Achieving determinism and real-time in the Mu3e experiment

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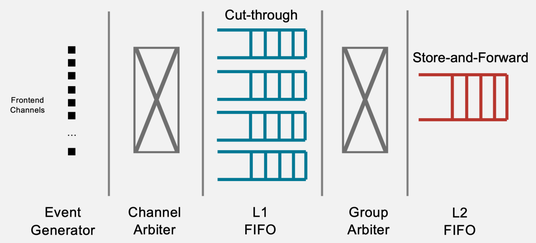
1 Introduction

The Mu3e experiment[1] is under commissioning at PiM5 beamline, aiming to search for cLFV (charged lepton-flavor violation) in $\mu^+ \rightarrow e^+e^-e^+$ channel at 2×10^{-15} sensitivity in Phase I. With SM prediction of $< 10^{-54}$ background, any signal event must be new physics. Meeting this challenge requires a triggerless DAQ (data acquisition) system that achieves line-rate **throughput**, strict **determinism**, and **zero data loss**, known as the "impossible triangle".

We present an FPGA datapath architecture with enhanced data flow dynamics, designed to sustain line-rate processing while maintaining temporal order. This design directly addresses **timestamp bursts caused by recurling particles**, which can strike multiple detector layers within nanoseconds and generate clusters of nearly simultaneous events. Such bursts, when handled with conventional RR (round-robin) arbitration, lead to timestamp reordering and bufferbloat due to micro-burst in data traffic.

2 Common architectural barriers



Typical event aggregation fabric

The **triggerless** and full **online real-time reconstruction** requires events from all subdetectors to arrive simultaneously at the designated ports, e.g., farm node, for a global picture of reconstruction.

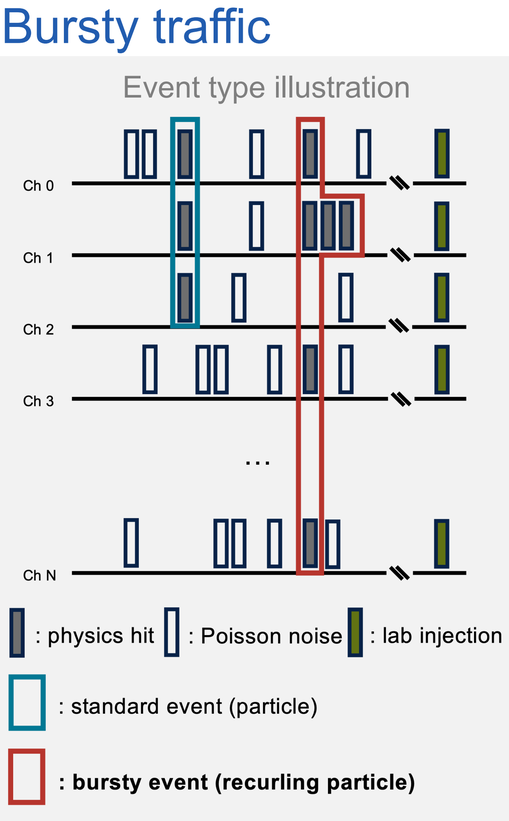
While RR arbiters maximize bandwidth, they introduce *reordering*. Although FIFOs can absorb apparent bursts locally, globally these bursts still **accumulate**, contributing to overall delay jitter.

$$\Lambda = \lambda_0 + \sum V$$

Λ : Reordering Time Offset (**RTO**)
λ_0 : RTO of the first non-order-preserving part
V : delay jitter of non-order-preserving part

Delay jitter accumulates along the chain[2]

3 Bursty traffic



Challenge: Bursty traffic from recurling particles amplifies the limitations of a common DAQ architecture.

Requirement: Our DAQ must withstand these adverse effects while still delivering events on time.

Solution: A new architecture is needed to resequence data streams that are out-of-order, indeterministic, and bursty.

Sketch of Mu3e event types

4 New architecture dynamics

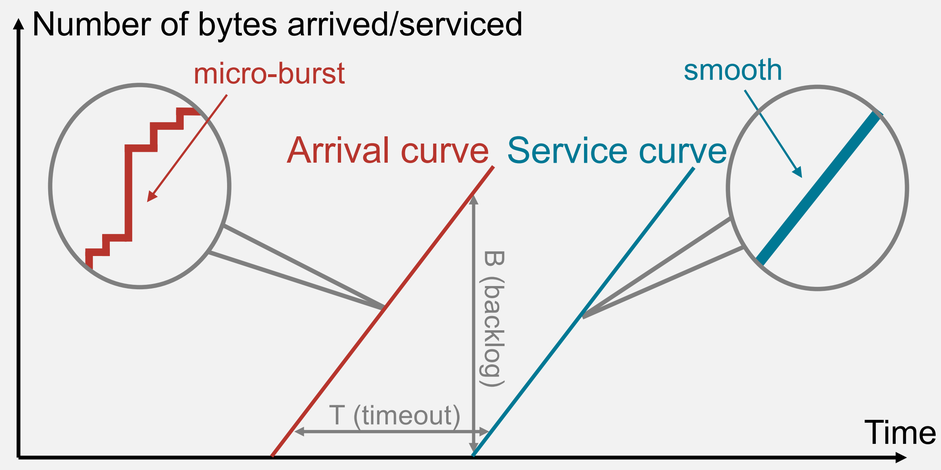
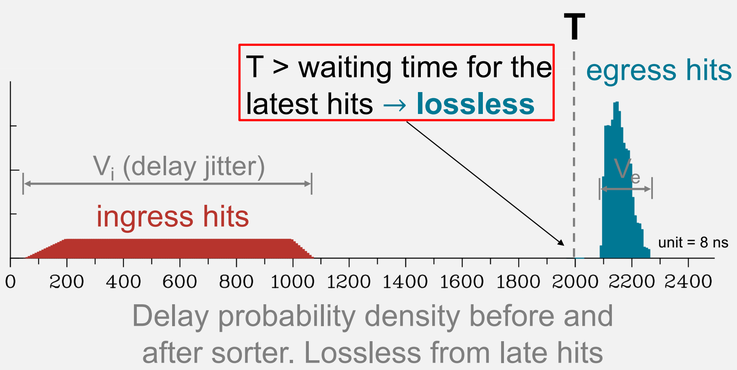
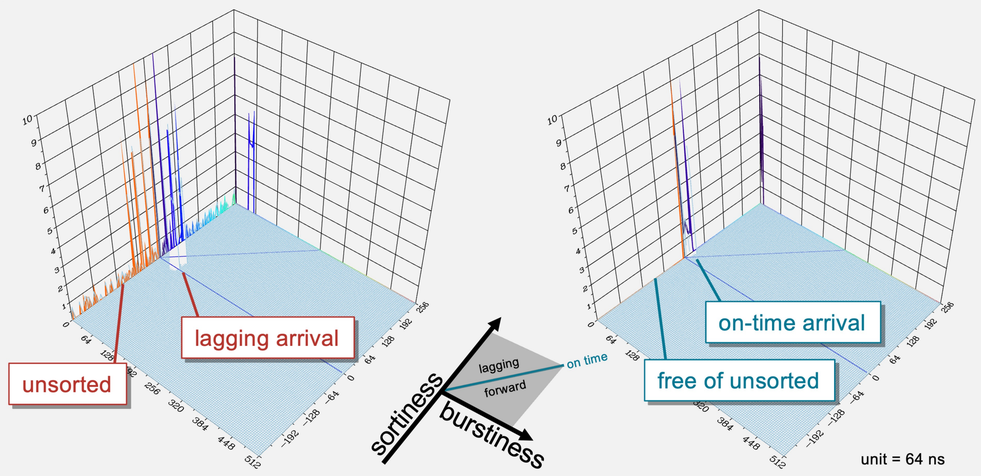


Illustration of traffic burstiness before and after sorter



Delay probability density before and after sorter. Lossless from late hits

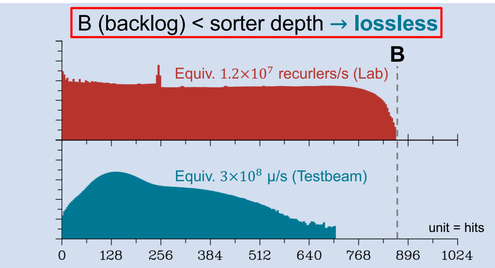
We visualize the data flow before and after the newly added *sorter*. The fabric still remains conventional. The sorter smooths out bursty traffic, squeezes delay jitter and fixes ordering, at the price of merely adding a **constant** offset in time = T.



Sortiness vs burstiness 2d histogram of log probability density before and after sorter

5 Conclusion

The Mu3e DAQ system aims at the beam rate of 10^8 μ/s for Phase I, where conventional architectures fail to simultaneously guarantee determinism, lossless and line-rate throughput under bursty traffic. By introducing a novel sorter (resequencing buffer[2]) into the new architecture, we demonstrate that **all three corners of this "impossible triangle" can be achieved at once**, establishing the foundation for fully triggerless real-time reconstruction of all events.



Sorter fill-level log probability density under pressure tests. Lossless from overflow (depth=1024 hits)

NOTE:
[1] All histograms are measured through a novel in-band network telemetry, **Histogram Statistics IP**, for capturing data dynamics.
[2] Recurlers are modeled under the worst-case assumption that each particle struck the same position 40 times before disappearing.
[3] *Reordering* means the hit temporal sequence is not mono-increasing.

References

1. K. Arndt et al., "Technical design of the phase I Mu3e experiment," Nucl. Instrum. Methods Phys.
2. E. Mohammadpour and J. -Y. Le Boudec, "On Packet Reordering in Time-Sensitive Networks," IEEE/ACM Transactions on Networking.

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