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Enabling Ultra-low Power Machine Learning at the Edge

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Event Sensors for Embedded Edge AI Vision Applications

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Outline

- Introduction event-based vision
- Event sensors for edge-AI applications – requirements and design targets
- Design and implementation:
  – Sensor features
  – Processing features
  – Data formats and interfaces
  – Power modes
- Summary / Conclusion

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Image Sensing and Computer Vision

Image Sensor

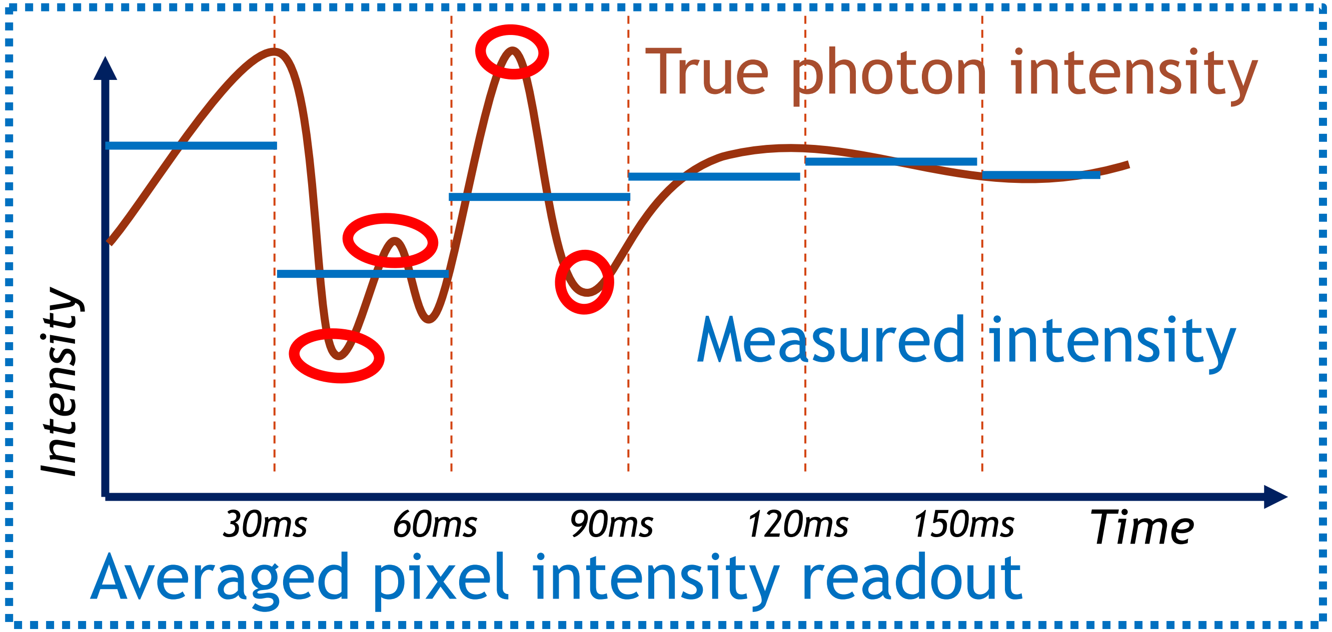
- Integrate light intensity in a time interval (exposure time)
- read out *average* exposure
- at *regular* intervals (frame rate)
- for *all* pixels

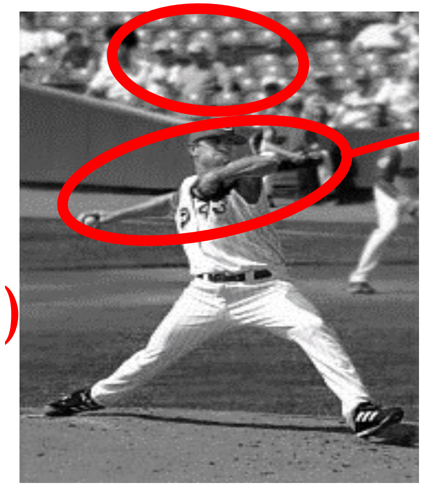
➔ Image = snapshot in time (static)

CV: Motion acquisition based on series of *static* images

Problems with frames in CV:

1. Temporal details lost (under-sampling)
2. Displacement, blur (under-sampling)
3. Redundant data (over-sampling)





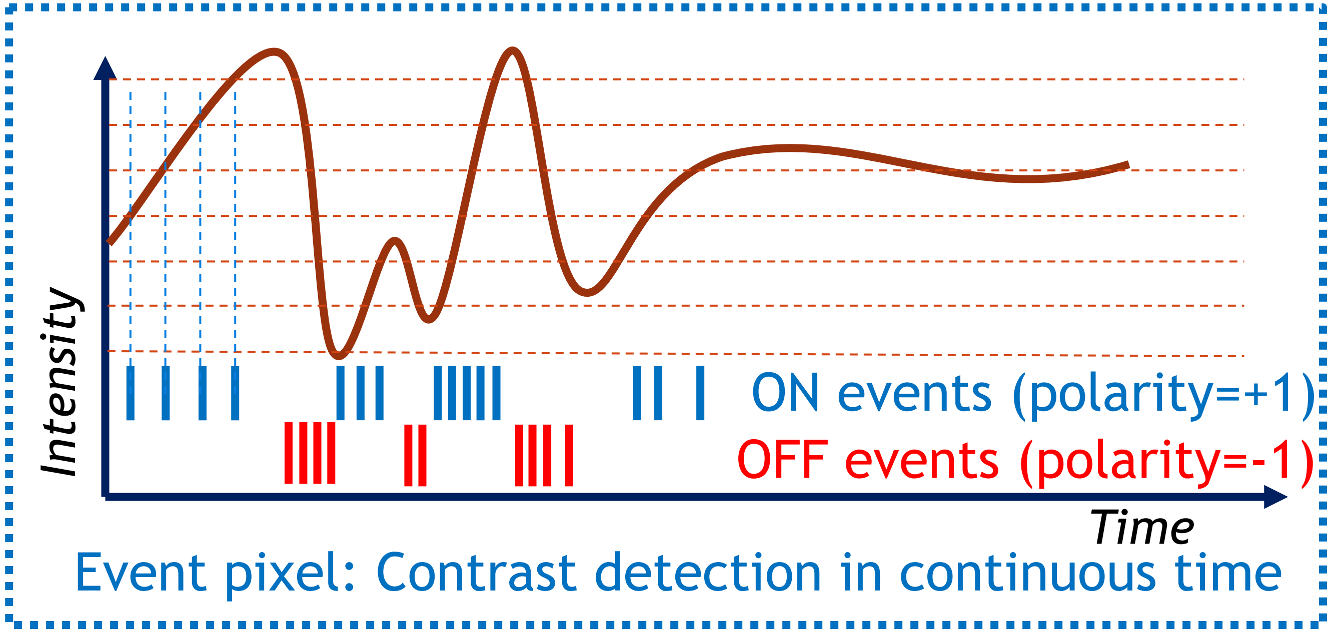
Introduction Event-based Vision

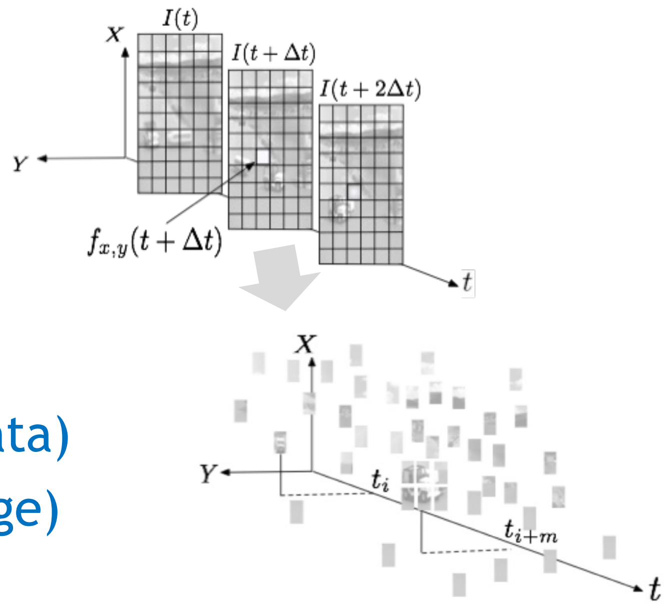
Different dynamics in different parts of the scene
- Each pixel sees a different signal

Not one sampling rate for all pixels (=frame rate)
- but **many** (= as many as pixels), and
- sampling rates can **vary,** on the fly, and **pixel-individually**

How? Each pixel individually controls its own sampling based on the input signal
- Change sampling domain→ from time to **amplitude**
- Encode information in "**events**“

From images to stream of pixel-individual data

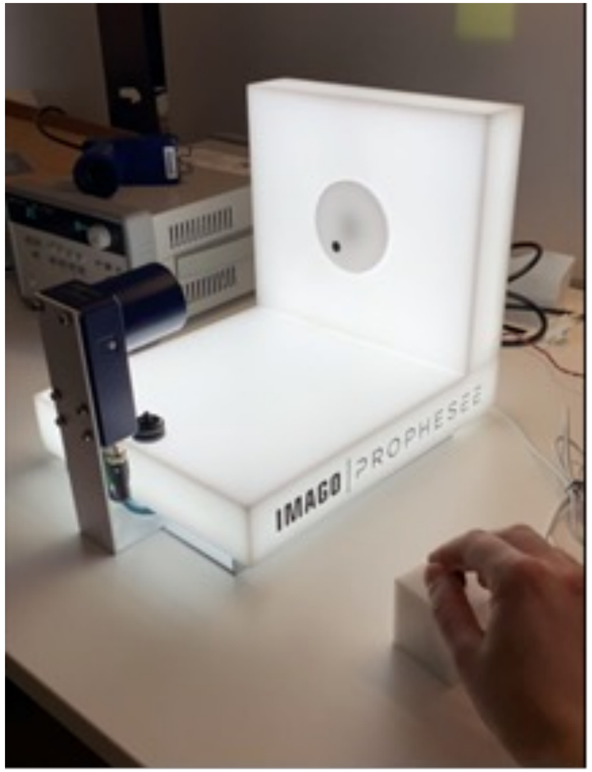


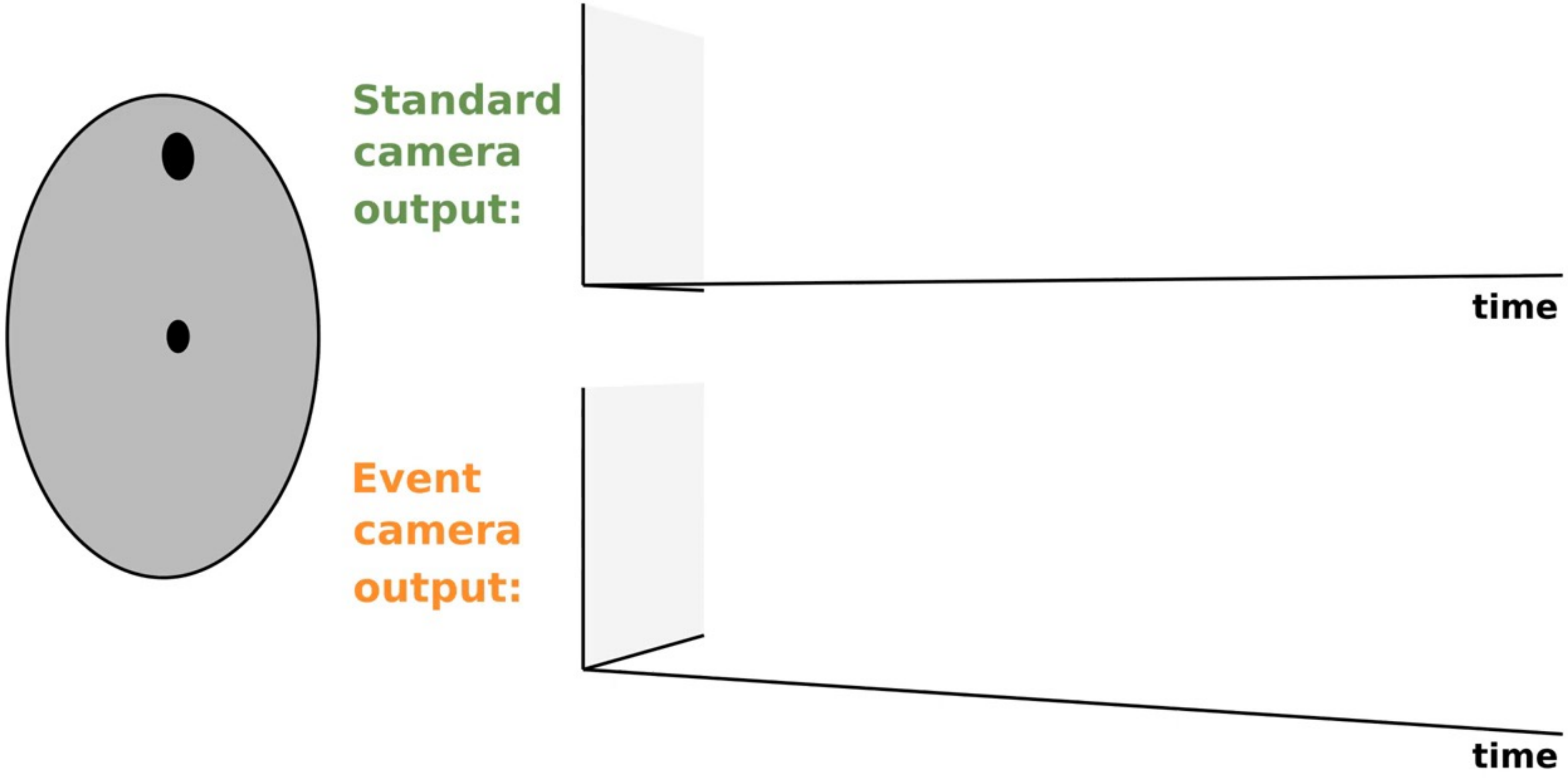


Event sensor characteristics

- Captures fine temporal detail of motion → **fast**
- Inherent data compression by eliminating redundant information → **sparse** (focus on relevant dynamic data)
- Pixel-individual log-domain operation (relative change) → high **dynamic range**

Introduction > Event Sensor Acquisition Principle





UNIZH, Robotics and Perception Group, https://rpg.ifi.uzh.ch/

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Event Sensors for Edge-AI Applications

Challenges for event sensors usage and integration

- Diverse fields of application for event sensors: Industrial, surveillance, IoT, AR/VR, mobile, automotive, …
- Unconventional format of the event data
- Unfamiliar encoding of dynamic visual information as events
- Non-constant data rates
- Non-standard interfaces and data formats, non-standardized interface protocols

Prophesee has developed the first of a new generation of event sensor designed with the explicit **goal** to improve **integrability** and **usability** of **event sensing** technology in **embedded at-the-edge vision system.**

Design Targets

Integrability and usability in embedded edge-AI and IoT vision systems

- **Interfacing and system integration**
  - Flexible/programmable event data pre-processing, filtering and formatting
  - Industry standard interface compatibility (MIPI, DCMI)
  - Low-latency connectivity for low-power uCs, neuromorphic processor architectures, SNN accelerators, …
- **Power optimization**
  - Hierarchy of power-modes for adaptative application-specific power optimization
  - Ultra-low power/always-on operation with sensor and system wake-up features
  - On-chip power management
  - Embedded microcontroller core for improved sensor flexibility and useability at-the-edge (data statistics, meta data, microcode execution)

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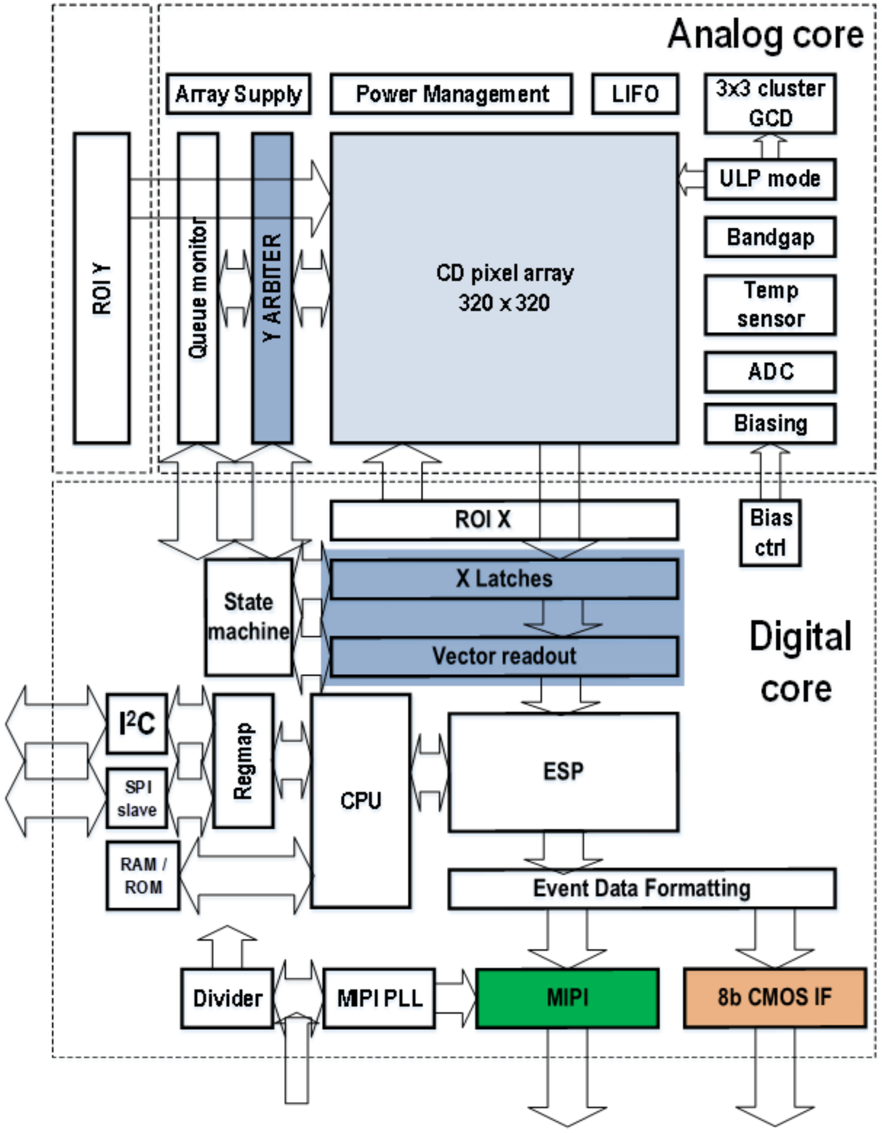
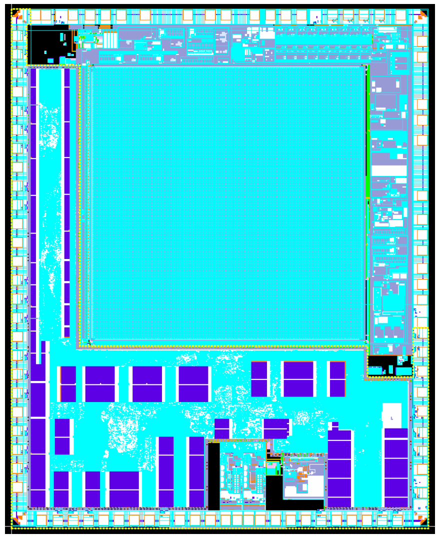
Sensor Chip Overview



- **320x320 pixels, 1/5" optical, 13mm² die**
  - Cu-Cu Stacked BSI, (CIS 65nm, CMOS 40nm)
  - Pixel pitch: 6.3um



- **Sensor features:**
  - Global Contrast Detector (GCD)
  - Pixel-level Flexible Region-of-Interest (ROI)
  - Temperature sensor
  - Ambient light sensor
  - ULP ultra-low power modes
- **Processing features:**
  - Digital ESP (Event Signal Processing) pipeline with
  - Noise/Flicker Filters, Edge enhancement, ERC, EDF
  - Embedded RISC-V CPU
  - Data interfaces: MIPI (D-PHY), CMOS Parallel (DCMI, AER)
  - Configuration interfaces: SPI/I²C

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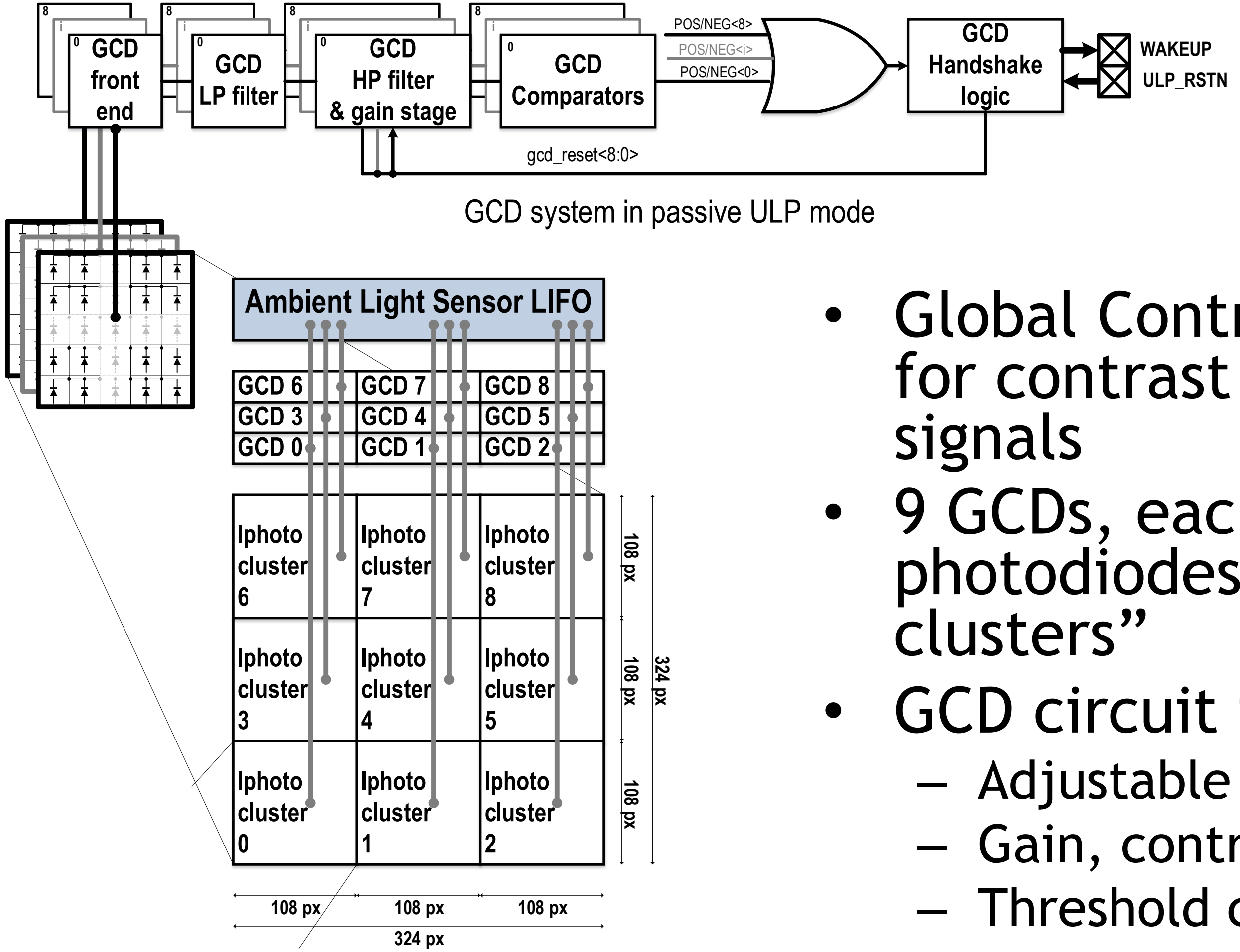
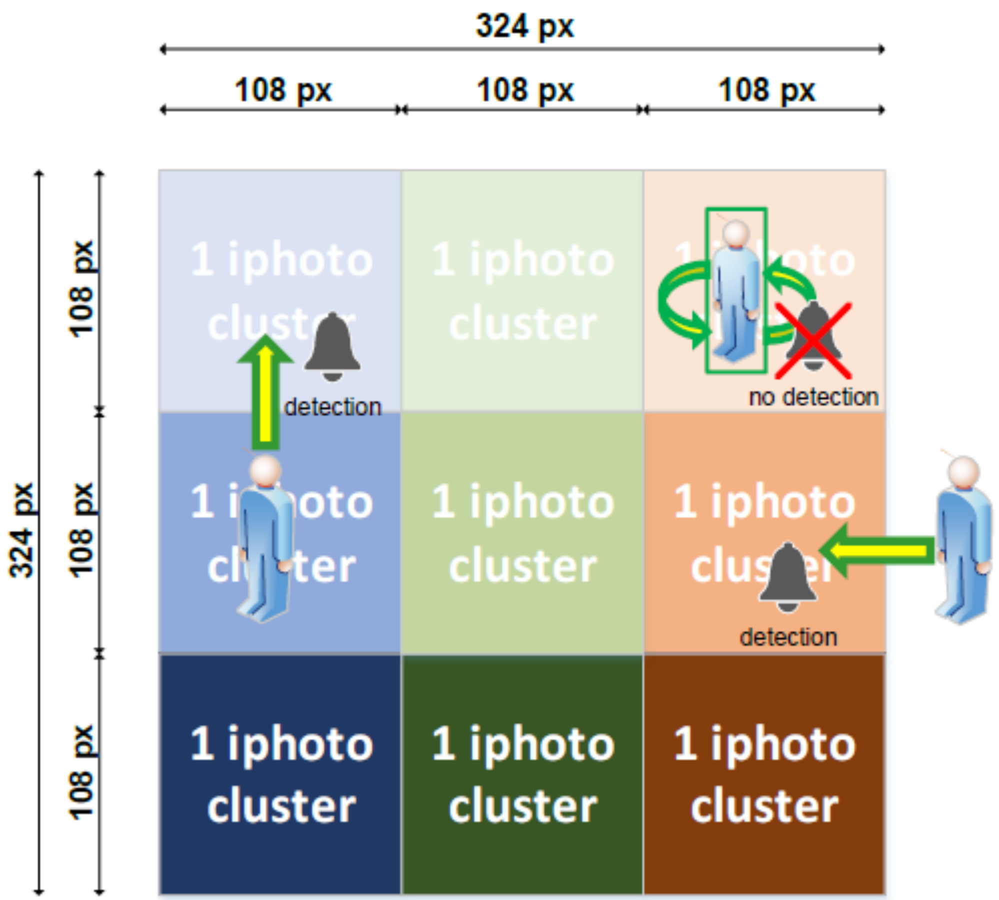
Sensor Features > Global Contrast Detector



- Global Contrast Detector (GCD) → circuit block for contrast detection from multiple photodiode signals
- 9 GCDs, each connected to 108x108 photodiodes, forming a 3x3 matrix of “pixel-clusters”
- GCD circuit features:
  - Adjustable low/high-pass filter
  - Gain, contrast sensitivity controls
  - Threshold comparators
- Enables smart motion detection at ultra-low power consumption

Sensor Features > Global Contrast Detector

- GCD detect moving object entering/exiting pixel-cluster’s FoV
- Enables ultra-low power / always-on smart scene activity detection
- Create internal and external (chip pin) wake-up signals in Passive Ultra Low-Power mode.



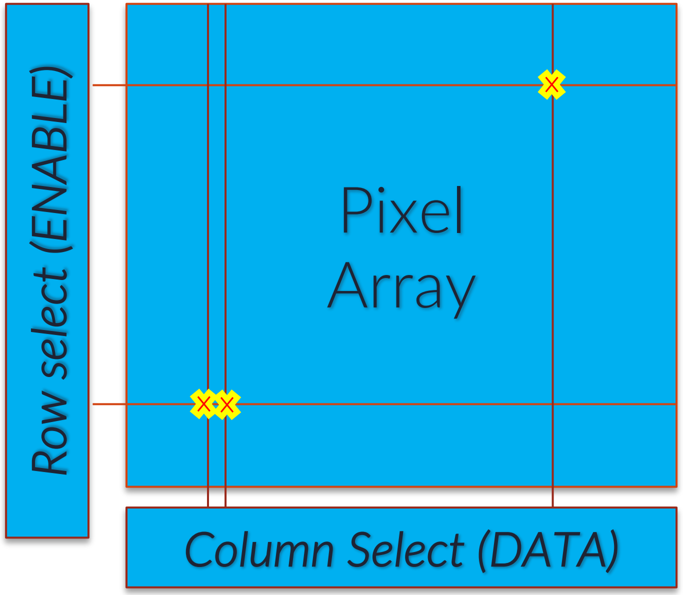
Passive ULP mode

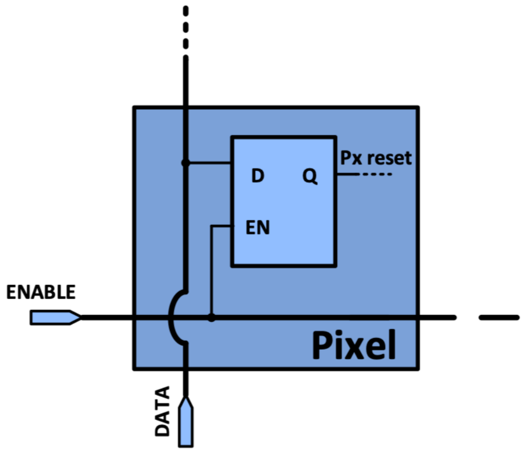
Sensor Features > Pixel-level Flexible ROI

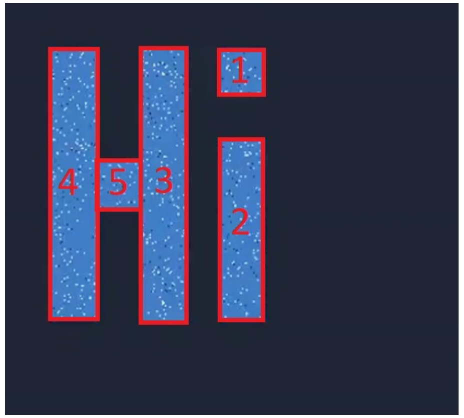
- All pixels embed in-pixel latch for activation/deactivation
- Each latch is individually controllable
- Real-time operation

- Usages:
  - Hot pixel removal
  - Fully customizable ROI shapes
  - Dynamic saliency
  - Limit power consumption outside ROI

- Windows mode ROI controller:
  - Ease user programming of multiple rectangular pixel array regions
  - Speed-up programming for dynamic usage
  - Manages automatically up to 18 ROI windows







Pixel array with 5 ROI Windows programmed

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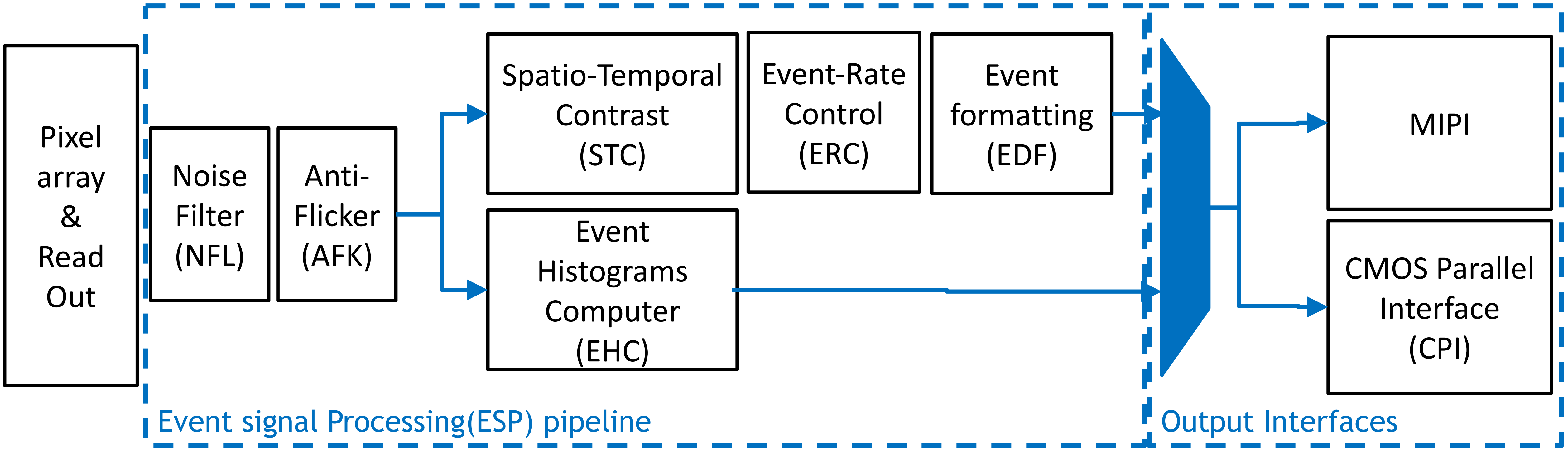
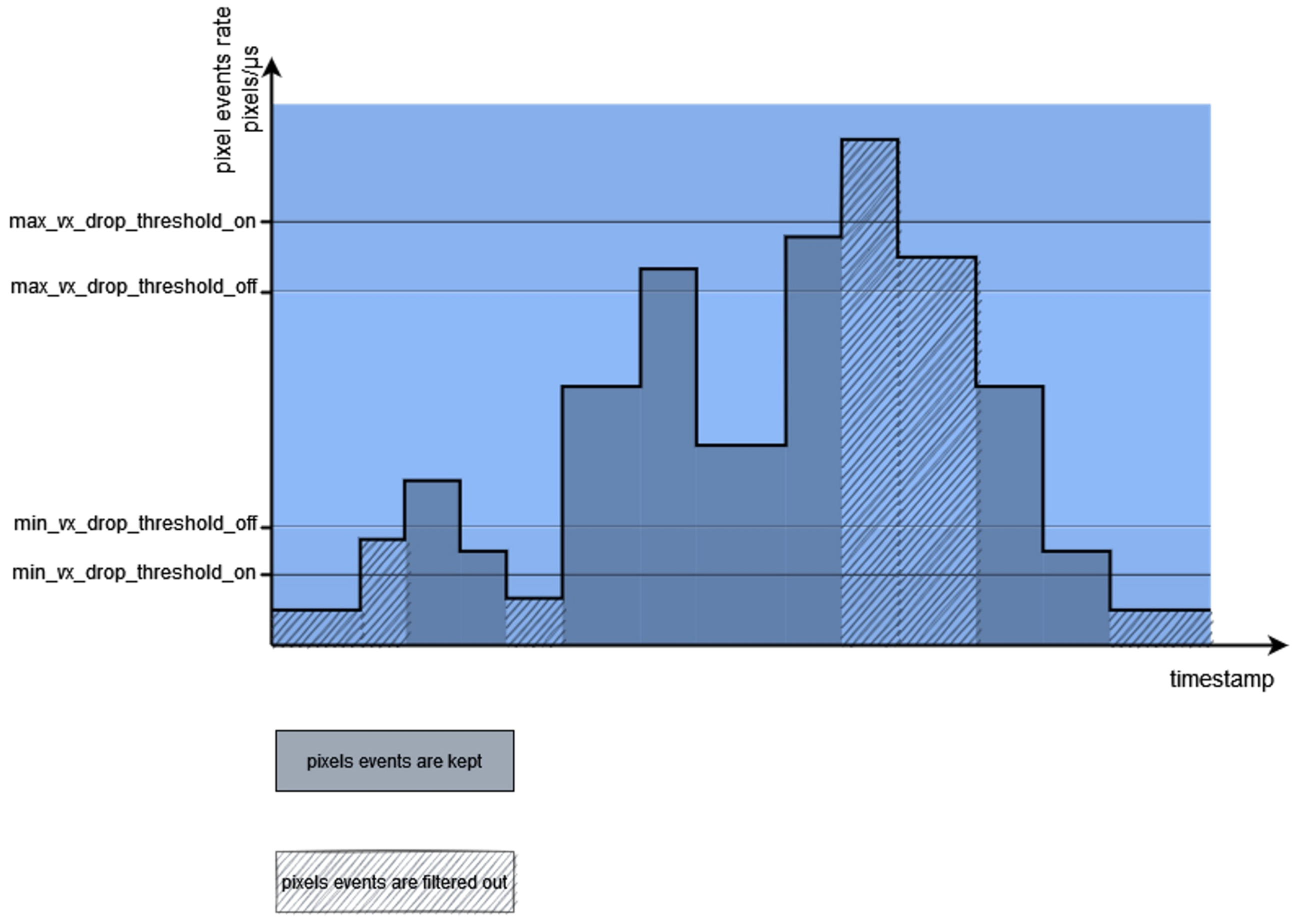
Processing features > ESP-Event Signal Processing



Processing features > Noise Filter (NFL)

- NFL removes events according to instantaneous event rates during a sliding time window.
- Programmable thresholds are used to determined if the NFL is dropping or passing incoming events
- Thresholds are programmable separately for the two event polarities

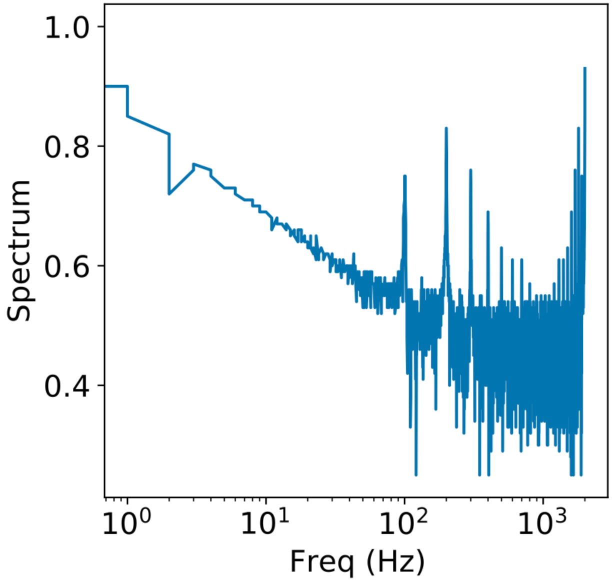


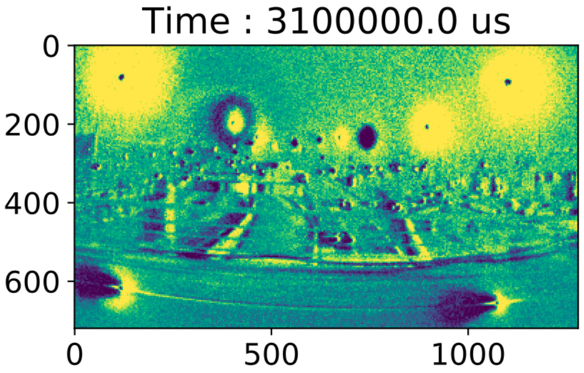
Processing features > Anti-Flicker Filter (AFK)

Natural scenes often contain light sources flickering at constant frequencies: Fluorescent lights, LEDs, screens, …

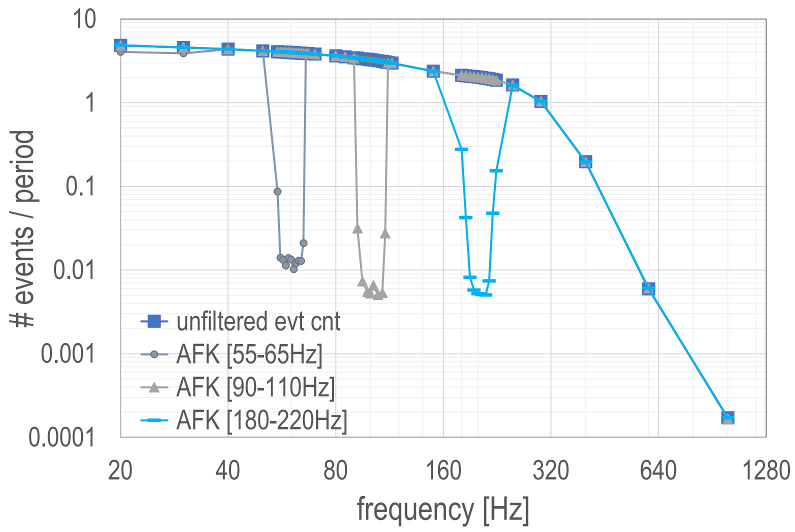
AFK requirements:

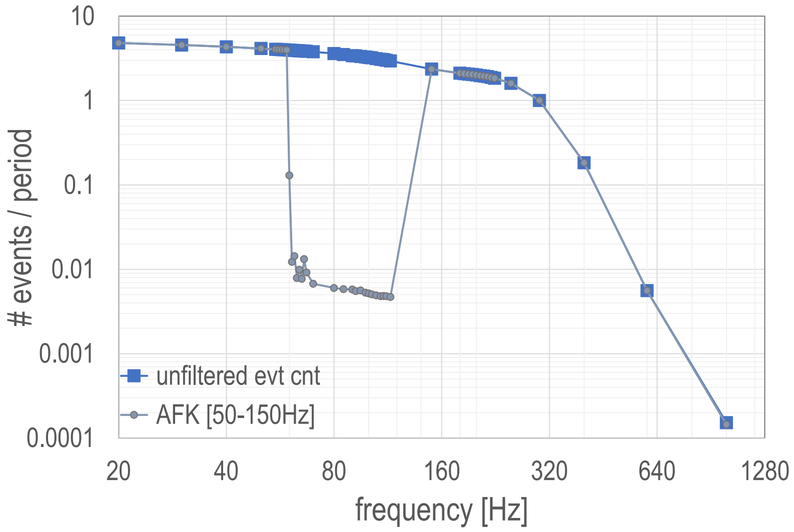
- Digital band stop (notch) filter
- Programmable center/width
- Frequency Range 50-500Hz
- Invertible (band pass)

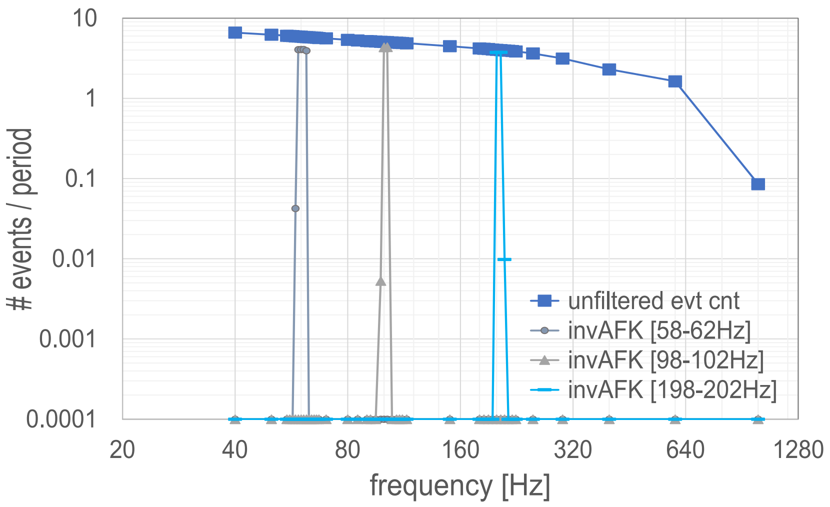




Processing features > AFK Measurements







Band stop (notch)

- Center frequencies: 50Hz, 100Hz, 200Hz
- Bandwidth ±10% of center
- Typical attenuation ~50dB

Band stop

- Center frequency: 100Hz
- Bandwidth 100Hz
- Attenuation >50dB

Inverted (band pass)

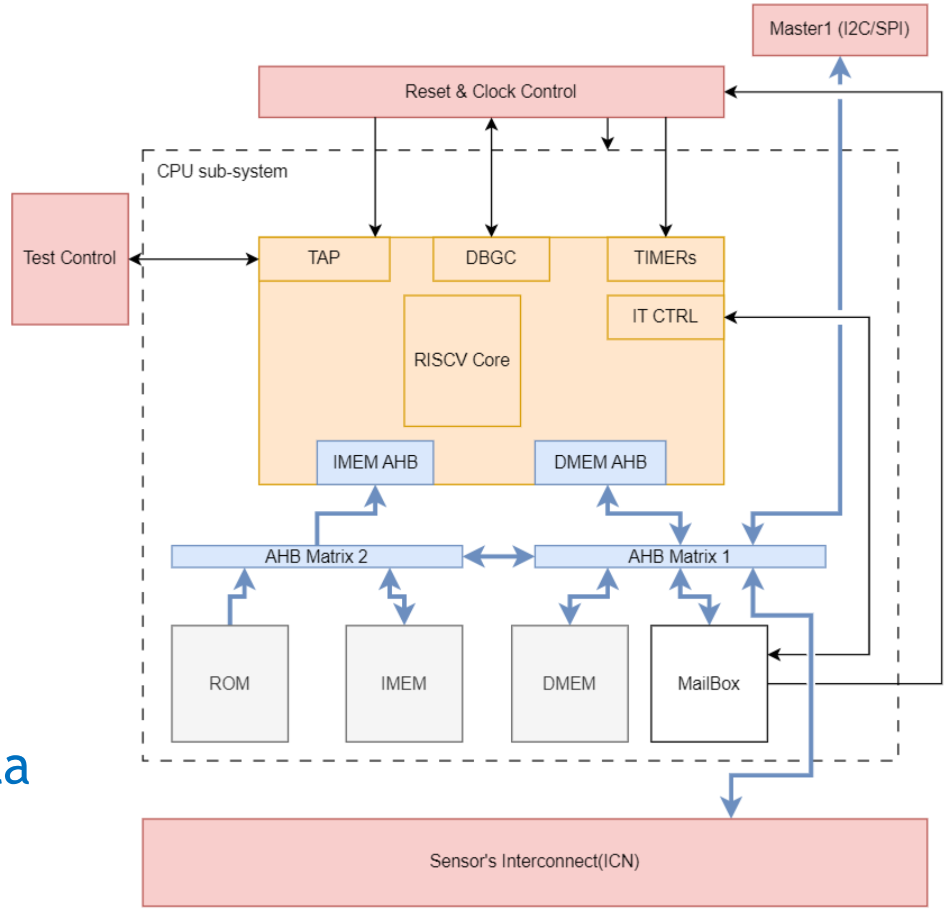
- Center frequencies: 50Hz, 100Hz, 200Hz
- Bandwidths ±2Hz of the center

Processing features > Embedded CPU (RISC-V)

RISC-V RV32IMC ISA

- Interrupt controller, 16 IRQ lines
- Peripherals:
  - 3 x 64-bits Timers; Real Time Clock (1MHz)
  - Mailbox system for host communication
  - JTAG interface, HW breakpoint

- Usage:
  - Boot Initialization (Time to First Data)
  - Power manager (entering/exiting power modes)
  - MIPI meta data insertion (e.g. frame number, data statistics, etc…)
  - (No algo-based event data processing)



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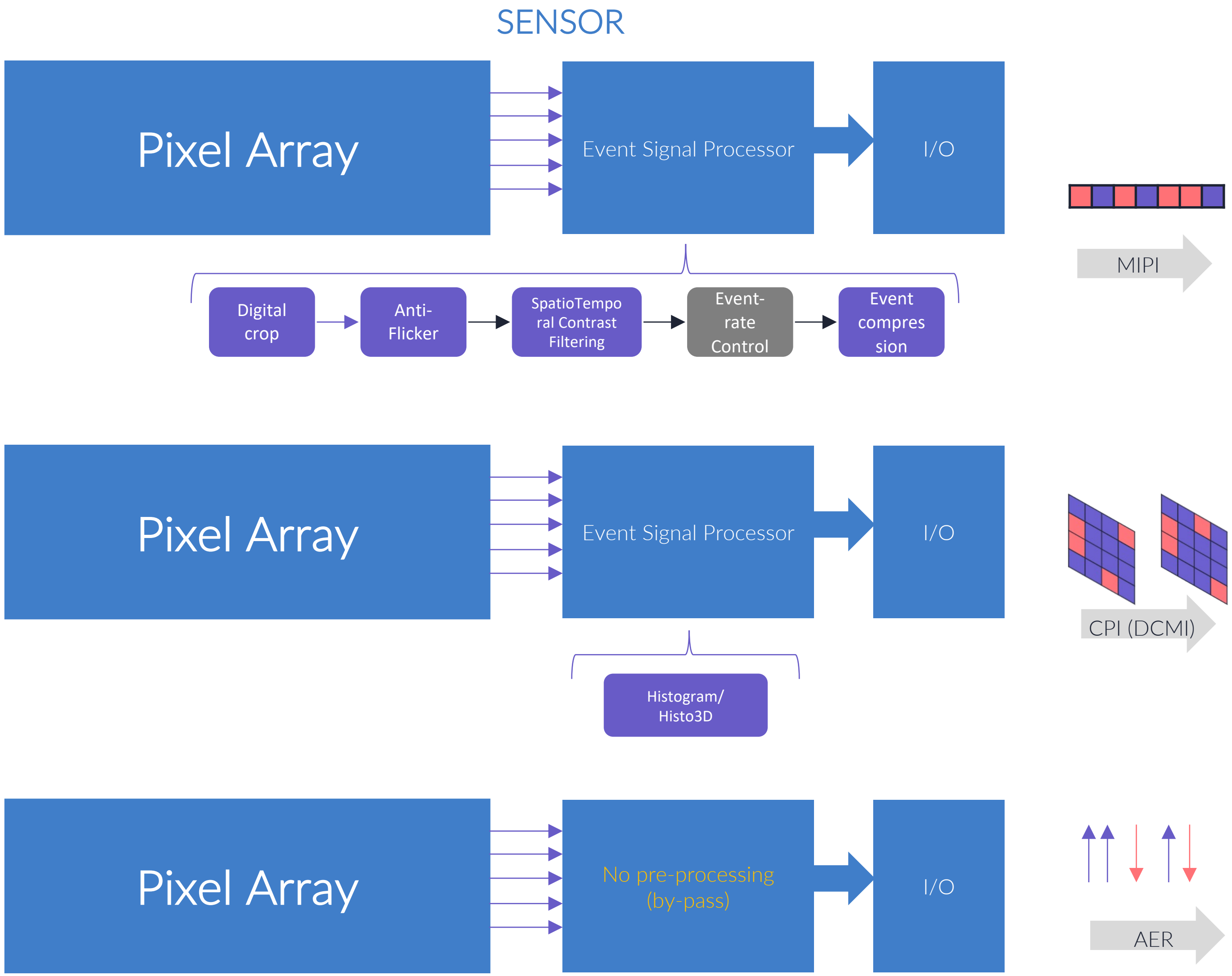
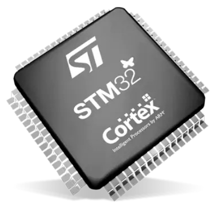
Event Sensor → Compute Platform

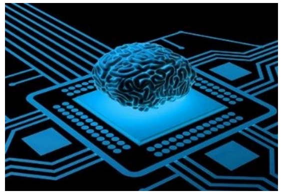


COMPUTE

Application Processor
Continuous EVT Stream
Embedded vision applications



Microcontroller
Direct 2D event frames / histograms with controllable rate and activity thresholds,
Smart wake-up
e.g. CNN-based edge-AI applications



Neuromorphic processor
Direct AER input (spiking NN)
AI Algos for object detection and tracking, motion analysis, optical flow, attention tracking, surveillance, gesture recognition, …

Data Formats

Event streaming

- **EVT2.0:** legacy, low event rate, 32-bit per pixel, uncompressed, timestamp
- **EVT3.0:** compressed vector 16-bit encoding, high event rate, removes redundant event data, best encoding on average
- **EVT2.1:** vectorized, high event rate, 64-bit based
- **AER:** **A**ddress **E**vent **R**epresentation format, legacy format used by the first event-based sensors. Low latency, no timestamps

Data formats	CPI @50MHz		MIPI @1.5Ghz
	4 bits Mevt/s	8bits Mevt/s	Mevt/s
EVT2.1	100	200	750
EVT2.0	6.25	12.5	46.87
EVT3.0	133.33	266.67	1000
AER	10	16.67	N/A

Event accumulation

- **Histograms:** Accumulating events into a 2D grid structure
  - fixed time window
  - fixed number of events
- **Accumulation methods:**
  - **Histo3D:** 2 separate containers per pixel (positive, negative events)
  - **Diff3D:** 1 container per pixel (add positive, substract negative events)

Output Data Interfaces

AER
- X, Y, polarity only (no TS)
- Low latency (no buffering)
- Variable data rate

TS Event Streaming
- X, Y, polarity, TS
- Variable data rate
- Lossless Compression using EVT format

3D Histograms
- X, Y, polarity accumulated
- time period or number of events
- Fixed size, NCHW data org (for NPU DMA)

CPI PARALLEL INTERFACE:

- **4/8-bit** CMOS parallel
- Up to **400Mbps @50Mhz (267Mevt/s)**
- **Low-power** (PLL not required, clock can be adjusted for different bandwidth reqs)
- **Low** end-to-end **latency** (very little buffering)
- Different transmission modes:

Protocol	Pin config	Output Data format		
		AER	EVTx	Histogram
PSEE-IF	4/8bits	X	X	
DCMI-JPEG	8bits	X	X	
DCMI-Mono	8bits		X	X
AER-IF	4/8bits	X		

Low-power / Low-latency

MIPI INTERFACE:

- **1 lane**, up to **1.5Gbps @1.5Ghz (1Gevt/s)**
- Compliant with **MIPI D-PHY V1.2**
- Supported formats:
  - Compressed/uncompressed vector formats (EVTX.X)
  - Event histograms
- Frame size, frame rate configurable
- Optionally fixed frame size/fixed frame rate with data padding to comply with standard configuration for FB cameras.

High Bandwidth

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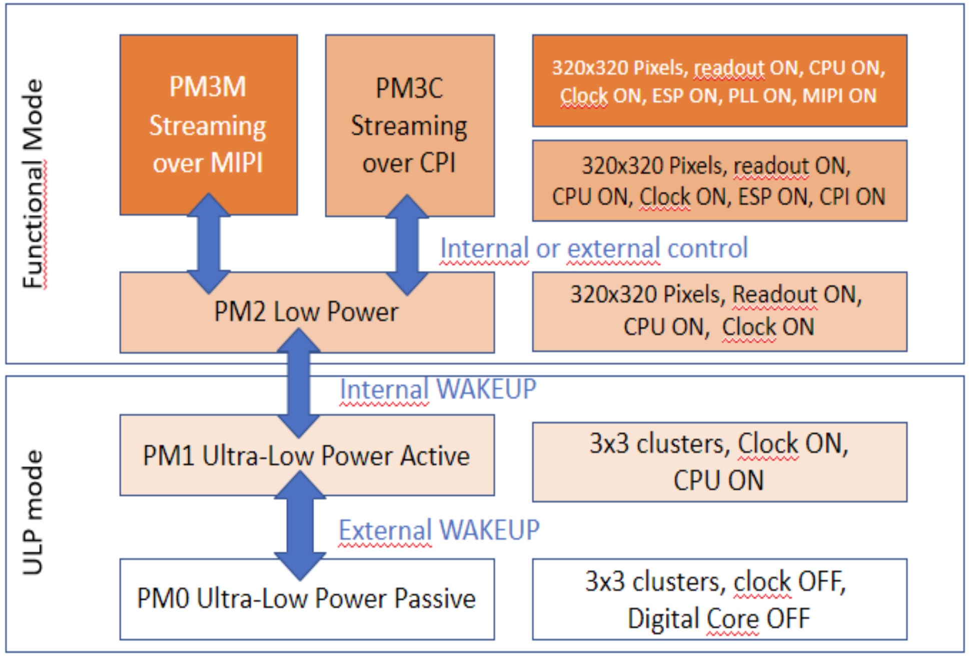
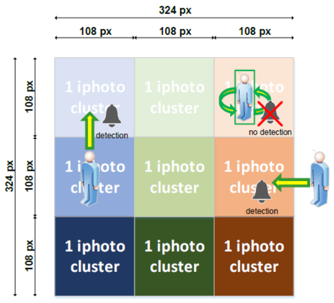
Power Modes - Overview

- **PM0**: Digital Core is OFF, activity detection based on Analog GCD
- **PM1**: Digital CPU-only is ON, activity detection with advanced CPU processing on GCD data
- **PM2**: Digital Core is partially ON, activity detection with advanced CPU processing on pixel data, no streaming
- **PM3C**: All ON (except PLL), full streaming on CPI interface
- **PM3M**: All ON, full streaming on MIPI interface

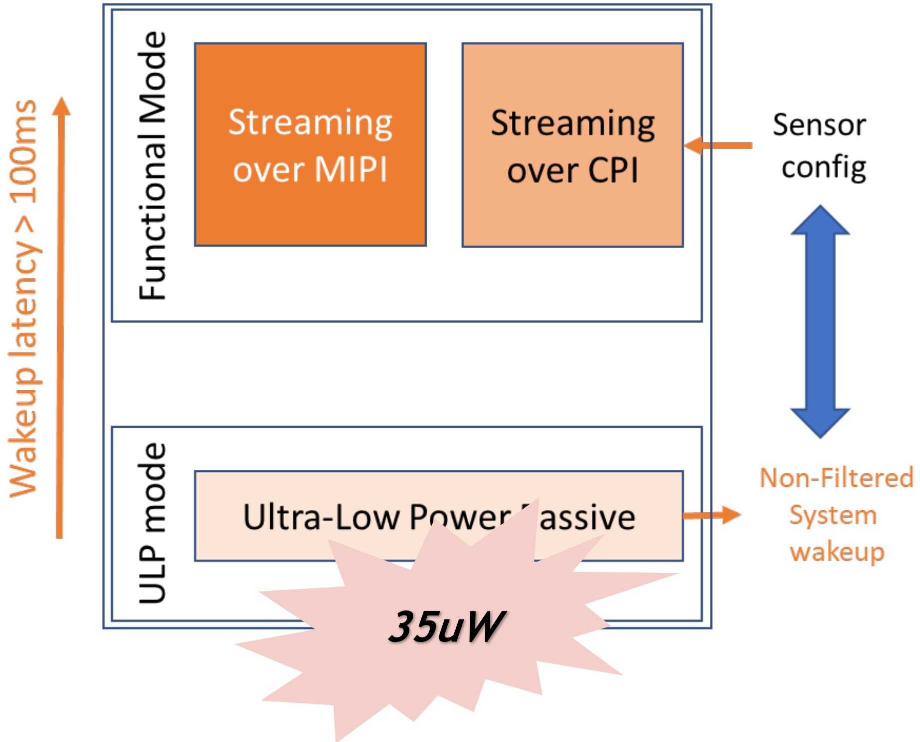


Mode	**Ultra Low Power passive PM0**	**Ultra Low Power active PM1**	**Low Power PM2**	**CPI streaming PM3C**	**MIPI streaming PM3M**
Sub-system			100kEPS	100kEPS CPI @10MHz	100kEPS 800MHz
Pixel array	3x3 GCD resolution	3x3 GCD resolution	Full resolution	Full resolution	Full resolution
Digital Registers+CPU	Power off	powered, clocked	powered, clocked	powered, clocked	powered, clocked
Digital readout	Power off	powered, clock gated	powered, clocked	powered, clocked	powered, clocked
Digital ESP + Output IF	Power off	powered, clock gated	powered, clock gated	powered, clocked	powered, clocked
	Analog: 35μW Digital: 0	Analog: 35μW Digital: 915μW	Analog: 1.2mW Digital: 1.3mW	Analog: 1.2mW Digital: 2.3mW	Analog: 1.2mW Digital: 5mW MIPI+PLL: 10mW
	Total: 35μW	**Total: 950μW**	**Total: 2.5mW**	**Total: 3.5mW**	**Total: 16.2mW**

Power Modes and Wake-Up Features

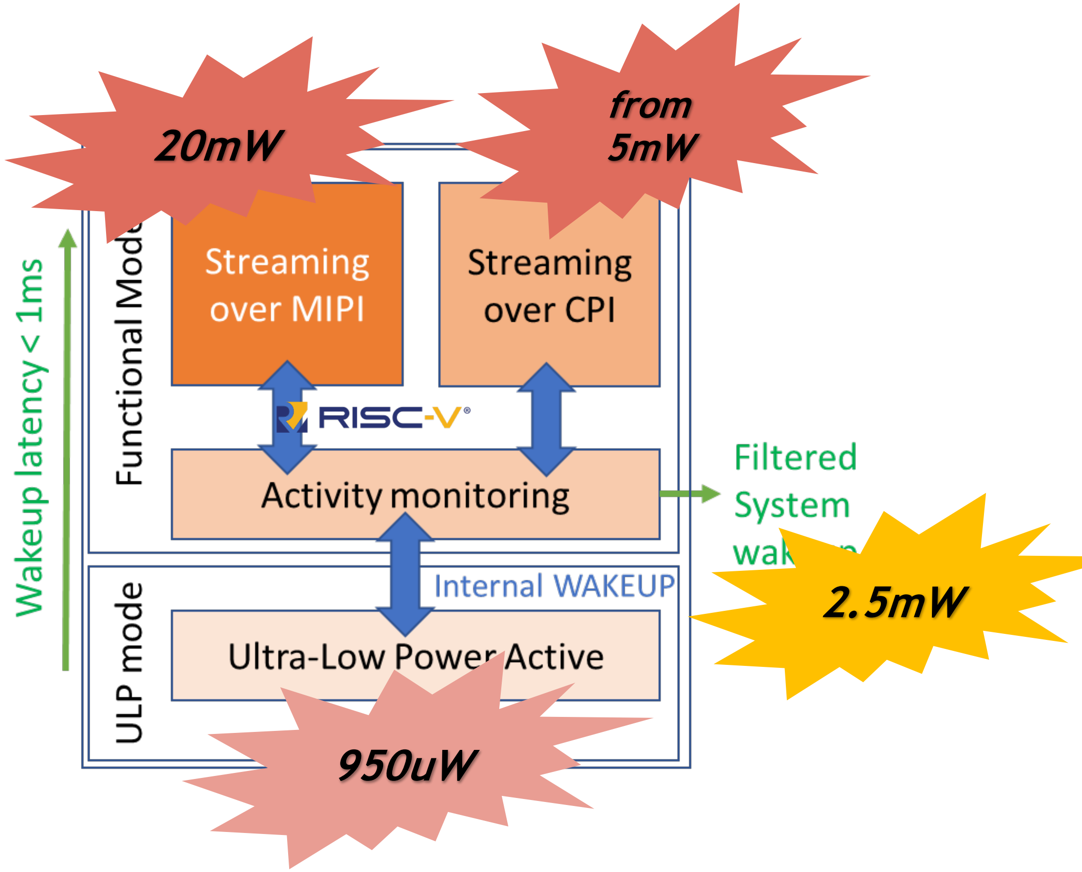


Passive ULP mode



Wake-up on events from 3x3 clusters

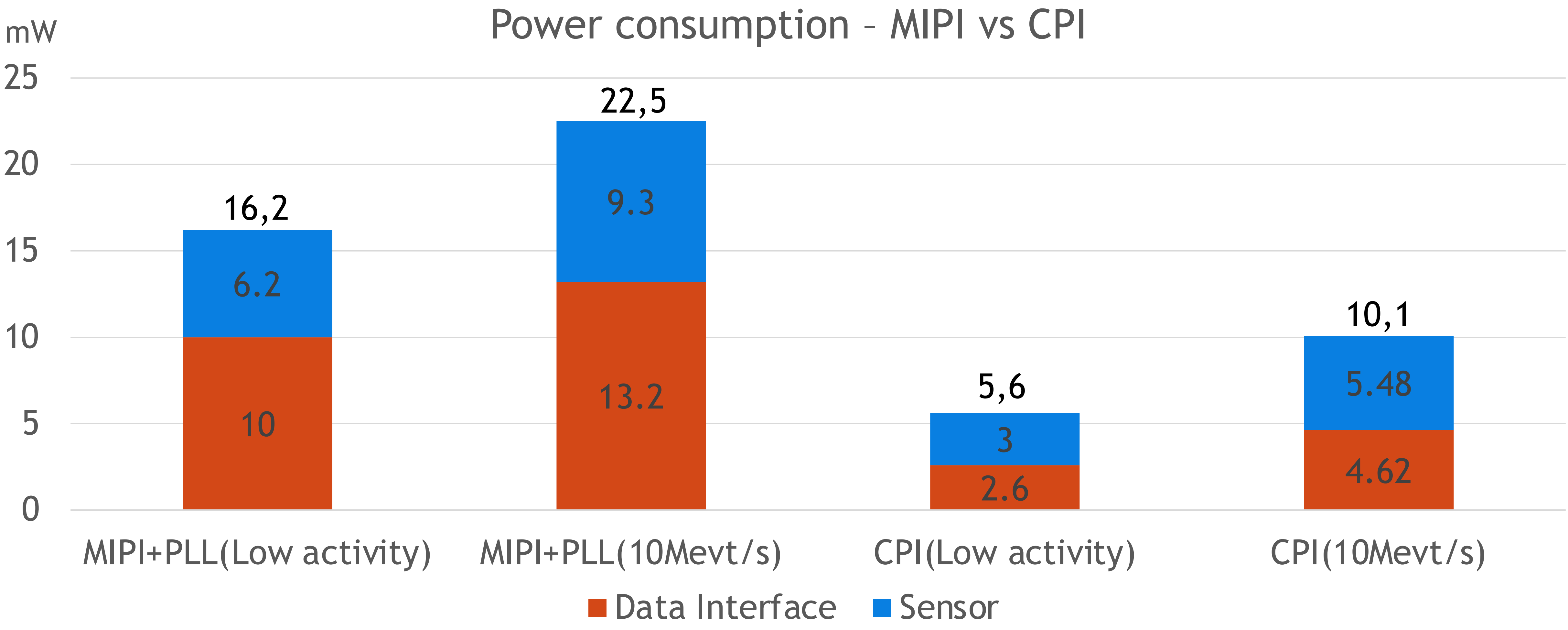
- Internal: Power-mode cycling
- External: system wake-up signal on pin



PM2: Activity monitoring in 4x4 programmable zones

- Tuneable thresholds
- CPU statistical processing for wake-up filtering (false positive)

Power Modes > Streaming Modes: MIPI vs CPI



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Summary / Conclusion

- Specifically designed for embedded vision at-the-edge
- Cu-Cu Stacked BSI CIS on CMOS (65nm/40nm)
- Features multiple data pre-processing, filtering and formatting functions to adapt to variety of use cases and processing platforms
- Two data interface covering low latency applications (CPI) and high bandwidth applications (MIPI)
- Multiple transmission options in both interfaces ease integration and compliance to industry standards
- Adaptative hierarchical power modes facilitate operability in power-sensitive edge vision applications
- On-chip power management and an embedded uC core further improve sensor flexibility and useability at-the-edge

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