Emerging approaches for a flexible and energy-efficient readout

Prafull Purohit

CPAD Workshop 2023

@BrookhavenLab

Outline

- Background
  - Imaging applications
  - Readout mechanisms
- Arbitration mechanisms:
  - Tree-based arbitration
  - Ring-based arbitration
- Trade-offs
- Summary

Before we begin...

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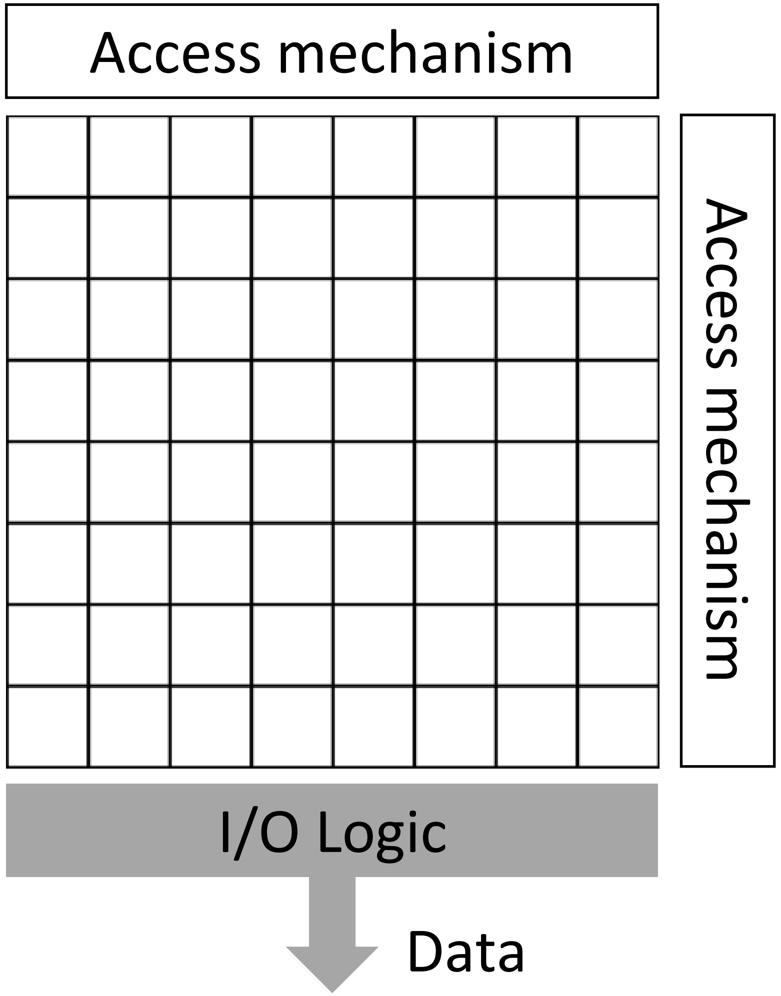
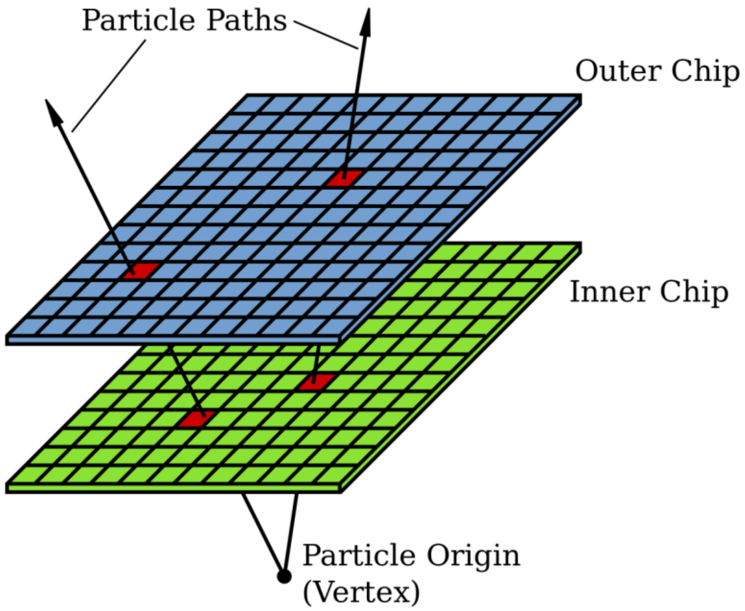
Pixel array

- Consists of:
  - 2D array of pixels
  - **Readout circuit**
- Different types of detectors
  - Applications
  - Capabilities/features
- Detectors for scientific applications



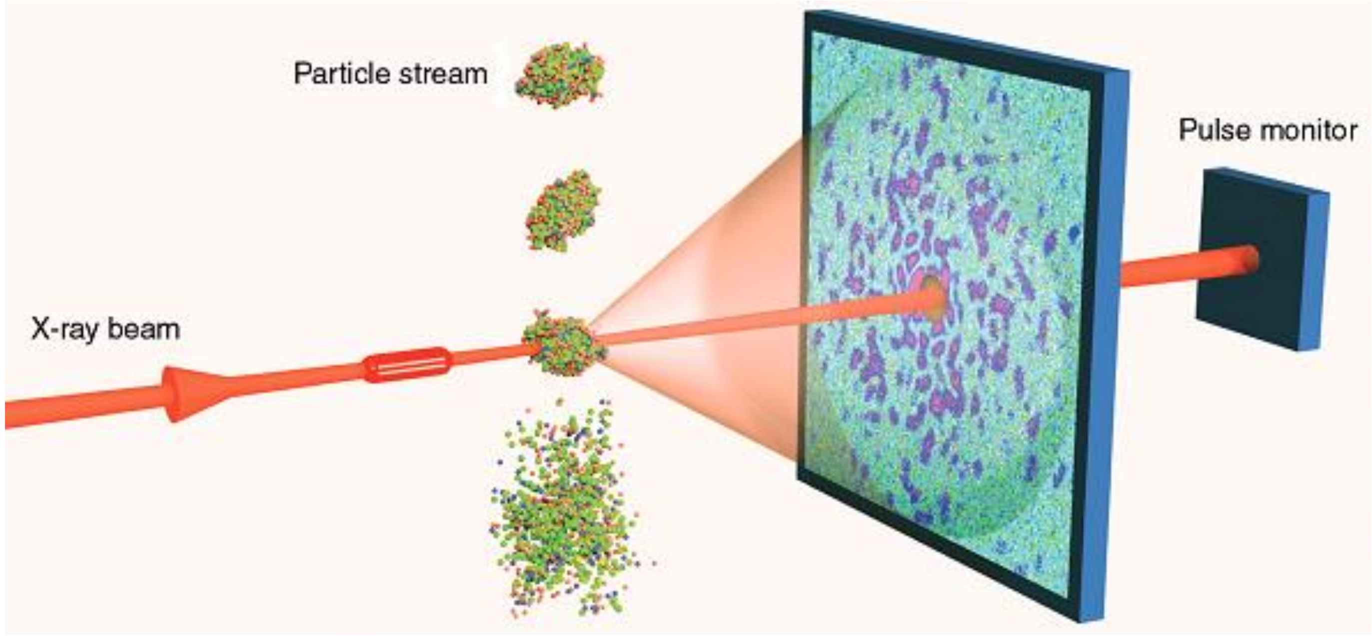
“Sparse” imaging

Vertex tracking



[Wikipedia.org]

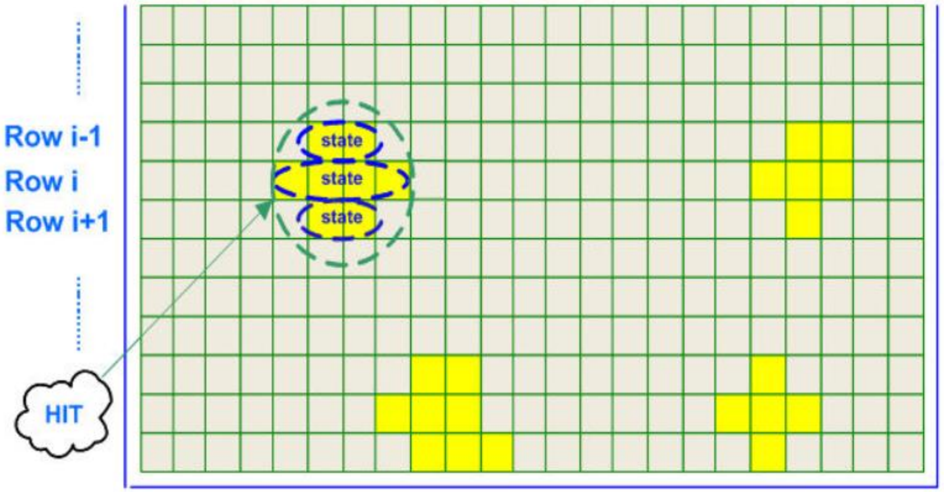
Single shot imaging



H. N. Chapman, et al. (2007)

“Cluster” or Region-of-Interest (ROI)

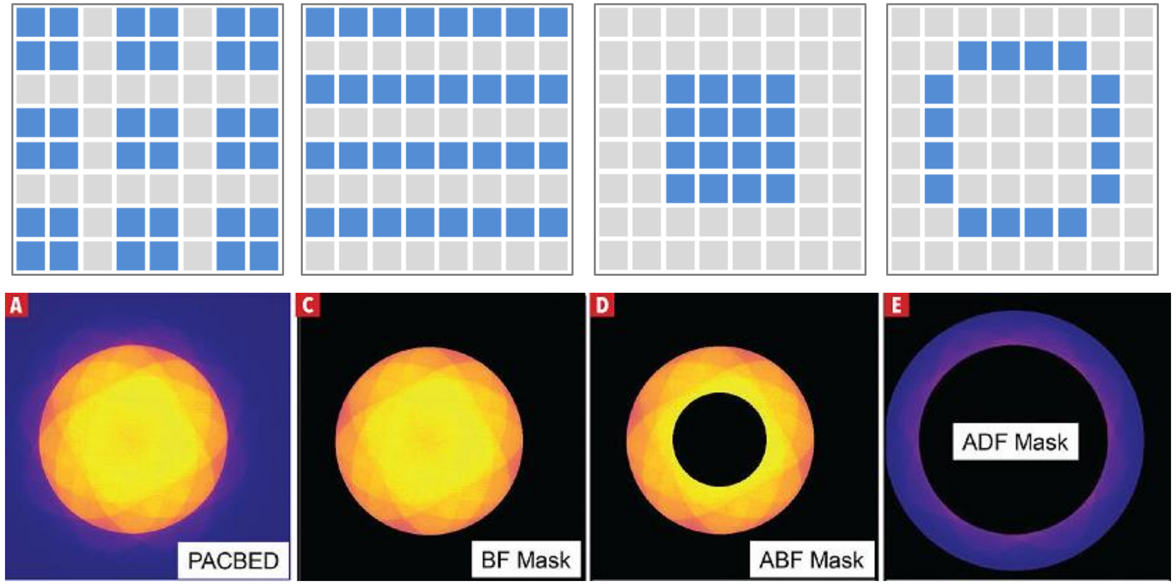
“Hit” cluster



Representative HIT cluster

A. Himmi (2009)

Read region-of-interest



Levin, Barnaby DA, et al. (2020)

Full-frame readout or “Imaging”

X-ray tomography

- Provides 3D structural properties
- Multiple images at different angles
- Information from all pixels
- 100s to 1000s of such images

4D STEM

- Collect full 2D diffraction pattern at each scan position
- Different imaging masks applied in post processing
- 100s to 1000s of such images
- Requires high-speed readout

Readout approaches

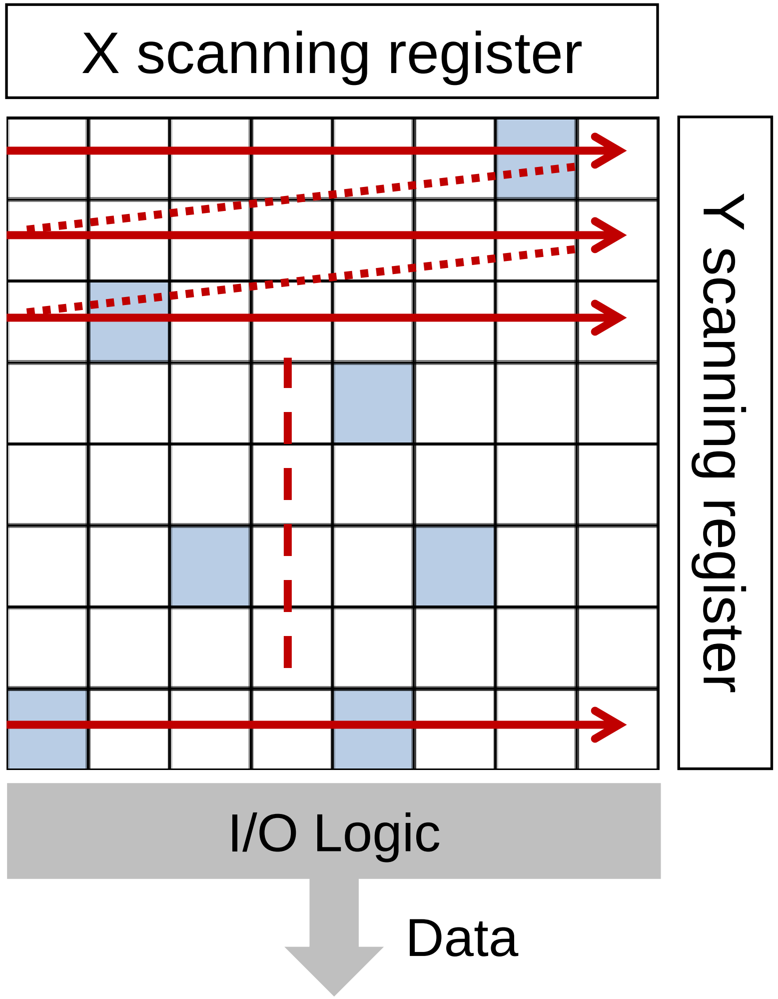
- A detector supporting different readout modes:
  - Sparse mode (mode-S)
  - Cluster mode (mode-C)
  - Full-frame mode (mode-F)

- Different (existing) ways to read an array:
  - Scanning readout
  - Compressed readout
  - Arbitrated readout

Scanning readout

- Passive data readout
- Sequential, one pixel at a time
- I/O bandwidth: high
- Latency: high
- Ex: CCD, CMOS imagers

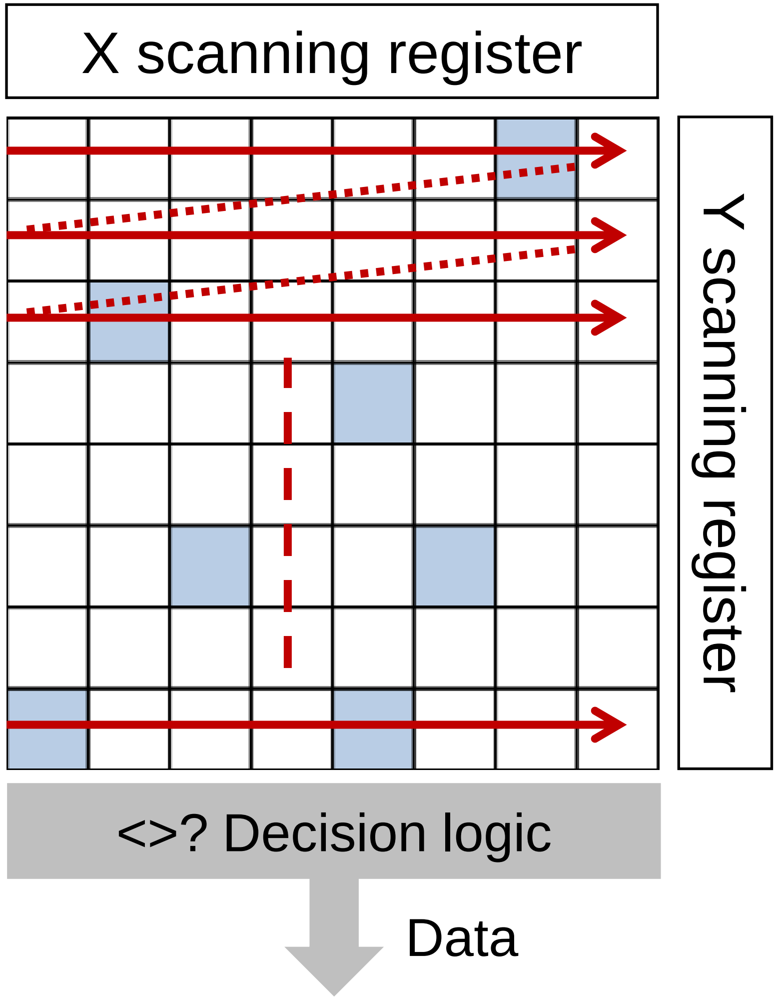
+ banking, column parallel readout, etc.



Compressed readout

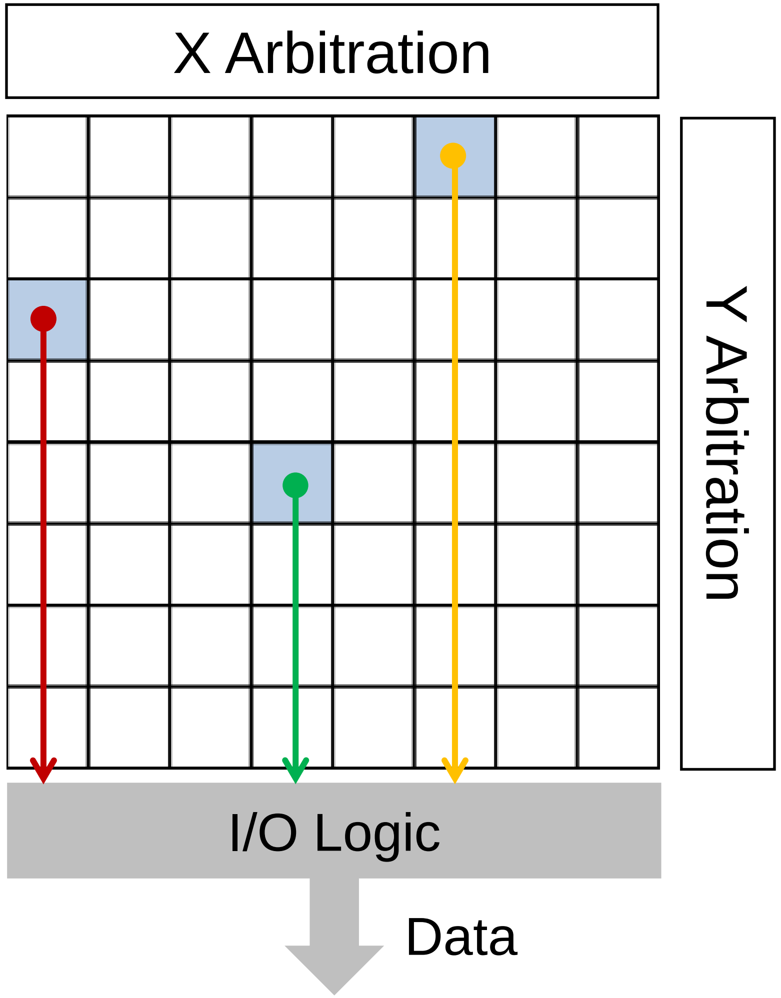
- Passive data readout
- Sequential (with smart encoding schemes)
- I/O bandwidth: lower
- Latency: high
- Ex: scientific imagers

+ ROI, zero-thresholding, sub-sampling, etc.



Arbitrated or Event-driven readout

- Active data readout
- One pixel at a time (arbitrary row/column)
- I/O bandwidth: low
- Latency: low
- Ex: event-camera, dynamic vision sensor
- Pixel ID is part of the data

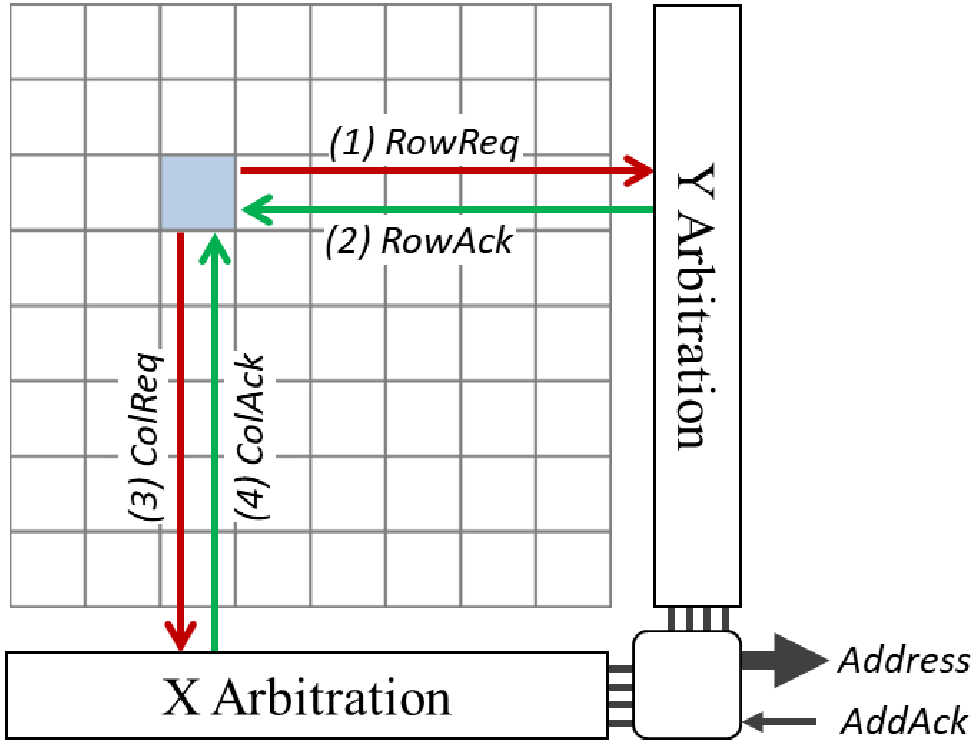


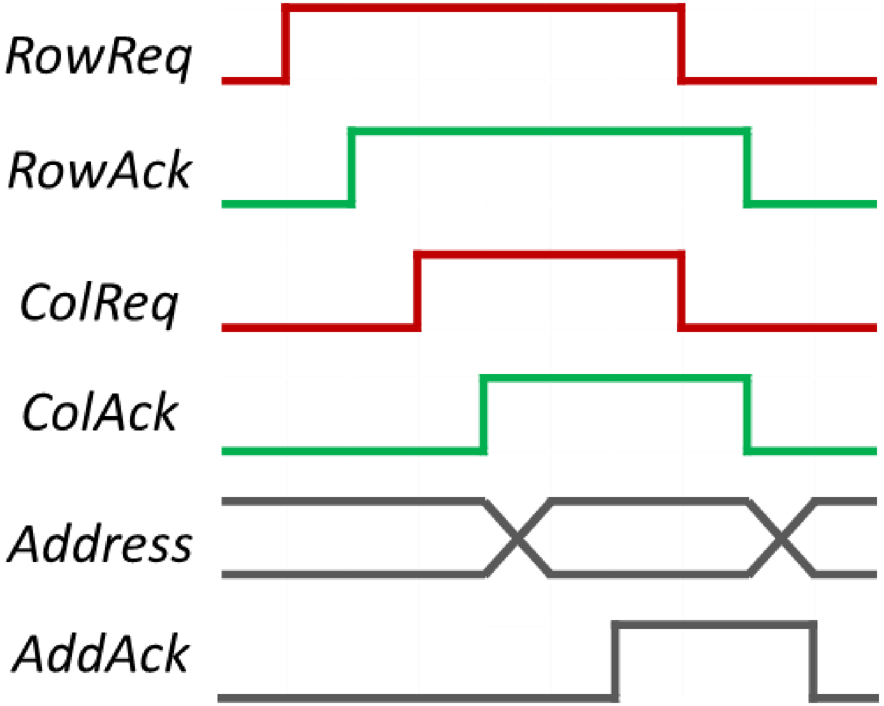
Readout modes and approaches

	Sparse mode (mode-S)	Cluster mode (mode-C)	Full frame mode (mode-F)
Scanning readout	✗	✗	✓
Compressed readout	✗	✔	✓
Arbitrated readout	✓	✓	✔

✗ Not supported ✓ Supported ✔ Not efficient

Arbitrated readout



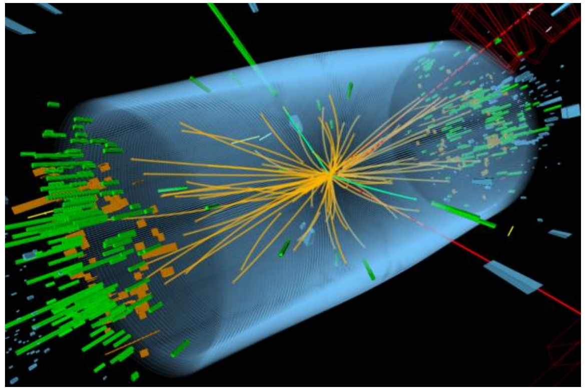


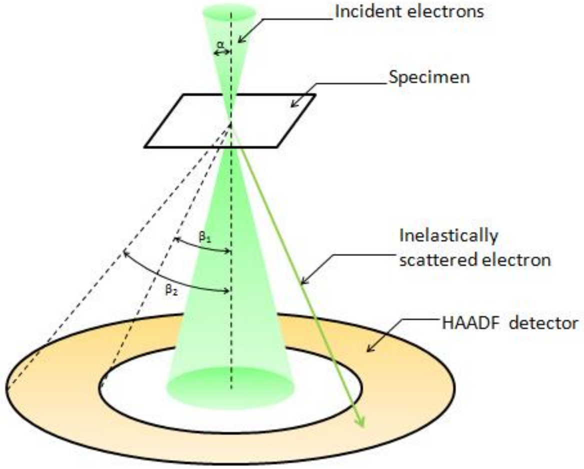
Event-driven Imaging

- Originated from Silicon Retina project
  - Mahowald and Mead in early 90s
  - Designed an imager inspired by human retina

- Many visible light imagers designed
  - DVS, ATIS, DAVIS, etc.

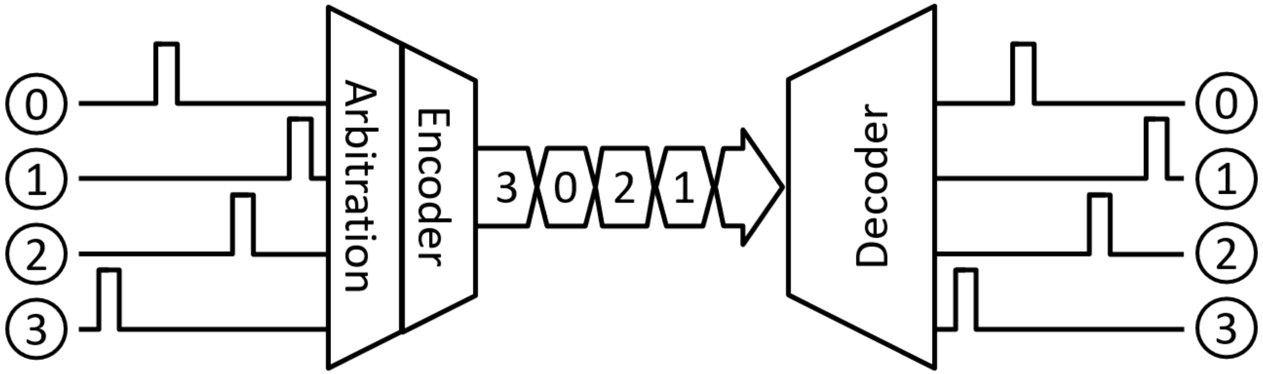
- Application in scientific imaging:
  - High Energy Physics
  - Synchrotron Radiation Imaging
  - Electron Microscopy



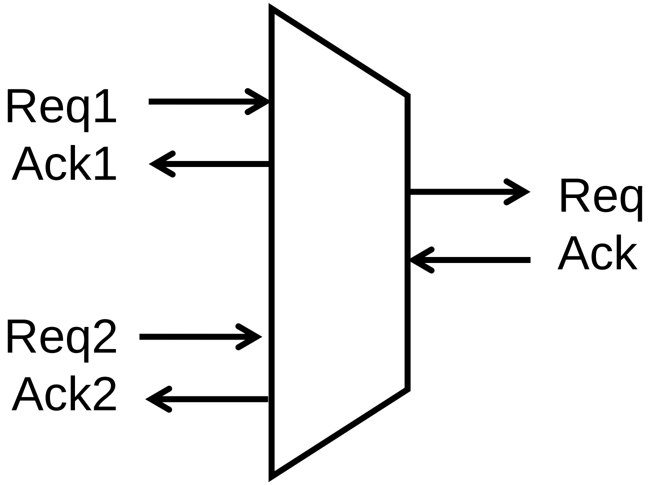


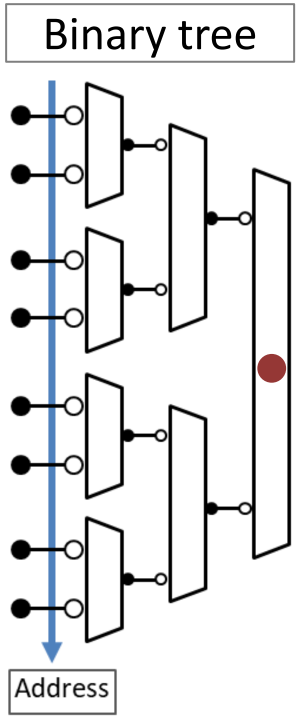
Address-Event Representation (AER)

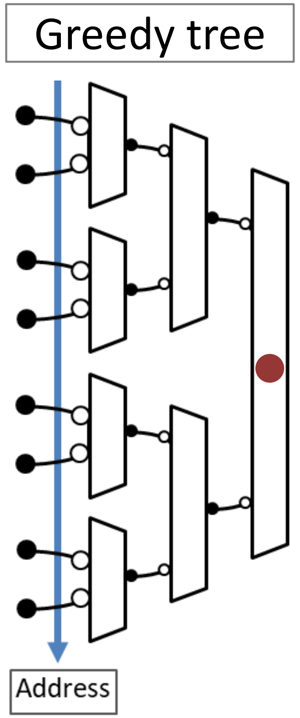
- Asynchronous communication protocol
  - encode sparse neural events
  - event ID is encoded as address
  - time-multiplex that information onto a shared output channel
- Proposed for communication between neuromorphic chips
  - used in imagers to communicate pixel ID



Tree-based arbitration

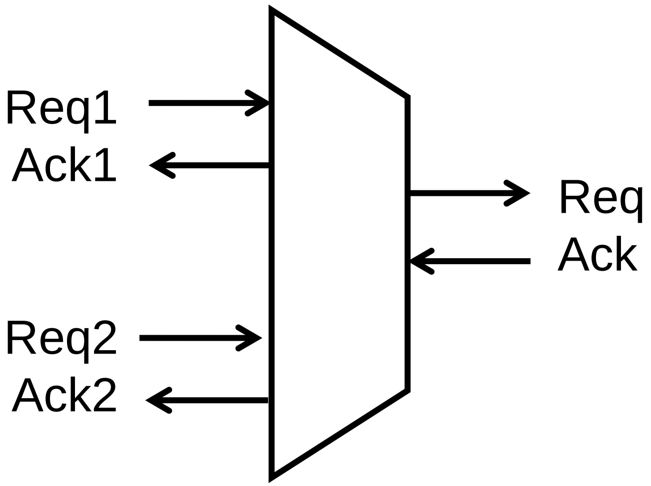


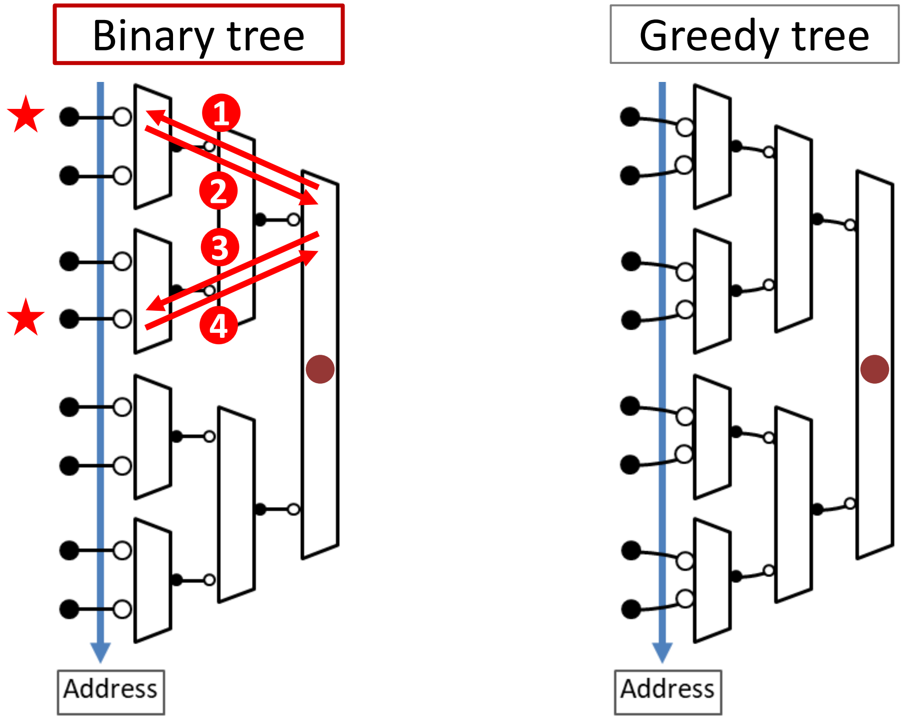




● Token
●—○ Channel
—● Active end
—○ Passive end

Tree-based arbitration





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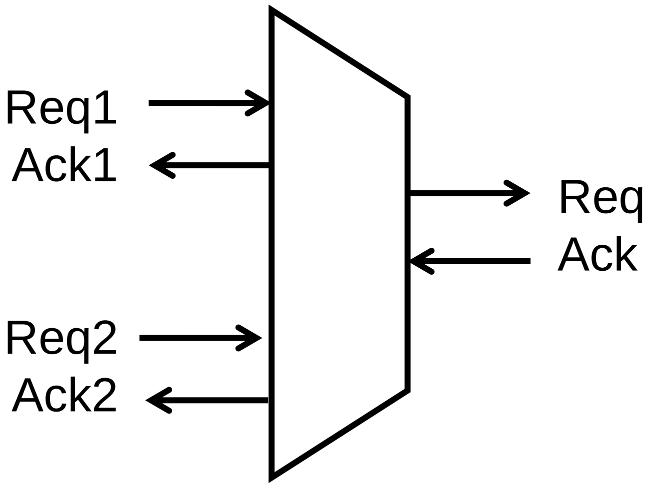

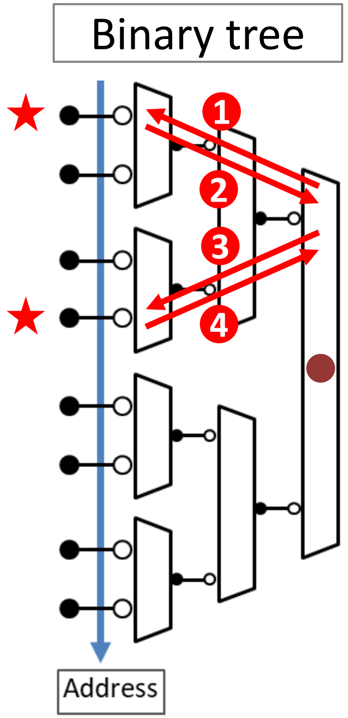

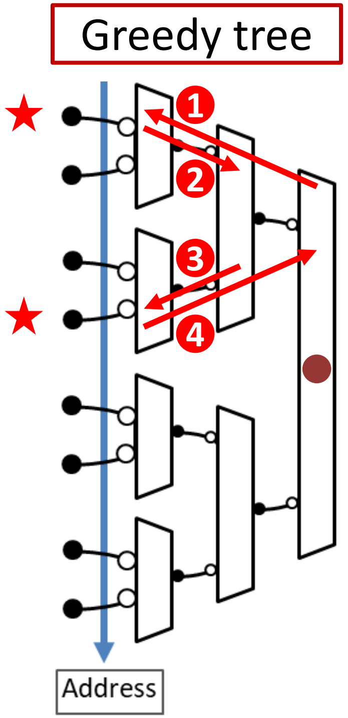

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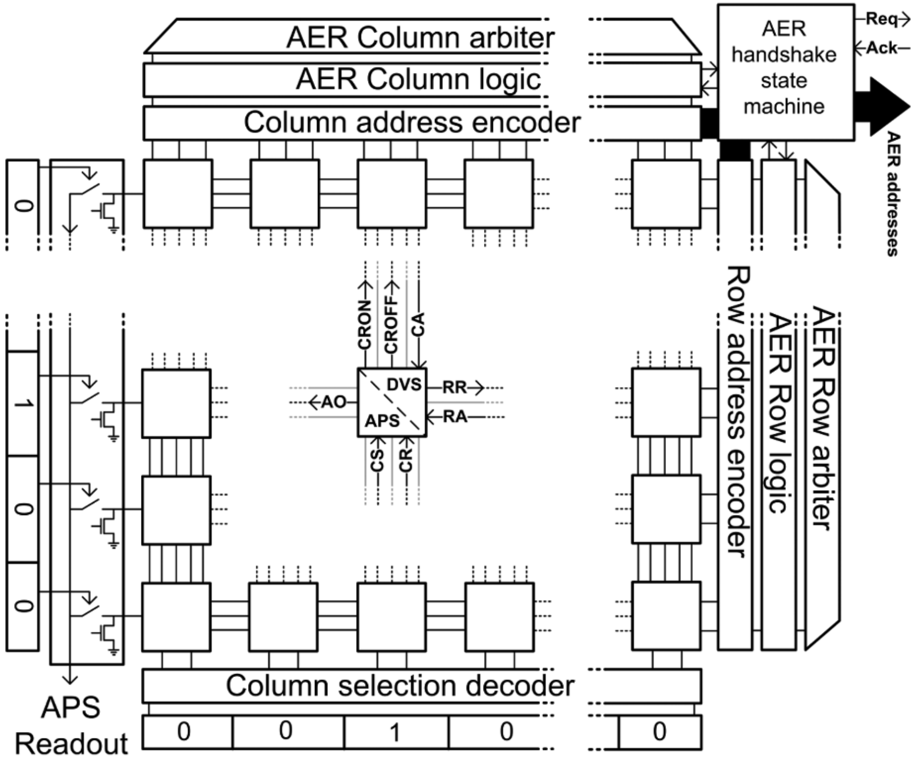
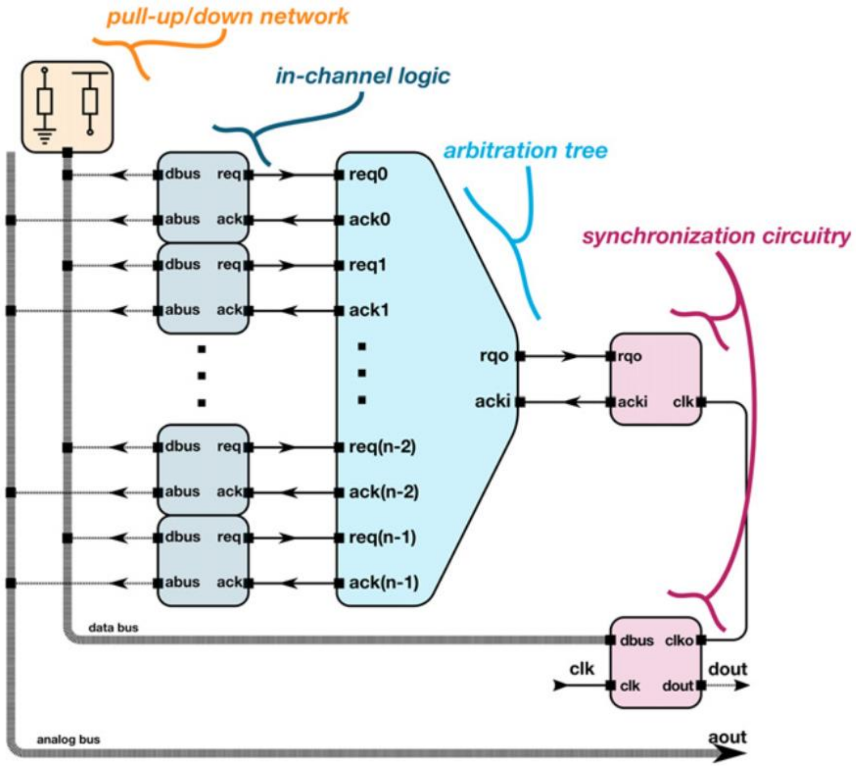
Data with AER

Event-cameras are good at reporting events. What if you have data from each pixel?



T. Delbruck, et al. (2014)

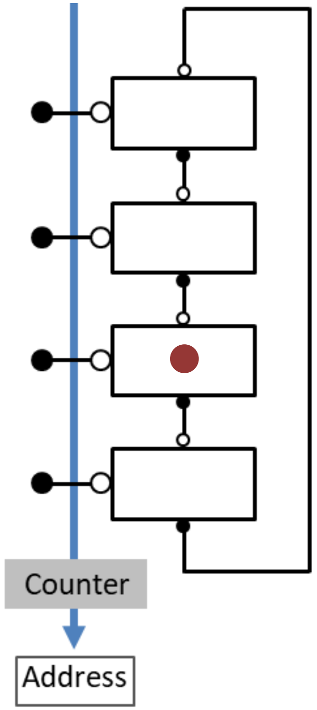


D. Gorni, et al. (2021)

- Top/right edge logic for event-driven readout
- Bottom/left for scanning readout

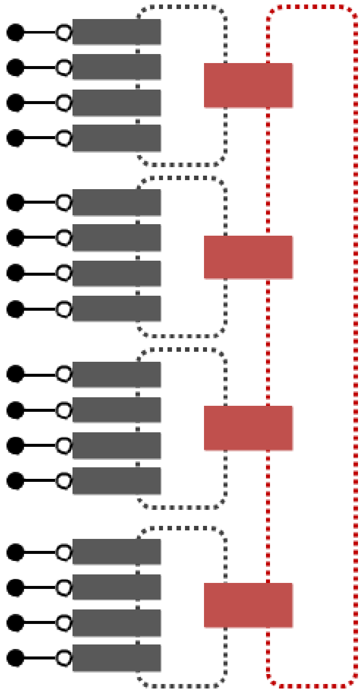
Ring-based arbitration

Linear token-ring



N. Imam, et al. (2013)

Hierarchical token-ring



P. Purohit, et al. (2021)

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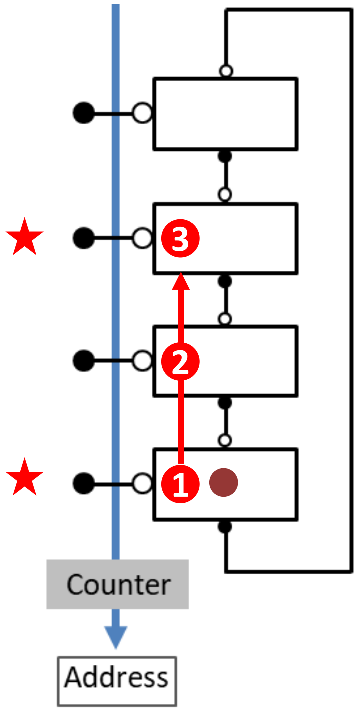

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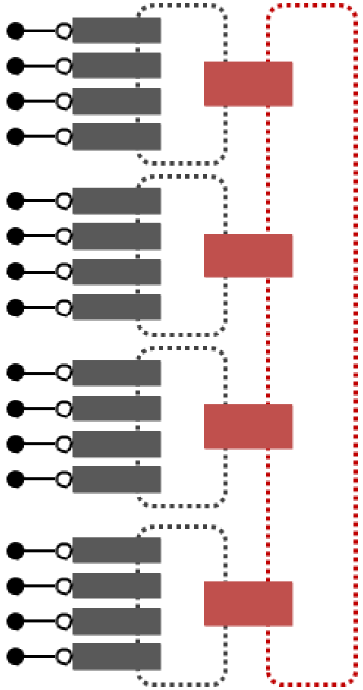

P. Purohit, et al. (2021)

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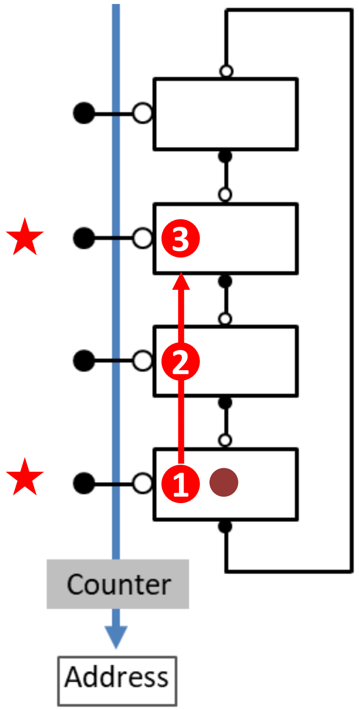

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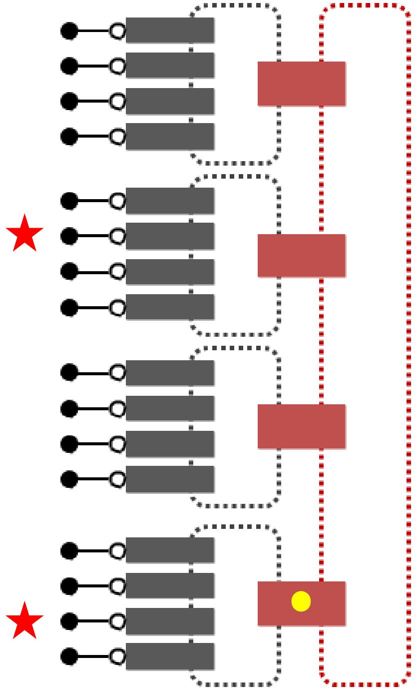

P. Purohit, et al. (2021)

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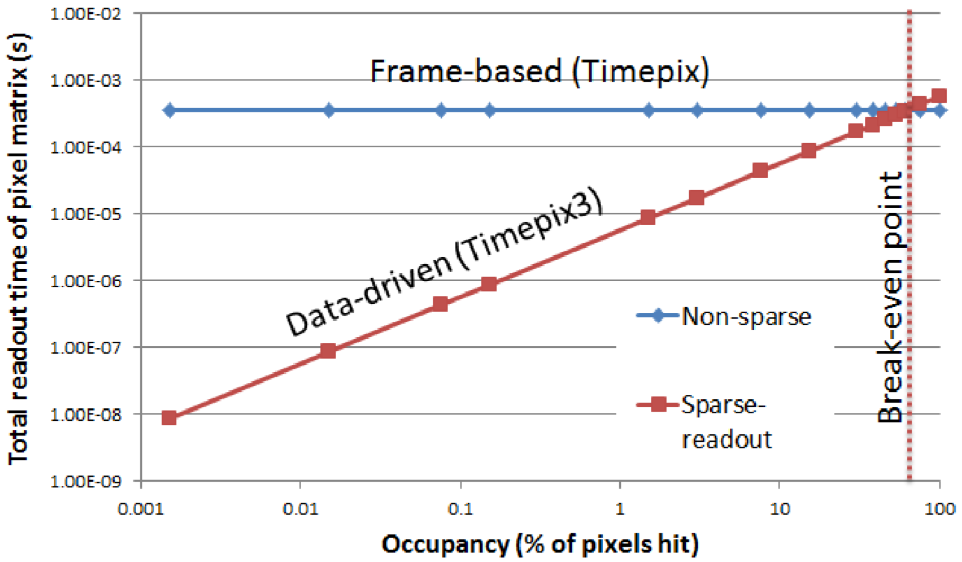
Trade-offs

Performance depends on:

- Amount of information/communication
- Arbitration mechanism
- Locality of the events

Amount of Information

- For every event:
  event-address, data, & timestamp!
- Read one data packet per event
- Data rate is proportional to event rate
- Good for low to moderate event rate



$$T_{\text{readout}} = N_{\text{pixels}} * bits_{\text{pixel}} / BW$$

T. Poikela, et al. (2014)

- Example: 28 bits/pixel, and 14-16 bits of address
- For occupancies ≥ 50 % → full-frame readout becomes faster

Arbitration mechanism - evaluation

- Number of token hops

		Delay	**K=16**	**K=64**	**K=256**
Sparse mode^{+}	🟧 *Binary tree*	$2 * (\log_2 K - 1)$	6	10	14
	🟧 *Greedy tree*	$2 * (\log_2 K - 1)$	6	10	14
	🟥 *Token ring*	$(K + 1)/2$	8.5	32.5	128.5
	🟩 *Hier-ring*	$(H + L)/2$	4	8	16
Full frame mode	🟥 *Binary tree*	$2K * (\log_2 K - 1)$	96	640	3584
	Greedy tree	$3K - 6$	42	186	762
	🟩 *Token ring*	K	16	64	256
	🟧 *Hier-ring*	$K + 2H$	24	80	288

P. Purohit, et al. (2021)

- K = number of inputs = (H * L)
- H = input in H-ring
- L = input in L-ring

🟥 worst

🟩 best

🟧 good

Arbitration mechanism - evaluation

- SPICE simulations

		K=16 (ns)	***K=64 (ns)***	***K=256 (ns)***
Sparse mode$^+$	*Binary tree*	1.4	2.1	2.8
	Token ring	8.2	34.6	140.2
	Hier-ring	4.2	8.4	16.8
Full frame mode	*Binary tree*	22.4	134.4	716.8
	Token ring	17.6	70.4	281.6
	Hier-ring	25.6	86.4	313.6

- *K* = number of inputs = (H * L)
- H = input in H-ring
- L = input in L-ring

🟥 worst

🟩 best

🟧 good

P. Purohit, et al. (2021)

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Summary

- Scanning readout

  Number of pixels ↑ → Power ↑ , Required bandwidth ↑

- Event-driven readout has potential

  Number of events ↑ → Latency ↑ , Timing ↓

- Need to customize readout mechanism for pixel detectors