Bordeaux

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ADAPTIVE COMPRESSIVE SENSING FOR RADIO-FREQUENCY RECEIVERS

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Combien de verres de vin doit on consommer <u>au minimum</u> pour détecter la presence de la villageoise parmis les 8 bouteilles incluant celles de la cave du palais de l'Elysée ?

<u>*Astuce :*</u> Grouper les vins entre eux

<u>*Réponse : Pour détecter K=1 bouteille parmis N=8 :*</u> $N=8 \Rightarrow \text{Log}_2(8)=3$

OUTLINE

1 Preliminary

2 Fundamentals of Compressive Sensing (CS) acquisition

3 Potential CS applications for RF signal processing

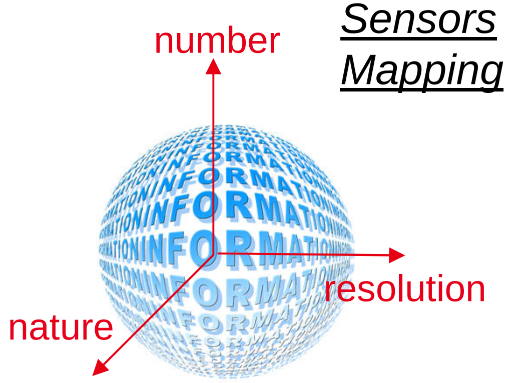
4 Review of existing CS architectures for RF

5 Novel adaptive CS acquisition scheme : NUWBS

6 Summary & Perspectives

MOTIVATIONS OF COMPRESSIVE SENSING (I)

- Explosion of digital data volume



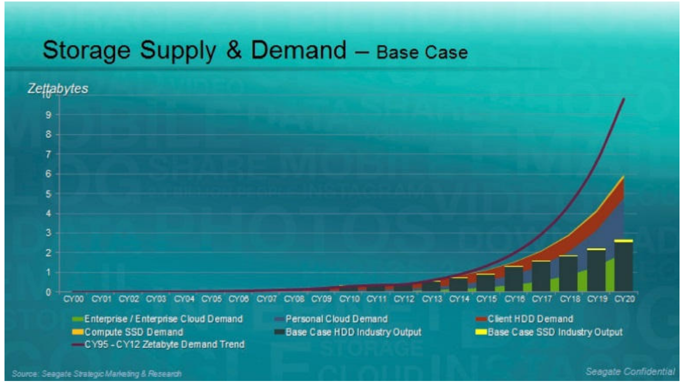
Sensors Mapping

MOTIVATIONS OF COMPRESSIVE SENSING (II)

- Data management issues :
  - Data storage issues :

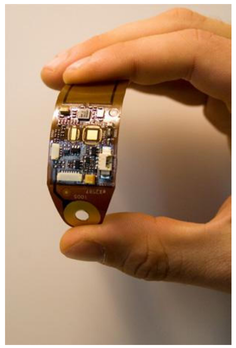
Segate Report " *It's far easier to generate zettabytes of data than to manufacture zettabytes of data capacity. A yawning gap is emerging between data production and hard drive and flash production*"

=> *Trends is Use data instantaneously or loose it*

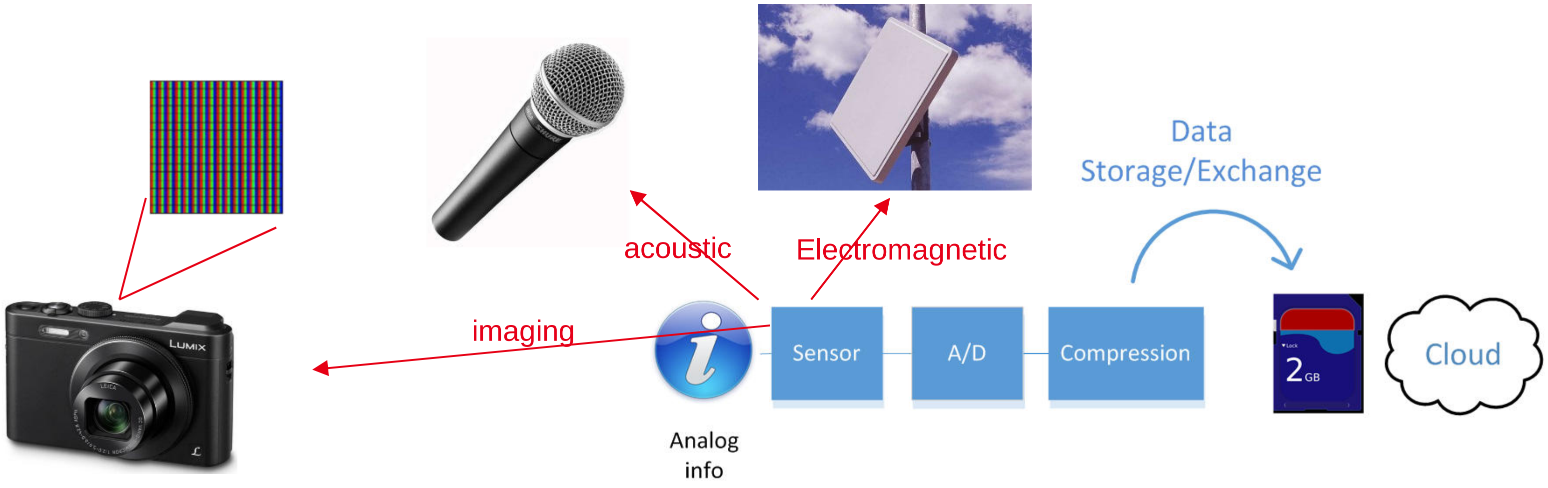


  - Data communication transmission rate is growing lower than the data volume explosion

  - Power consumption of wireless data transmission becomes the bottleneck in many wireless portable medical device



TOWARD A THE NEW PARADIGM



- It is useless to try to analyze all the data because *At 1.5% of the total, target- rich data is a much more manageable area of discovery* *(Sources IDC,2014*

Why go to so much effort to acquire all the data when most of what we get will be thrown away ?

PRINCIPLE OF COMPRESS SENSING

- What to do ? Acquire a compress representation with little information loss through dimensionality reduction

  $\Rightarrow$ *shrink storage constraint + huge amount data processing requirement*

  $\Rightarrow$ *No more physical representation of the signal*

- How to do it ?
  - compressive sensing only captures a certain amount information
  - Be careful information =! from data
  - Measure directly in a compressed form

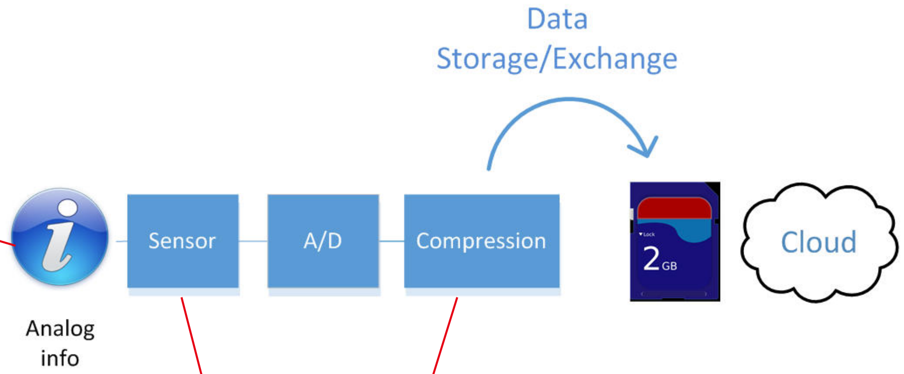
- How is it possible ?
  - A priori signal modelling : Sparsity

  (real world signals are sparse or very compressible in a suitable basis)

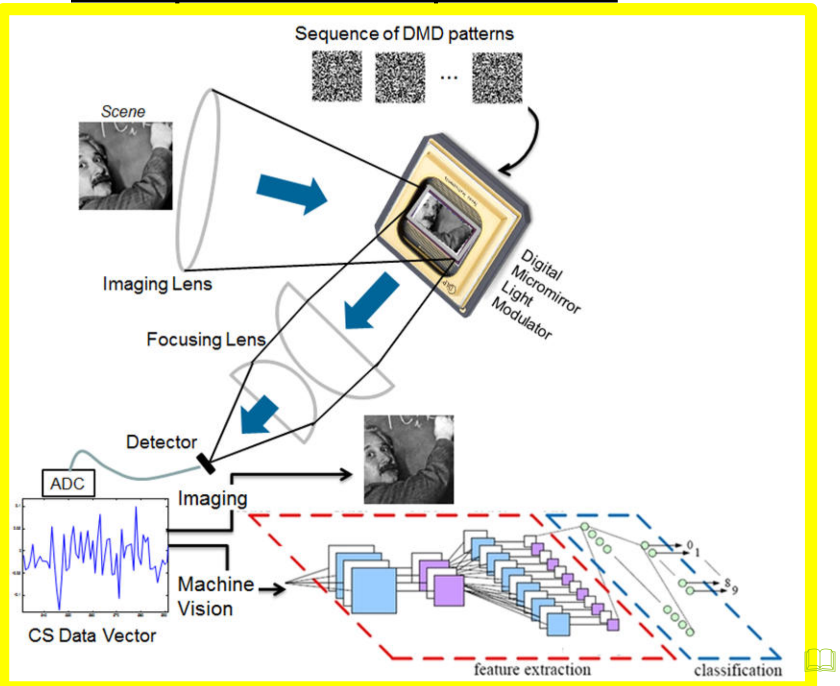
PRINCIPLE OF COMPRESS SENSING

- Standard acquisition :

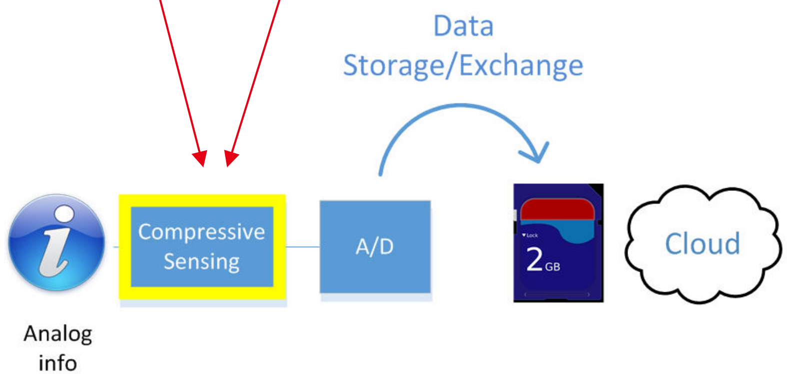
imaging



- Compressive acquisition :



Sense & Compress
at the same time

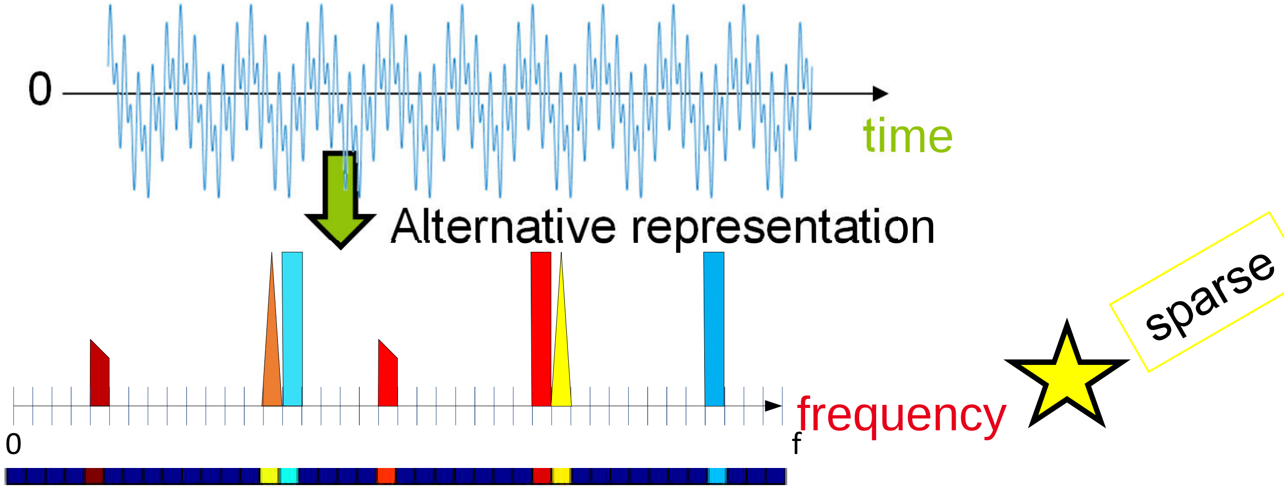


(Rice university,2006)

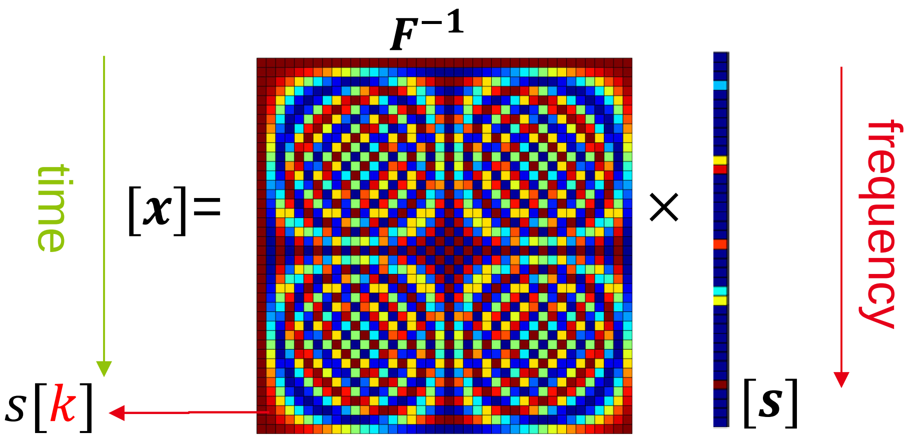
WHAT IS A SPARSE SIGNAL (II) ?

- *Ex 2 : Sparsity in frequency domain :*

- RF Signal waveform :



- Sparsity basis : Fourier matrix

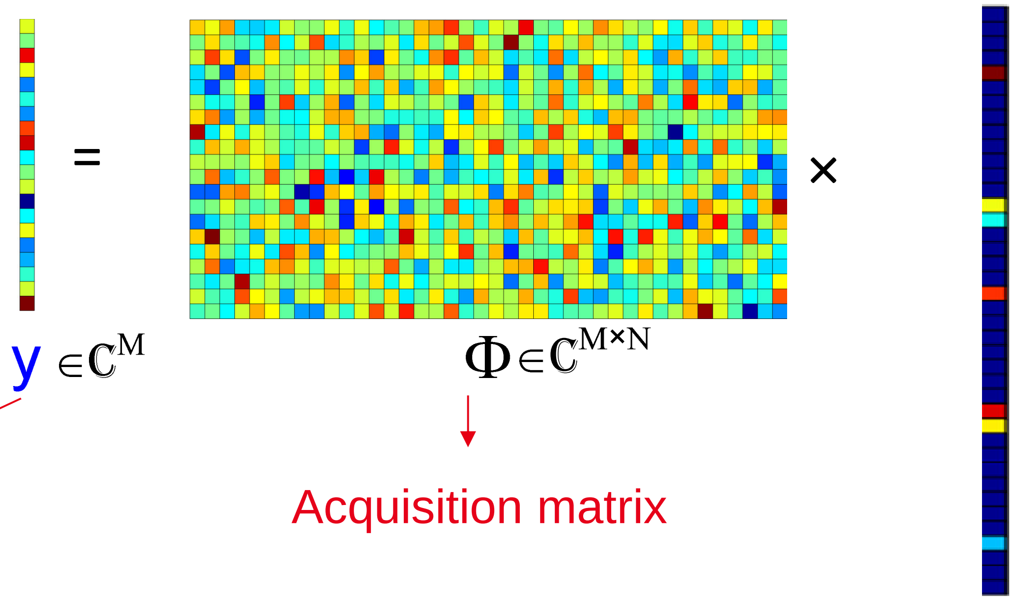


$$x[n] = \frac{1}{N}\sum_{k=1}^{k=N} e^{2i\pi\frac{k}{N}}.\, s[k]$$

- Key relationship : $\boldsymbol{x} = \boldsymbol{F^{-1}s}$

PRINCIPLE OF COMPRESSIVE SENSING ACQUISITION

- **Principle :**
  - Acquiring minimal number of measurements M such that M<< N while keeping all the information of the incoming signal in dimension N
  - When signal is sparse, we can acquire a condensed representation of it with no information loss through linear dimension reduction

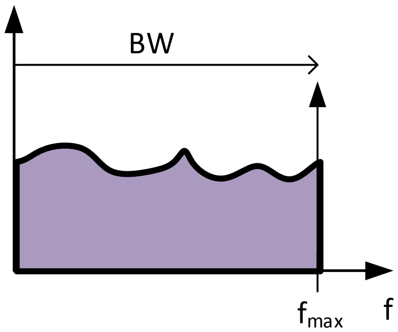


- **Remarks :**
  - Sparse Signal $\boldsymbol{s}$ is projected thanks to a sensing matrix $\boldsymbol{\Phi}$
    - NB : Since $\boldsymbol{\Phi}$ is not full rank => signal recovery $\hat{\mathbf{s}}$ from measurement $\mathbf{y}$ is not possible, without any a-priori/model on signal structure …

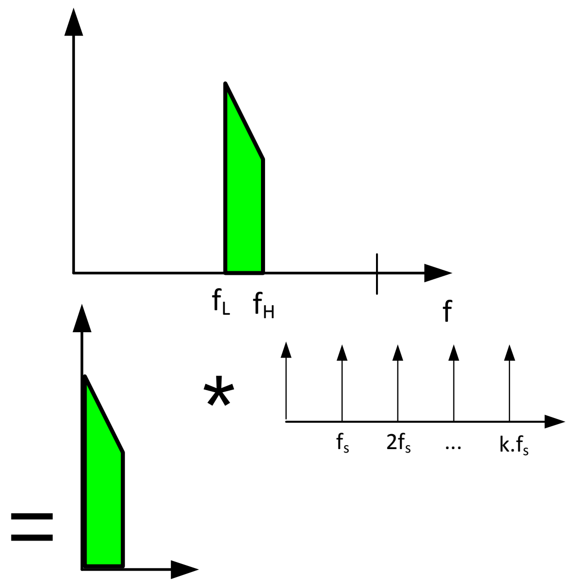
  => *Sparsity comes into play*

FROM BANDPASS SAMPLING TO COMPRESS SENSING

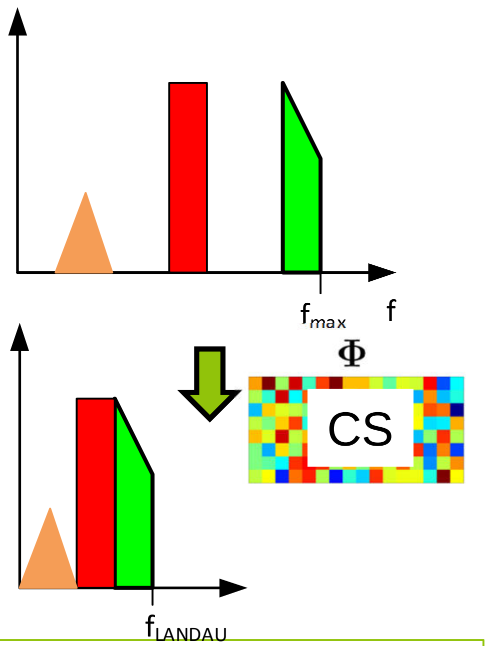
Nyquist sampling	Band-Pass Sampling	Compress sampling
🕮 (Shannon 1949).	🕮 (Vaughan et al. 1991)	🕮 (Landau 1967).
• Any signal :	• Band-limited signal :	• K sparse signal :



$f_s > f_{NYQ} = 2BW$



$$\frac{2f_h}{k} \leq f_s \leq \frac{2f_l}{k-1}$$



$$f_{LANDAU} = \sum_i BW_i < f_{NYQ}$$

INFORMATION RECOVERY

- **Compact formulation of acquisition scheme :**

$$\boxed{\boldsymbol{y} = \boldsymbol{\Phi x} = \boldsymbol{\Phi \Psi}\ \boldsymbol{s}}$$

$\Longrightarrow$ *Main Challenge is : recover signal x from measurements y*

$\boldsymbol{\Phi}$ is not square/full rank
$\Rightarrow$ ill-posed problem
unless sparsity conditions :

$$\boldsymbol{x} = \boldsymbol{\Psi s}, \|\boldsymbol{s}\|_0 = K$$

- **Compact Formulation of reconstruction problem :**

$$\hat{\mathbf{s}} = \underset{\mathbf{z}}{\operatorname{argmin}} \|\mathbf{z}\|_1 \text{ subject to } \mathbf{z} \in \mathcal{B}(\mathrm{y}) \text{ where } \mathcal{B}(\mathrm{y}) = \{\mathbf{z} : \|\mathbf{\Phi\Psi z} - \mathbf{y}\|_2^2 \leq \varepsilon\}$$

Convex approximation using l1 norm

additive noise consideration

Many application involve signal inference and not reconstruction

Detection < classification < estimation < reconstruction

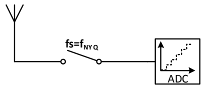
CHALLENGES IN COMPRESS SENSING

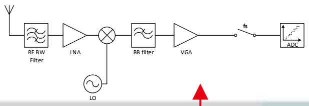
- 1. Face up to robustness issues
  - *Limitation of the degradation of the Signal To Noise ratio during acquisition*
- 2. Deal with measurement quantization
- 3. Develop more realistic signal models
- 4. Develop practical sensing matrices beyond random
  - *4,1-Reduction of number of sensing measurements*
  - *4,2-Optimization number of sensing nodes (hardware serialization)*
  - *4,3-Optimization of the use of the sensing power*
- 5. Develop more efficient recovery algorithms
- 6. Develop rigorous performance guarantees for practical CS systems
- 7. Exploit signals directly in the compressive domain
  - *Reduction of the complexity of the signal reconstruction or classification algorithm to be computational extractable*

OUTLINE

SPECTRUM SENSING AND COGNITIVE RADIO

- **Definition (FCC) :** *Cognitive radio is a radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets*."





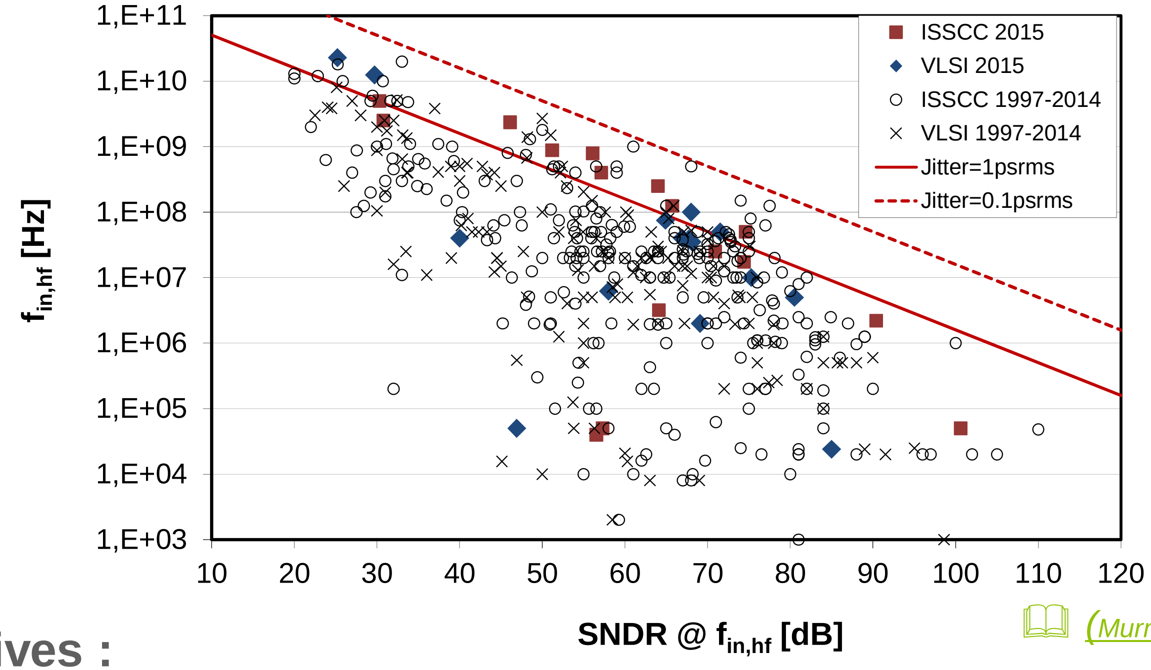
Type	Nyquist wideband sensing		Sub-Nyquist wideband sensing	
Algorithm sub-type	Standard ADC [5, 6]	Sweep-tune/filter bank sampling [6, 8]	Compressive sensing [9–11]	Multichannel sub-Nyquist sampling [13–15]
Advantage	Simple structure	Low sampling rate, high dynamic range	Low sampling rate, signal acquisition cost	Low sampling rate, robust to model mismatch
Disadvantage	High sampling rate, energy cost	High implementation complexity	Sensitive to design imperfections	Requires multiple sampling channels
Challenges	Reduce sampling rate, save energy	Develop feasible and practical model	Improve robustness to design imperfections	Relaxes synchronization requirement

(Hongjian et al. 2013).

- **Objectives :**
  - Downscaling the sampling rate thanks to CS approach may democratize the spectral sensing capability of RF receiver (primary/secondary user management)
  - Provide new toolbox for RF Link Quality Estimation (cross layer optimization in IoT)
  - Interference mitigation for high end radio

ANALOG TO INFORMATION CONVERTER

For a given sampling rate, ADC cannot exceed a certain signal-to-noise-and-distortion-ratio (SDNR)

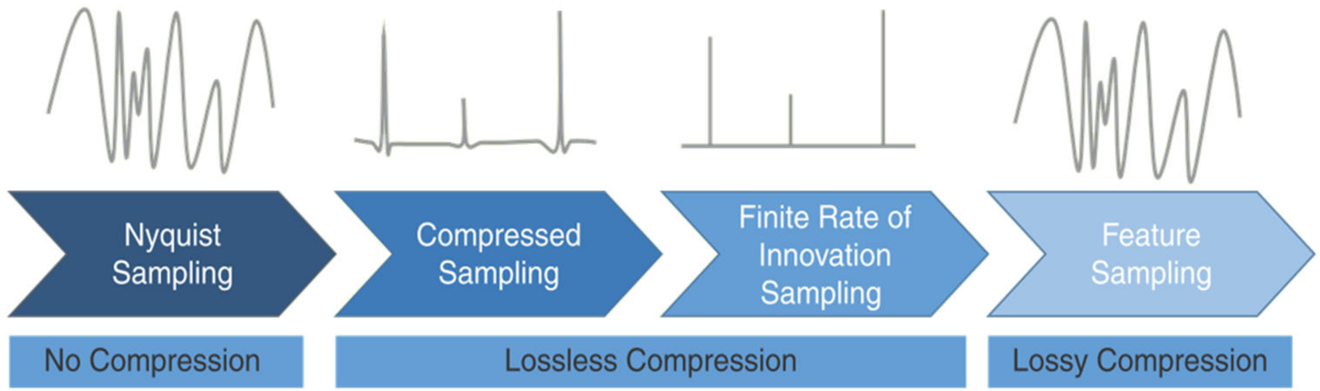


(Murmann 2015).

- **Objectives :**
  - Boosting the ADC effective bandwidth by leveraging sparsity assumption of incoming signal.
  - OR for a given bandwidth leveraging the additional dynamic range of sub-Nyquist sampling ADCs to enhance its resolution.
- **Tricks :**
  - Sampling near signal's (low) "information rate" rather than its (high) Nyquist rate

ANALOG TO INFORMATION & FEATURE CONVERTER

- **Principles :**
  - Reduce the dimensionality of the signal
  - Focus on signal freedom degree or relevant feature (link to machine learning)



A Priori Information	Signal = Bandlimited	Signal = Sparse in Certain Basis	Signal = Has Finite Degrees of Freedom per Time Unit	Signal = Contains Relevant (Feature) Information in Sea of Other Data
Information Rate (IR) Versus Physical Bandwidth (PB)	IR ≅ PB	IR < PB	IR << PB	IR<?> PB Though Not All Information Relevant

(Verhelst et al. 2015)

- **Objectives :**
  - Extraction of signal features rather than entire signal recovery
  - Signal classification rather than signal reconstruction by means of analog analytics

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NUS : NON UNIFORM SAMPLING PRINCIPLE

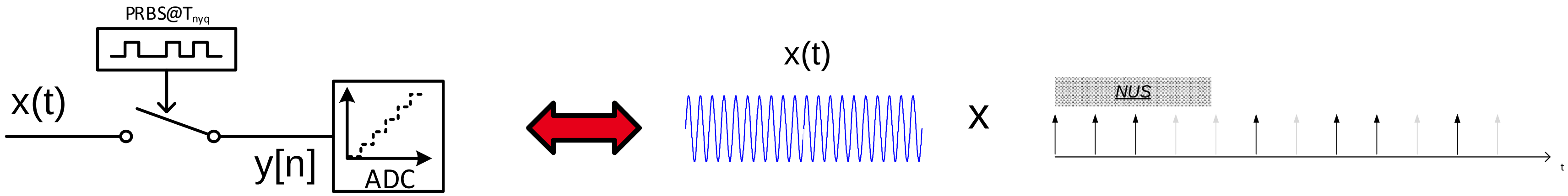
PRINCIPLE :

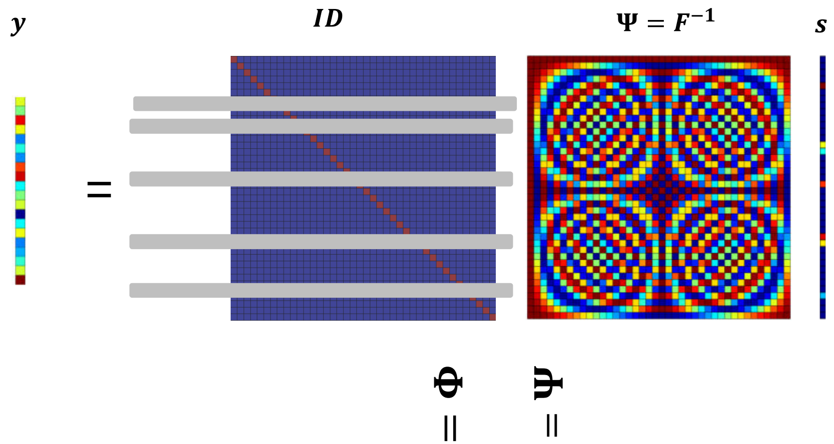
- **Pick up a subset of time samples among all possible that may be available from a full Nyquist sampling rate**

SUB CATEGORY :

- **randomized non-uniform sampling (RNUS) :**
  - deploys a sampling sequence that is composed of randomly chosen periods from a set of time intervals
- **periodic non-uniform sampling (PNUS) :**
  - sequence of non-uniform sampling periods that are repeated
- **level-triggered non-uniform sampling (LTNUS)**
  - Level-triggered non-uniform sampling samples

RANDOM NUS (I) : PRINCIPLE





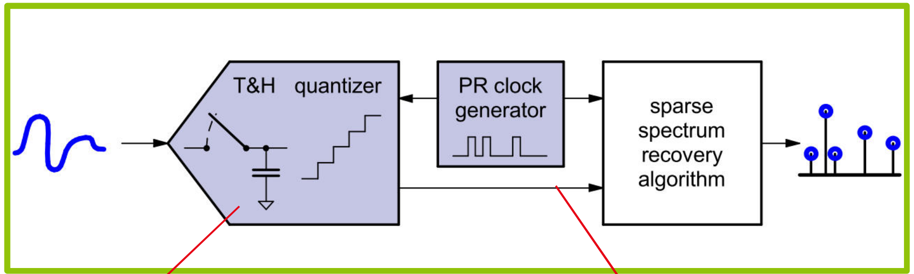
$$\boxed{y = R_T I_D F^{-1} s}$$

Downsizing Selector
(Random rows)

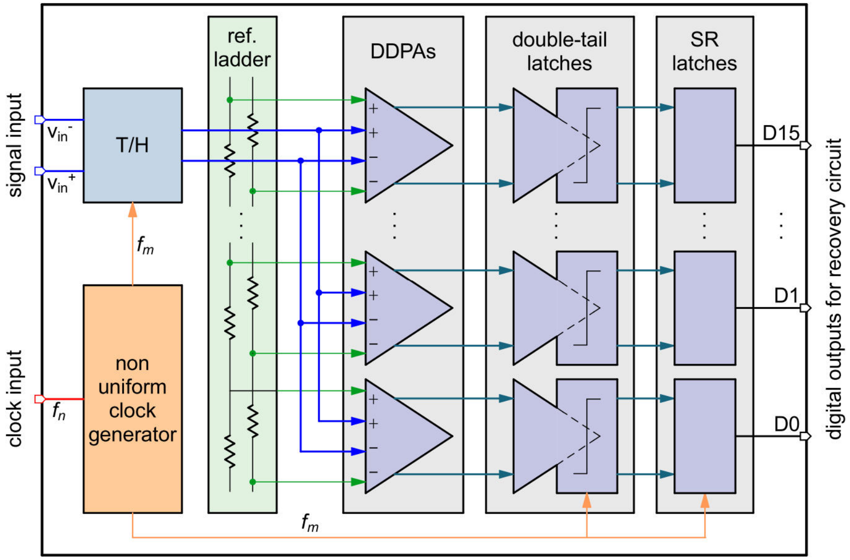
Projection basis
(Canonical)

Sparcifying matrix
(Fourier)

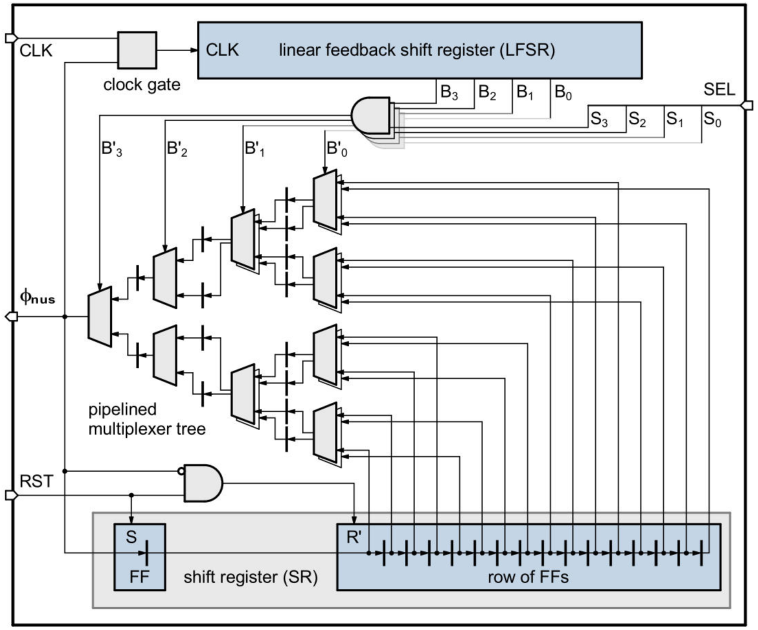
RANDOM NUS (II) – IMPLEMENTATION EXAMPLE



(Bellasi et al. 2013)



4-bit NUS Flash with 16 comparators



non-uniform clock generator
with configurable under-sampling factor

VRS : VARIABLE RATE SAMPLING

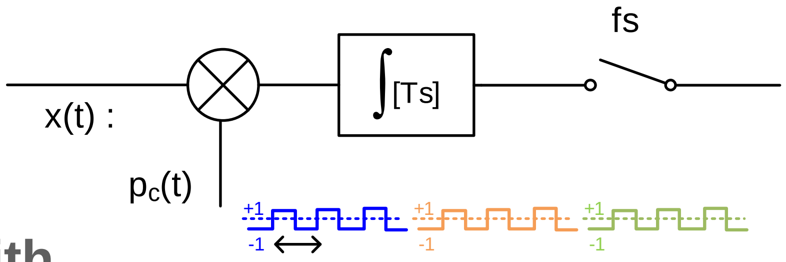
PRINCIPLE :

- **Multiple branches with variable rate**
- **Each branch performs Band-pass sampling**

SUB CATEGORY :

- **Synchronous Multi-rate sampling**
  - Fixed rate for each branch, all in phase
- **Asynchronous Multi-rate sampling**
  - Fixed rate for each branch, non coherent
- **Nyquist Folding Receiver :**
  - Continuous time variable sampling rate

RM : RANDOM MODULATION



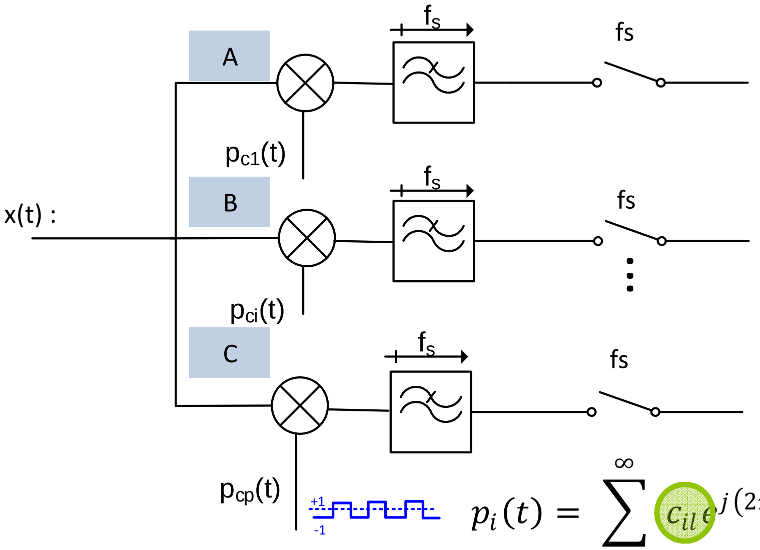
PRINCIPLE :

- **Encode the input signal by mixing with random code sequence (like spread spectrum)**

SUB CATEGORY :

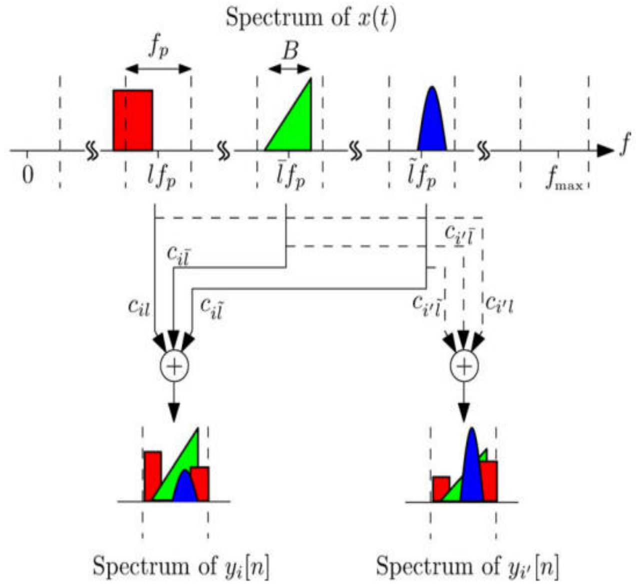
- **The random DeModulator (RD)**
- **The random Modulation Pre-Integrator (RMPI)**
  - = RD with multiple branches
- **Modulated Wide Band convertor (MWC)**
  - Code sequence is periodic

MODULATED WIDE BAND CONVERTOR : MWC



$$p_i(t) = \sum_{l=-\infty}^{\infty} c_{il}\, e^{j(2\pi/T_p)lt}$$

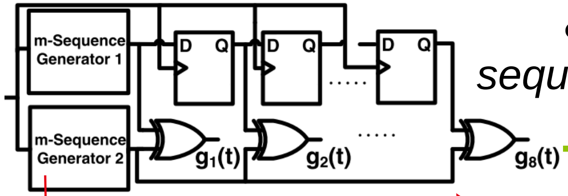
⇔



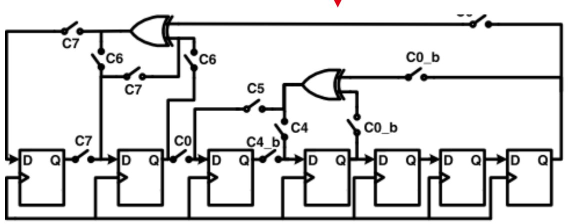
(Mishali et al. 2011)

$$Y_i\left(e^{-j2\pi f n T_s}\right) = \sum_{l=-L_0}^{l=+L_0} c_{il} X(f - l f_p)$$

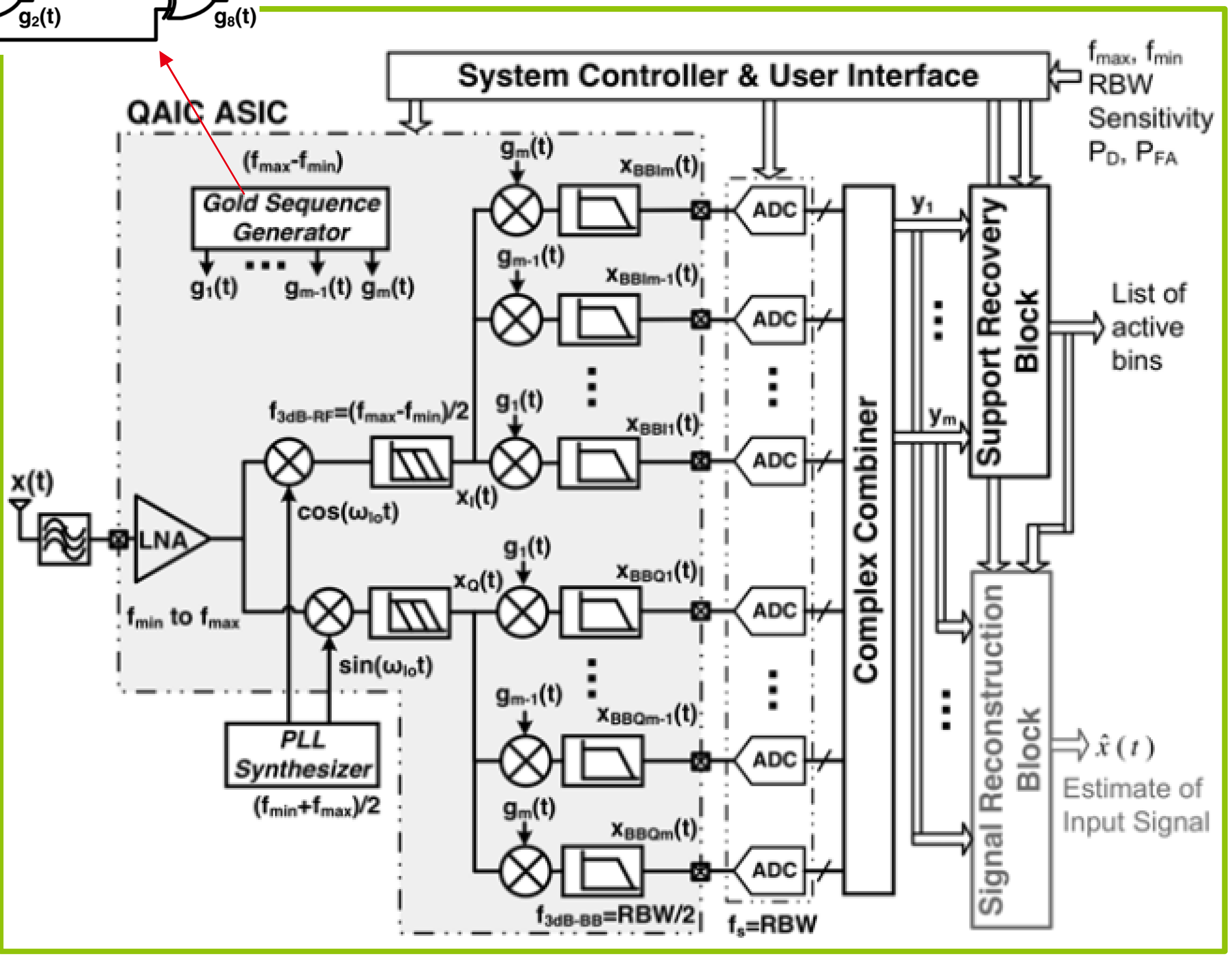
MWC – IMPLEMENTATION EXAMPLE : QAIC



8 unique gold sequences generation



m-sequence generators based on an LFSR implementation



(Yazicigil et al. 2015)

WHAT ARE THE LIMITATIONS OF CURRENT SOLUTION ?

Hardware implementation bottleneck	Architecture
The Nyquist-rate is still present : - Track & hold → *high bandwidth* ✗ - Random generator → *high power consumption* ✗	NUS & MRS RMPI, RD
Number of branches required ✗	MRS, MWC
Lack of re-configurability and versatility ✗	MWC, MRS
Sensitivity to timing jitter ✗	NUS, MRS

- The **lack of structure** within the acquisition scheme
  - → **excessive storage memory requirements:** random sequences on both ends of acquisition and reconstruction (NUS, RMPI)
  - → Complex recovery requirement algorithm that are **power hungry**
- **Random projection** suffers from fundamental limits **:**
  - On **input SNR** due to **aliasing effect**
    => Might be an issue in RF if sensitivity is required
  - **Lack of adaptivity** to the signal class or specific signal features
    => there is no specific method to extract specific features

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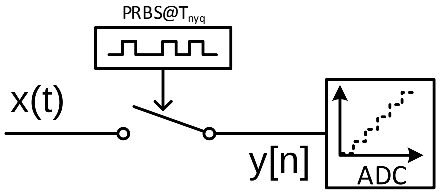
NOVEL METHOD : NON UNIFORM WAVELET BANDPASS SAMPLING (NUWBS)

Band Pass Sampling Impulse Adaptive
Compressive sensing MRI
Wavelet Quench signal
Multiscale

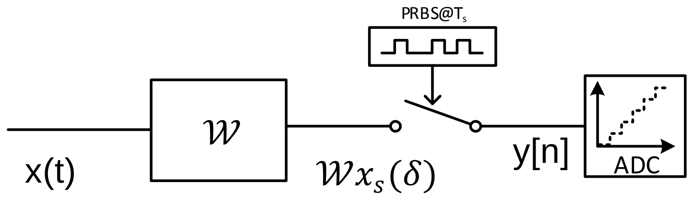
- Non Uniform Sampling :



$$y = R_T I_D F^{-1} s$$

structured acquisition

- NUWBS : Non Uniform Band Wavelet Pass sampling



$$y = R_T W^T F^{-1} s$$

“ Non-Uniform Wavelet Sampling for RF Analog-to-Information Conversion”, M Pelissier & C Studer IEEE Transactions on Circuits and Systems I: Regular Papers, accepted for publication 12/2016

WHY SHOULD WE USE WAVELET FRAMES ?

- Ability to tune the **time-frequency window** in a manner to track **dynamic variation** of the signal statistical parameters

- The **reconfigurable structure** of the transform introduce **adaptability and versatility** into the system. Depending on the needs or the **features** to be extracted we can adapt the wavelet accordingly (detection abrupt discontinuities, central frequency, etc.)

- Ability to arrange the time-frequency tiling in a manner that **minimizes the disturbances** By flexible design of the time-frequency windows, the effect of noise and interference on the signal can be minimized

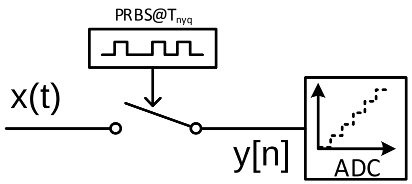
- Wavelets are a priori well suited to the **adaptive scheme** since it has an inherent tree structure, coming from recursive decomposition (DWT, WPT, QMF, …) cf. JPEG200

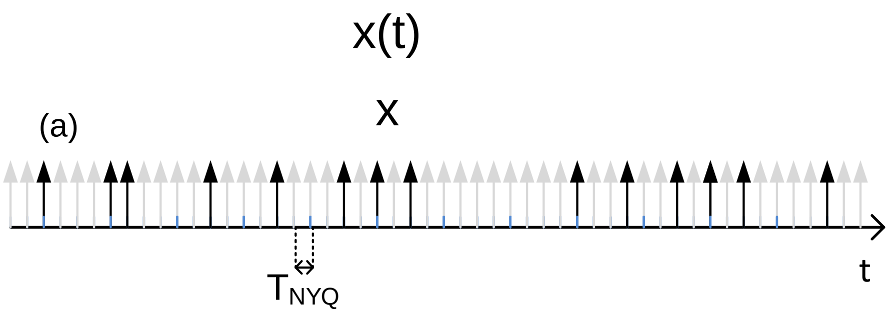
- **Hardware complexity is manageable** for both from acquisition chain (for instance pulse generation) but also algorithm (Morlet WT processing time of O(N) is the minimal theoretically possible of all signal-processing methods)

Wavelet may provide a "sustainable and green solution for cognitive radio" 🕮 *(Nikookar 2013)*

NUWBS : PRINCIPLE

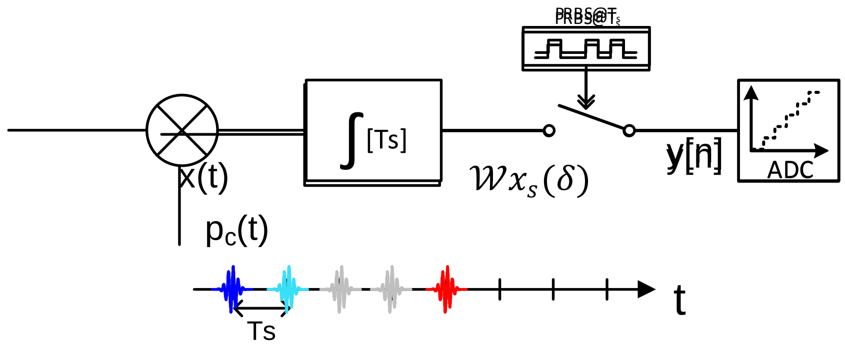
- <u>NUS : Non Uniform Sampling</u>

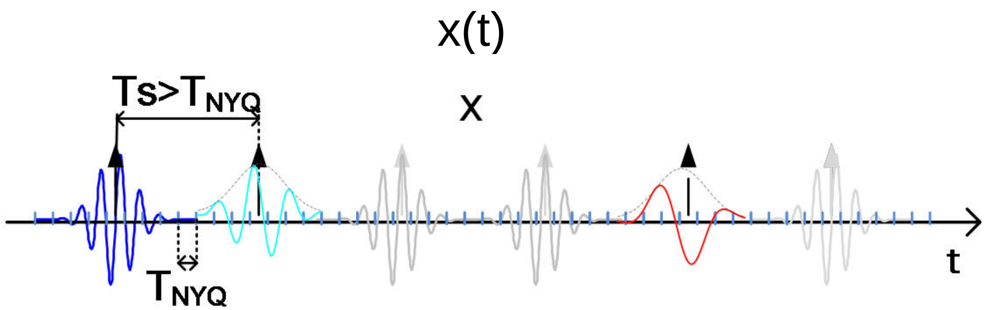




- Nyquist rate accuracy requirement
- High bandwidth requirement
- Sampling with 1 freedom degree

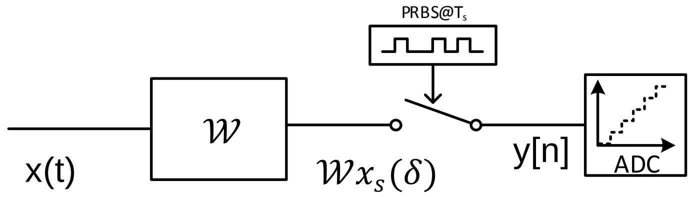
- <u>NUWBS : Non Uniform Wavelet Band Pass sampling</u>



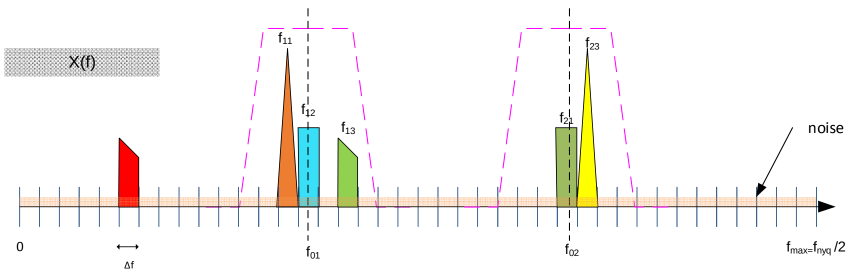


- Sub-Nyquist accuracy requirement
- Low (BB) bandwidth requirement
- Sampling with 3 degrees of freedom → versatile

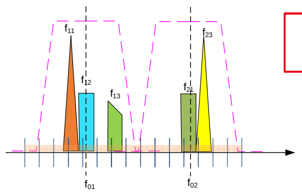
NUWBS : BENEFITS



Features	Benefits
Wavelet 'smear out' the samples : instead of measuring x(t), we modulate the signal around time δ with a pulse wave p(t) translated at frequency fc and integrate	Bandwidth reduction of sampling hardware (track/hold, ADC)
The pulse duration and central frequency is adjusted according needs	Possibility to match the acquisition to the signal of interest (disturbance resilience)
The results of the integration is down sampled in time	Reduce number of measurements

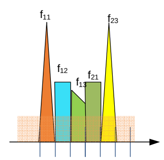


Signal Matching



- Prior on signal required
- 'windowing effect'
- Disturbance mitigation

Compressive



- No prior
- 'compression effect
- Noise aliasing

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SUMMARY

- Summary of CS Main features :
  - Compressive sensing is an enabler technology to cope with big data processing assuming sparse representation of the information
  - RF signal processing can leverage CS approach in various domain : sensing, beamforming, block/chain performance booster

- Summary of CS acquisition for RF signal processing :
  - Sub-Nyquist sampling rate for RF sparse signal processing has been demonstrated with both off the shelf and ASICs proof of concept.
  - Most of periodic solution relies on “encoded bandpass sampling” solution that creates diversity of the alias so as to recover information

- The Non Uniform Wavelet Band Pass sampling (NUWBS) features :
  - Dedicated solution to deal with frequency sparse RF multiband signal
  - Solution matched to the band of interest => optimal noise/interference resilience
  - Solution offers sampling scheme with 3 freedom degrees => flexibility

TRENDS AND HOT TOPICS

- improve the RSNR and overcome structural limitation of CS with respect SNR performances by considering additional structure into the signal.
- Provide dynamic acquisition process to handle sparsity fluctuation in time
- Activate the subset of features most beneficial under specific operating conditions in analog feature converter => Toward adaptive scheme
- Overcome hardware limitation due to fixed amount of parallelization and branches.
- Target real-time decision and relax signal inference constraints from signal reconstruction to signal classification by processing data directly in compressive domain.

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