Paolo Carbone

- IMEKO
- Sustainability in Electronics

Dipartimento di Ingegneria, Università degli Studi di Perugia

METROLOGIA 2025

30 anos SBM

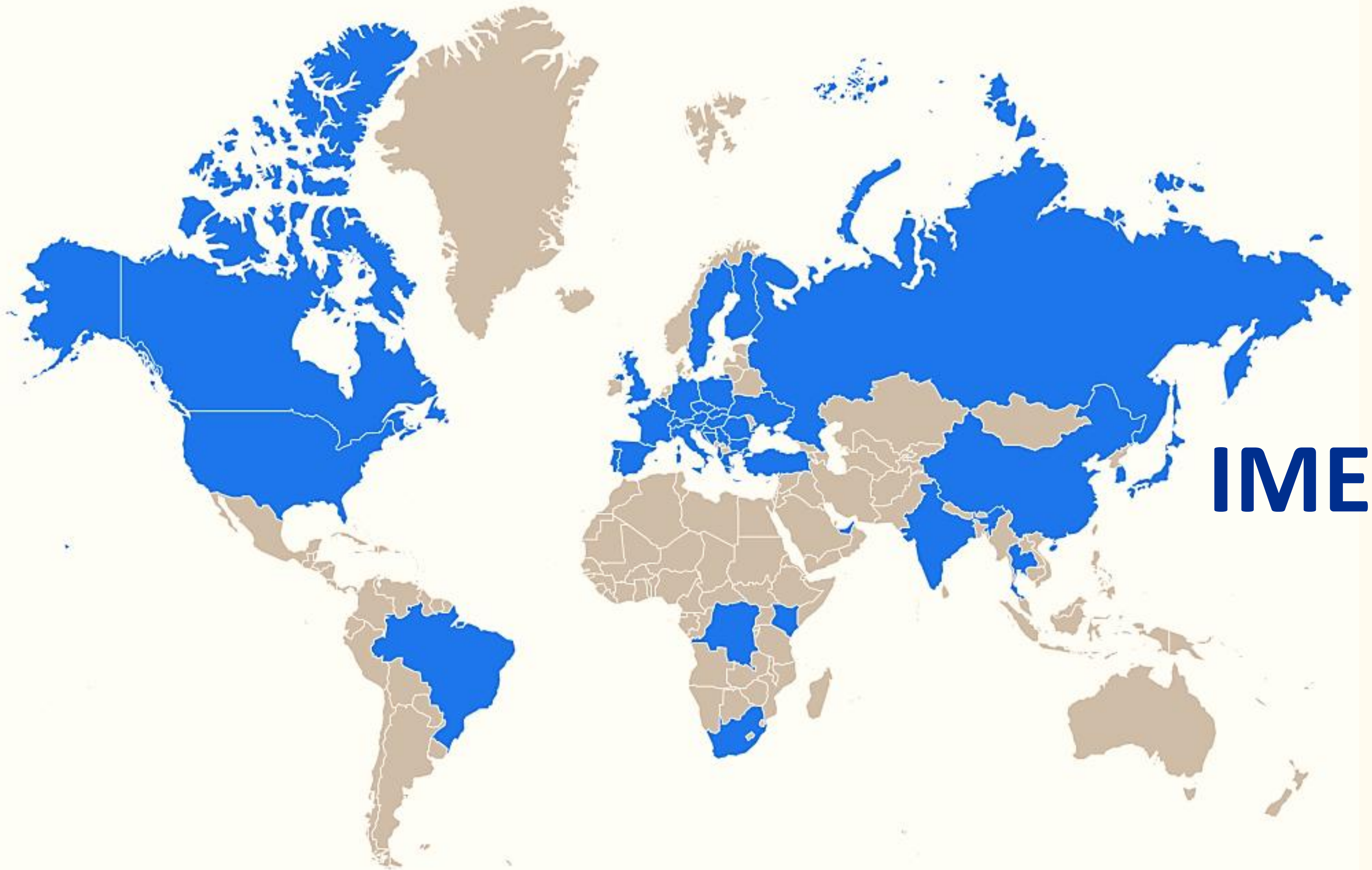
150 anos de confiabilidade para um futuro sustentável

1-4 December Brazil

WITH IMEKO PRESENCE

IMEKO

International Measurement Confederation



IMEKO in 2025

www.imeko.org

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IMEKO President

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Chairperson of the
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of IMEKO

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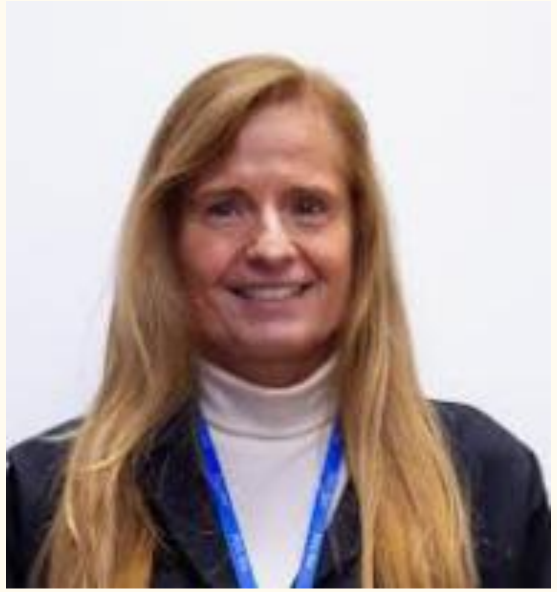

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External Relations

IMEKO Technical Committees

- TC1 – Education and Training in Measurement and Instrumentation
- TC2 – Photonics
- TC3 – Measurement of Force, Mass, Torque, and Gravity
- TC4 – Measurement of Electrical Quantities
- TC5 – Hardness Measurement
- TC6 – Digitalization
- TC7 – Measurement Science
- TC8 – Traceability in Metrology
- TC9 – Flow Measurement
- **TC10 – Measurement for Diagnostics, Optimization & Control**
- TC11 – Measurement in Testing, Inspection and Certification
- TC12 – Temperature and Thermal Measurements
- TC13 – Measurements in Biology and Medicine
- TC14 – Measurement of Geometrical Quantities
- TC15 – Experimental Mechanics
- TC16 – Pressure and Vacuum Measurement
- TC17 – Measurement in Robotics
- TC18 – Measurement of Human Functions
- **TC19 – Environmental Measurements**
- TC20 – Measurements of Energy and Related Quantities
- TC21 – Mathematical Tools for Measurements
- TC22 – Vibration Measurement
- TC23 – Metrology in Food and Nutrition
- TC24 – Chemical Measurements
- TC25 – Quantum Measurement and Quantum Information
- **TC26 – Metrology for Cultural Heritage**

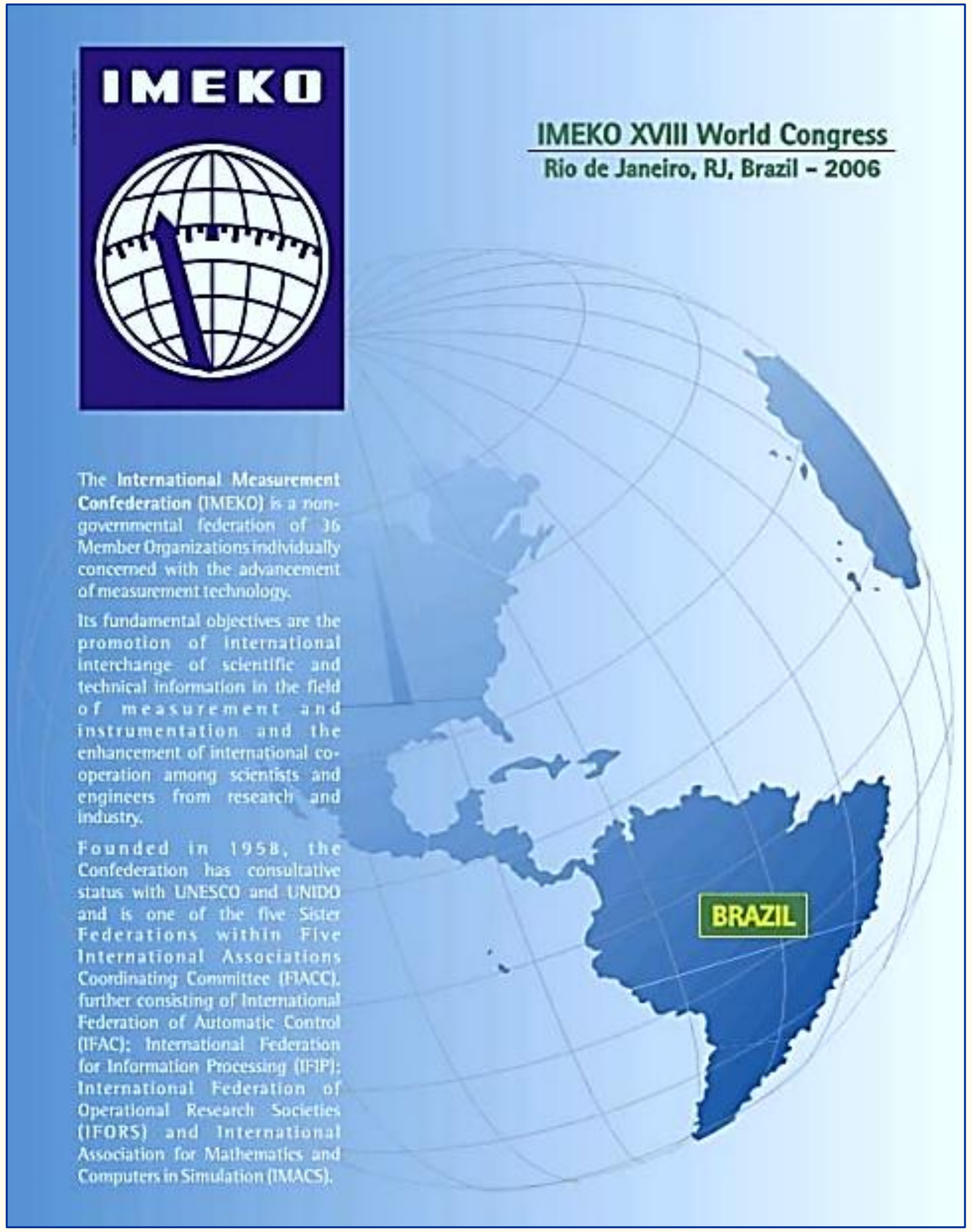
Brazilian Presence

In the Technical Committees – IMEKO’s Technical Work

34 Members in 21 Technical Committees

Technical Committee activities:

- workshops,
- seminars,
- symposia, and
- conferences
- publishing proceedings of events,
- textbooks, glossaries, and studies

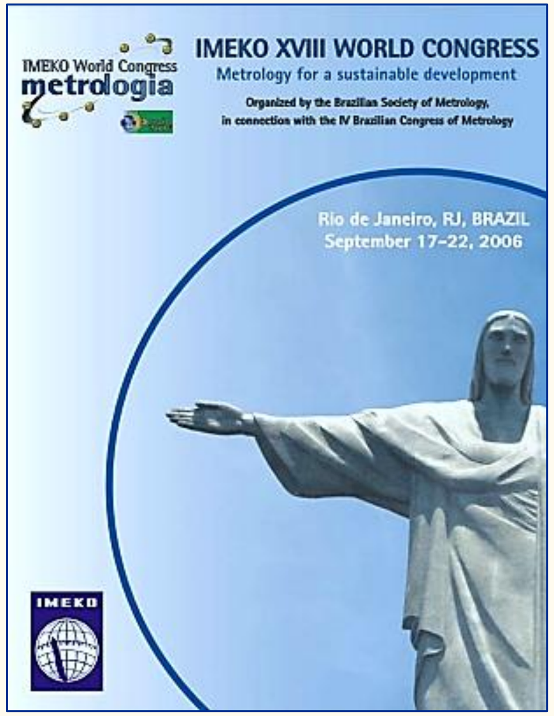


Brazilian Presence in IMEKO

XVIII IMEKO World Congress, 17 - 22 September 2006 Rio de Janeiro Brazil

A highly successful Congress with:

- 823 participants from
- 59 countries of the globe enjoyed the presentation of
- 548 contributions (oral and posters).



IMEKO Presence at METROLOGIA 2025

SEMETRO – XVI International Congress of Electrical Metrology

IMEKO TC4 Measurement of Electrical Quantities Workshop 2 - 3 December, Maceió – Alagoas.

Time	December 2, 2025, Tuesday	December 3, 2025, Wednesday
11:00 AM – 12:30 PM	Parallel Sessions 1 Each block with 6 oral presentations of 15 min CBM/CBM/RBMLQ-I/SEMETRO (IMEKO TC4) – Schedule (UTC -3)/CIMMEC/CBMRI	Parallel Sessions 3 Each block with 6 oral presentations of 15 min CBM/CBM/RBMLQ-I/SEMETRO (IMEKO TC4) – Schedule (UTC -3)/CIMMEC/CBMRI

30 ANOS SBM

IMEKO - International Measurement Confederation

METROLOGIA 2025

150 anos de confiabilidade para um futuro sustentável

1-4 December Brazil
WITH IMEKO PRESENCE

13 Conferences in 2025 – 2026

- TC3 Measurement of Force, Mass, Torque, and Gravity, TC5 Hardness Measurement, TC16 Pressure and Vacuum Measurement, TC22 Vibration Measurement, the Third International Conference on Dynamic Measurement, 23-27 March 2026, Hangzhou, China.

- TC9, Flow Measurement, FLOMEKO2026, 17-20, May 2026, Nara/Japan.

Events 2027

- The XXV. IMEKO World Congress, Metrology for Humanity 30 August – 3 September 2027, Rimini, Italy.

- TC2 Photonics, International Symposium on Modern Photonic Metrology, PHOTOMET 2025, 1-3 September 2025, Modena, Italy.

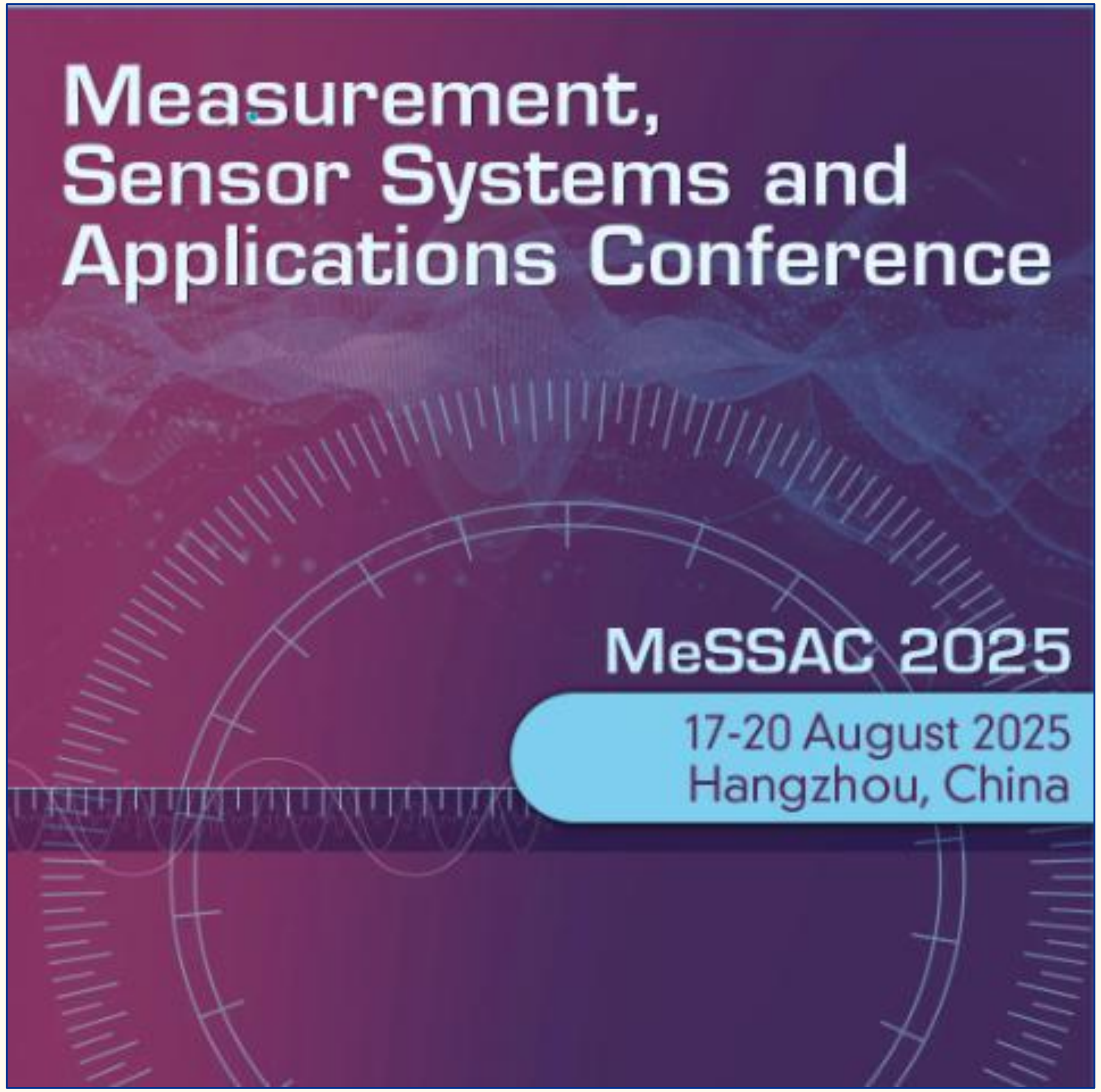
- TC6 Digitalisation, Second International Conference on Metrology and Digital Transformation, M4Dconf 2025, 3-5 September, Benevento, Italy.

- TC7, Measurement Science and TC13, Measurements in Biology and Medicine, "Test and Measurement" conference, 15-17 September 2025, Pretoria, South Africa.

- TC8, TC11, and TC24 joint conference (TC8 Traceability, TC11 Measurement in Testing, Inspection and Certification, and TC24 Chemical Measurements) will be held from 14-17 September 2025, in Torino, Italy.

- TC12 Temperature and Thermal Measurements, TEMPMEKO-ISHM 2025, 20-25 October, Reims, France

Measurement, Sensor Systems and Applications Conference 2025

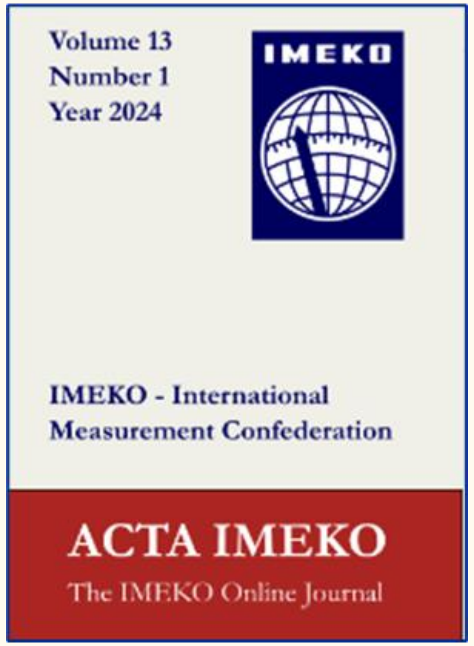


MeSSAC 2025 with 200 registrations!

- included all scientific domains where measurements are applied, from chemistry to food, from physics to engineering, from metrology to sensors and instruments.
- was a unique event and one of the most important conferences in the field of sensors and measurement.

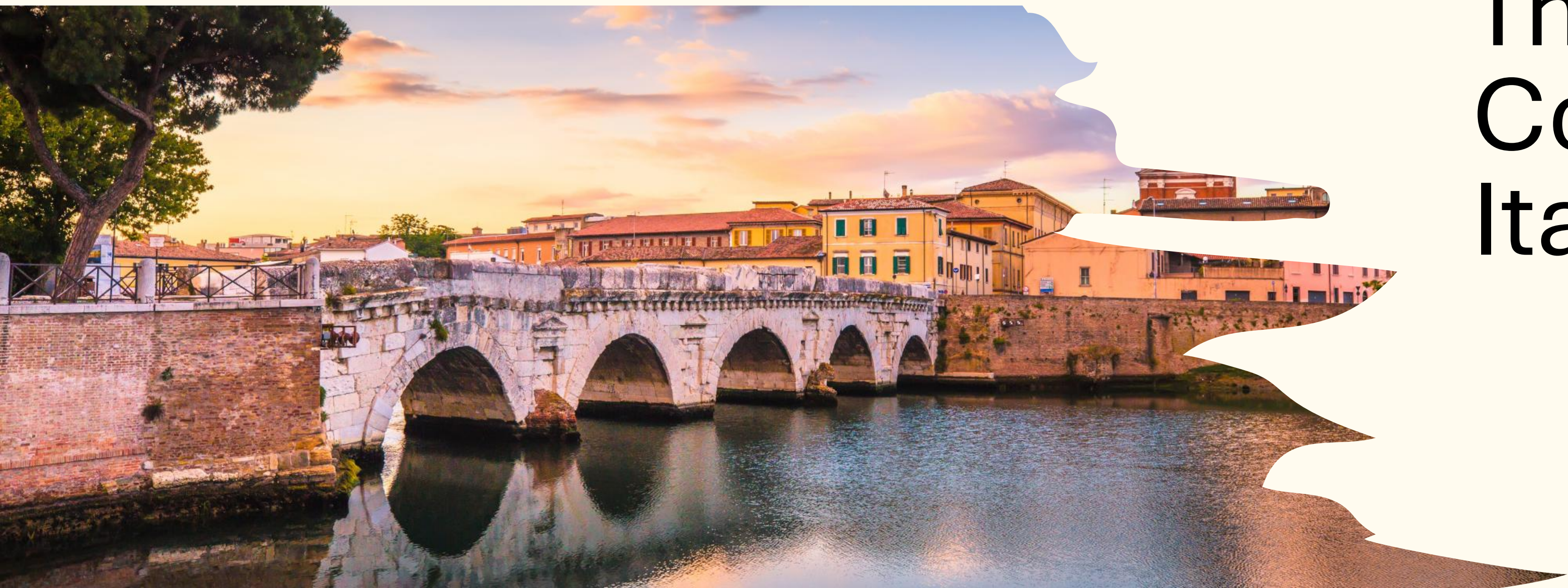
Our Journals

New!



IMEKO Journals published by Elsevier show a very positive upward trend, better than the major competitors. Measurement's impact factor 5,6.

IMEKO's own open access Journal with 4 issues a year.
Impact factor 1.



The next IMEKO World Congress 2027 Rimini, Italy

A PERSONAL STORY …

SUMMER SCHOOLS ON SUSTAINABILITY

2009

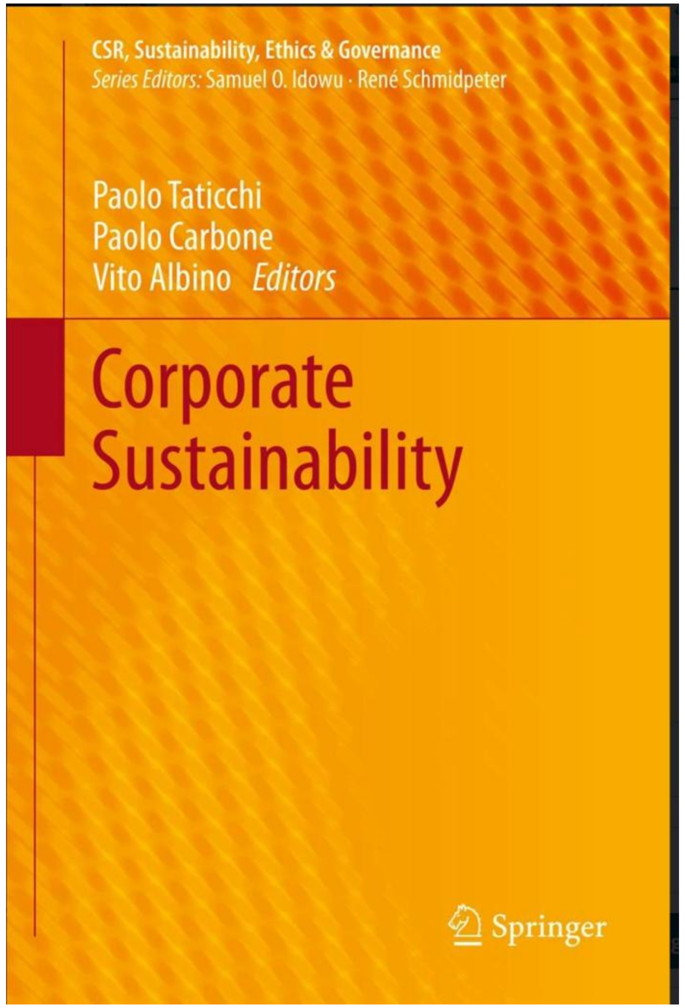
Pace University

2010

Columbia University

2011

NYU Poly

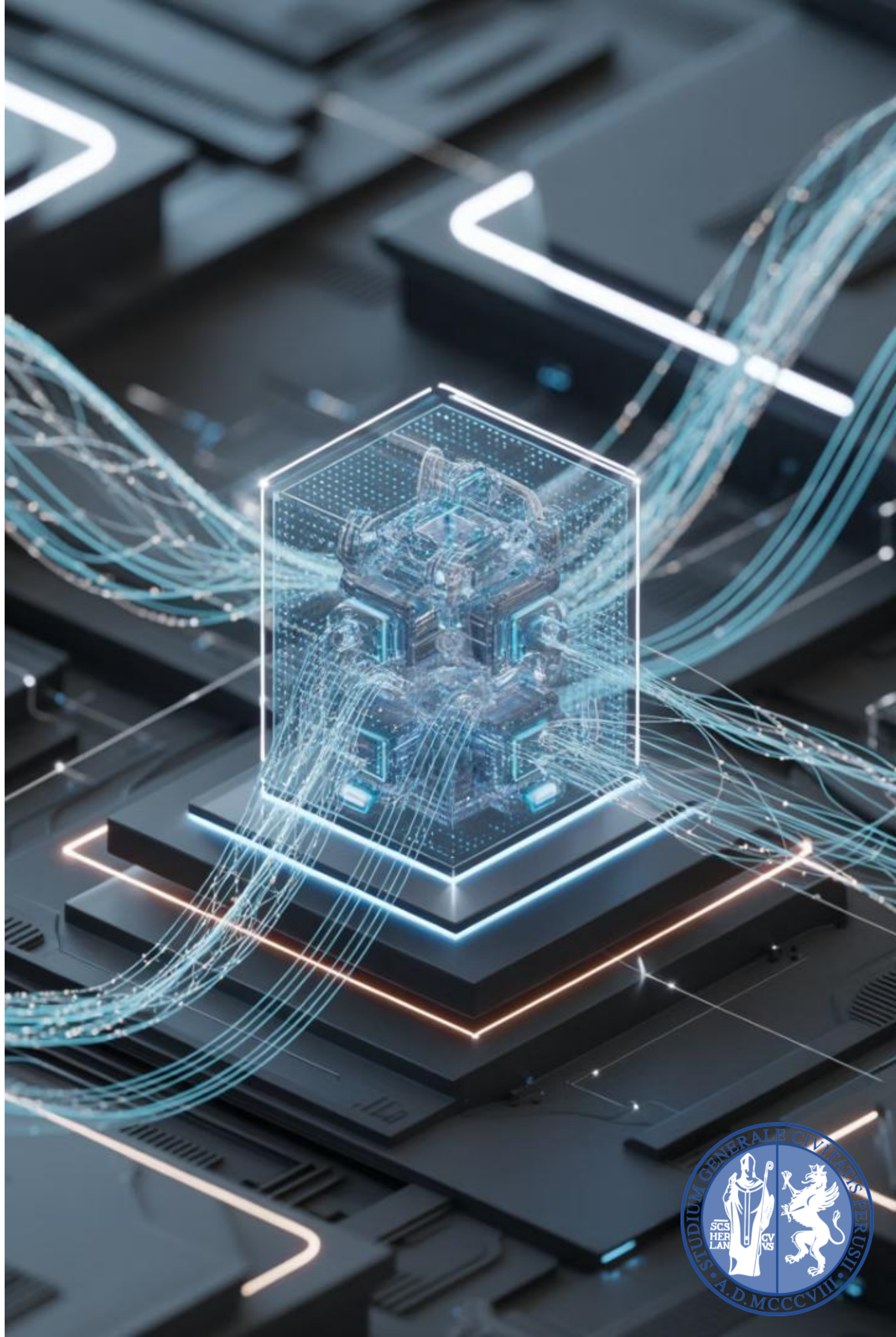


2012 NYU Poly

Climate-aware electronics

Electronic sustainability and Electronics for sustainability

Dipartimento di Ingegneria, Università degli Studi di Perugia



UNITED NATIONS, 1987

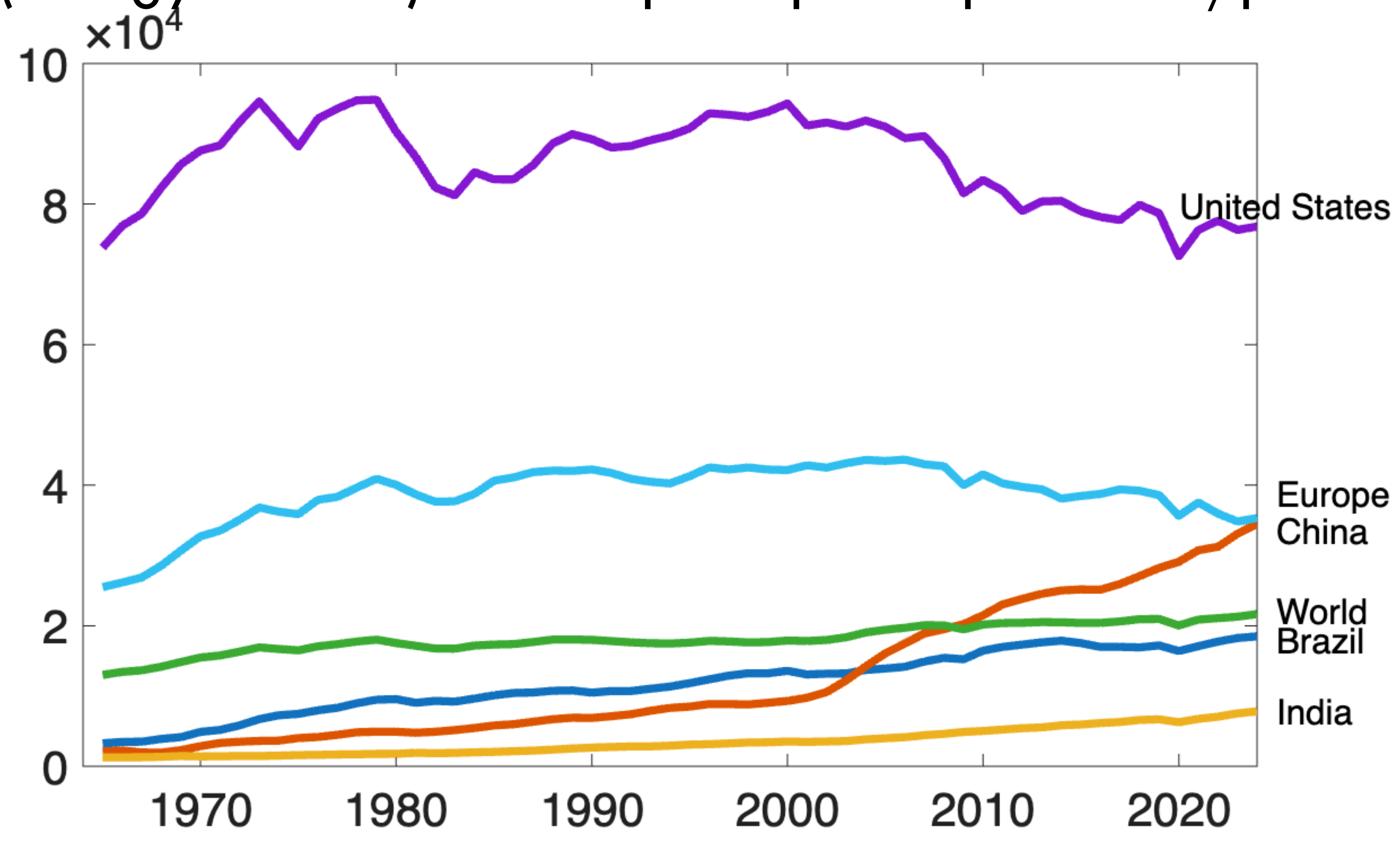
sustainability=meeting the needs of the present without compromising the ability of future generations to meet their own needs.

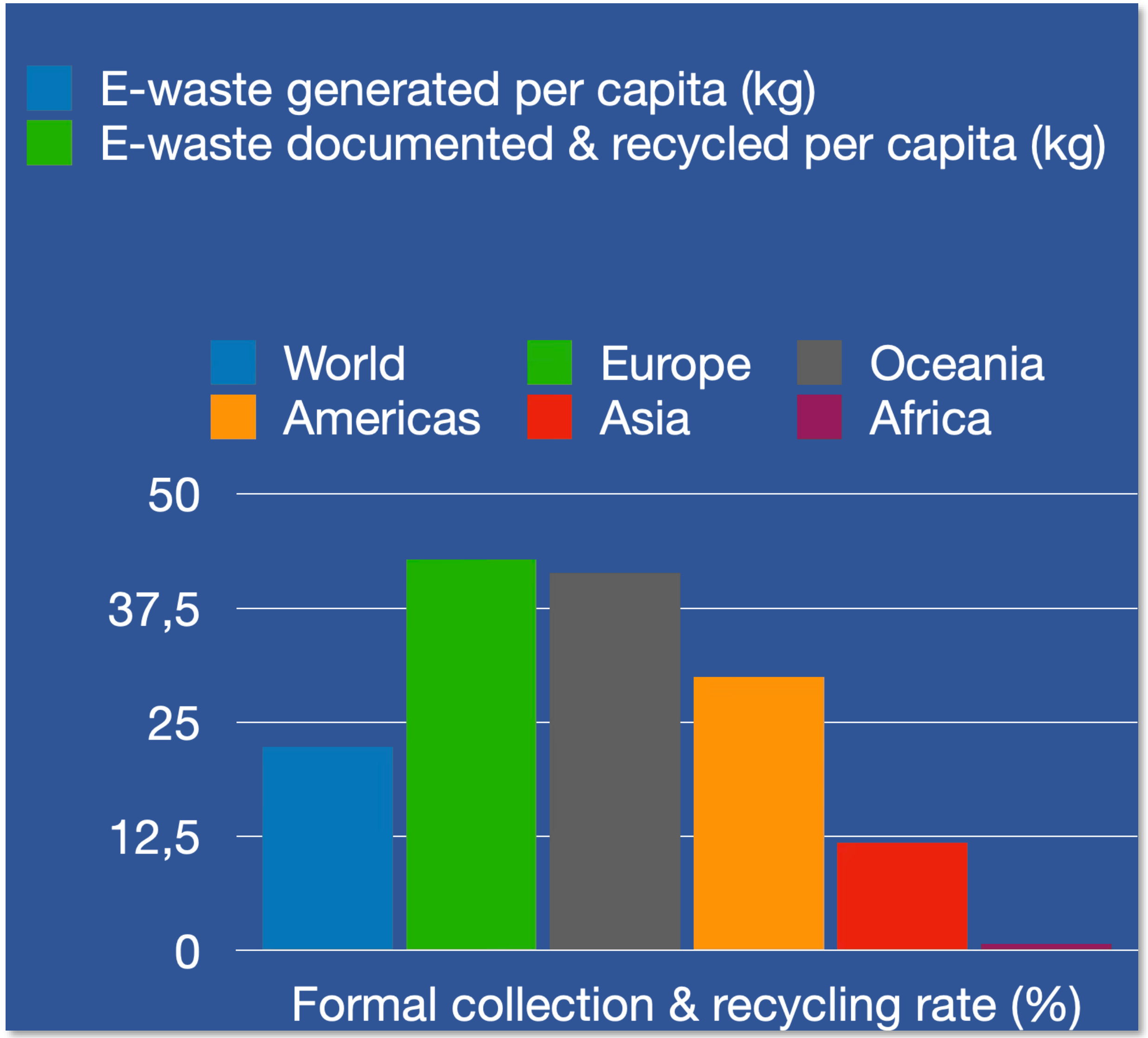
How does electronic affect the environment?

Impacts of electronics to the environment

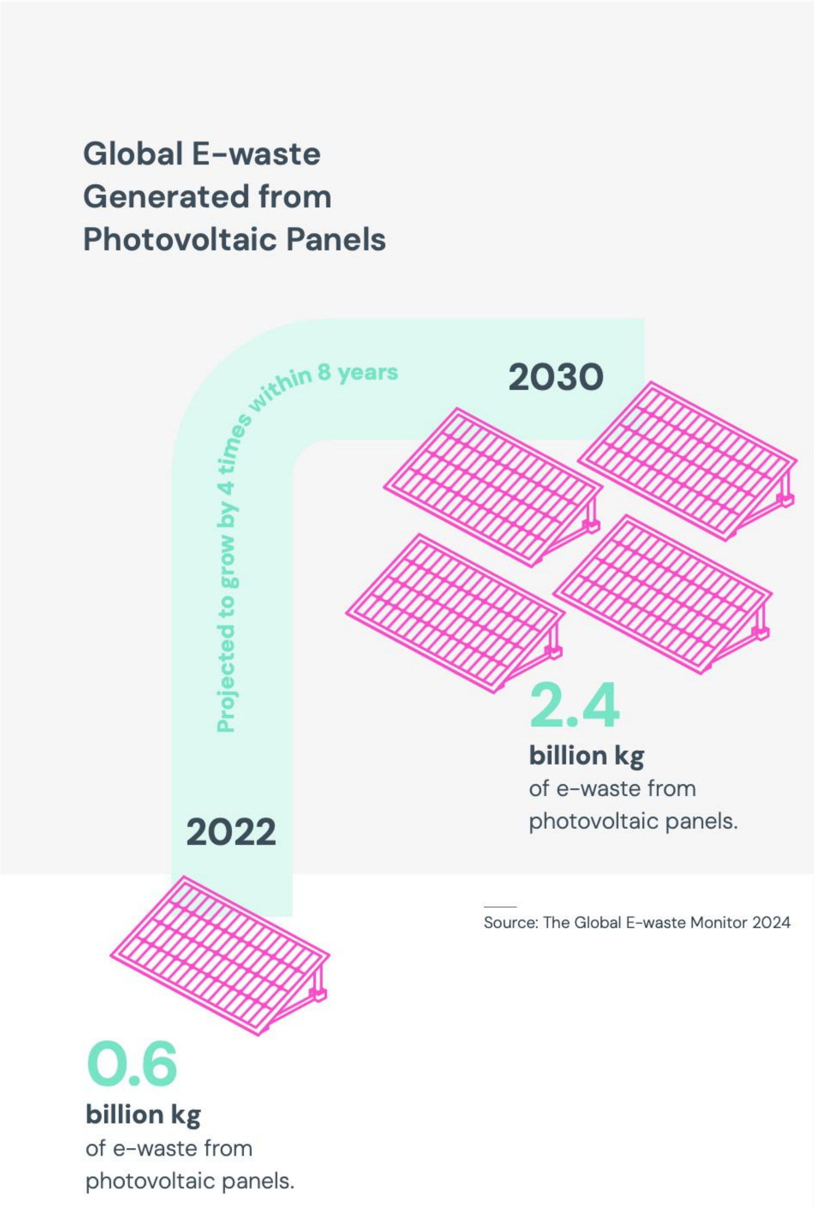
ONE END - LIFECYCLE LENS

(Energy context) consumption per capita kWh/person

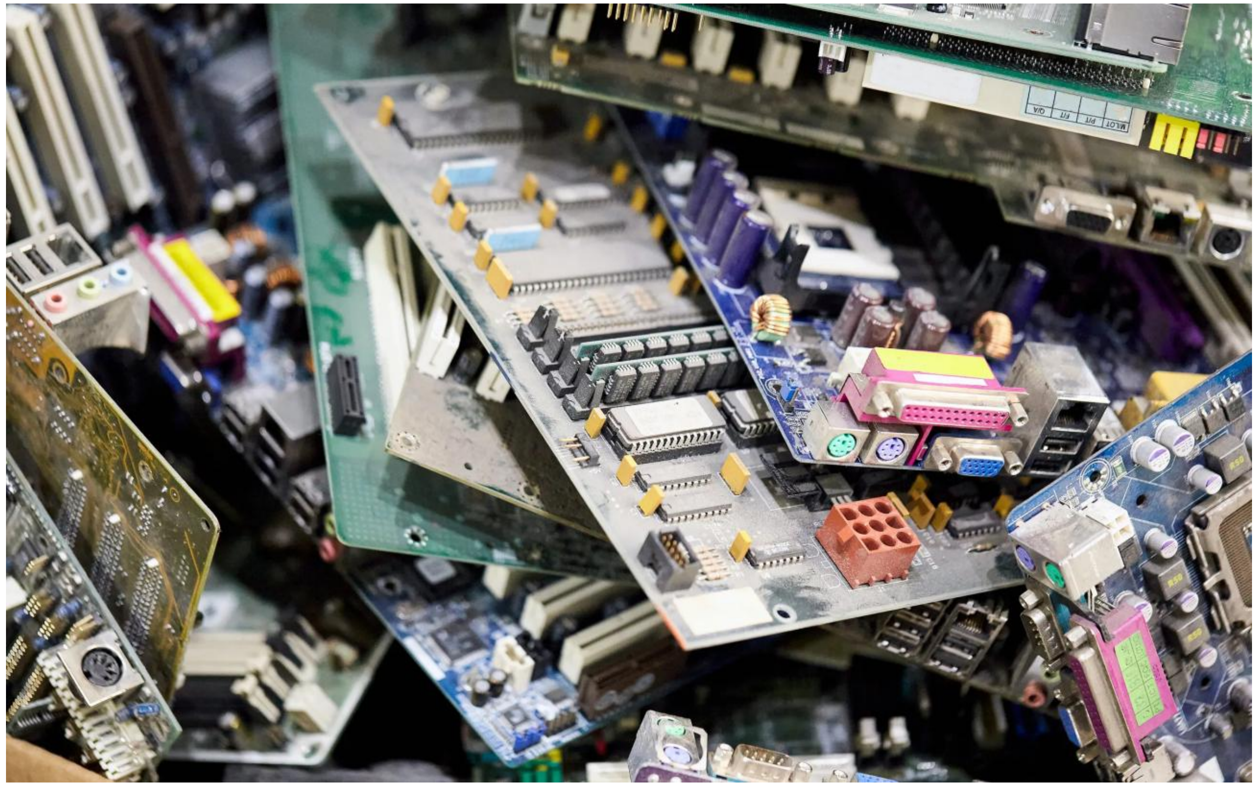


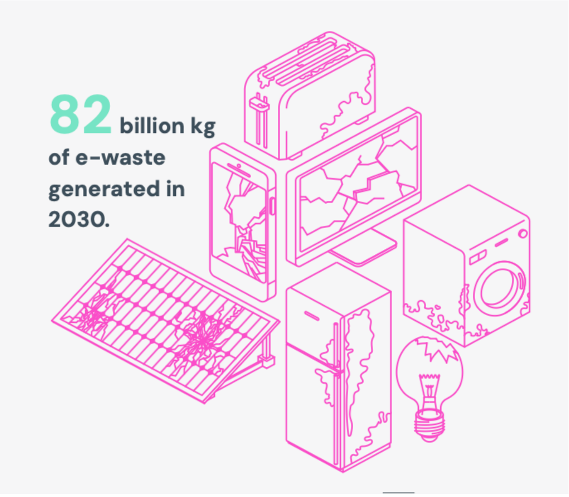


WHAT DO WE ENVISION FOR FUTURE YEARS?



E-cigarettes
Batteries
Stargate

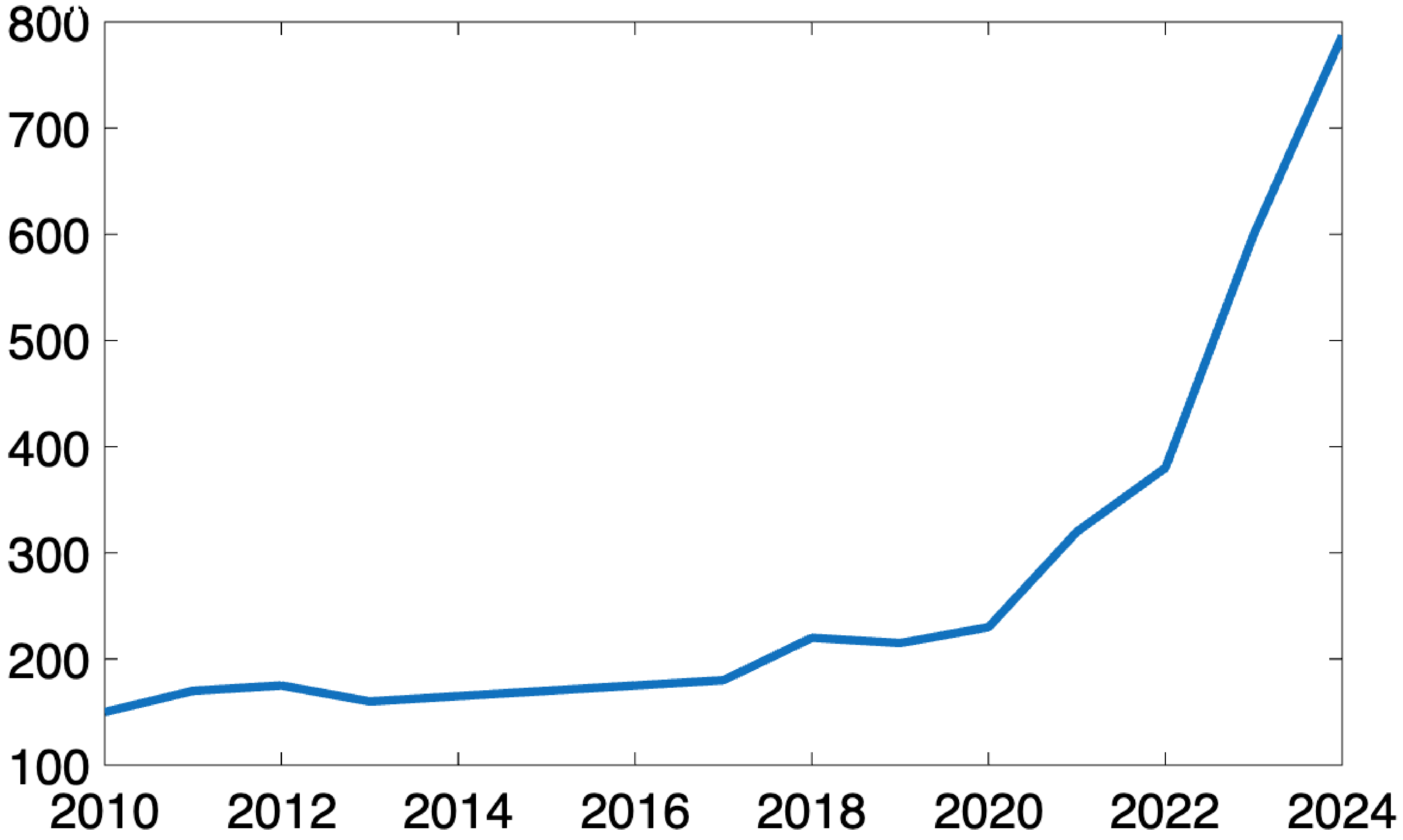




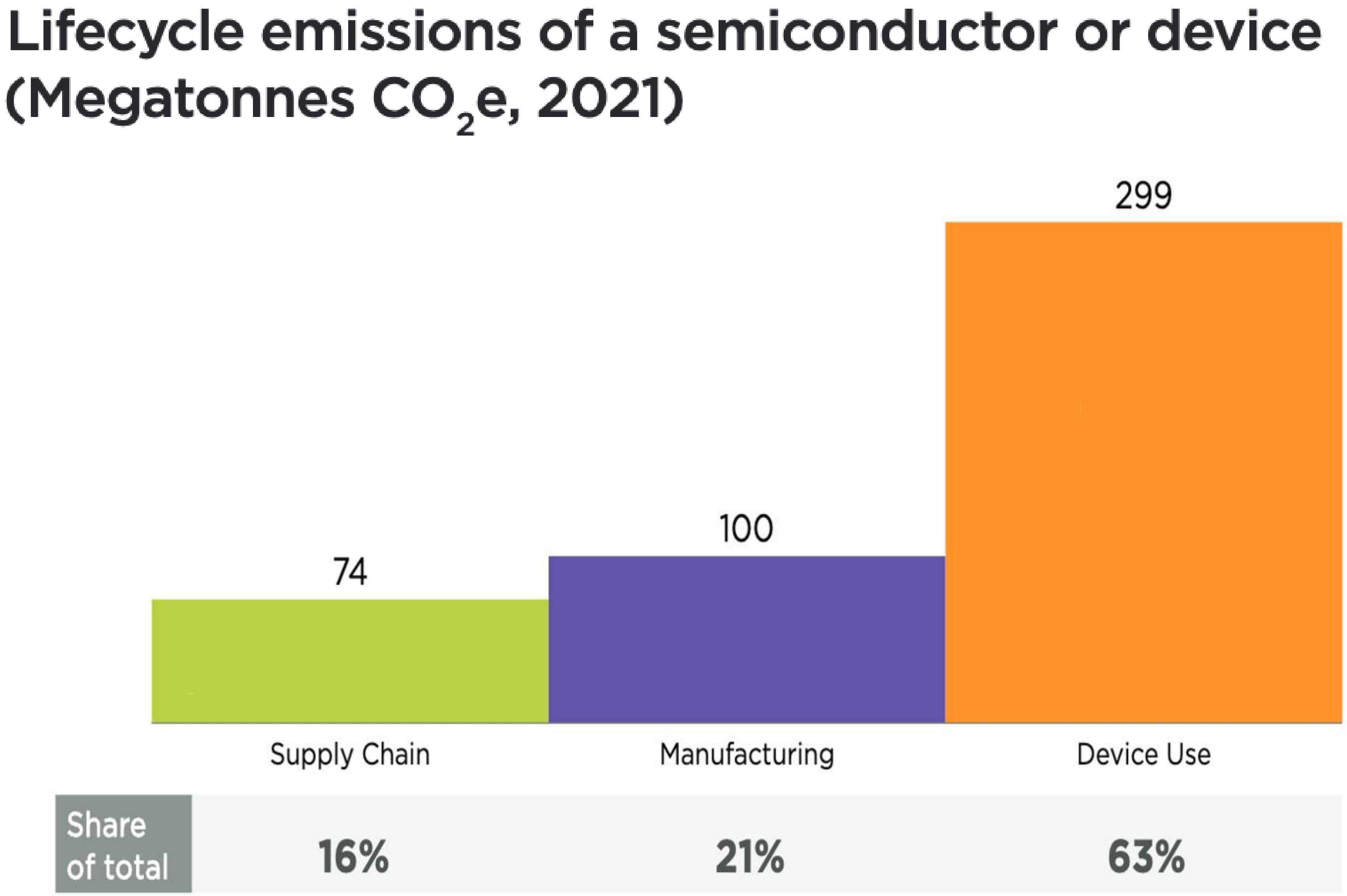
The Global E-Waste Monitor

PATENT APPLICATION FOR E-WASTE RECYCLING TECHNOLOGIES AS A SHARE OF TOTAL APPLICATIONS

(PER MILLION)



The other end: Impact of IC production



https://discover.semi.org/rs/320-QBB-055/images/Transparency-Ambition-and-Collaboration-BCG-SEMI-SCC-20230919.pdf

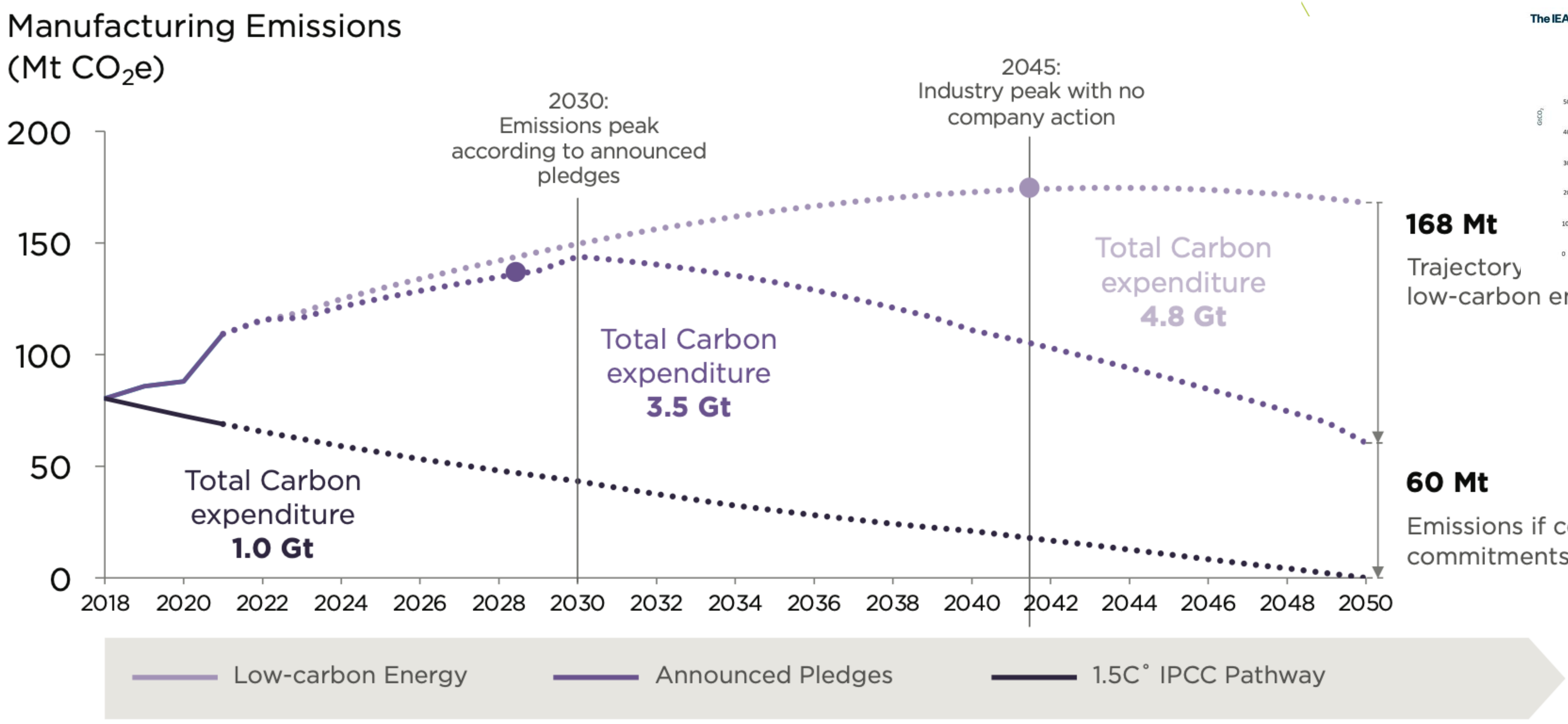
https://ourworldindata.org/co2-emissions

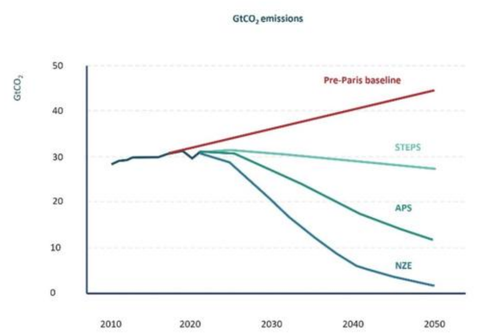
IC MAKING: MATERIAL CONSUMPTION

- One IC fab can use tens of millions litre per day
- Large amounts of raw materials (silicon, GaAs, Copper, Tungsten, Tantalium, …)
  - Mining and refining of these materials have high carbon footprint, produce toxic tailings, sometimes occur in regions with weak environmental regulations
  - Supply chain circularity for ultra-high-purity materials is almost non existent today
  - Solid and liquid waste (solvents, acids, …): effluents need multi-stage treatment to remove fluorides, heavy metals, and organics before discharge

Transparency, Ambition, and Collaboration:

Advancing the Climate Agenda of the Semiconductor Value Chain





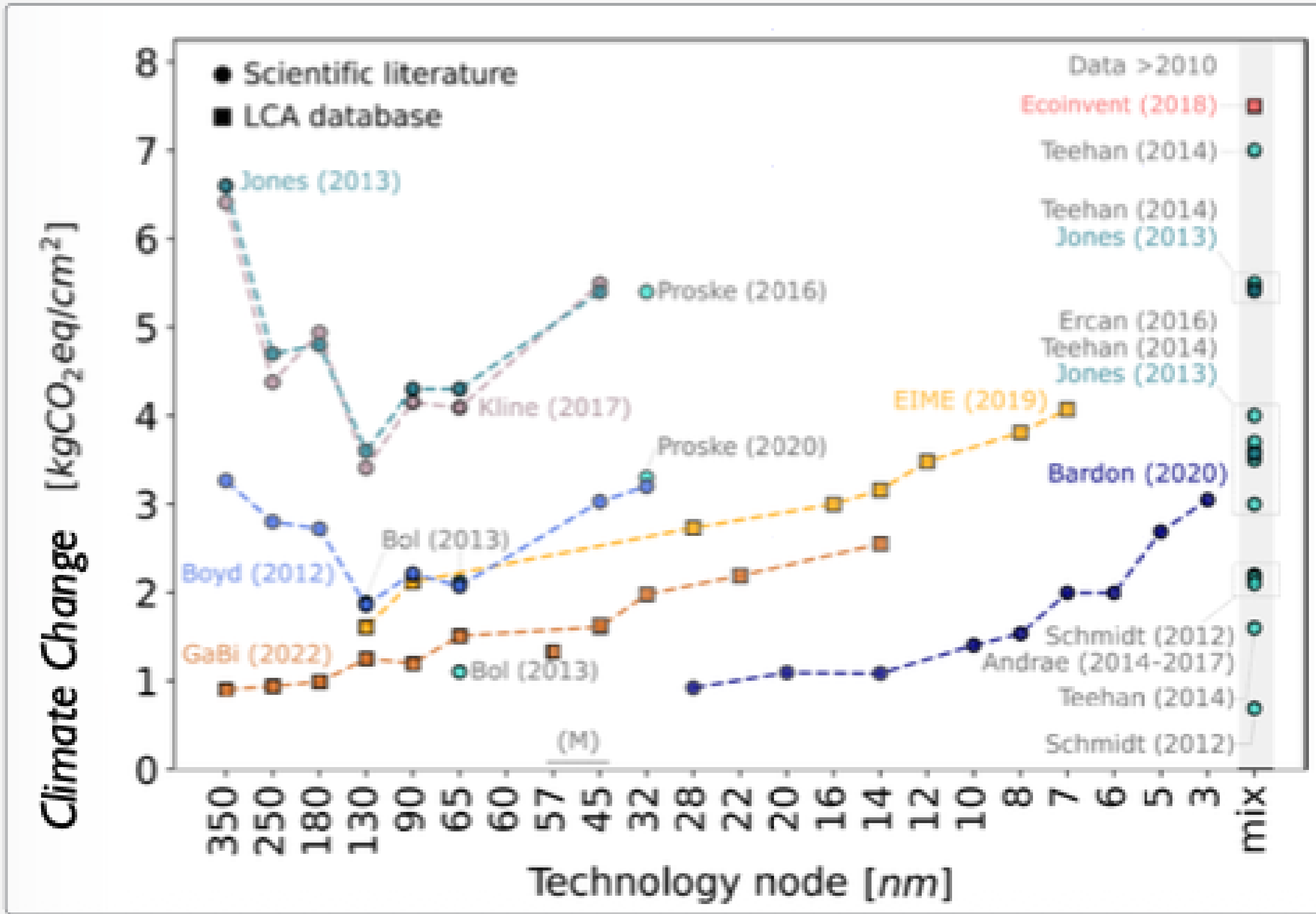
The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change.

1 Emissions growth based on projected capacity growth (3.25%) and average intensity growth (1.01%), all else constant
Note: Low-carbon energy scenarios use IEA STEPS for North America, Europe, and Asia-Pacific. Source: BCG analyses on data from: CDP, imec, SEMI, IEA

https://discover.semi.org/rs/320-QBB-055/images/Transparency-Ambition-and-Collaboration-BCG-SEMI-SCC-20230919.p

WMO UN environment programme Nobel 2007 PEACE PRIZE

Lifecycle assessment literature to increase awareness



Literature / LCA database uses variable:

- Scope
- Data sources (primary vs. secondary)
- Approaches (bottom-up vs top-down)
- "creative" plugging of data gaps

Source: Pirson et al., 2023
Review, Analysis, and Less

Reporting as tool to create awareness and involve stakeholders, e.g., HT Micron

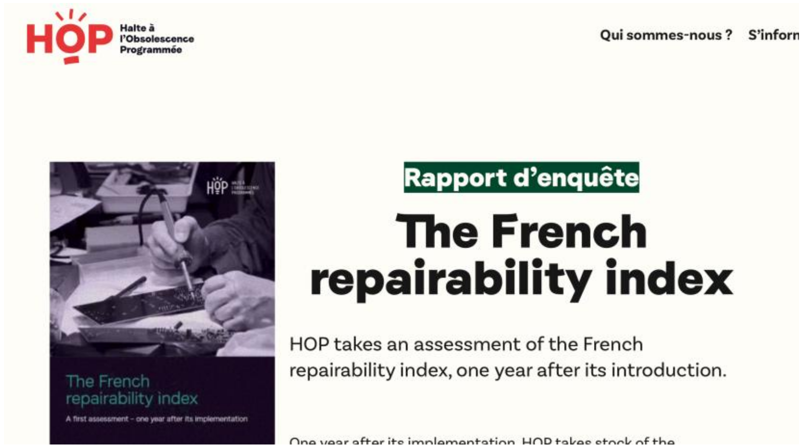
E-WASTE: WHAT IS EFFECTIVE IN CHANGING BEHAVIORS?

Community “Repair Cafés”

•**Repair-friendly design and labeling:**
Making repairability scores *visible at the point of sale* (as in France)

Peer comparison for energy use:
(e.g., “your office uses 20% more standby energy”)

Offering cash rewards or discounts for returning old phones, batteries, or devices increases return rates dramatically



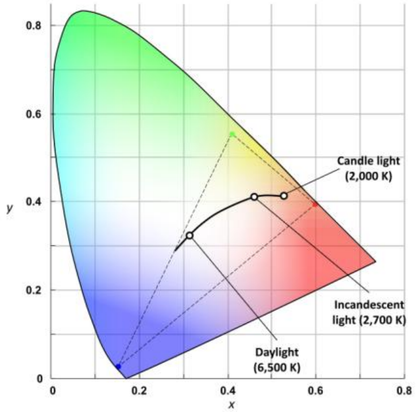
•Mechanism: **Leverages *loss aversion***—people dislike leaving value unclaimed

•Apple’s Trade-In program and EU deposit-refund pilots achieve recovery rates above 80%.

HOW CAN ELECTRONIC POSITEVELY AFFECT THE ENVIRONMENT?

Impacts of electronics to the environment ?

BREAKTHROUGHS …




白色LEDランプ
効率よく発光
製造コスト半分
日亜化学
色バランス維持
室内外照明にも

High efficiency blue LED Shuji Nakamura, Hiroshi Amano and Isamu Akasaki (1993) – 2014 (Nobel prize)

20% reduction in night energy consumption reported from the introduction of LEDs between 2009–2011and 2015-2016

Energy Efficiency (2021) 14: 68
https://doi.org/10.1007/s12053-021-09983-8

ORIGINAL ARTICLE

Check for updates

Measuring aggregate electricity savings from the diffusion of more efficient lighting technologies

Julián Moral-Carcedo · Julián Pérez-García

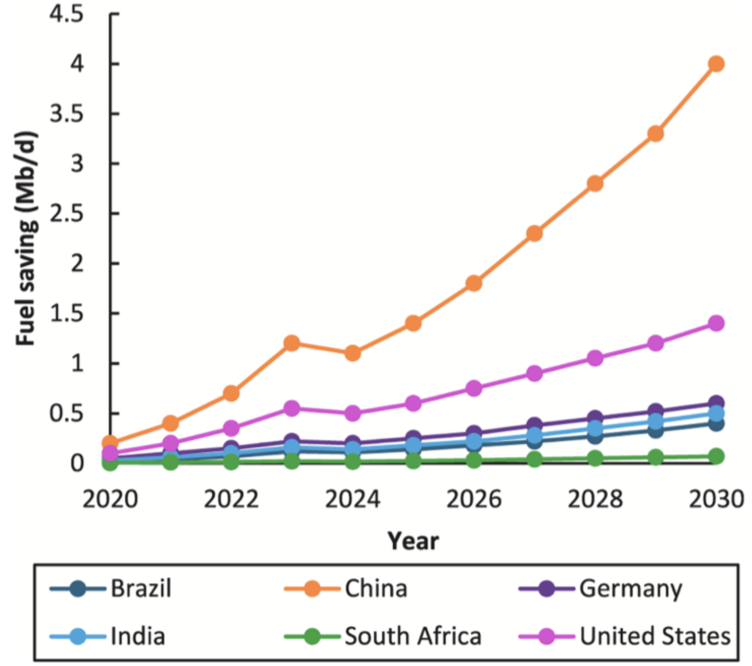


Fig. 8. Projected fuel savings from EV Adoptions (2020–2030) across major economies.

Review article

Societal, environmental, and economic impacts of electric vehicles towards achieving sustainable development goals

Ahmed A. Arefin[a], Sheikh T. Meraj[b], M.S. Hossain Lipu[c], Md. Siddikur Rahman[d], Tuhibur Rahman[c,*], Kamrul Hasan[f], Mahidur R. Sarker[g,h], Kashem M. Muttaqi[c]

INCREMENTAL IMPROVEMENTS

Power electronics involves efficient conversion and control of electrical power using switching devices

Conversion efficiencies of up to 98–99%

Power electronics enable up to 30% energy savings in electric motor drives in industry

Need in-field on-chip measurements, BIST, to measure properties online to cope with variations in the IC behavior due to production process imperfect control, also with aging

Other field emerge such as packaged photonics that raise new test challenges

These technologies are foundational to modern electrical systems and are instrumental in optimizing power usage across various sectors.

Do we need measurements?

Yes! — measurement support cutting waste, saving energy, and making electronics safer.

ROLE OF METROLOGY:

When making ICs

Common problem in IC making is variability:

- goal reduce variability – disciplines and new procedures
- Reducing false defect: better measurement, fewer decision errors -> Metrology is at the forefront of yield
- Emerging techniques for wafer inspection and IC testing

For the environment:

- Need standards, measurements to sustain e-waste recycling process optimization and lifecycle assessment
- Environmental Monitoring Systems
- Metrology, accreditation, conformity assessment, and market surveillance are key players

https://semiengineering.com/defeating-overkill-metrologys-role-in-reducing-false-defects/

What can STEM education do?

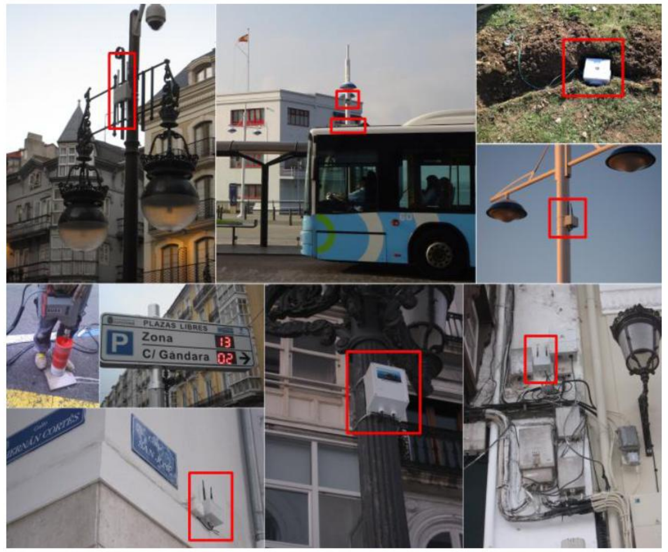
Include sustainability in the taught disciplines

Historically, engineering programs emphasize how to design systems not how they break down,

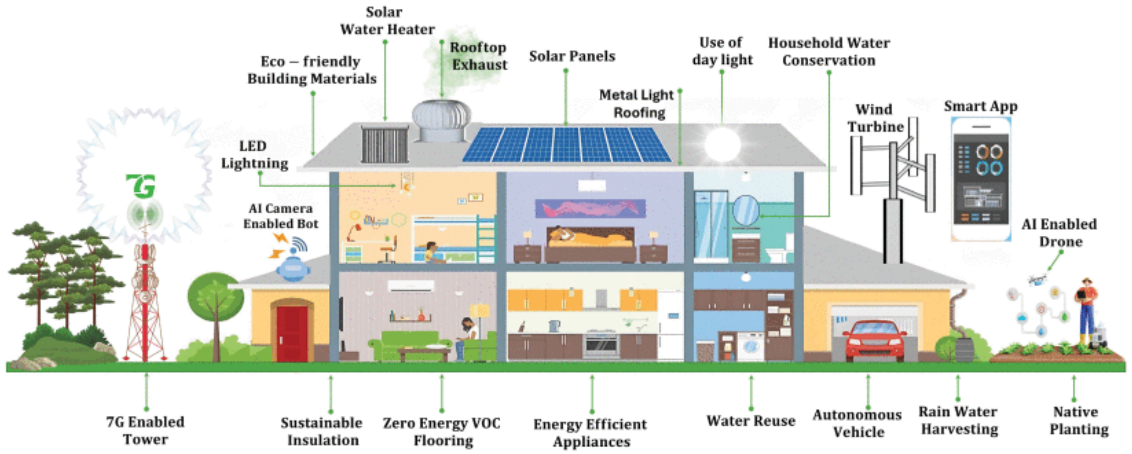
nor how to care for system’s lifecycle

DESIGN FOR SIMPLE MEASUREMENT SYSTEM

NEW CHALLENGES: MEASUREMENT AND SENSING



Key Trends:
•Miniaturized Sensor Development:
•Emergence of Wireless Sensor Networks:
•Increased Adoption of IoT and Connectivity:

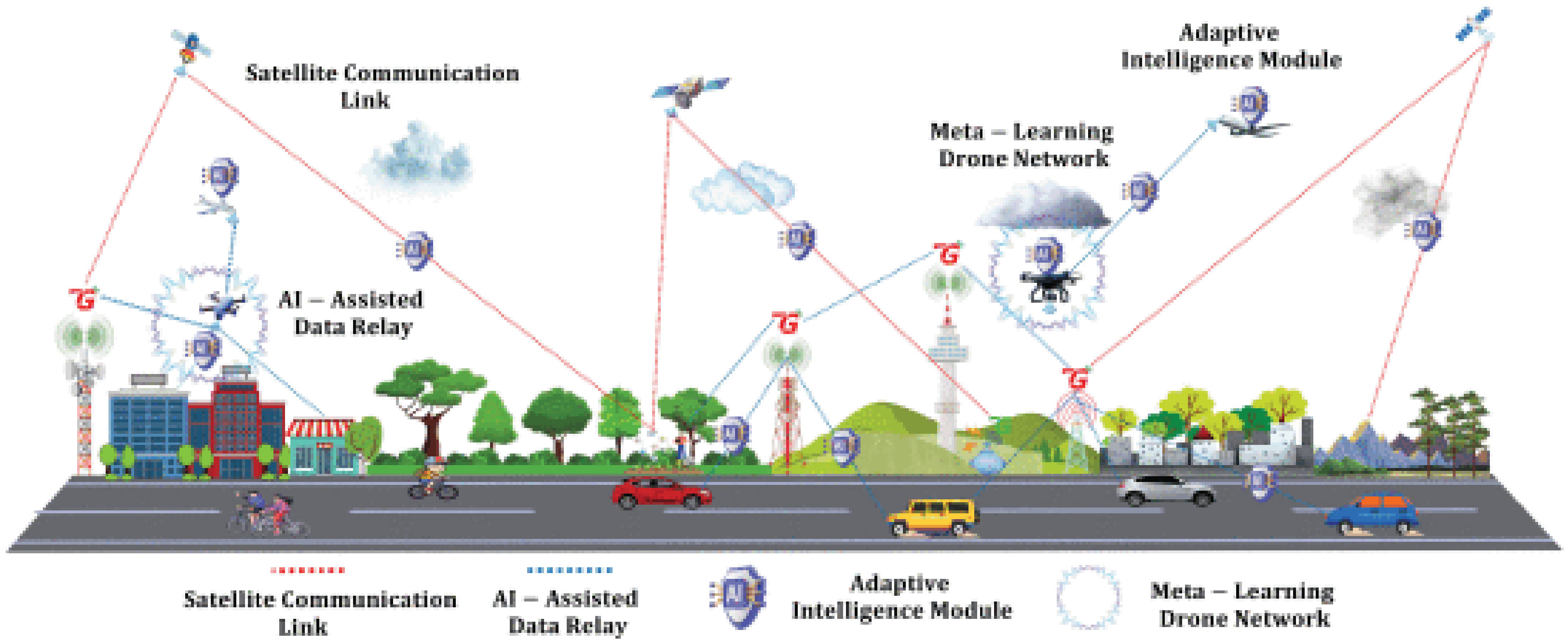


Santander: the smart Spanish city with more than 10,000 deployed sensors

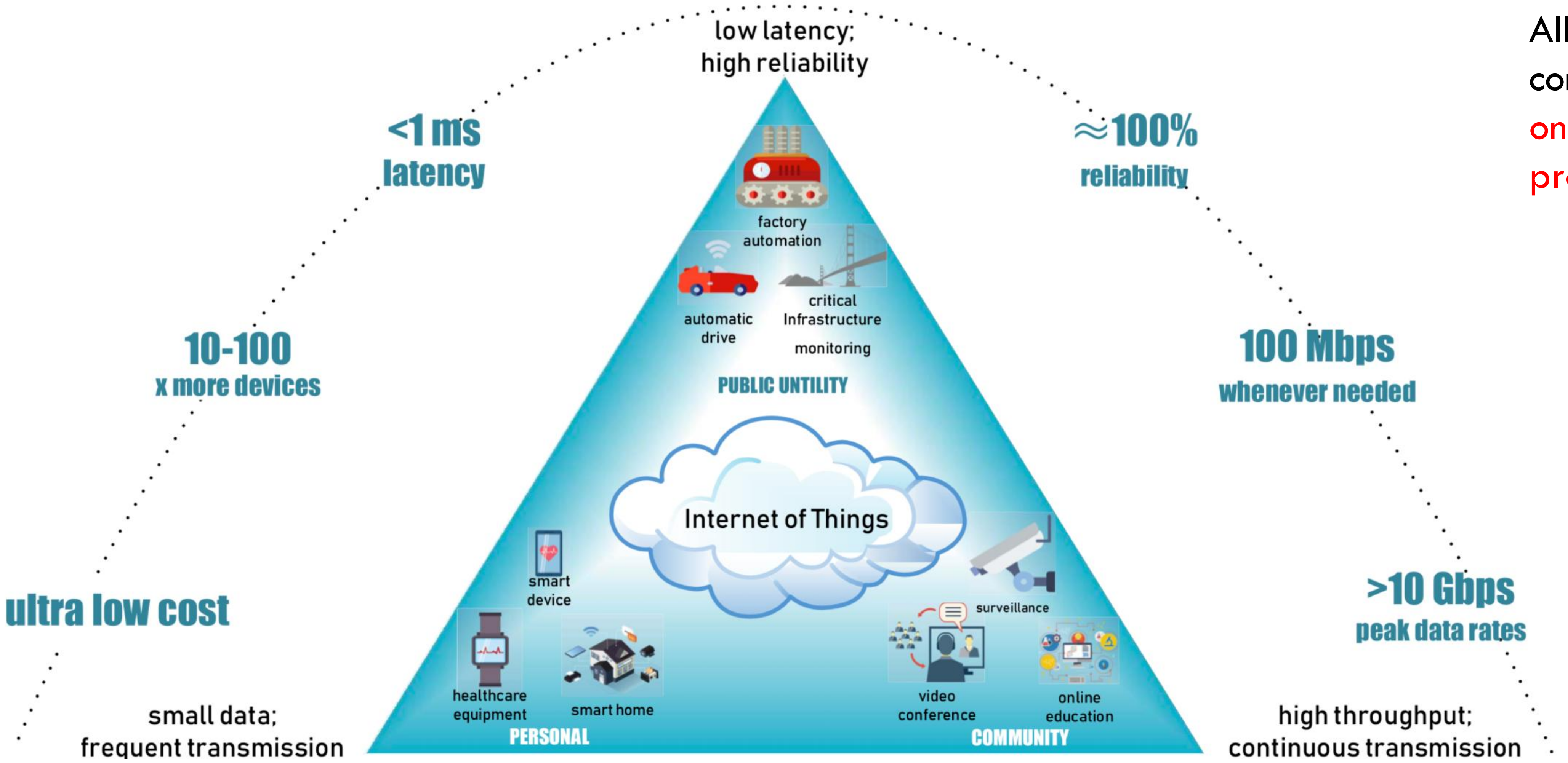
California monitoring of freeway system based on 40,000 sensors within the Performance Measurement Systems

Wide-area sensor networks would benefit from self-sensing and BIST capabilities

NEW CHALLENGES: 7G



ONE-BIT TO FIT VARIOUS DEMANDS



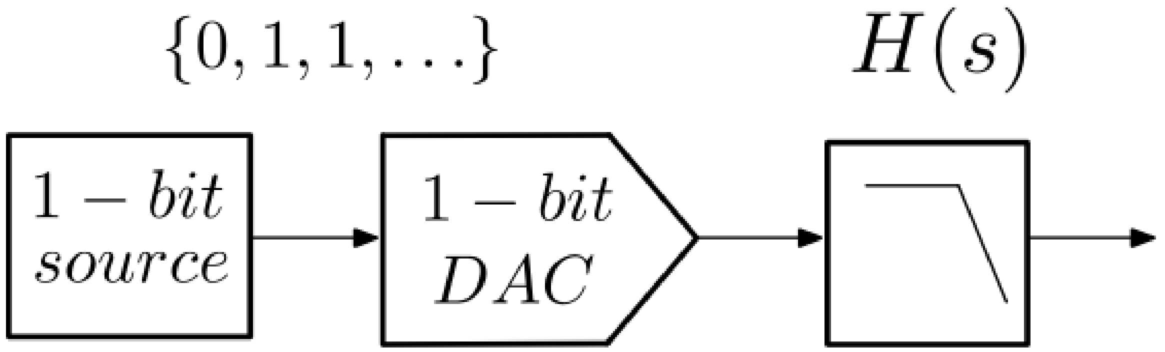
All applications in an IOT context could benefit from one-bit data acquisition and processing

Toward Massive Connectivity for IoT in Mixed-ADC Distributed Massive MIMO
DOI: 10.1109/JIOT.2019.2957281

LOW-COMPLEXITY MEASUREMENT AND TESTING

ONE-BIT SYNTHESIS OF ANALOG SIGNALS

- Filtered binary sequence to generate continuous signals from binary sequences
- Properties of binary signal defined in the frequency-domain



- **Why?**
  - To ease operations at IC level
  - To provide analog signals for BIST purposes
  - To optimize hardware resources
  - To simplify hardware, reduce peak consumption, optimize battery life

Design binary sequence to optimize frequency behavior

SYNTHESIS OF ANALOG SIGNALS: HOW

Quadratic binary unconstrained optimization (QUBO)

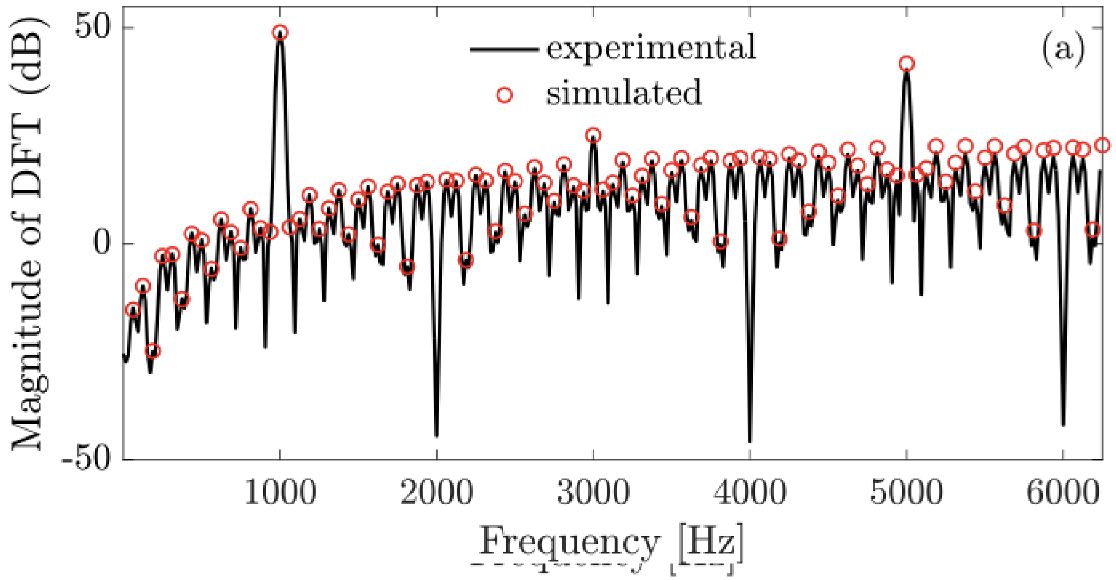
$$\min_{\mathbf{x}\in\{0,1\}N} \mathbf{x}^T\mathbf{Q}\mathbf{x}$$

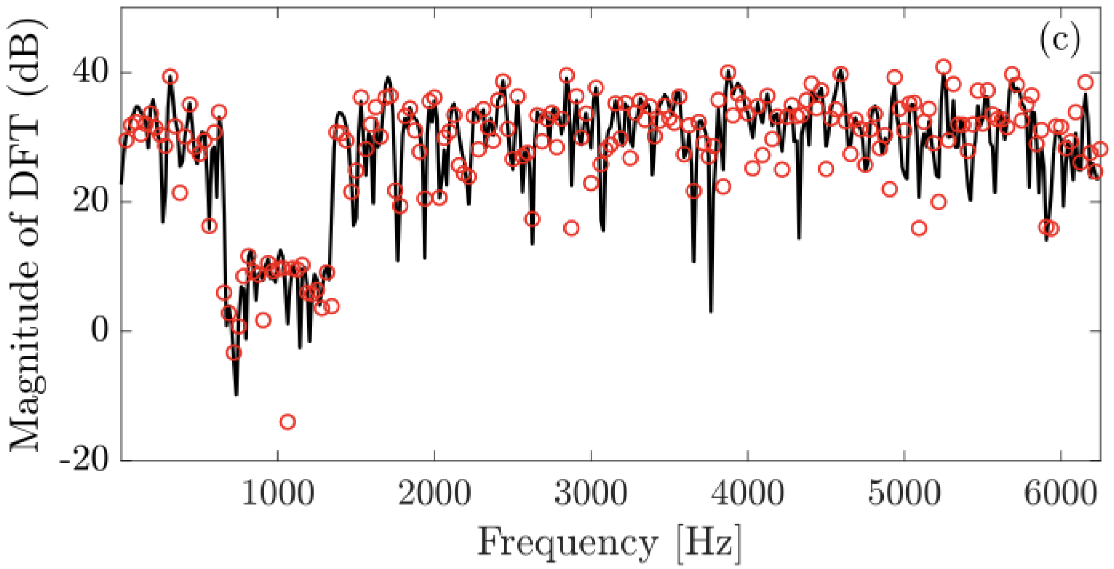
Q is a *N* ×*N* matrix of constant values, originating from a *Fourier* matrix

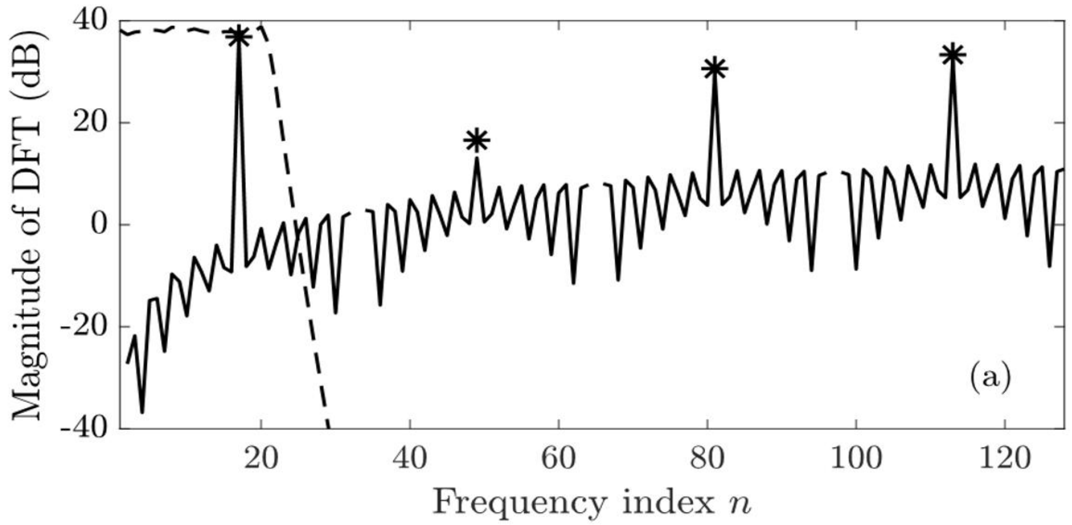
Objective: given **Q** such that it represents frequency domain behavior, find binary **x** to maximize cost function

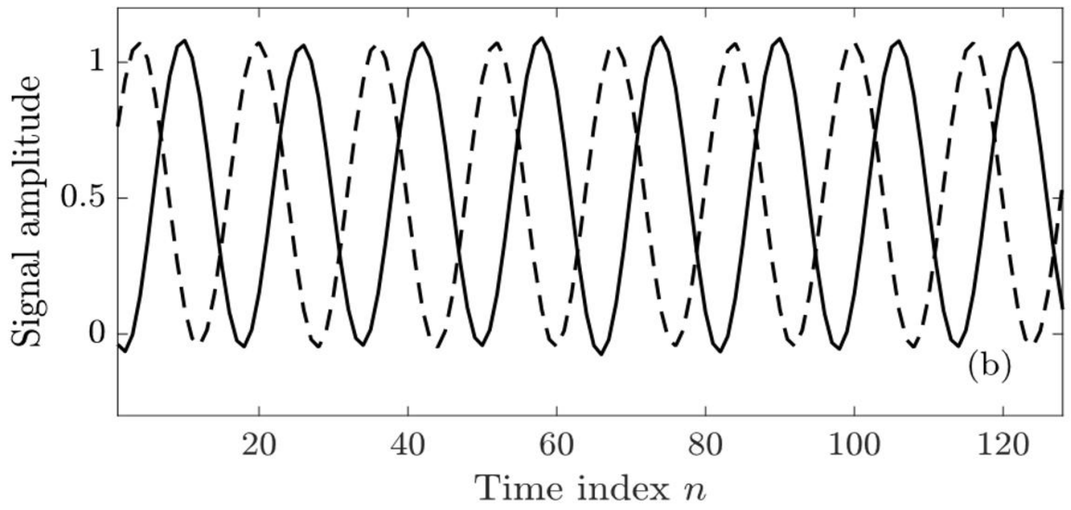
Problem can be cast into a problem solvable by QUANTUM ANNEALERS

EXPERIMENTAL RESULTS





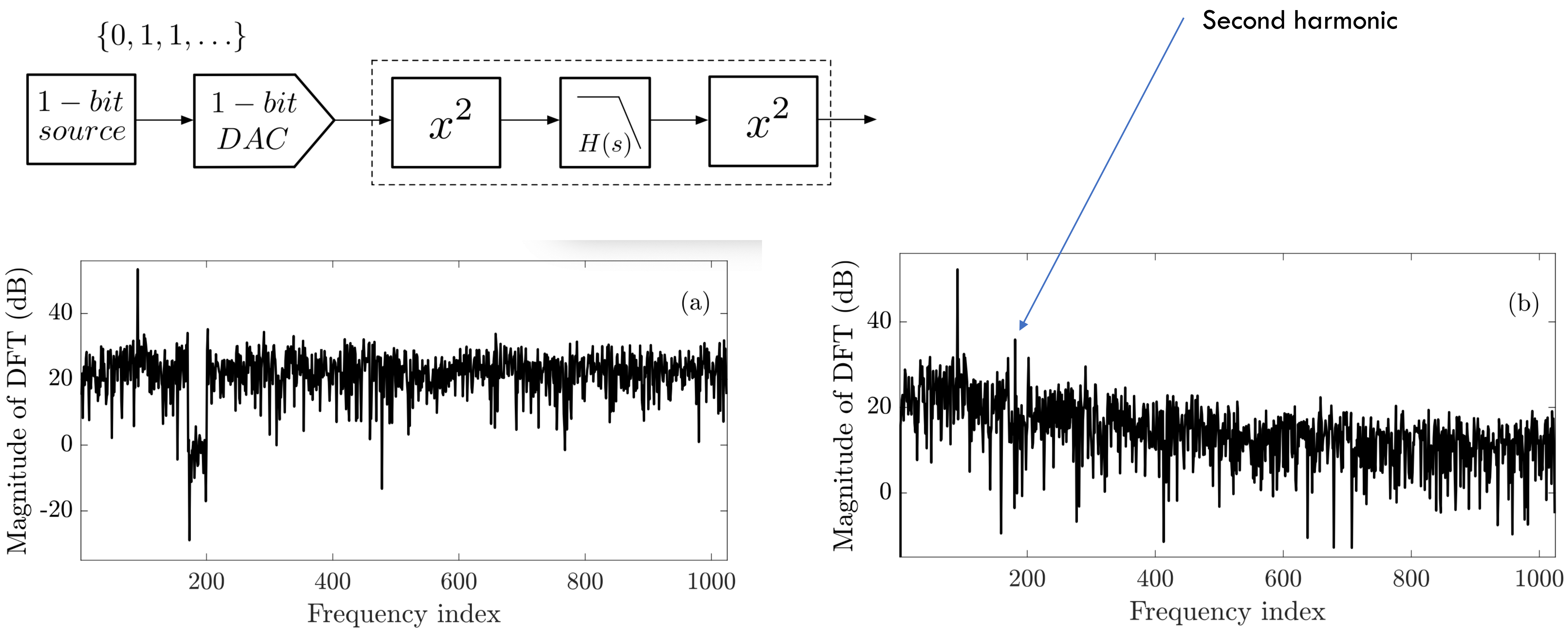




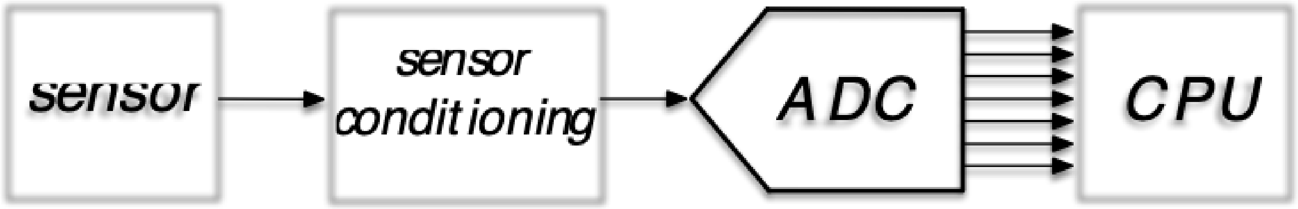
Quality of reconstructed analog signal depends on the used reconstruction filter

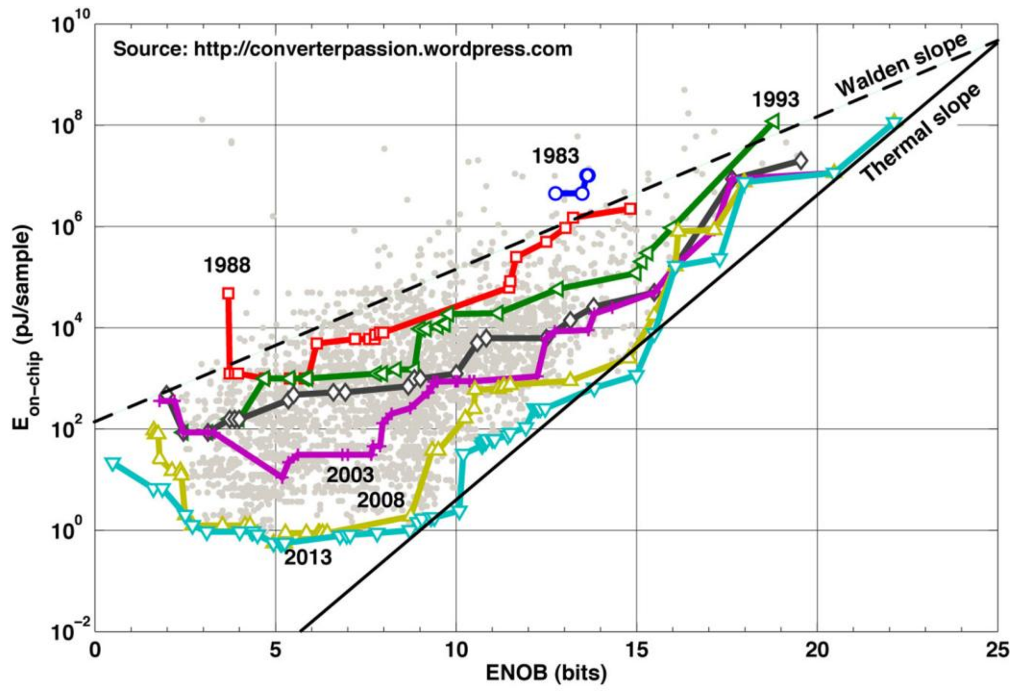
Values of SINAD of 52.6 dB when using N=8192 samples and an elliptic low-pass filter

EXAMPLE: SIMPLE IDENTIFICATION OF HAMMERSTEIN-WIENER MODEL



VISION OF LOW-POWER, LOW-COMPLEXITY MEASUREMENTS

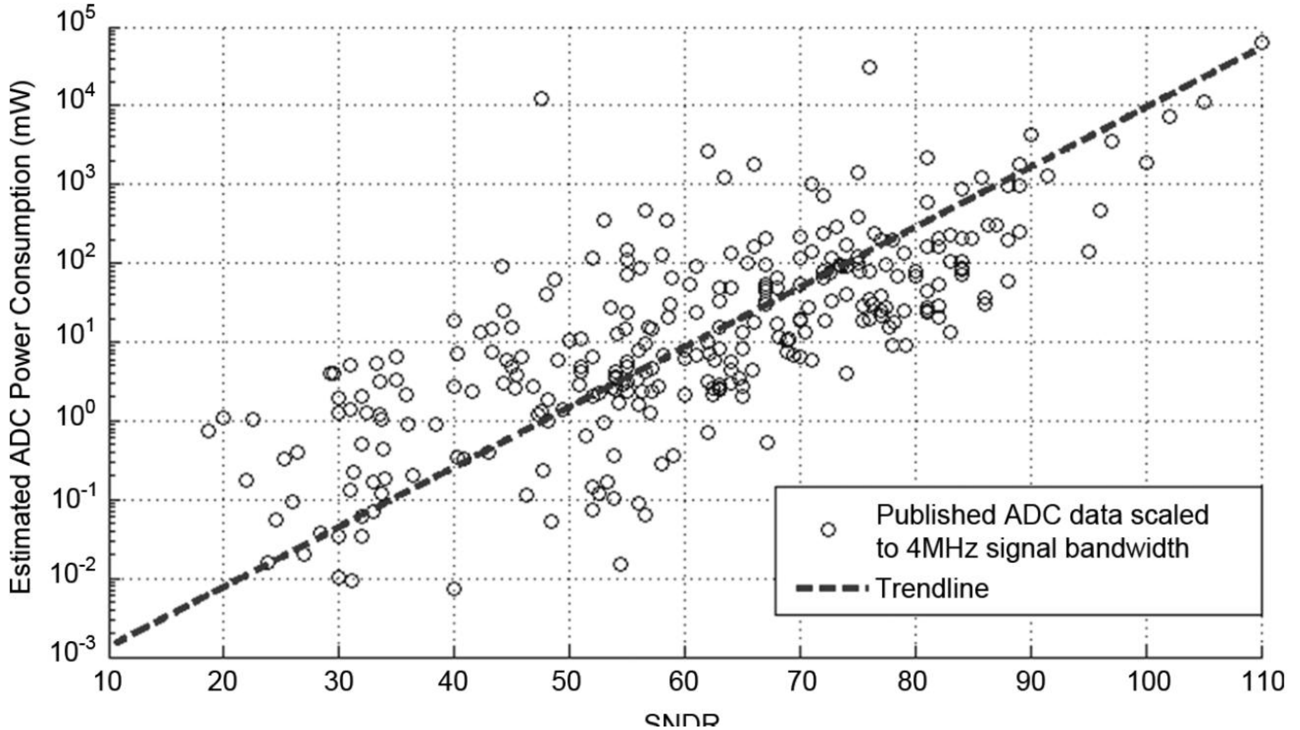




From analog to digital:

Push for faster, higher resolution ADCs

Power consumption in ADCs increases exponentially with number of resolution bits



IEEE TRANSACTIONS ON VERY LARGE SCALE INTEGRATION (VLSI) SYSTEMS, VOL. 20, NO. 2, FEBRUARY 2012

UHF Receiver Front-End: Implementation and Analog Baseband Design Considerations

Raghavendra Kulkarni, Student Member, IEEE, Jusung Kim, Student Member, IEEE, Hyung-Joon Jeon, Jianhong Xiao, and Jose Silva-Martinez, Fellow, IEEE

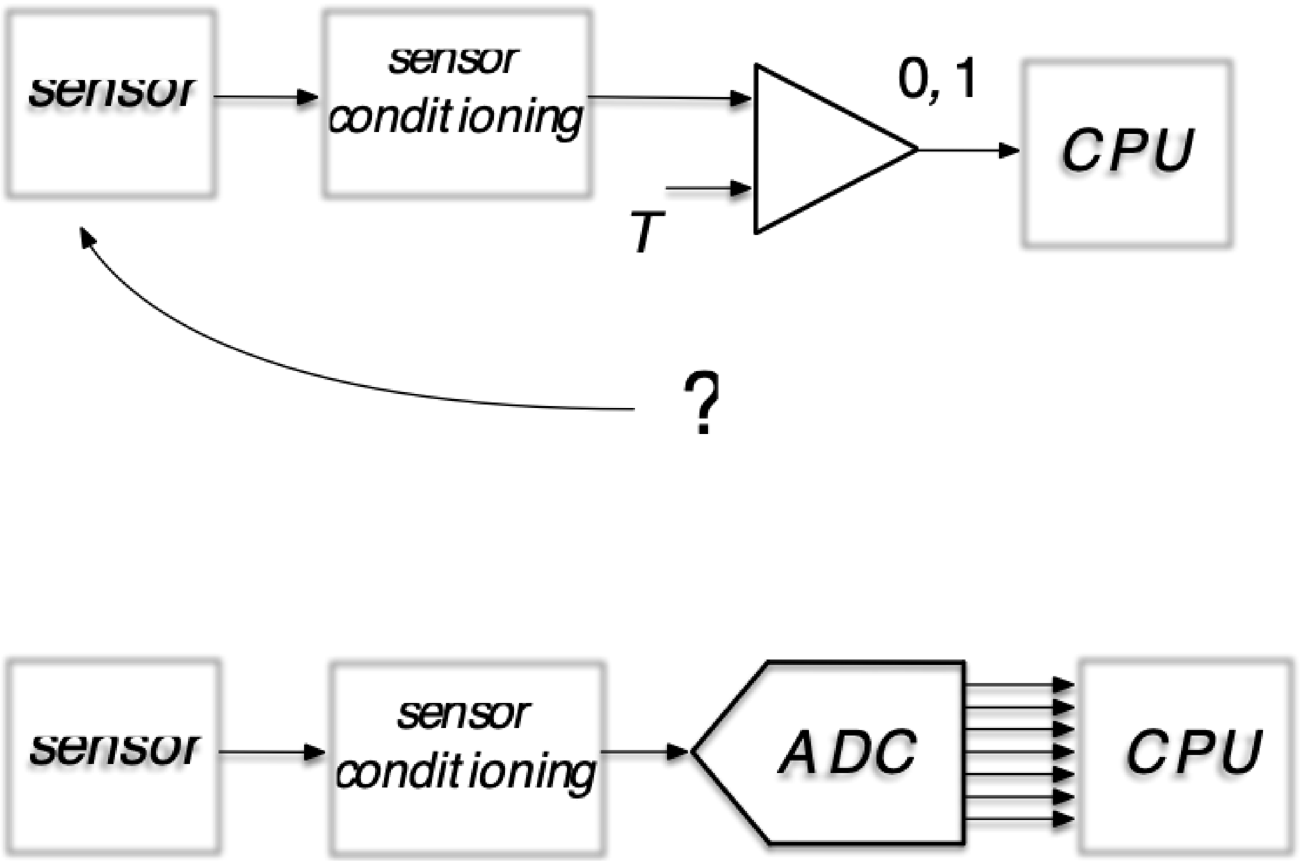
Massive parallel Ultrasound and Photoacoustic PC-based system

Weylan Thompson, Hans Peter Brecht, Sergey A. Ermilov, and Vassili Ivanov
PhotoSound Technologies, Inc., 9511 Town Park Dr., Houston, Texas 77036, USA

ONE-BIT SENSING AND MEASUREMENT

- **One-bit** is the simplest possible digital measurement approach
- When low-power is a constraint
- When system complexity can be a problem, e.g. in *analog built-in self test* systems
- When having **massive** number of channels, e.g. hundreds of channels in photoacoustic, laser-induced ultrasound, and X-ray acoustic real-time imaging applications
- When sampling at large sampling rates (e.g., >1 GSa/s) to reduce cost/complexity/power
- When reliability must be increased
- Overall, it offers new opportunities to expand measurement processes
- New developments: one-bit LLMs

THE MAIN ACQUISITION PROBLEM



- Can we still say something meaningful about the signal produced by the sensor?
- How much information can we extract from the binary data?
- How do we use prior information available about the signal?

SYSTEM AND SIGNAL SETTINGS

Assistive signals: not present, stochastic vs deterministic, no information, mean and variance known, distribution known, samples known.

Signal to be measured: periodic, quasi-periodic, sampled synchronously, asynchronously

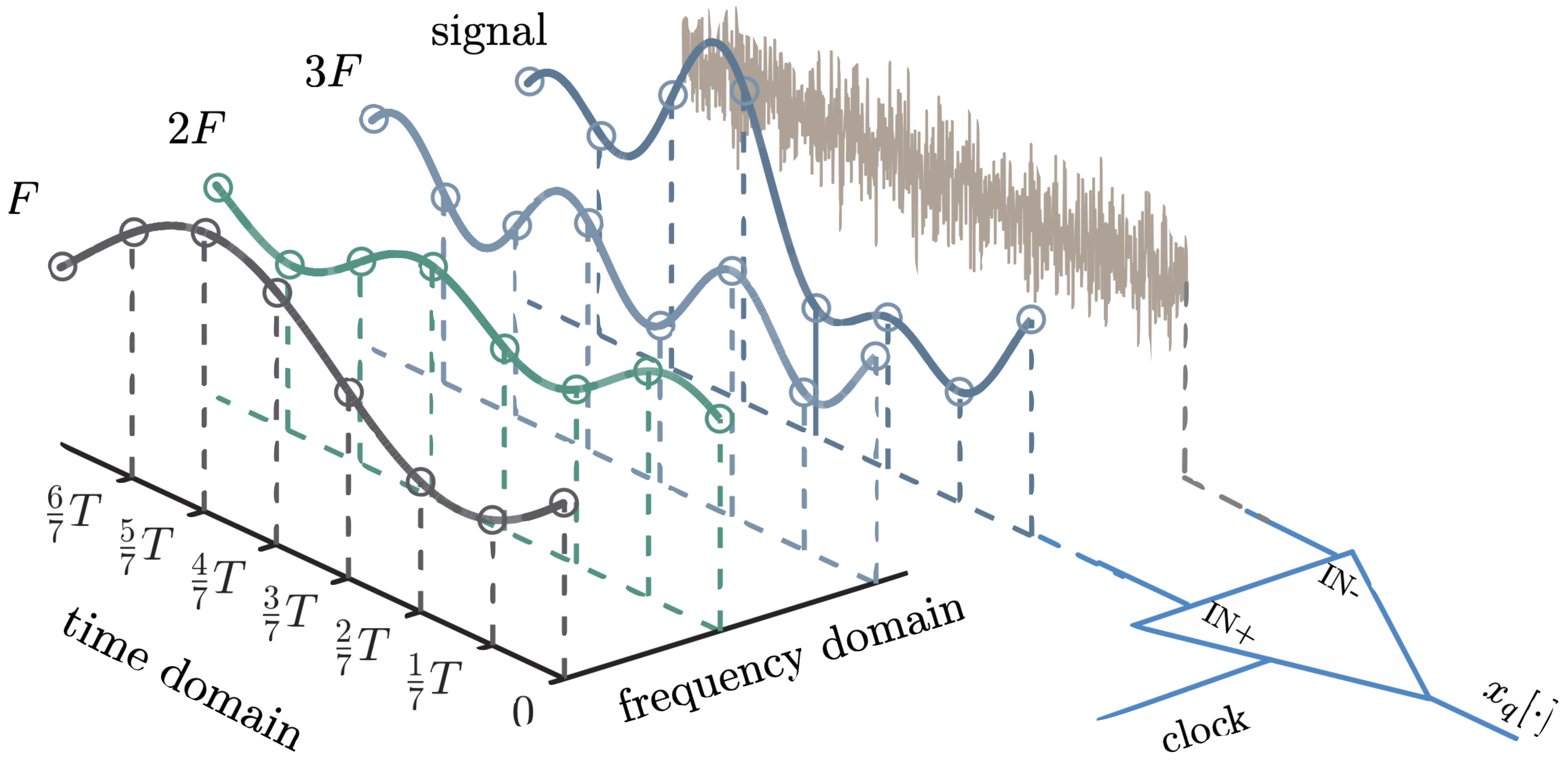
Noise: with known/unknown PDF

Various approaches available: a one-bit framework can be setup

one method is described: stochastic dither, PDF known

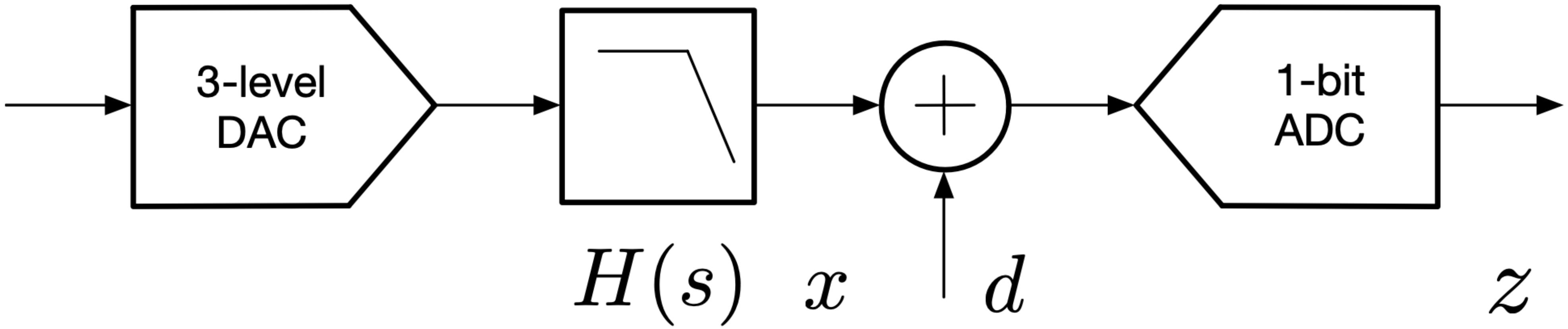
THE SETTING

- **Periodic** signal (sampled synchronously) and **random** dither (assistive signal)
- Signal frequency known
- Know the *dither* probability density function (PDF)
- **Estimate amplitudes** and **phases** using one-bit sequence



EXAMPLE: 1.5 BIT FOURIER ANALYZER

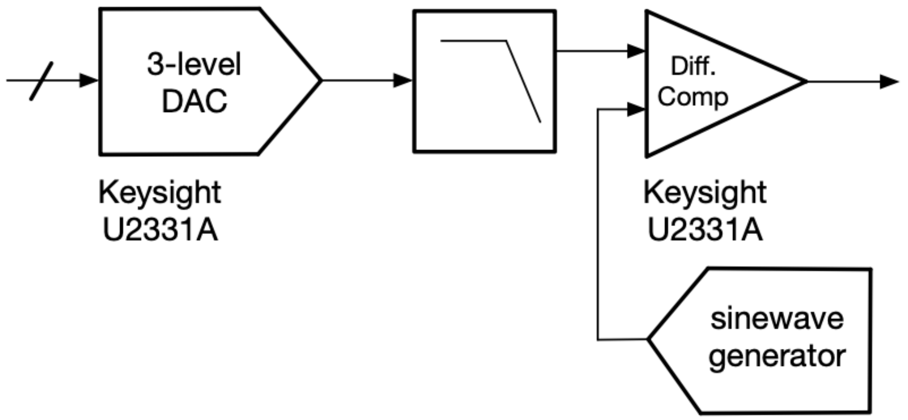
Measure the FRF of a linear system

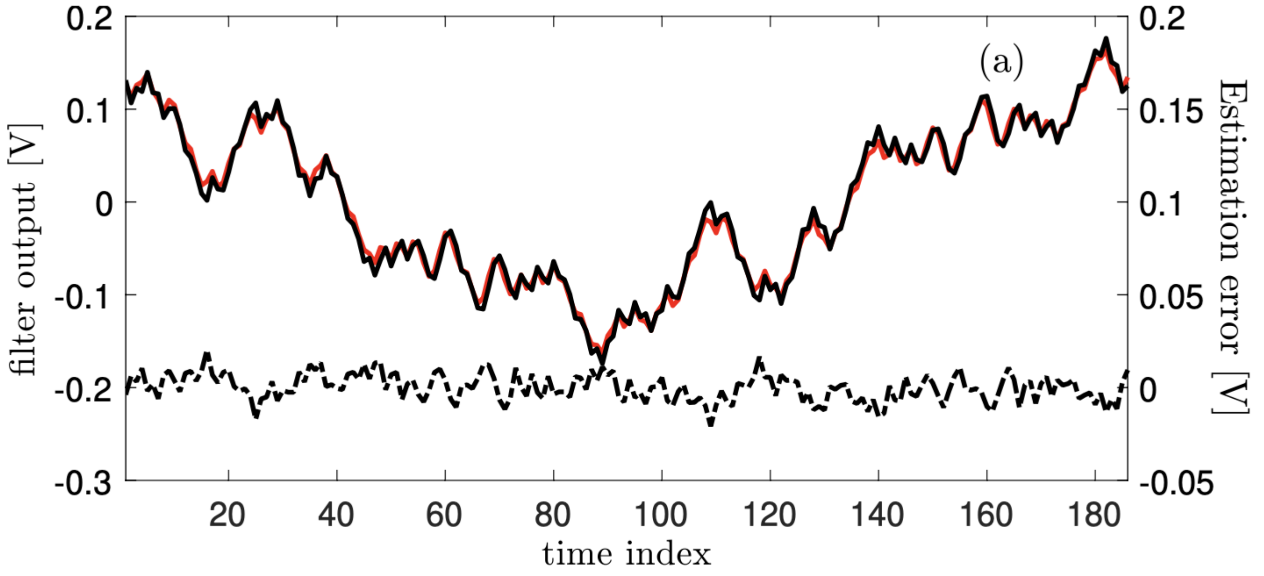


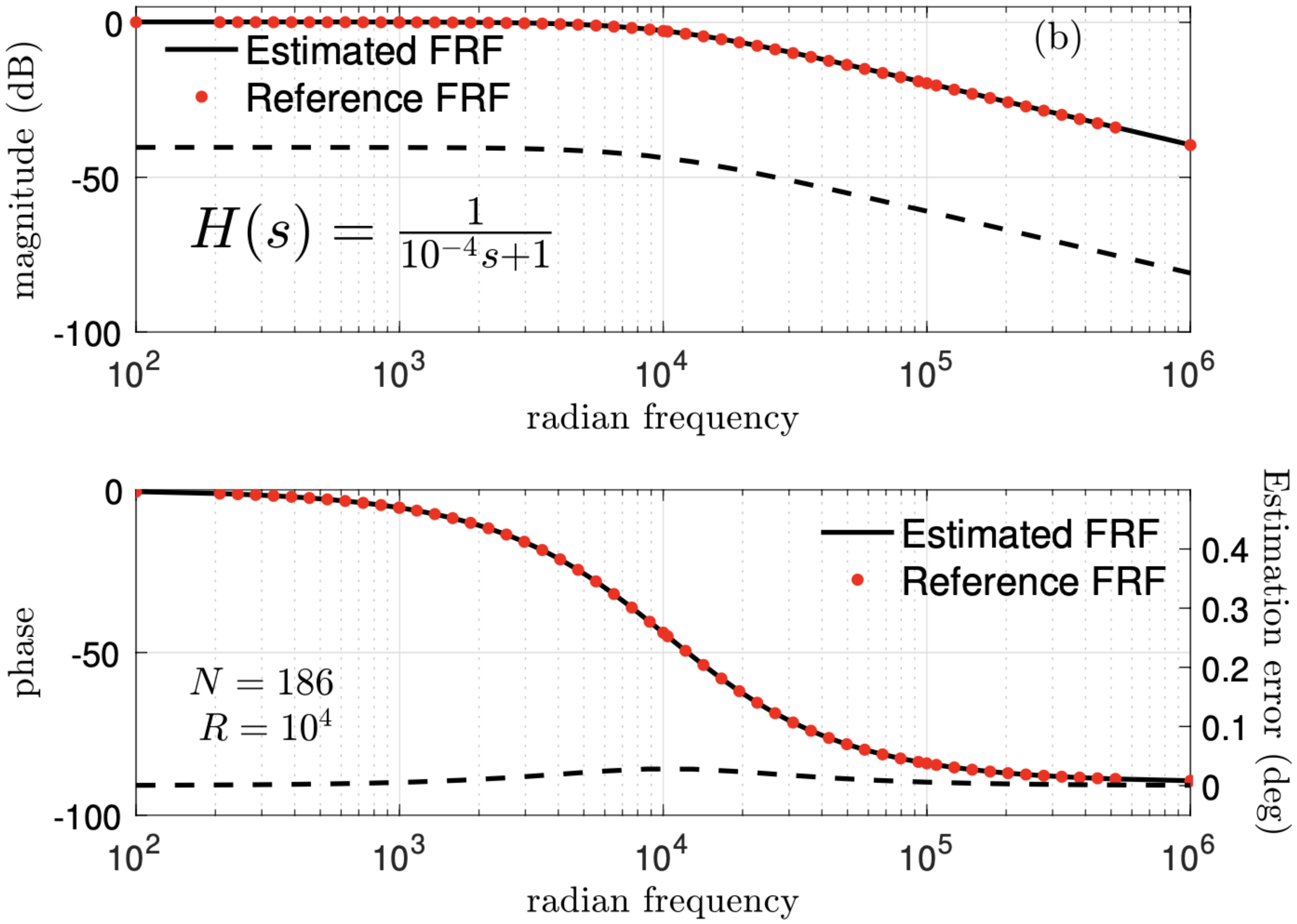
3-level DAC to allow detection of **nonlinear** behavior; binary DAC would suffice otherwise

Sinewave dither (treated as **random** dither) with known PDF (bath-tube)

MEASURING THE FRF: EXPERIMENTS







WORKING EXAMPLES

MATERIAL SENSING USING ONE-BIT

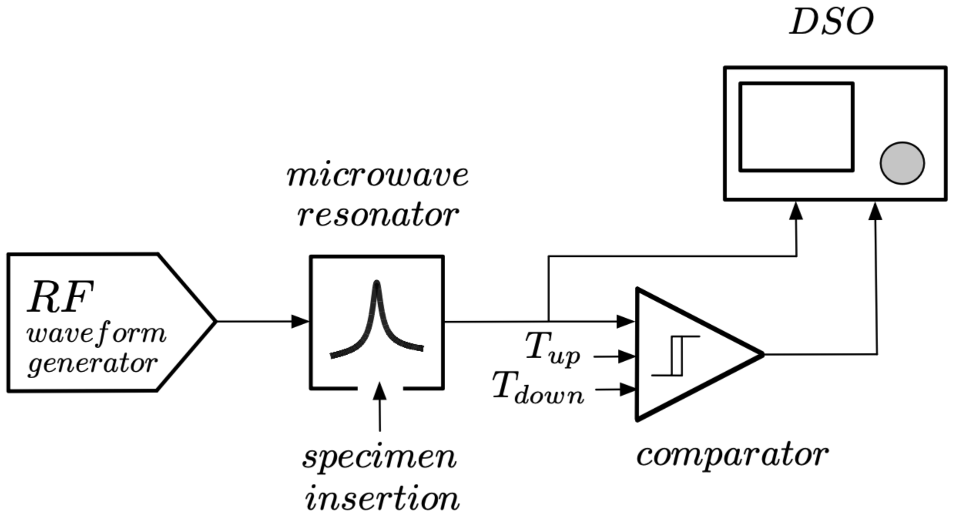
Conventional approach uses energy detector / RF direct digital receivers

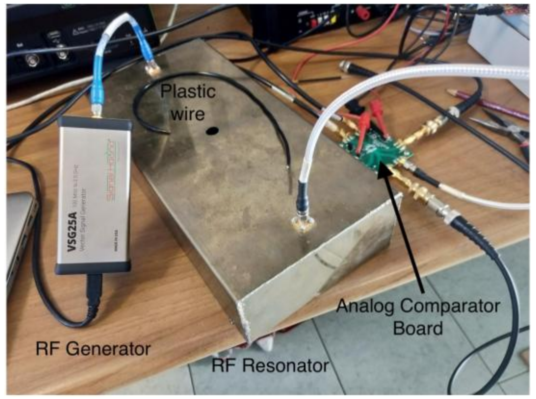
Time-domain analysis based on commercial one-bit comparator @ 1.745 GSa/s

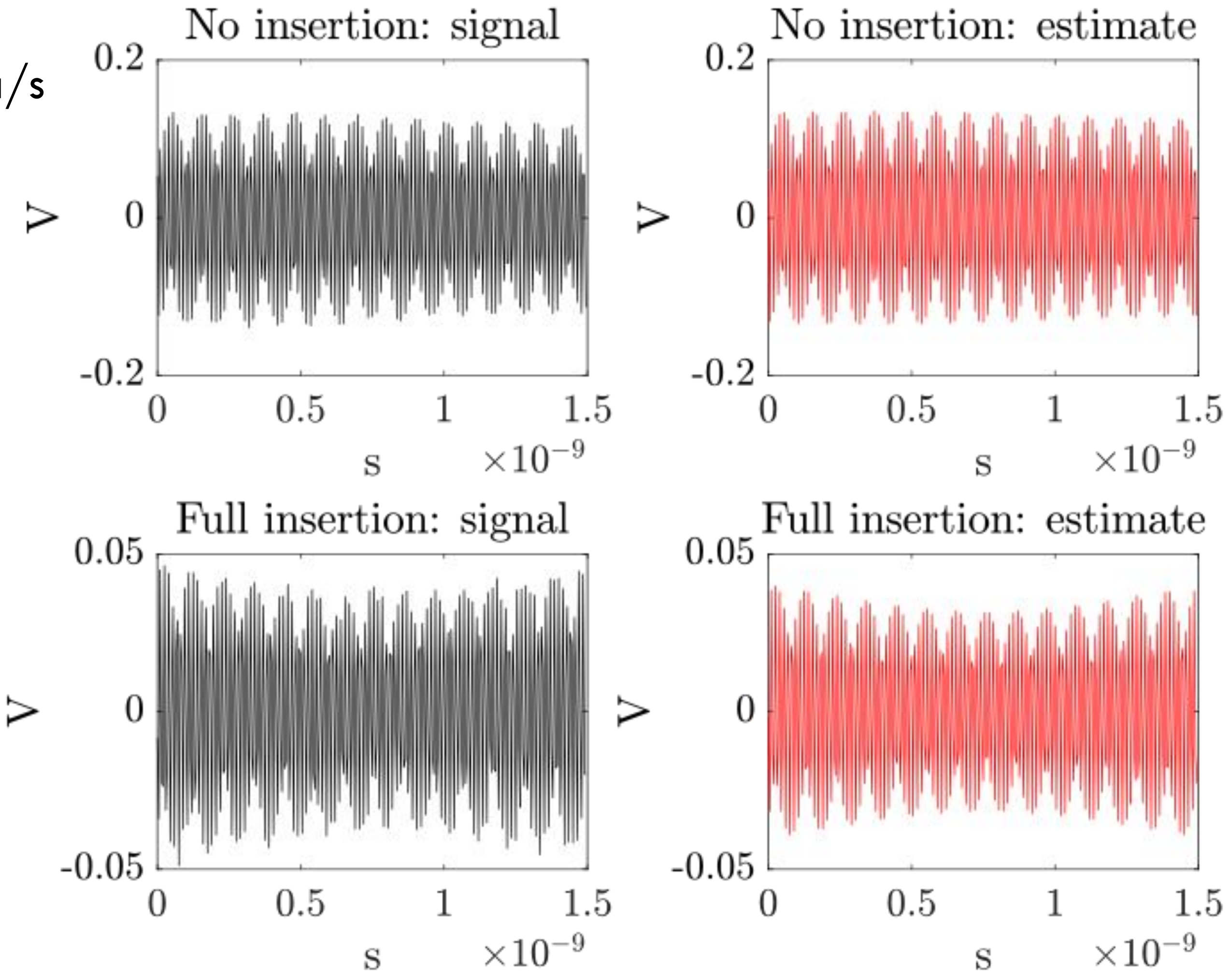
FRF response function shifts as a function of the MUT

Texas instruments comparator TLV 3801, laboratory microwave resonator, Teledyne Lecroy DSO

Two component excitation signal – no assistive signals





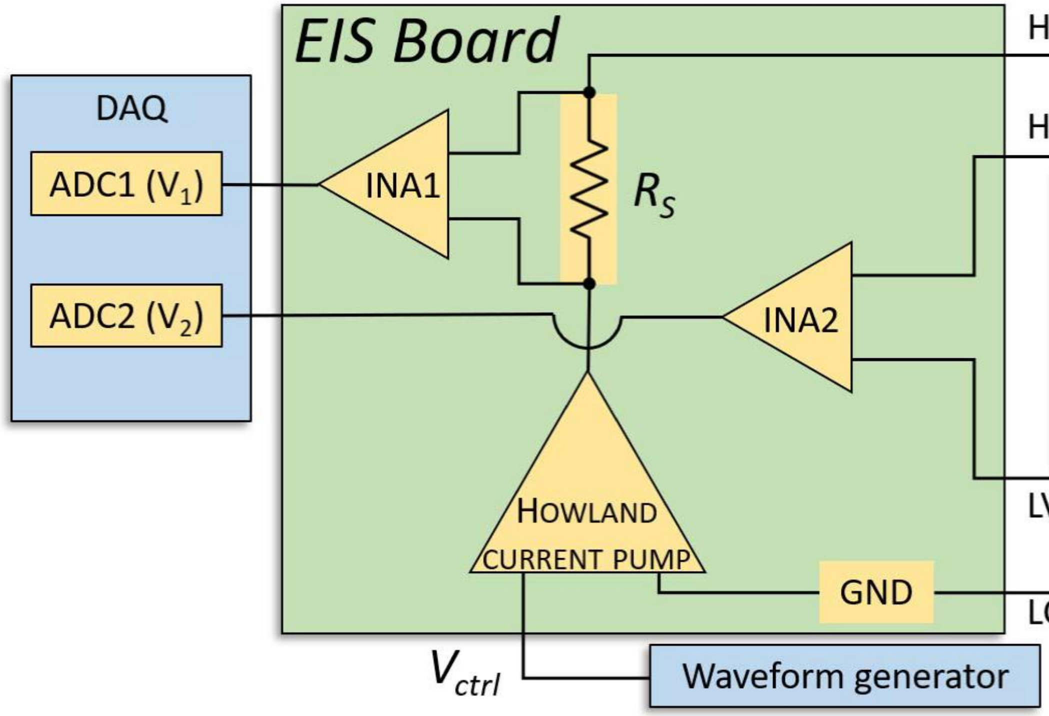


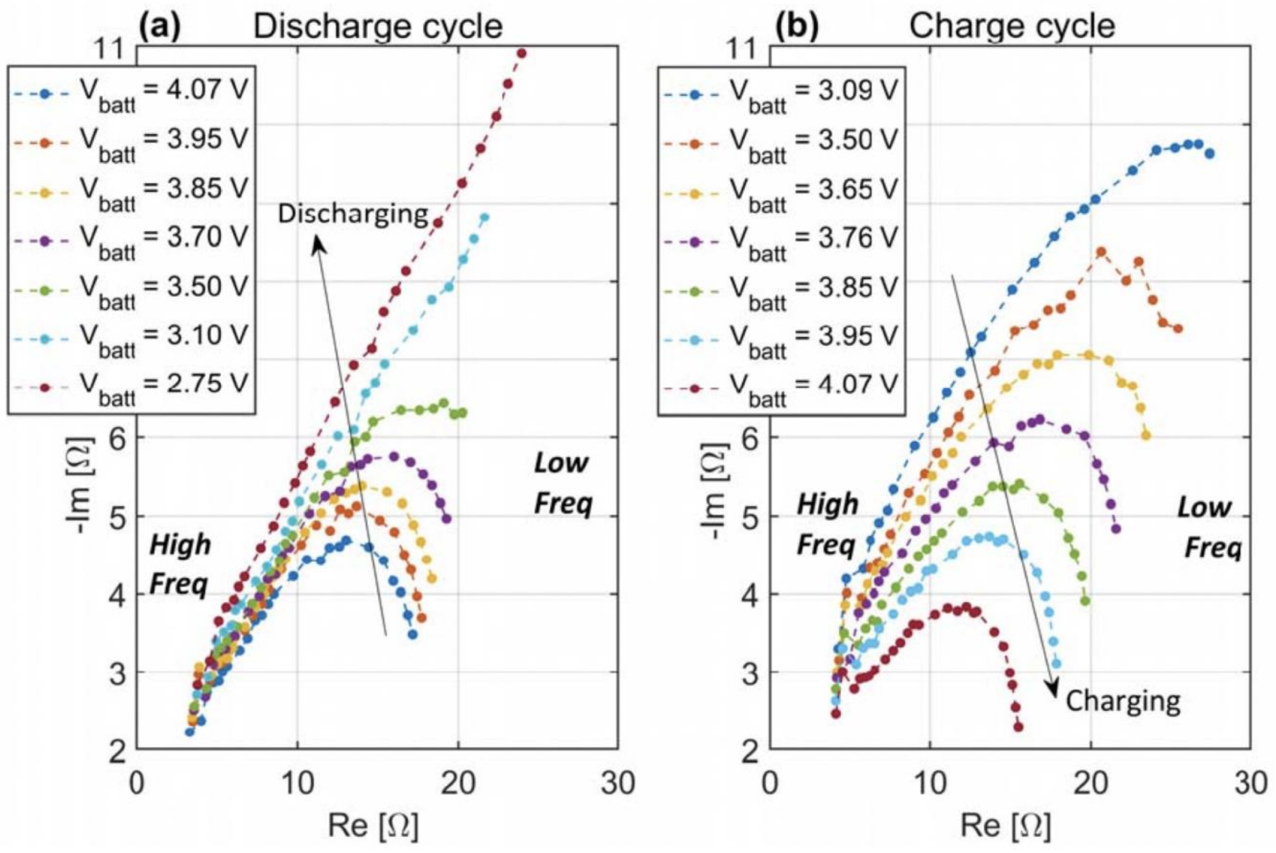
MEASURING THE IMPEDANCE OF A RECHARGEABLE BATTERY

Electrochemical impedance spectroscopy (EIS) for assessing SOC, SOH of rechargeable batteries

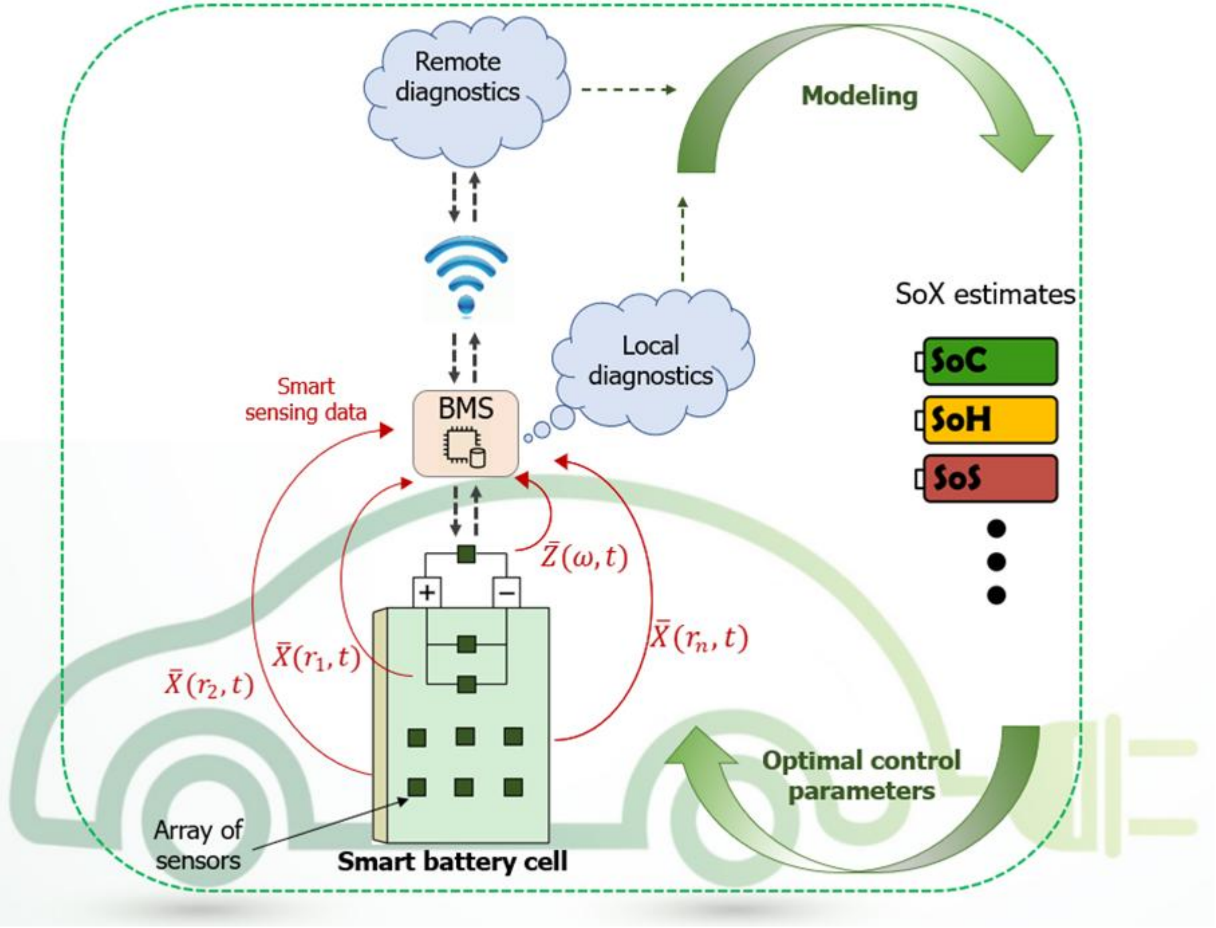
Measure battery impedance

Simplest setup: current excitation and voltage measurements at the battery contacts





ONLINE EIS OF BATTERY CELLS



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IN-SITU monitoring

Compact system or integrated into the battery cell

Low-cost system for mounting on every single cell

VLSI technology enables simple integration within the battery

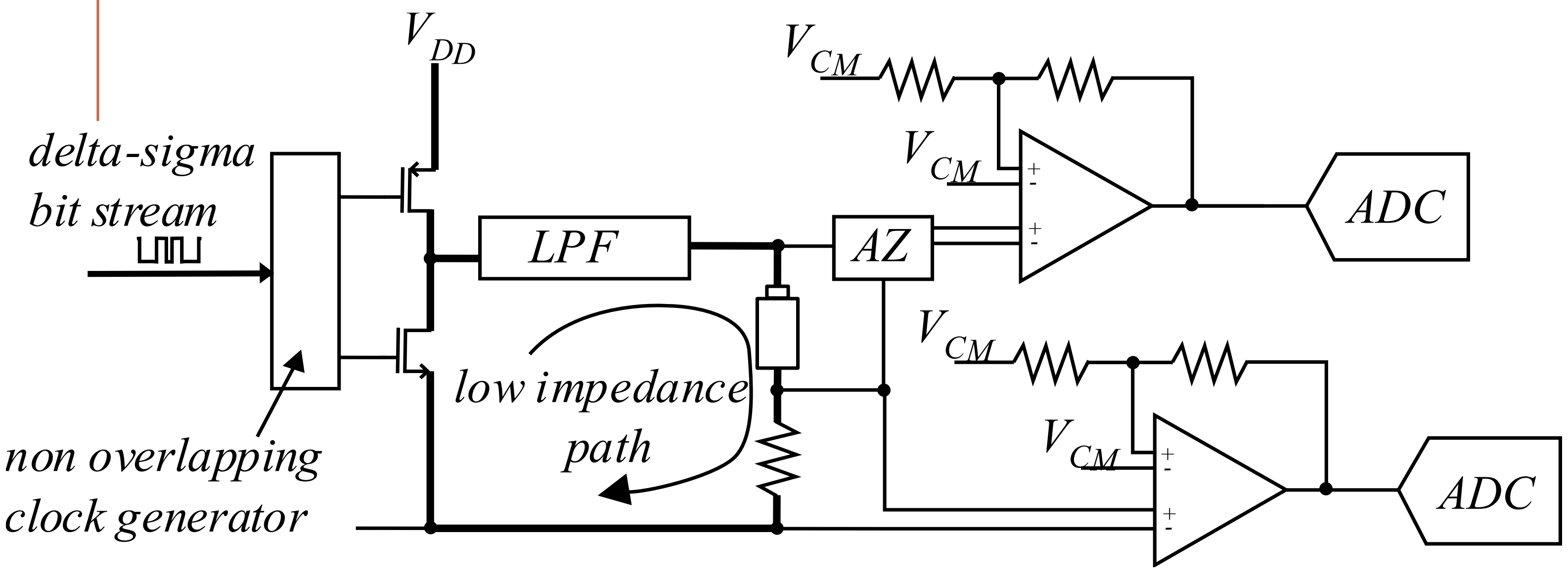
IN-OPERANDO monitoring

Fast measurement time while the battery is working

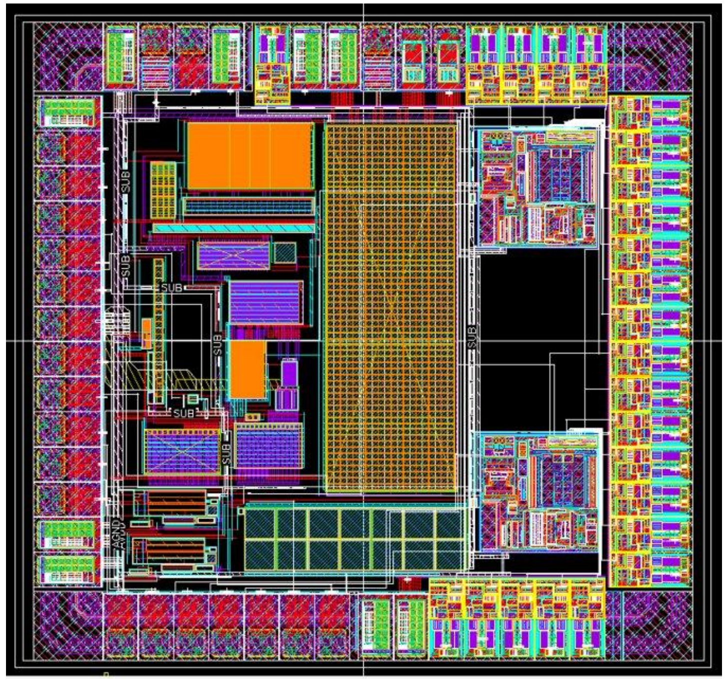
Accurate estimate of small battery impedance values

Efficient estimation algorithms

IN-SITU: INTEGRATED EIS MEASUREMENT SYSTEM



BCD110ap 90 nm



Taped-out in May 2025

Extended current excitation up to 50 mA

Half-bridge excitation exploiting BCD110ap capabilities

1.5 bit excitation (push/pull current and totally off)

Automatic AZ circuit for DC battery voltage removal

2-voltage measurement with offset adjustment

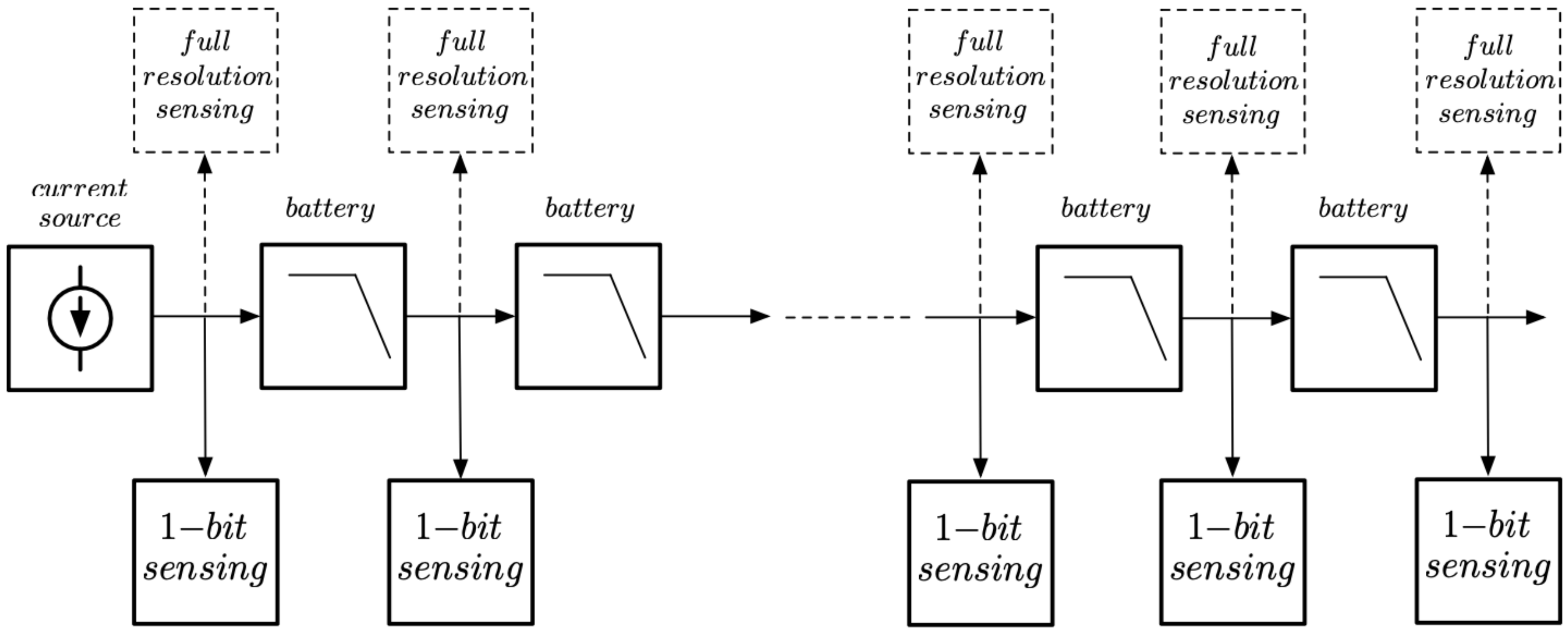
Low-impedance node designed using integrated thick copper layer

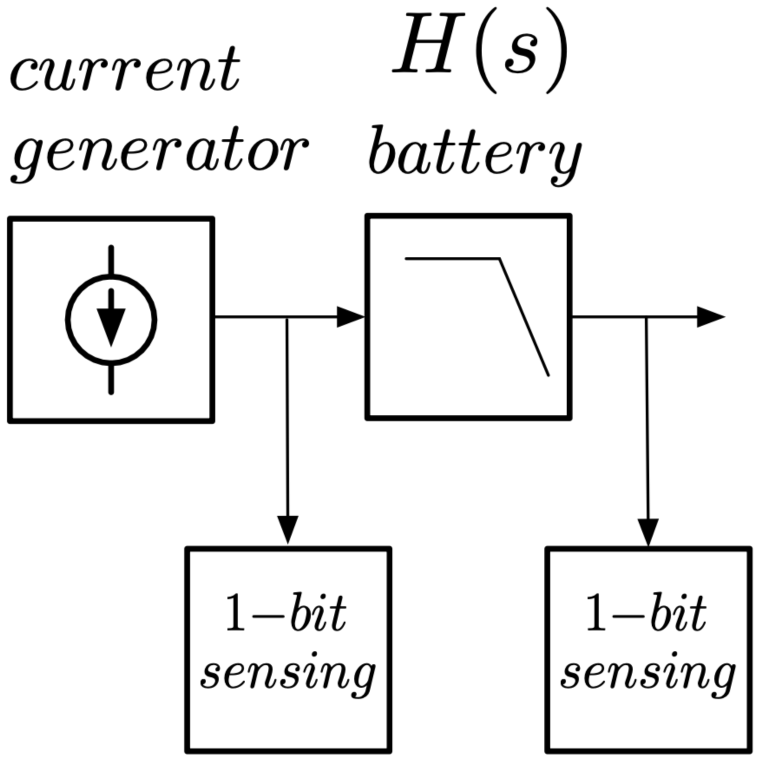
Integrated 10-bit ADC for coherent sampling

MODULE/PACK-LEVEL ONE-BIT ARCHITECTURE

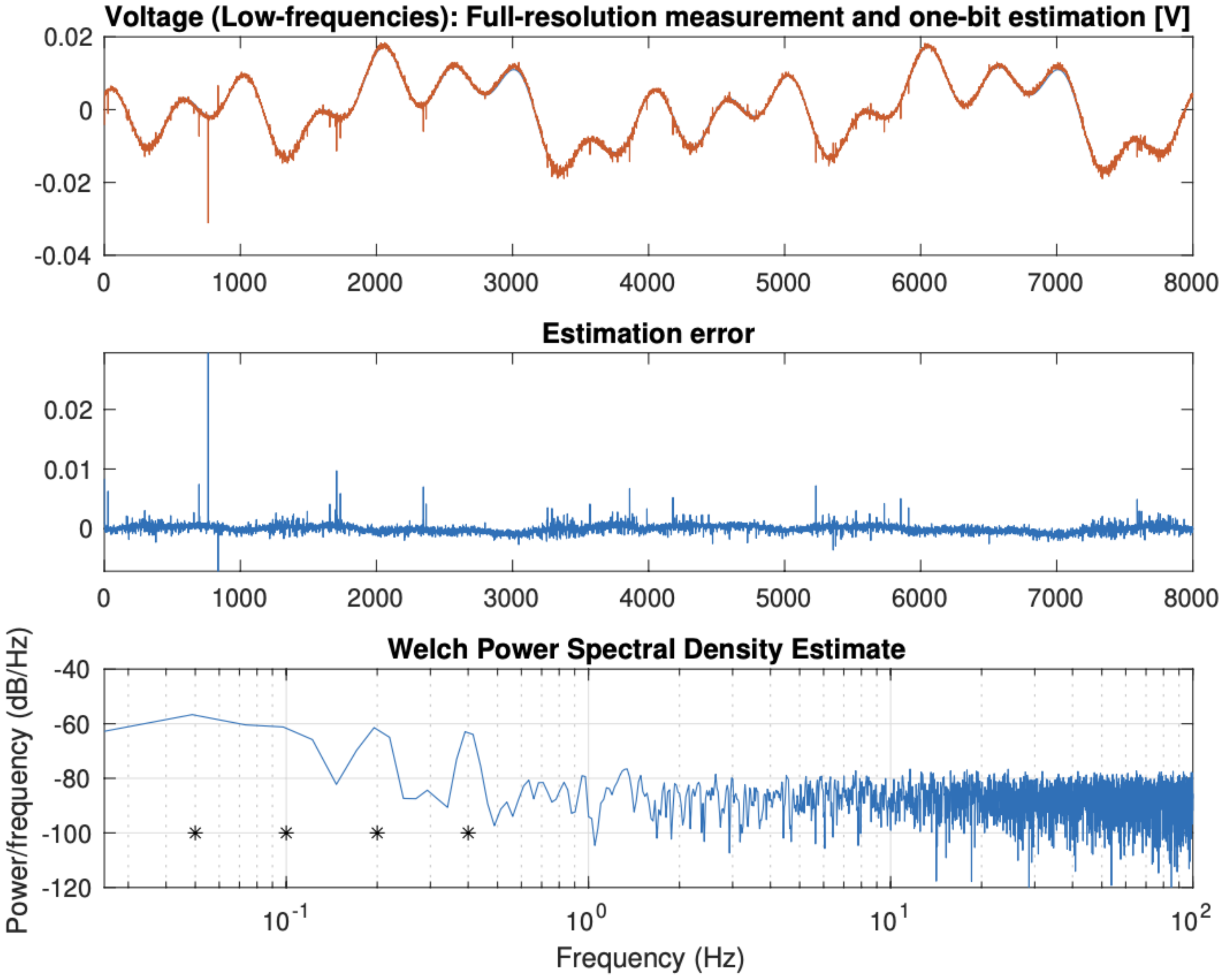
Systems may include thousands of rechargeable battery cells

Would it be possible to realize a one-bit simplified architecture to perform EIS at battery cell level?



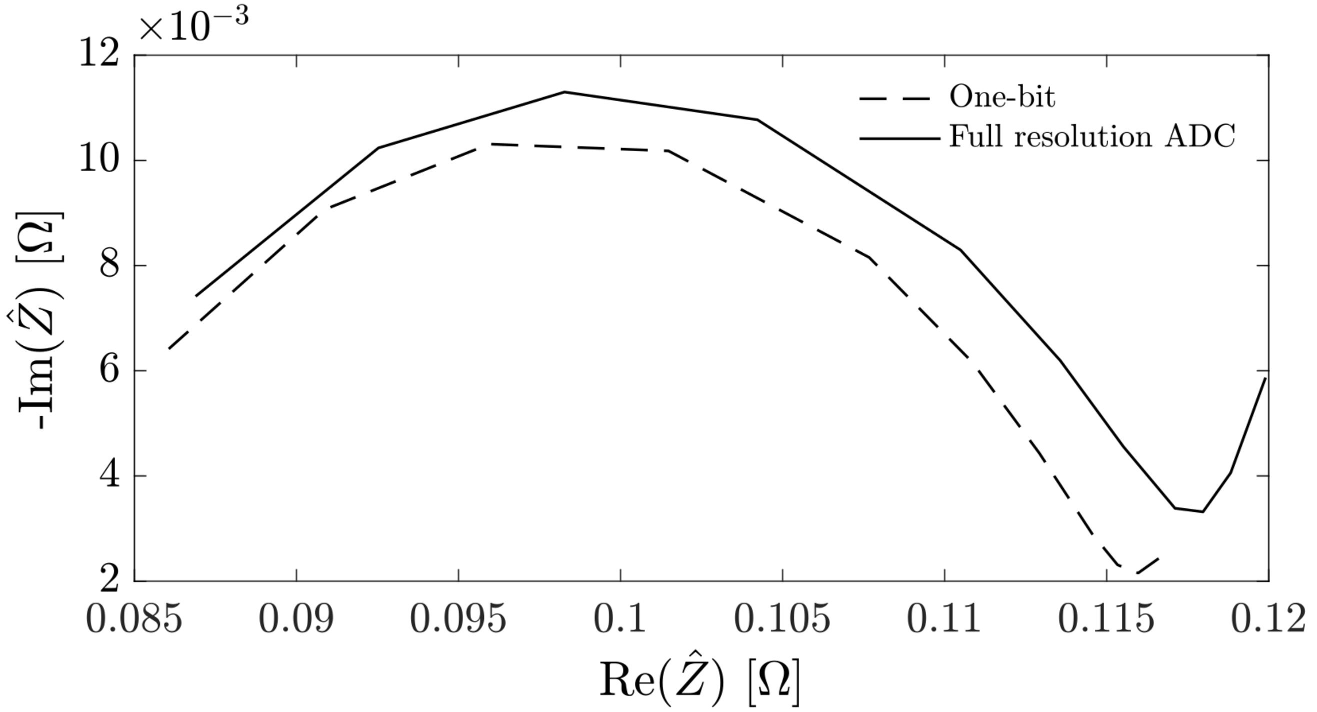


ONE-BIT EIS: MEASUREMENT RESULTS

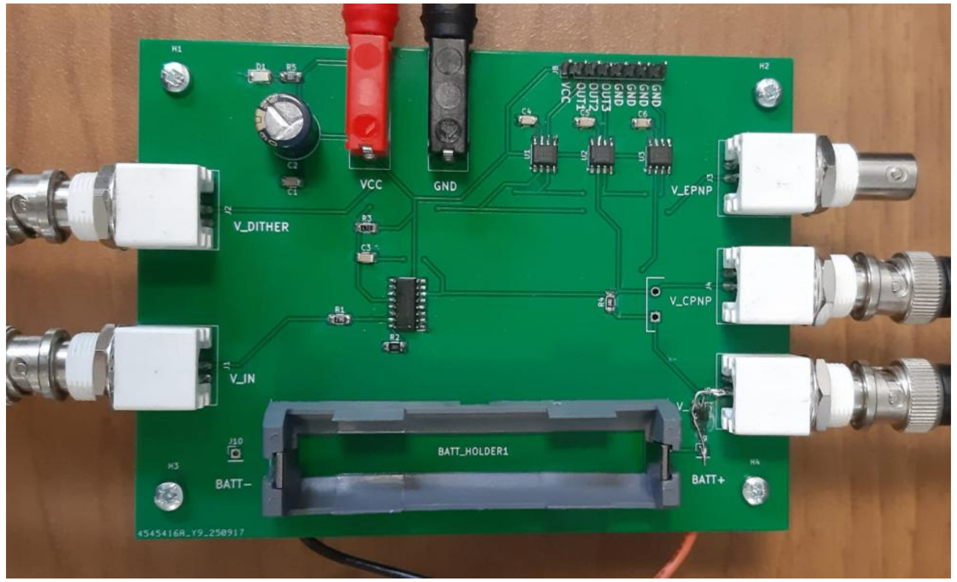


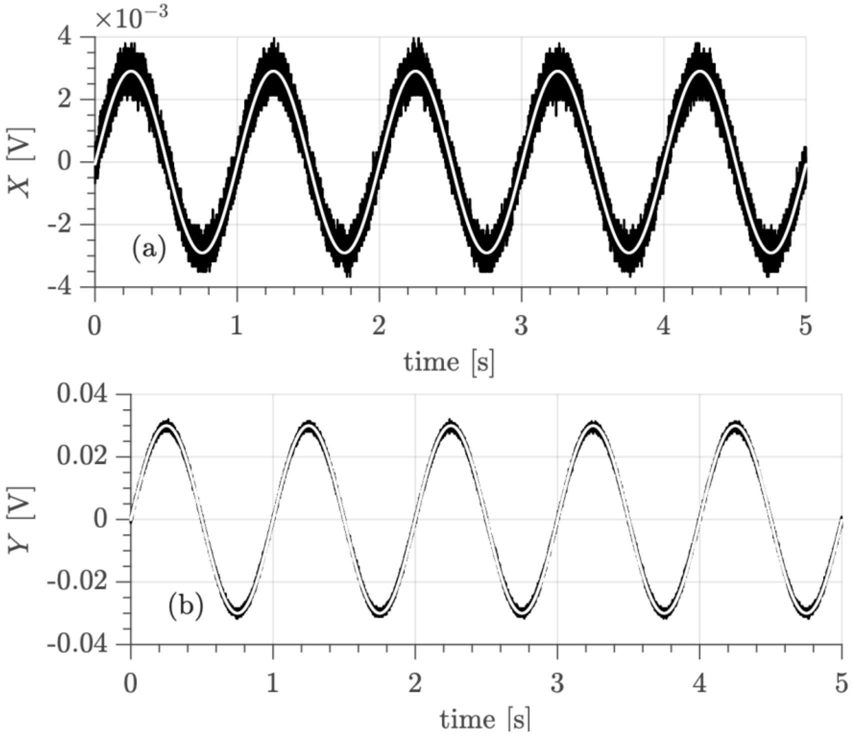
Voltage and current measurements

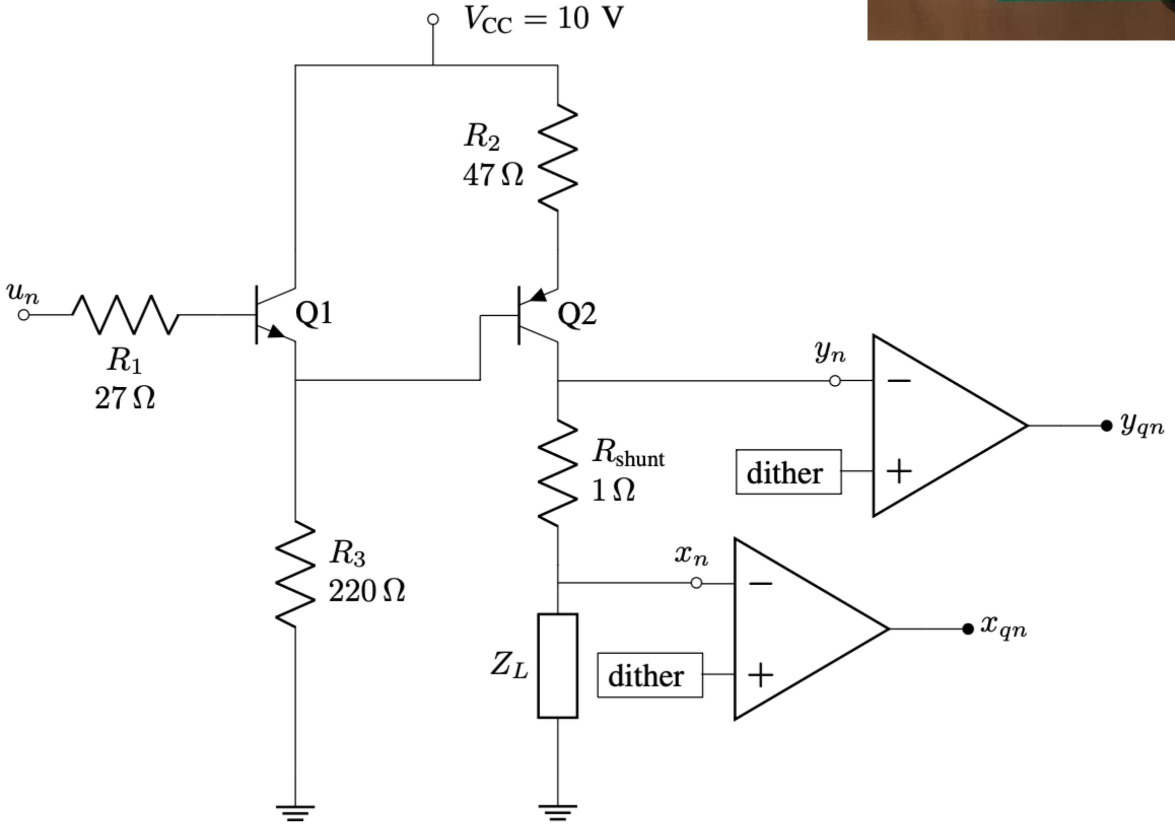
16 bit full-resolution measurements shown for comparison

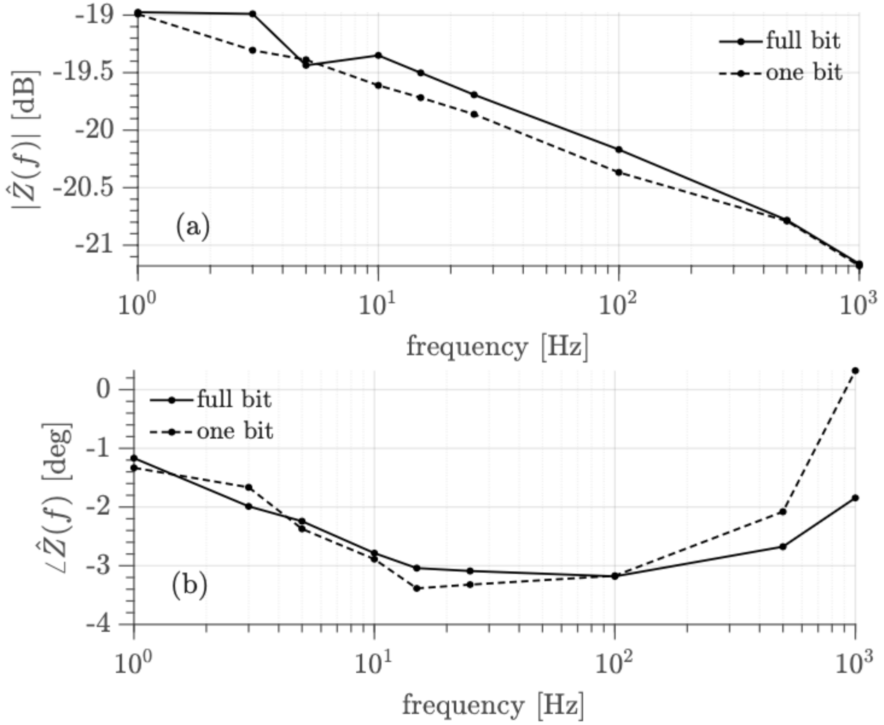


REALIZATION









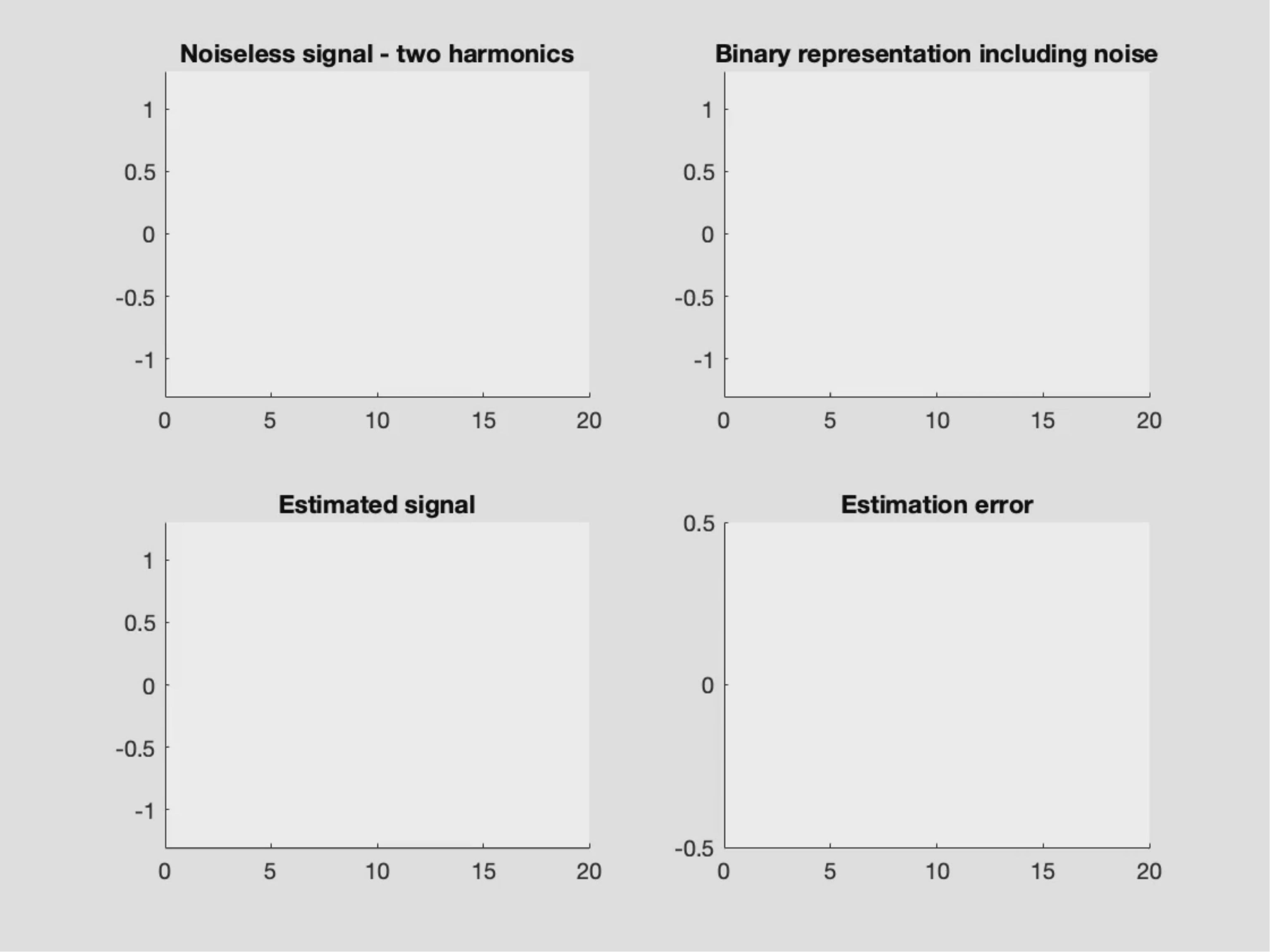
SEQUENTIAL ALGORITHM

two-component signal, **no assistive signals**, Gaussian noise, threshold at 0.25 V

sudden change in signal amplitude after 10 s

Estimation based on processing the most recent 4(samples (*windowed* approach)

Estimation starts after the first 400 samples



CONCLUSION

- **Sustainable electronics requires new ways of thinking**
Low-complexity, low-power measurement approaches are essential for reliable, energy-efficient systems

- **Metrology is a driver of sustainability**
From IC manufacturing to e-waste recycling, meaningful measurements reduce waste, improve yield, and support responsible lifecycle design

- **Education shapes future impact**
Embedding sustainability, lifecycle awareness, and eco-design into STEM curricula empowers the next generation to engineer responsibly

- **Innovation enables climate-aware behavior**
Clear communication, transparent reporting, and user-centric tools help individuals and industries make better environmental decisions

- **The path forward**
Combine advanced measurement science, sustainable engineering, and global collaboration to create electronics that serve both humanity and the planet

IN THE END, REMEMBER …

Obrigado!

Periodic signal recovery using binary samples is possible with random/deterministic assistive signals, e.g. FRF measurement

Validation might be possible by estimating the error PDF after the estimation
Calibration might be necessary
Works as well when periodic signal sampling is asynchronous
More complex algorithms when the signal frequency is unknown
Few conditions must be respected for consistent signal estimation (e.g. what if all zeros or ones?)
Other techniques available that do not require assistive signals

Obrigado