Software driven implementation of the latency buffer and supernova buffer with COTS solutions

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Upstream DAQ Readout Technology Review July 30, 2020 (CERN)





Implementation of the 10s latency buffer

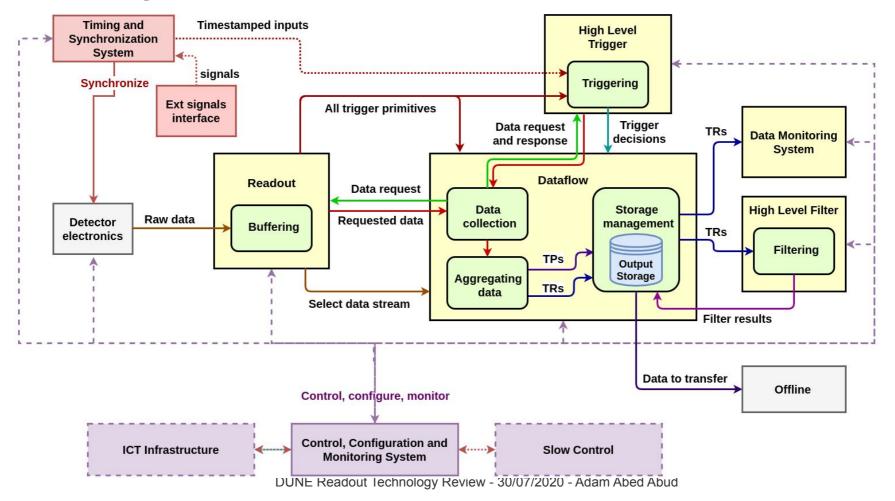
- Description of the latency buffer
- Implementation and integration in ProtoDUNE-SP Phase 1
- COTS technology: market overview (CPUs and interconnects)

Supernova storage buffer with COTS solutions

- Description of the supernova storage buffer
- Implementation with COTS solutions
- COTS technology: market overview (storage devices)

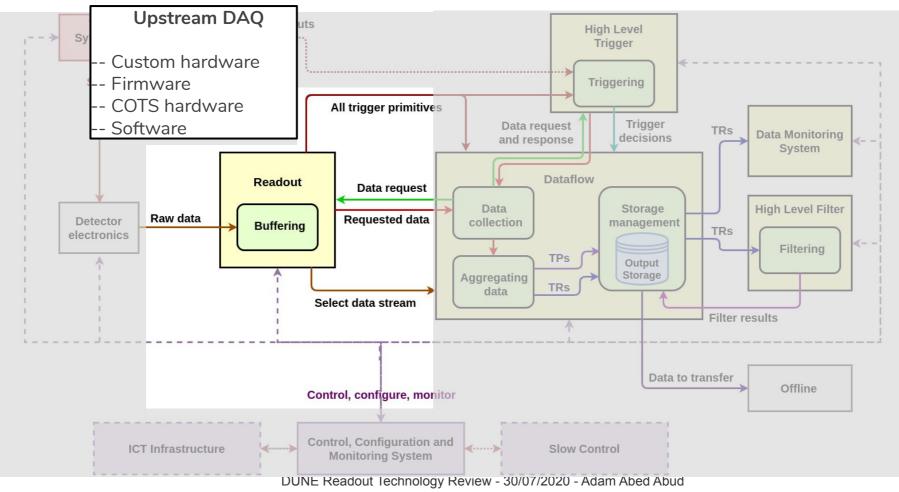
Conclusion and outline

DUNE DAQ System design

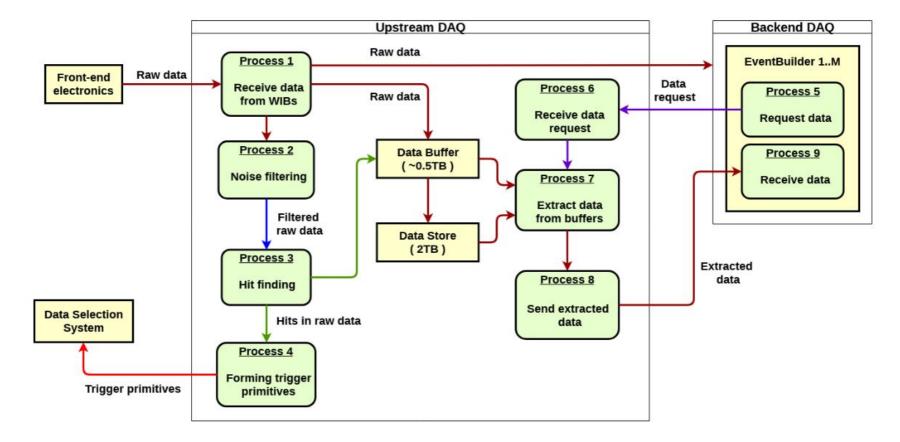


DUNE DAQ

System design



Upstream DAQ System design

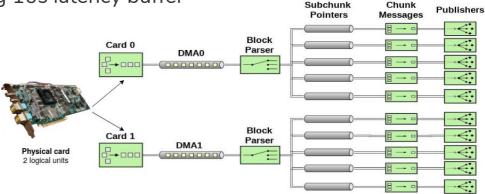


Software driven implementation of the latency buffer



Readout system in ProtoDUNE FELIX readout

- All data is transferred from the FELIX card to the host's DRAM continuously via DMA
- Block data is parsed from DMA buffers to circular buffers (i.e. 10s latency buffer)
 - Implementation based on lock-free SPSC queue from <u>folly</u> library
- For each of the ten FELIX links there is a corresponding 10s latency buffer
 - User payload: 464 bytes @ 2 MHz per link
 - Firmware aggregation of the data payload
 - 5568 bytes (superchunk) @ 166 kHz
 - Lower memory I/O operations
 - Total rate for 10 links (per APA): 8.8 GB/s *

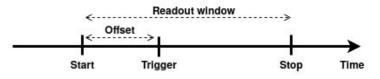


(* for rough estimates we may refer to 10 GB/s for a single APA)

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FELIX OnHost BoardReader Application

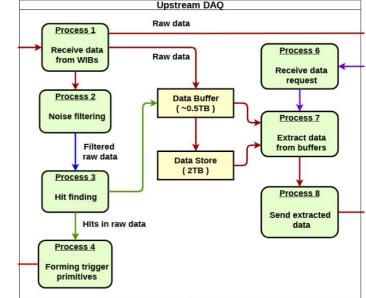
- Serializes and buffers up the superchunks (aggregated WIB frames) from the DMA blocks
- Receive trigger information (timestamp and event identifier)
 - Note: in PDSP trigger requests are time ordered
- On trigger request:
 - Calculate position of requested data using timestamp of the queue's oldest WIB frame
 - WIB frames are continuous and time ordered
 - Use 25ns ticks to convert timestamp request into position request for the SPSC queue
 - Pop items from queue until requested timestamp is matched (time ordered requests in PDSP)
- Extract data defined by a specific readout window (configuration parameter)
 - Note: extraction would also work if window size is given with trigger request
- Form artDAQ fragments from extracted data



Implementation of the data buffer

Features demonstrated in ProtoDUNE (1/2)

- Receive data from links for a full APA
- Buffer raw data
- Data request handling (trigger matching)
- Data extraction from buffer
 - Serve data for software based hit finding
 - Long readout window extraction (dataflow long window tests)
 - Feed data to accelerators
 - Hardware accelerated compression
 - ML/DL inference



Implementation of the data buffer Features demonstrated in ProtoDUNE (2/2)

• Interface with Dataflow system

- Form artDAQ fragments
- Send fragments to event builders for downstream processing

• Interface with CCM

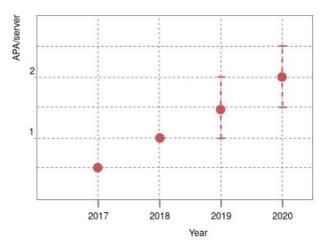
- BoardReader fully integrated into the CCM software of NP04
- Control and configuration by using RPC libraries (xmlrpc)
 - Example: Link initialization, configuration, GTH resets
 - Use of low level tools provided by the FELIX software suite
- Monitoring of the link status
- Prototype of SNB data store **integrated** and **tested** with BoardReader application

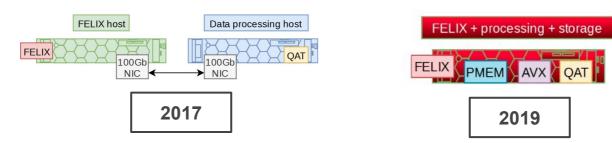
Implementation of the latency buffer Adaptability of the solution

- Support both SW and FW based hit finding solutions
- Feed the data to hardware accelerators
 - Demonstrated both hardware accelerated compression and ML/DL inference
- Adapt to evolving computer architectures and promptly integrate them in the system
 - Successfully transitioning from 2 servers for a single APA to testing 2 APAs with one server (in 2 years)
- Flexibility provided by using a software defined solution
 - Adapt to new requirements (e.g. variable trigger windows with different offsets)
 - Low level software and consolidated integration tools provided by COTS solutions

Implementation of the latency buffer Adaptability of the solution

- FELIX default operation: read from latency buffer over a 100Gb network interface
- Adapt to evolving computer architectures:
 - Higher memory bandwidth systems
- Promptly integrate developments into production system
 - 2017: reading half of APA with 1 server
 - 2020: testing 2 APAs in a single server





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Readout operation modes of DUNE

DUNE requirement	ProtoDUNE testing
Long readout tests	Tested 1s readout window
10s offset	Tested and verified
Optional data compression on ouput	Tested in PDSP
Handling non-time ordered requests	In progress: modification of queue access mechanism
2 APAs on single host	In progress: testing 2 FELIX card

- Provide data for some or all channels with a variable readout window and offset
 - Data requests are not time ordered
 - Readout and offset variability on event by event basis
 - Partial overlap of trigger windows
- Readout requirements and their implementation with COTS solutions
 - Efficiently adapt to different readout modes
 - Tested several DUNE requirements with ProtoDUNE-SP

Reliability of the latency buffer Failures and mitigation

- Detection of failures: rate for a single link drops to 0 or rate fluctuation are detected
- Reliability in case of individual link failures
 - Recovery mechanisms are in place on the FELIX side
 - E.g: transceiver misalignment failure: control, realign, reset links and flush buffers (if needed)
 - Enabling/Disabling single links
- Data inspection and anomaly detection on the WIB content <u>not implemented</u> yet
 - Need to be evaluated for ProtoDUNE-II

Long term support and maintenance COTS components and invested effort

• Balance between in-house development and COTS components

- Latency buffer implementation with COTS solution relies **only** on server grade memory modules
 - Requirement for 10 links: 12 second buffer x 10 GB/s ---> 120 GB
- Profit from developments made by industry on memory bound high throughput applications
- Large user community using the same technologies (e.g. large in-memory databases, high-speed video streaming, RDMA for high speed low latency applications)
- Invested time effort for the integrated system:
 - Core development of basic functionality: ~6 months by 3 FTE developers
 - Interfaces and extensions of this for final datataking: ~3 months by 2-3 students

Current setup

Testing platform used in ProtoDUNE

- Example of platform used for testing
 - Wide range of servers tested in ProtoDUNE as FELIX host (mid range to very high end)
 - Example: Intel[®] Xeon[®] Gold (high mid-range server), dual socket, 48 threads in total
 - 192 GB DDR4 2666 MHz DRAM (used approximately 65% for the BoardReader application)
 - Memory bandwidth per socket: ~120 GB/s
- During operation the OnHost BR application has an impact of ~30-40 GB/s on active memory throughput of the system (30% of single socket's maximum throughput)
- Advantages of sw driven implementation of 10s latency buffer
 - Scale up the system with marginal cost increase (mainly due to cost of DRAM)
 - With current setup extra memory is still available for other tasks

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Resource requirements for OnHost BoardReader Resources used and future prospects to reduce them

- CPU utilization is ~30-45 % for each of the ten core threads
 - Many factors affecting the system: L3 cache size, BIOS configuration, NUMA awareness, interrupt balancing
- Configuration for maximum throughput
 - Pinning threads to physical cores
 - Tuned NUMA locality
- Future prospects to best exploit performance:
 - Systematic study of interconnect technologies and cache-friendly optimizations on different computing architectures

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Setup evolution for DUNE Testing 2 APAs in a single host

- Target goal for DUNE: run 2 APAs (i.e. 2 FELIX cards) on a single host
- Consequences on the latency buffer
 - Double the amount of DRAM available: 120 GB x 2 ---> 240 GB
 - Maximum throughput achieved by fully populating memory DIMMs

• NOTE:

- 2 card setup is being evaluated
- In progress: optimization of the FELIX driver for a 2 card setup
- Hit finding studies made possible thanks to the COTS solution (see Phil's talk)



Test with two card setup on a single host

Setup evolution for DUNE Testing 2 APAs in a single host - "Hot off the press"

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- BoardReader applications buffering data from 2 APAs (APA2 and APA6)
- Integration with OnHost BR in PDSP (~5s buffering)
 - Not enough memory available on host for 10s setup
- Memory throughput scales accordingly
- Core pinning and tested also without
 - \circ $\,$ Same cores are parsing both of the cards

rsipos@np04-srv-028:/nfs/sw/felix/new-software/sw-master-uptodate/x86_64-centos7-gcc62-opt

• Logs available on np04-srv-028

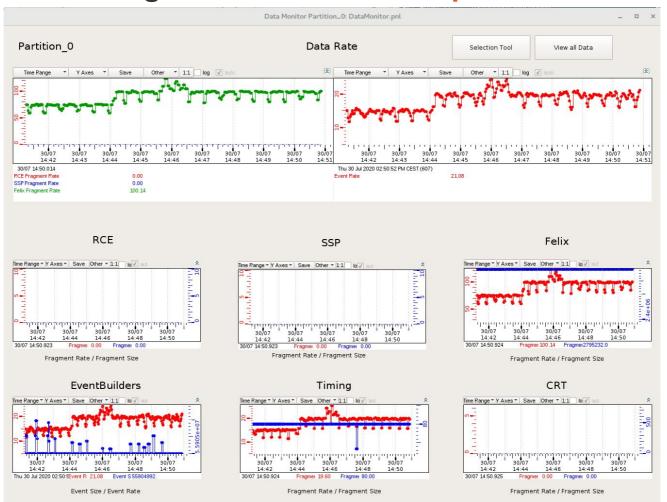
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Swp

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0,	Memory Channel Monitoring Memory Channel Monitoring
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1 103 Setup	Writes(MB/s): 1899.81 Writes(MB/s): 6512.29 Mem Ch 1: Reads (MB/s): 632.16 Mem Ch 1: Reads (MB/s): 4581.69
	Writes(MB/s): 1899.19 Writes(MB/s): 6513.20
	Mem Ch 2: Reads (MB/s): 643.41 Mem Ch 2: Reads (MB/s): 4584.34
	Writes(MB/s): 1902.44 Writes(MB/s): 6515.55 Mem Ch 3: Reads (MB/s): 620.47 Mem Ch 3: Reads (MB/s): 4668.61
	Writes(MB/s): 1890.91 Writes(MB/s): 6503.36
	Mem Ch 4: Reads (MB/s): 627.43 Mem Ch 4: Reads (MB/s): 4663.48
	Writes(MB/s): 1887.59 Writes(MB/s): 6504.35
	Mem Ch 5: Reads (MB/s): 625.34 Mem Ch 5: Reads (MB/s): 4665.36
	Writes(MB/s): 1888.96 Writes(MB/s): 6503.23
	NODE 0 Mem Read (MB/s) : 3772.78 NODE 1 Mem Read (MB/s) : 27746.65 NODE 0 Mem Write(MB/s) : 11368.90 NODE 1 Mem Write(MB/s) : 39051.97
	NODE 0 P. Write (T/s): 155073 NODE 1 P. Write (T/s): 679697
	NODE 0 Memory (MB/s): 15141.68 NODE 1 Memory (MB/s): 66798.62
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8 7.0 25533544 13901936	
0 0.0 112724 976 pts/0	
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Setup evolution for DUNE Testing 2 APAs in a single host - "Hot off the press"

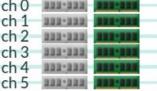


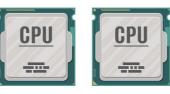
Long term support and maintenance Can the COTS solution profit from R&D outside DUNE?

- Developments and R&D driven by datacenter industry
 - Solution relies on software and low level tools written by industry
 - Higher memory bandwidths (today's maximum ~120 GB/s, recent architectures over 200 GB/s)
 - Increased memory channel density for higher throughput applications
 - Today 6 channels per CPU socket; 8 channels per socket already existing
 - DUNE bandwidth requirements are <u>feasible with current generation</u> of COTS technologies

Example of current dual-socket computer architecture with memory throughputs for six channels:

	C
	c
~20 GB/s per	c
channel	c
	C







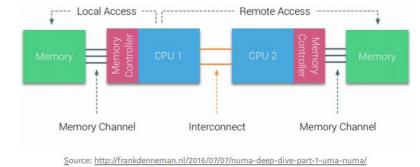


~20 GB/s per channel

COTS technology Today's trends

• CPU:

- Increasing number of physical cores per socket
- \circ Fixed processor clock speed
- Memory:
 - Higher memory-CPU bandwidths
- Interconnect
 - PCIe 4th Gen is on the market
 - PCIe 5th Gen specification is ready and <u>CXL</u> (Compute Express Link) for fast interconnect has been agreed by major companies
- Advantages for DUNE:
 - Server configuration and memory bandwidth will not be a critical element
 - Current generation architectures already provide required bandwidths



Conclusion and outlook

- Software implementation of the 10s latency buffer is feasible with today's technologies
 - Tested and verified several DUNE requirements with ProtoDUNE readout system
 - **Flexibility** of the BoardReader application is provided by the COTS implementation
 - <u>Example</u>: change trigger readout windows and adaptability to multiple interfaces
 - Satisfy DUNE requirements by taking advantage of developments in industry
 - COTS technologies evolving in favor of DUNE use-cases
- Current readout software is at still a prototype, it may be redesigned for DUNE

Outlook

- Reliability: error handling for data loss and data corruption to be tested in ProtoDUNE-II
- Demonstrate 2 FELIX card setup on a single host
- Evaluate server configurations relevant for DUNE readout system

Software driven supernova storage buffer with COTS solution



DUNE Upstream DAQ

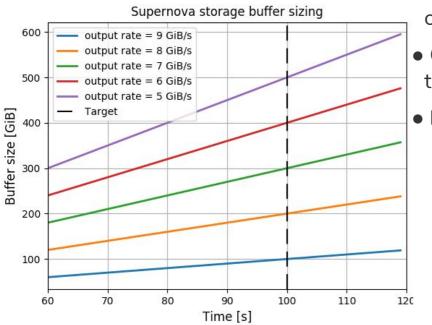
Supernova storage buffer (SNB)

- Goal:
 - Store more than 100s of continuous data stream from the detector
 - Design storage solution capable of writing out data files with required throughput for 2 APAs
- DUNE requirements:
 - Throughput of 10 GB/s per APA (DUNE requirement: two APAs in single host 20 GB/s)
 - On trigger continuously persist 1 TB of data per APA (2 TB for two APAs in single host)
 - Store data volume for 2 supernova events (4 TB in total for 2 APAs)

• Software defined storage solutions

- Develop functional aspect of the solution <u>independently</u> of the underlying hardware
- Suitable COTS technologies relevant today for the supernova buffer:
 - PCIe 4 SSD and 3DXPoint storage devices
 - RAID system
 - Persistent memory devices

Software defined storage implementation



- Simulation of the latency buffer size assuming input bandwidth of 10 GB/s
- Output bandwidth (sequential writing) of different storage technologies affects the total size of the latency buffer
- Examples for a target data taking time of 100s
 - \circ $\,$ Fast storage device with output bandwidth of 8 GB/s $\,$
 - Oversize latency buffer by 200 GB of DRAM
 - Commonly available in today's servers
 - Slow storage device with output bandwidth of 5 GB/s
 - Oversize latency buffer by 500 GB of DRAM
 - Supported on current generation of servers

Balance performance of storage technologies, features provided and overall sizing of the system

Storage technologies suitable for SNB PCIe 4th gen SSDs and modern storage media

• PCIe 4 gen SSDs

- Bandwidths up to 8 GB/s for a 4 lane device
- Reasonable to expect an average bandwidth per device of ~ 5 GB/s
- High bandwidth achieved by using performance tools developed by industry (e.g. <u>SPDK</u>)
- Some devices already available today on the market [EXAMPLE]
 - NVMe PCIe 4th Gen x4 lanes with sequential write bandwidths 5 GB/s
 - Combining two devices already satisfies throughput requirement for 1 APA
- 3DXPoint storage devices (e.g. Intel/Micron)
 - Claimed 9 GB/s in sequential write throughput (single device for one APA)
 - Establishing partnership and preparation of a testing platform in the next months
 - Planning full evaluation of the technology to test suitability for DUNE DAQ applications

Storage technologies suitable for SNB RAID system

- RAID = Grouping multiple disks to form a single logical volume
- Applications for the DUNE supernova storage buffer:
 - Load balancing
 - Increase throughput
 - Data redundancy
 - Device hot swapping in case of failures
- RAID systems based on PCIe 4.0 x16 lanes SSD adapters already existing [LINK]
 - Connect up to 4 SSD devices with bandwidths up to 20 GB/s (realistically 15 GB/s)
 - Comfortably satisfies supernova buffer throughput requirement for single APA
 - Procurement expected in the next months to test the technology

Storage technologies suitable for SNB Example of RAID configurations with today's SSDs

- Example of RAID0 (stripe) system with PCIe 4th Gen (x4 lanes) SSDs
 - Single drive write bandwidth: 4.5 GB/s
 - 2 <u>non-redundant</u> RAID groups for two APAs
 - Each RAID group with 3 drives of 1 TB:
 - Total bandwidth per APA: **13500 MB/s**
 - Comfortably satisfies supernova DUNE requirements for 2 APAs
- Example of possible RAID10 system based on PCIe 4th Gen (x4 lanes)
 - Single drive write bandwidth: 4.5 GB/s
 - 2 redundant RAID groups for the two APAs
 - Each RAID group with 4 drives of 1 TB
 - Total bandwidth per APA: 9000 MB/s
 - Almost fully satisfies DUNE requirements for 2 APAs with data redundancy

Storage technologies suitable for SNB Persistent memory devices



- Memory devices with high bandwidth: O(10) GB/s
 - Suitable candidates for the DUNE supernova buffer
- Affordable large capacity
 - \circ $\;$ Available device sizes: 128 GB, 256 GB, 512 GB $\;$
 - Today's maximum capacity per CPU socket 3 TB
 - Suitable for two APAs
- Persistent Memory Development Kit (PMDK)
 - Well established low level software stack to develop applications for PMEM devices
 - Multiple use cases: object storage, data logging, memory mode
 - Performance optimization:
 - Direct access operation
 - High writing throughput less dependent on blocksize (contrary to storage devices)

Supernova storage buffer with persistent memory Features

- Validated feasibility of persistent memory devices for the supernova storage buffer
 - Sustained <u>80% of required data throughput</u> for a single APA
 - Stored superchunks of 5568 bytes at 166 kHz per link
 - Produced and persisted more than 100 seconds of data for a single APA
- Integration with Upstream DAQ
 - Fully integrated the SNB prototype with the OnHost BoardReader application
 - Implemented trigger command to send data to persistent memory devices instead of forming artDAQ fragments for downstream processing

Supernova storage buffer with persistent memory Example of data stored

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0000470:	963e	0ccc	a983	983d	d36a	1389	3a8f	dd9e	.>=.j:
0000480:	7358	3994	c2d4	23a8	3c98	ab13	d869	938d	sX9#. <i< td=""></i<>
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00004e0:	9c41	dbdc	b9a3	9c3d	de96	5369	3990	b91c	.A=Si9
00004f0:	0309	3a8e	a162	d3b9	3789	fed9	c8e8	8f98	:.b7
0000500:	0000	d942	02ae	578c	0000	0000	aaaa	aaaa	BW
0000510:	76e9	59c8	958e	7aa8	a923	9639	1c92	0ae3	v.Yz#.9
0000520:	9c3e	d2cd	8983	a23f	ed52	5309	3a8e	bdfb	.>?.RS.:
0000530:	d358	3993	d9db	3348	3c8d	230f	caf9	968d	.X93H<.#
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Example of binary output in the persistent memory device

Created 10 files in total, one for each link

• 100 GB for each PMEM file

-rw-rr	1	np04daq	np-comp	105G	Jul	16	16:45	pmem_pool_file_channel_0
-rw-rr	1	np04daq	np-comp	105G	Jul	16	16:45	<pre>pmem_pool_file_channel_1</pre>
-rw-rr	1	np04daq	np-comp	105G	Jul	16	16:45	pmem_pool_file_channel_2
-rw-rr	1	np04daq	np-comp	105G	Jul	16	16:45	<pre>pmem_pool_file_channel_3</pre>
- rw-rr	1	np04daq	np-comp	105G	Jul	16	16:45	pmem_pool_file_channel_4

Supernova storage buffer with COTS solutions Adaptability

- Software defined storage makes the system independent of the underlying storage hardware
 - Treat the SNB buffer as a directory where to store binary files
- Possibility to include new features once the SNB event is stored
 - Post-processing on the collected data
 - Compression (if needed)
- Expose the data to different file formats:
 - Example: store the data output as HDF5 files if needed by Dataflow
- Possibility to use of the data store for other applications
 - Example: store debugging stream

Supernova storage buffer with COTS solutions Reliability

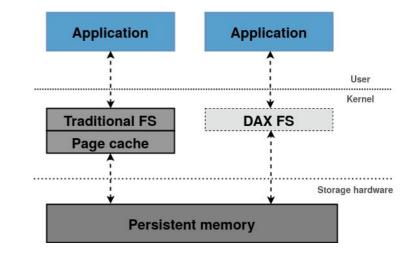
- Data integrity can be achieved at the application level
 - Design software to handle data integrity issues caused by memory hardware errors
 - PMEM tools are available to handle error correction and check data integrity
 - Not tested yet in the current prototype
- Data redundancy
 - RAID: copy the collected data
 - Hot swapping of failing disks
- Different reliability features provided by different storage technologies

Current setup for persistent memory solution Testing platform used in ProtoDUNE

- Hardware:
 - Cascade Lake Xeon® Platinum L SKU processor (high end server)
 - PMEM performance validated also on lower end servers
 - Currently testing SNB buffer integration on lower end servers
 - 192 GB DRAM and 6 TB persistent memory
- Software
 - Mounted PMEMs as **direct-access** (DAX) filesystem
 - Low level tools used to write directly to PMEM

(pure device operation)

- Prepare an empty PMEM file
- Memory map it (function provided by PMDK)
- Persist in PMEM devices



Current setup for persistent memory solution

Resource requirements per APA

- Used separate physical cores for each FELIX link
 - Core pinning to each CPU socket is necessary to avoid remote access between NUMA nodes
- SNB storage has <u>limited impact on memory utilization</u> (less than 10%):
 - Advantages of using COTS tools to copy data directly into storage system (specific pmem copy function)
 - Direct access operation: bypass operating system cache
 for higher throughput
- Future development for DUNE:
 - Optimize the software layer to achieve maximum performance from PMEMs

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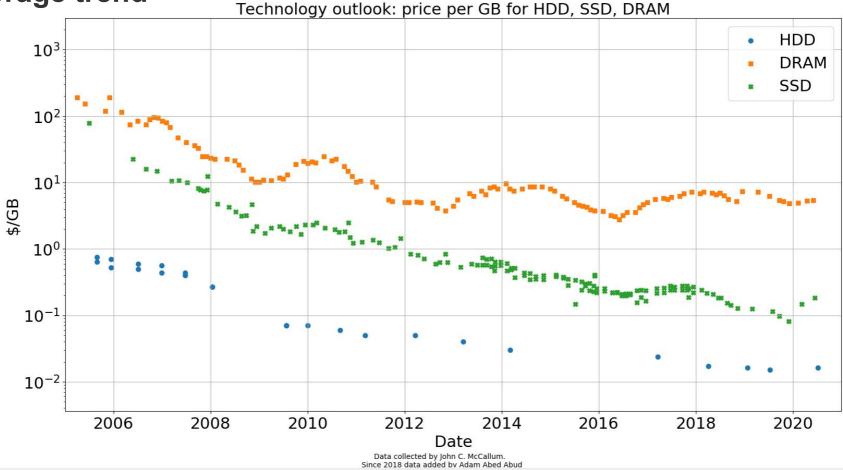
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Supernova storage buffer with COTS solutions Long term support and maintenance

- High performance storage developments are driven by data center and cloud provider needs:
 - Active user community [LINK] : Cisco, Dell EMC, Huawei Cloud, Oracle, etc.
 - Many use-cases relevant for DUNE applications:
 - Improve performance of by using modern storage media
 - Advanced caching layer for low latency applications [EXAMPLE]
- Advantages provided by solution fully based on COTS components
 - Profit from R&D made by industry and use consolidated development tools
 - Use of extensively tested integration tools (configuration and debugging of the solution)
- Learning and development time for the SNB implementation with persistent memory
 - 4 months by 1 person (PhD student)
 - Further testing and integration with other sub-systems in the next months
 - Test data integrity tools provided by the PMEM technology

COTS technology

Storage trend



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Conclusion and outlook

- Software based implementation of the SNB buffer is possible today with COTS technologies
 - Different solutions available: PCIe 4 SSDs, 3DXPoint devices, RAID system, PMEM devices
 - Implementation with PMEM devices developed only in a few months
 - Satisfies 80% of throughput requirement for a single APA
 - Further improvements/optimizations can still be made
- Storage trend is promising and in the right direction for DUNE applications
 - Large memory capacity and fast SSDs are becoming widely spread in industry
 - Industry is moving towards high throughput storage applications

Outlook for the next months

- Optimize workloads for SNB implementation with PMEMs
- Test **storage** solutions
 - Benchmark performance of PCIe 4th gen SSD devices and/or modern storage media
 - Deploy RAID system DUNE Readout Technology Review 30/07/2020 Adam Abed Abud

Thank you Questions?

Adam Abed Abud (Univ. Liverpool / CERN)

adam.abed.abud@cern.ch



Cost estimate for RAID system with PCIe 4 SSDs

RAID10 with "Sabrent Rocket" (PCIe 4th Gen x4 lanes SSDs) [LINK]

- Single drive write bandwidth: **4.5 GB/s**
- 2 redundant RAID groups for two APAs
- Each RAID10 group with 4 drives of 1 TB:
 - Total bandwidth per APA: 9000 MB/s
 - Cost: 1600 CHF for the storage and 200 CHF for the RAID

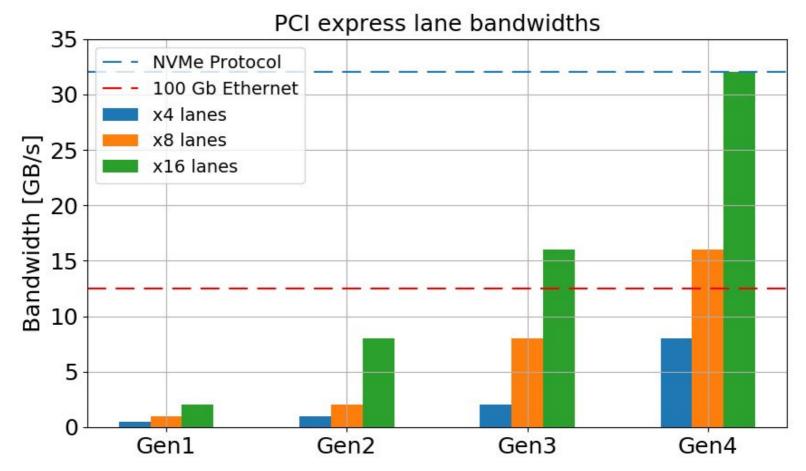
RAID 10 (Striped mirrors) Performance Calculation:

Total Performance = 18000 MB/s	Compare two RAID configurations
Total usable capacity = 0.00 TB	Calculate RAID10 capacity
Reads 0%, Writes 100%	Notes:
Number of RAID groups = 2	Minimum number of drives per RAID10 group = 4
Number of drives per RAID group = 4	Must have even number of drives.
Total number of drives = 8	IO penalty (read) = 1/1 (one RAID IO per each host IO)
Single RAID group performance = 9000 MB/s	IO penalty (write) = 2/1 (2 RAID IOs per each host IO)
Single drive cost = 200	Fault tolerance = 1 (min) to 2 (max) disk drives per RAID group
Cost per TB usable = 400000.00	
Total cost = 1600.00	

[LINK]

COTS technology

PCIe lane bandwidths



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