Energy-efficient design of an event-driven smart visual sensor

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Outline

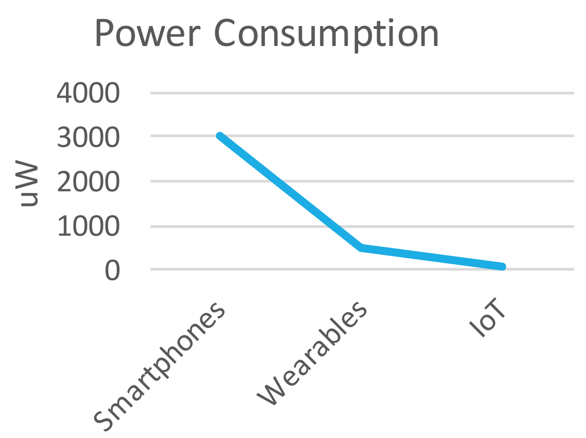
- Motivation
- Camera System Architecture
- Evaluation and Results
- Conclusion and Future Work

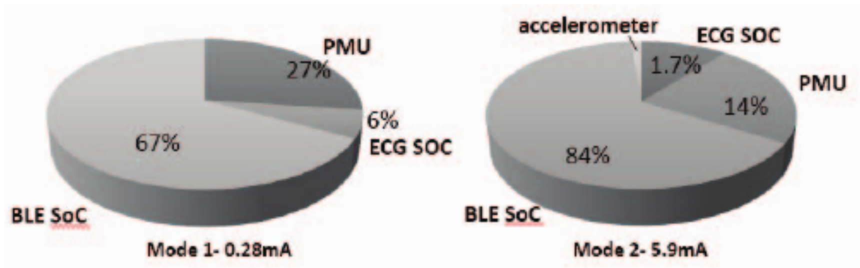
Motivation

Energy-efficiency for smart devices

Energy-efficiency is a key feature for **smart always-on** systems and IoT devices. Need to reduce power consumption to µW range.

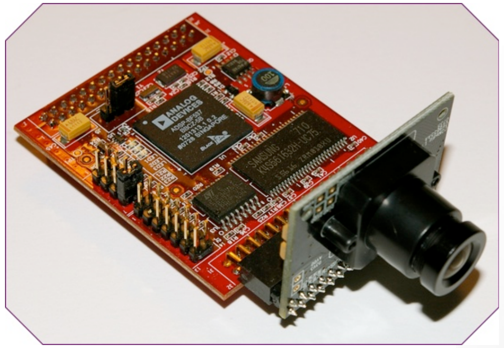
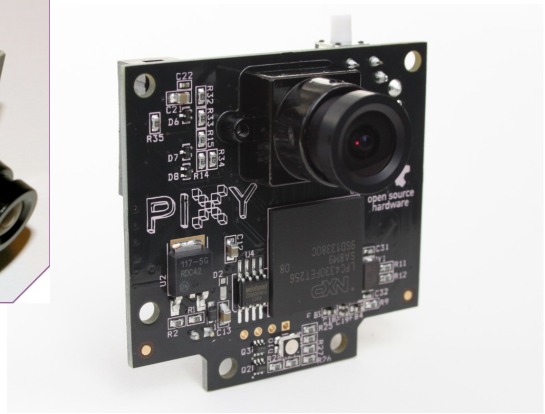
- **Local processing** allows to drastically reduce the communication power (Tx/Rx) which is commonly dominant in wireless devices, even if a reduction of 10x has been achieved during last years.
- An **efficient computational model** coupled with an **aggressive power management strategy** within the system leads to considerable power saving (e.g. duty cycling, DVFS techniques).

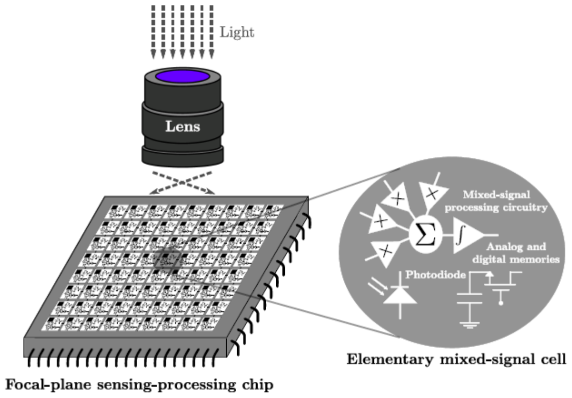




Smart Camera Systems

Traditional smart camera systems typically require **high power consumption** (tens to hundreds of mW) and feature **high sensor-processor bandwidth** in addition to the **elevated computational power**.



Focal Plane Processing allow to extract visual features directly on the sensor die

The proposed smart camera architecture brings together the **energy-efficiency of analog focal plane processing** and **the flexibility of near-threshold parallel digital processing**. Ultra low-power-vision applications can then be implemented by exploiting an **optimized event-driven computational model**.

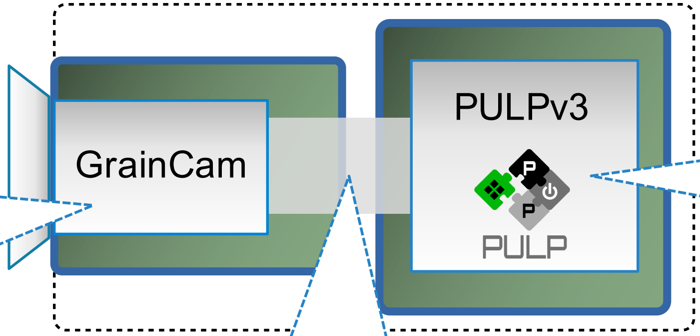
System Architecture

SMART VISUAL SENSOR

System Overview

Smart Visual Sensor, able to exploit local-processing to extract digital signature from visual sensed data

The imager **continuously** handles visual sensing at **ultra-low-power** consumption and extract low level features by means of **analog pre-processing**



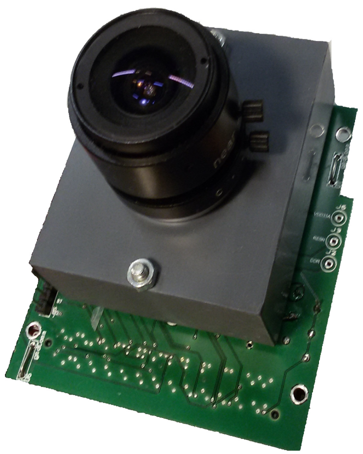
Analog Event-Based Imager

Digital Paralle Processor

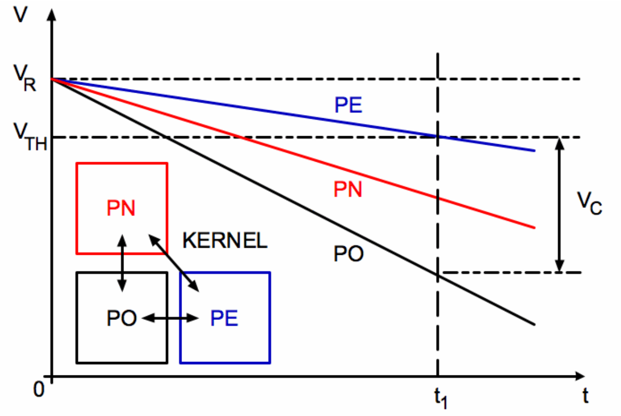
The parallel processing **speeds-up** the data-post processing to eventually reduce the system power consumption. The digital processing is applied on the computed features, according to an **event-driven processing**.

The **smart interface** enables the digital processor, normally in deep-sleep mode, **only if some relevant events are detected** from the sensor.

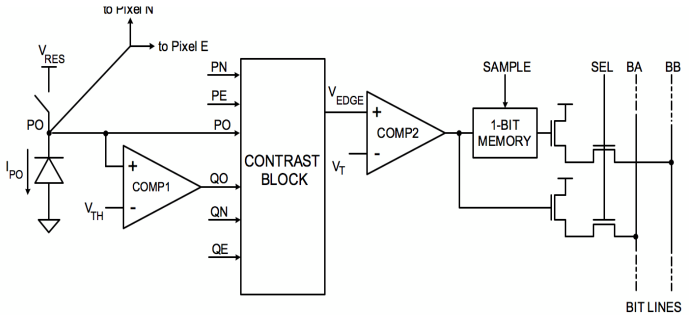
Graincam (1)



Pixel-level spatial-contrast extraction



$$V_C = V_{PE}(t_1) - V_{PO}(t_1) = (V_R - V_{TH})\left(\frac{I_{PO} - I_{PE}}{I_{PE}}\right)$$



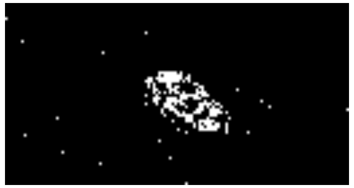
Analog internal image processing:

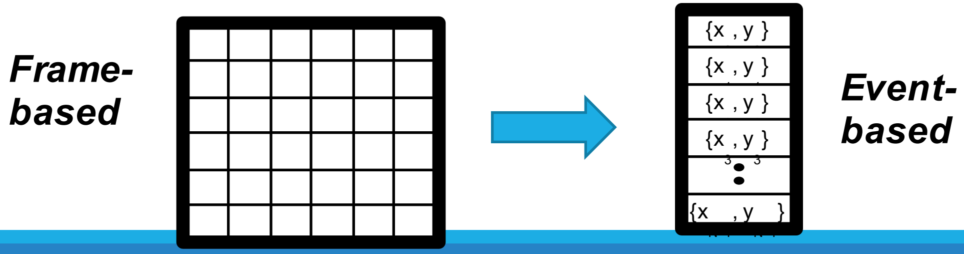
- **Contrast Extraction**
- **Motion Extraction**, differencing two successive frames
- **Background Subtraction**, differencing the reference image, stored in the memory, with the current frame

Graincam (2)

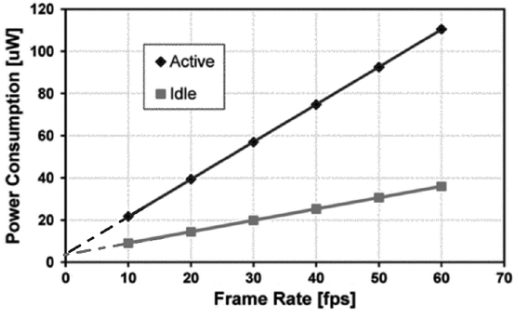
- **Readout modes**:
  - **IDLE**: readout the *counter of asserted pixels*
  - **ACTIVE**: sending out the addresses of asserted pixels (address-coded representation), according raster scan order

- **Event-based** sensing: output frame data bandwidth depends on the external context-activity

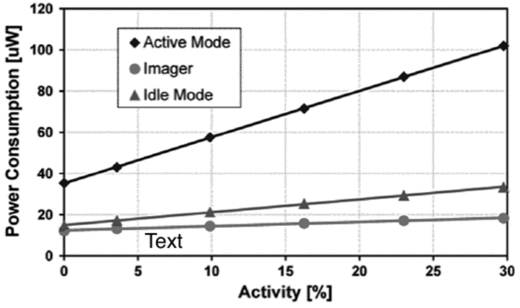




- **Ultra Low Power Consumption e.g. 10-20uW @10fps**

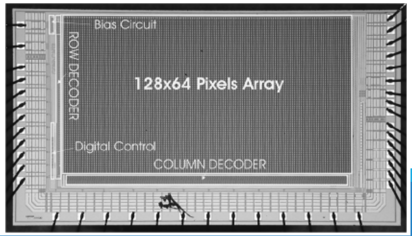


(a)



(b)

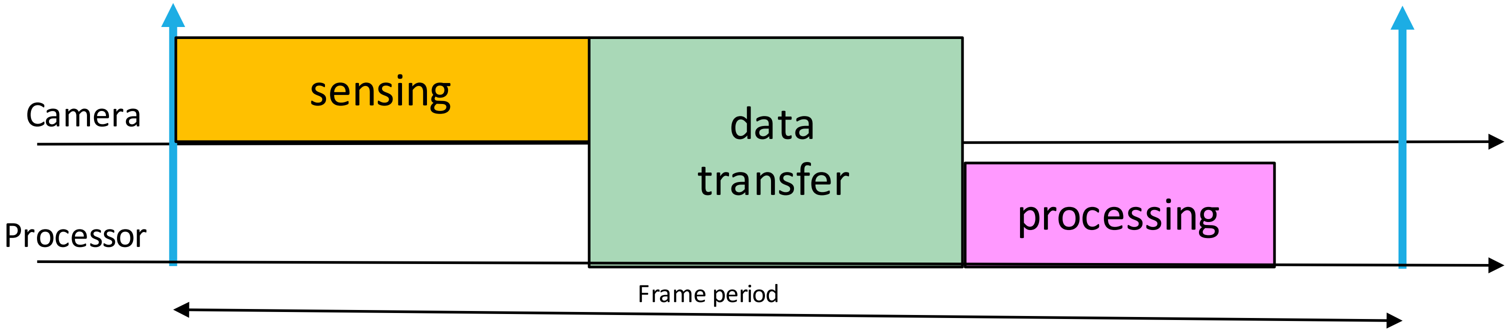
- Main chip specification



Parameter	Value
Technology	CMOS 0.35 μm DP TM
Array Size	128 × 64 pixels
Chip Size (pad incl.)	4.5 mm × 2.5 mm
Pixel Size	26 μm × 26.5 μm
Number of trans/pixel	45
Fill Factor	20 %
Contrast Sensitivity	∼ 10%
Power Consumption	100 μW @ 3.3 V and 50 fps
Sensor readout time (Acive Mode)	150 μs
Sensor readout time (Idle Mode)	60 μs (with 25 % pixel activity)
Max frame rate	4000 fps

A system-level viewpoint

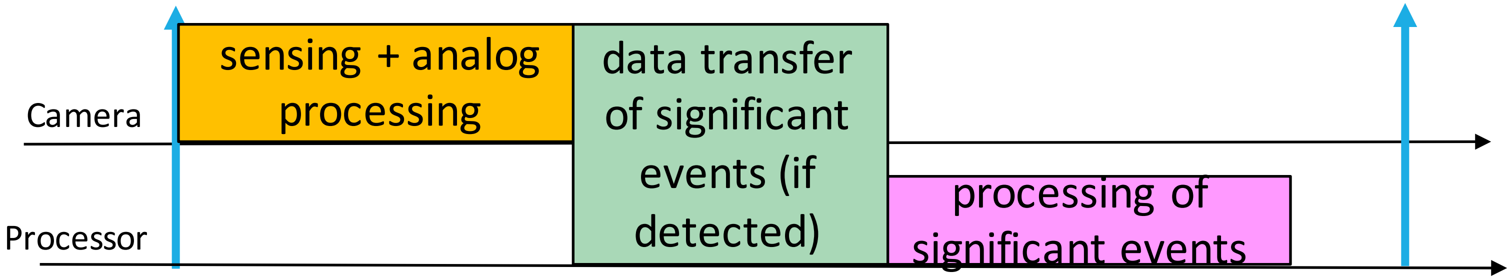
TRADITIONAL FRAME-BASED MODEL



Main **weak point**: data transfer and processing occur even if sensed data does not contain any significant features

Energy waste!

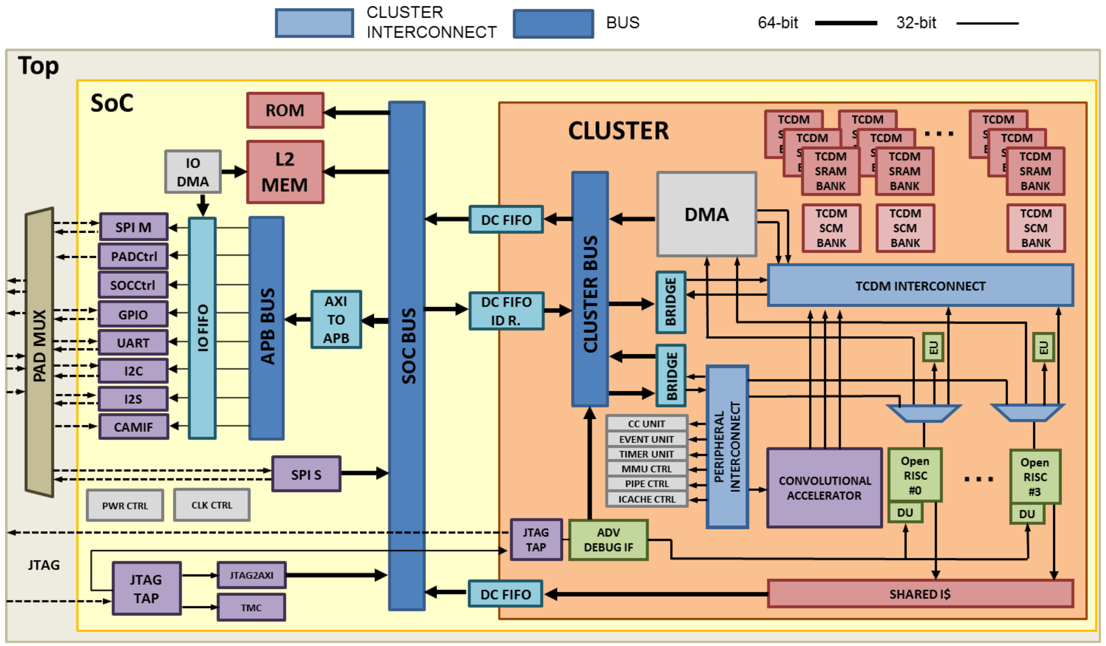
PROPOSED EVENT DRIVEN MODEL



Advantages:

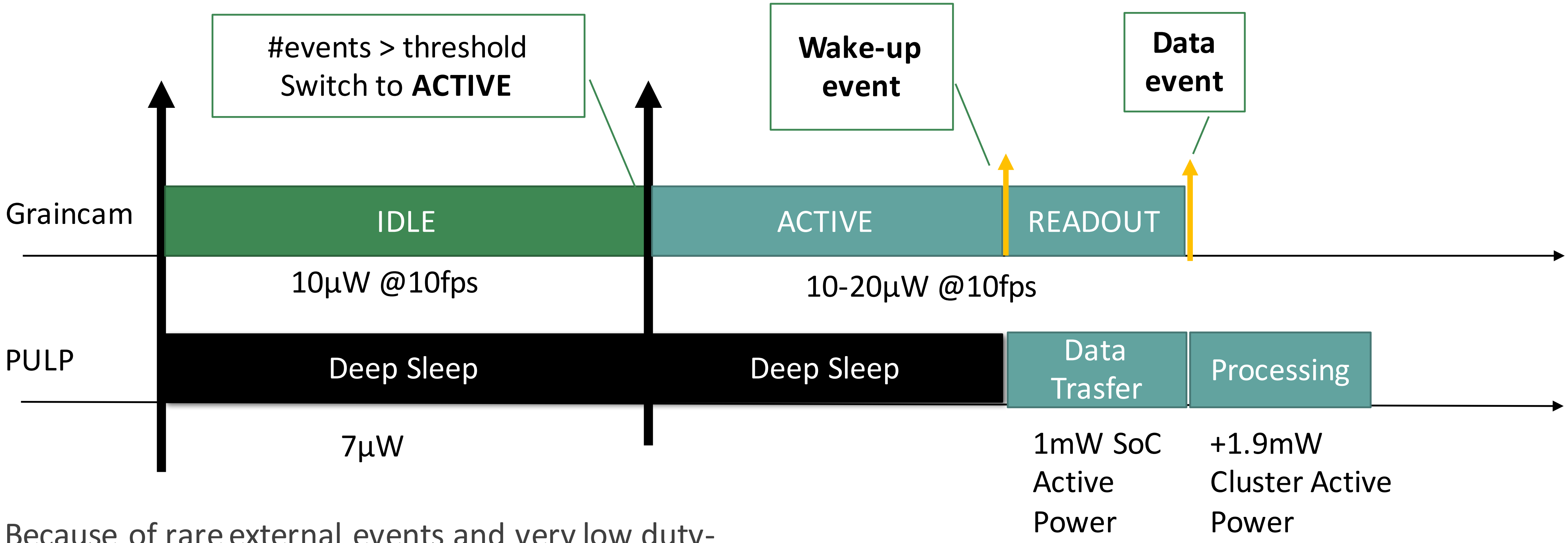
- Digital processor **wakes-up only if** relevant events are detected by the sensor
- Digital processing occurs **only on significant events** detected by the sensor, lowering the computational time

PULP (Parallel Ultra Low Power)



- Joint project between UNIBO & ETHZ
- Energy-efficient **near-threshold parallel computing** (PULP3 reaches up to 300GOPS/W, estimated for 28nm FD-SOI implementation)
- Fine-grain tuning of frequency and voltage (**DVFS**) + power management unit allowing always-on sensing
- Processor micro-architecture based on OpenRISC ISA

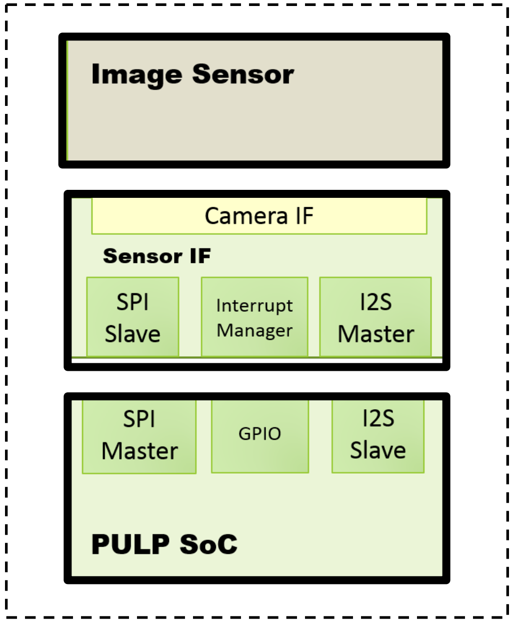
Event-Driven Computational Model



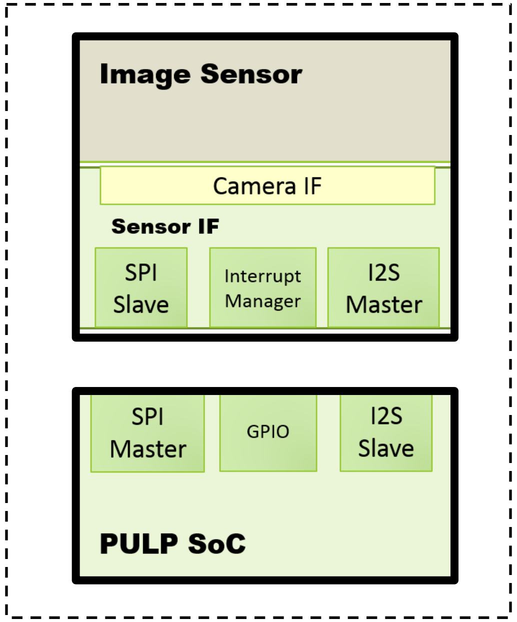
Because of rare external events and very low duty-cycle during active time, **the average power can be dominated by the sleep/idle power**!!

➡ Need to optimize data processing and transfer

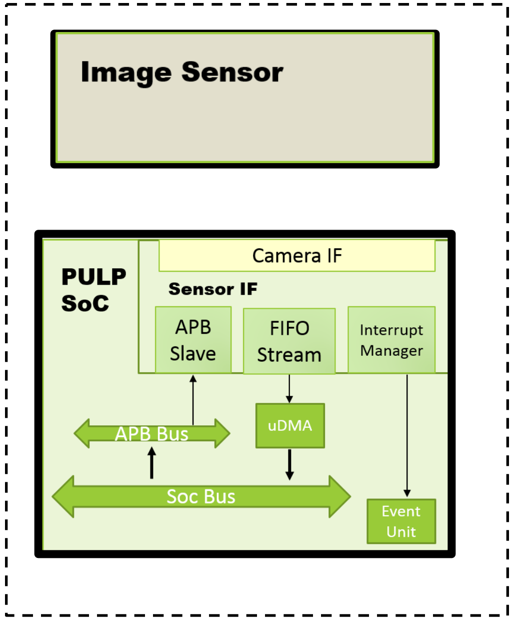
How to implement it?



Sensor IF block as **external components** (Programmable Logic)

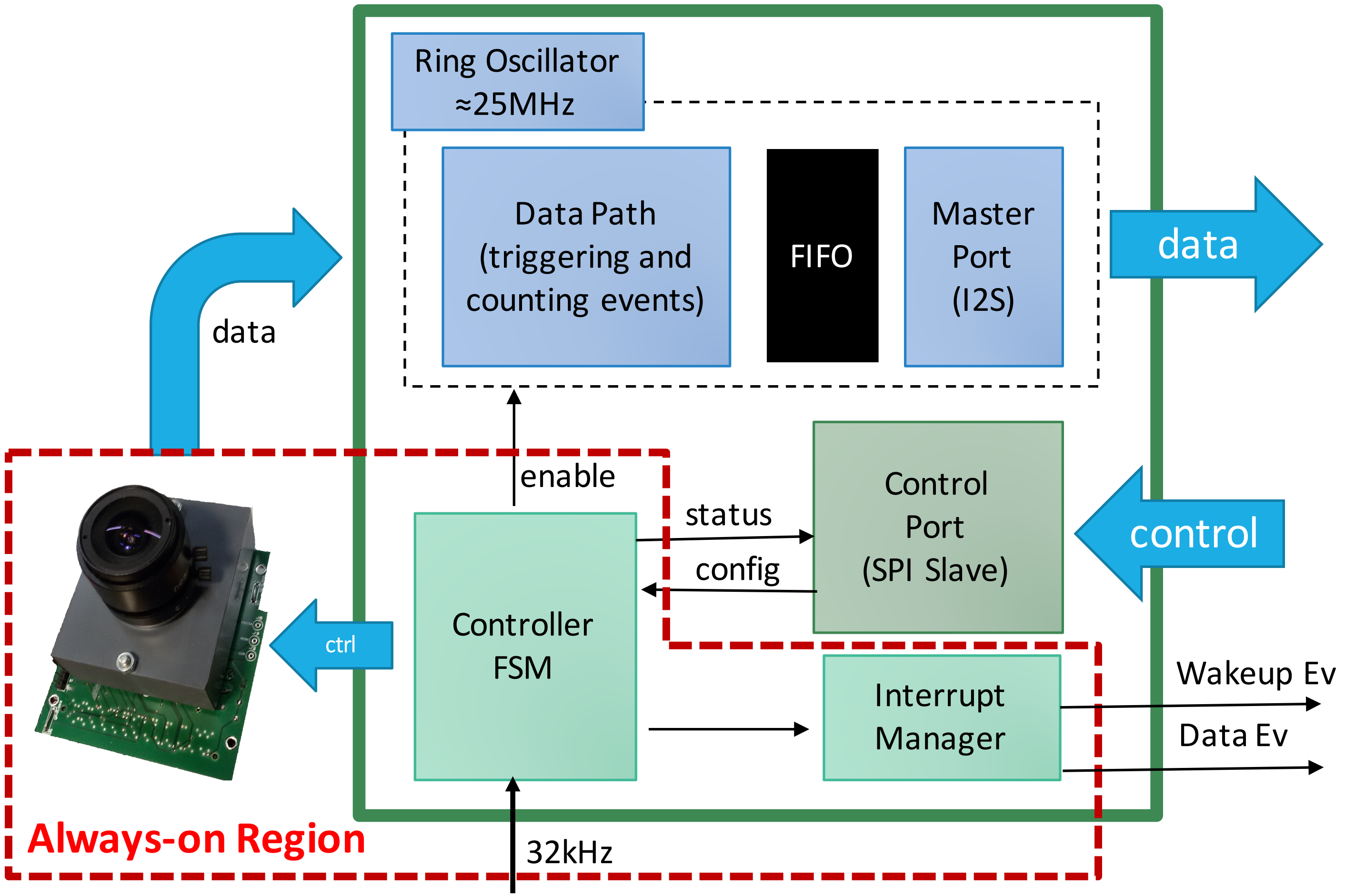


Sensor IF block as **image sensor digital front-end**



Sensor IF block **within the PULP SoC**

Low power interface – External (FPGA)



Controller FSM:

- Always-on 32KHz camera controller
- Continuously handles sensor timing signals and switch sensor from/to active/idle
- Activates data-path block during readout phase
- Triggering Interrupt Signals:
  - **Wake-up Event**, to request High-Speed Clock activation
  - **Data Event**, to signal data transfer completion

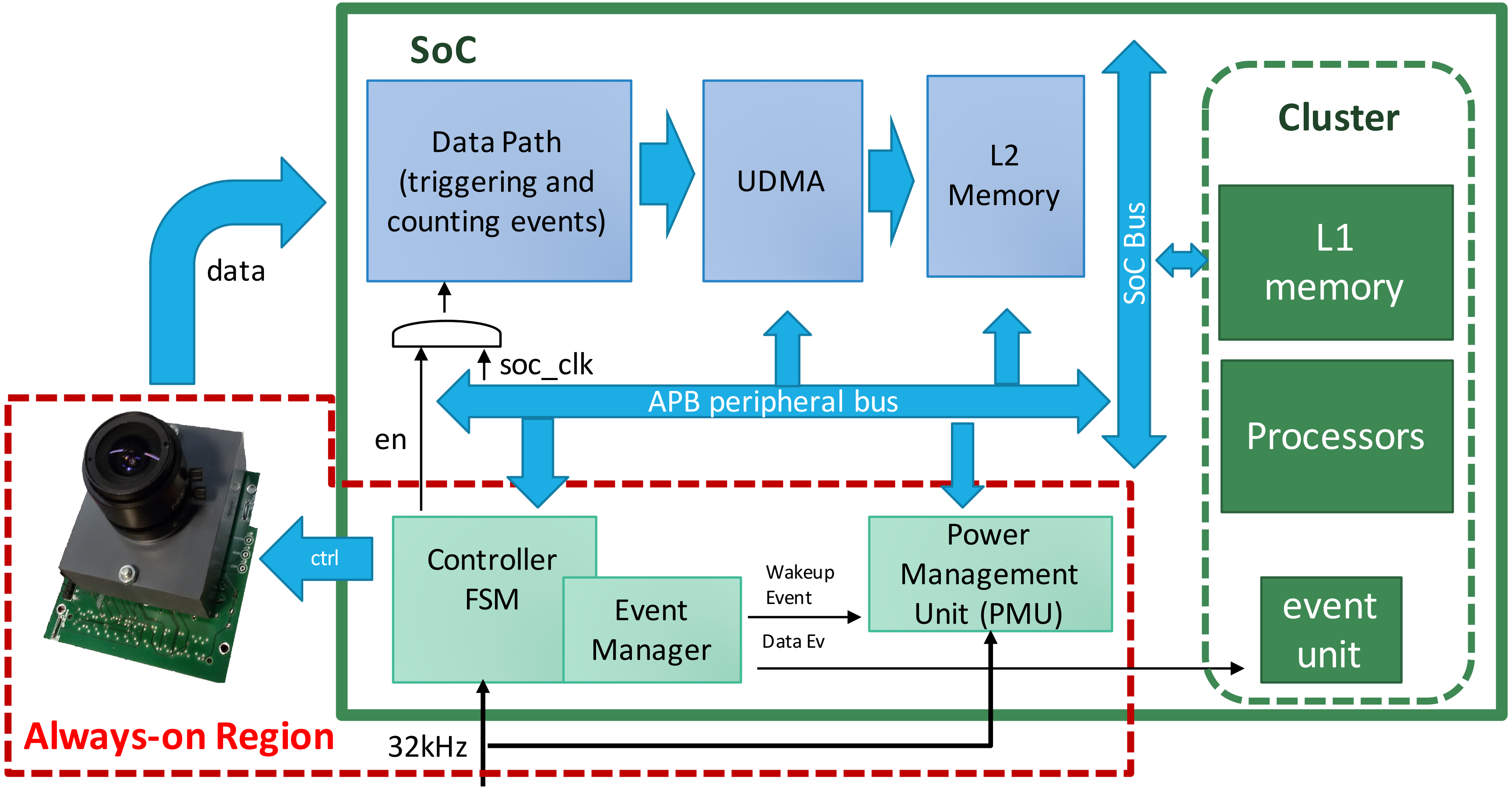
Master port interface transfers data to the memory sub-system of the host system.

Control Port interface to set-up sensor interface parameters

Implemented on ULP FPGA (IGLOO NANO)

Mode	Power	Note
Idle	114µW	
Active	147µW	10fps – 25% pixel activty

Integration within the SoC



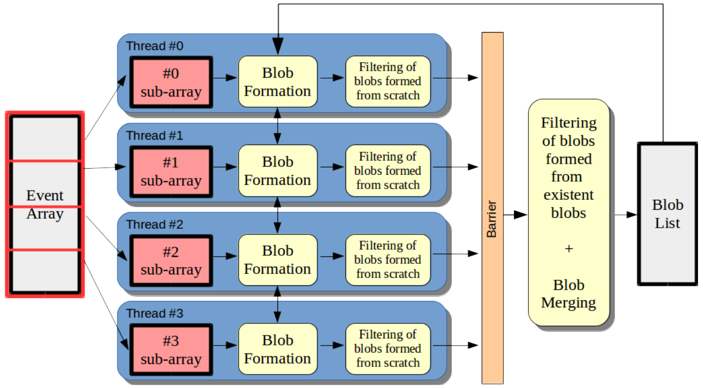
Always-on camera peripheral

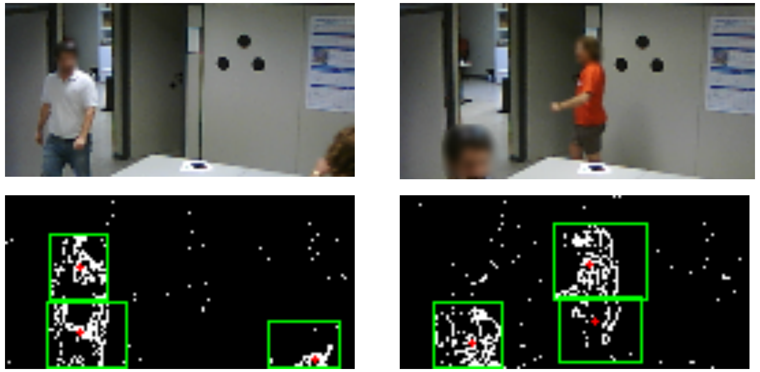
- **SoC always-on region** (driven by 32kHz clock) include the camera controller to **continuously handle camera acquisition**
- During data readout, the **uDMA block autonomously handle data transfer** from the sensor to the L2 memory, without cluster activation

Evaluation & Results

Detection and Tracking of moving objects

Inspiring from neuromorphic engineering and event-based sensor processing (e.g. DVS sensors), a parallel event-driven processing has been explored for clustering incoming events into blob descriptors, based on distance criteria.

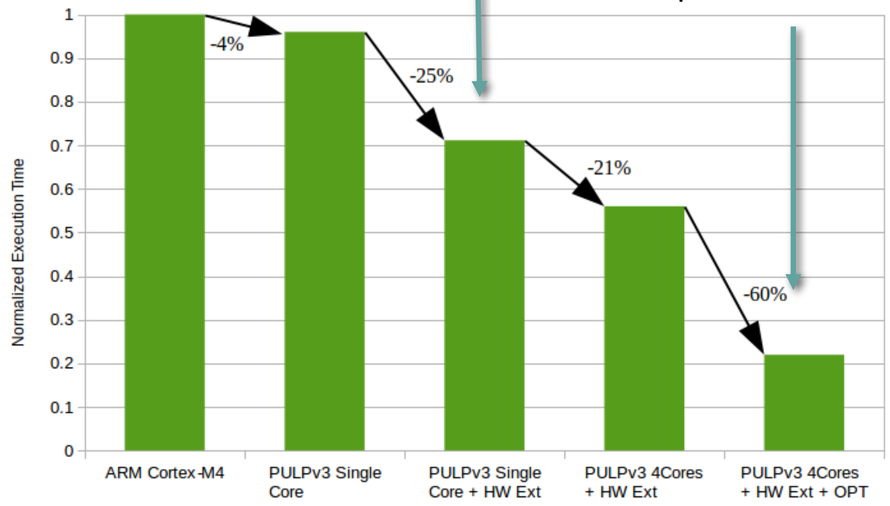




Computational Time speed-up thanks to PULPv3 parallel computing and DSP processor extensions.

HW extension

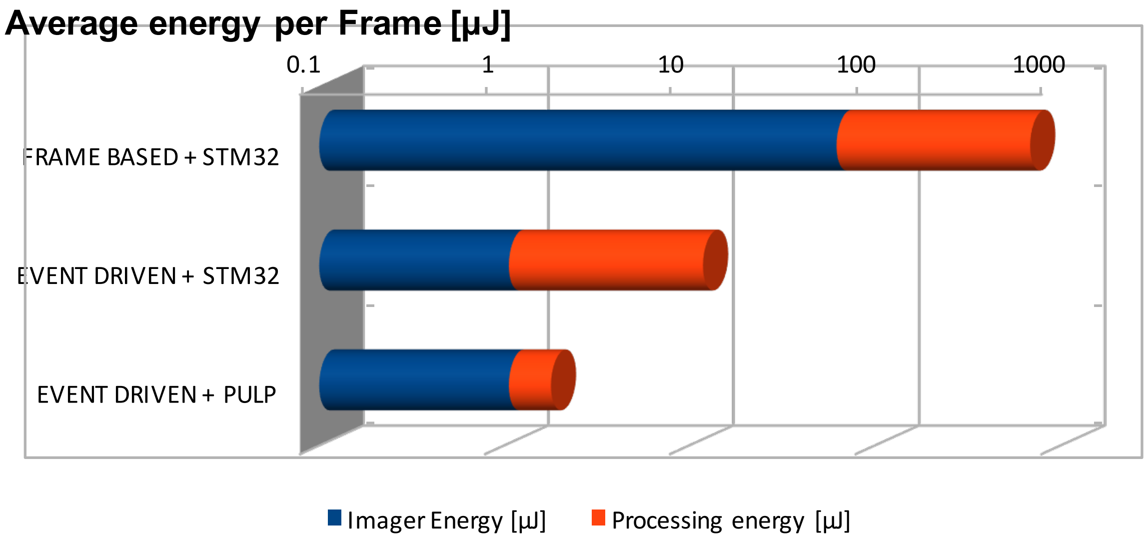
Optimized parallel runtime



Energy estimation

Energy-efficiency Improvements Estimation

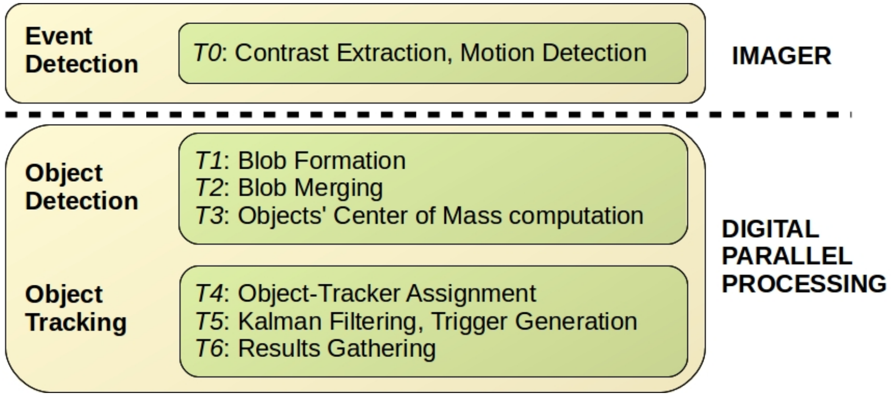
- A **57.7x processing energy saving** on low-power MCU is reached thanks to the **event-based imager and the event-driven processing** approach w.r.t. a traditional frame-based traditional system
- **PULPv3 post-processing** speed-up achieves 2.5x, leading to **an energy saving of 6.64x** compared to an low-power MCU
- **The overall system energy cost is reduced by 383x**, achieving an overall cost of 1.79µJ per frame

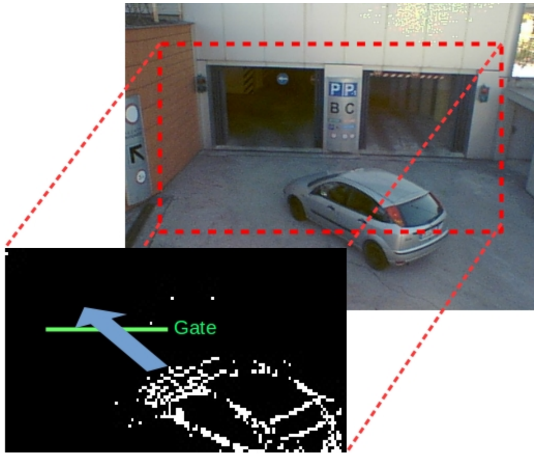


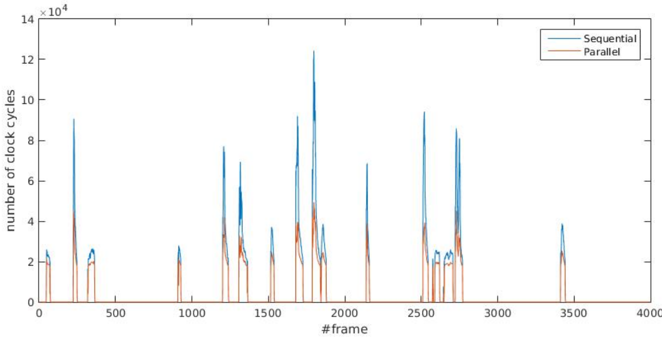
More than 2 order of magnitude of energy saving!

Smart Visual Trigger

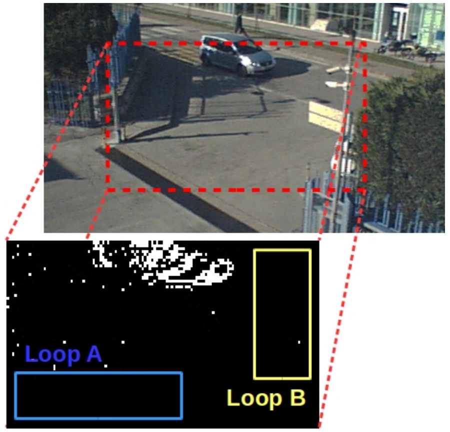
Triggering alert signals if a tracked object enters an interesting area

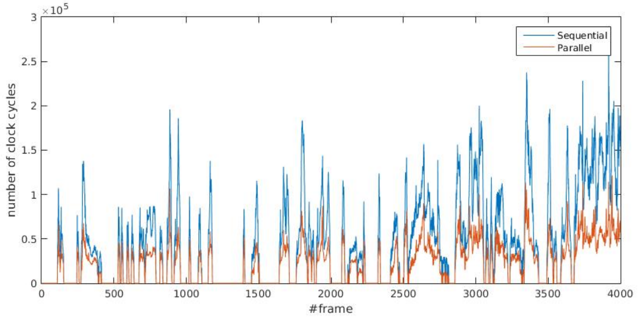






No processing occurs when no moving objects appear in the camera field of view.





Conclusion and Future Work

Always-on vision sensing can be enabled by considering an ultra-low-power system architecture and an efficient computational model.

Next steps:

- System HW evaluation within more complex always-on application domain (e.g. recognition)
- Exploration of event-driven image processing meyhods to extract meaningful features from images produced by event-based analog sensors.

Thank you for the attention!