INtelligent signal processing for **F**ront**IE**r **R**esearch and **I**ndustry (**INFIERI**)

"on the complete signal processing for 21st Century Instruments"

A review on

Front-end Multiplexing

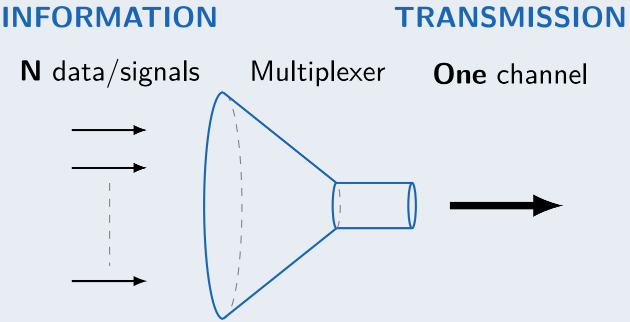
Outline

1. Introduction
   - Generalities
   - Multiplexing as a modulation
   - Limitations and requirements
2. Multiplexing
   - Multiplexing type
   - Time domain multiplexing
   - Frequency domain multiplexing
3. Applications
   - Technological considerations
   - Example of time domain multiplexing
   - Example of frequency domain multiplexing

Outline Introduction

Multiplexing general

Transmission of N signals over 1 channel with higher "capacity"



Introduced for telegraphy at the end of the 19^{th} century and widely applied in **telecommunications** during the 20^{th} century :

several telephone calls may be carried using one wire

Multiplexing notice

⚠ To transmit N signals *via* one channel, **the "channel" must provides better performances** than for a single signal transmission.

⇒ The increasing of the required performances are directly linked to the number N of multiplexed signals.

⇒ The affected performances are both :

- Band Width
- Dynamic / Signal to Noise Ratio

the multiplexing **divides the capacity of the high-level communication channel** into several **low-level sub-channels**, one for each message, signal or data to be transmited.

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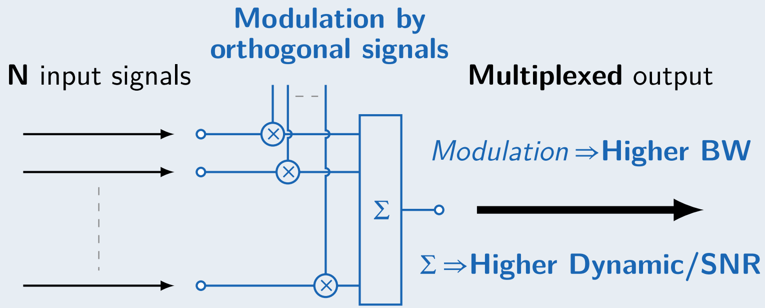
Multiplexing *vs* modulation

There are intersections between modulation and multiplexing

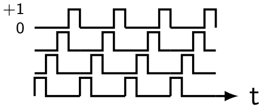
Multiplexing = modulation of input signals by orthogonal signals :



Orthogonal : **boxcar functions** or **carriers at different frequencies**.
Orthogonality ⇒ demultiplexer **able to recover each input signals without interference from the other.**

Orthogonal functions

- boxcar functions ≡ **sampling**



- carriers ≡ **modulation**
- linear codes ≡ **coding**

Orthogonal functions

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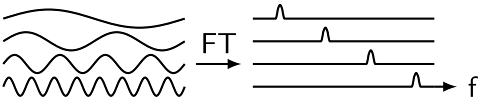

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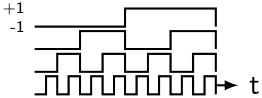
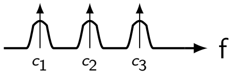


*. as used for error-detection/correction code. Especially, Hadamard/Walsh code could be used for multiplexing.

limitations

Multiplexing ≡ **modulation/sampling/coding + summation**

- Frequency modulation → cross-talk between two carriers / **bandwidth margin required**



- Nyquist–Shannon sampling † theorem → aliasing ‡/**noise margin required** and cross-talk

- Summation → increasing of the amplitude range : **dynamic margin required**

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†. A time domain multiplexer do not "see" the input signal all the time

‡. High frequencies are mixed with low frequency / White noise increase

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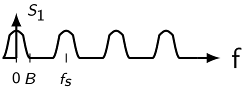

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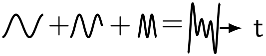

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Requirement for multiplexing

To multiplex a signal, the readout system (multiplexer) **must have better performances** than to read-out a single pixel.

If the readout channel has **performances better** *than what it is needed for the readout of a single pixel, a multiplexing can be performed* **without signal degradations**.

The multiplexer must have better :

- **bandwidth** ,
- **dynamic** range and/or
- **noise** performances.

than for a readout of one pixel.

The increasing of the needed performances for a N to 1 multiplexer must be better **by a factor of about** $\sqrt{N}$ *to few N ...*

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Outline Multiplexing

Outline Multiplexing - Multiplexing type

Multiplexing (Coding) type

- Multiplexing
  - **Time Domain Multiplexing (TDM)**
  - **Frequency Domain Multiplexing (FDM)**
    - Wave length Domain Multiplexing for optical fiber
  - Coded Domain Multiplexing (CDM)
- Coding
  - Amplitude Shift Keying (ASK)
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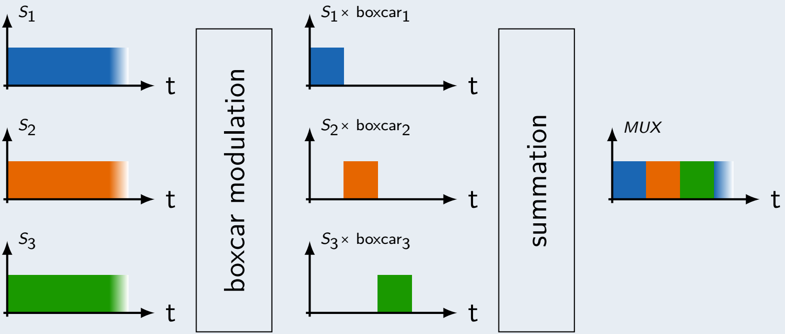
Time Domain Multiplexing (TDM)

Time slot of limited duration of each input signal (S_x) is summed

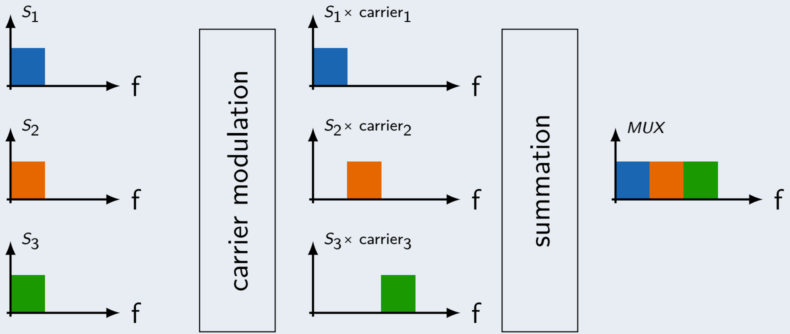


- Requires a specific boxcar (time shifted) modulation / signal
- *Limited duration* ≡ **sampling**

$\Rightarrow$ increasing of the bandwidth
= risk of noise aliasing

Frequency Domain Multiplexing (FDM)

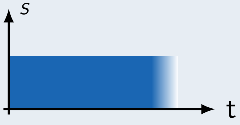
Frequency transposition of each input signal (S_x) is summed

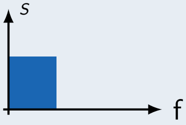


- Requires a specific frequency carrier / signal
- *Summation* ≡ *increasing the* **bandwidth** *and the* **dynamic**

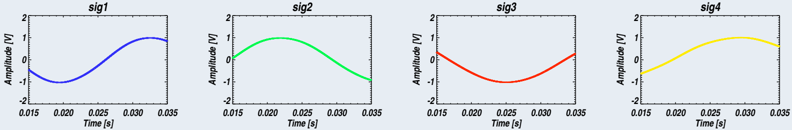
Sine waves multiplexing

until now, signal has been represented as a time or freq. *"tophat"*



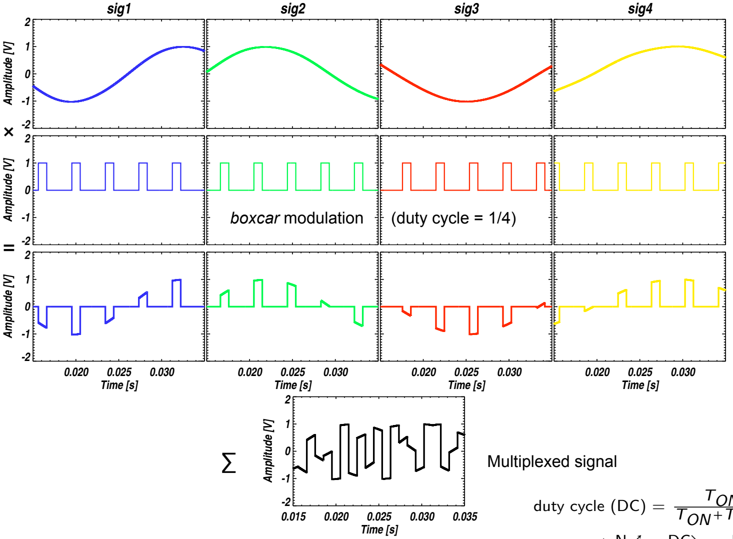


from now, signals will be represented as 4 sine waves (+ noise)



Outline Multiplexing - Time domain multiplexing

Boxcar modulation + Summing

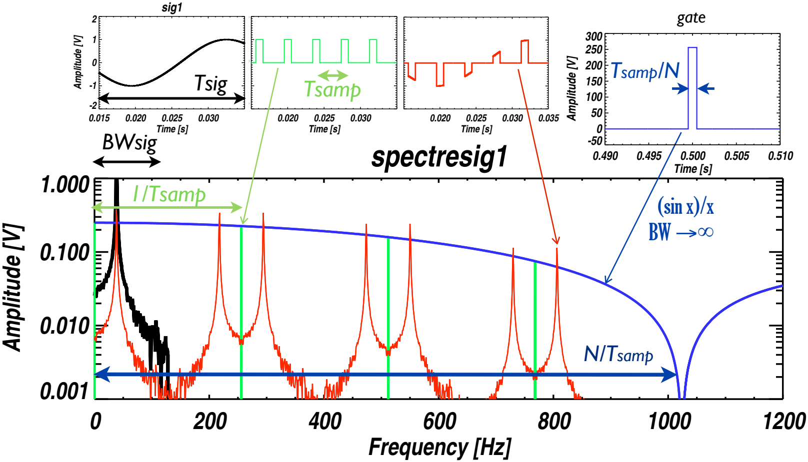


Multiplexed signal

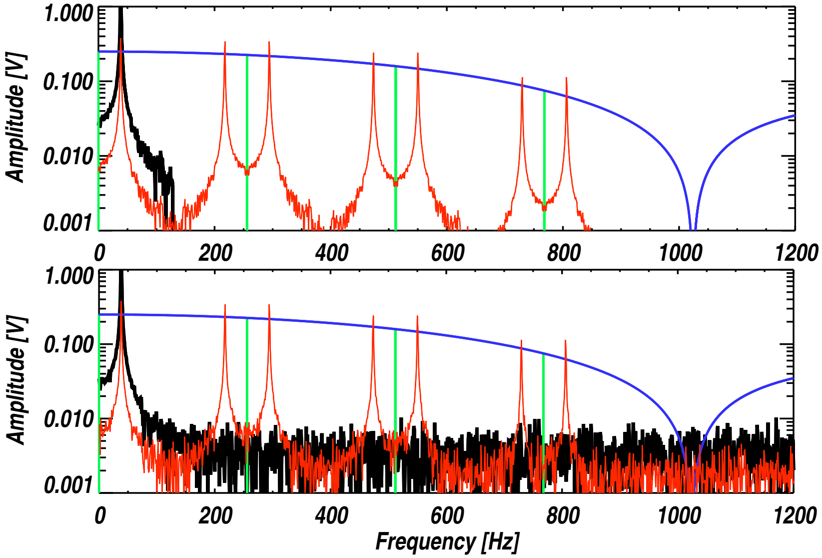
$$\text{duty cycle (DC)} = \frac{T_{ON}}{T_{ON}+T_{OFF}}$$

$\Rightarrow N\nearrow \rightarrow DC\searrow \rightarrow BW\nearrow$

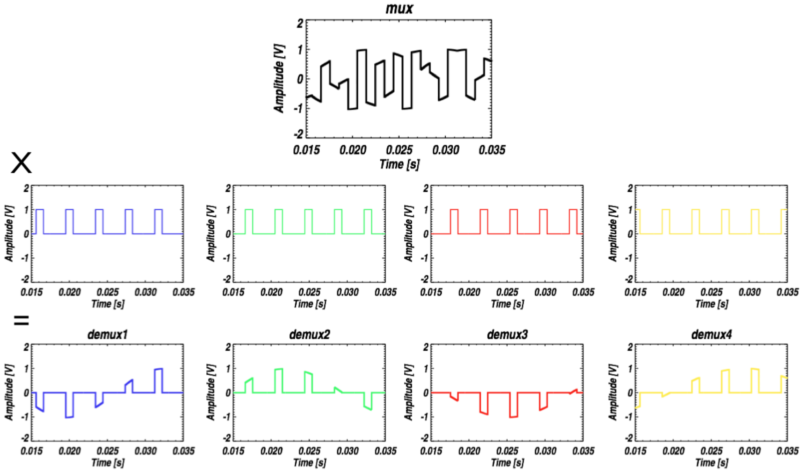
Spectrum of a boxcar modulation



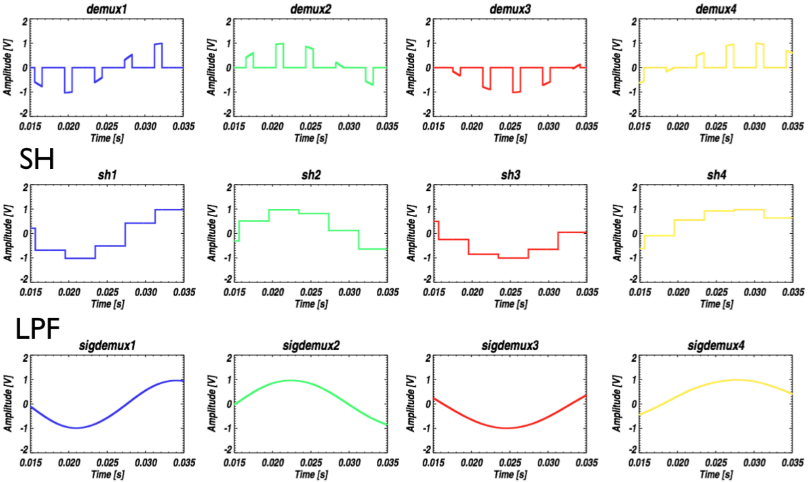
Unsatisfied the Shannon-Nyquist ⇒ Aliasing



Demultiplexing - Demodulation



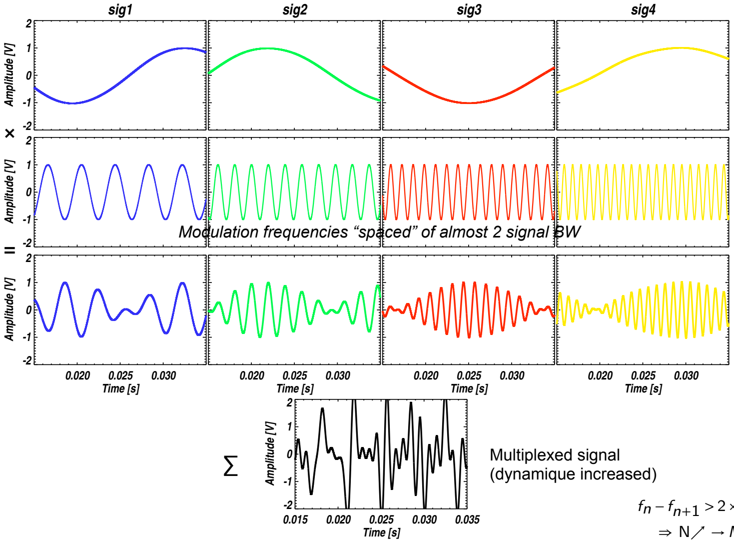
Demultiplexing - Sample and Hold



Sample and Hold (SH) + Low Pass Filtering (LPF)

Outline Multiplexing - Frequency domain multiplexing

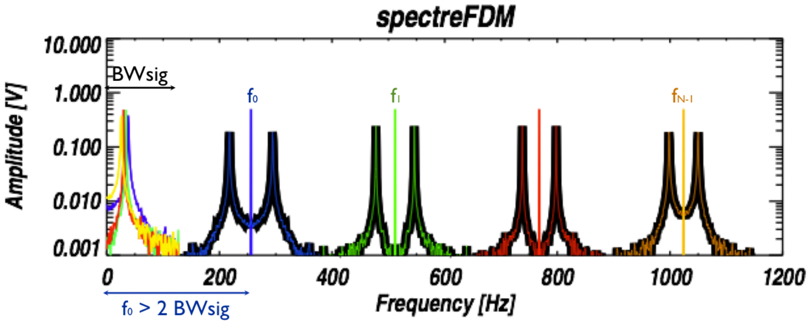
Carrier modulation + Summing



Multiplexed signal
(dynamique increased)

$f_n - f_{n+1} > 2 \times Signal_{BW}$
$\Rightarrow$ N↗ $\rightarrow MUX_{BW}$ ↗

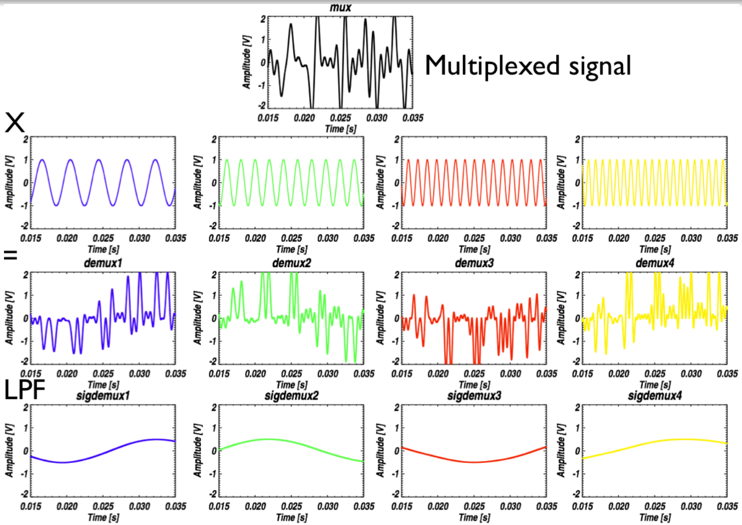
Spectrum of the frequency domain multiplexing



Increasing of the required band width

$BW_{FDM} > 2 \times N \times BW_{sig}$

Demultiplexage ≡ Demodulation + filtering



Low Pass Filtering (LPF)

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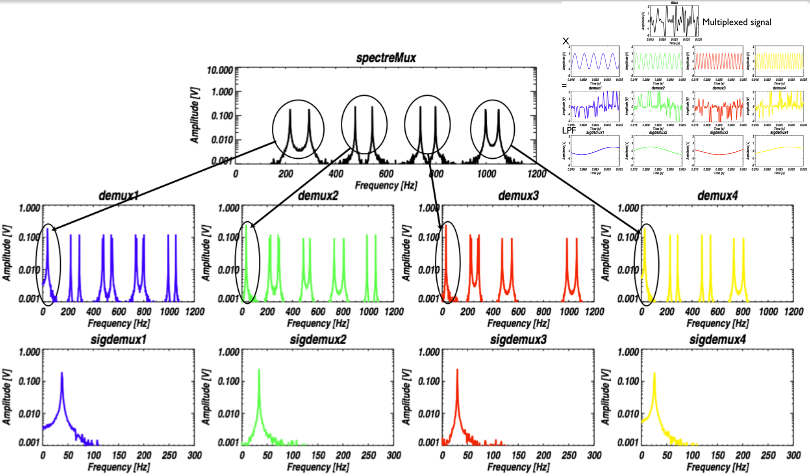


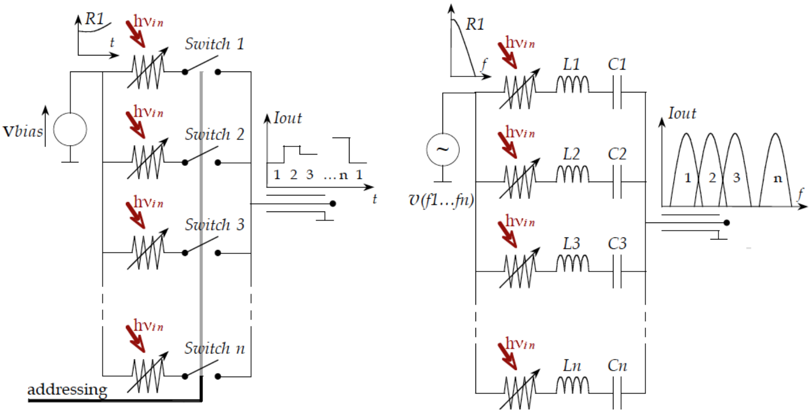
Demodulation of each carrier *ie* each input signal

+ low pass filtering (LPF)

Outline Applications

Outline Applications - Technological considerations

Topologie of a multiplexer



- **N switches or N LC filters**
- **N signals** for the addressing of the switch or the modulation

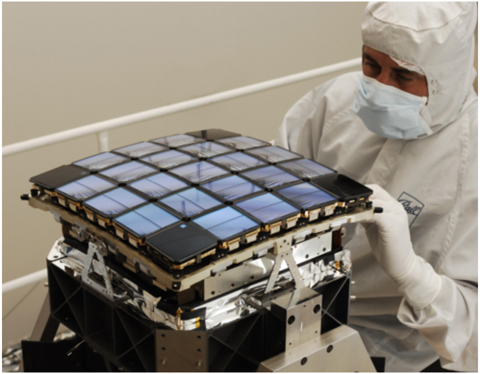
Outline Applications - **Example of time domain multiplexing**

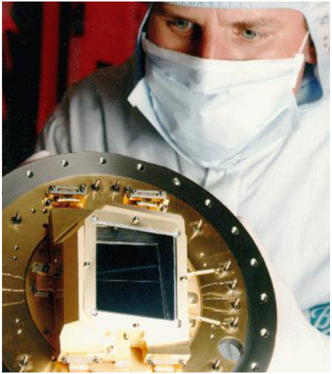
CCD (Charge Coupled Device) in astronomy

CCD is widely used in astronomy (examples : Kepler  and Hubble )

to achieved high-quality image despite a low photon flux

- high quantum efficiencies.





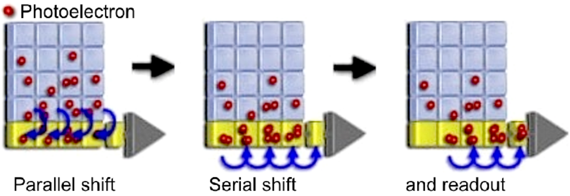
NASA/ESA and Ball Aerospace

CCD - Charge-Coupled Device : Charge Transfert ≡ TDM

- **CCD** was **invented in 1969** by Boyle & Smith - Bell Labs
- They were **Physics Nobel Prize 2009**, for the CCD concept

CCD technologies are based on array of sensors using photoelectric effect. However, **discovery of the law of the photoelectric effect** (photon to e^- conv.) is the **"Einstein Nobel Prize 1921"**

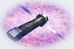
⇒ Reconised as new in the CCD, is the readout technic based on the **charge transfer** : *Parallel-in Serial-out shift register*



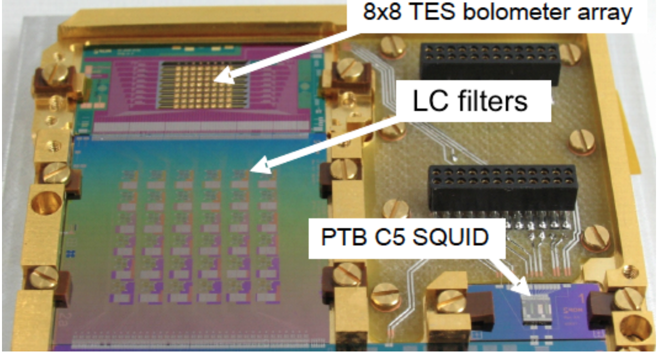
Outline Applications - **Example of frequency domain multiplexing**

TES Frequency Domain Multiplexing

- Array of TESs (**Transition Edge Sensors**) are used in astronomy (mm and X-ray)
- Athena is a proposed ESA X-ray observatory

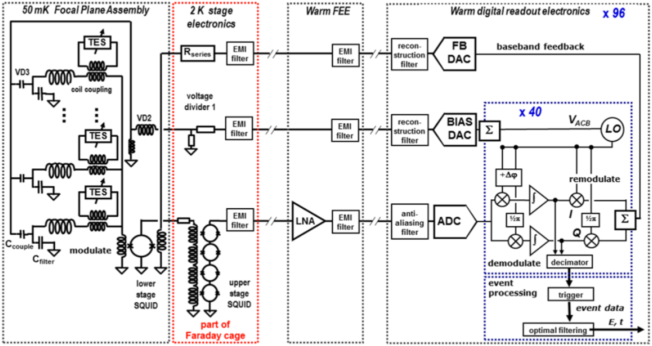


One of the instrument is based on **TES array + FDM** :

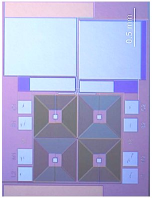


SRON - Safari & Athena FDM demonstration

TES Frequency Domain Multiplexing - LC resonator



Athena XIFU BBFB - Hartog et Al - SPIE



Conclusion

- Multiplexing for the readout of large arrays

  Reduction of the wiring

- The multiplexer must have better :
  - **bandwidth** $> 2 \times N \times BW_{Sig}$,
  - **dynamic** range and/or
  - **noise** performances $\propto \sqrt{N}$.

  than for a readout of one pixel

- Multiplexing is like a modulation + summation
  - **TDM is based on "boxcar" modulation**

    Switchs or shift
  - **FDM is based carrier modulation**

    LC filters

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