
- Central FPGA: event trigger (pre-reco).

Benefits:

- Reduced coincidence window (tens of ns)
- Flexible trigger logic



Proposal: White Rabbit architecture for attenuation detectors

Detector Characteristics:

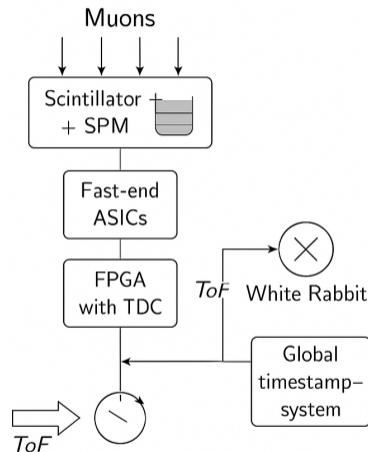
- Scintillator + SiPM
- Few ns intrinsic resolution
- ToF estimation for background reduction

Proposed Architecture:

- SiPM + fast front-end
- FPGA with TDC (50–100 ps)
- White Rabbit synchronization
- Global timestamping system

Benefits:

- Absolute time synchronization (< 1 ns)
- Improved ToF resolution
- Distributed trigger capability



Impact on muography

Modularity, scalability and timing-enabled intelligence

Modularity and scalability

Ethernet-based distributed systems can:

- Enable scalable architectures (nodes)
- Allow optimal time multiplexing
- Reduce cabling and FE complexity

Time-based discrimination

Precise inter-plane synchronization enables:

- Narrow coincidence windows ($\mathcal{O}(\text{ns})$)
- Direction tagging (up/down discrimination)
- Suppression of uncorrelated hits

ToF-related observables

- Temporal consistency between planes
- Track validation and quality estimation
- Improved background rejection
- Momentum estimation

FPGA-based smart triggering

Synchronized clocks allow FPGA logic to:

- Real-time trajectory interpretation
- Reject or clean incoherent hit/track patterns
- High-quality muon trajectory data

Summary

- 1 Timing is becoming a critical dimension in muography.
- 2 Ethernet-based decentralized and modular communication solutions enable scalable deployments.
- 3 PTP/White Rabbit + FPGA logic opens new trigger, ToF estimation and DAQ paradigms.
- 4 Make the most of intrinsic temporal resolution in advanced muography detection systems.

Outlook

Technology transfer and adaptation from HEP and advanced electronics can significantly enhance industrial muography systems.

Thank you

I look forward to receiving any questions or comments

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References



Tanaka, H.K.M., Bozza, C., Bross, A. et al. (2023)

Muography

Nat Rev Methods Primers 3, 88. <https://doi.org/10.1038/s43586-023-00270-7>



IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems

IEEE Std 1588-2008 (Revision of IEEE Std 1588-2002) , vol., no., pp.1-269, 24 July 2008

<https://doi: 10.1109/IEEESTD.2008.4579760>



Chip Design of PTP Time Synchronization for Industrial IoT

IEEE Access, vol. 13, pp. 21966-21979, 2025 [doi: 10.1109/ACCESS.2025.3533384](https://doi.org/10.1109/ACCESS.2025.3533384)



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White Rabbit Specification (latest version)

GitLab, 2011. [https://gitlab.com/ohwr/project/wr-std/-/wikis/Documents/White-Rabbit-Specification-\(latest-version\)](https://gitlab.com/ohwr/project/wr-std/-/wikis/Documents/White-Rabbit-Specification-(latest-version))