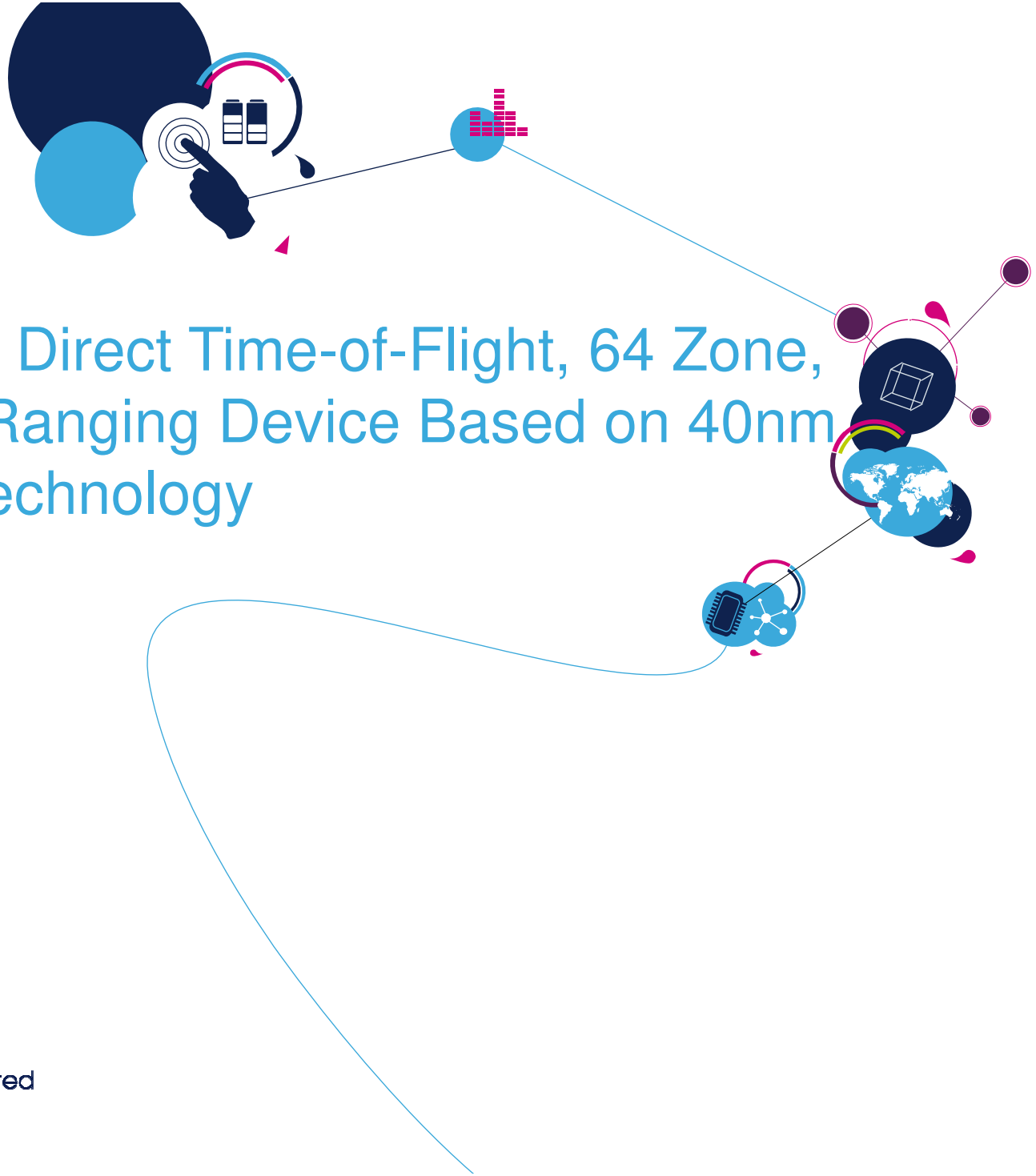


A SPAD-Based, Direct Time-of-Flight, 64 Zone, 15fps, Parallel Ranging Device Based on 40nm CMOS SPAD Technology

Pascal Mellot / Bruce Rae

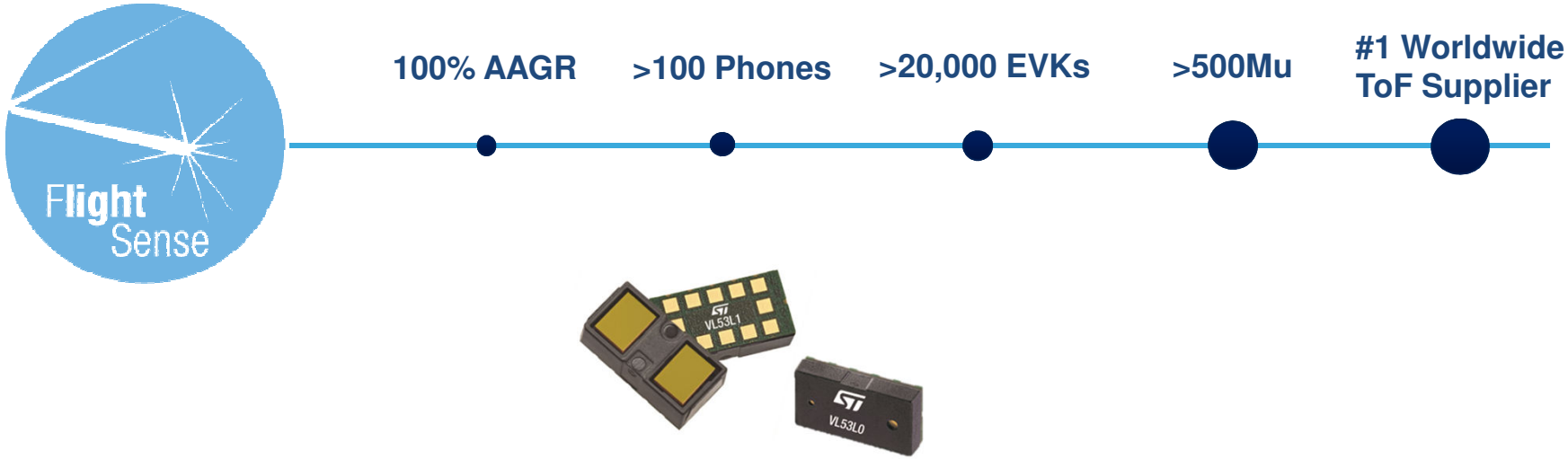
27th February 2018

life.augmented

Summary

- Introduction to ranging device
- Summary of C40SPAD technology platform
- SPAD pixel and array
- SPAD array re-configurability
- SPAD output – TDC to histogram
- Histogram processing
  - Range extraction
  - Cross-talk mitigation
  - Dynamic scene adaption

FlightSense™ Market Highlights



life.augmented

FlightSense™

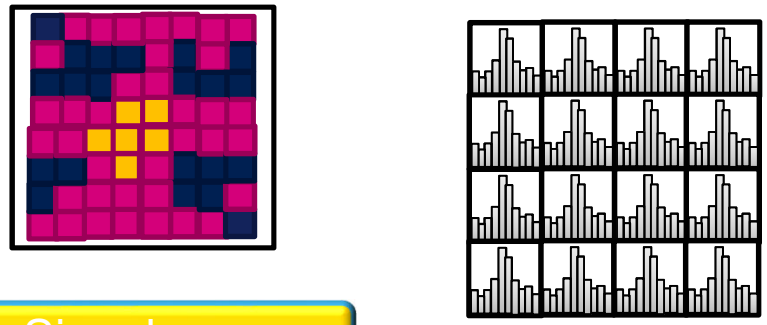
… making light work

life.augmented

Abstract

- SPAD based direct time of flight multi-zone parallel device
- Implemented in STMicroelectronics C40SPAD technology
- Capable of 64 zones at 15fps for both signal and distance
- All in one device including on-chip VCSEL driver and in module VCSEL
- 16 parallel full histogram readout channels capable of multiple target detection

Device Overview



8x8 signal map
+ 16 histograms for each subranging period

Signal map

128Bits @ 1GHz

16 TDC frontend

16 histograms Standard logic

32bits 250MHz MCU + Custom HW acceleration

Flexible user interface

Commands / use cases

Results data / use cases

I2C

8kbit OTP

VCSEL V→Photons

VCSEL Driver

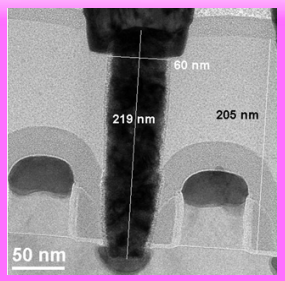
125ps pulse width granularity

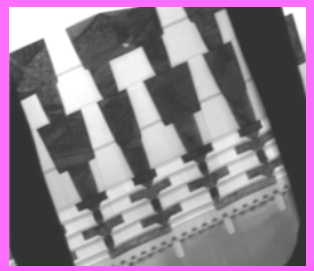
life.augmented

C040 Technology Platform

40nm CMOS Core Process

- **Dual Gate Oxide**
- **Single/Dual Vt MOS**
- **7 Copper Dual Damascene Metal Levels**
- **0.14µm metallization pitch**
- **Ultra low k dielectrics**



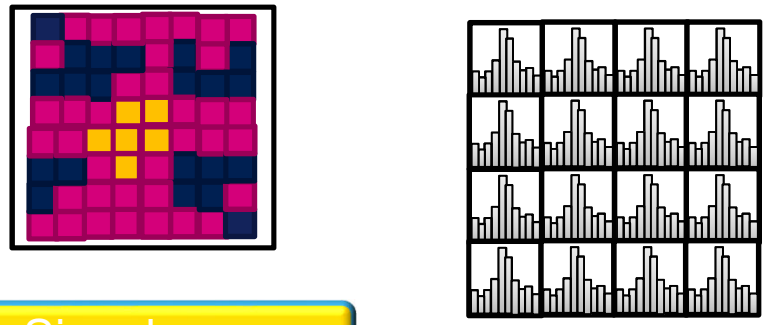


N & P extended Drain MOS
Schottky Diode
N & P XHPA MOS
Natural drift MOS
RF MOM Capacitor

Technology available since 2010 - Source : Crolles 12”

CMOS040_LP technology is designed for Low Power (1.1V) to serve battery operated and wireless applications. It is a single IO oxide + single core oxide dual-Vt process. It gives access to standard Vt transistors (SVT), low Vt transistors (LVT) & SRAM using LP core oxide and IO transistors. IO transistors (1.8 V or 2.5 V) are using IO oxide (32 or 50A respectively). It uses Copper metallization with 7 metal levels (5 thin + 2 thick) and ultra low-K dielectrics (k=2.55).

Device Overview



8x8 signal map
+ 16 histograms for each subranging period

Signal map

128Bits @ 1GHz

16 TDC frontend

16 histograms Standard logic

32bits 250MHz MCU + Custom HW acceleration

Flexible user interface

Commands / use cases

Results data / use cases

I2C

8kbit OTP

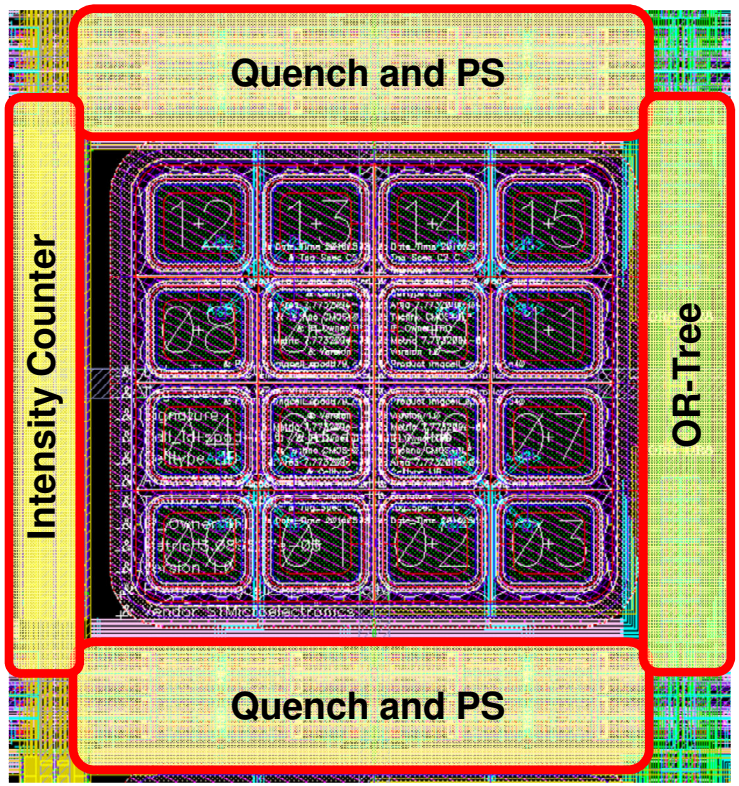
VCSEL V→Photons

VCSEL Driver

125ps pulse width granularity

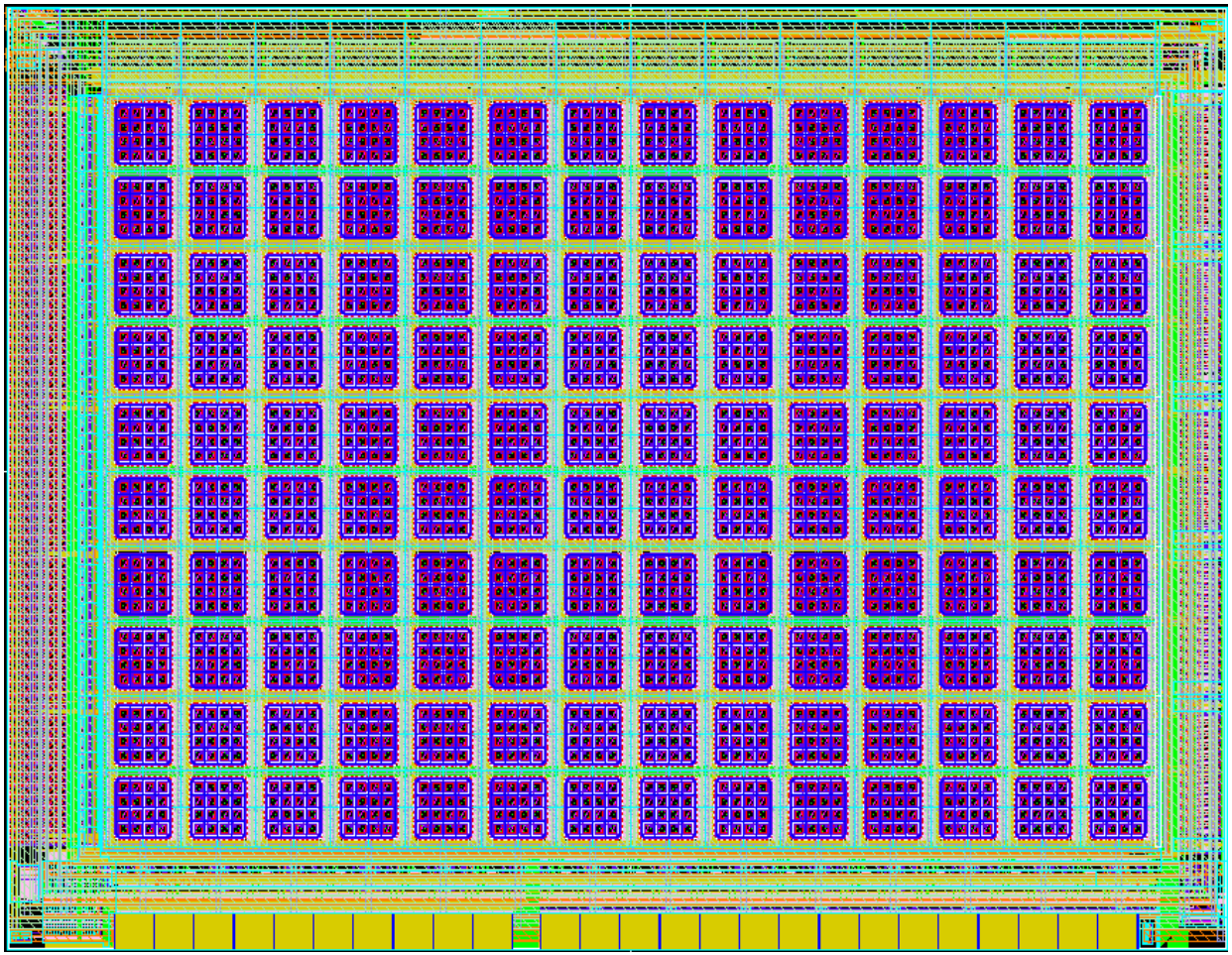
life.augmented

4x4 Macro-Pixel

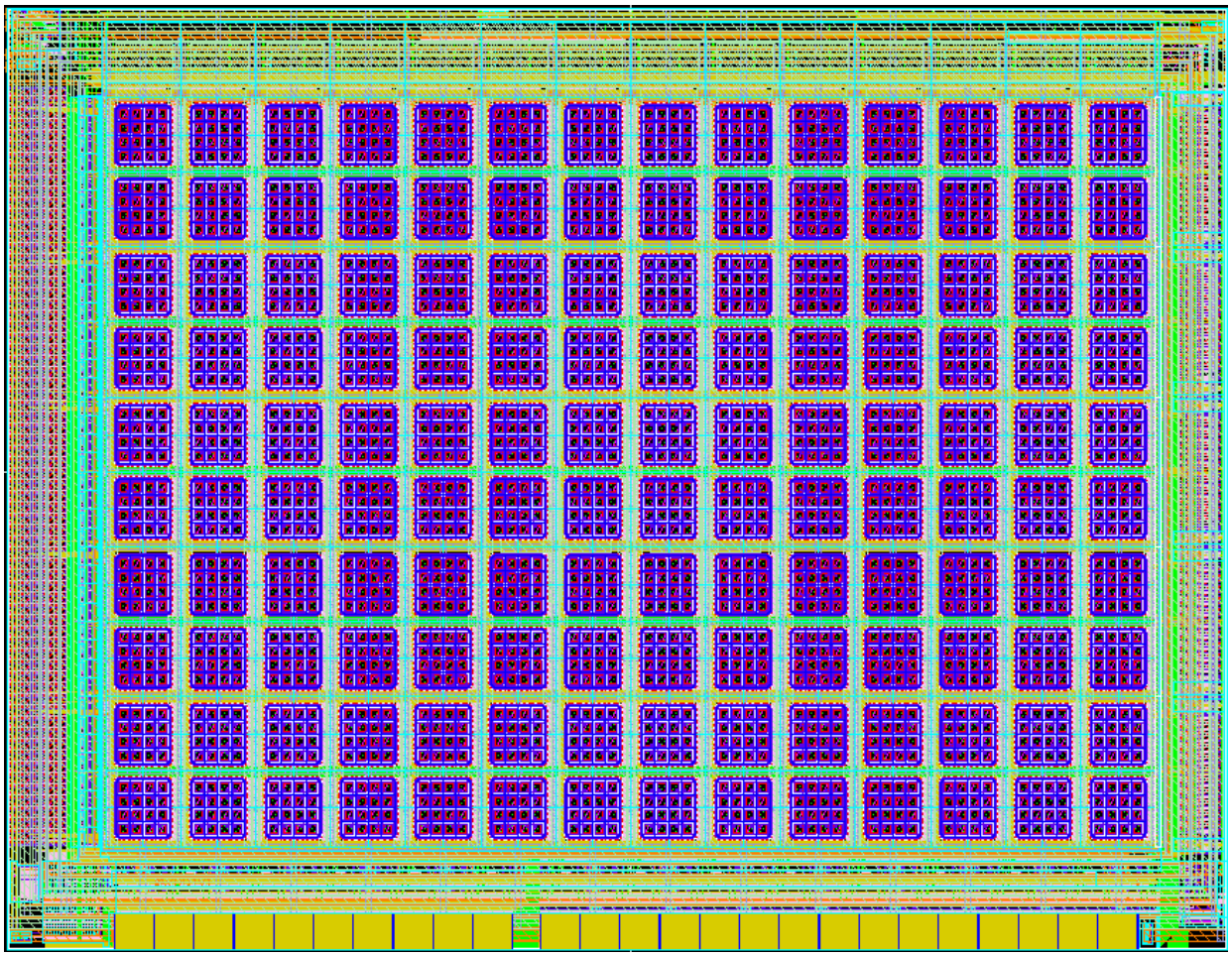


- 40% fill factor (with micro-lens)
- Per diode quench circuit and pulse shaper
- OR-tree used to aggregate pixel outputs
- Local intensity counter to monitor per macro-pixel signal rate

Multi-Zone SPAD Array

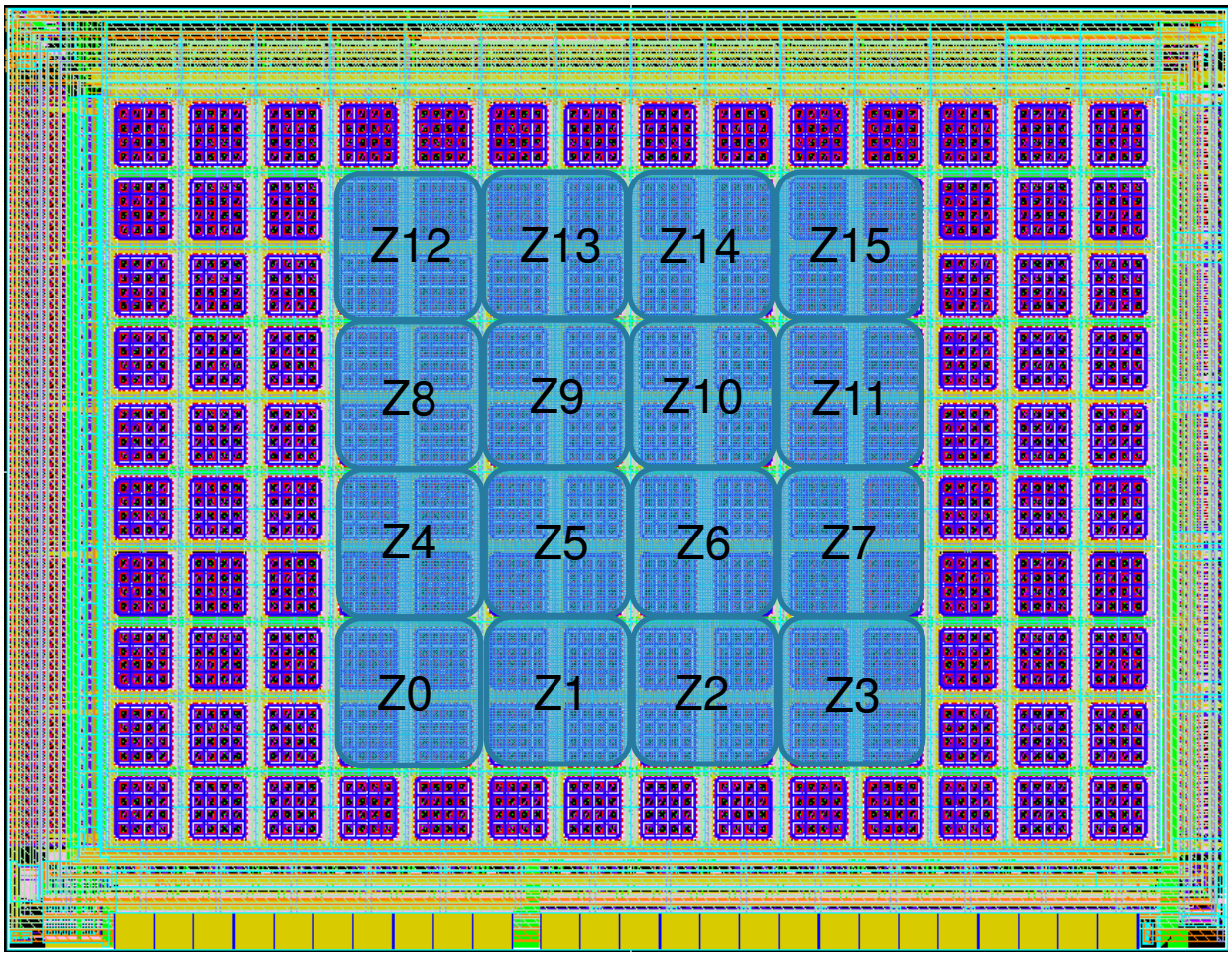


Multi-Zone SPAD Array



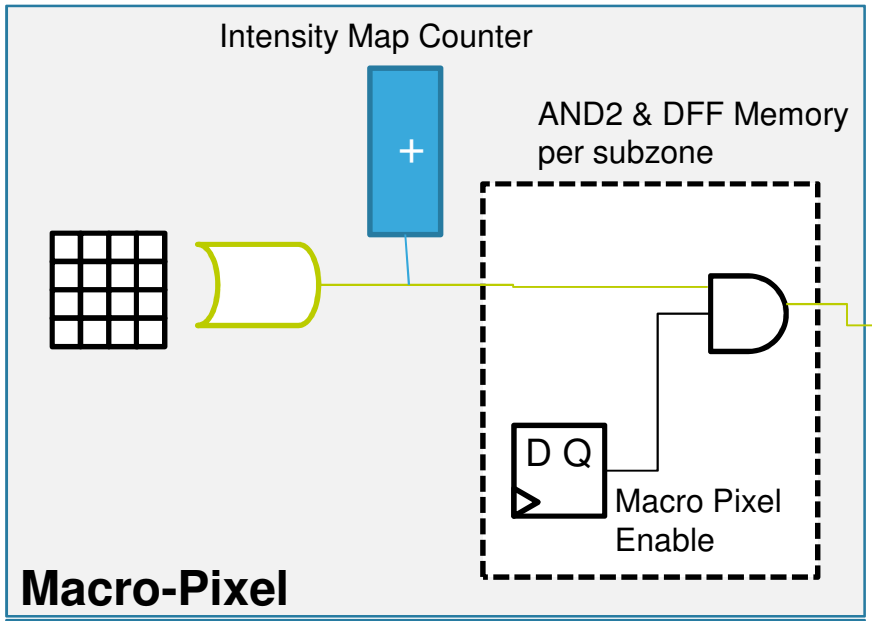
- 14 x 10 array of macro-pixels
- Each macro-cell features 16 didoes
- System features 16 parallel readouts from array
- Location and size of each zone is configurable

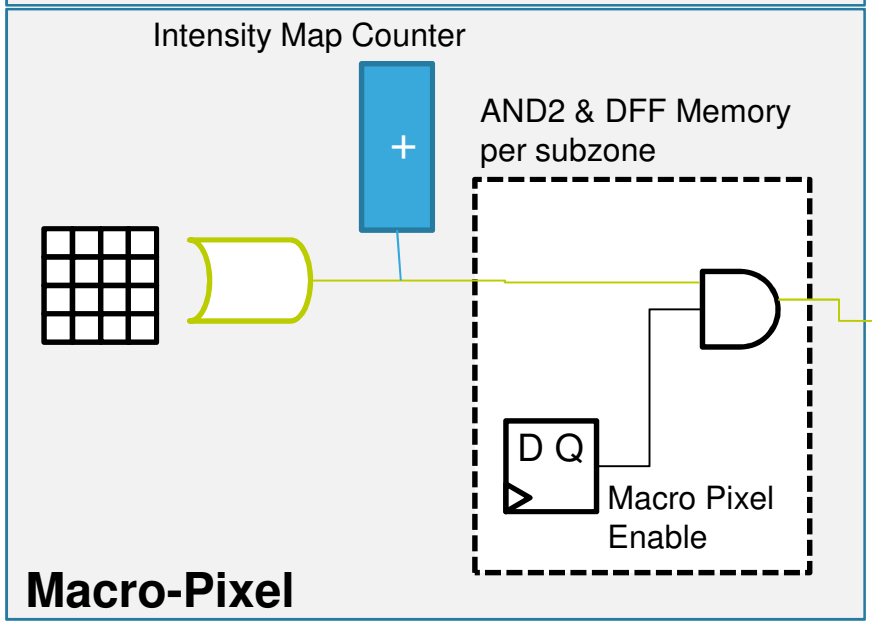
Multi-Zone SPAD Array

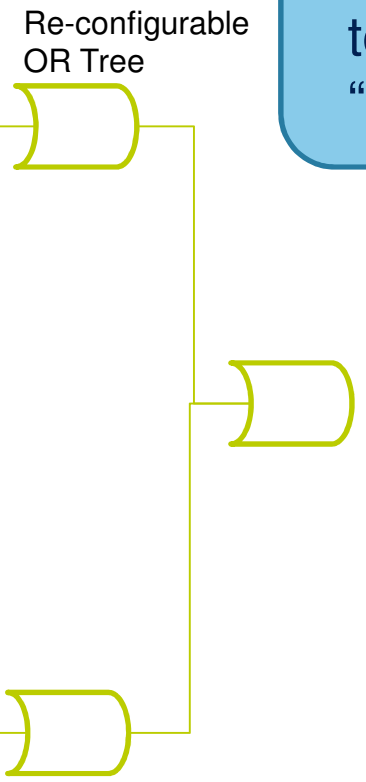


- 16 primary array zones
- In default configuration each zone features 64 SPADs
  - Aggregation of outputs from 4 “macro-pixels”

Macro-Pixel Enable



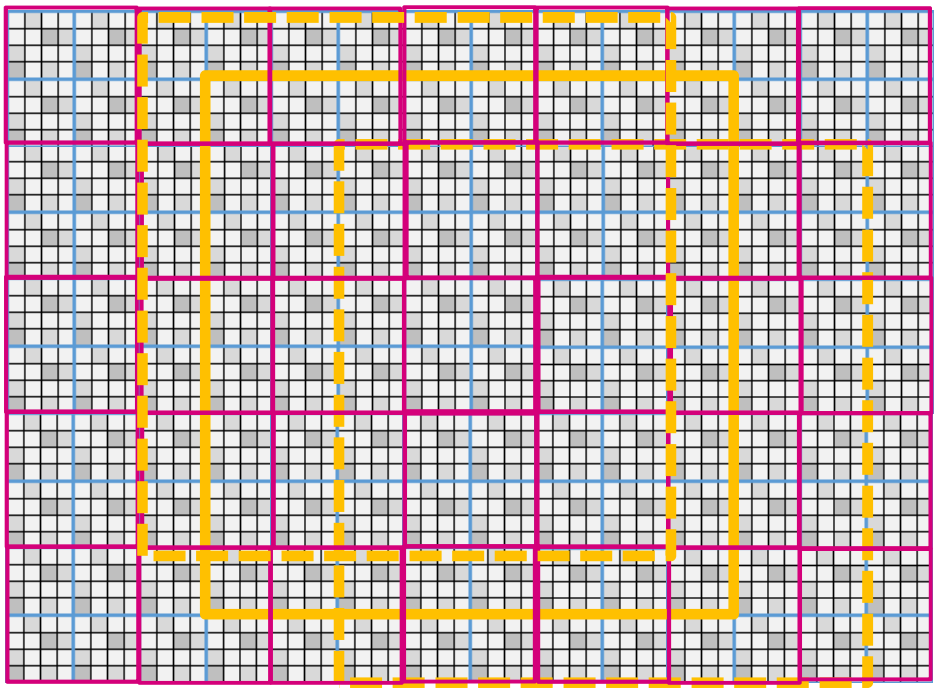


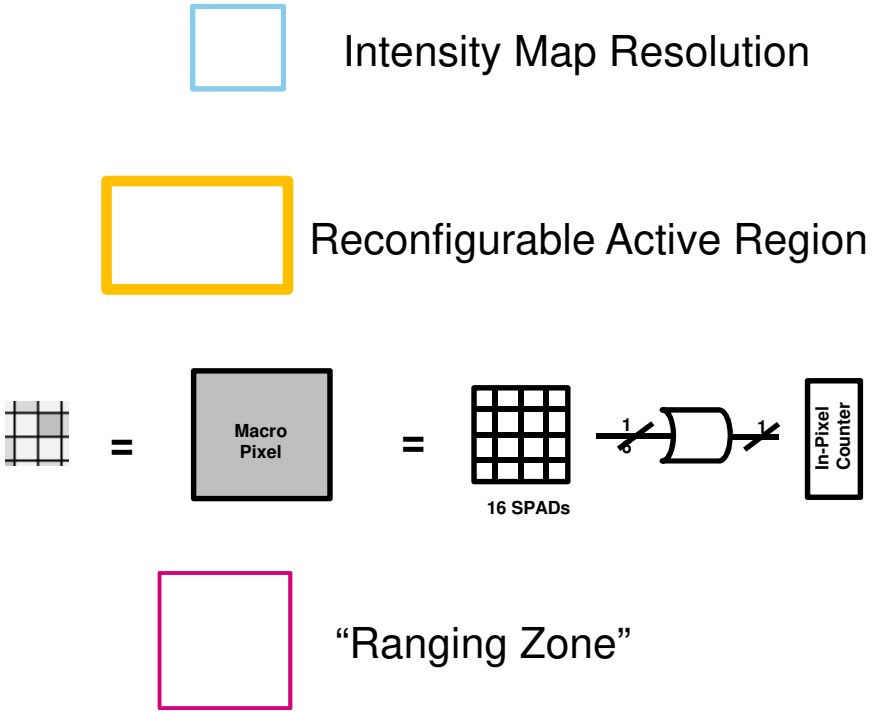


TOF ZONE OUTPUT

- Individual macro-pixel outputs can be summed together to create “ranging zones”

Reconfigurable SPAD Array

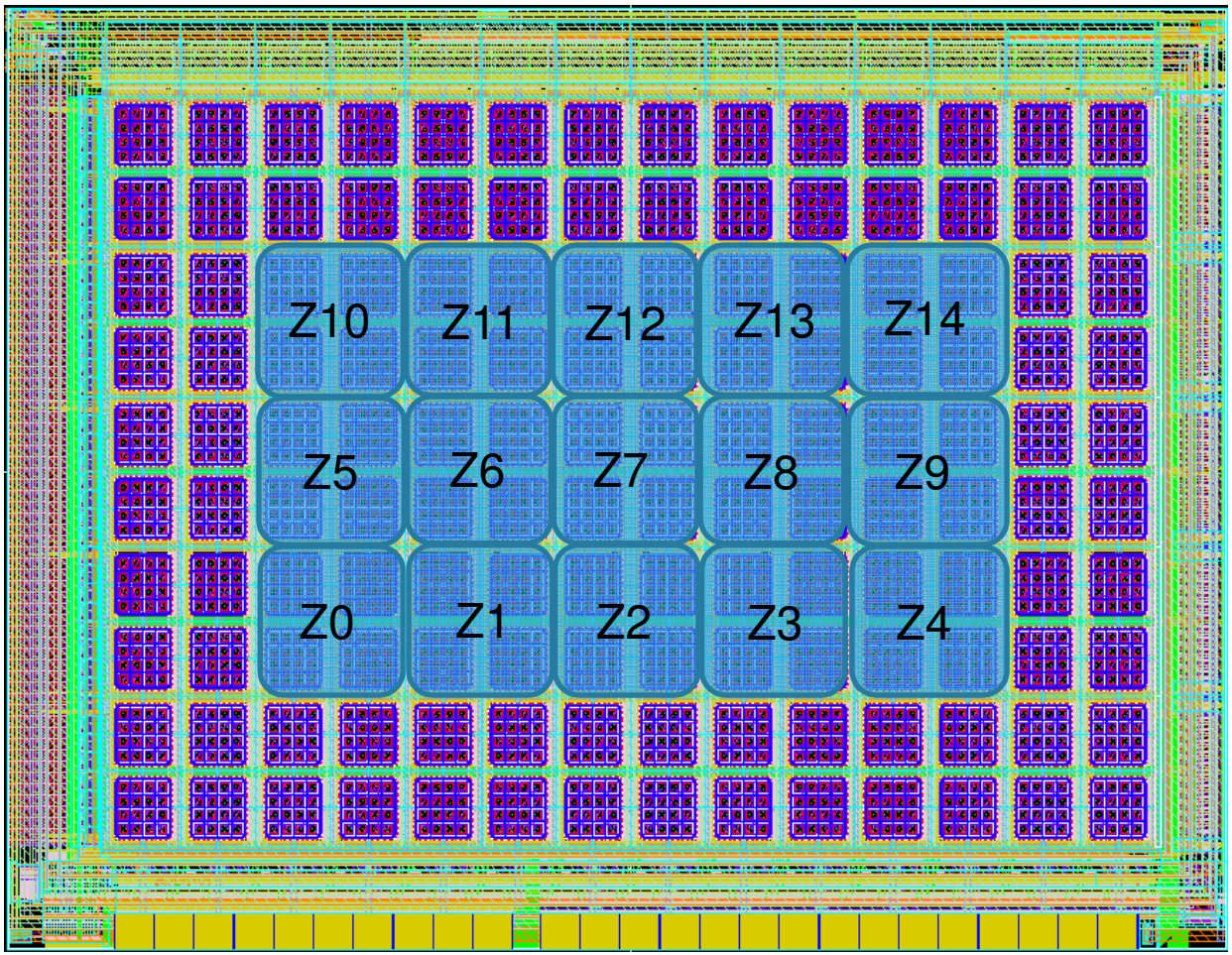




- The SPAD Array is over-sized to allow active area to be dynamically adjusted.
- Default mode: 4x4 parallel ranging zones with 8x8 signal map (no. of ranging and signal zones can be adjusted to system needs)
- Each ranging zone made up of 2x2 macro pixels (although this is configurable)
- Ranging zone position can be adjusted in X and Y with macro-pixel resolution
- Allows the active array ROI to be adapted to compensate for build tolerances or application needs

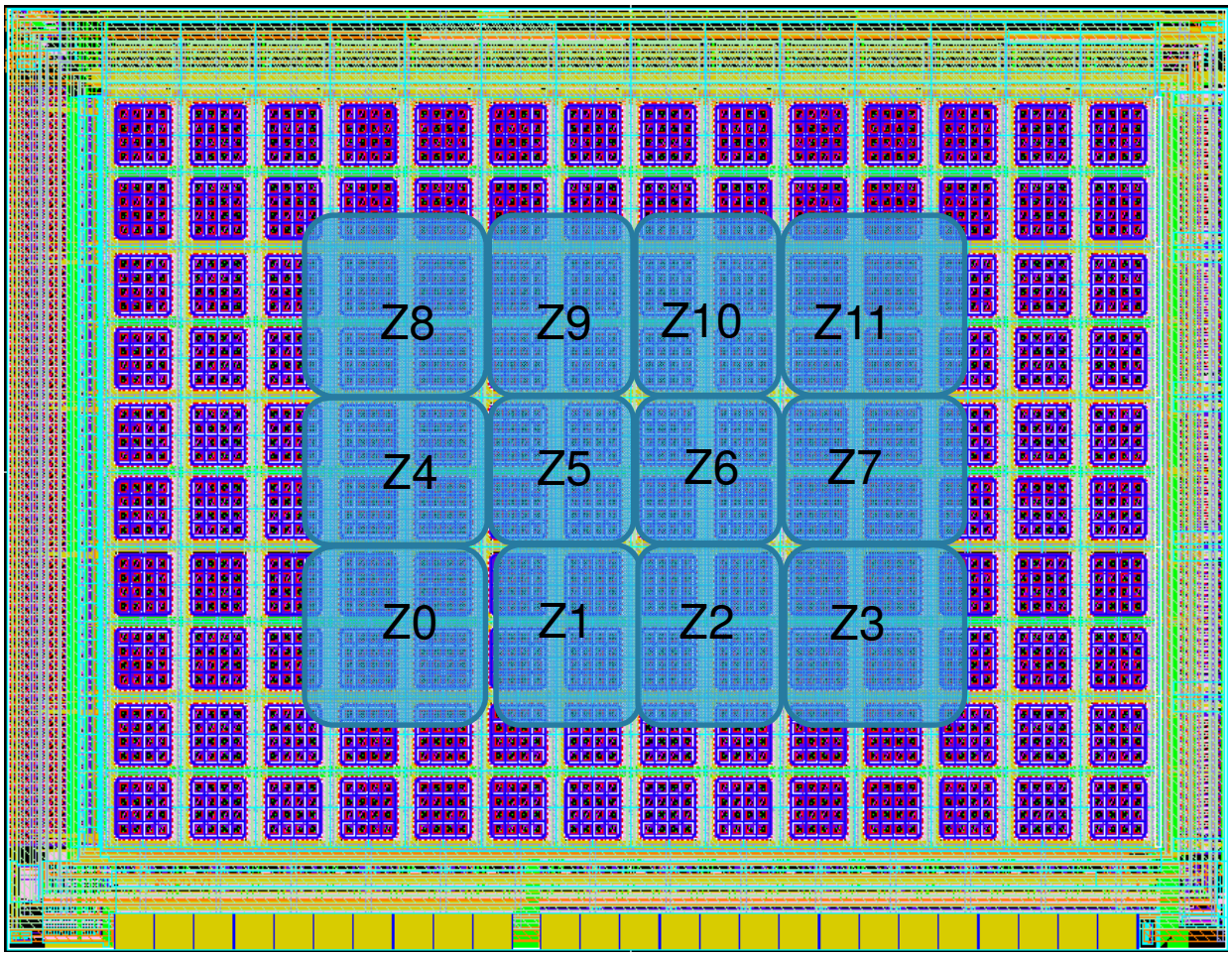
life.augmented

Multi-Zone SPAD Array – Alternative Configurations



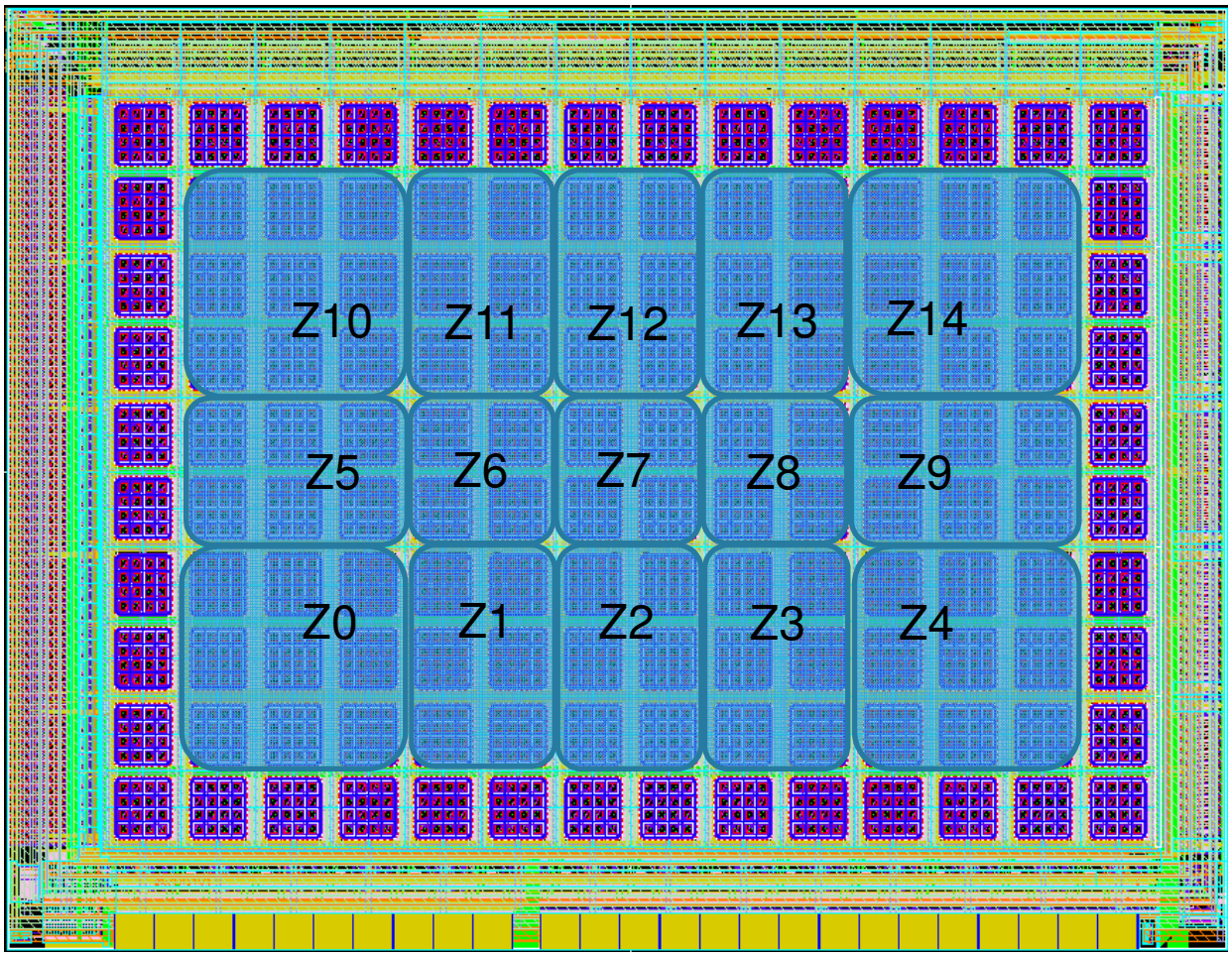
- 5 x 3 zones in 16/9 format

Multi-Zone SPAD Array – Alternative Configurations



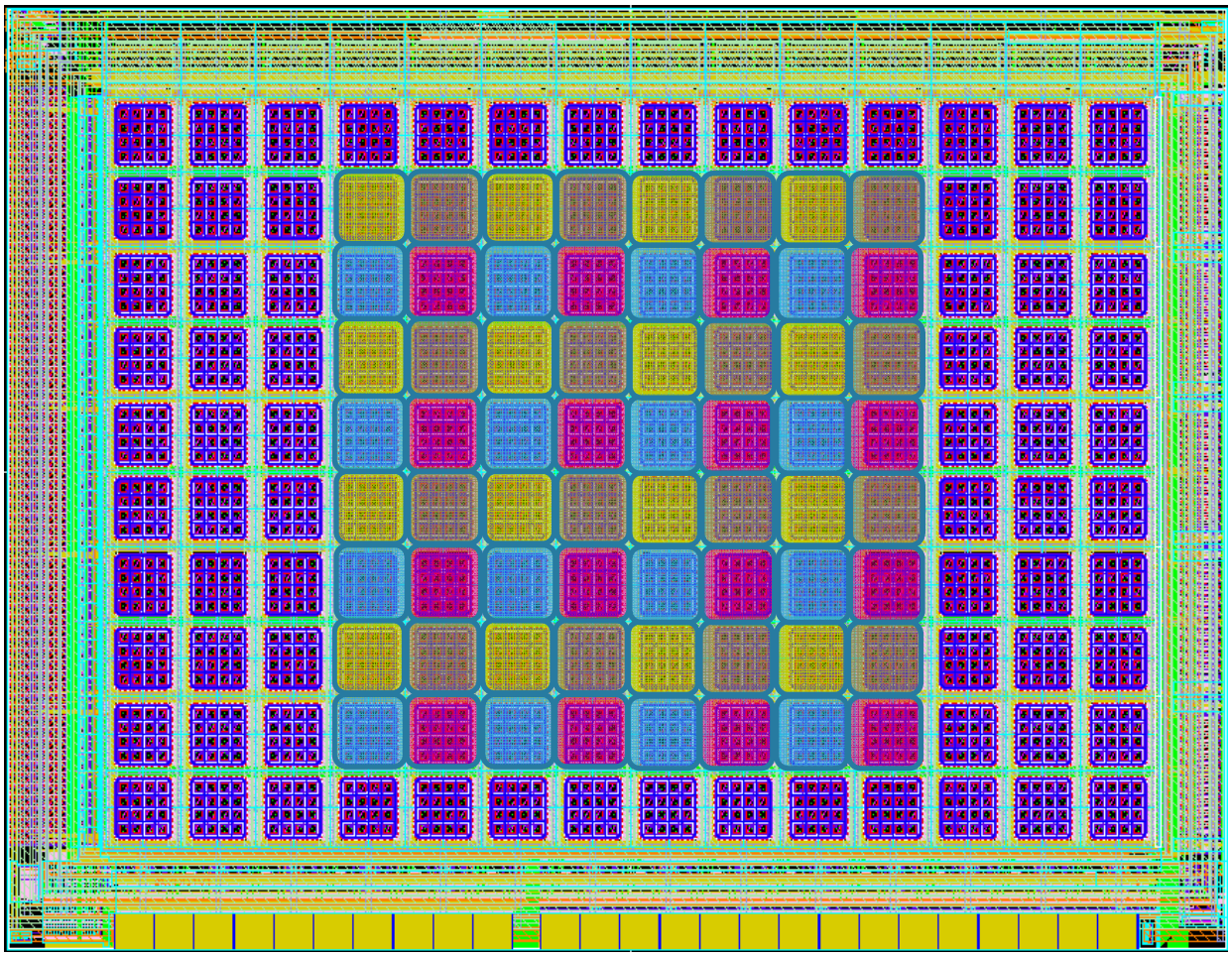
- 4 x 3 zones in 4/3 format
- SPAD diode resolution zone size

Multi-Zone SPAD Array – Alternative Configurations



- Over-sizing of peripheral zones to compensate for lens roll-off
- Possible to have gaps between sub-zones if application requires it

Multi-Zone SPAD Array



- 64 zones can be readout over 4 sequential range measurements at a rate of 15fps

Frame 1

Frame 2

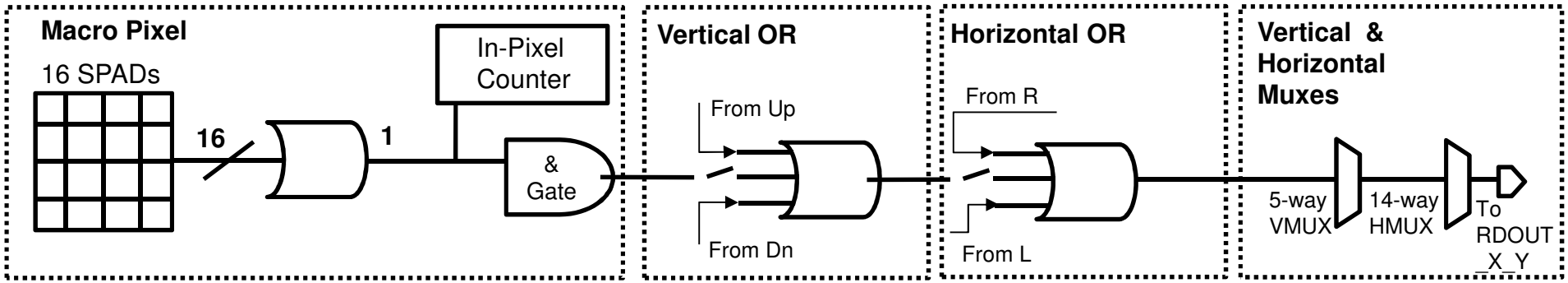
Frame 3

Frame 4

life.augmented

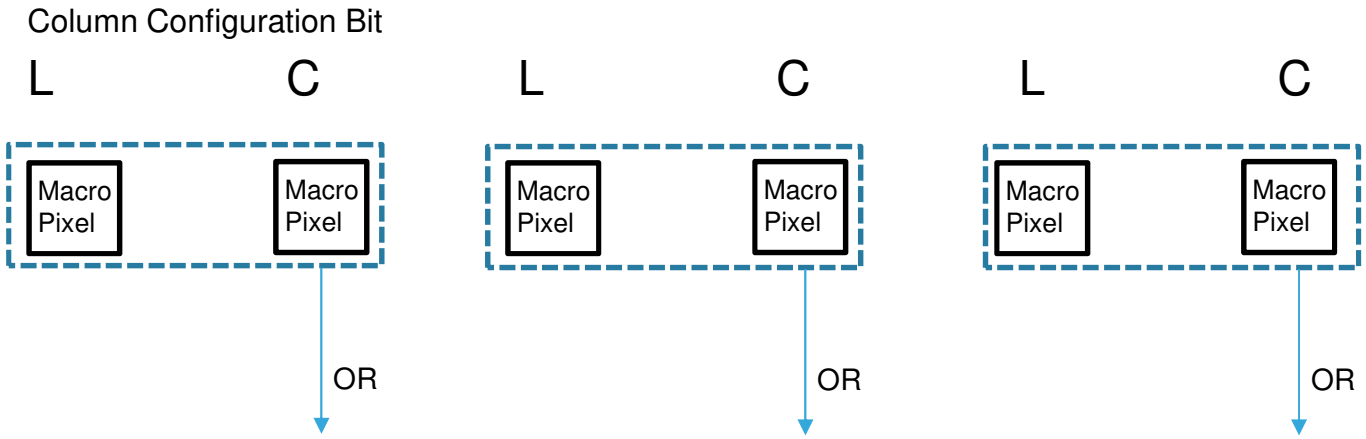
Re-Configurable OR Tree

- Three stage re-configurable OR tree:

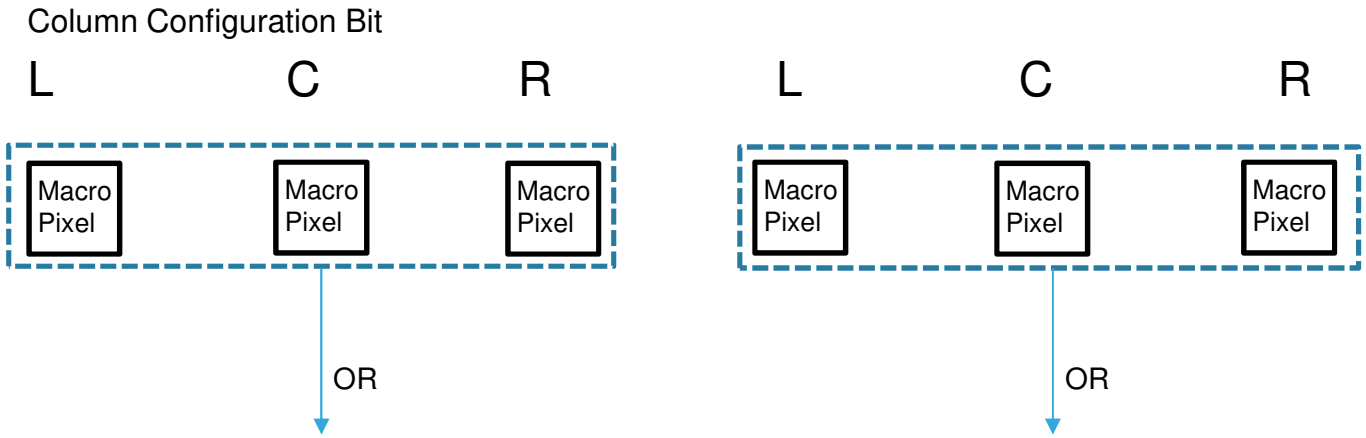


Re-Configurable OR Cell Combinations

2 Macro Pixel OR

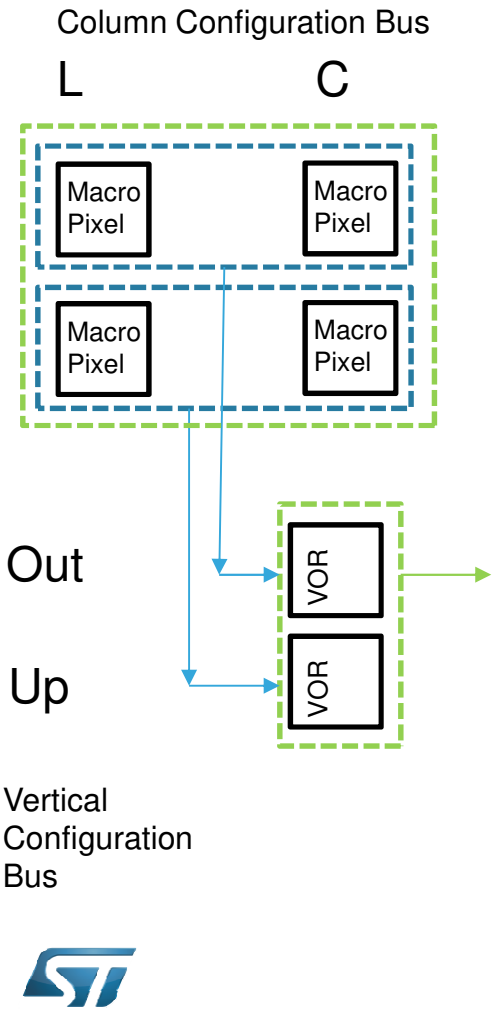


3 Macro Pixel OR

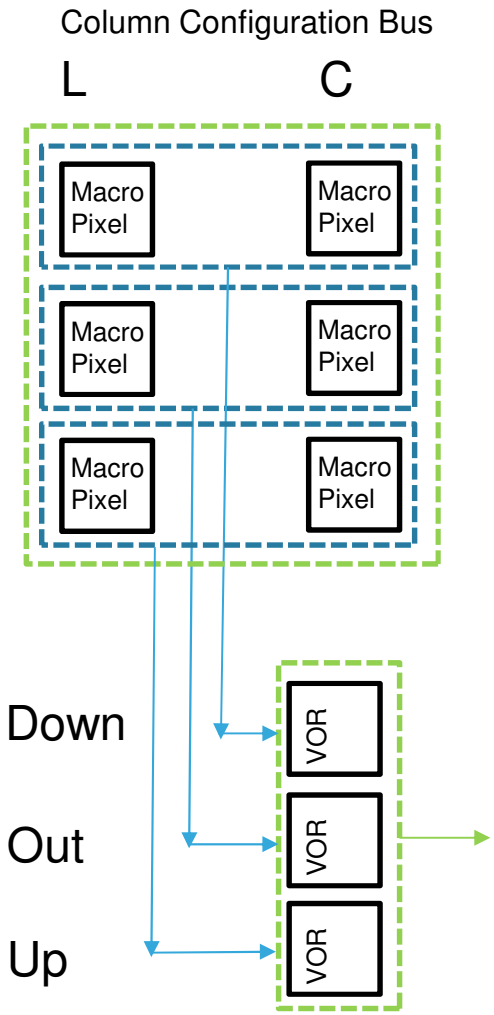


Re-Configurable OR Cell Combinations

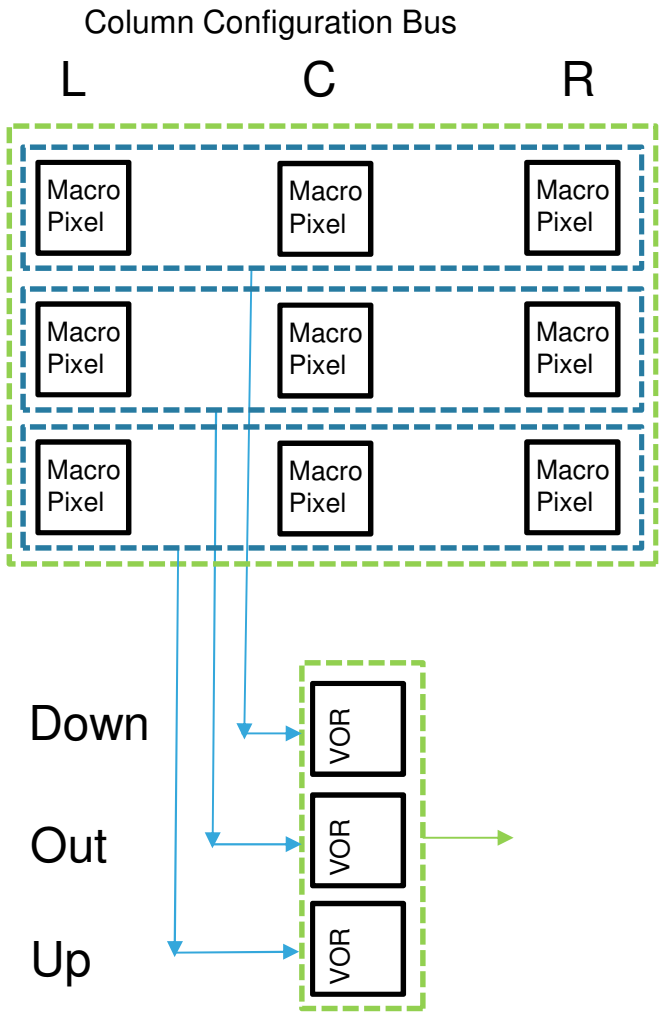
2x2 Macro Pixel OR



2x3 Macro Pixel OR

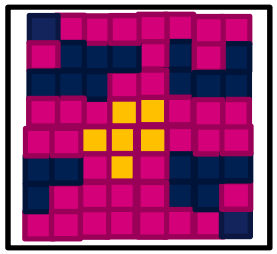


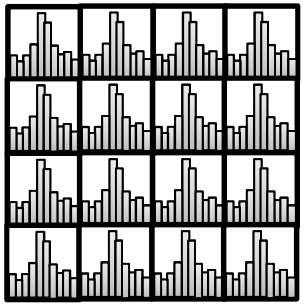
3x3 Macro Pixel OR



life.augmented

Device Overview





8x8 signal map
+ 16 histograms for each subranging period

Signal map

128Bits @ 1GHz

16

16 TDC frontend

16 histograms Standard logic

32bits 250MHz MCU + Custom HW acceleration

Flexible user interface

Commands / use cases

Results data / use cases

I2C

8kbit OTP

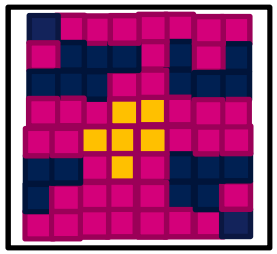
VCSEL V→Photons

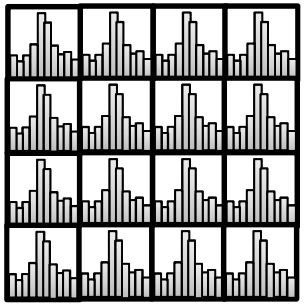
VCSEL Driver

125ps pulse width granularity

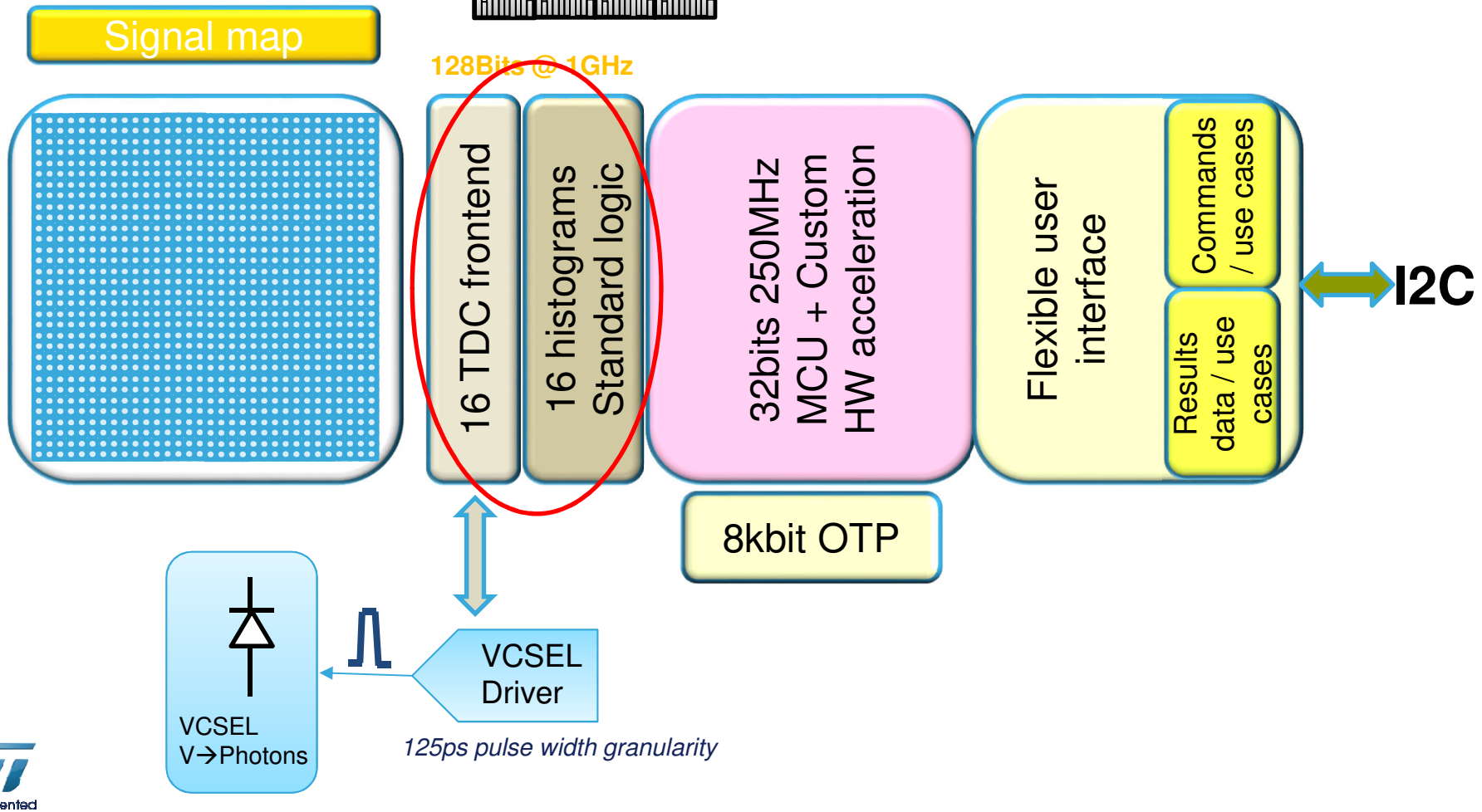
life.augmented

Device overview



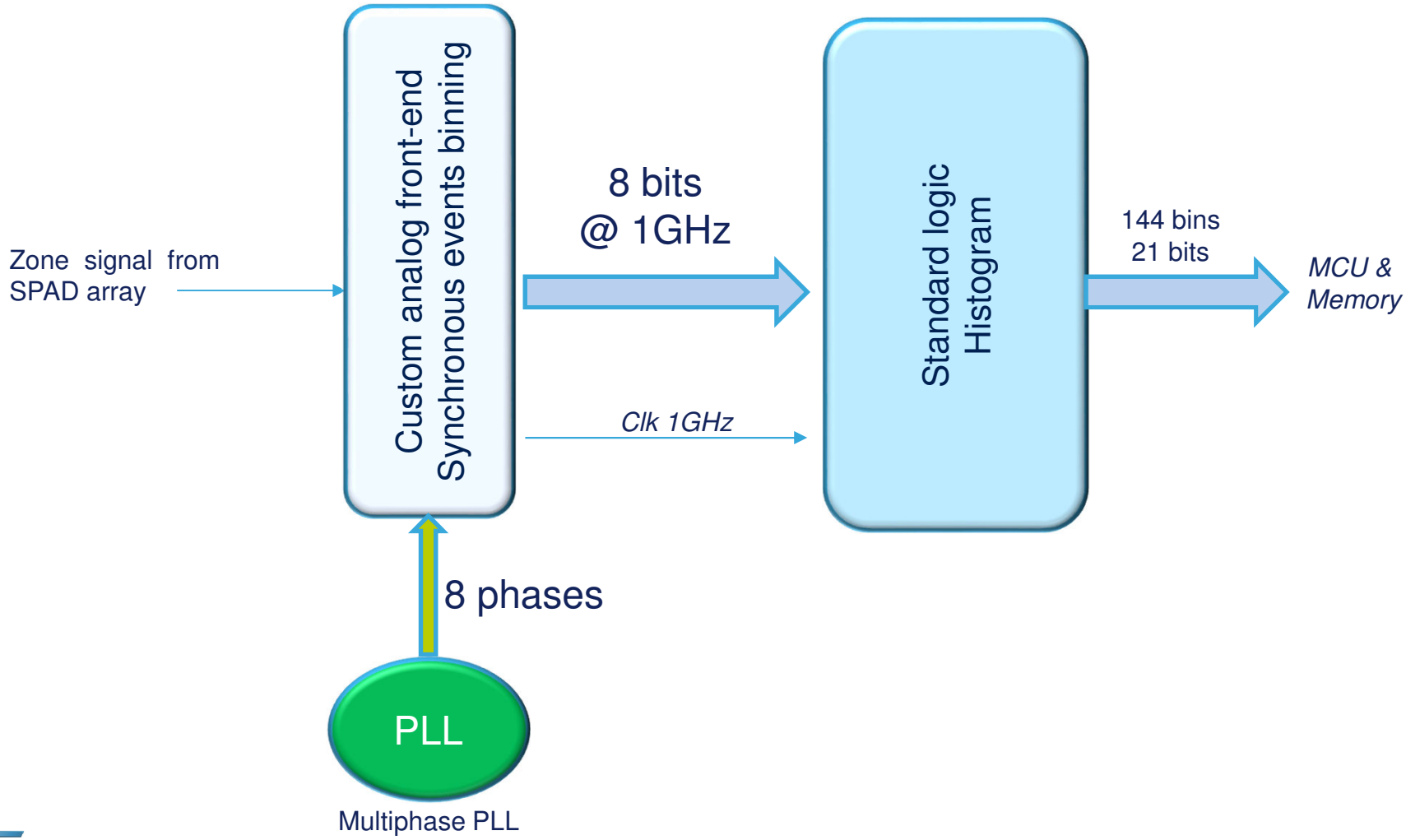


8x8 signal map
+ 16 histograms for each subranging period



life.augmented

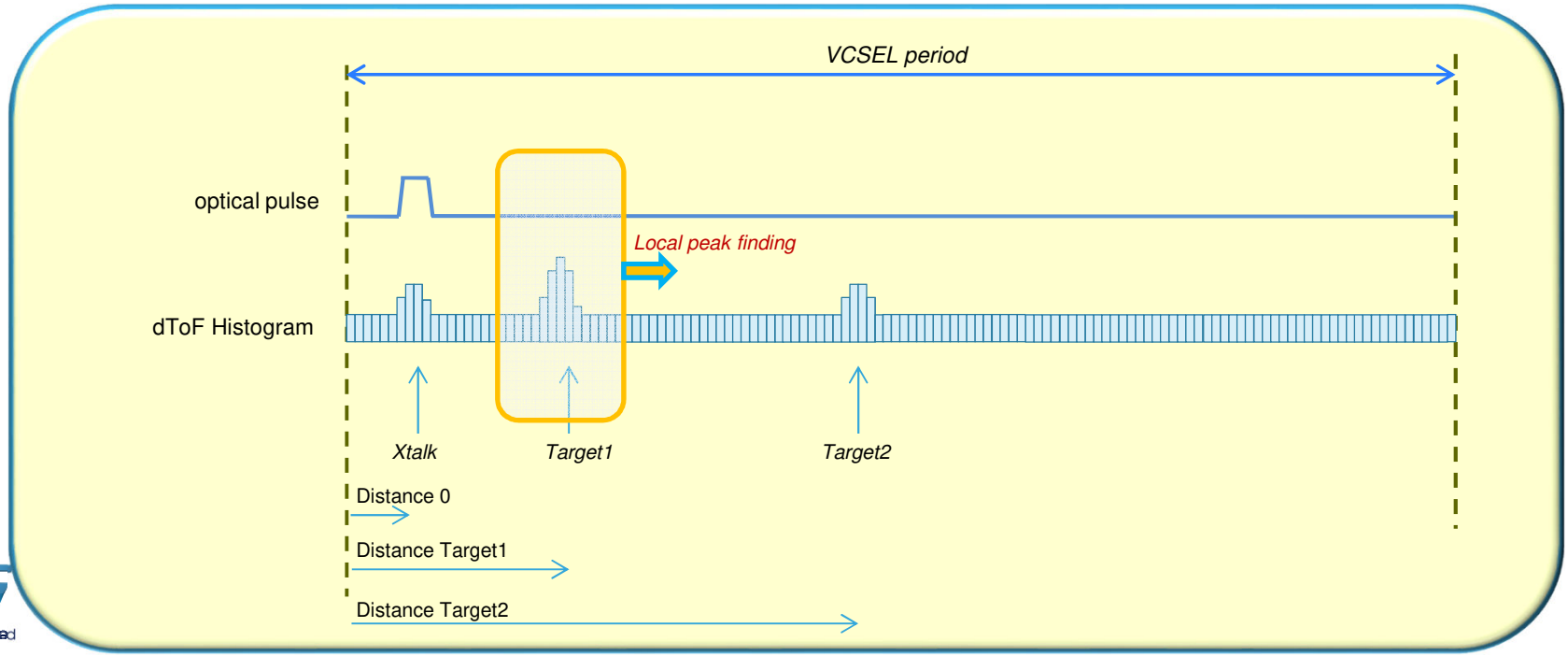
TDC to histograms



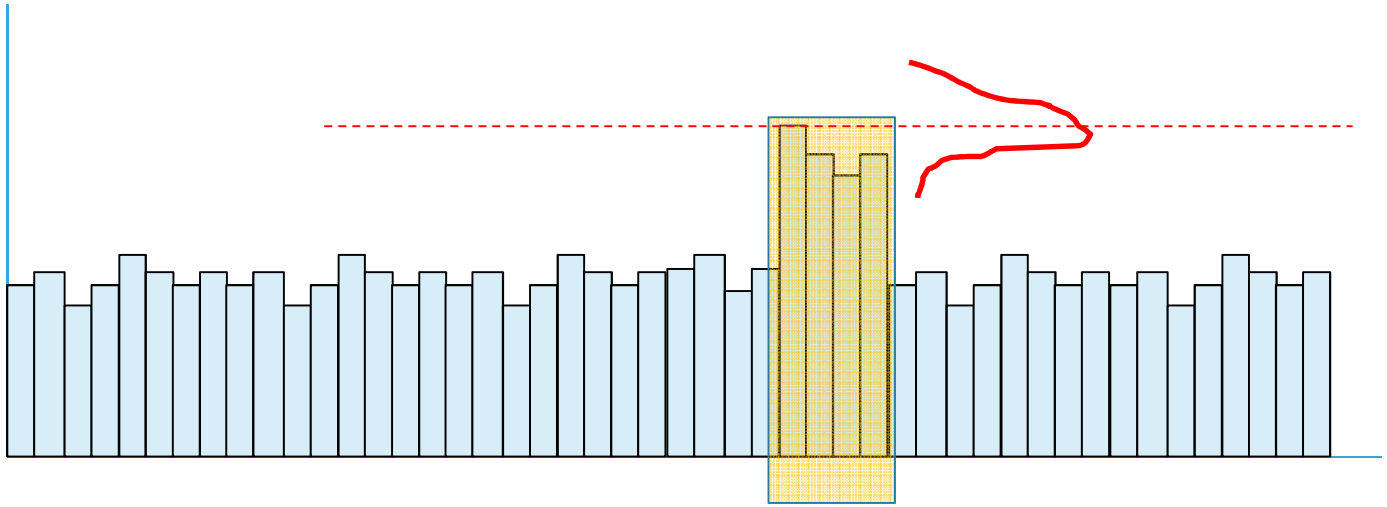
Direct ToF: Crosstalk & multiple target detection

- The device is designed to subtract Xtalk peak, and then detect up to 4 targets per histogram

- On-board detection algorithm designed to report leading & falling edge position as well as interpolated median pulse position with **mm** resolution. For each detected target, the MCU is reporting these, as well as confidence level and expected accuracy.



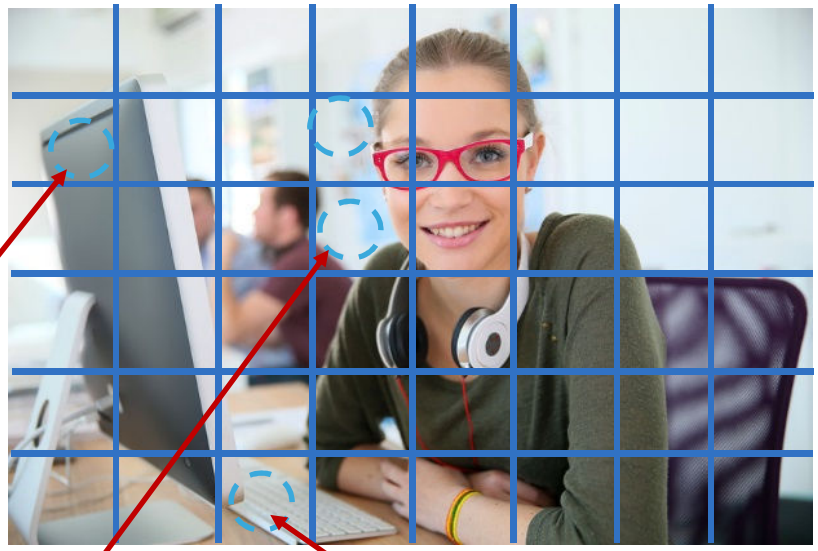
Adapting laser pulse to each situation



- LONG PULSE allows for low SNR detection (long distance over ambient)
- SHORT PULSE allows for selective close multiple target discrimination

Scene dynamic range management

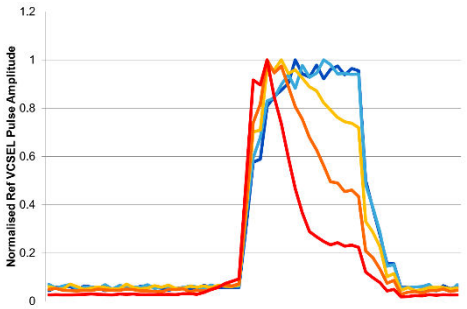
- One of the challenge in ToF system is the management of the scene dynamic range
  - Low ambient/ High ambient
  - Close / Far target
  - Dark / Bright targets



Further darker target

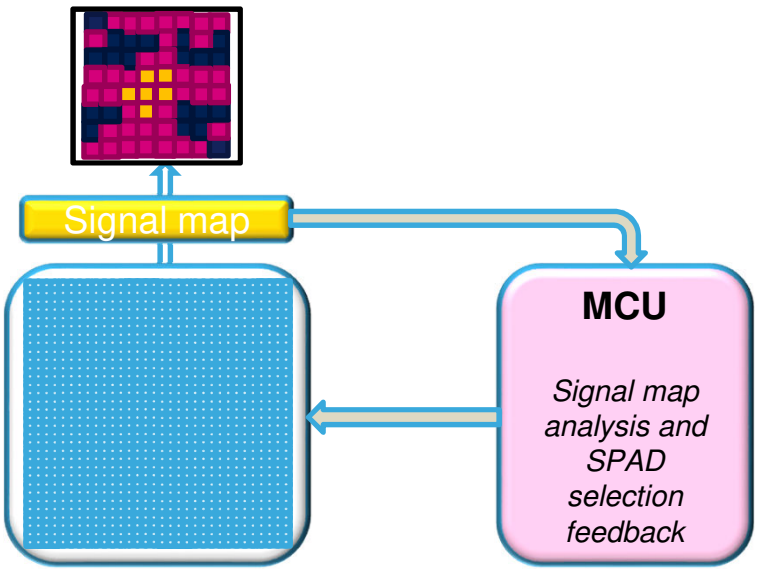
High ambient background

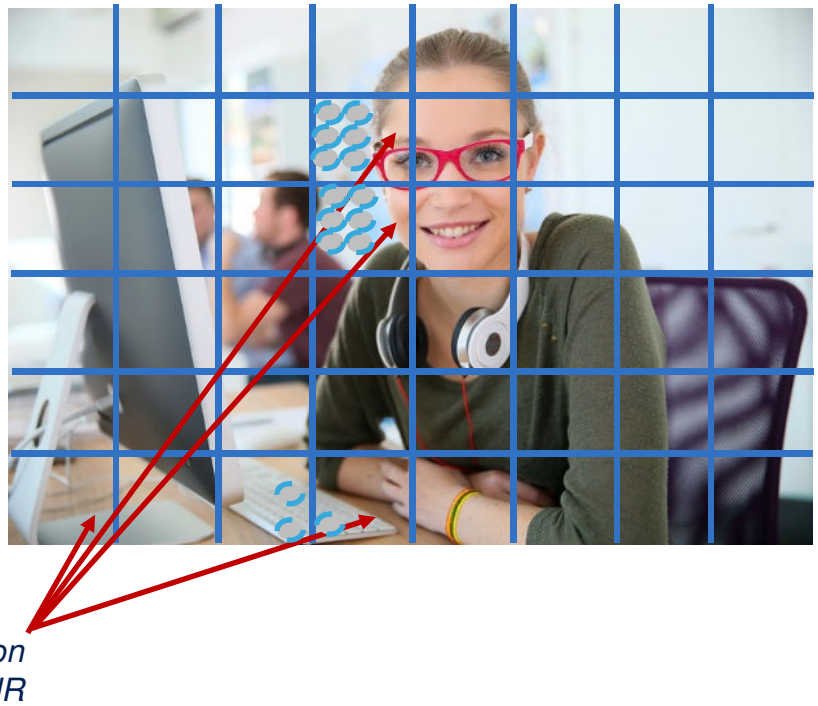
Close high reflective zone



life.augmented

Scene dynamic range management





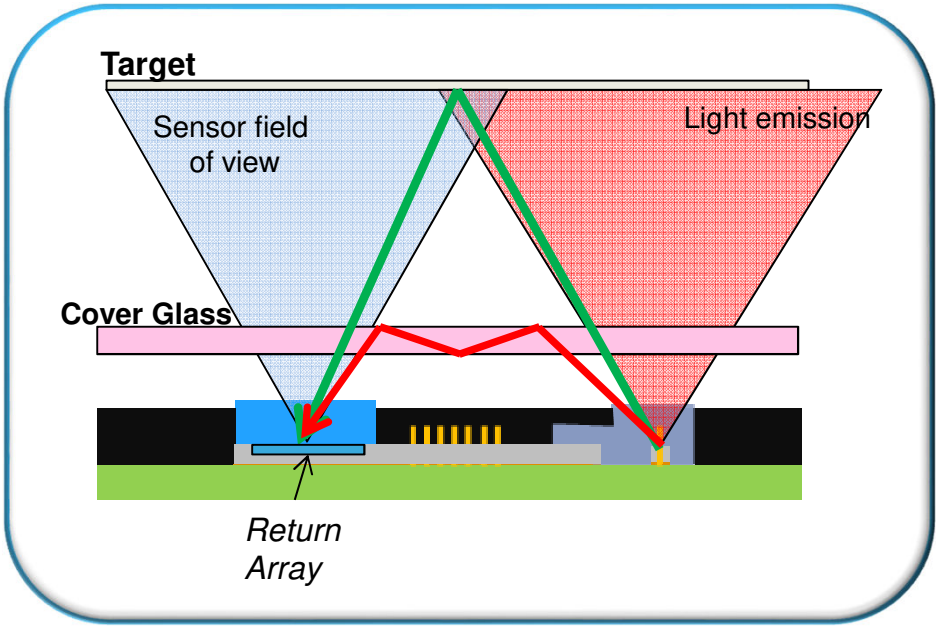
Range on zone portion that offers best SNR

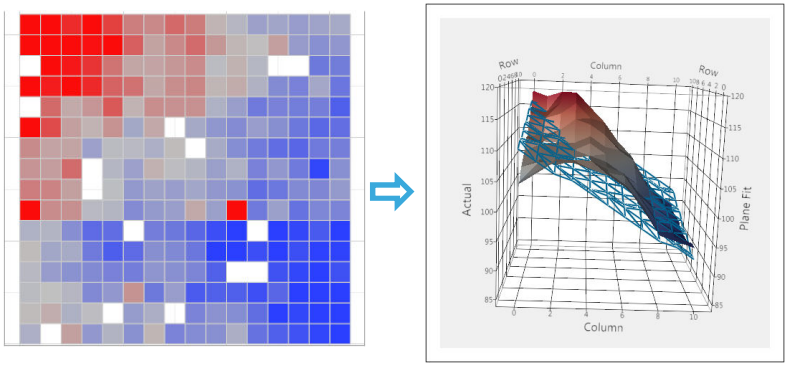
- Thanks to embedded live signal/background map, the device can dynamically assess the SNR for each zone and disable individual SPADs that contribute poorly or negatively to the ranging of the zone

Dynamic crosstalk management

- Crosstalk from cover glass can be significant
- Thanks to histograms, natural immunity exists beyond the point of the emitted pulse width
- But below, at shorter distance, the Xtalk still needs subtracting to not add a ranging offset error to the extracted pulse position
- Moreover, on a larger multizone array, the crosstalk may not be uniform accross.

➔ **Our device includes a dynamic crosstalk extraction and application taking into account the spatial non uniformity of the crosstalk**





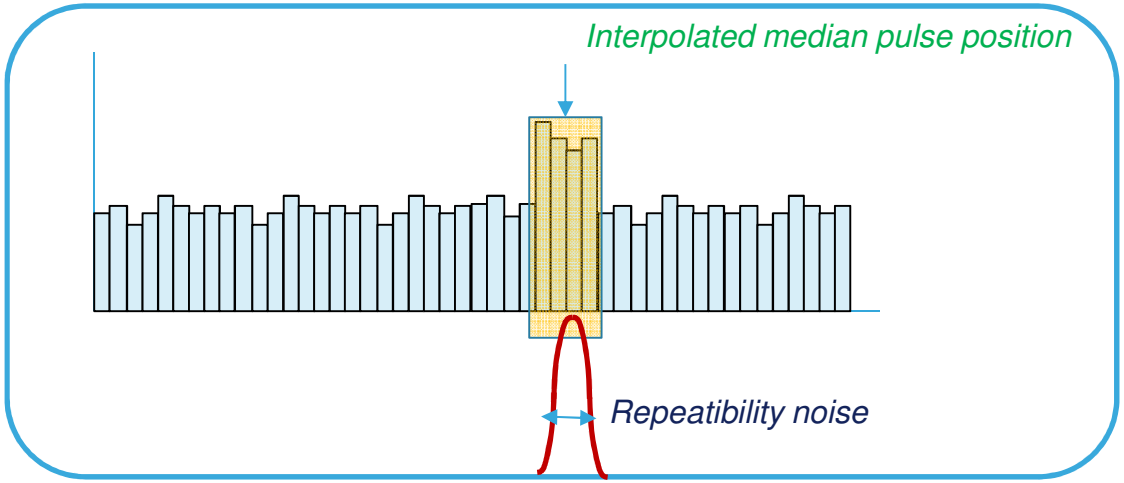
Example of spatial non uniform Xtalk rate

life.augmented

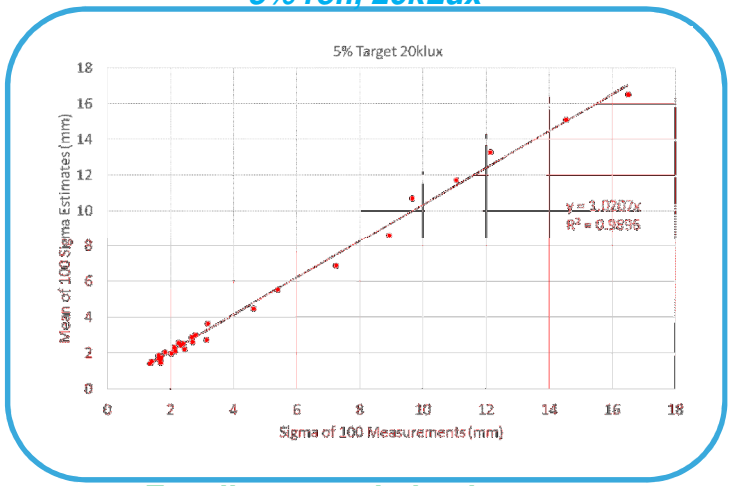
Noise prediction: sigma estimation

Purpose

- Estimates the expected uncertainty given a single range measurement.
- The estimated standard deviation should be equivalent to the measured standard deviation from a large number of measurements (e.g. 100).
- This gives an indication of the repeatability of the measurement reported by the device.
- The sigma estimator is intended for reporting range quality.



5% refl, 20kLux



Excellent correlation between estimator and measured

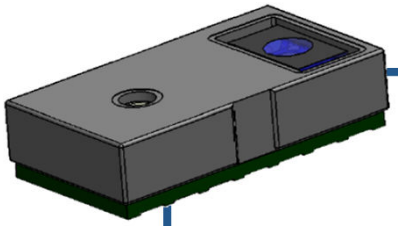
For each target reported, the device takes into account the ambient, signal and crosstalk rate, as well as pulse width, in order to accurately estimate the noise associated with this target.

This is easing considerably the job of the user to estimate the confidence of the reported data

life.augmented

Device overview

Wide Angle Parallel Multi-zone detection



Highlights

- **All-in-one compact lensed module**
  - Class 1 certified **940nm invisible VCSEL**
  - **61˚ FoV**
  - ToF processing on **embedded 32bit MCU**
- **Target specification**
  - Functional under **100klux daylight & direct light**
  - **8x8 15fps** operation mode
  - Cover glass **xtalk calibration free**
  - **Zero lag** Region of Interest reporting
- **Power modes**
  - **Fully autonomous** 1.4mW Presence detection
  - **Smart power management** based on ambient light level
- **Spatial scene understanding**
  - **Multiple object detection**
  - Cover glass **xtalk immune** & **dynamic subtraction**

life.augmented

Conclusions

- A SPAD-Based, Direct Time-of-Flight, 64 Zone, 15fps, Parallel Ranging Device Based on 40nm CMOS SPAD Technology
- A SPAD-based, direct TOF device is presented
- Up to 64 independent range measurements across FoV can be made
- Zone position and size configurable
- 16-channel histogram processing
- Histogram processing includes
  - Range and signal rate extraction
  - Cross-talk removal
  - Dynamic signal rate management

Acknowledgements

- ST Imaging Division
  - Edinburgh and Grenoble silicon and module design teams
  - Architecture Team
  - Applications