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Low-Power Event-driven Image Sensor Architectures

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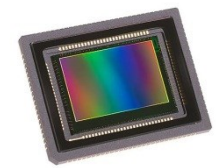
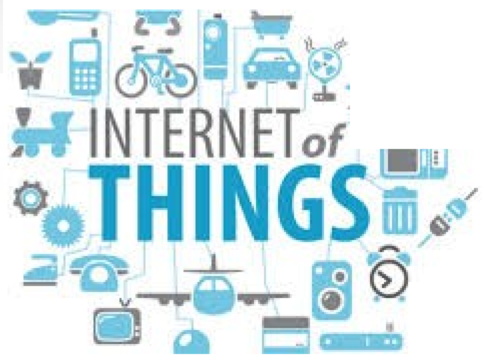
Internet of Things Challenges

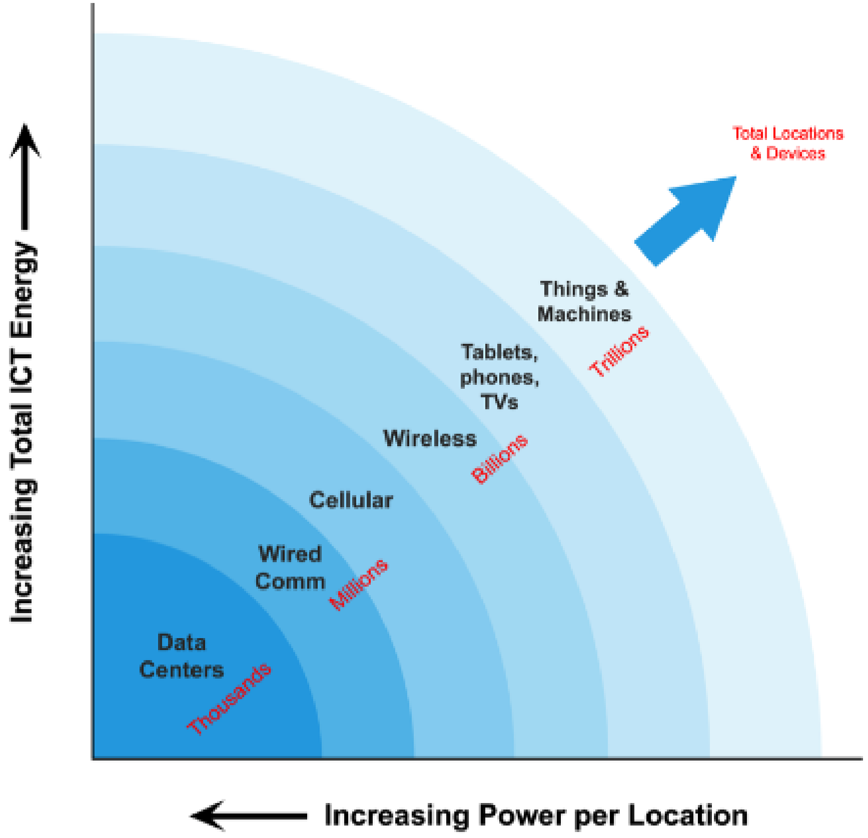




+ more data
+ more storage
+ more communications
+ more consumption

Upcoming Challenges

Where electricity is consumed in the digital universe?



Source: Digital Power Group

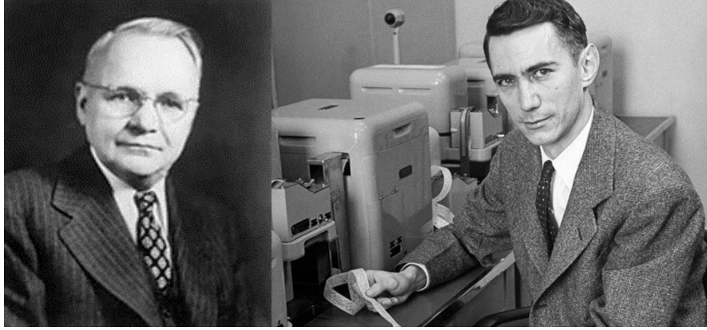
- **10% of the world electricity consumption**
- **Growth is exponential**
- **Need fossil energy or more nuclear power plants**

Not really ecological!

Outline

- **Another way for sampling**
  - Sampling without Shannon?
  - Nonuniform Sampling
- **Sampling an image**
  - State of art: Conventional Image Sensors
  - State of art: Event-based Image Sensors
  - An architecture for low-power Image Sensors
- **Conclusions**

Important questions



Harry Nyquist and Claude Shannon

Claude Shannon and Harry Nyquist are they responsible of the digital data deluge?

- We will not answer to this question but the big data is today a reality!

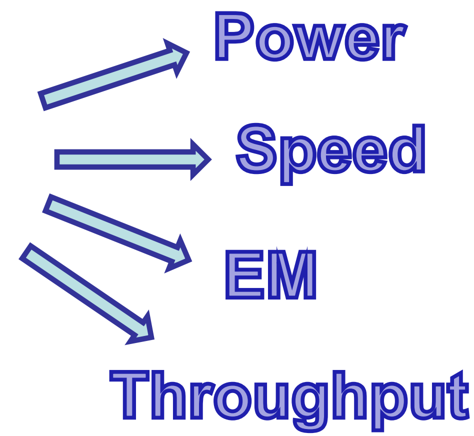
Can we find a better sampling scheme to stem this digital data deluge and stop the energy waste?

- We hope so !!!

Sampling is the success key

- Sampling based on the Shannon-Nyquist theorem
  - Efficient and general theory… **whatever the signals!**

- Smart sampling techniques
  - **More efficient** but less general for **specific signals**!

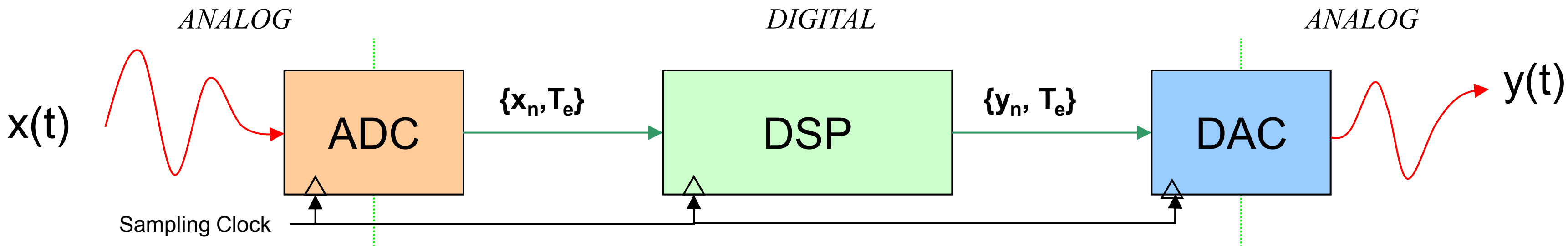


  - Need a more general mathematical framework
    - **F. Beutler**, "*Sampling Theorems and Bases in a Hilbert Space*", Information and Control, vol.4, 97-117,1961

- Sampling should be **specific to signals and applications**

What can we do?

Uniform and Synchronous



Nonuniform and Event-driven (Asynchronous)

Direct processing of the nonuniform samples

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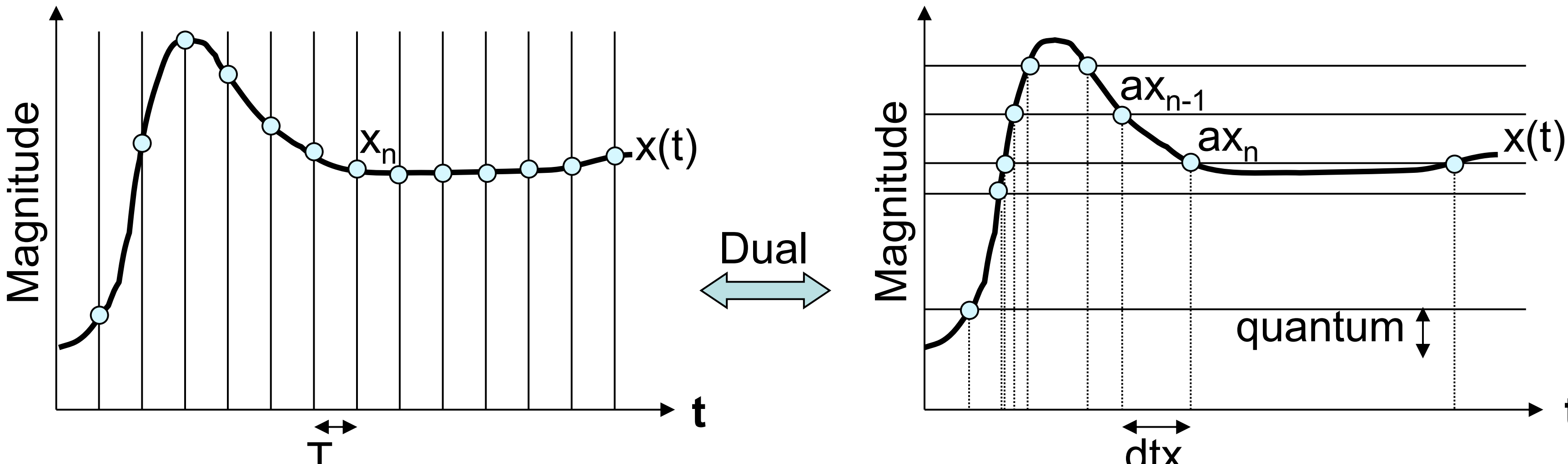
Differently sampling

Uniform sampling | **Non uniform sampling**



Uniform sampling

- Respect the Shannon theorem
- **Instants exactly known**
- Information: T_{sample}, { i_k }
- In an ADC: **Amplitude quantization**
- Many useless samples

Non uniform sampling

- "Level-crossing sampling" (LCSS)
- **Amplitudes exactly known**
- Information: quanta, { dti_k }
- In an A-ADC: **Time quantization**
- Only useful samples

SNR with non-uniform sampling

- SNR for a sinusoid:

$$SNR_{dB} = 1,76 + 6,02.N$$ ⇨ **Number of bits**

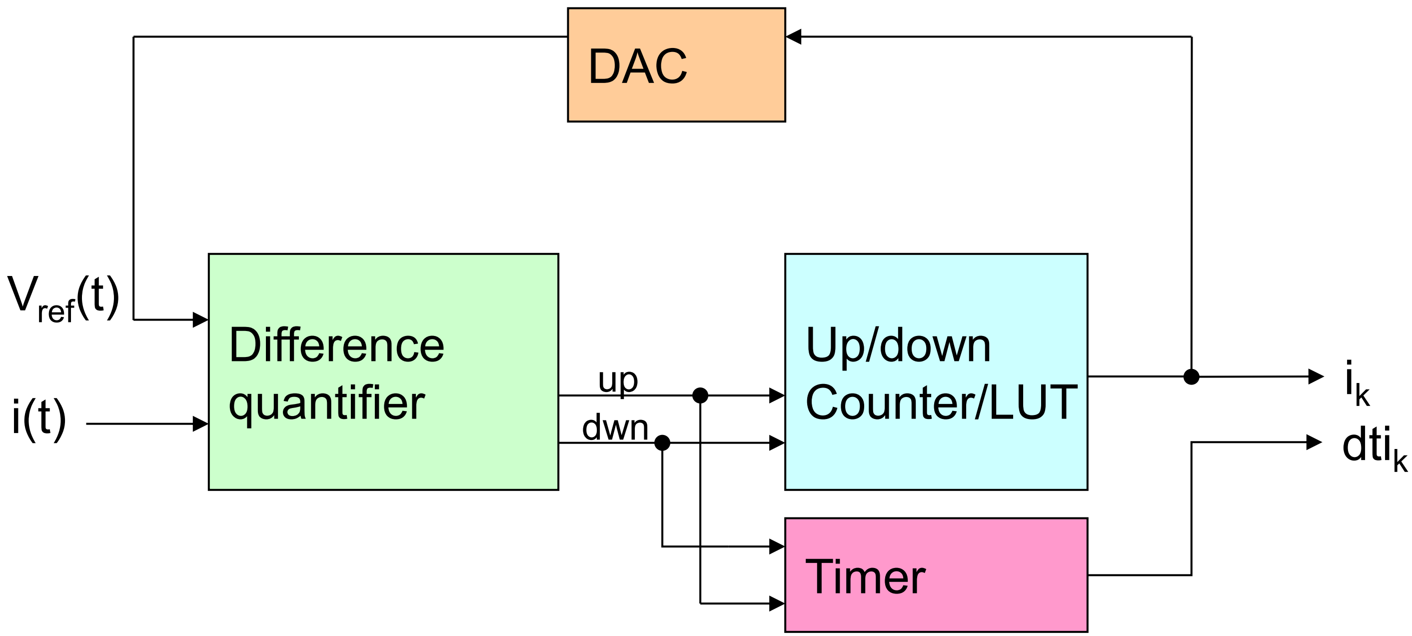
- Theoretically, noise is only due to amplitude quantization
- With non-uniform sampling, the time is quantized

$$SNR_{dB} = -11,2 - 20\log(fT_c)$$ ⇨ **Timer period**

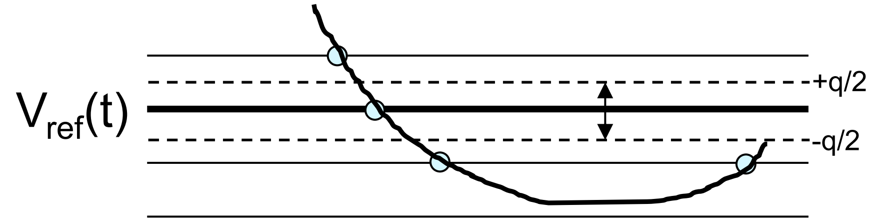
- Noise only depends on the **timer resolution** whatever the threshold distribution

A-ADC or ADC for LCSS

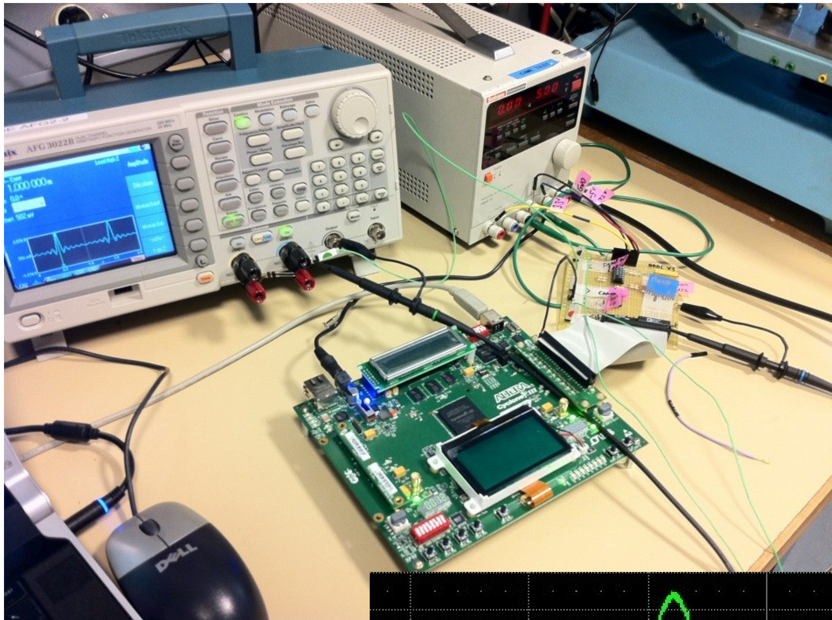
- A-ADC for Non Uniform Sampling



- If (i(t) – Vref(t)) > q/2 → up
- If (i(t) – Vref(t)) < -q/2 → dwn
- Else up = dwn = 0



A-ADC

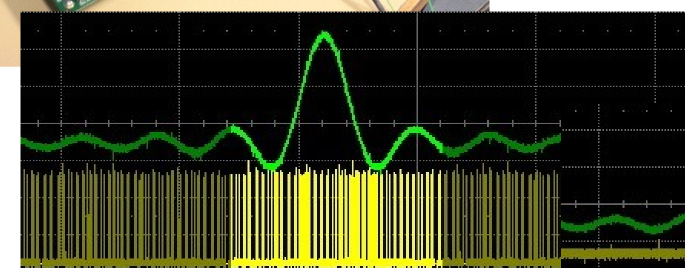


A-ADC

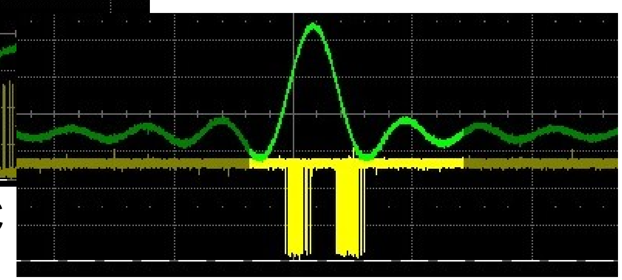
realized with circuits on-the-shelf.

(FPGA+DAC+Comparators)

E. Allier et al. 05
Aeschlimann et al., 06
Beyrouthy et al., 11



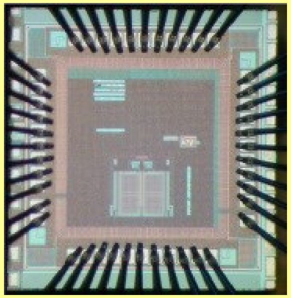
Synchronous ADC



Asynchronous ADC

A-ADC testchips

Microphotography of the A-ADC
In CMOS 130 nm technology from
STMicroelectronics



E. Allier et al., Async, 2003

A level-crossing flash asynchronous analog-to-digital converter

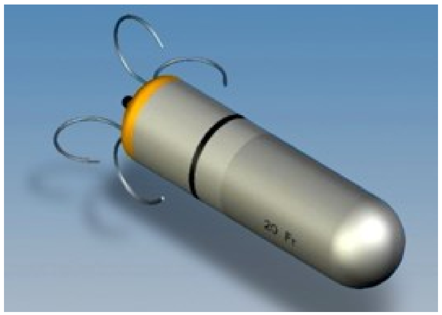
F. Akopyan et al., Async, 2006

A Clockless ADC/DSP/DAC System with Activity-Dependent Power Dissipation and No Aliasing

Y. Tsividis et al., ISSCC, 2008

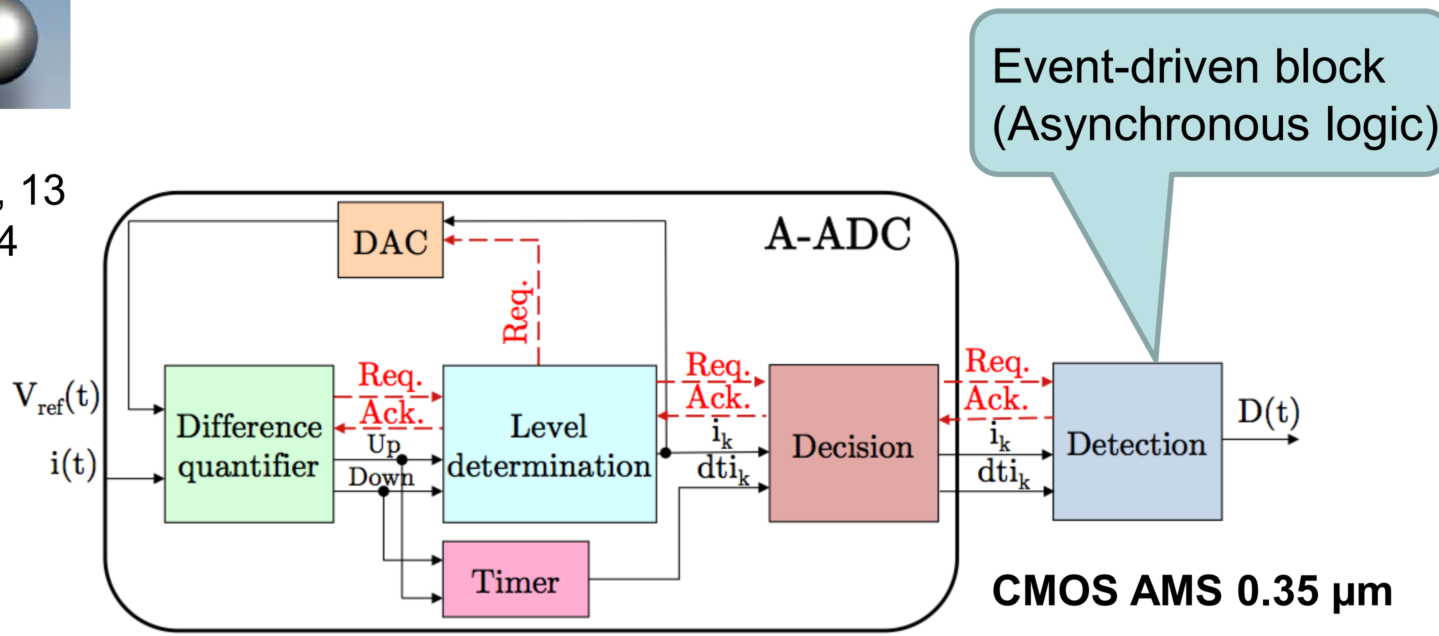
Lowering in one step the **storage**, the **processing**, the **communications** and the **power consumption!**

A successful experiment



- Context of the **medical implants**
- **Activity patient measurements**

T. Le Pelleter et al., 13
L. Fesquet et al., 14



CMOS AMS 0.35 µm

Experiments based on **real physiological signals** (recorded on the patients)

What we learned
with this experiment

With the medical implant

- No pre-processing
- **Less than 1% of data** compared to the uniform sampling
- **3 orders of magnitude reduction** on power

In general

- **Be more specific** to signals and applications
- **Non-general approach**, but **reproducible**

- **Non-uniform sampling well-suited to sporadic signals**

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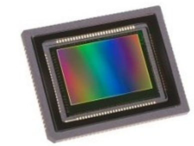
Low-power Image Sensors?

Objective of this presentation



- No image sensor really dedicated to low-power
- High resolution sensors requires a high speed ADC
  - High power consumption

- How to reduce the power in Image Sensors
  - Use **advanced technology nodes** (expensive)
  - **Reduce the data flow** / activity
  - **Rethink analog-to-digital conversion**

→ Apply nonuniform sampling in 2D

→ Event-based image sensors

Darwish et al. 2014, 2015
Posch et al. 2008, 2011,
Delbruck et al. 2004,
Qi et al. 2004

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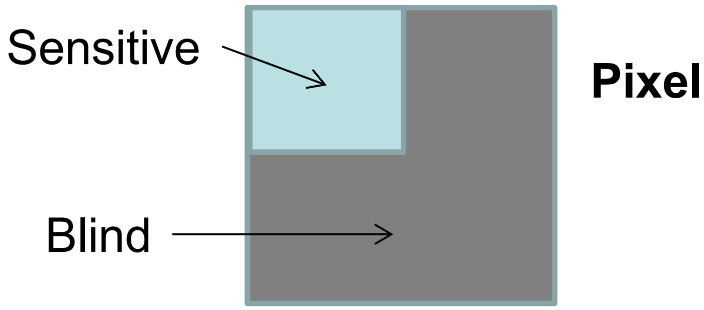
Image sensor principles

- Based on **photodiodes**
- Pixel fill factor = optical quality
- **All pixels are read in sequence**
- Larger the sensor, higher the throughput (fixed frame rate)
- Higher the throughput, higher the ADC consumption

- The **ADC is the first contributor of power consumption**



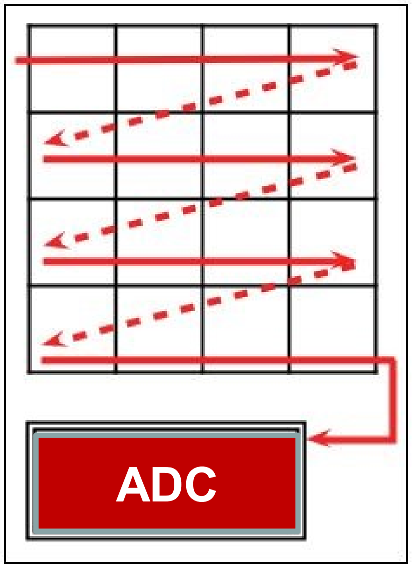
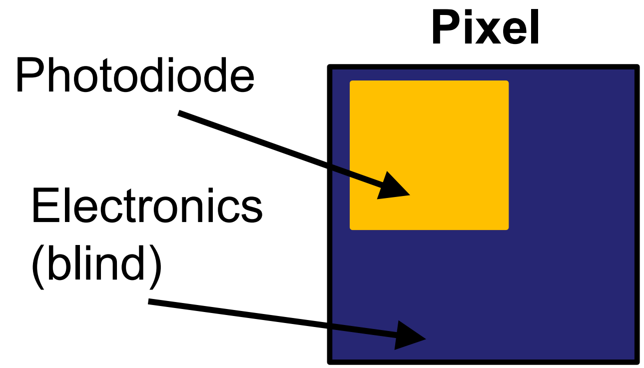
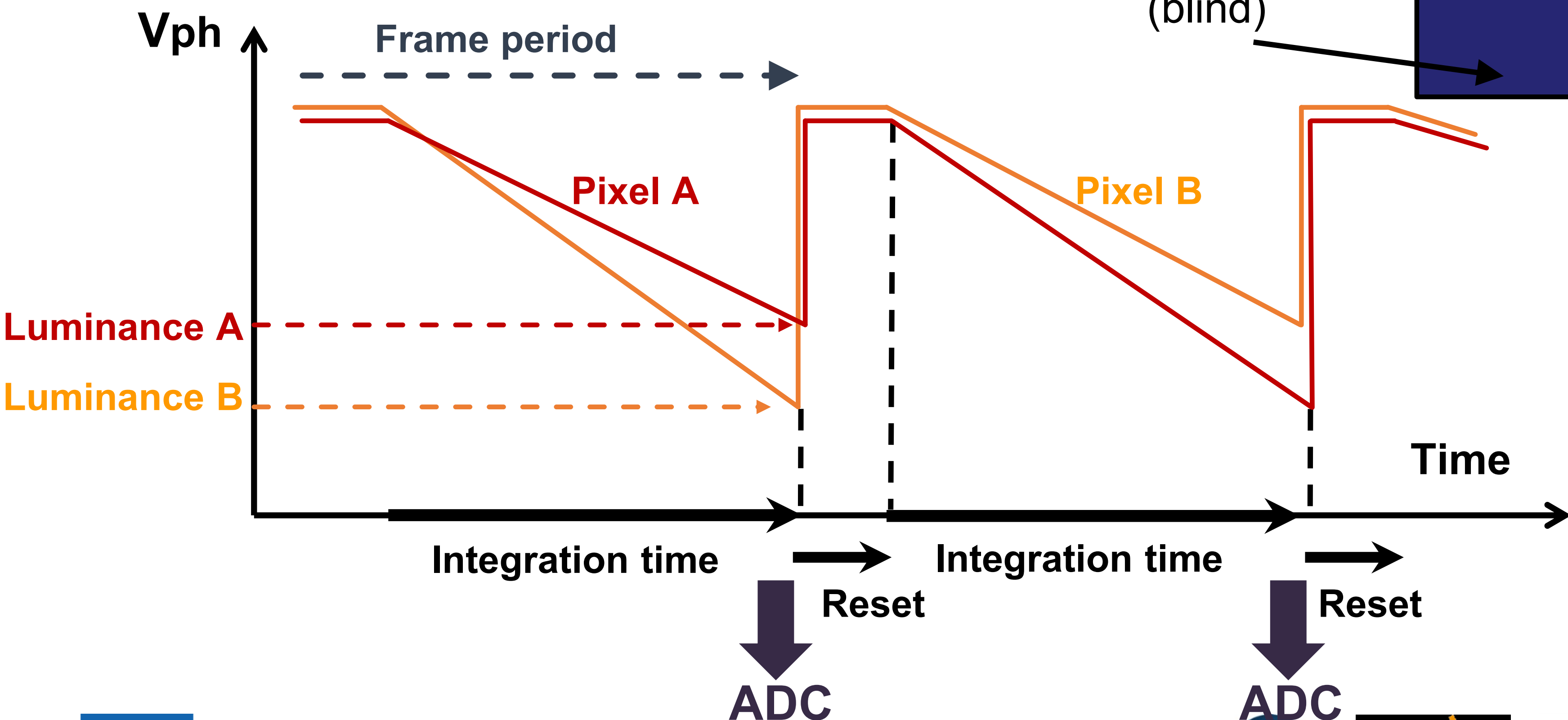


Image Sensor Principles

Most common feature for an APS:

- Fill factor, SNR, Sensitivity, Dynamic, …





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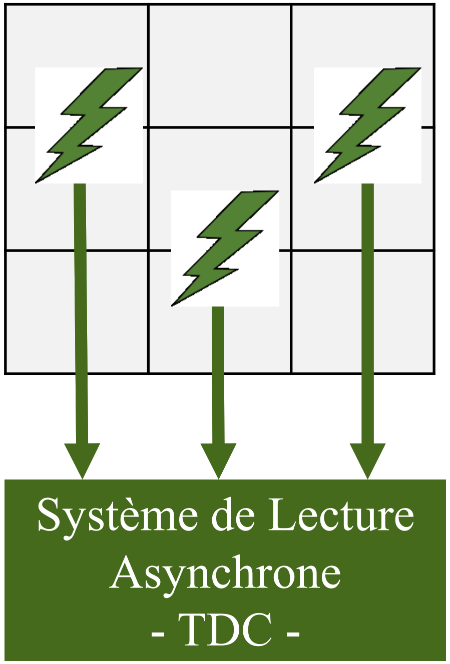
Event-based Image Sensors

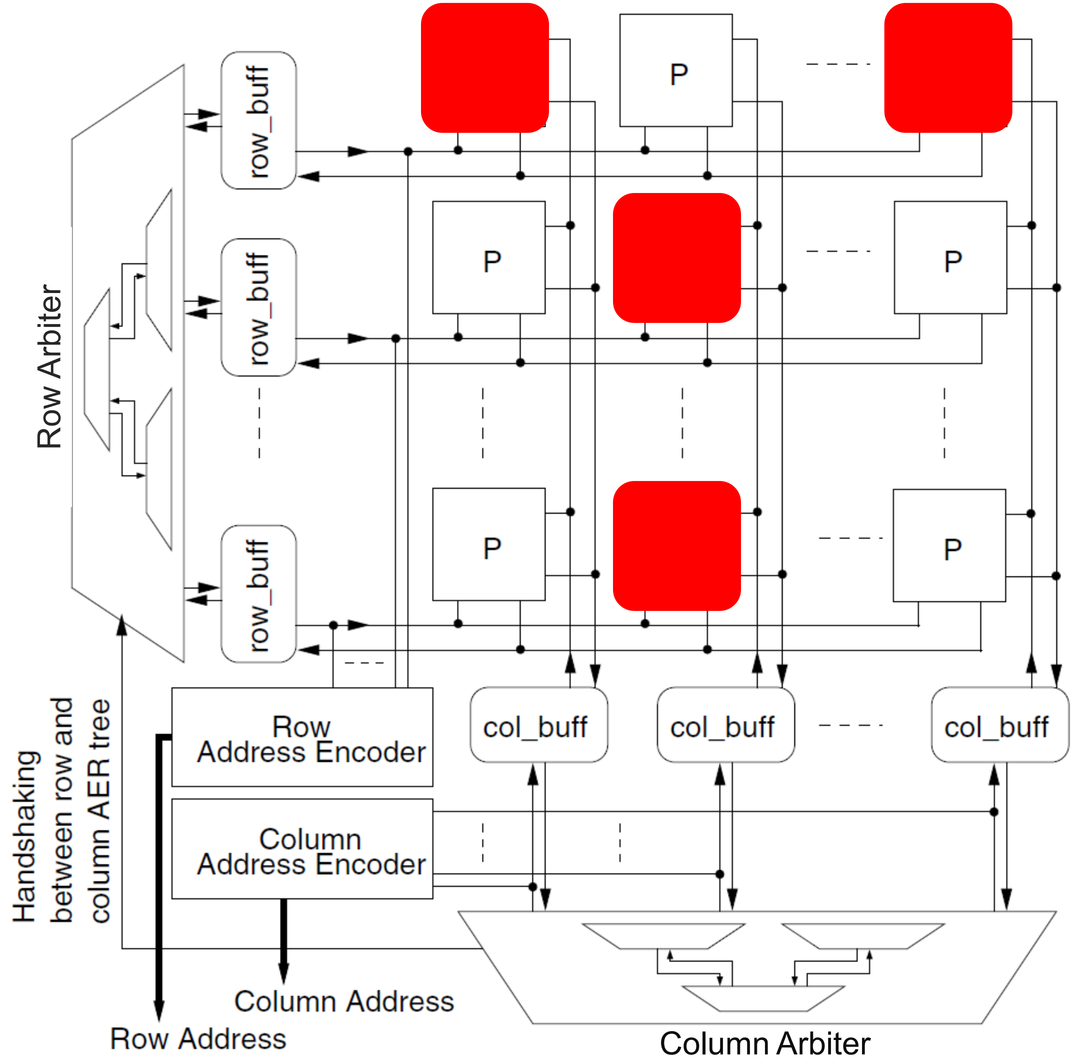
- **Pixel reading on event**
  - Initiated by the pixel itself
  - Frameless sensor
  - No frame rate
- **Address Event Representation** (AER)
- **Event-based pixel**
  - Asynchronous communication
  - Time-to-First Spike encoding (TFS)
- **Time-to-Digital Conversion** (no more ADC)



- **Sensor activity depends on the captured scene**
- **Reduced dataflow**

Event-based Image Sensors

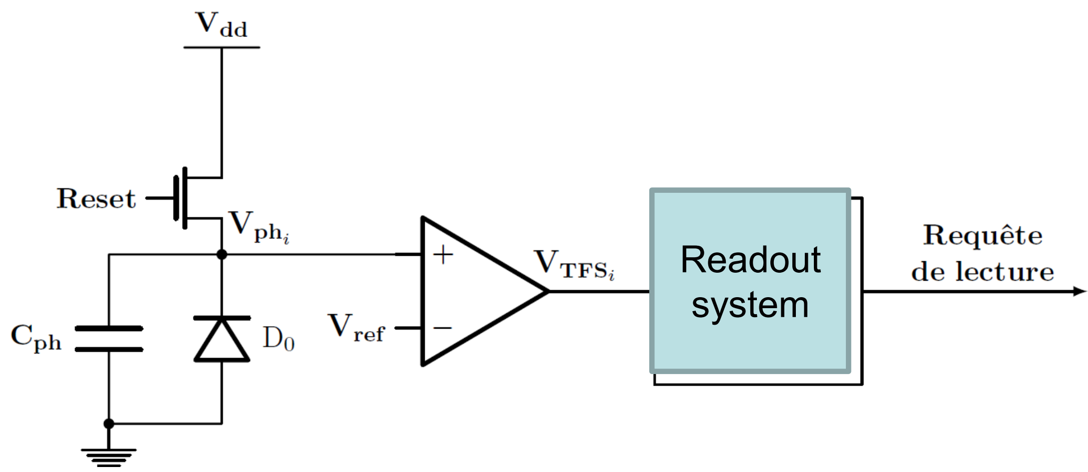
- Need to manage multiple pixel requests
- Event-based Image Sensors need arbitration
- Complex Circuitry
  - Exponentialy growth with the image sensor resolution
- Inaccurate time stamping
- Fixed priority arbiters are unfair



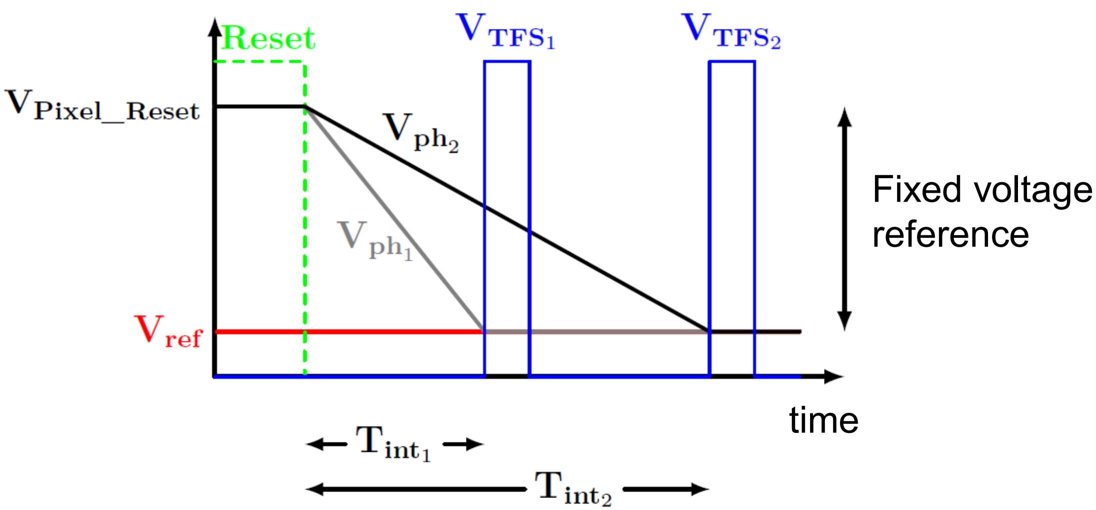
Ref : Myat2011

Time-to-First-Spike
a bio-inspired approach

- **Time represents the information**
  - **Spike time stamping**
  - **Time quantization**



- **Advantages**
  - Read on events
  - One integration time per pixel
  - Dynmaic range controlled by the TDC
  - Robust (digital readout circuit)

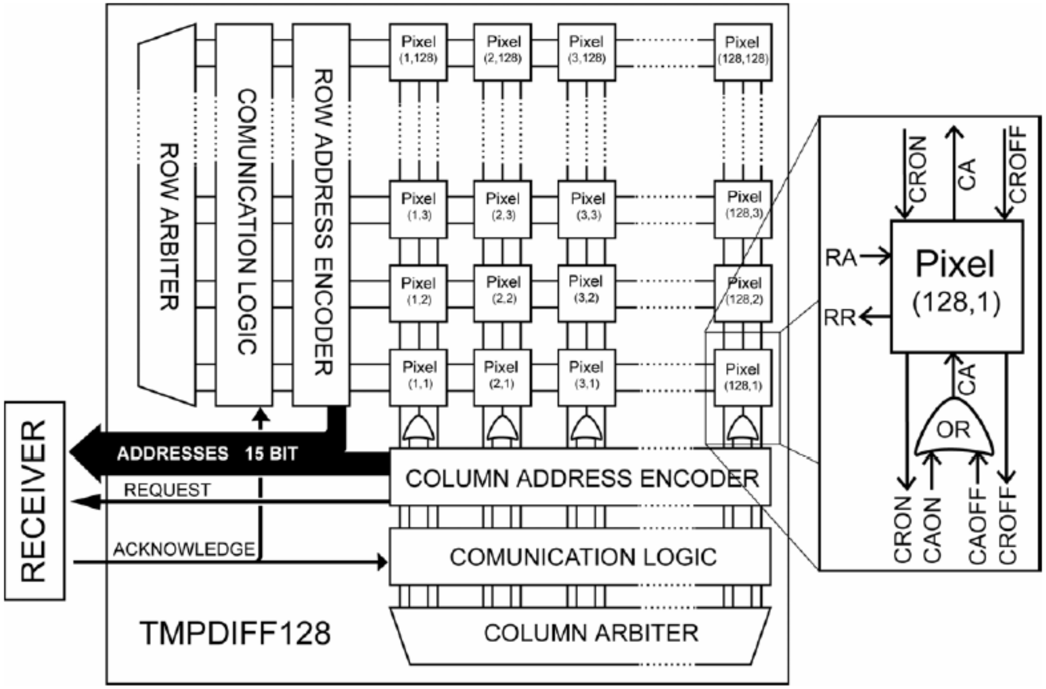


- **Drawbacks**
  - Large pixel area
  - Variability of the analog part (comparator)

Event-based Image Sensor: state of art

Delbrück/Lichtsteiner : Dynamic Vision Sensor (DVS)

- Neuromorphic approach
- **Detect changes in pixel luminance** (send a request)
- High dynamic range sensor (logarithmic pixel)

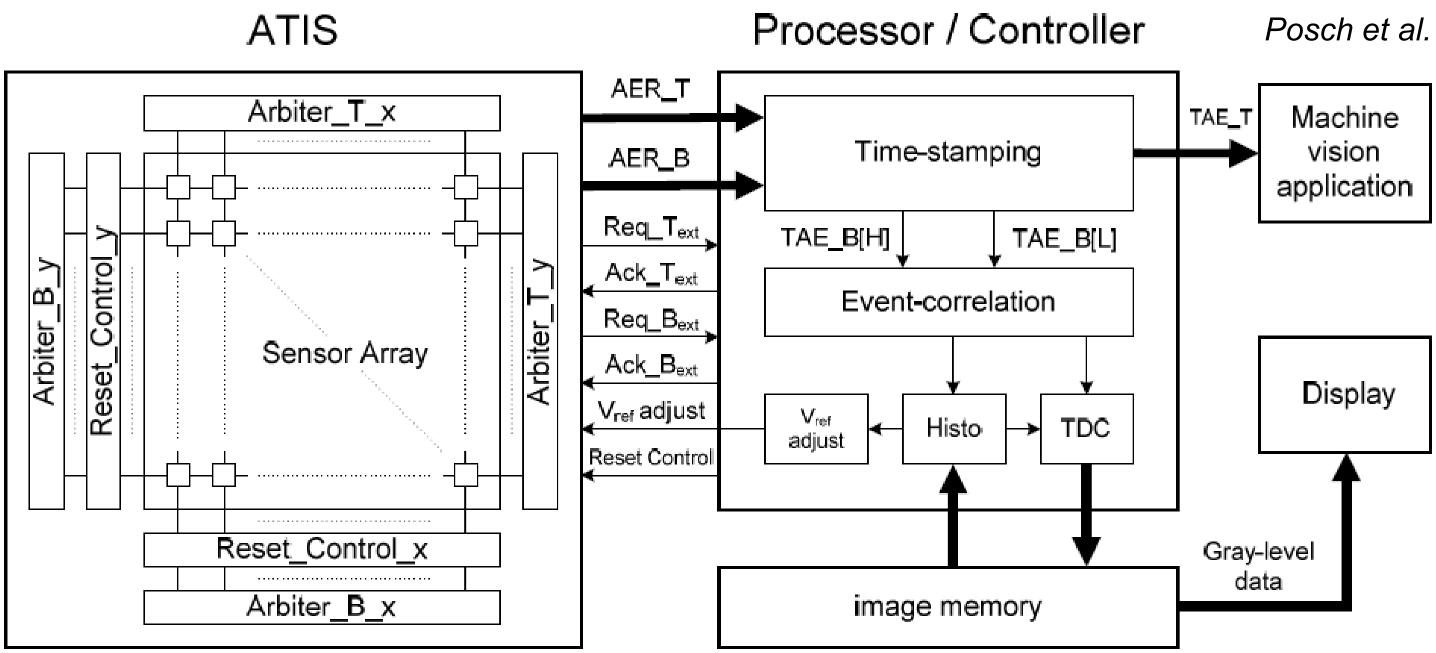


Lichtsteiner et al. 2006

Event-based Image Sensor: state of art

Posch :

- Double arbiter
- **Temporal redundancy reduction**
- High dynamic range(~ 140 dB)
- large pixel area (89 transistors, 2 capacitances, 2 photodiodes)
- Fill factor < 14 %



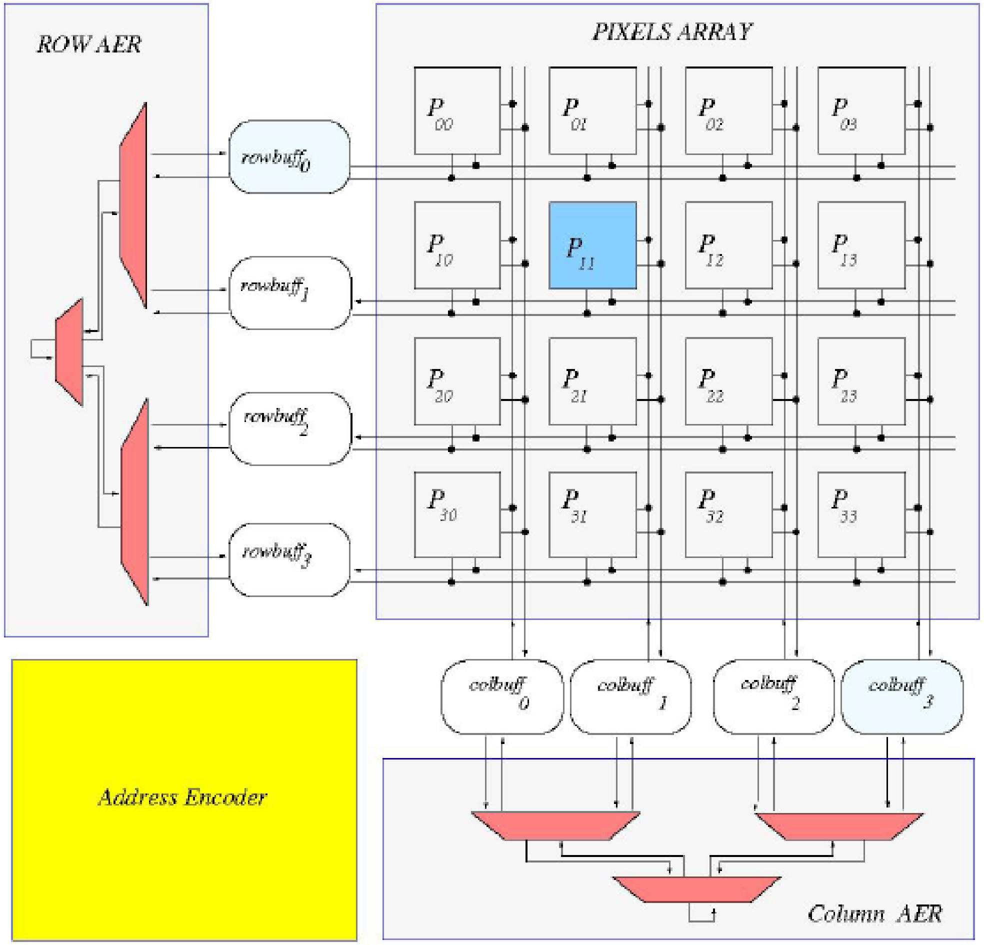
Posch et al. 2011

Event-based Image Sensor: state of art

Shoushun, Bermak 2006

Bermak / Shoushun :

- **Pipelined arbiter** with alternate priority
- Local pixel reset
- Pixel is idle after reading
- **Low power design**
- **Simple pixel design**



Event-based Image Sensor: state of art

Parameters	Conventionnal Image Sensors	Event-based Image Sensors
Sampling Scheme	Uniform	**Nonuniform**
Integration Time	One for the whole sensor	**One per pixel**
Readout System	Sequential	**Event-based**
Protocol	Sequential and **Exhaustive**	Sequential and Event-based (AER)
Data Flow	Fixed and Redundant	**Nonuniform and Reduced**
Pixel Complexity	**Simple**	Complex
Power Consumption	Sub-optimal (redundancy)	**Reduced**
Frame Rate	Fixed	**Event-dependent**

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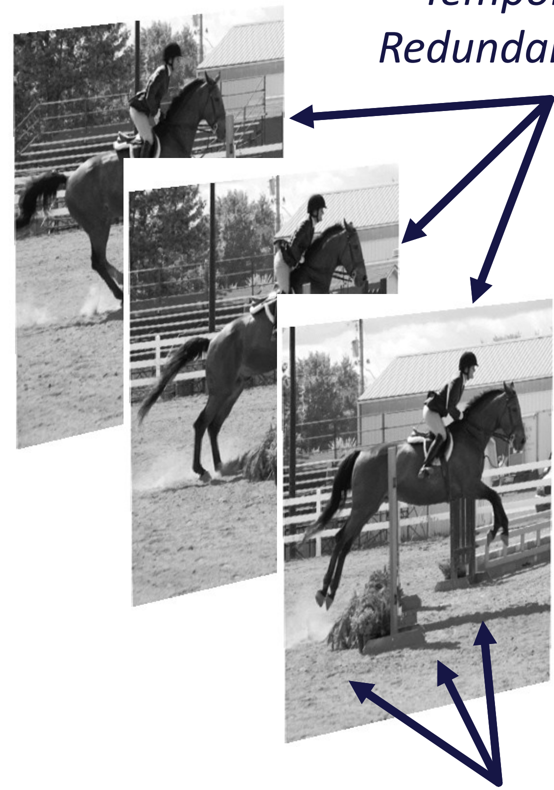
Changing the paradigm in a realistic manner

- **Keep the fill factor reasonable** (important for industrial products)

- **Reduce the throughput** without changing the frame rate

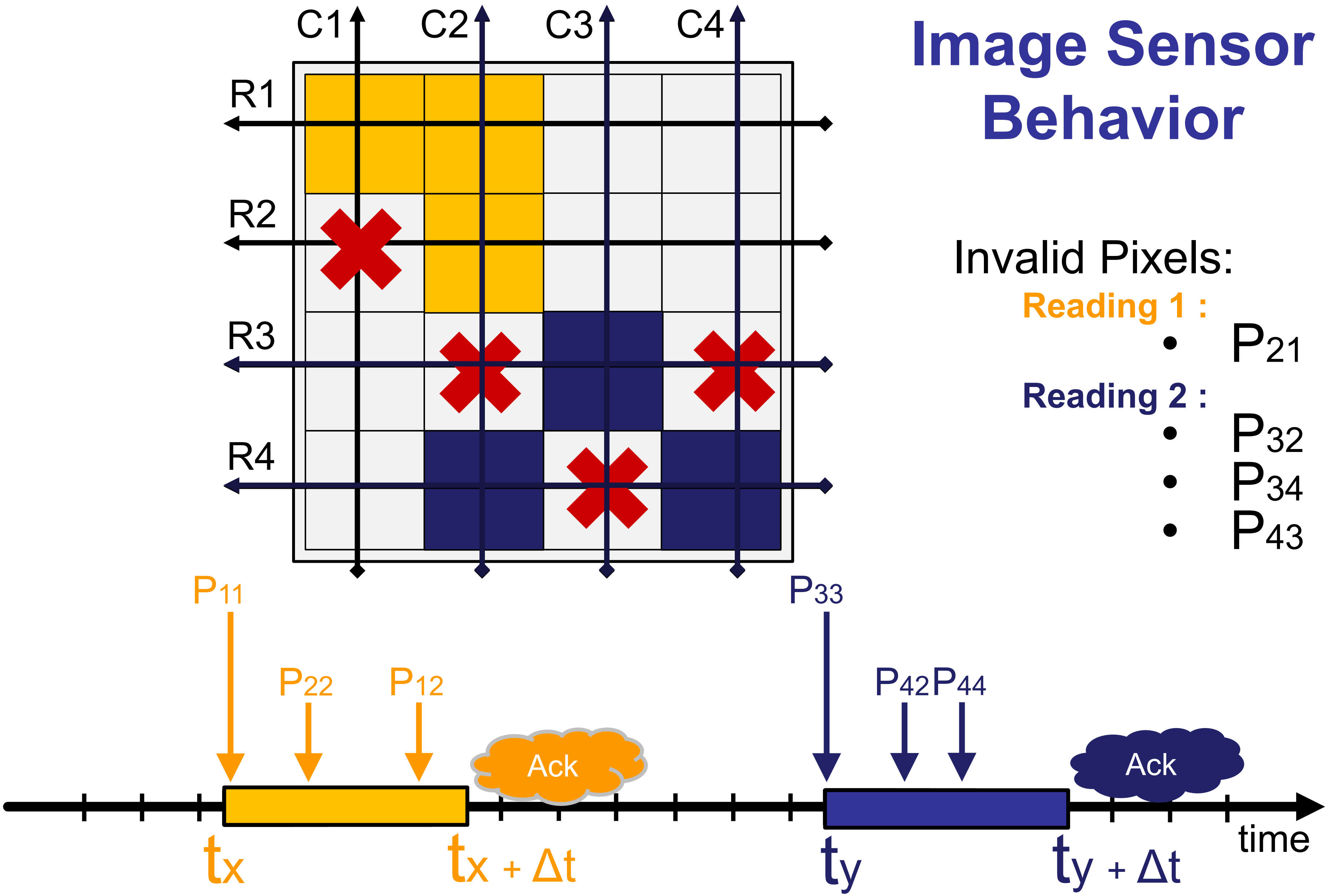
- **Remove the ADC to limit power** consumption
- Replace it by a digital circuit (more easy to implement)

Changing the paradigm in a realistic manner



- **Suppress redundancies**
- **Prefer Time-to-Digital conversion**
- **Use Event-Driven logic (asynchronous)**
  - **Global Clock** is *replaced* by **local channels** (handshaking)
  - **Power is only consumed when data are really processed**

Image Sensor Behavior



Invalid Pixels:

Reading 1 :

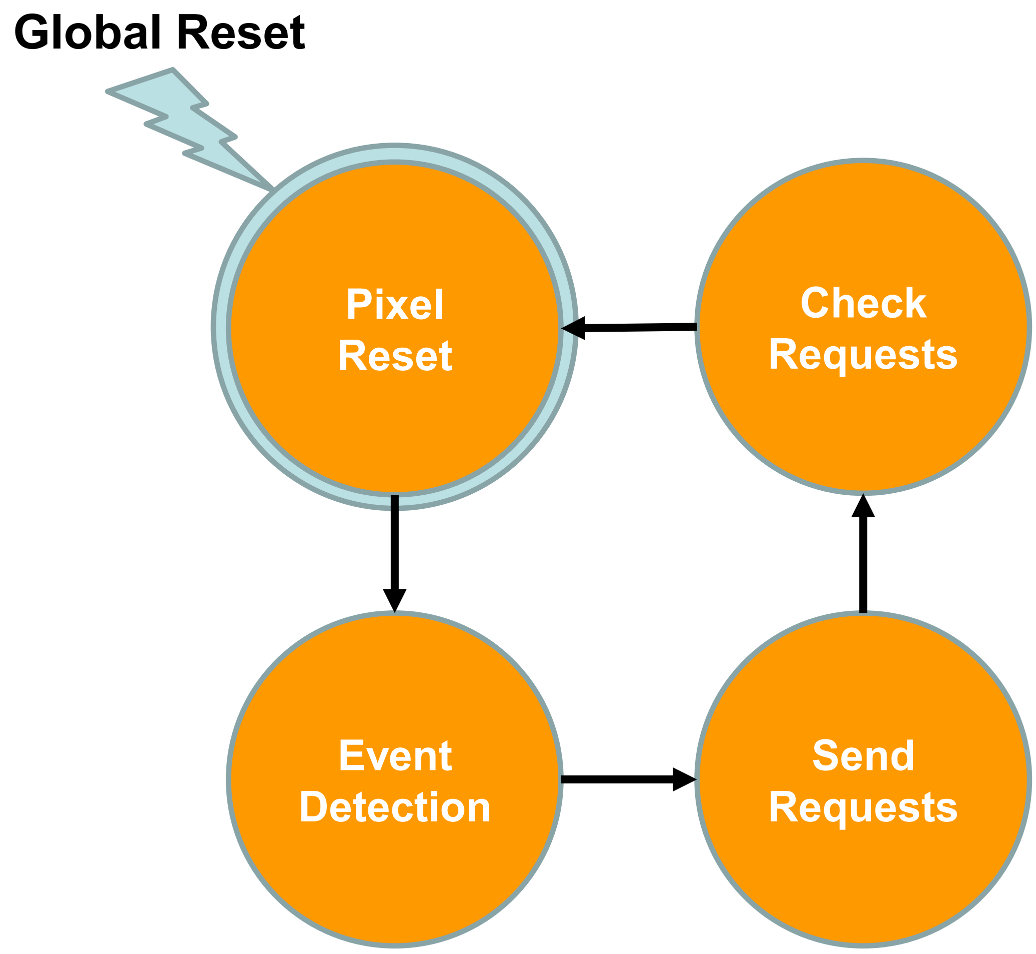
- P_{21}

Reading 2 :

- P_{32}
- P_{34}
- P_{43}

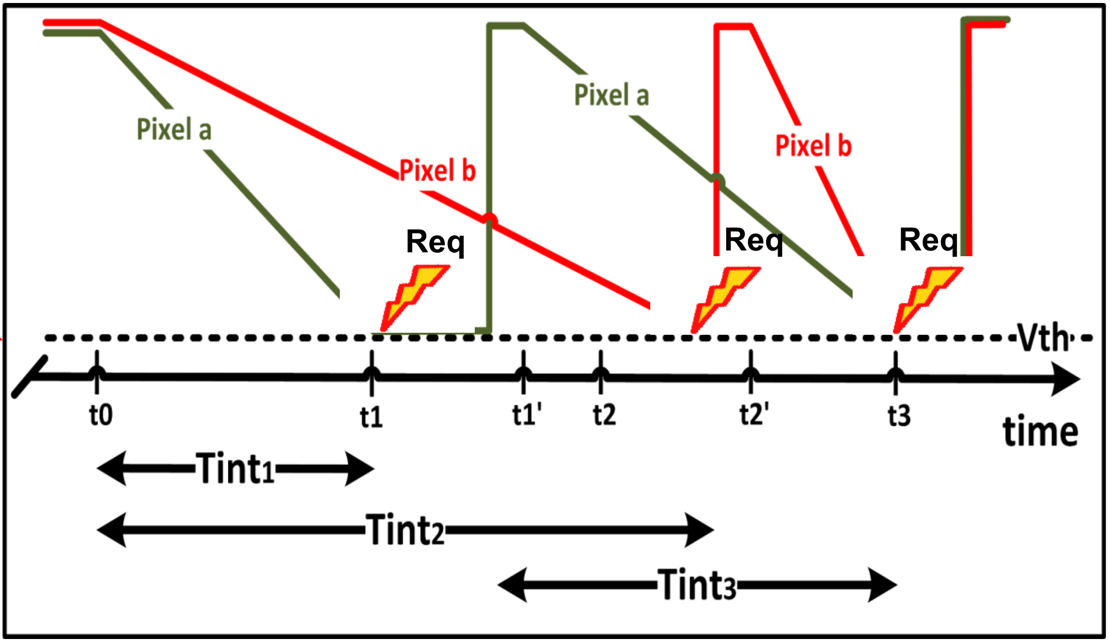
High-level Pixel Model

- **4-phase pixel**
  - Event detection
  - Send requests
  - Check requests
  - Reset pixel



Pixel behavior

Adjust the image sensor sensitivity
=
High Dynamic range



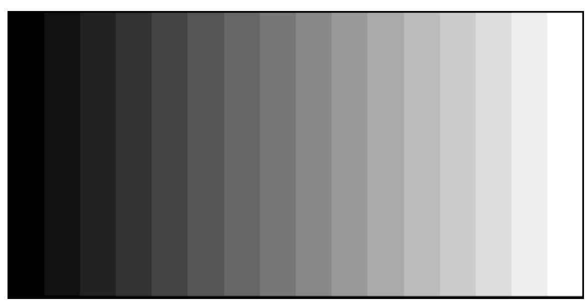
- Based on **event-detection**
- **1-level crossing sampling** scheme
- **Unique integration time per pixel**
- **Time to first spike** encoding

A. Darwish et al., EBCCSP, 2015
A. Darwish et al., NewCAS, 2014

Specific behavior of our sensor

Discussion on Δt

- **Δt : deadtime after time stamping**.
- No other time stamping allowed during Δt even if events occured
  - Control the time stamping resolution
  - Equivalent to ADC quantum ΔV
  - Control the **maximal number of readings** or **greyscale levels**
- **Trade-off between image quality and readout rate**



Δ = 16

Performance Evaluation

- *Asynchronous Image Sensor Readout Rate (AISSR)*
  - Compute the read pixel number by our architecture (M columns x N rows)
  - **Reading operations bounded by the number of luminance values**
  - **d is the image dynamic range**

$$\mathrm{AISRR}(\%) = 100 \cdot \left(\frac{\mathrm{d}}{\mathrm{M} \cdot \mathrm{N}}\right)$$

- PSNR (Peak Signal to Noise Ratio)
  - Evaluate the distorsion induced by the compression
  - For grayscale image, 30dB et 50dB are prety goo values

$$\mathrm{PSNR}_{dB} = 10 \cdot \log\left(\frac{\mathrm{d}^2}{\mathrm{MSE}}\right)$$

- MSSIM (Mean Structural SIMilarity)
  - Take into account the human perception (luminance, contrast, image structure)
  - Best is 1, worst is 0

Reference Image
Readout rate = 100%
MSSIM = 1

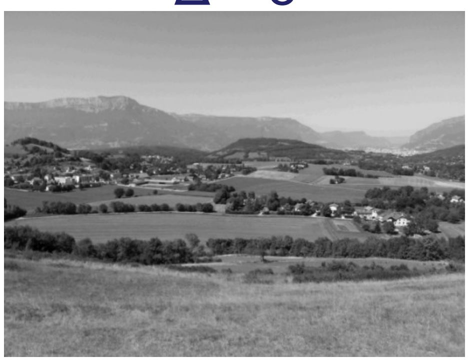
Δ = 2

Readout rate = 0.13 %
PSNR = 40.03dB
MSSIM = 0.999

Δ = 4

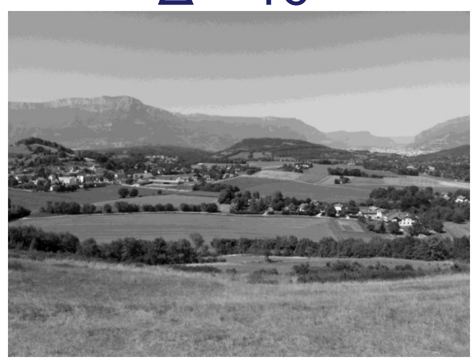
Readout rate = 0.042 %
PSNR = 38.1dB
MSSIM = 0.919

Δ = 8



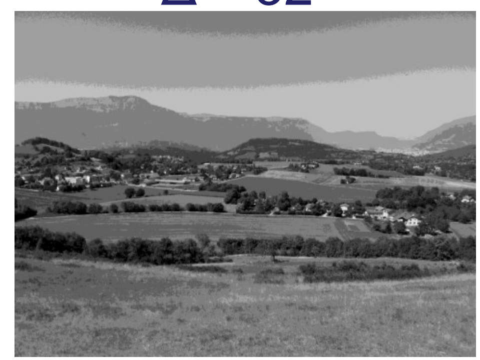
Readout rate = 0.018 %
PSNR = 36.29dB,
MSSIM = 0.765

Δ = 16



Readout rate = 0.008 %
PSNR = 31.46dB
MSSIM = 0.635

Δ = 32



Readout rate = 0.004 %
PSNR = 22.51dB
MSSIM = 0.483

Reference Image
Readout rate = 100%
MSSIM = 1

$\Delta = 2$

Readout rate = 0.084 %
PSNR = 31.1dB
MSSIM = 0.987

$\Delta = 4$

Readout rate = 0.029 %
PSNR = 30.34dB
MSSIM = 0.942

$\Delta = 8$

Readout rate = 0.012 %
PSNR = 28.36dB
MSSIM = 0.813

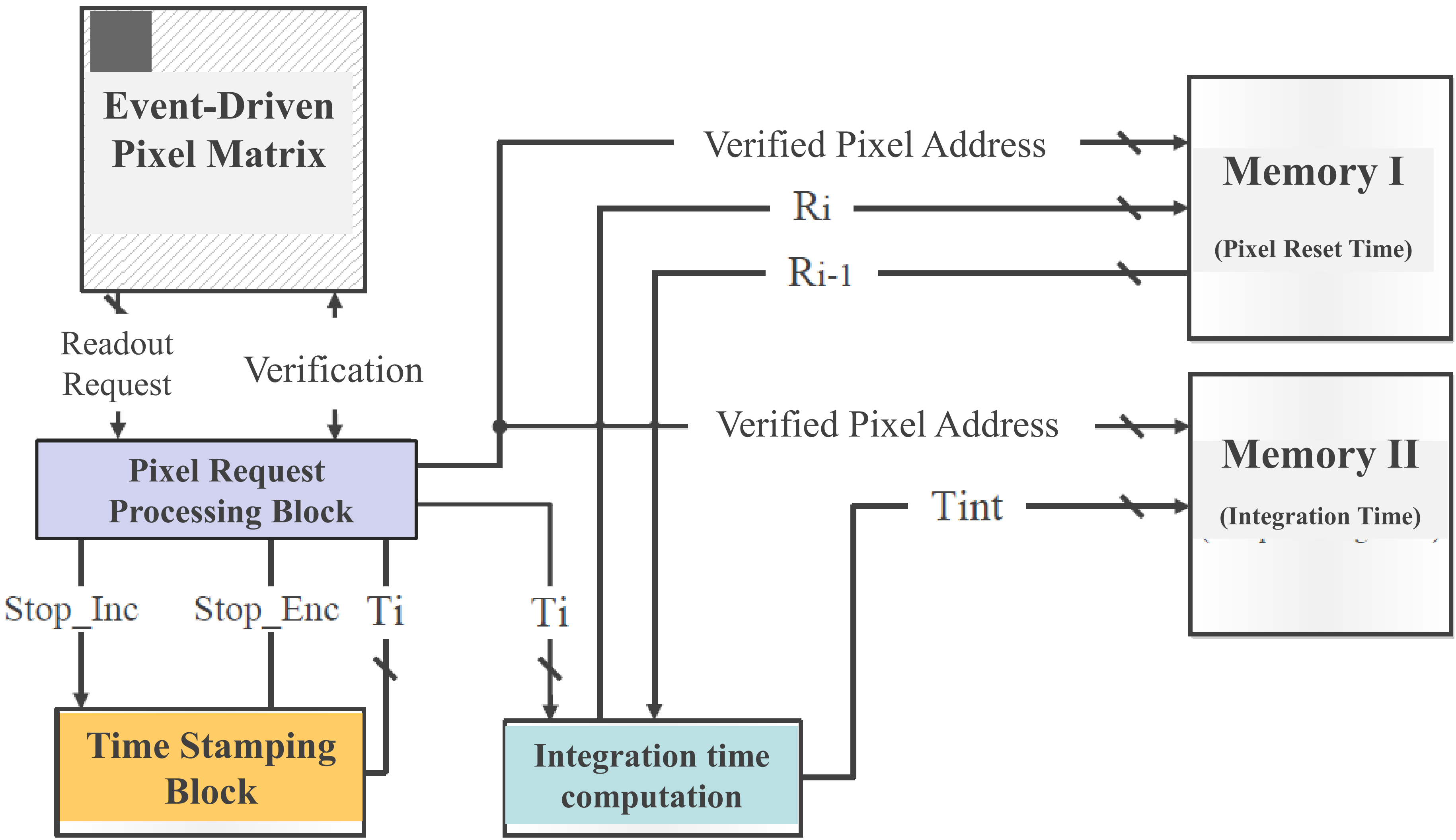
$\Delta = 16$

Readout rate = 0.006 %
PSNR = 26.24dB
MSSIM = 0.605

$\Delta = 32$

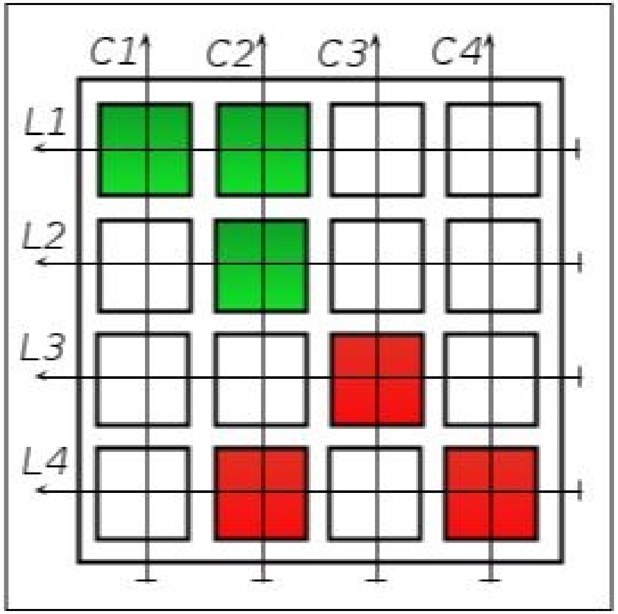
Readout rate = 0.003 %
PSNR = 22.13dB,
MSSIM = 0.392

Asynchronous readout architecture

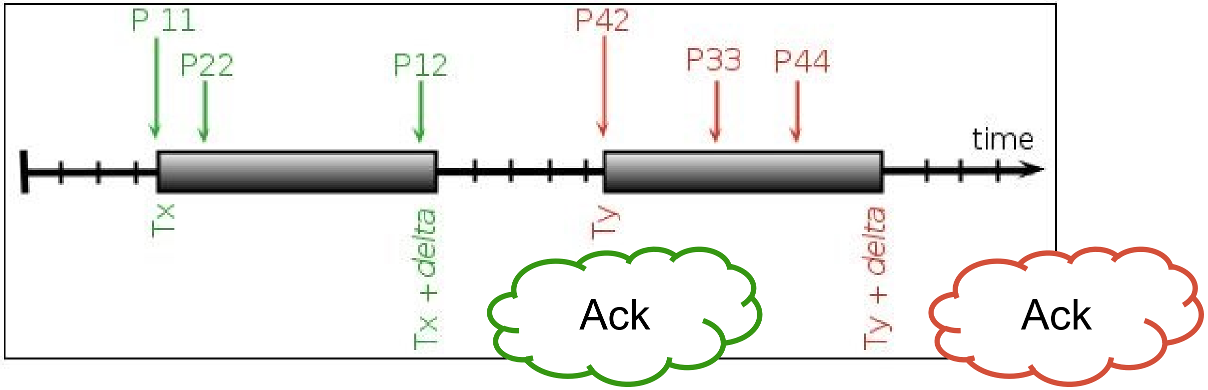


How do we suppress Spatial Redundancy ? (again)

4 x 4 image sensor



Darwish et al., 14



What we learned
with image sensors

- **1-level crossing sampling** in 2D
- Low percentage of readings per column (< 1 %)
- Image **data flow reduction**
- **Event-driven** digital circuitry
- **Adjustable resolution** and **dynamic range**

- **Don’t need an ADC** (power consuming)
- **Intrinsic A-to-D conversion**

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General Conclusion

- Lesson 1: **Determine** the most efficient sampling!
- Lesson 2: Fit well **Event-Driven Circuits** (asynchronous)
- Lesson 3: **Ultra-Low Power**

- Less samples means:
  - Less computation, less storage, less communications,
  - **less power**

A more energy efficient approach of digital processing

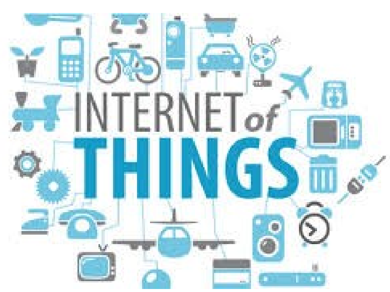

Image Sensor Conclusion

Parameters	Delbrück / Lichtsteiner	Posch	Bermak / Shoushun	Our work
Readout Protocol	Sequential	Sequential	Sequential	**Parallel**
	Non-deterministic	Non-deterministic	Non-deterministic	**Deterministic**
Arbiters	Yes	Yes	Yes	**No**
Readout rate	*Pixel Rate*	*Pixel Rate*	*Pixel Rate*	***Reading Rate***
Data Compression	Metadata	Temporal Redundancies	No Compression	**Spatial Redundancies**
Pixel Size	☺	☹	☺☺	**☺ to ☺☺**

Image Sensor Pespectives

- Image sensor fabrication and test

Sampling scheme is **signal-dependent**

- How to directly process the image data flow?

➡ Smart Image Sensor for Vision and Robotics

Non-uniform sampling is the future of digital universe!

Thanks for your attention