



# New Sampling Paradigm Dedicated to RF ultra-wideband Receivers

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Beyond Nyquist...

Your signal is sparse!

Signal recovering

Signal Processing Evolution

### ③ Application

We can reach better efficiency !

## Introduction

Required Energy for Basestations in 2010 in Germany



- **3300 GWh in 2010**
- This is 50% of the small Nuclear Power Plant Isar 1 (6200 GWh)
- This is 100% of the big Water Power Plants
  - Altenwörth (1970 GWh) and Greifenstein (1720 GWh)

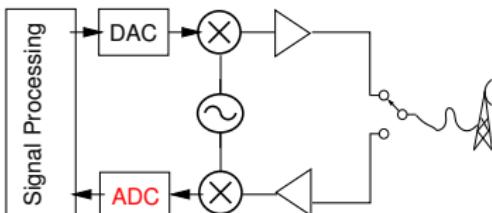


- Urgent need for Basestations with improved efficiency

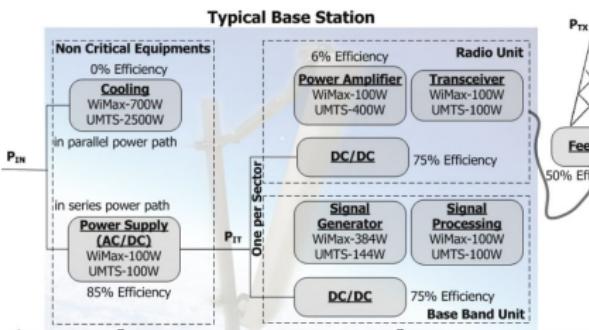
data from Infineon [1]

## Introduction

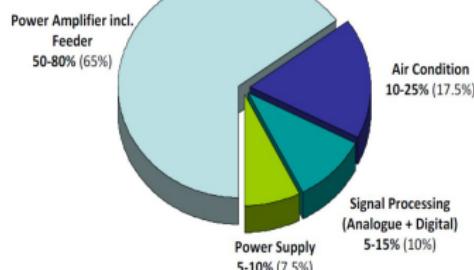
- Designing RF front-end



- Base-station example

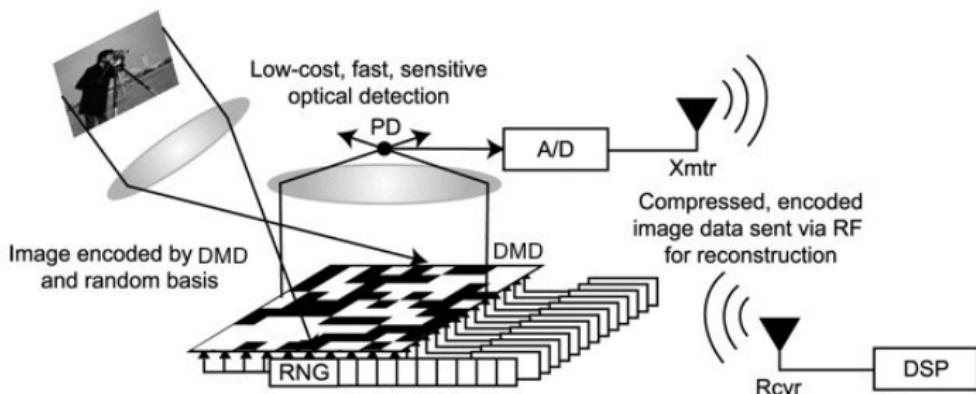


Architecture and efficiency [2]



Energy consumption = 6 kW [3]

# The Rice University : A Single-Pixel Camera [4]



Original

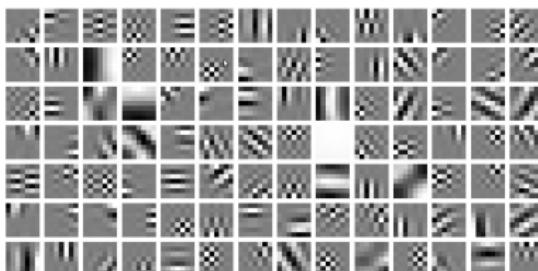
16384 Pixels  
3300 Measurements  
(20%)16384 Pixels  
1600 Measurements  
(10%)65536 Pixels  
3300 Measurements  
(5%)65536 Pixels  
1300 Measurements  
(2%)

# The Munich University : Analysis Operator Learning [5]

- Training



- Atom identification  $n = 49(7 \times 7)$   $k = 2.n = 98$



# The Munich University : Analysis Operator Learning [5]

- Image reconstruction



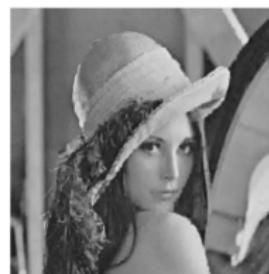
(a) Masked 60% missing pixels.



(b) Inpainted image,  $PSNR$   
35.6dB.



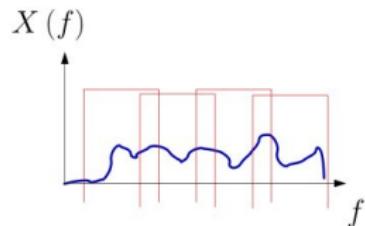
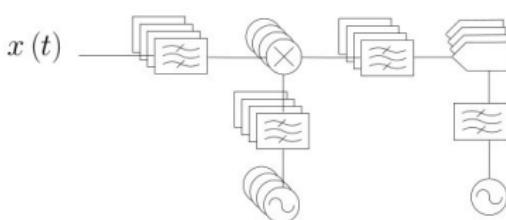
(c) Masked 90% missing pixels.



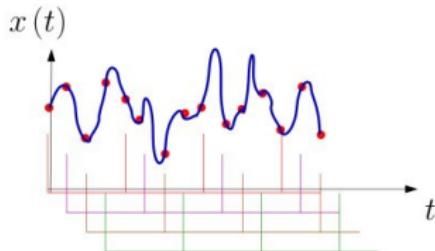
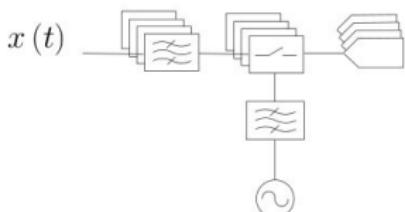
(d) Inpainted image,  $PSNR$   
28.2dB.

## Broadband RF Sampling

- Frequency domain sampling



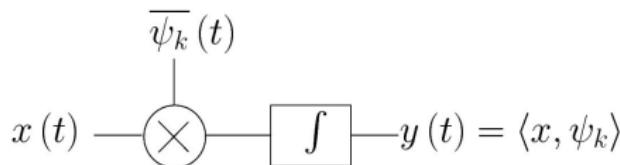
- Time domain sampling



## Compressed Sampling

$$\begin{aligned}\mathcal{D} &= \{\psi_k\}_{k \in \Gamma} \\ \langle x, \psi_k \rangle &= \int_{-\infty}^{+\infty} x(t) \cdot \overline{\psi}_k(t) . dt \\ \tilde{x}(t) &= \sum_{k \in \Lambda} \langle x, \psi_k \rangle \cdot \psi_k\end{aligned}$$

- Select a dictionary  $\mathcal{D}$
- Inner-product  $\langle x, \psi_k \rangle$



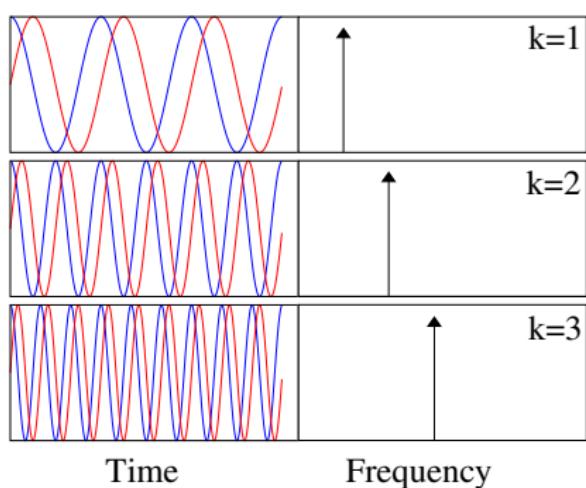
- Minimizing the number of measurements : optimizing  $\Lambda$

## What is a Fourier Transform ? [6]

- $\mathcal{D} = \{\psi_f(t) = e^{j \cdot 2\pi \cdot f \cdot t}\}$
- $X(f) = \langle x, \psi_f \rangle$
- $x(t) = \int_{-\infty}^{+\infty} X(f) e^{j \cdot 2\pi \cdot f \cdot t} df$
- $X(f) = \int_{-\infty}^{+\infty} x(t) e^{-j \cdot 2\pi \cdot f \cdot t} dt$
- $x(t) \approx \sum_k X(k \cdot f_0) e^{j \cdot 2\pi \cdot k \cdot f_0 \cdot t}$

Standard LSNA uses boxcar window

Projection basis :

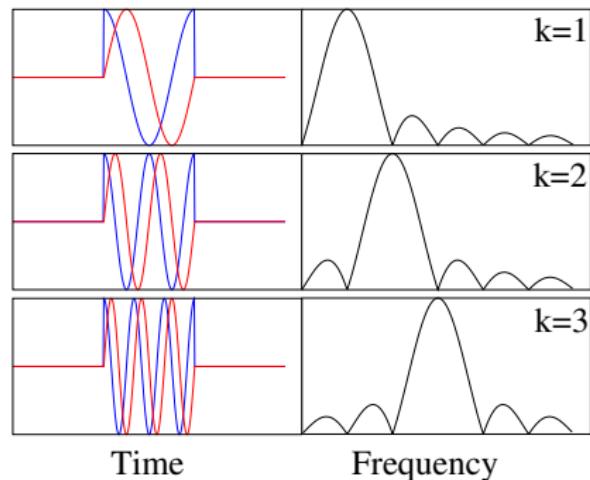


## The Short Time Fourier Transform [6]

Rectangular STFT is well suited for harmonic analysis

Projection basis :

- $\mathcal{D} = \{\psi_{k,\tau}(t)\}$
- $\psi_{k,\tau}(t) = P_k \cdot \psi_k(t - \tau)$
- $\psi_k(t) = \Pi(f_0 \cdot t) e^{j \cdot 2 \cdot \pi \cdot k \cdot f_0 \cdot t}$
- $P_k = f_0 \cdot e^{j \cdot 2 \cdot \pi \cdot k \cdot f_0 \cdot \tau}$
- $X(k \cdot f_0, \tau) = \bar{P}_k \cdot x(t) * \bar{\psi}_k(t)$



$$X(k \cdot f_0, \tau) = \bar{P}_k \cdot \mathcal{F}^{-1} \{ X(f) \cdot \bar{\Psi}_k(f) \}$$

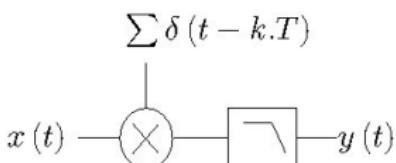
# Measurement matrix of the harmonic sampling

$$x \in \mathbb{R}^N$$

$$y \in \mathbb{R}^P$$

$$P \ll N$$

- Spase signal in the frequency domain

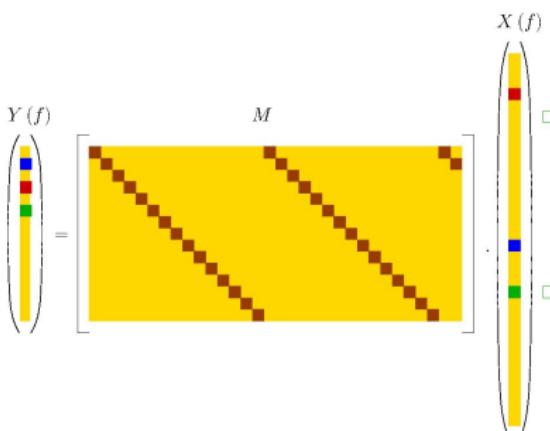


$$(Y) = [M] . (X)$$

$$(y) = [\mathcal{F}_p]^{-1} . [M] . [\mathcal{F}_n] . (x)$$

$$(y) = [U] . [\mathcal{F}_n] . (x)$$

$\mathcal{F}_i \in \mathbb{C}^{i \times i}$  is the DFT matrix

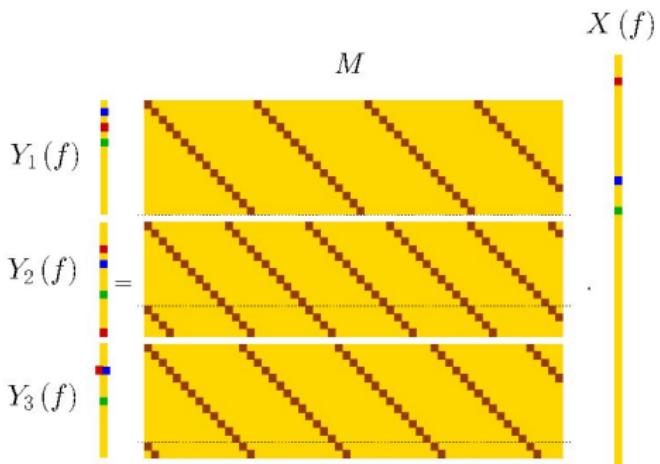
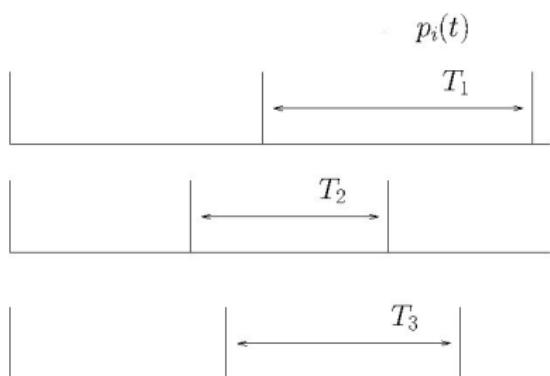
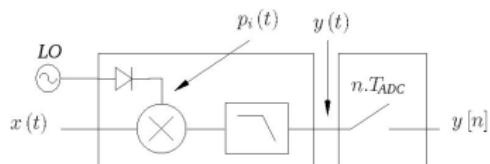


- General case with  $\mathcal{D} = \{\psi_k\}_{k \in \Gamma}$

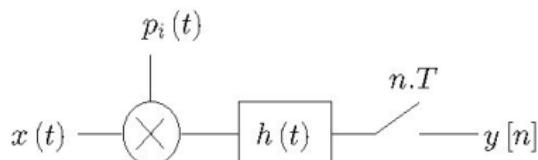
$$y = U \Psi x + b$$

with  $U \in \mathbb{C}^{P \times N}$  et  $\Psi \in \mathbb{C}^{N \times N}$

## Non-uniform subsampling



## Random sampling [7] [8]



$$\begin{aligned} p_i(t)|_{t=n.T} &\in \{\pm 1\} \\ x(t) &= \sum_k \alpha_k \psi_k(t) \end{aligned}$$

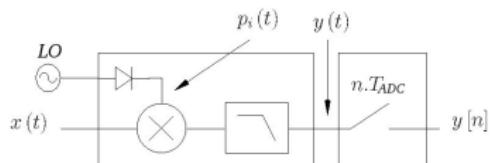
$$y[n] = \int_{-\infty}^{+\infty} x(\tau) \cdot p_i(\tau) \cdot h(t - \tau) d\tau \Big|_{t=n.T}$$

$$y[n] = \sum_k \alpha_k \cdot \int_{-\infty}^{+\infty} \psi_k(\tau) \cdot p_i(\tau) \cdot h(n.T - \tau) d\tau$$

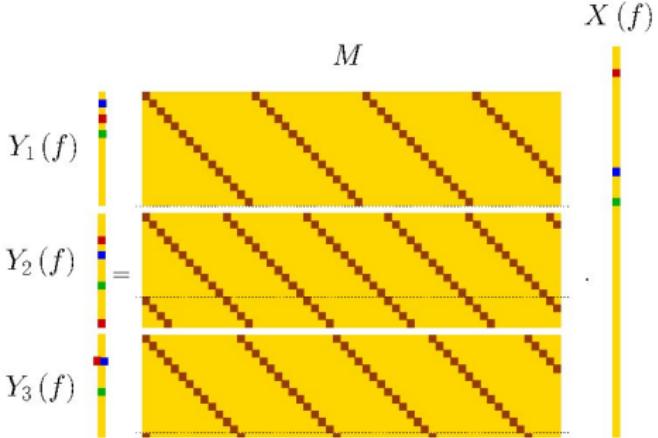
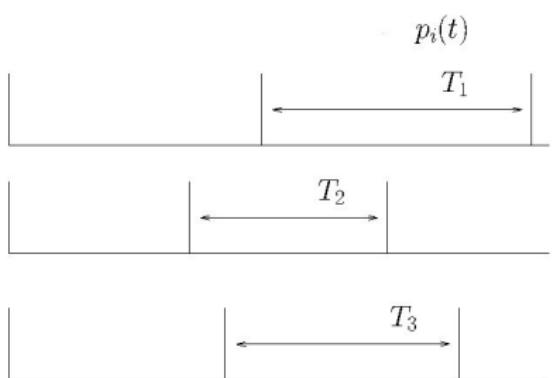
$$\begin{pmatrix} \vdots \\ y[n] \\ \vdots \end{pmatrix} = \begin{bmatrix} & \vdots & \\ \dots & U_{n,k} & \dots \\ & \vdots & \end{bmatrix} \cdot \begin{pmatrix} \vdots \\ \alpha_k \\ \vdots \end{pmatrix}$$

	Rice [7]	Technion [8]
$f_e$ ADC $f_e$ Demodulator Number of demodulator	400 kHz 3.2 MHz 1	280 MHz 2 GHz 4

## Non uniform sub-sampling

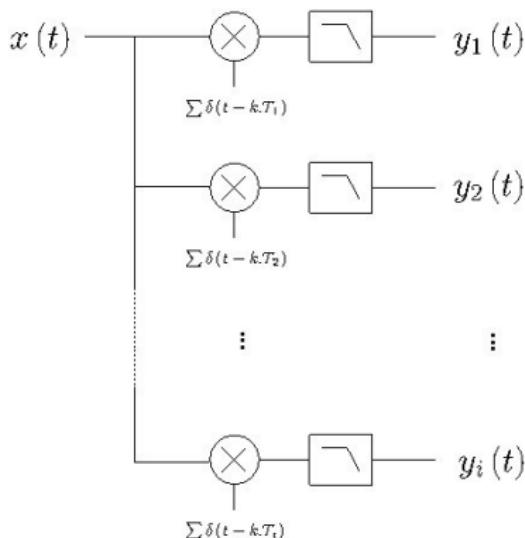


$f_{LO}$	Technology	$f_{MAX}$
16 MHz $\leftrightarrow$ 20 MHz	Sampler	50 GHz
$\rightarrow$ 500 MHz	Sampler	20 GHz
$\rightarrow$ 1 GHz	Sampler	20 GHz
$\rightarrow$ 800 MHz	Sampler	35 GHz
$\rightarrow$ 2 GHz	THA [9]	18 GHz



Recovering  $x(t)$ 

- Independant Measurements



- Sparse Regression [10]

Assuming  $X = \Psi.x$ , then

$y = U.X + b$  leads us to the solution :

$$X \in \arg \min_{\|y - U.X\|_2^2 < \epsilon} \|X\|_1$$

Optimization Algorithms :

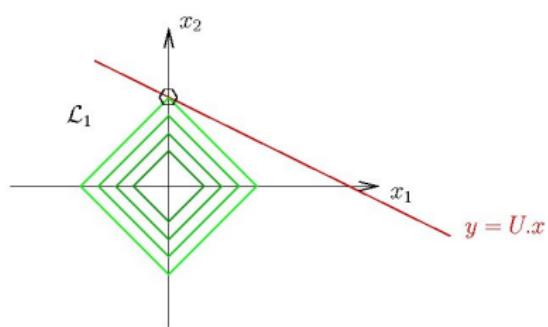
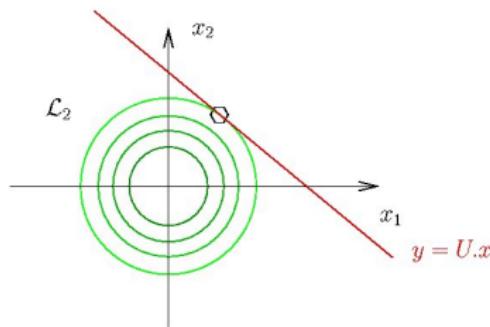
- Pursuits methods
- Lasso
- Dantzig Selector
- $\mathcal{L}_1$  norm minimizer

Optimization on  $\mathcal{L}_1$  norm

- Definition of  $\mathcal{L}_p$  norm

$$\|x\|_p = \left( \sum_i |x_i|^p \right)^{\frac{1}{p}}$$

- Illustration on balls  $\mathcal{L}_p$



- The solution on  $\mathcal{L}_1$  is sparse

# on the use of Signal Processing

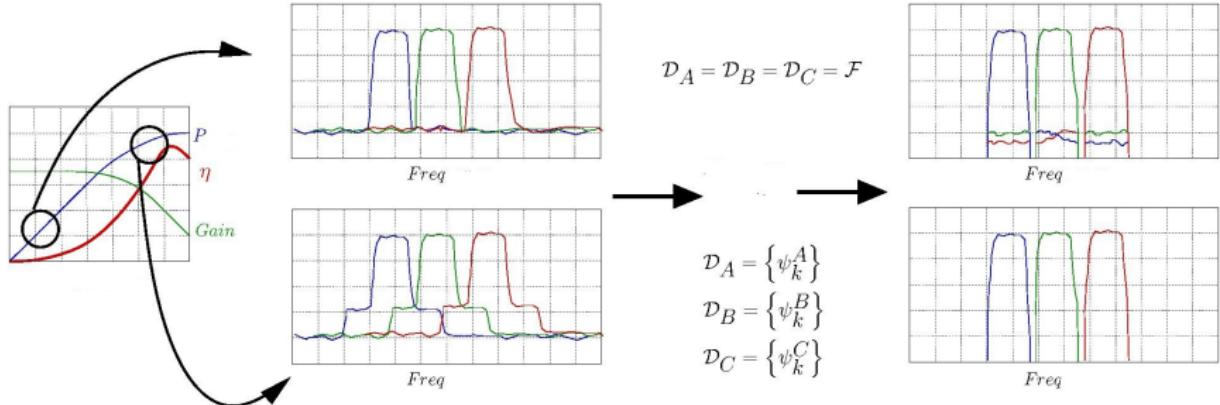
- Keywords survey on IEEE Xplore between 1991 and 2011 in journals "IEEE Transaction on..."

	Fourier (1822)	Gabor (1946)	Wavelet (1984)	Compressive Sensing (2006)
Signal Processing	3374 (1)	346 (1)	1971 (1)	87 (1)
Image Processing	1184 (12)	342 (2)	1646 (2)	31 (5)
Circuits and Systems I & II (4 jnls)	1457	82	591	5
Antennas and Propagation	2388 (2)	59 (14)	284 (14)	2
Instrumentation and Measurements	1376 (8)	72 (12)	358 (11)	3
Microwave Theory and Techniques	1833 (5)	15	174	1
Electron Device	503	14	13	0

- (.) : rank
- Circuits and Systems I : "Regular Paper" and "Fundamental Theory and Applications"
- Circuits and Systems II : "Express Briefs" and "Analog and Digital Signal Processing"

We can reach better efficiency !

- Improving RF front-end efficiency



# References I

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- [1] Helmut Vogler. Microwave components research and innovation in the eu a company perspective. 2008.
- [2] G. Koutias and P. Demestichas. A review of energy efficiency in telecommunication networks. *Journal TELFOR*, November 2010.
- [3] L.M. Correia, D. Zeller, O. Blume, D. Ferling, Y. Jading, I. Góðor, G. Auer, and L. Van Der Perre. Challenges and enabling technologies for energy aware mobile radio networks. *Communications Magazine, IEEE*, 48(11):66–72, November 2010.
- [4] Rice University. Compressive imaging: A new single-pixel camera. In <http://dsp.rice.edu/cscamera>.
- [5] S. Hawe, M. Kleinsteuber, and K. Diepold. Analysis operator learning and its application to image reconstruction. *Arxiv preprint arXiv:1204.5309*, 2012.
- [6] T. Reveyrand and Z. Popovic. A new method to measure pulsed rf time domain waveforms with a sub-sampling system. In *IEEE MTT-S Digest, IMS 2012, TH2A-2, Montreal, Canada*, 2012.
- [7] T. Ragheb, J.N. Laska, H. Nejati, S. Kirolos, R.G. Baraniuk, and Y Massoud. A prototype hardware for random demodulation based compressive analog-to-digital conversion. In *Midwest Symposium on Circuits and Systems (MWSCAS)*, pages 37–40, 2008.
- [8] M. Mishali, Y.C. Eldar, O. Dounaevsky, and E. Shoshan. Xampling: Analog to digital at sub-nyquist rates. CCIT Report 751, EE Dept., Technion - Israel Institute of Technology, December 2009.
- [9] www.inphi.com. Inphi 1821TH Data sheet.
- [10] Y. de Castro. A short geometric tour of the sparse regression. Technical report, Institut de Mathmatiques de Toulouse, France, February 2011.

## References II

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- [11] Hossein Mamaghani, Nadia Khaled, David Atienza Alonso, and Pierre Vandergheynst. Design and Exploration of Low-Power Analog to Information Conversion Based on Compressed Sensing. *IEEE Journal of Emerging and Selected Topics in Circuits and Systems*.