New Trends in High-Dynamic Range Analog-to-Digital Converters

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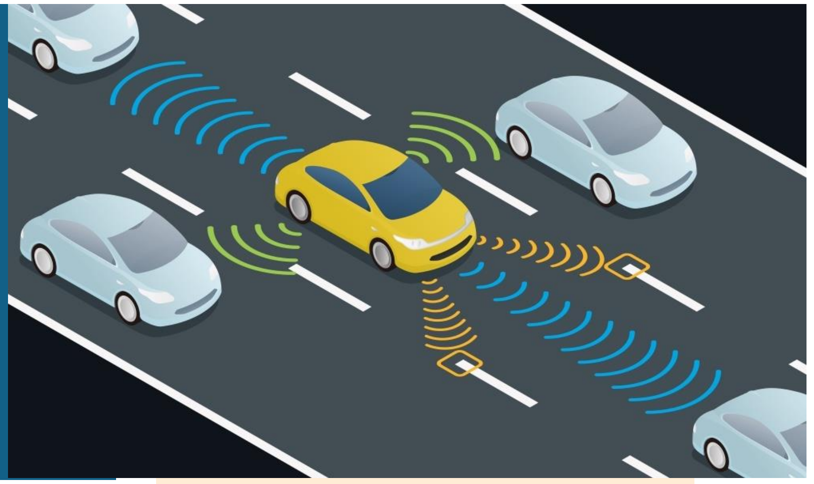
13 May 2025

We Live In An Analog World


Medical Imaging

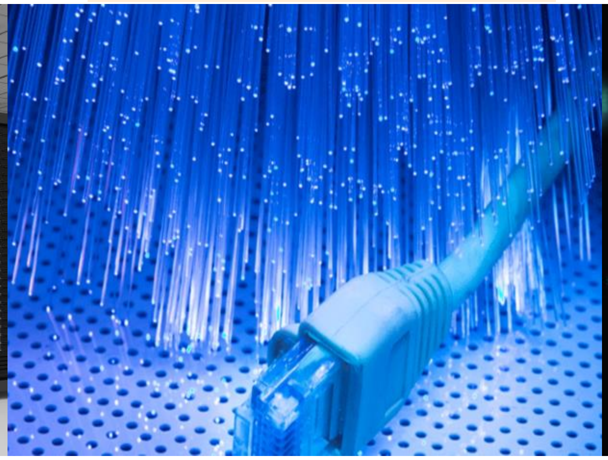

Communication

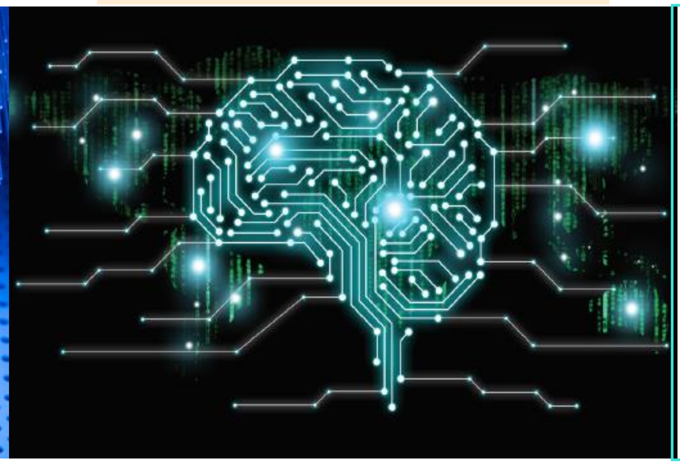

Sensor Networks


Autonomous Cars

- We like to process things digitally!

Storage


Transmission


Processing


Power


Cost


* All the images are taken from Google images

We Live In An Analog World


Medical Imaging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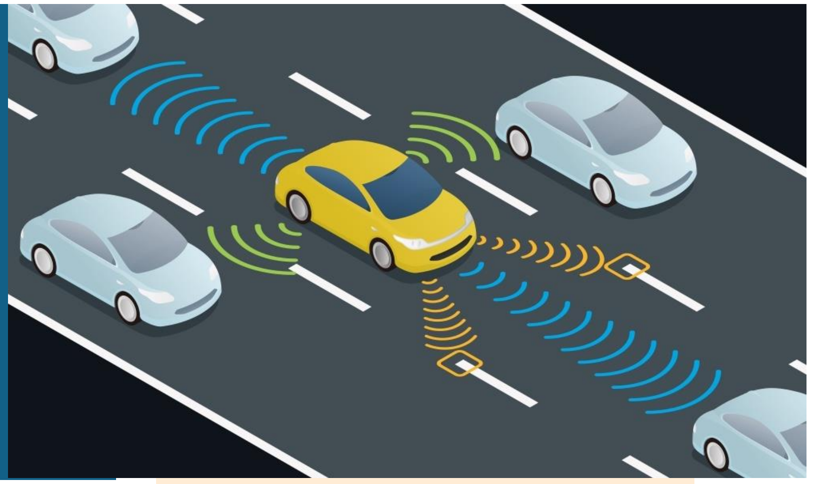
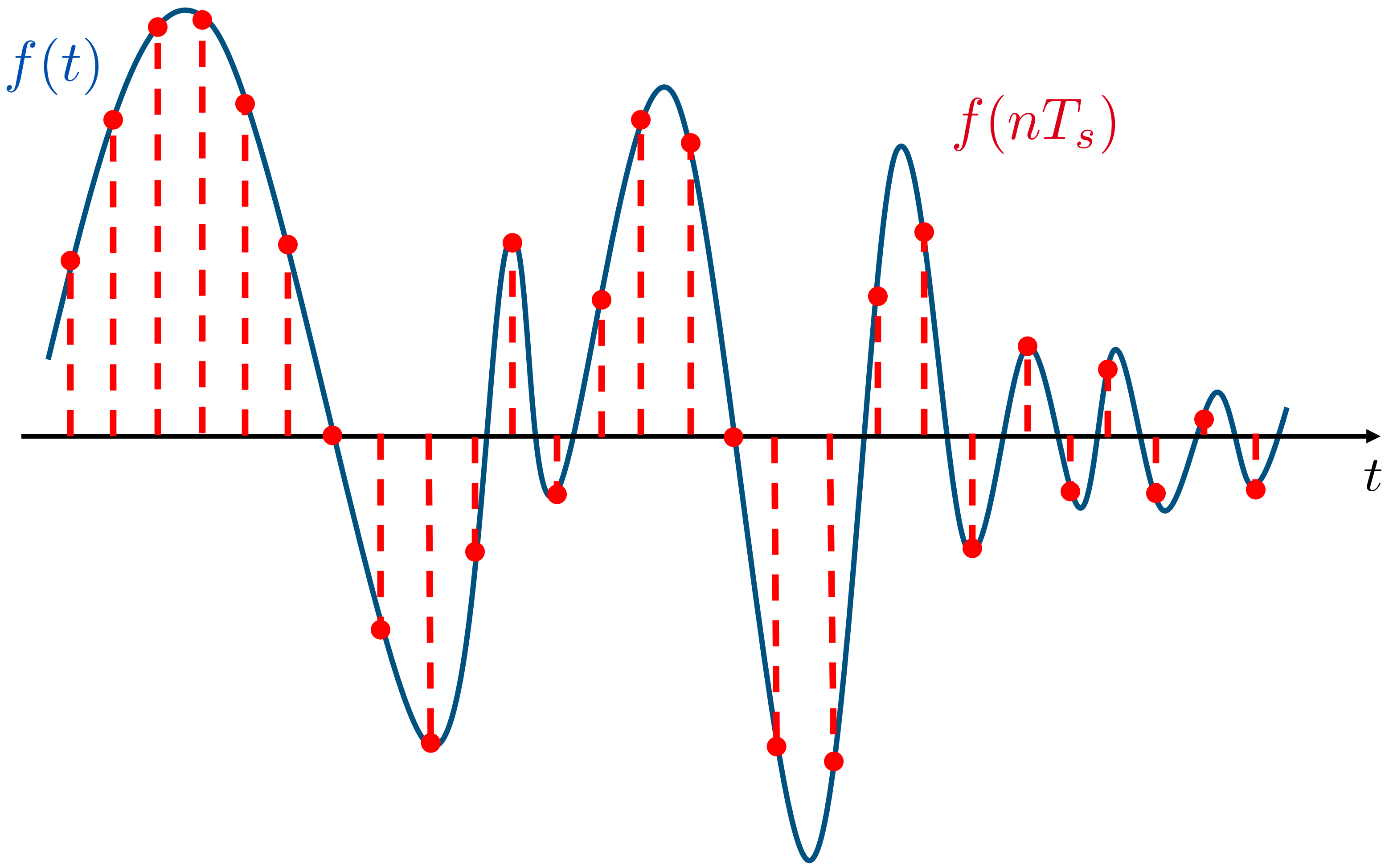
Sensor Networks

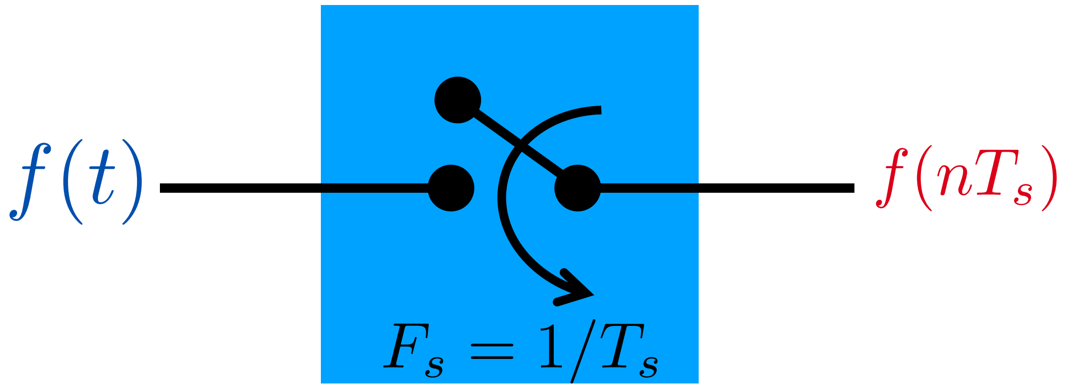

Autonomous Cars

- We like to process things digitally!
- ADCs are everywhere and acts as bridge between the two worlds

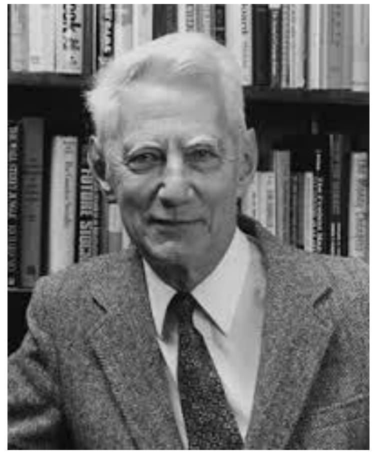
* All the images are taken from Google images

An ADC in Action - Sampling





Bandlimited Signal Sampling: History


1. C. Shannon


2. H. Nyquist


3. E. T. Whittaker


4. J. M. Whittaker

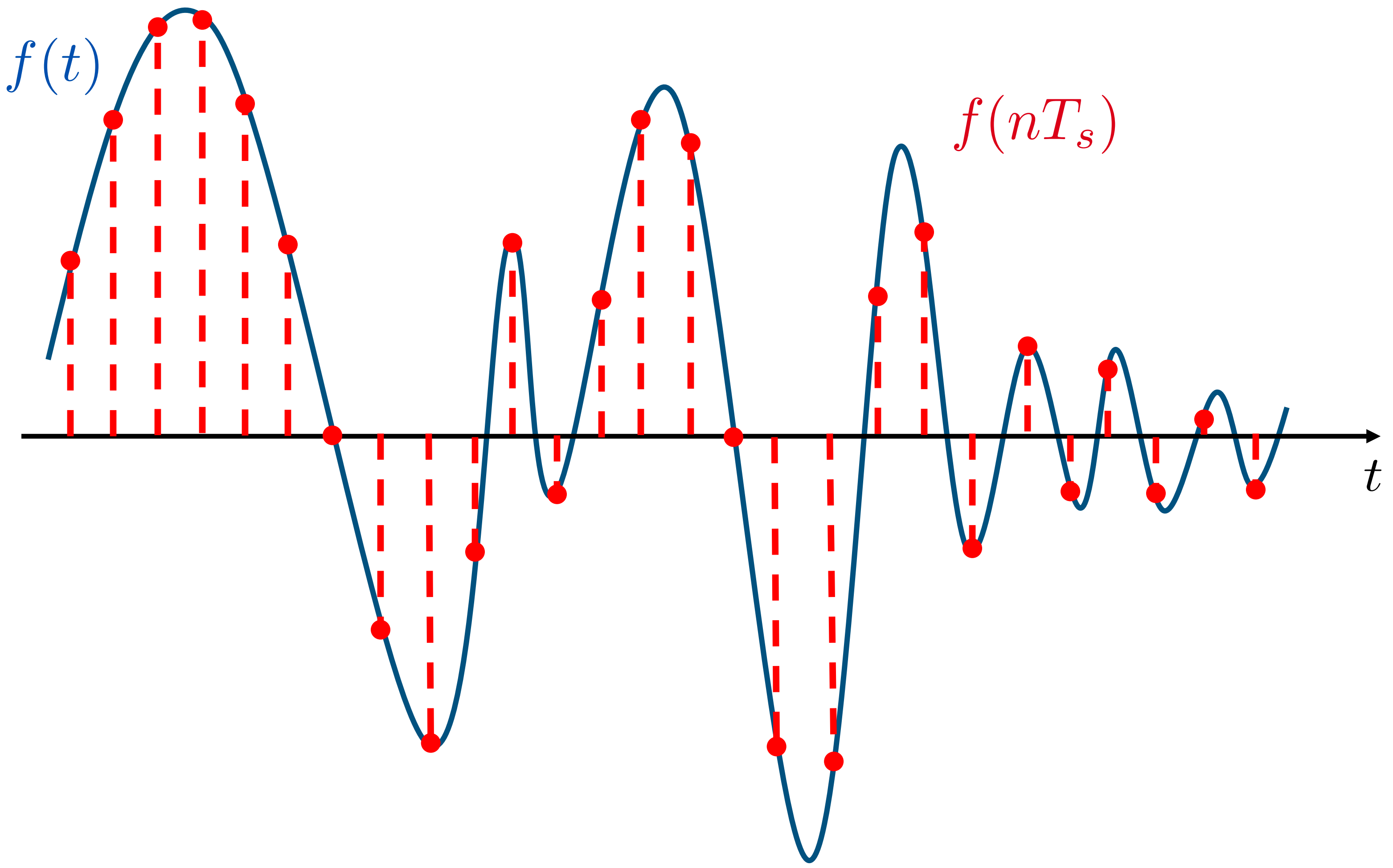

5. V. Kotelnikov

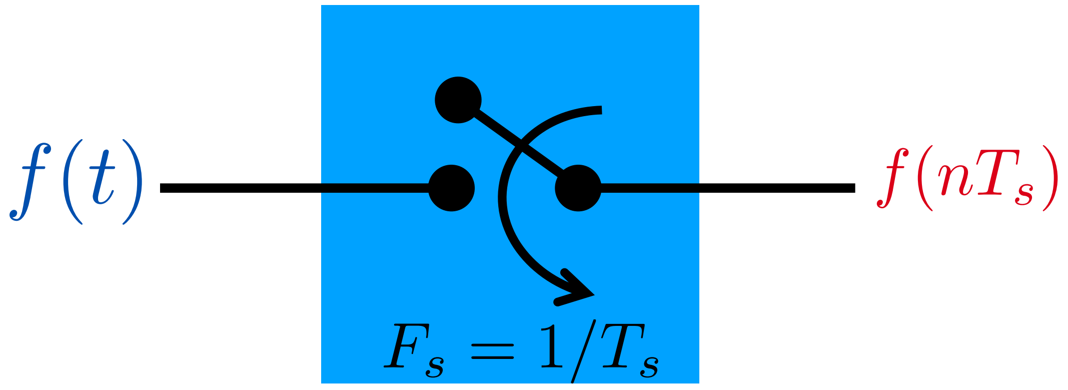

6. K. S. Krishnan

1. Communication in the presence of noise - 1949
2. Certain topics in telegraph transmission theory - 1928
3. Expansion of interpolation theory - 1915
4. Interpolation theory function - 1935
5. On transmission capacity of ‘ether’ and cables in electrical communications - 1933
6. A simple result in quadrature - 1948

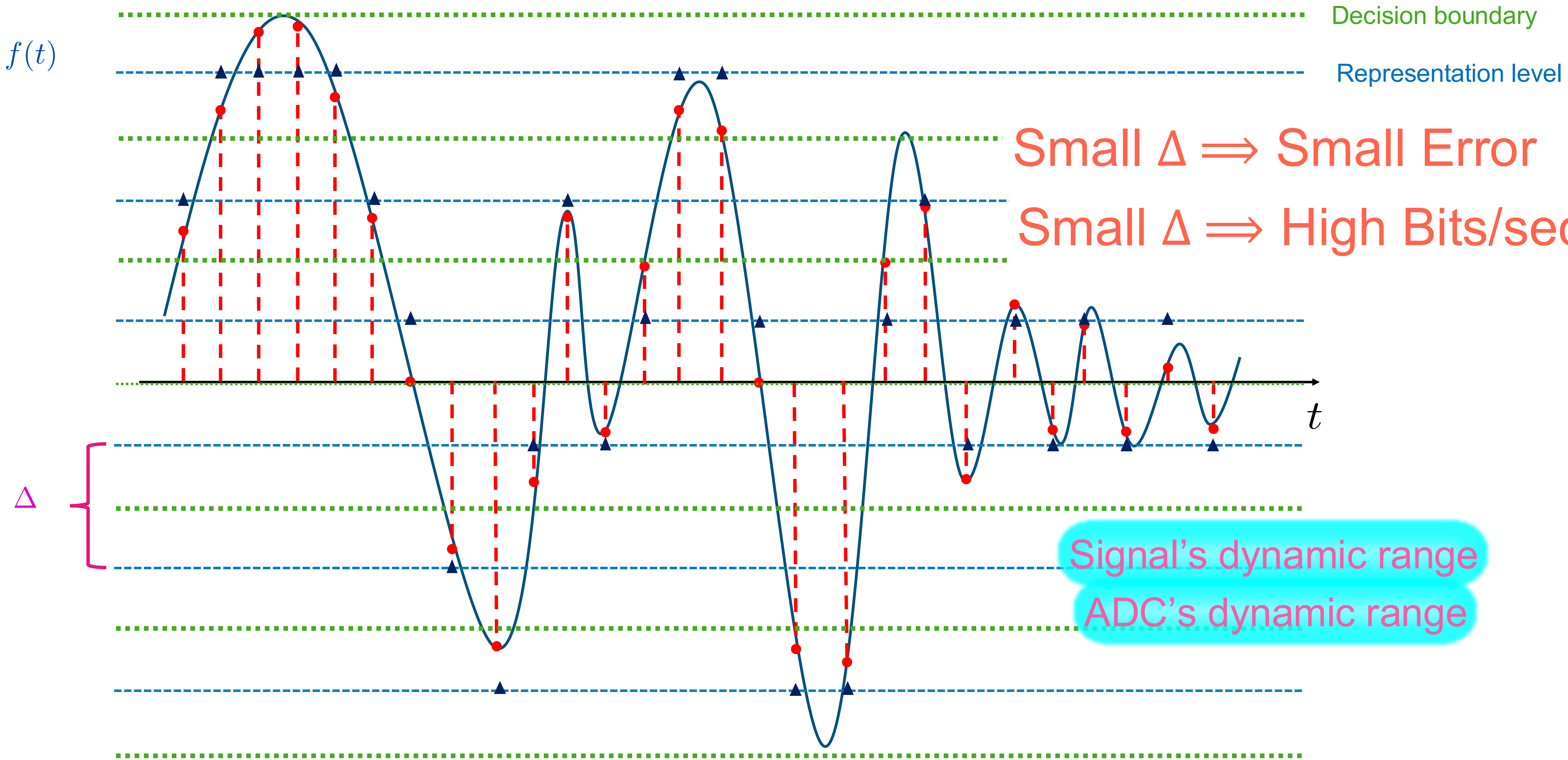
* All the images are taken from http://en.wikipedia.org

An ADC in Action - Quantization





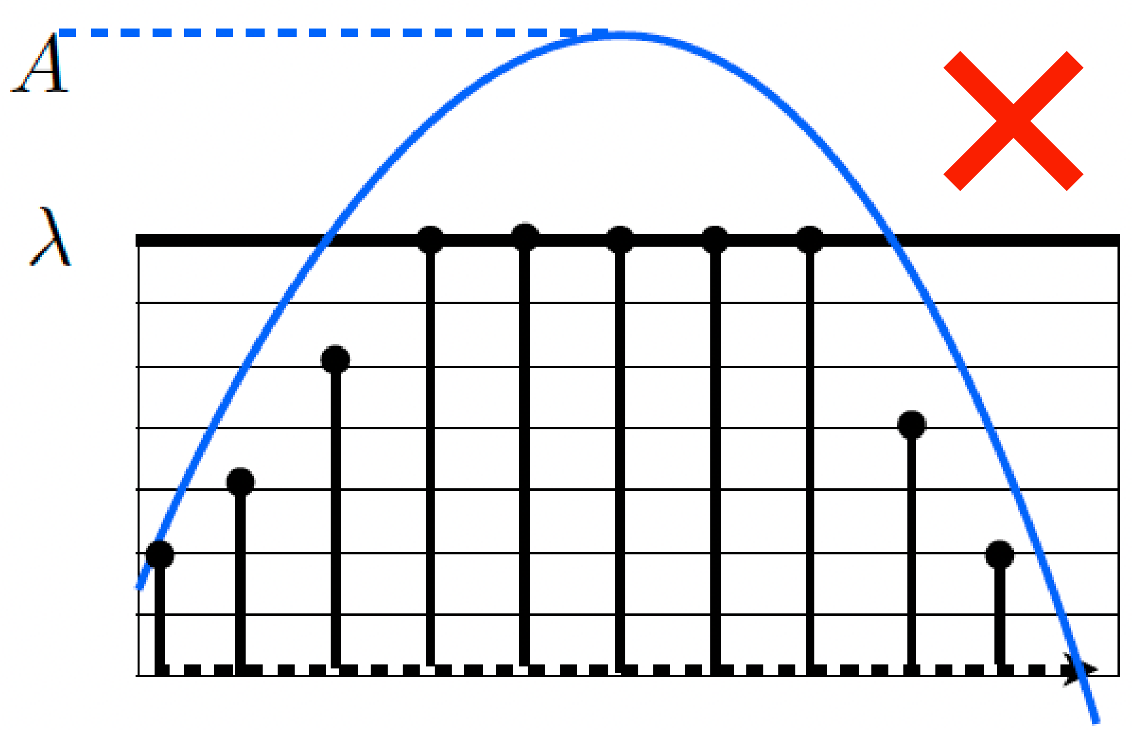
An ADC in Action - Quantization



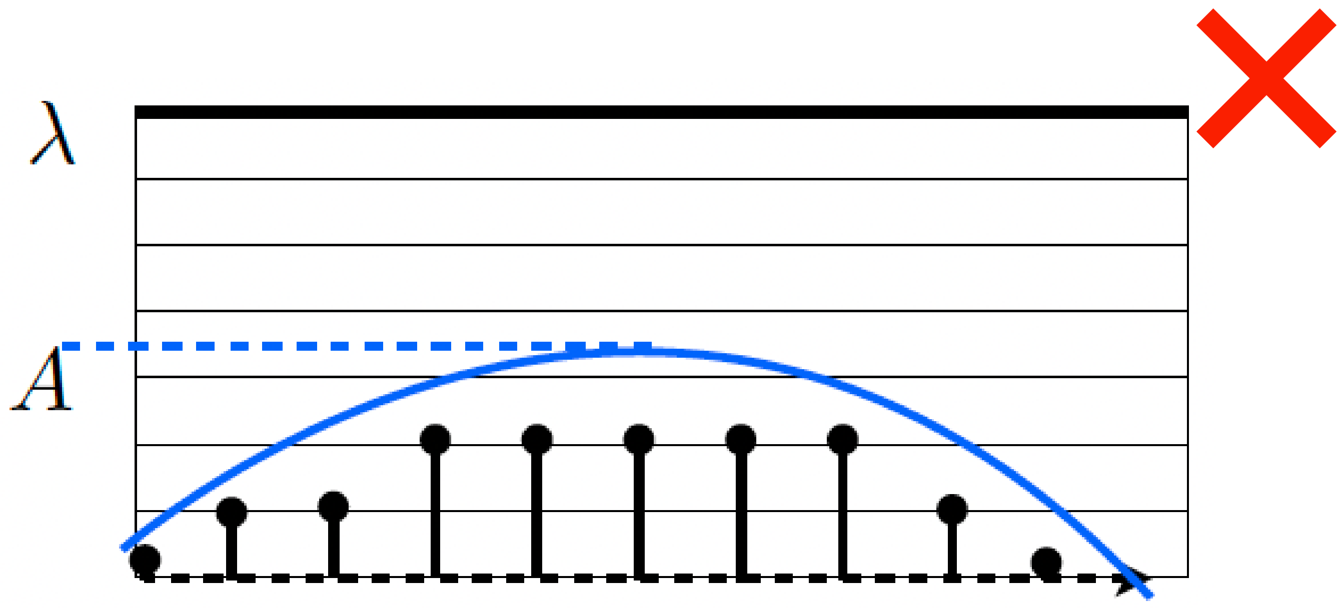
Small $\Delta \Rightarrow$ Small Error

Small $\Delta \Rightarrow$ High Bits/sec

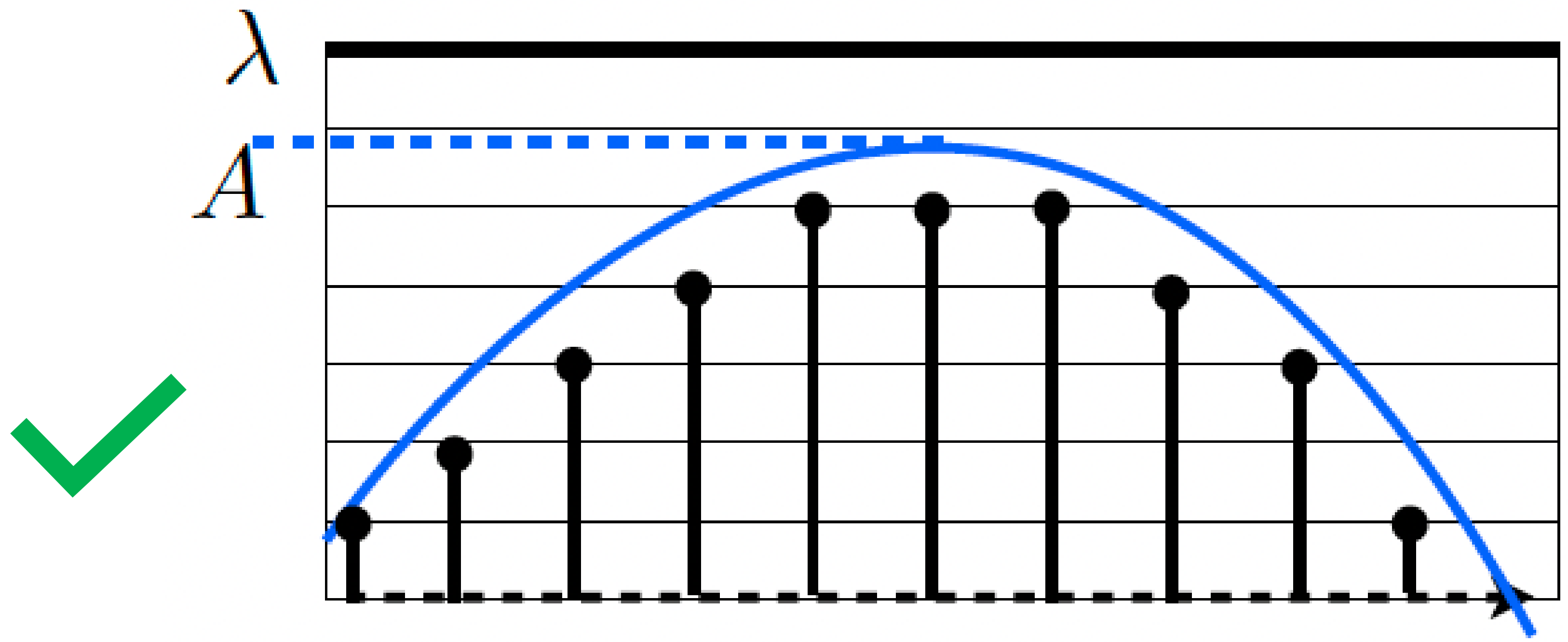
Dynamic Range of an ADC



Clipped



No variation



Desired

Dynamic Range of an ADC

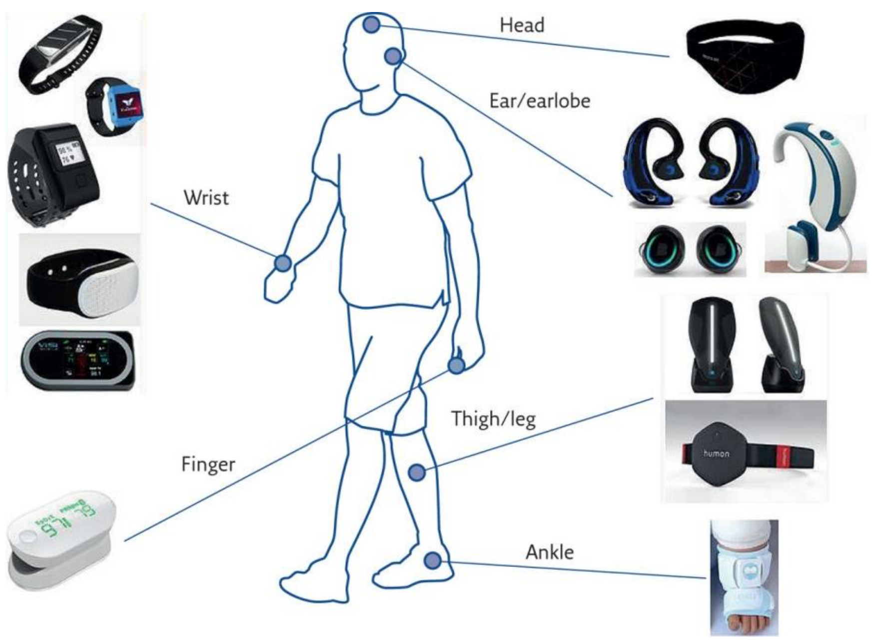
Clipped

Desired

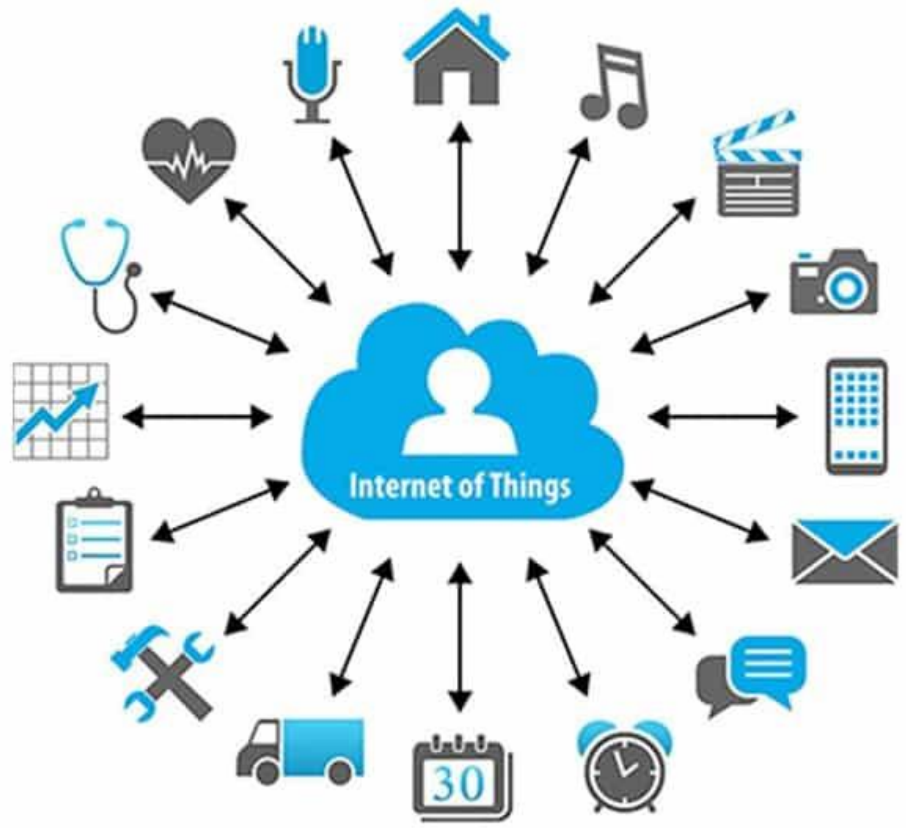
No variation

Power Consumption of an ADC

Power Consumption of an ADC



Wearable bio-medical devices



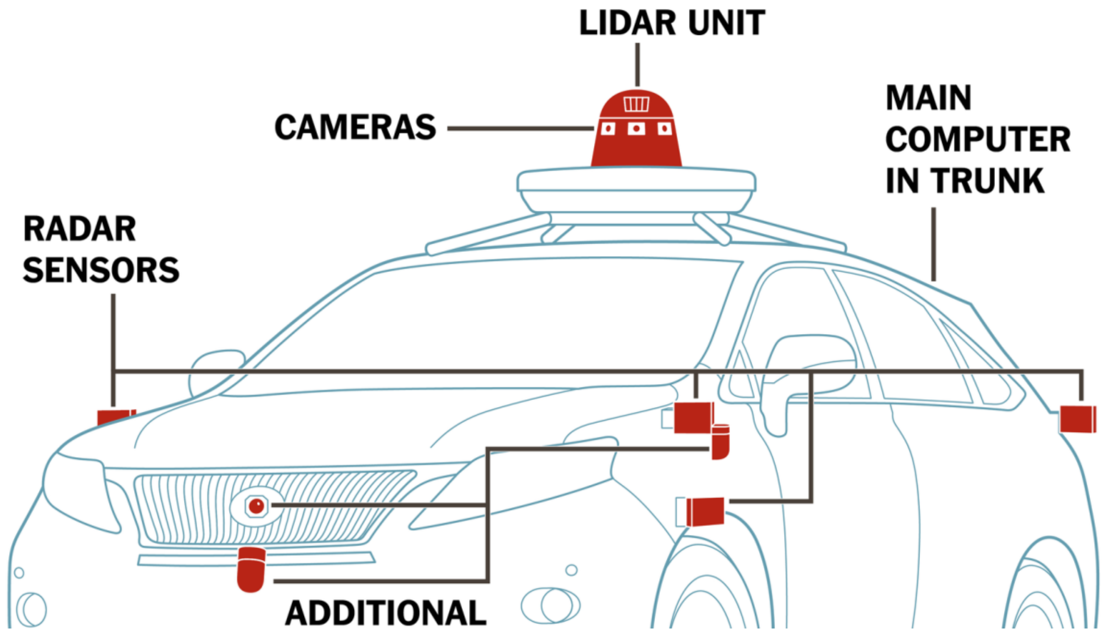
IoT sensors

"Alexa"

"Ok Google"

"Hey Siri"

Voice assisted systems



Autonomous driving system

* All the images are taken from Google images

Low-Power ADCs

Sundstrom et al. IEEE TCS-I,2009

- Sampling rate
- Bits
- Dynamic range

ADC

$$P_{\mathrm{ADC}} \propto f_s \; 2^n$$

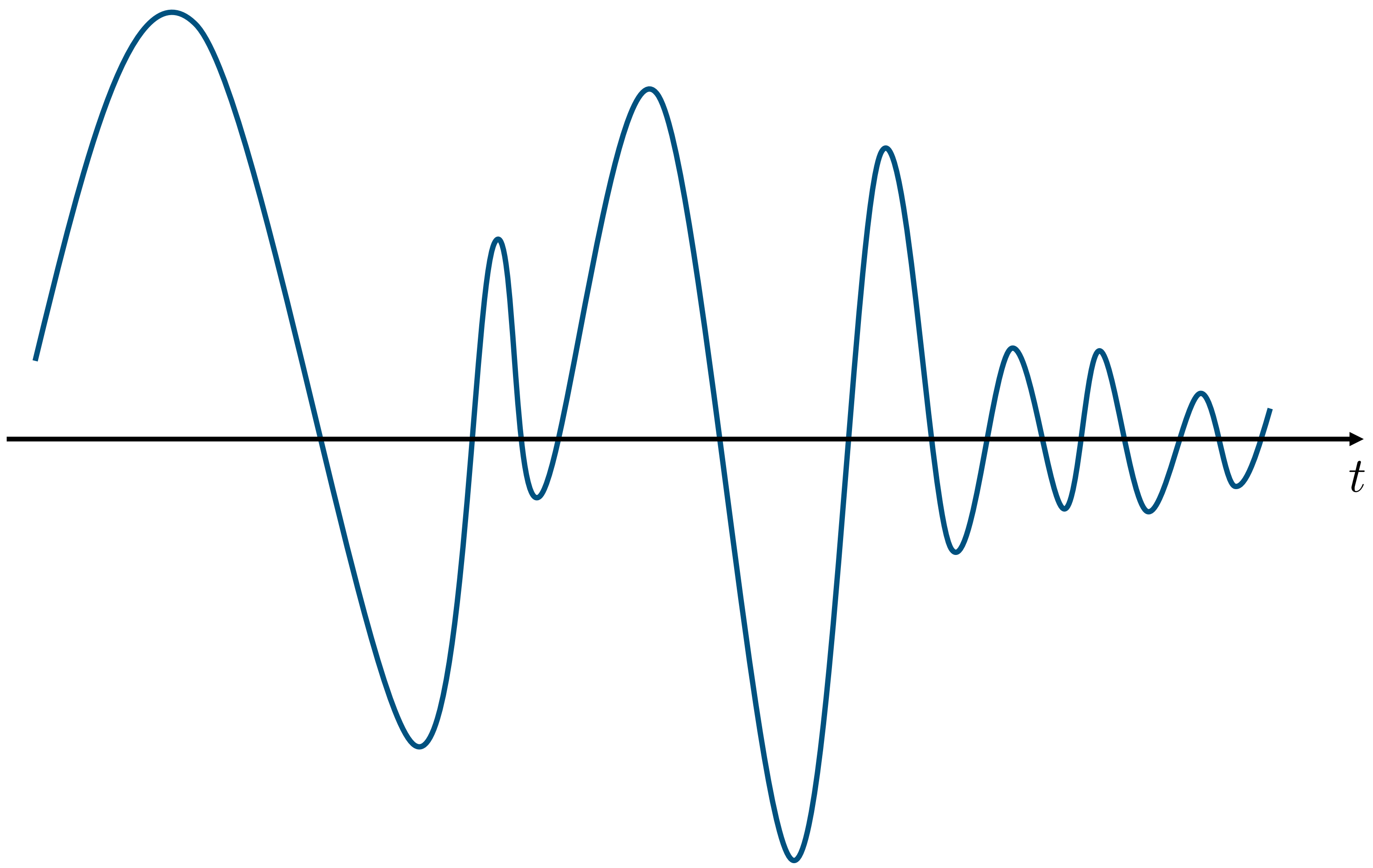
High-dynamic range ADC → Higher #bits for same error

Can we sample a high-dynamic-range signal with a low-DR ADC?

Advantages: Fewer bits – Memory efficiency – Lower power

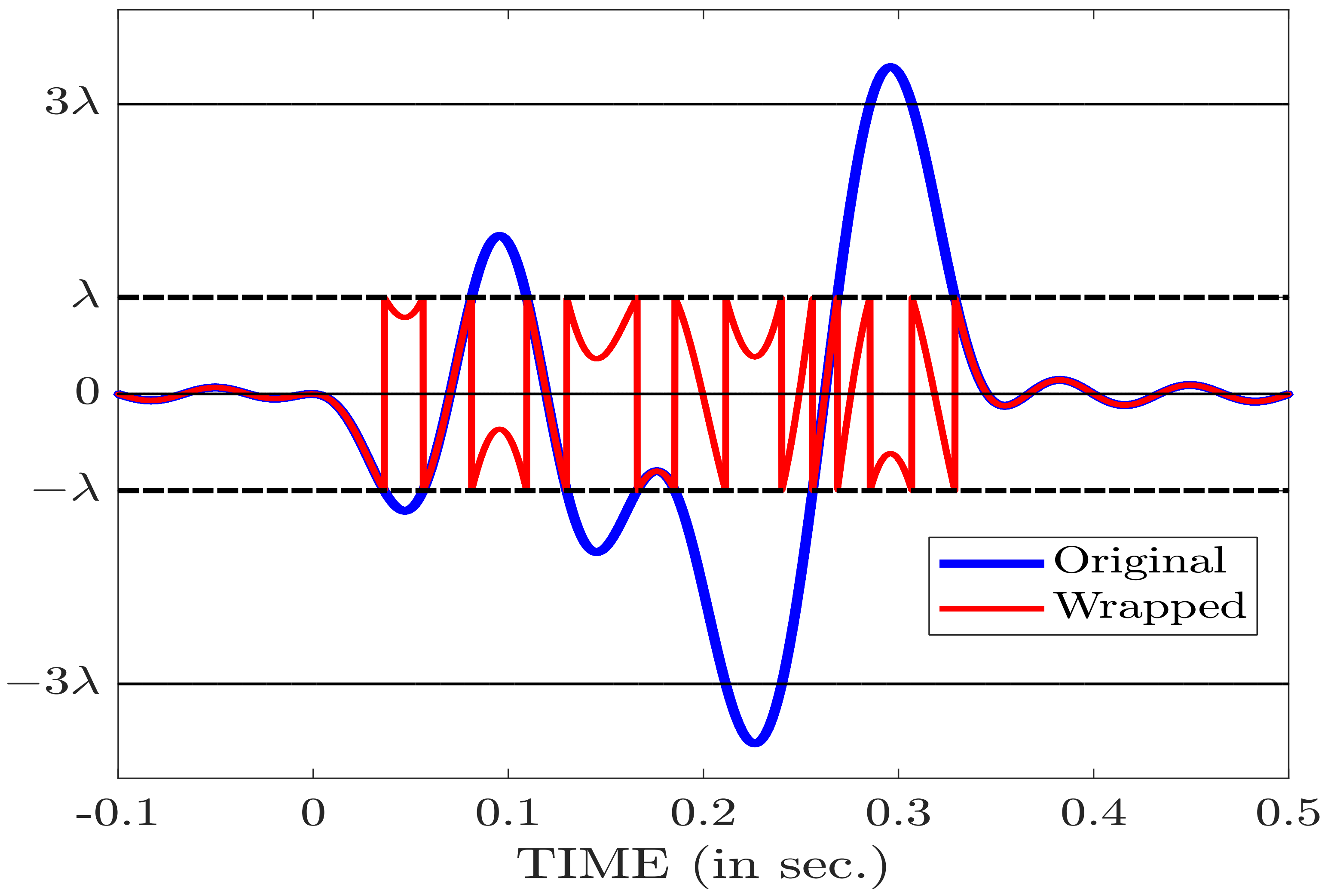
Attenuation?

- Will attenuation helps?
- AGCs?



- Signal variations can be buried under the noise

Unlimited Sampling or Modulo ADC



On unlimited sampling

Publisher: IEEE Cite This PDF

Ayush Bhandari ; Felix Krahmer ; Ramesh Raskar **All Authors**

Abstract

Document Sections

I. Introduction

II. Self-Reset ADC and Modulo Samples

III. A Sufficiency Condition and a Sampling Theorem

IV. Conclusions

Appendix Proof of Proposition 1

Show Full Outline ▾

Authors

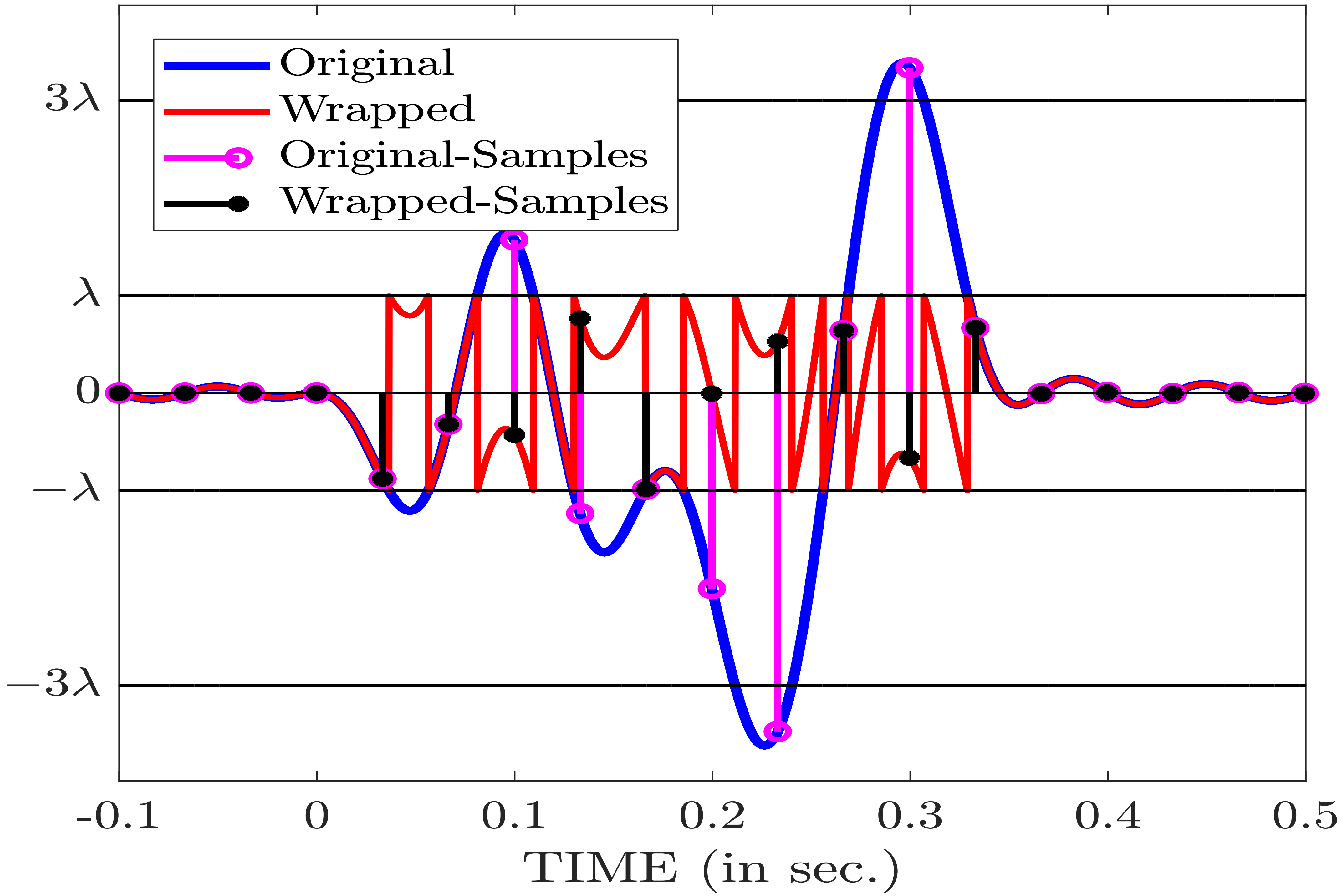
Figures

Abstract:
Shannon's sampling theorem provides a link between the continuous and the discrete realms stating that bandlimited signals are uniquely determined by its values on a discrete set. This theorem is realized in practice using so called analog-to-digital converters (ADCs). Unlike Shannon's sampling theorem, the ADCs are limited in dynamic range. Whenever a signal exceeds some preset threshold, the ADC saturates, resulting in aliasing due to clipping. The goal of this paper is to analyze an alternative approach that does not suffer from these problems. Our work is based on recent developments in ADC design, which allow for ADCs that reset rather than to saturate, thus producing modulo samples. An open problem that remains is: Given such modulo samples of a bandlimited function as well as the dynamic range of the ADC, how can the original signal be recovered and what are the sufficient conditions that guarantee perfect recovery? In this paper, we prove such sufficiency conditions and complement them with a stable recovery algorithm. Our results are not limited to certain amplitude ranges, in fact even the same circuit architecture allows for the recovery of arbitrary large amplitudes as long as some estimate of the signal norm is available when recovering. Numerical experiments that corroborate our theory indeed show that it is possible to perfectly recover function that takes values that are orders of magnitude higher than the ADC's threshold.

Published in: 2017 International Conference on Sampling Theory and Applications (SampTA)

Date of Conference: 3-7 July 2017 **INSPEC Accession Number:** 17154325

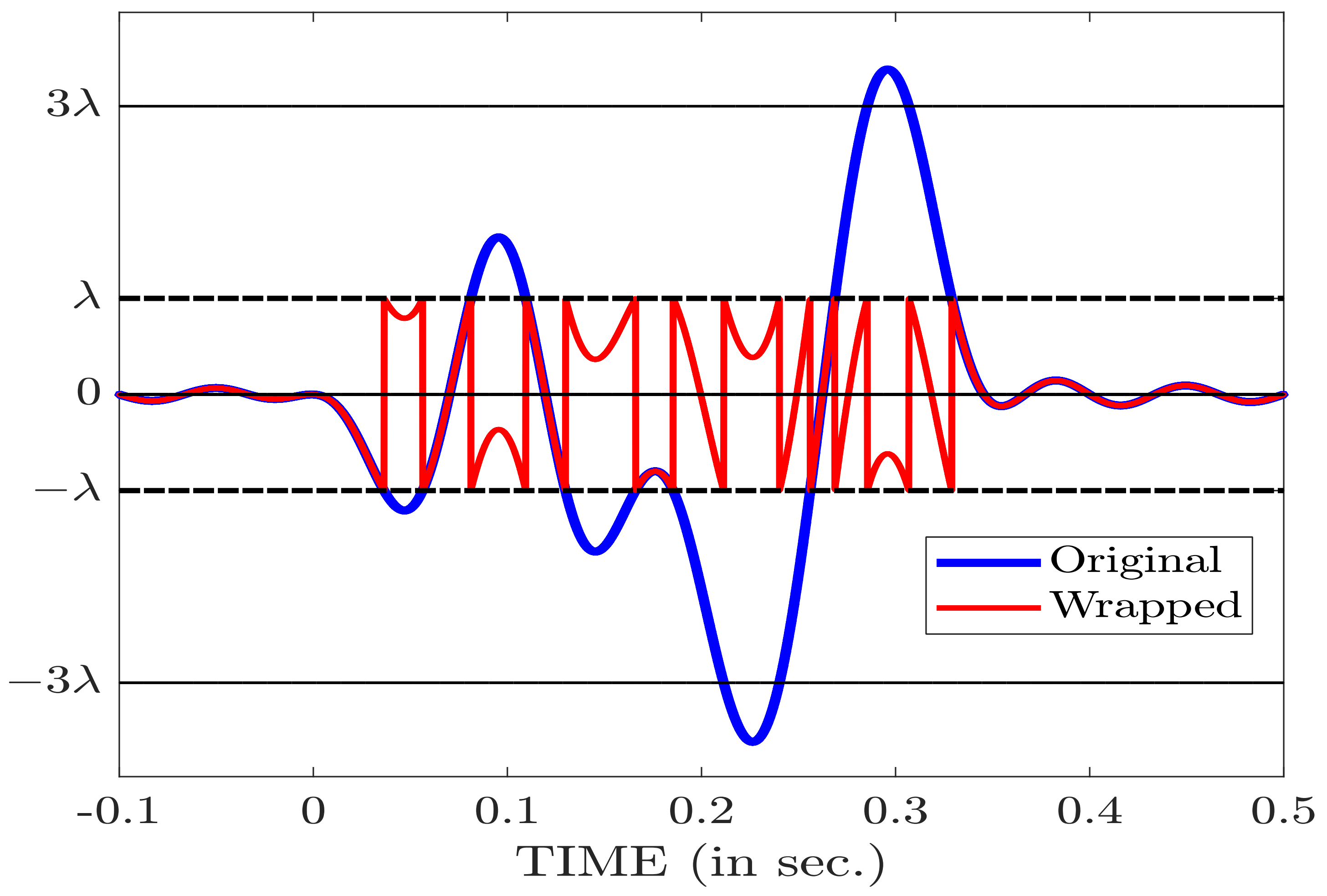
Unlimited Sampling or Modulo ADC

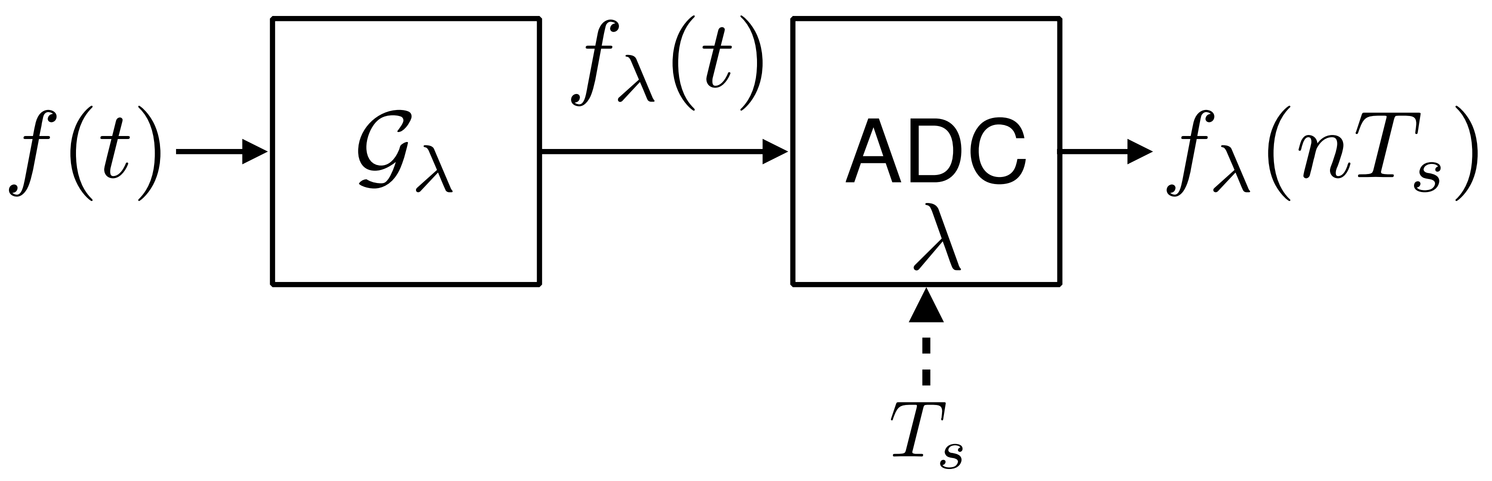


5 mod 3 = 2

12 mod 3 = 0

Unlimited Sampling or Modulo ADC





It solves our problem!

1. How to recover original signal from the folded samples?
2. Do we need to sample above the Nyquist rate?

Unfolding Algorithm

Get these   From these

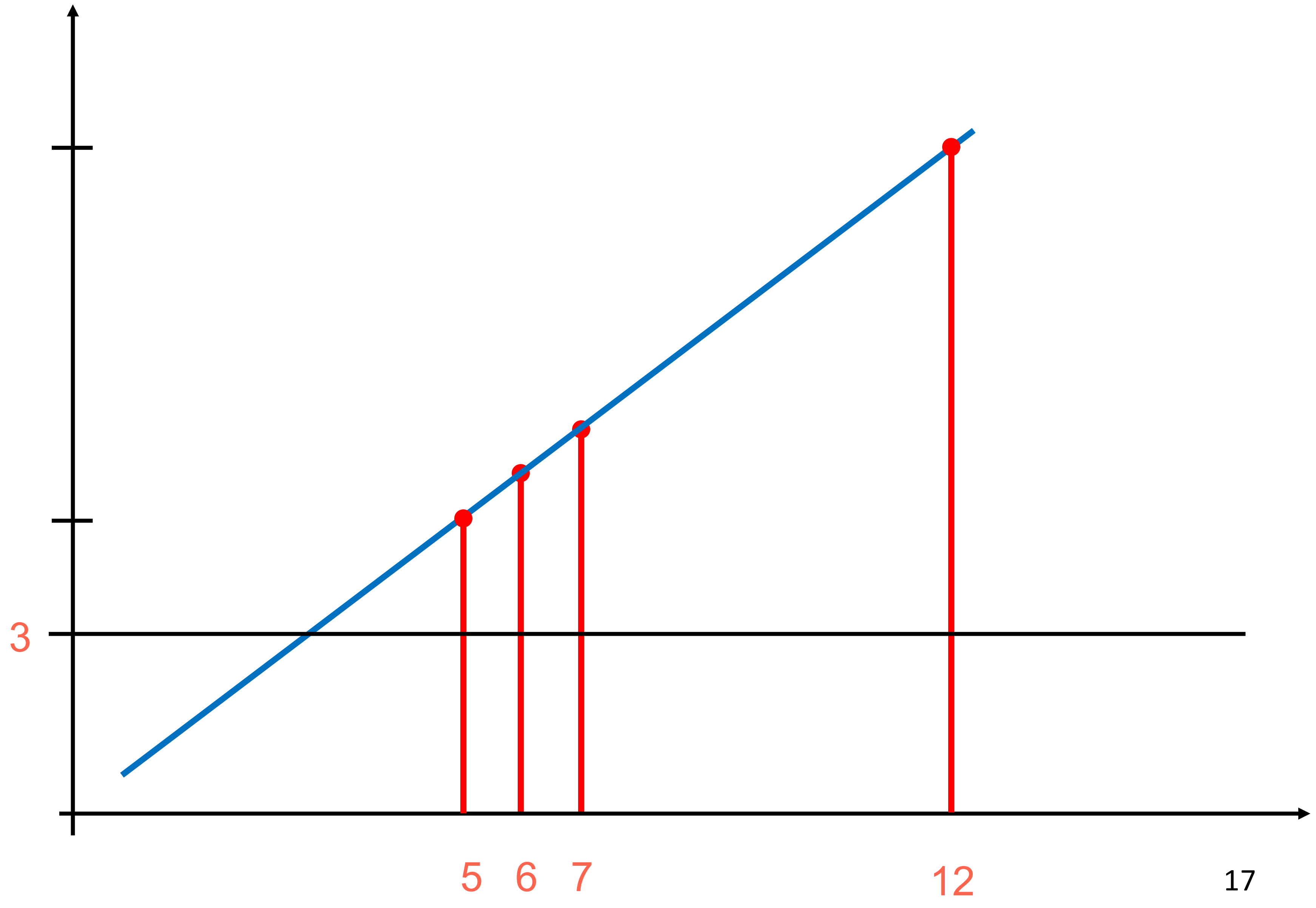
5 mod 3 = 2

6 mod 3 = 0

7 mod 3 = 1

12 mod 3 = 0

If we assume that the signal samples are not changing significantly, then we can recover unfolded samples up to a constant factor



Difference-Based Unfolding

Recover original samples up to a constant factor if $|f((n+1)T_s) - f(nT_s)| \leq \lambda$

The corresponding sampling rate could be much higher than the Nyquist rate

On unlimited sampling and reconstruction [PDF] arxiv.org

A Bhandari, F Krahmer, R Raskar - IEEE Transactions **on** Signal …, 2020 - ieeexplore.ieee.org

… When we think of **sampling** theory, in most cases, variation **on** the theme arises from … or **sampling** architecture (uniform or non-uniform **sampling** grid). **On** the other hand, a hypothesis **on** …

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On unlimited sampling [PDF] arxiv.org

A Bhandari, F Krahmer, R Raskar - … Conference **on Sampling** …, 2017 - ieeexplore.ieee.org

… only relevant for the **reconstruction**. Hence only then, a bound for the supremum norm of the signal is required, the ADC itself is truly **unlimited** in that T does not depend **on** g and hence …

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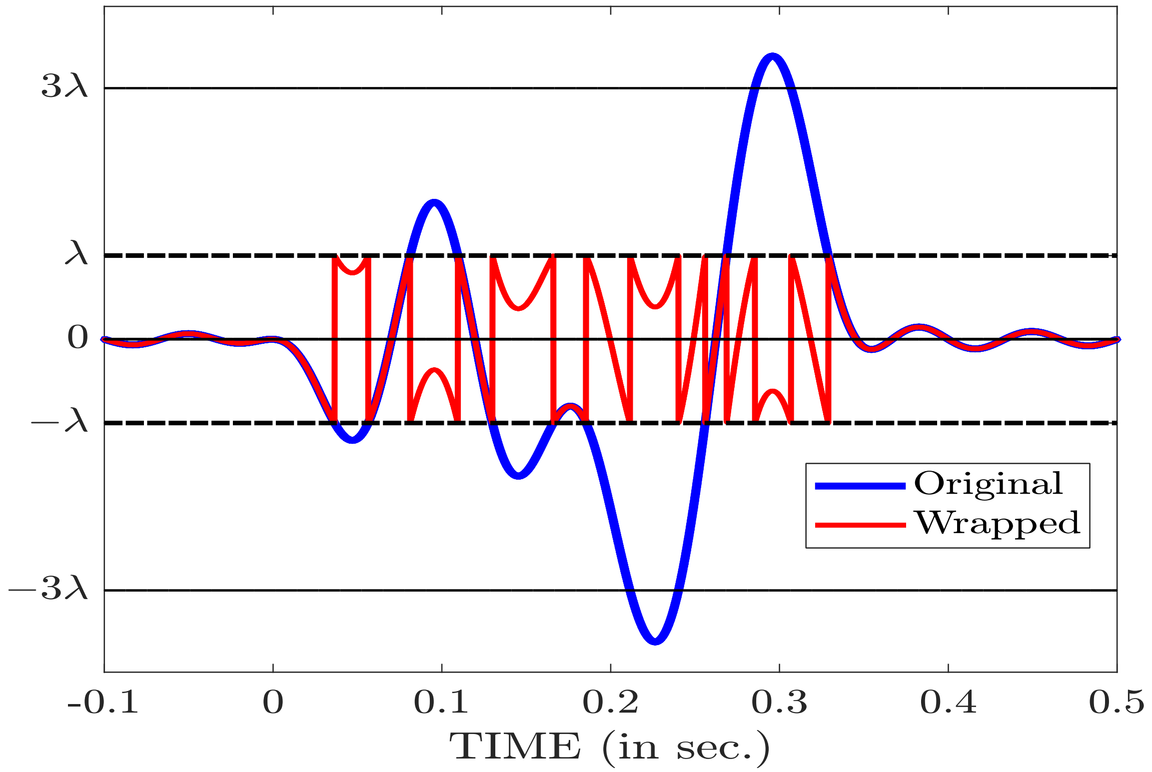
OF$\geq$ 17

A Comparison



OF should be small

	Dynamic range	Sampling rate	# bits	Bit rate	Power
Conventional ADC	$[-A, A]$	$f_s \geq f_{Nyq}$	N_A	$N_A \; f_{Nyq}$	$f_{Nyq} \, 2^{N_A}$
Modulo ADC	$[-\lambda, \lambda]$	$OF \;\; f_{Nyq}$	$N_\lambda = N_A \; \dfrac{\lambda}{A}$	$\dfrac{\lambda}{A} OF \; N_A \; f_{Nyq}$	$OF \;\; f_{Nyq} \; (2^{N_A})^{\lambda/A}$

Follow Up Works

IEEE SIGNAL PROCESSING LETTERS, VOL. 26, NO. 8, AUGUST 2019

Above the Nyquist Rate, M
Folding Does Not Hu

WAVELET-BASED RECONSTRUCTION FOR UNI

Sunil Rudresh, Aniruddha Adiga, B

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Indian Institute o
Email: {sunilr, aaniruddha,

Journals & Magazines > IEEE Transactions on Signal P... > Volume: 70

The Surprising Benefits of Hysteresis in Unlimited Sampling: Theory, Algorithms and Experiments

Publisher: IEEE | Cite This | PDF

Dorian Florescu ; Felix Krahmer ; Ayush Bhandari ; All Authors

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Unlimited Sampling From Theory to Practice: Fourier-Prony Recovery and Prototype ADC

Publisher: IEEE | Cite This | PDF

Ayush Bhandari ; Felix Krahmer ; Thomas Poskitt All Authors

20 Cites in Papers | 915 Full Text Views

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he lowest number of sa

Robust Unlimited

Eyar Azar, Satish Mulleti, Yonina C. Eldar

Analog to digital converters (ADCs) act as a bridge between the analog and digita
It is also desired that the signals' dynamic range should be within that of the ADC
signal from the samples of the nonlinear operator, either high sa
flexible nonlinear operator which is sampling efficient. Moreover,
nonlinear samples of the proposed operator when sampled above
error while recovering the signal for a given sampling rate, noise
the lowest rate possible.

A hardware prototype of wideband high-dynamic range analog-to-digital converter

Satish Mulleti, Eliya Reznitskiy, Shlomi Savariego, Moshe Namer, Nimrod Glazer, Yonina C. Eldar

First published: 26 June 2023 | https://doi.org/10.1049/cds2.12156

Hardware Prototype

Unlimited Dynamic Range Analog-to-Digital Conversion

Adithya Krishna*, Sunil Rudresh*, Vishal Shaw*, Hemanth Reddy Sabbella, Chandra Sekhar Seelamantula, *Senior Member, IEEE*, and Chetan Singh Thakur, *Senior Member, IEEE*

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Unlimited Sampling From Theory to Practice: Fourier-Prony Recovery and Prototype ADC

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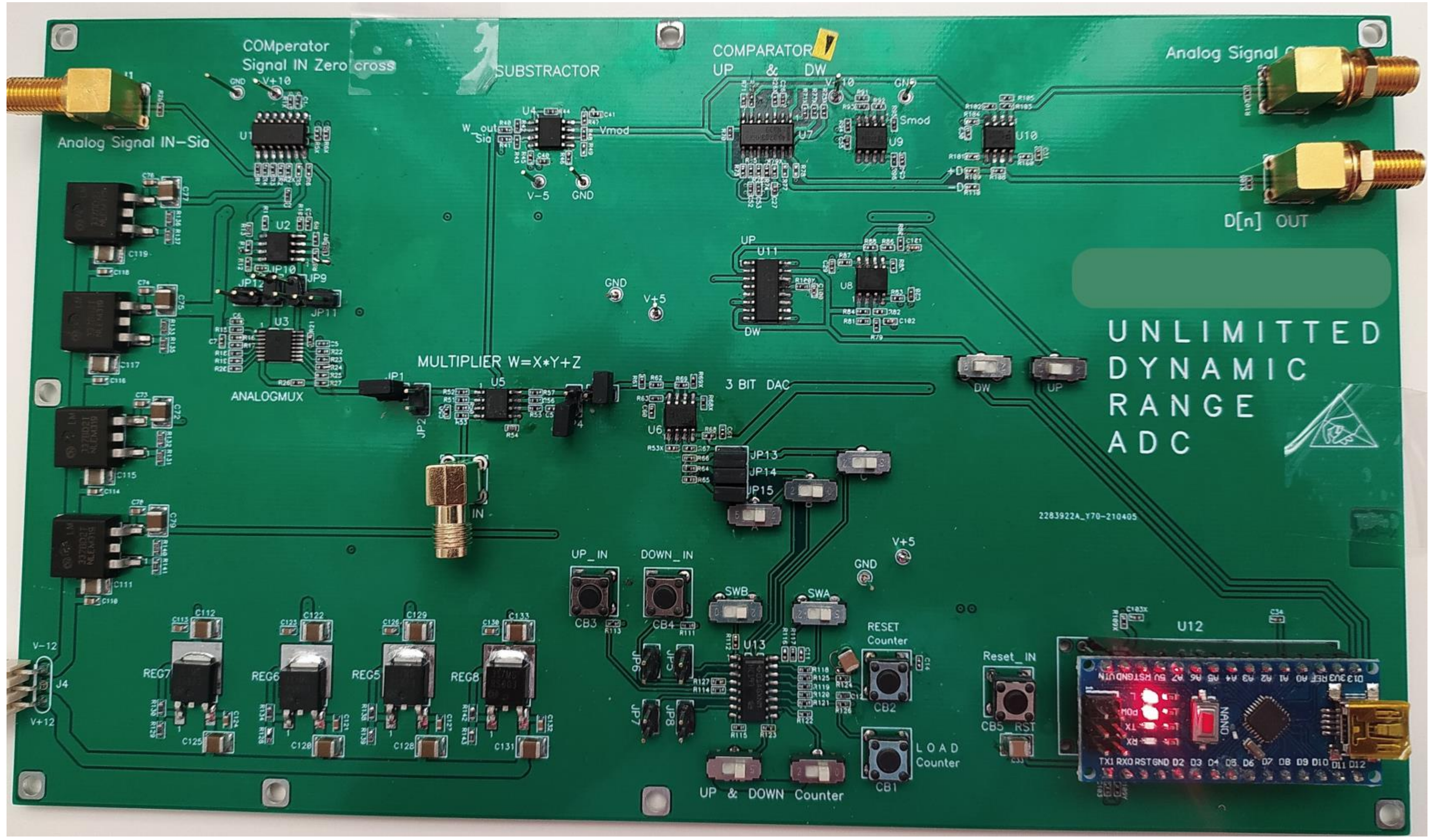
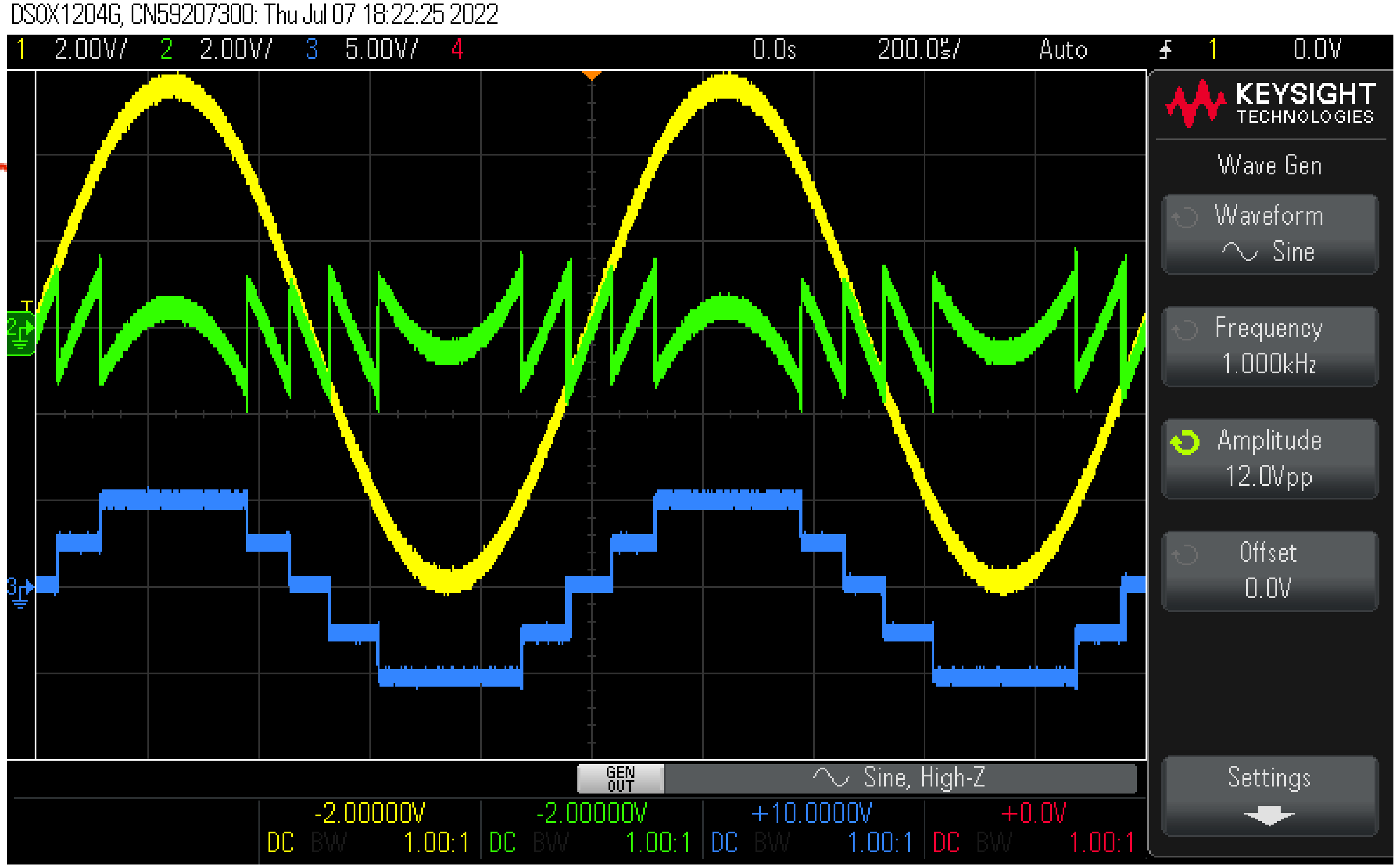
Hardware Prototype





A hardware prototype of wideband high-dynamic range analog-to-digital converter

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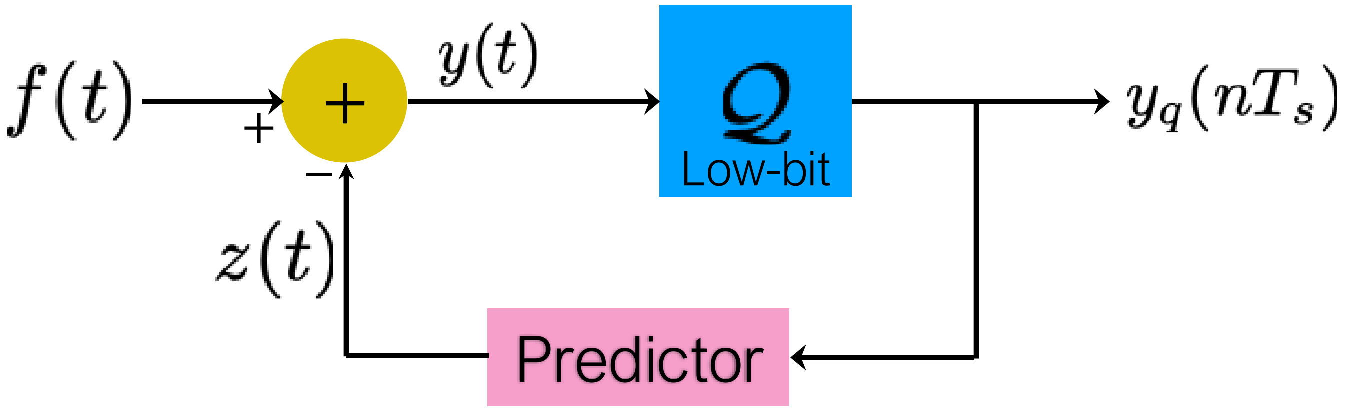
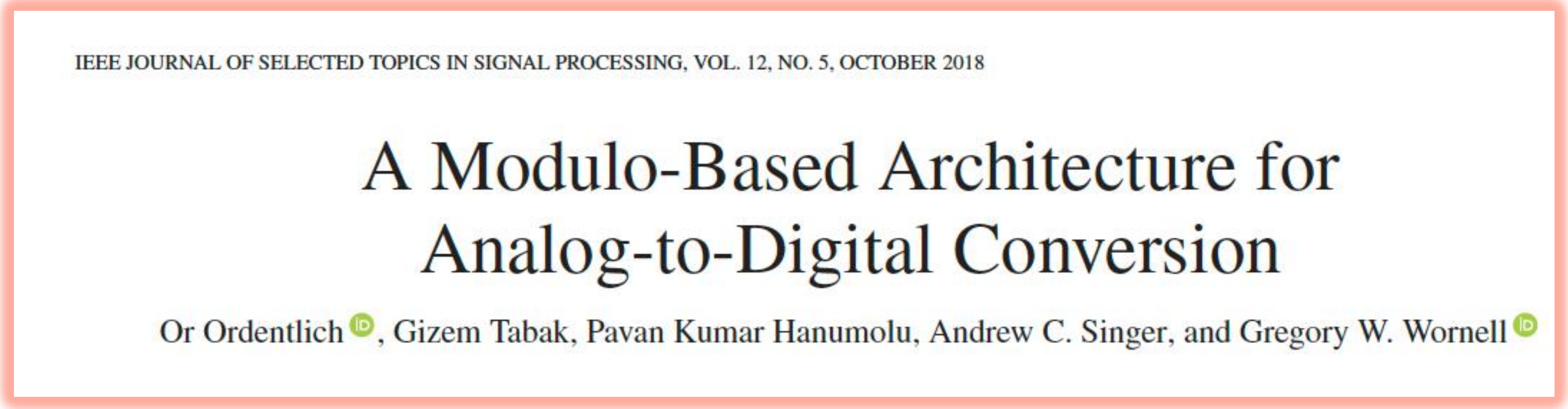
Oversampling – Low DR – A Well Known Concept?

- Delta modulation, Sigma-Delta, differential pulse code modulation, and more



- Lowpass-filter-based decoding

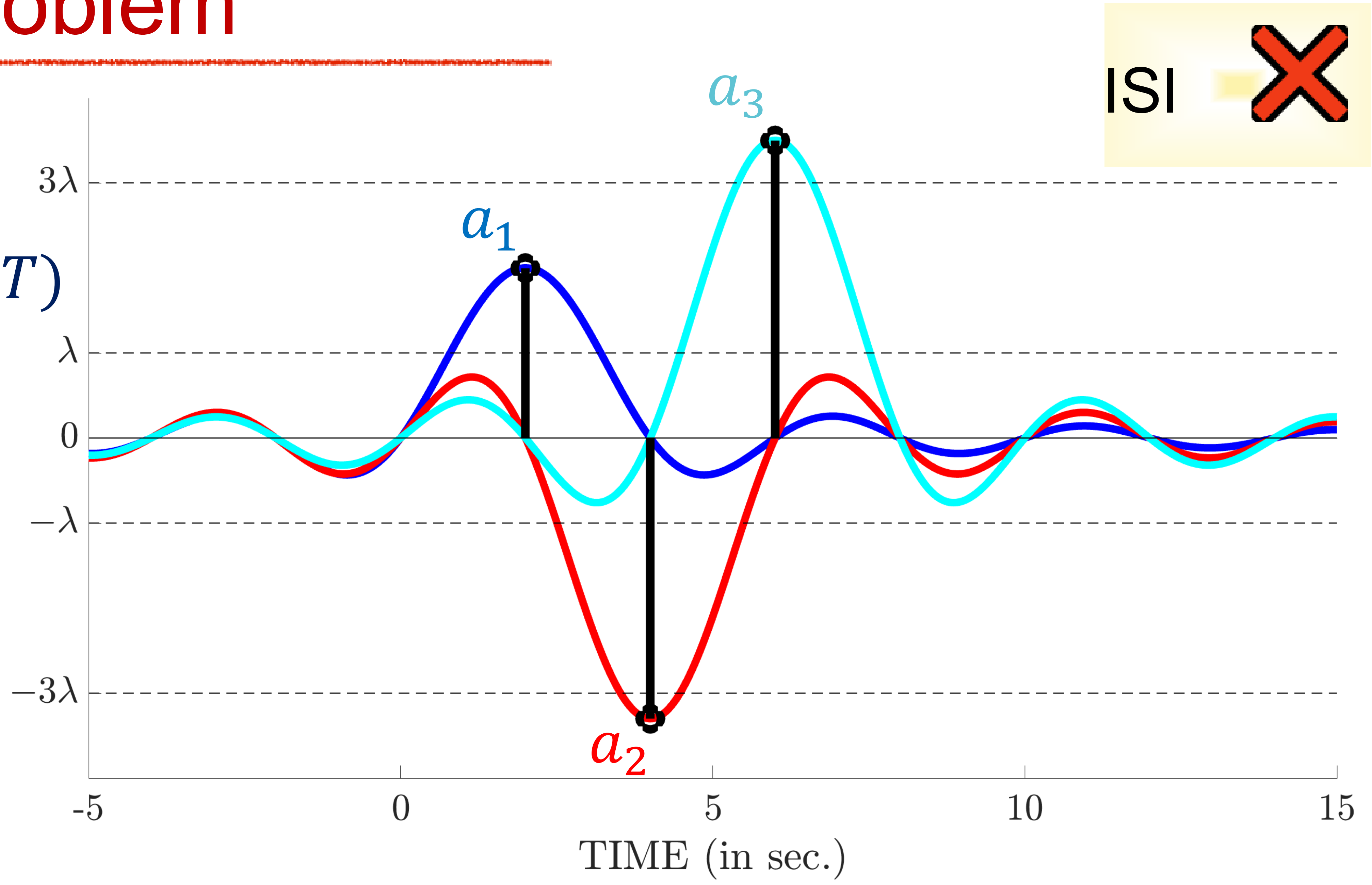

IEEE JOURNAL OF SELECTED TOPICS IN SIGNAL PROCESSING, VOL. 12, NO. 5, OCTOBER 2018

A Modulo-Based Architecture for Analog-to-Digital Conversion

Or Ordentlich, Gizem Tabak, Pavan Kumar Hanumolu, Andrew C. Singer, and Gregory W. Wornell

Digital-Communication Problem

- Rx signal: $f(t) = \sum_{k=1}^{K} a_k \, g(t - kT)$



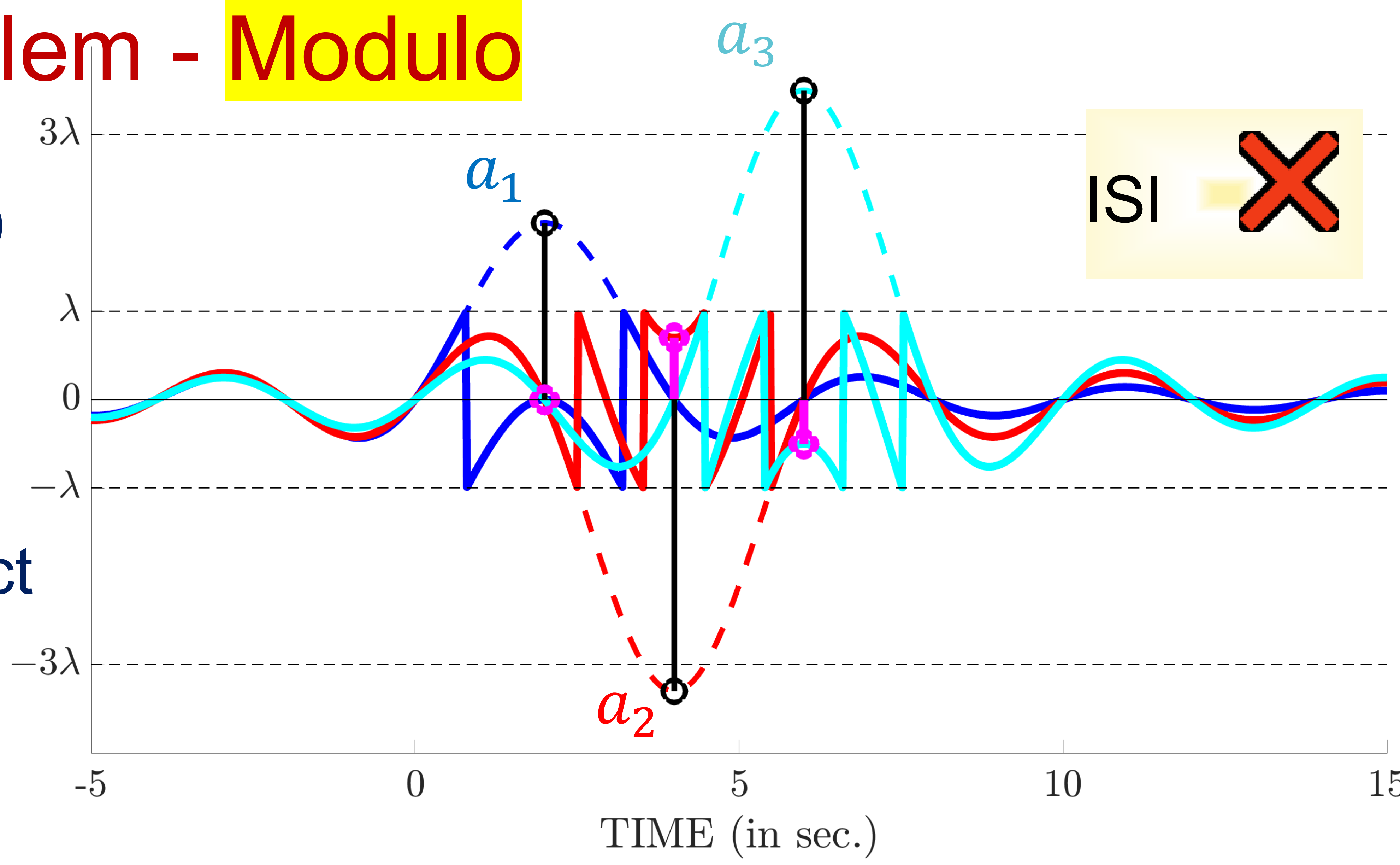
- Sample @ the symbol rate $\frac{1}{T}$ & detect

*In collaboration with K. Appaiah and S. B. Pillai

Digital-Communication Problem - Modulo

- Rx signal: $f(t) = \sum_{k=1}^{K} a_k \, g(t - kT)$

- Sample @ the symbol rate $\frac{1}{T}$ & detect



?

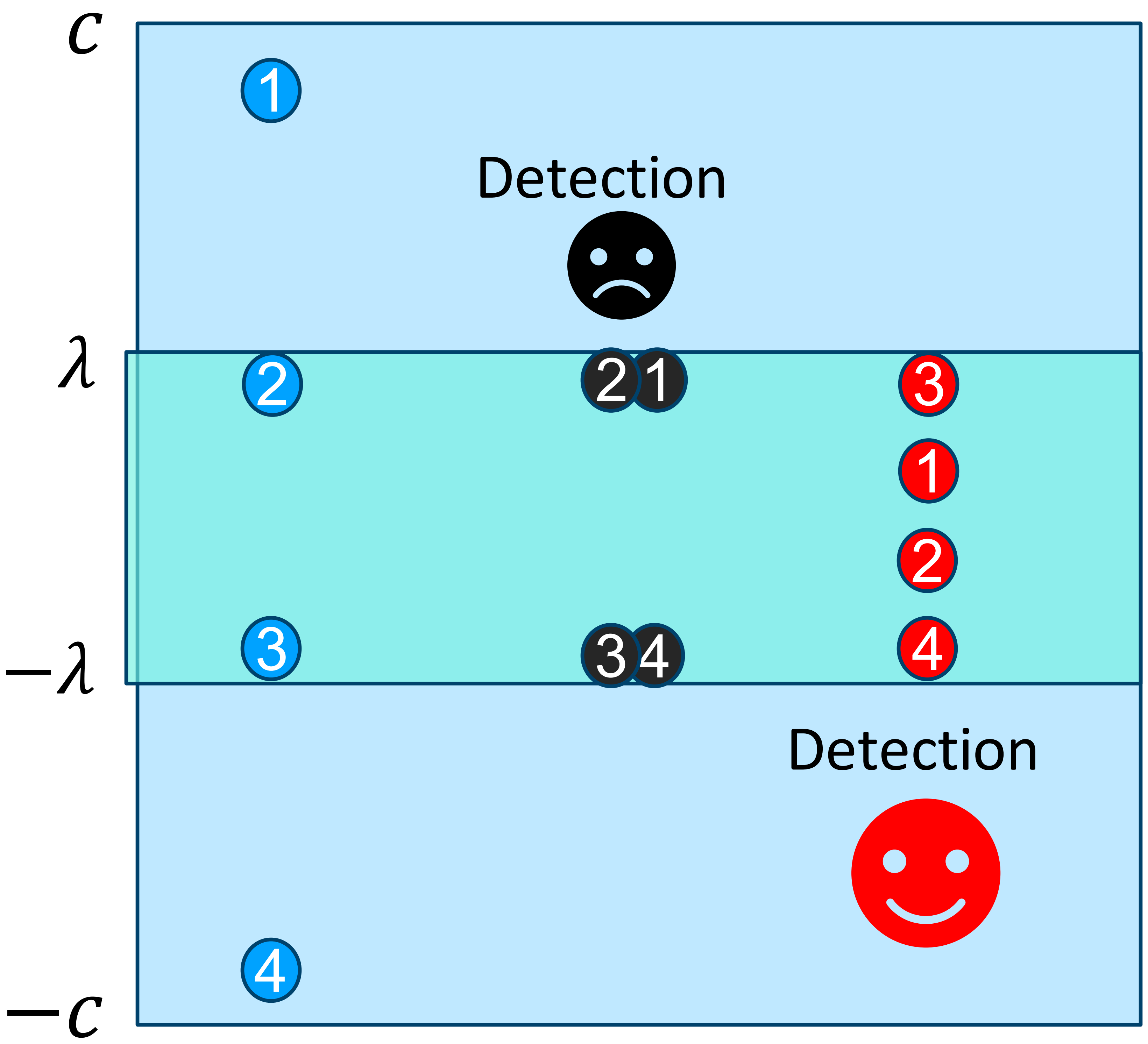
- Oversample → Unfold → Detect

Results in higher quantization error for fixed bits

*Liu et. al, "λ–MIMO: Massive MIMO via modulo sampling," IEEE Trans. Comm., 2023

Digital-Communication Problem - Modulo

- Rx signal: $f(t) = \sum_{k=1}^{K} a_k \, g(t - kT)$
- 2-ary PAM constellation: 1 2 3 4
- Folded-constellation: 1 2 3 4
- Folded-constellation: 1 2 3 4



Our Work - Detection Without Unfolding

- Rx signal: $f(t) = \sum_{k=1}^{K} a_k \, g(t - kT)$

- Derived conditions for uniqueness after folding

- Sampling at the symbol rate

- With quantization noise – same performance as conventional ADC

Performance Comparison - Detection Without Unfolding

TABLE I

PROBABILITY OF SYMBOL ERROR (IN %) FOR 3 & 6 BIT QUANTIZATION

SNR(in dB)—Bits	10-3	20-3	25-3	10-6	20-6	25-6
Conventional	4.5	0	0	1	0	0
Unfolding	76	75	32	74	67	1.6
Wrapped	62	11	0.8	61	1.6	0.5

Higher error & oversampling

Takeaway
NO
Oversampling & Unfolding

Similar performances

In Conclusion

- ADC’s power consumption can not be ignored
- Reduce the sampling rate, bits, and the dynamic range
- Modulo-folding can be used to represent high-DR data using fewer bits
- Unfolding is sampling inefficient – but can be avoided in some cases
- Of course, learning-based algorithms are developed for unfolding

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