Low-Power System Design

227-0781-00L

Fall Semester 2019

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Plan for Today

- Focus on methods for assessing power consumption
  - Direct measurements
  - Indirect measurements
  - Estimation methods
  - High dynamic range
- Scaling up the design space:
  - Network-wide view of state and power with sensor network testbeds
- Testing Methods
- Modeling Technique
- Validation using Formal Methods
- In-Band/In-System Validation using Assertions

Low-Power System Design

MODELING, TOOLS AND METHODS FOR POWER ANALYSIS

Highly Resource Constrained

Distributed State

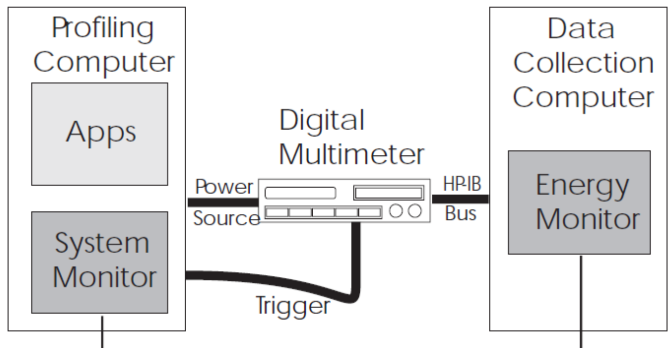
Wireless Networked Embedded Systems

Unreliable Communication

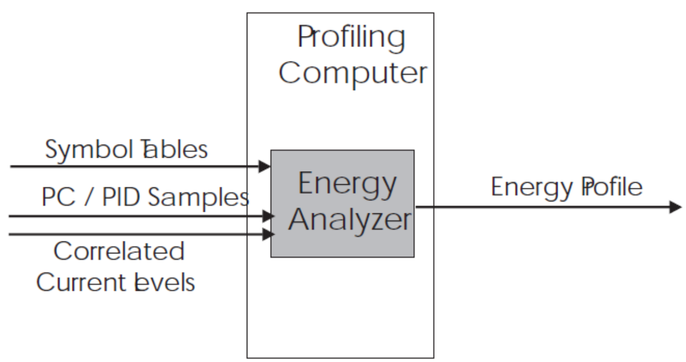
Interaction and Tight Embedding in Environment

Assessing Power Consumption

- Two main categories
  - Direct measurement using subsystem power sensors and meters



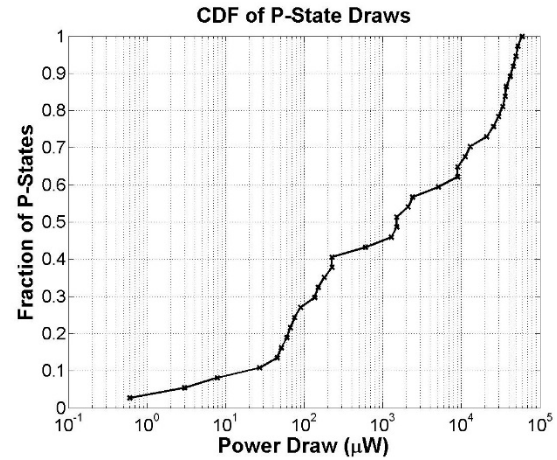
  - Indirect estimation based on information provided like temperature or performance counters and a model



Jason Flinn and M. Satyanarayanan, "Energy-Aware Adaptation for Mobile Apps.", SOSP'99, Kiawah Island, SC, 1999

Key Issues With RT Power Estimation

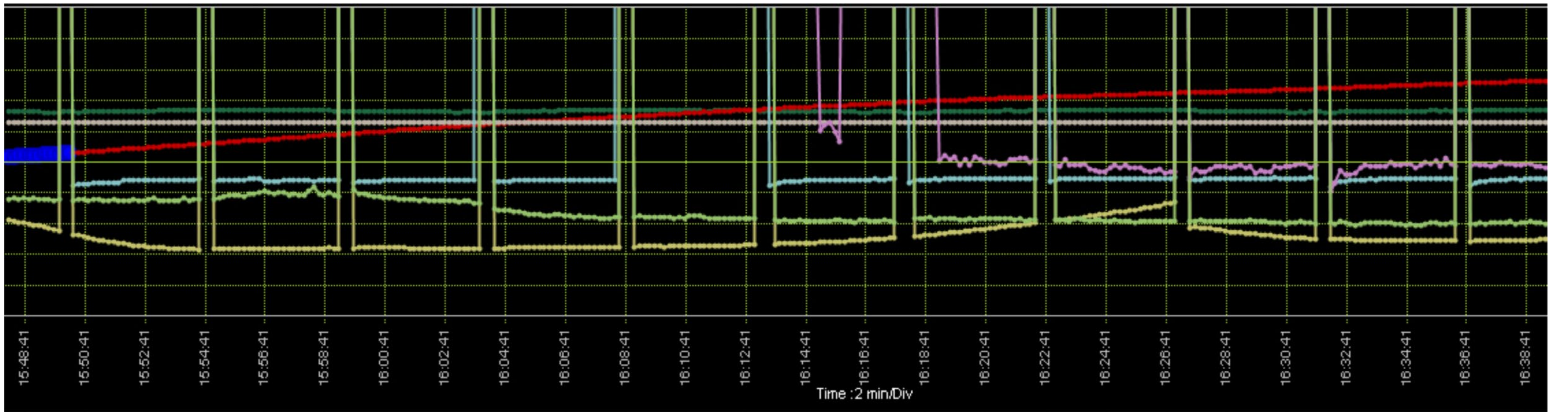
- Excessive dynamics
  - Large dynamic range
  - Fast transients
  - Spurious events (low frequency)
  - Capacitances smooth out details



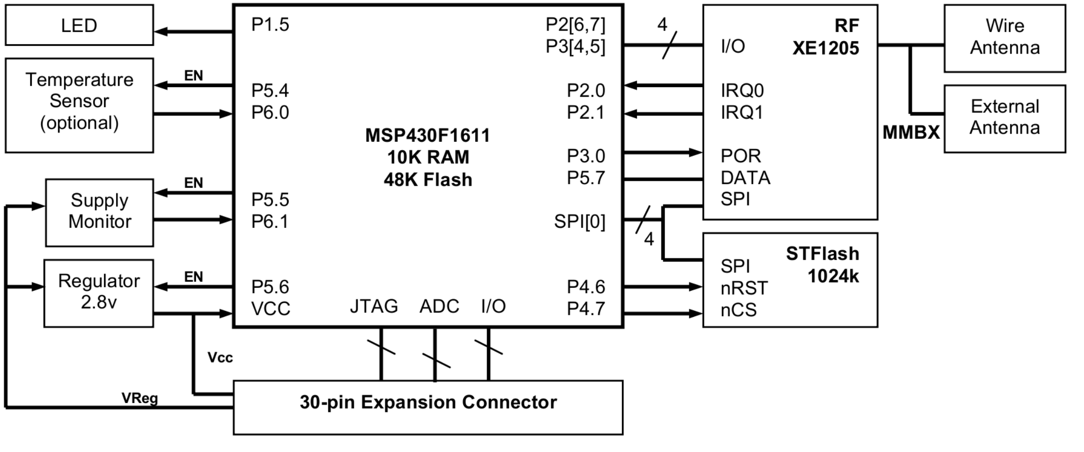
- Access to appropriate resources
  - Only few components have metering capabilities designed in

- Appropriate models
  - Dealing with complex, non-linear systems
  - Calibration
  - Often, simple approaches show remarkable success
  - Interpretation of power data

Power Traces are Complex and Long



… and a wireless node is MUCH more than the processor



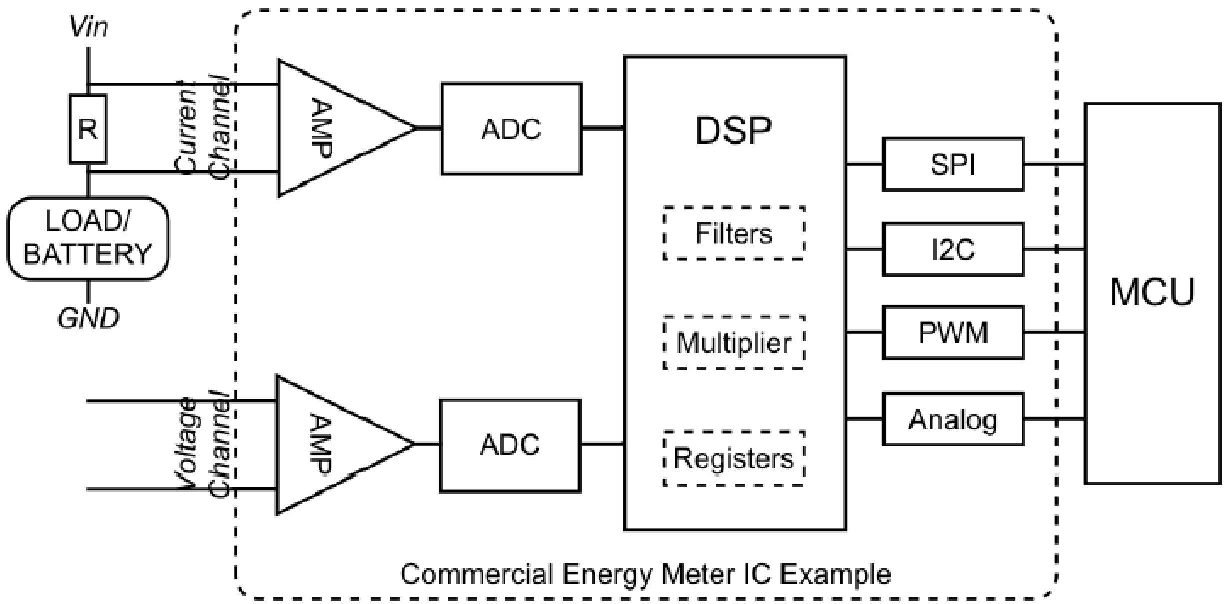
ETH zürich

Low-Power System Design

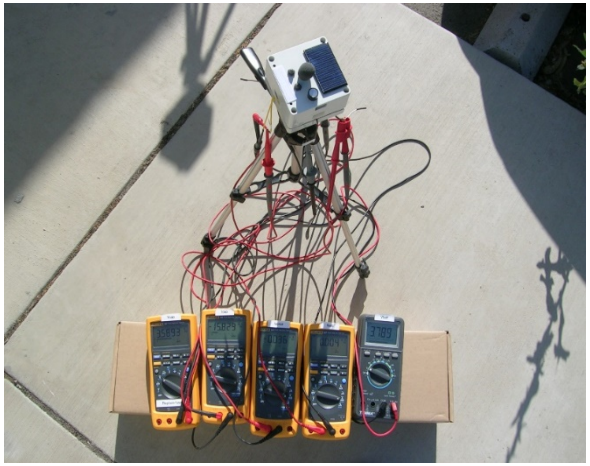
MEASURING POWER CONSUMPTION

A Basic Power Meter Architecture

- Resistive Method
- Shunt with differential amplifier
- Integrated in the power supply path

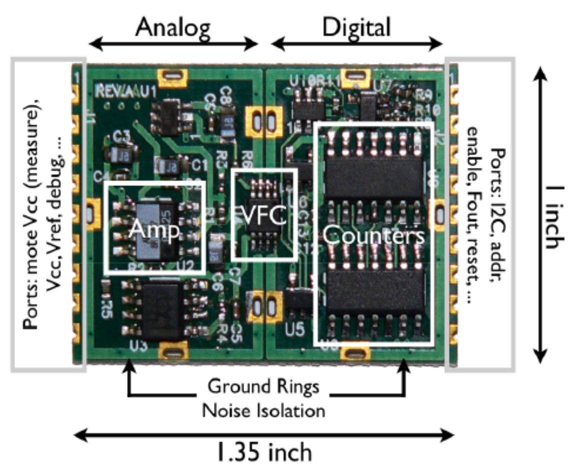


Current Metering Techniques



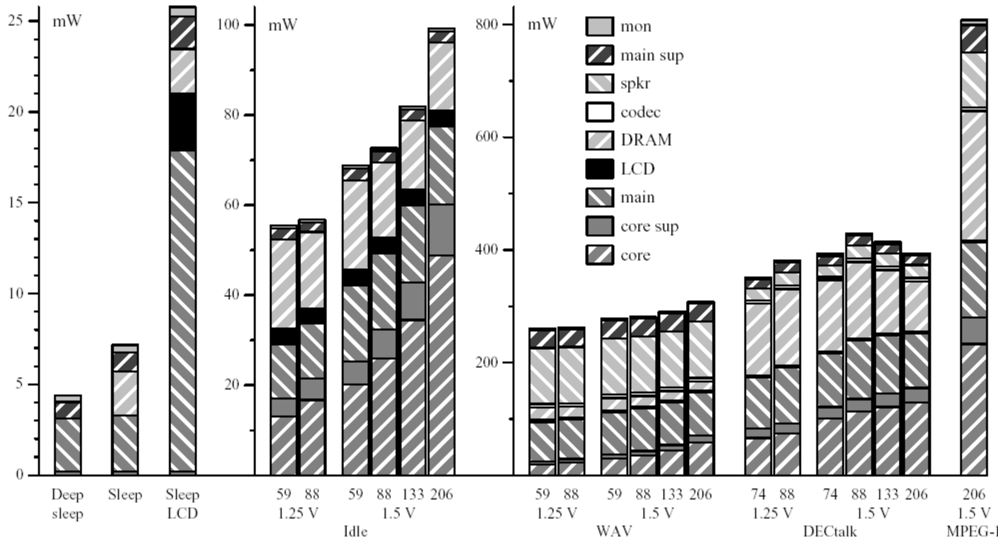
cumbersome, expensive, not distributed, not scalable, not embedded, low resolution

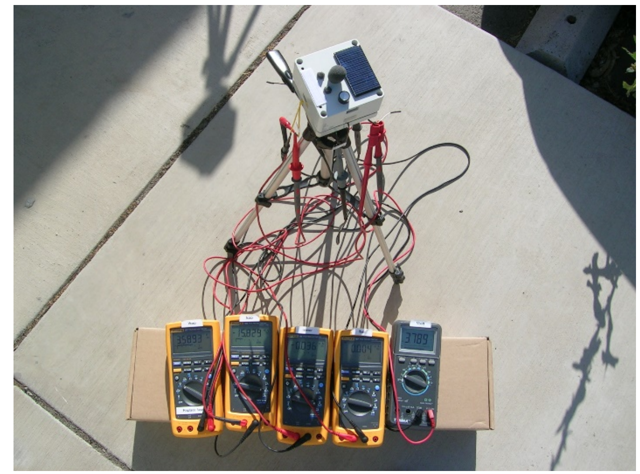
expensive, not distributed, not scalable, not embedded,



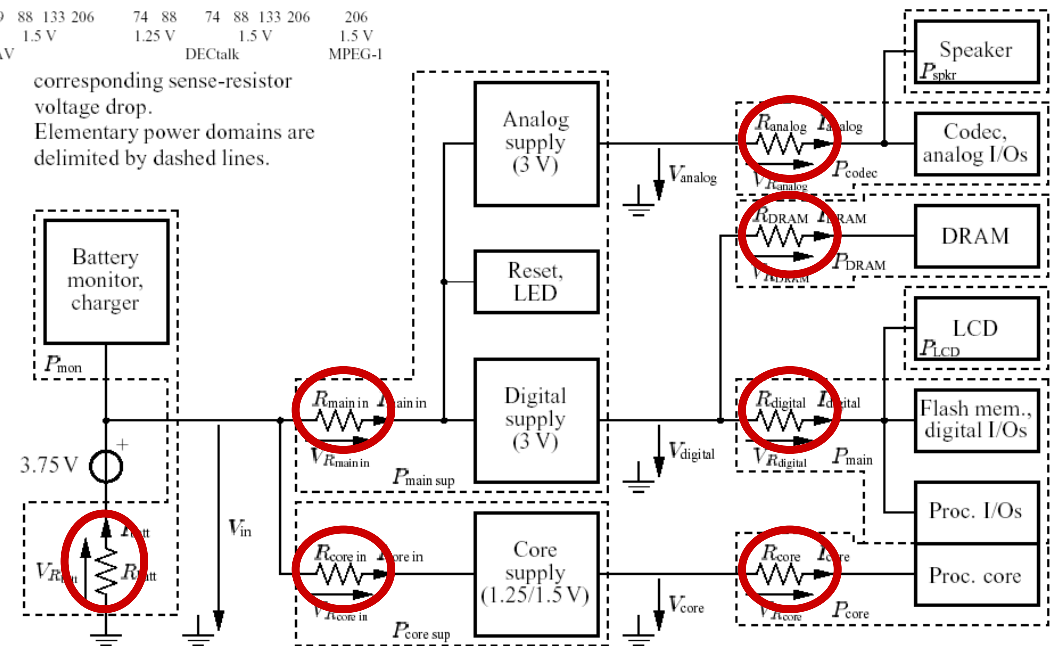
low resolution, low responsiveness, high cost, high quiescent power

Fine-grained Power Break-down





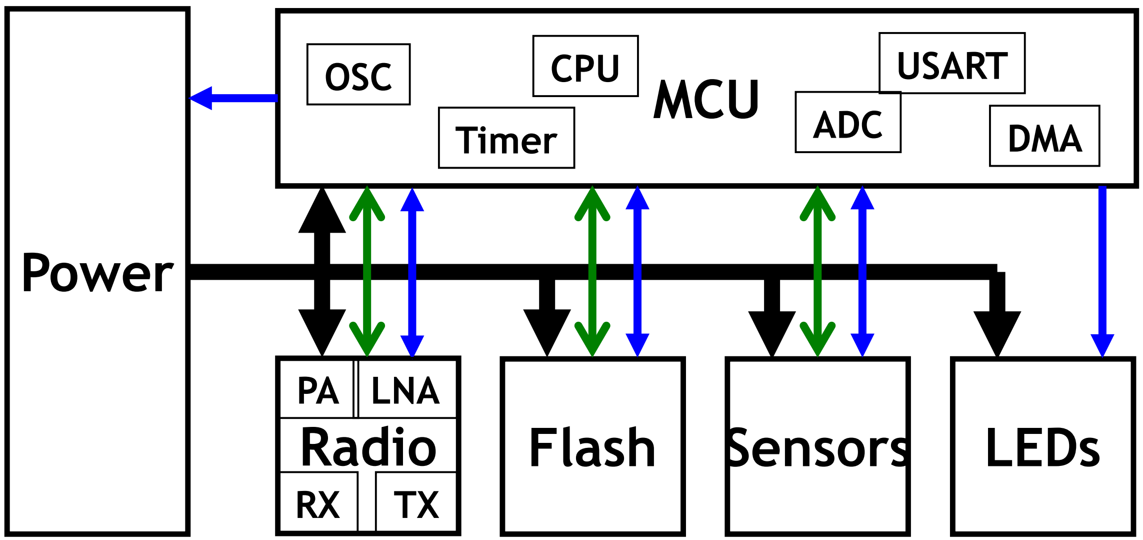
corresponding sense-resistor voltage drop.
Elementary power domains are delimited by dashed lines.



Marc A. Viredaz and Deborah A. Wallach, *"Power Evaluation of a Handheld Computer"*, IEEE Micro, Jan-Feb, 2003

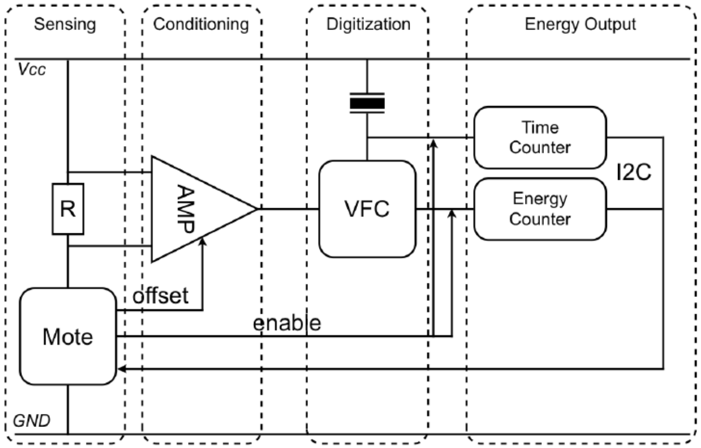
Not All Energy Sinks Can Be Instrumented

State-based characterization and simple system models

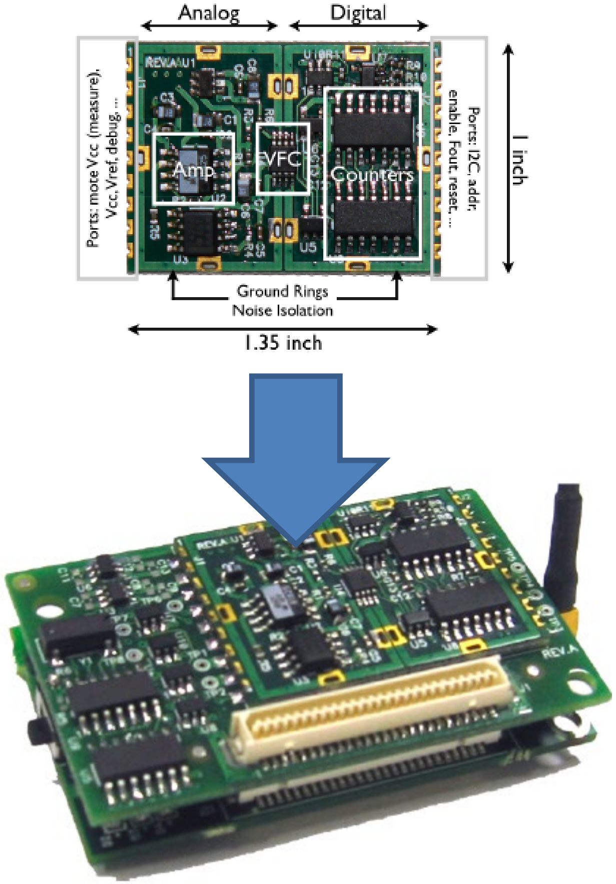


Energy Sink	Power State	Current
Microcontroller		
CPU	ACTIVE	500 μA
	LPM0	75 μA
	LPM1†	75 μA
	LPM2	17 μA
	LPM3	2.6 μA
	LPM4	0.2 μA
Voltage Reference	ON	500 μA
ADC	CONVERTING	800 μA
DAC	CONVERTING-2	50 μA
	CONVERTING-5	200 μA
	CONVERTING-7	700 μA
Internal Flash	PROGRAM	3 mA
	ERASE	3 mA
Temperature Sensor	SAMPLE	60 μA
Analog Comparator	COMPARE	45 μA
Supply Supervisor	ON	15 μA
Radio		
Regulator	OFF	1 μA
	ON	22 μA
	POWER_DOWN	20 μA
Batter Monitor	ENABLED	30 μA
Control Path	IDLE	426 μA
Rx Data Path	RX (LISTEN)	19.7 mA
Tx Data Path	TX (+0 dBm)	17.4 mA
	TX (-1 dBm)	16.5 mA
	TX (-3 dBm)	15.2 mA
	TX (-5 dBm)	13.9 mA
	TX (-7 dBm)	12.5 mA
	TX (-10 dBm)	11.2 mA
	TX (-15 dBm)	9.9 mA
	TX (-25 dBm)	8.5 mA
Flash	POWER_DOWN	9 μA
	STANDBY	25 μA
	READ	7 mA
	WRITE	12 mA
	ERASE	12 mA
LED0 (Red)	ON	4.3 mA
LED1 (Green)	ON	3.7 mA
LED2 (Blue)	ON	1.7 mA

SPOT: In-System Power Meter for Motes



Host CPU used for bookkeeping

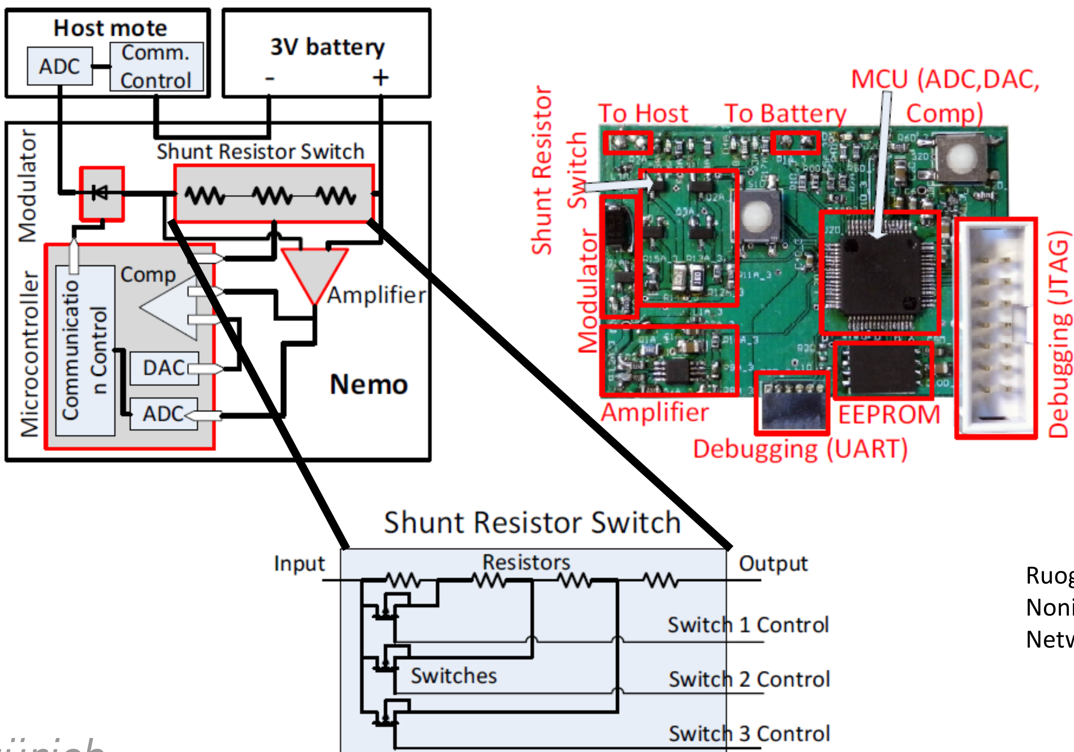


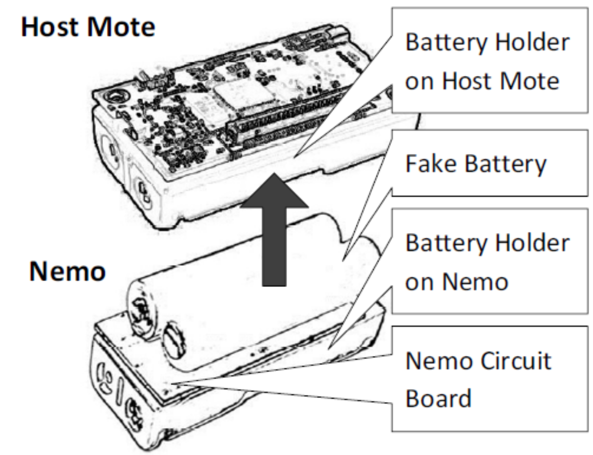
Metric	Requirement	SPOT
Dynamic Range	$> 10000:1$	$45000:1$
Resolution	$< 2\mu A$	$< 1\mu A$
Sampling Rate	> 20kHz	Internally at 1MHz Output at I2C speed
Perturbation	Minimal	1Ω additional load to DUT Energy measurement via I2C At least one read per hour
Integration	Easy	1.35"x1" all-in-one
Cost	$< \$25$	Off-the-shelf ICs

Xiaofan Jiang, Prabal Dutta, David Culler, and Ion Stoica: Micro Power Meter for Energy Monitoring of Wireless Sensor Networks at Scale. IPSN 2007.

NEMO: External Meter Sub-System

- External resistive meter
- Auto ranging for higher dynamic range
- Feedback to host CPU by modulation of power source

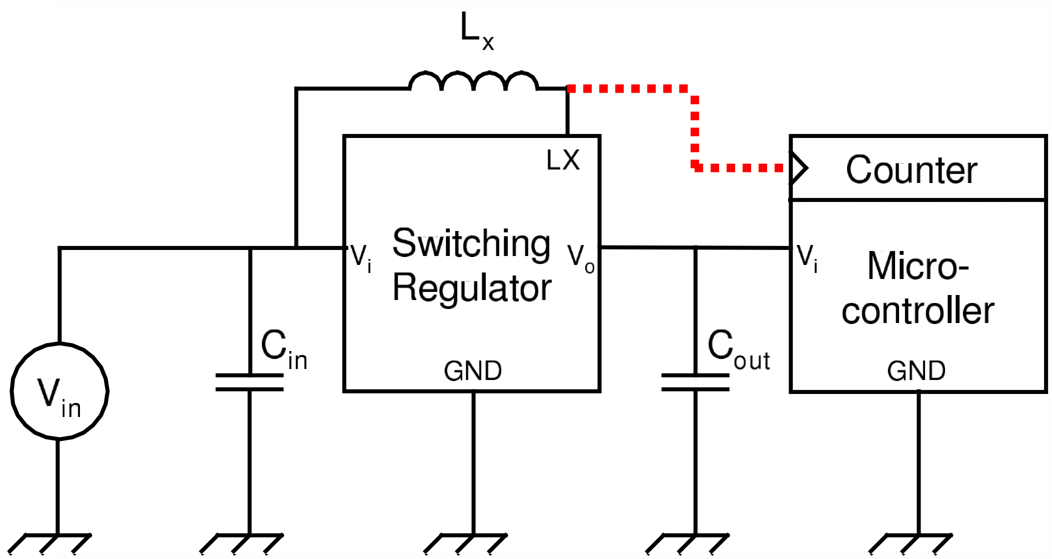




Ruogu Zhou, Guoliang Xing: Nemo: A High-fidelity Noninvasive Power Meter System for Wireless Sensor Networks. IPSN 2013.

Metering by Counting Switching Cycles

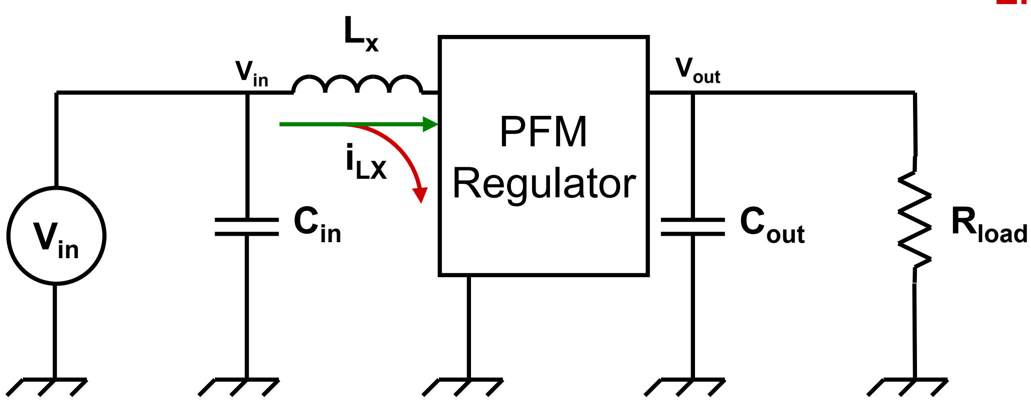
Combining a PFM switching regulator and counter

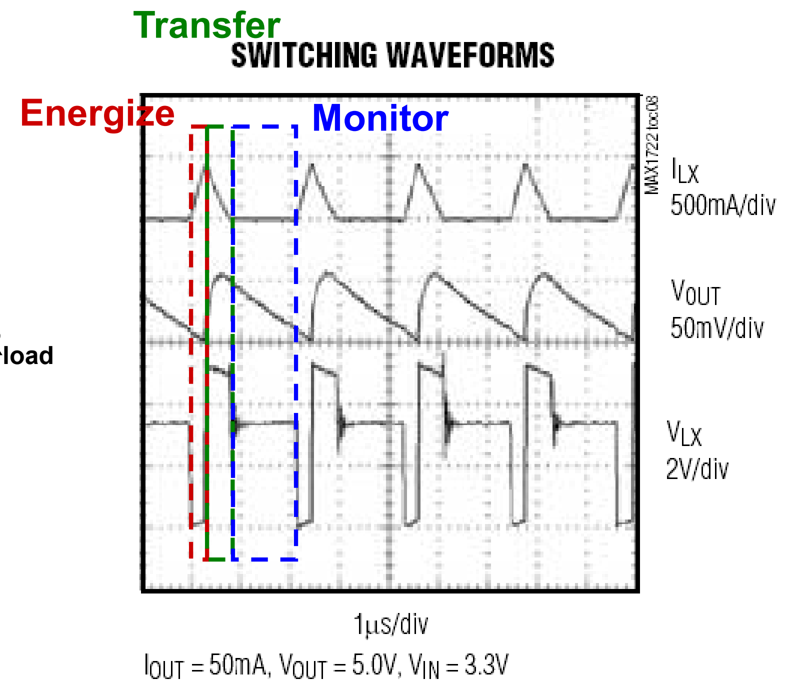


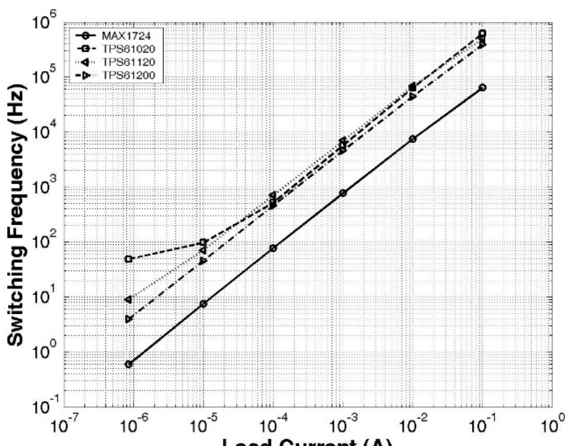
iCount
Dutta, P., Feldmeier, M., Paradiso, J., & Culler, D. (2008). Energy Metering for Free: Augmenting Switching Regulators for Real-Time Monitoring. IPSN 2008 (pp. 283–294). IEEE.

How Does iCount Work?

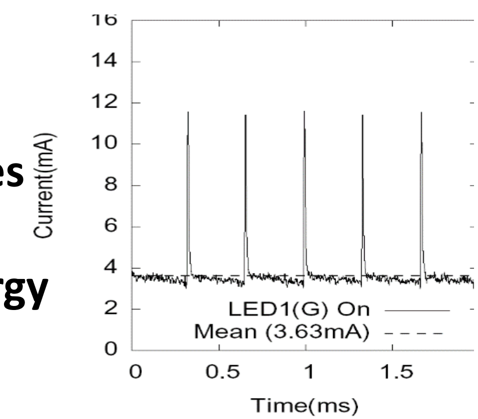
$\Delta E = \frac{1}{2} L i^2 \quad P = \Delta E / \Delta t$







Counting cycles translates to measuring energy



In-System Metering Comparison

	Nemo	iCount	SPOT
Dynamic range	250,000:1 (0.8 uA - 202 mA)	100,000:1	45,000:1 (1 uA - 45 mA)
Resolution	0.013 uA (<50 uA), 0.068 uA (50 uA-250 uA), 0.68 uA (250 uA-2.5 mA), 6.6 uA (2.5 mA -25 mA), 48 uA (>25 mA))	varies w/ sampling rate 10 uA (8 Hz), 100 uA (80 Hz), 1mA (800 Hz)	varies w/ sampling rate 10 uA(220 Hz), 100 uA (2200 Hz), 1 mA (22 KHz)
Sampling rate	8 KHz (w/ compression), 100 KHz (w/o compression)	66 KHz max 80 Hz @ 100 uA resolution	N/A
Measurement error	average 1.34%, max 8%	max ±20%	average 3%
Sleep power measurement	Yes	No	Yes
Power consumption	154 uA (0.1% duty-cycle) 195 uA (1% duty-cycle)	1% of host current plus energy loss on regulator (>10%)	1.7 mA
Host CPU overhead	0.6% w/ comm., otherwise none	13% at 8KHz sampling rate	N/A
Host resource usage	none	Timer, one I/O pin	I2C bus, multiple I/O pins
Ease of installation	very easy, wire-free plug n' play	soldering of wire to host mote	soldering of board onto host; extra 5.5V power supply

Low-Power System Design

METHODS FOR ESTIMATING POWER CONSUMPTION

Run-time Estimation Based on Workload in Server Systems

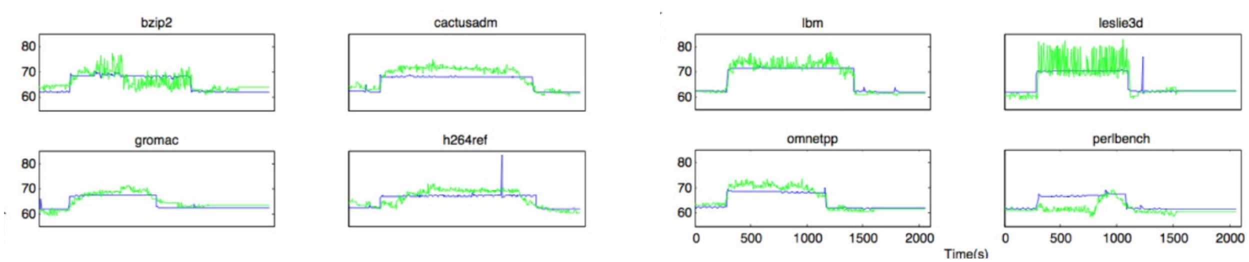
- **Idea:** measures disc accesses (iostat). Use these performance counters to compute an approximate disk power consumption.

$$E_{hdd} = P_{spinup} * t_{su} + P_{read} \sum N_r * t_r + P_{write} \sum N_w * t_w + \sum P_{idle} * t_i$$

- A first-order linear model for the whole system

$$E_{system} = \alpha_0 (E_{proc} + E_{mem}) + \alpha_1 E_{board} + \alpha_2 E_{hdd} + \alpha_3 E_{periph}$$

- Calibration using a set of benchmark applications

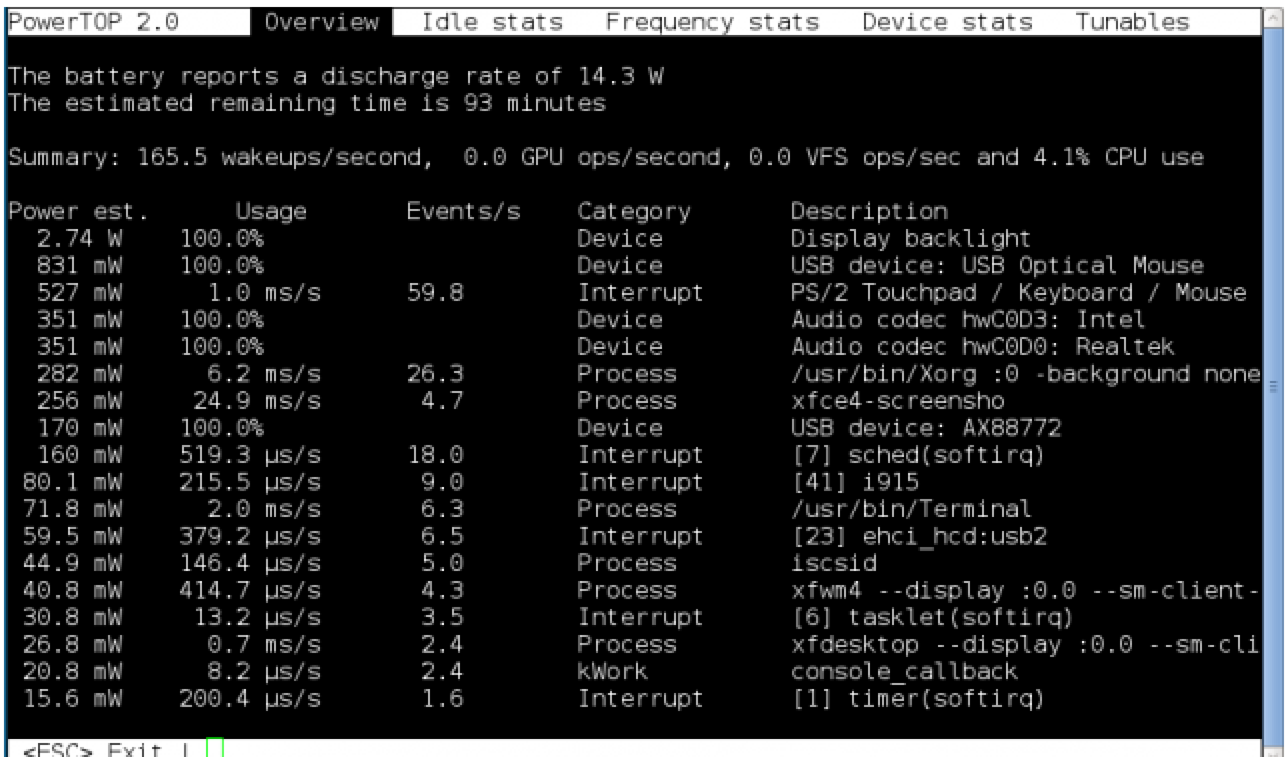


- Finer level-of detail using hardware performance counters

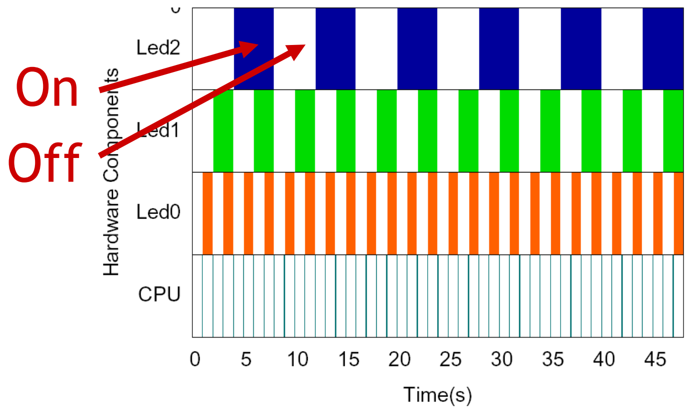
Run-time energy consumption estimation based on workload in server systems. Adam Lewis, Soumik Ghosh, N.-F. Tzeng. HotPower'08

PowerTOP (for Linux)

- A popular tool for Linux (laptops)
- Visualizes load, frequency and power modes
- Builds a simple component-based power model



Power State Tracking



- Instrument device drivers
  - Export device power states
  - Through narrow interface
  - OS tracks state transitions

```
async command void Leds.led0On() {
  call Led0PowerState.set(1);
  // Setting pin to low turns Led on
  call Led0.clr();
}

async command void Leds.led0Off() {
  call Led0PowerState.set(0);
  // Setting pin to high turns Led off
  call Led0.set();
}
```

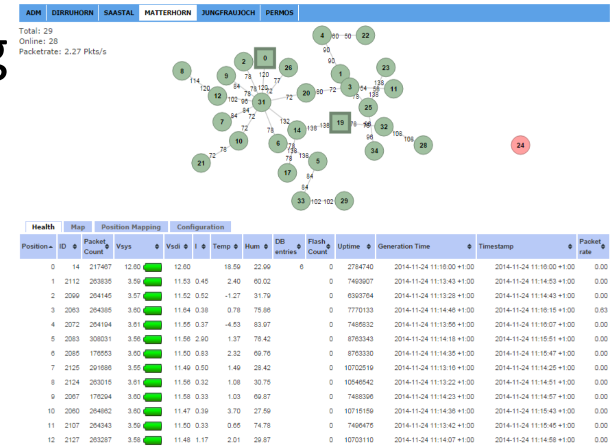
```
interface PowerState {
  // Sets the powerstate to value.
  async command void set(powerstate_t value);

  // Sets the bits represented by mask to value.
  async command void setBits(powerstate_t mask,
    uint8_t offset, powerstate_t value);
}
```

```
interface PowerStateTrack {
  // Called if an energy sink power state changes
  async event void changed(powerstate_t value);
}
```

H. Zeng et al. “ECOSystem: Managing Energy as a First Class Operating Systems Resource”, ASPLOS’02, 2002.

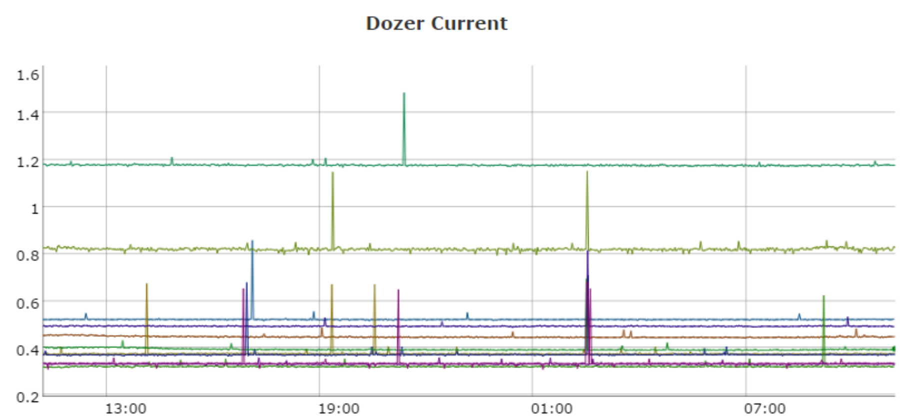
In-Band Power Monitoring: PermaSense SIB

- Coarse grained in-situ power monitoring
  - Battery and system voltages
  - Total current and subsystem current
  - Activity counter (TX, RX, CPU)



Position	ID	Packet Count	Vsys	Vsdi	I	Temp	Hum	DB entries	Flash Count	Uptime	Generation Time	Timestamp	Packet rate
0	14	217467	12.60	12.60		18.59	22.99	6	0	2784740	2014-11-24 11:16:00 +1:00	2014-11-24 11:16:00 +1:00	0.00
1	2112	263835	3.59	11.53	0.45	2.40	60.02		0	7493907	2014-11-24 11:13:43 +1:00	2014-11-24 11:14:53 +1:00	0.00
2	2099	264145	3.57	11.52	0.52	-1.27	31.79		0	6393764	2014-11-24 11:13:28 +1:00	2014-11-24 11:14:43 +1:00	0.00
3	2063	264385	3.60	11.64	0.38	0.78	75.86		0	7770133	2014-11-24 11:14:46 +1:00	2014-11-24 11:16:15 +1:00	0.63
4	2072	264194	3.61	11.55	0.37	-4.53	83.97		0	7485832	2014-11-24 11:13:56 +1:00	2014-11-24 11:16:07 +1:00	0.00
5	2083	308031	3.56	11.56	2.90	1.37	76.42		0	8763343	2014-11-24 11:14:18 +1:00	2014-11-24 11:15:51 +1:00	0.00
6	2085	176553	3.60	11.50	0.83	2.32	69.76		0	8763330	2014-11-24 11:14:35 +1:00	2014-11-24 11:15:47 +1:00	0.00
7	2125	291686	3.55	11.49	0.50	1.49	28.42		0	10702519	2014-11-24 11:13:16 +1:00	2014-11-24 11:14:25 +1:00	0.00
8	2124	263015	3.61	11.56	0.32	1.08	30.75		0	10546542	2014-11-24 11:13:22 +1:00	2014-11-24 11:14:51 +1:00	0.00
9	2067	176294	3.60	11.58	0.33	1.03	69.87		0	7488396	2014-11-24 11:14:23 +1:00	2014-11-24 11:14:57 +1:00	0.00
10	2060	264862	3.60	11.47	0.39	3.70	27.59		0	10715159	2014-11-24 11:14:36 +1:00	2014-11-24 11:15:43 +1:00	0.00
11	2107	264343	3.59	11.50	0.33	0.65	74.78		0	7496475	2014-11-24 11:13:42 +1:00	2014-11-24 11:15:45 +1:00	0.00
12	2127	263287	3.58	11.48	1.17	2.01	29.87		0	10703110	2014-11-24 11:14:07 +1:00	2014-11-24 11:14:58 +1:00	0.00

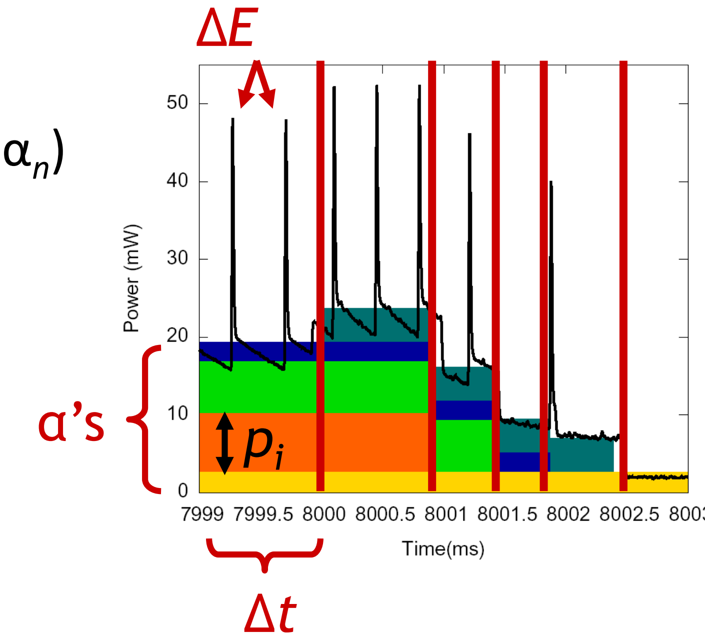
- Data is transmitted like sensor data
- Long-time series available over whole network population
- Overhead
  - Hardware/power consumption
  - Data logistics



PermaDAQ: A scientific instrument for precision sensing and data recovery in environmental extremes: Jan Beutel, Stephan Gruber, Andreas Hasler, Roman Lim, Andreas Meier, Christian Plessl, Igor Talzi, Lothar Thiele, Christian Tschudin, Matthias Woehrle, Mustafa Yuecel. IPSN 2009

Estimating Complex Breakdowns

- For every state transition
  - Snapshot system-wide power states ($\alpha_1, \ldots, \alpha_n$)
  - Snapshot global energy usage (ΔE)
  - Snapshot system clock (Δt)



- Generate an equation of the form

$$\Delta E/\Delta t = \alpha_1 p_1 + \ldots +, \alpha_n p_n$$

- (p's are the unknown power draws)
- Solve for p's using weighted multivariate least squares

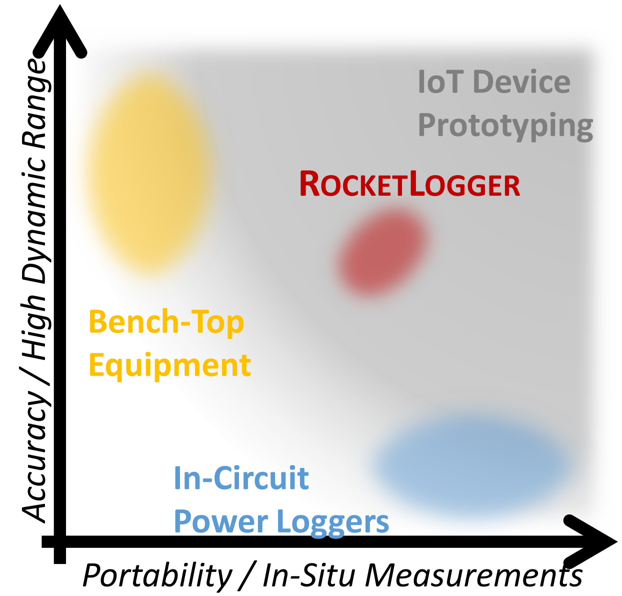
Requirement
High-resolution, high-speed power metering
is key for good results

Low-Power System Design

HIGH-DYNAMIC RANGE AND MIXED SIGNAL DAQ

Every Nano-Joule Counts

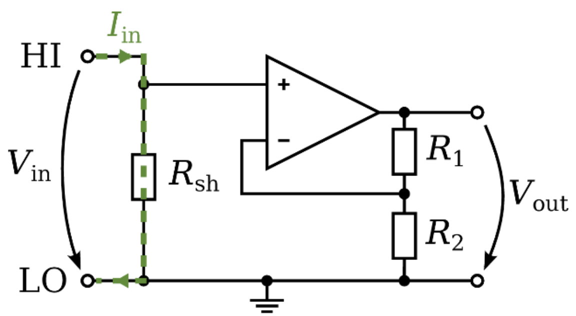
- Energy Harvesting design challenges
  - Powers from nW to W range
  - Deep-sleep, aggressive duty cycling, short high current active peaks
- Application specific, variable harvesting
  - Need portable and in-situ measurements



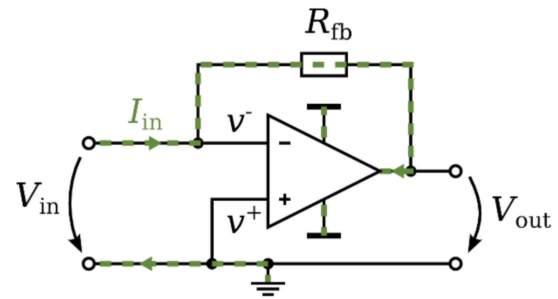
→ *Need for portable **and** high-dynamic range data logging for long-term in-situ measurements*

[Lukas Sigrist et.al.: Measurement and Validation of Energy Harvesting IoT Devices. Proc. 2017 Design, Automation & Test in Europe Conference & Exhibition (DATE 2017), Mar, 2017.]

The RocketLogger Idea – No Rocket Science



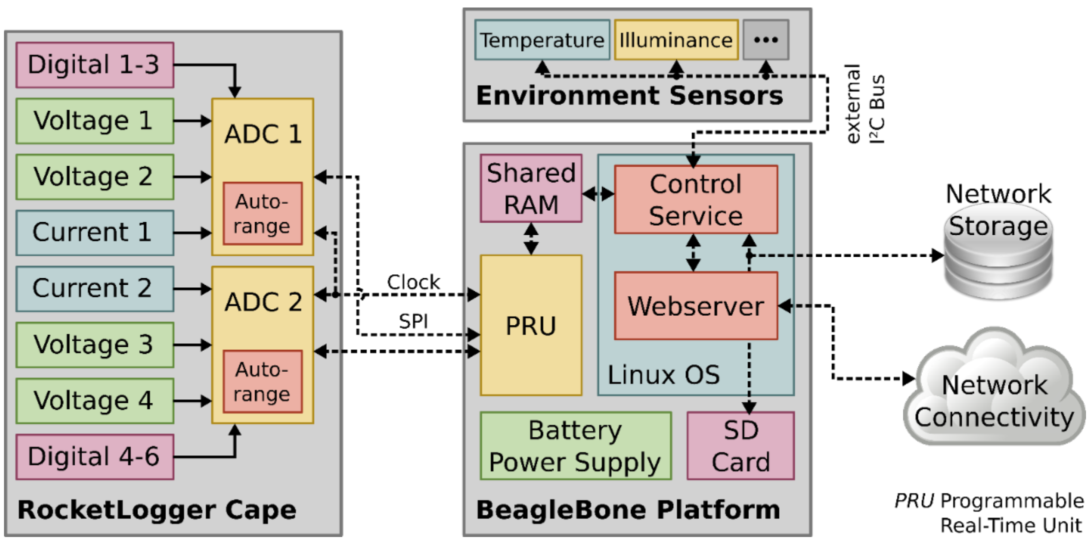
Shunt Ammeter



Feedback Ammeter

- + Switching circuit to combine advantages of both circuits
- + Environmental sensors to track harvesting conditions
- + BeagleBone Green as host platform
- + Smart students to realize the idea

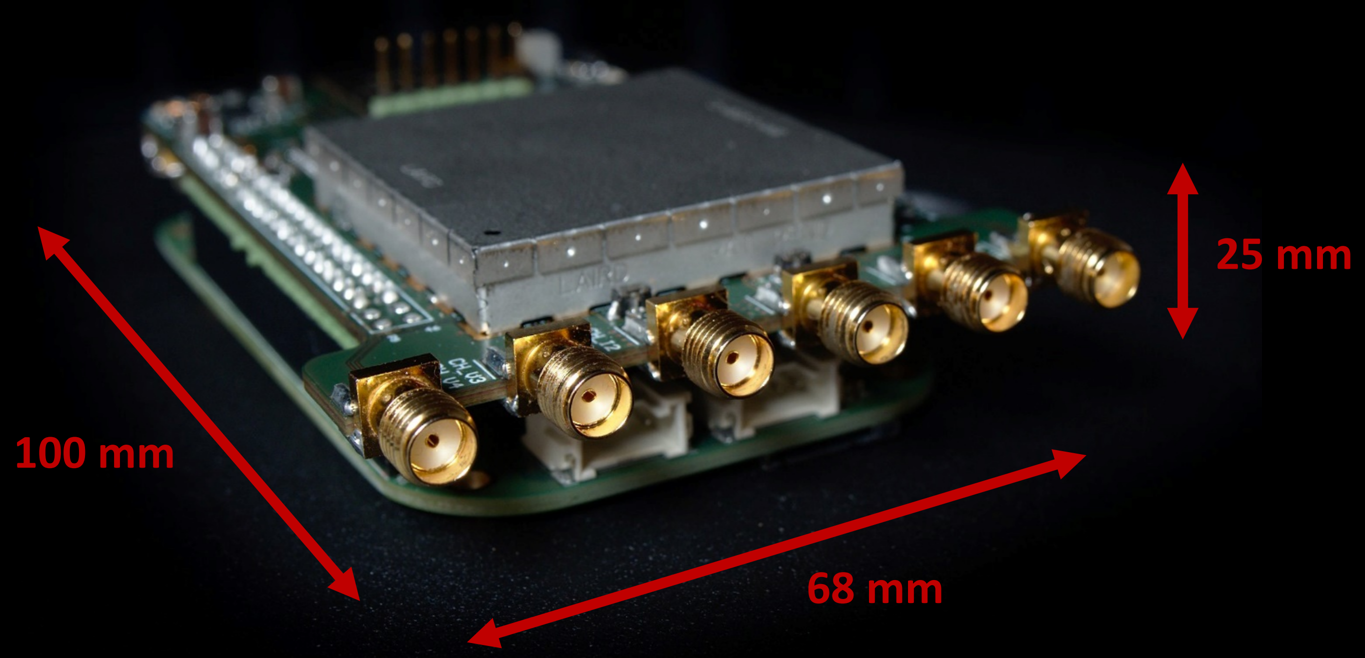
Managing Measurements and Data



- Real-Time Unit for low latency reactive readout
- Data management on top of Linux OS
- Web interface for remote control and observation in real-time

- 16 Mb/s ADC data
- 8.3 GB data stored per hour

The RocketLogger Hardware



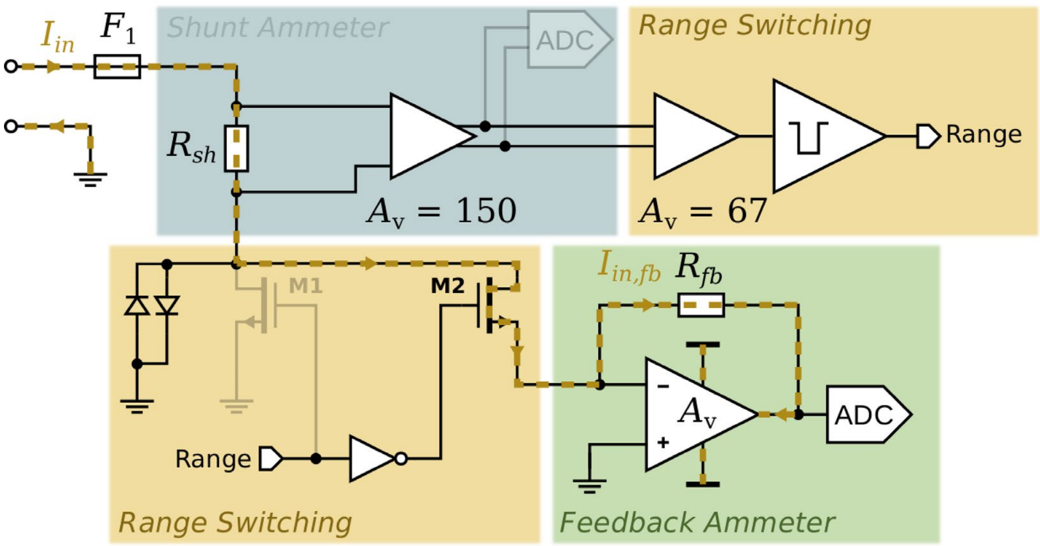
Open hardware and software
http://rocketlogger.ethz.ch

RocketLogger Measurement Performance

	Metric	Range/Value
General	Sampling Rate	1 kSPS up to 64 kSPS
	Measurement Bandwidth	up to 9.5 kHz
Voltage ±5.5 V (×4)	Noise	5.9 µV RMS (1.38 mV RMS)
	Input Leakage	~ 5 pA
	DC Accuracy	0.02 % + 13 µV
Current ±500 mA (2×)	Total Dynamic Range	175 dB
	Burden Voltage at 500 mA	47 mV
	Noise High Range	1.33 µA RMS (72 µA RMS)
	Low Current Range	±2 mA
	Noise Low Range	1.75 nA RMS (390 nA RMS)
	Range Switching Time	1.4 µs
	Transient Burden Voltage	max. 430 mV for ≤ 1.4 µs
	Accuracy Low Range	0.03 % + 4 nA
	Accuracy High Range	0.09 % + 3 µA
Digital (×6)	Input Leakage	< 1 pA
	Threshold Voltage (Configurable)	-6 V to +6 V

- Very-high accuracy
  4 nA / 13 µV
- Super fast range switching
  ≤ 1.4 µs
- Minimal impact on device under test
  ≤ 47 mV burden voltage,
  ≤ 430 mV when switching
- Negligible input leakage for simultaneous current and voltage measurement

Seamless Range Switching Implementation



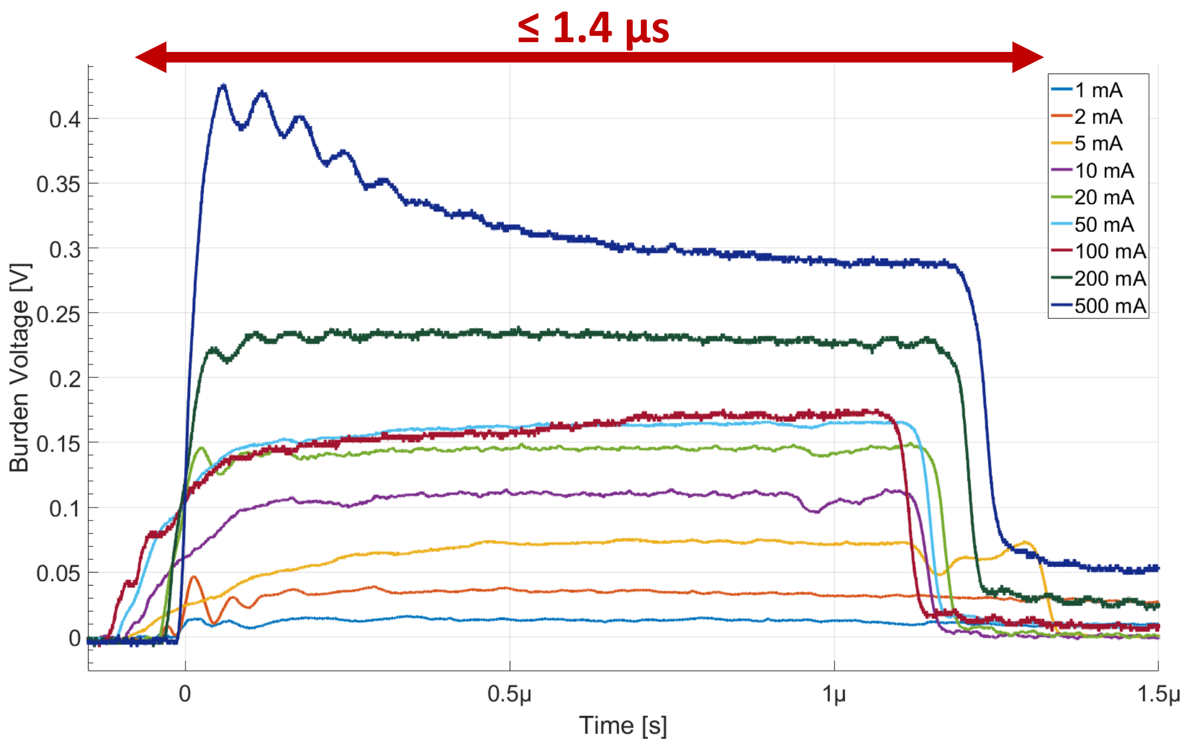
$I_{in} \geq 2$ mA: High Range

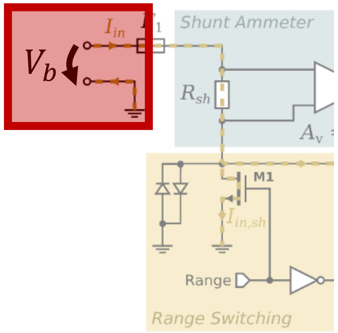
- M1 on
- Stunt ammeter only
- Low shunt resistor, low burden voltage

$I_{in} < 2$ mA: Low Range

- M2 on
- Feedback Ammeter
- High output voltage, high resolution

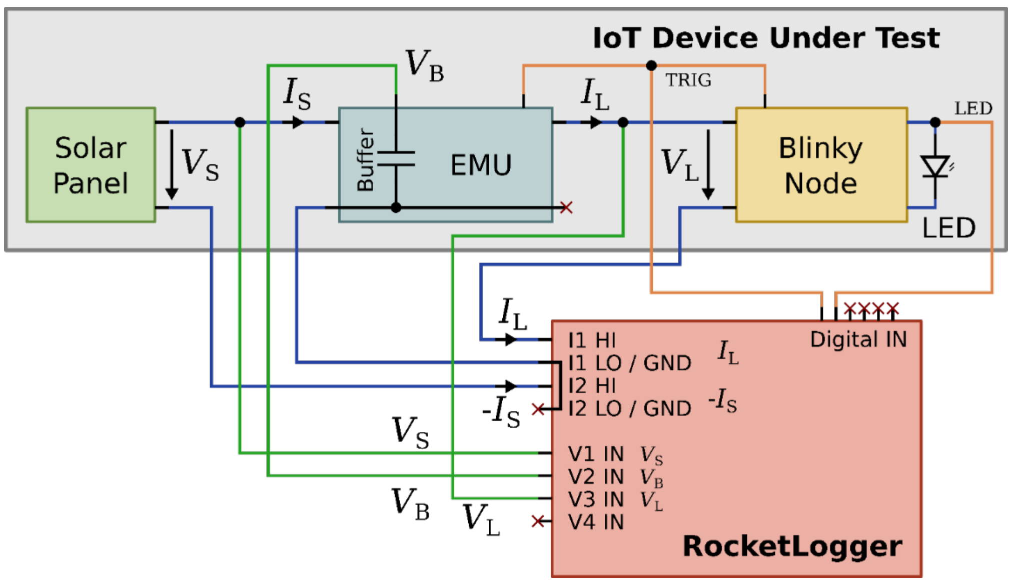
Seamless Range Switching Behavior





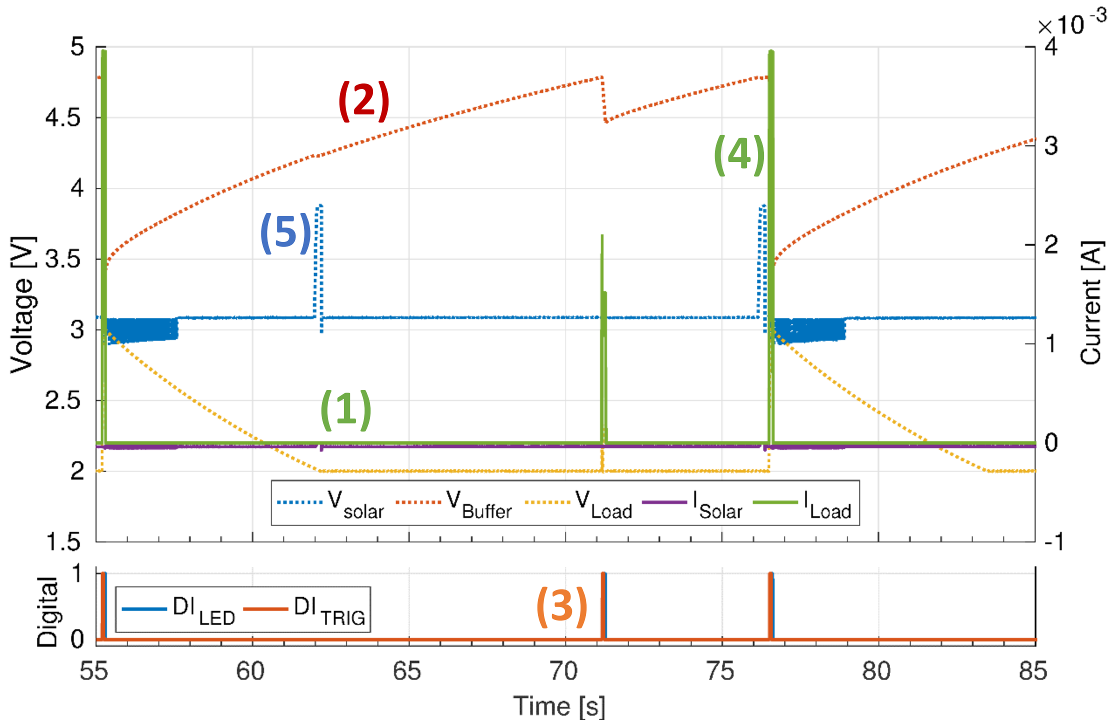
… And Action!

Demo: measurement of a batteryless “Blinky Node”



1. Accumulation of solar energy (P_S) in buffer (V_B)
2. Wake-up load when energy level reached
3. Load executes (P_L) using buffered energy
4. <repeat forever>

Demo: What to Observe



(1) Sleep mode power measurement (9 nA @ 2.0 V)

(2) Energy accumulation in the 220 µF buffer capacitance

(3) Wake-up trigger at 4.8 V buffer voltage

(4) Step from 9 nA sleep to 4 mA active current

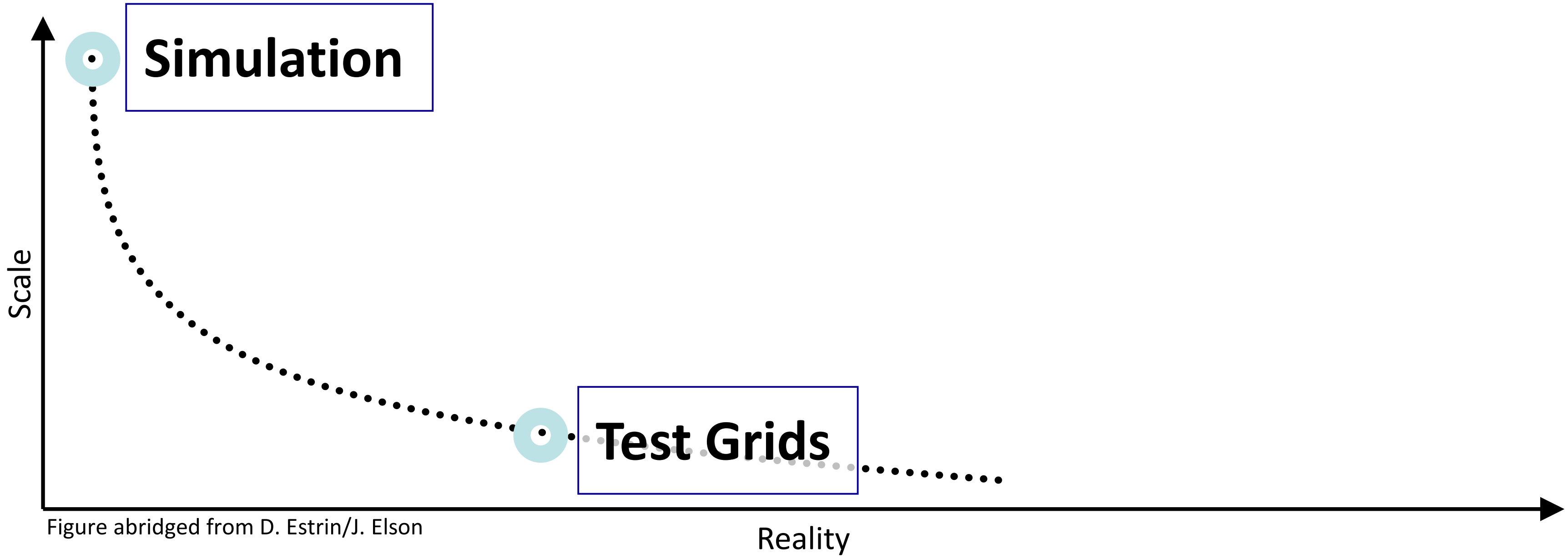
(5) Solar panel open circuit voltage sampling for MPPT

Plotting in Matlab is as easy as: `rld('measurement_file.rld').plot()`

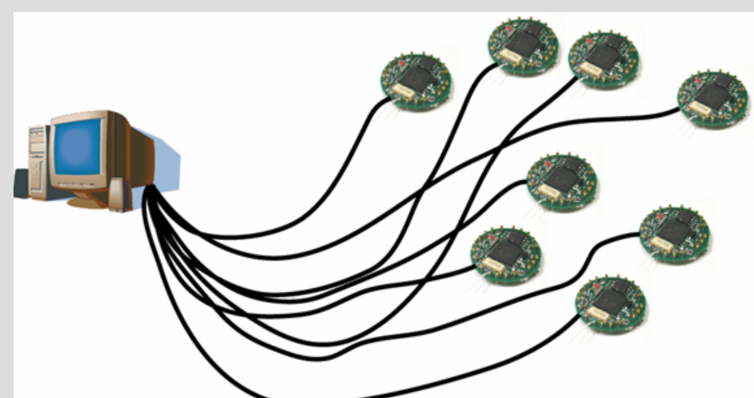
Low-Power System Design

SCALING-UP THE DESIGN SPACE: SENSOR NETWORK TESTBEDS

WSN Design and Development Tools



- Traditional test grid
  - Wired backchannel
  - Simple centralized control and data collection
- Alternative: In-band collection

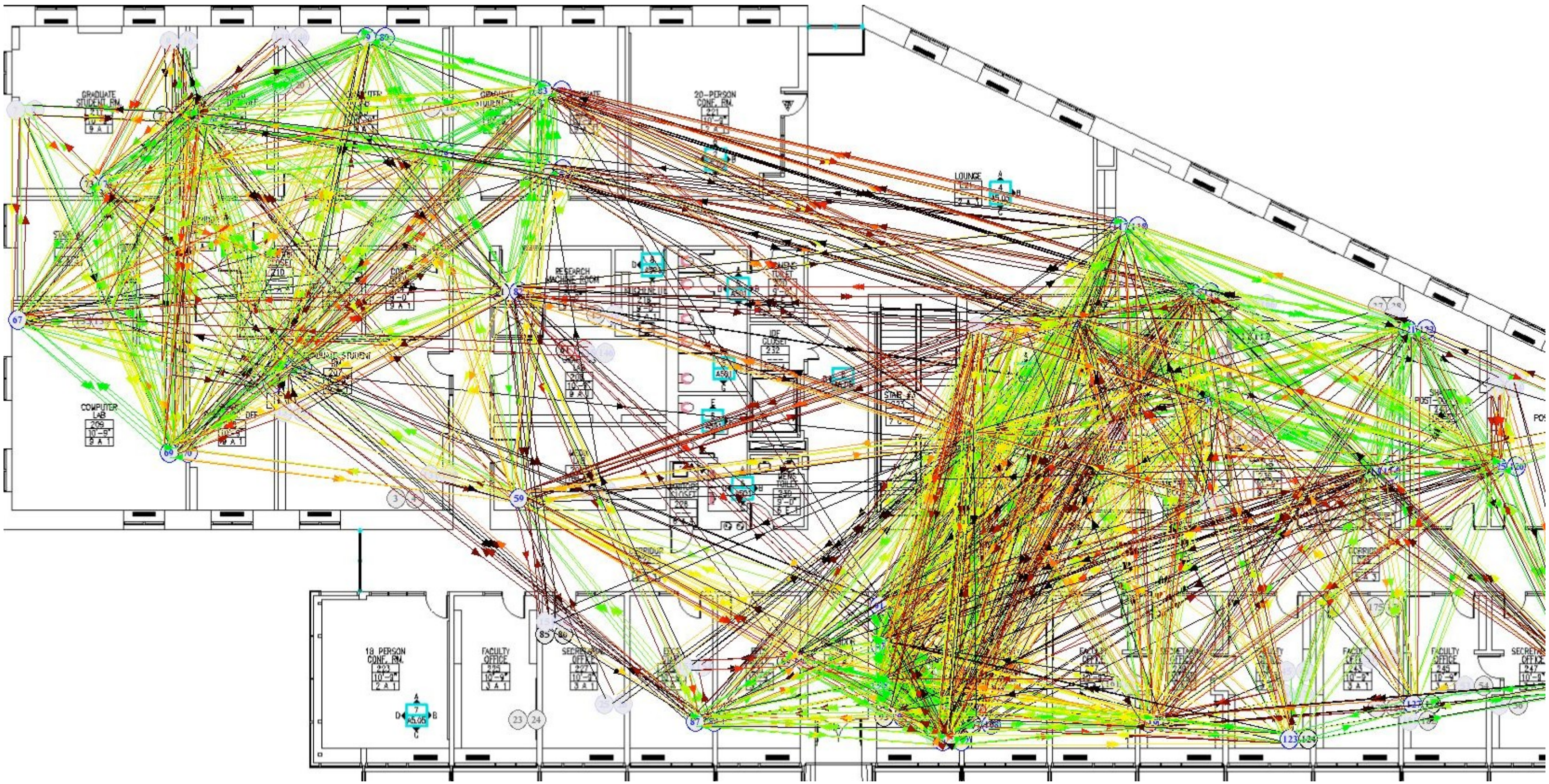


Example: MoteLab Testbed

- Harvard wireless sensor network testbed
  - Primary design philosophy: Testbed should be both **open** and **easy to use**
  - **Open: Users at multiple institutions should have access for experimentation**
  - **Easy to use: Web-based interface for programming, debugging, accessing**
- 190 Tmote Sky nodes deployed over 3 floors of EECS building
  - Each node connected to wall power and Ethernet for reprogramming and debug
  - Spanning approx. 70,000 sq. ft.
- Logging of serial port data to a database
  - Provides easy access to debugging and profiling data
  - SQL access to database in real time, or download ZIP file after run is complete
- Network bridge to serial port on each node
  - Each node given a specific IP address/port # for serial port access
  - Allows remote programs to send and receive data to individual nodes in real time

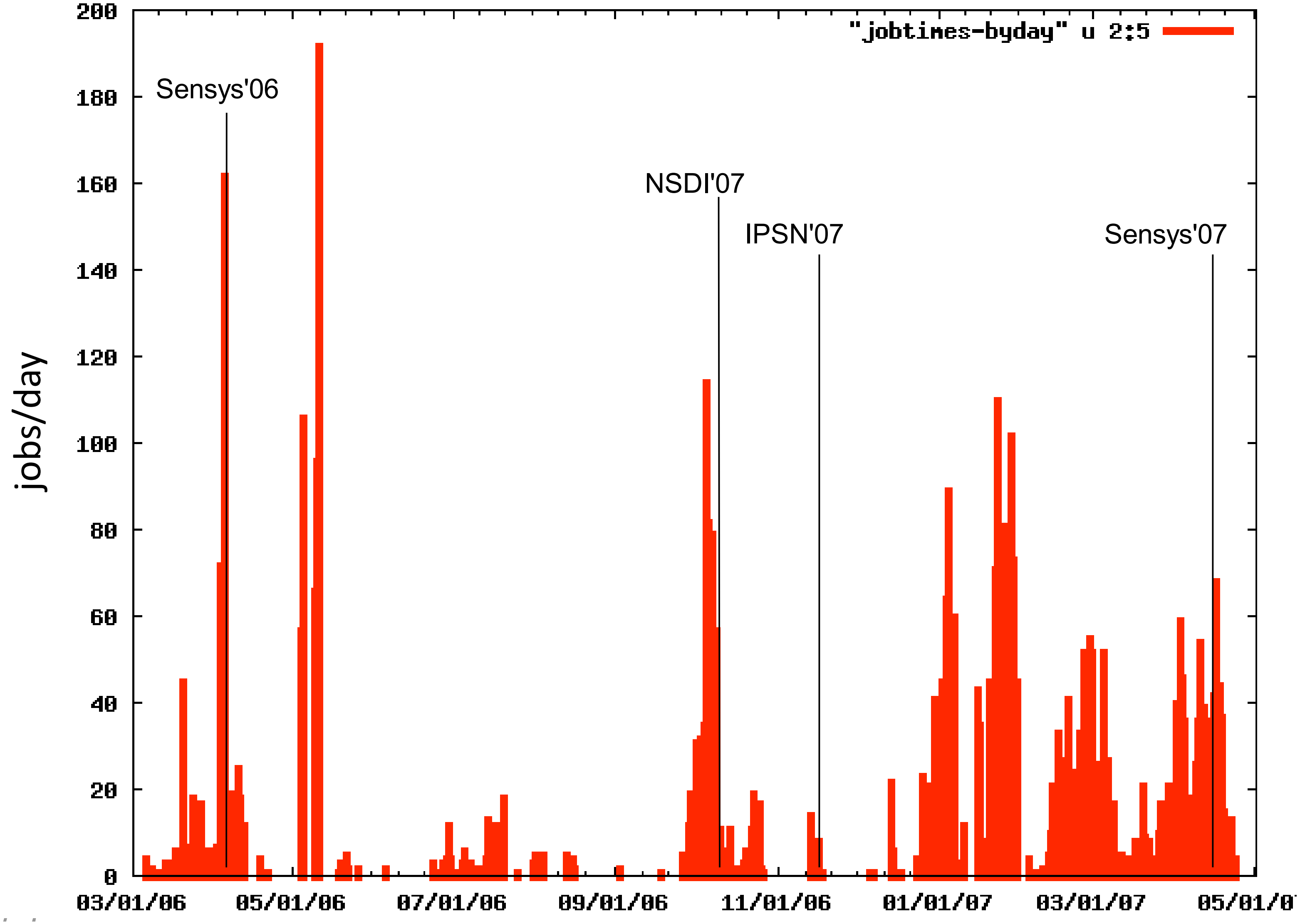
G. Werner-Allen, P. Swieskowski and M. Welsh. MoteLab: a wireless sensor network testbed. In Proceedings of the 4th international symposium on Information processing in sensor networks (IPSN 2005).

Example: MoteLab Testbed



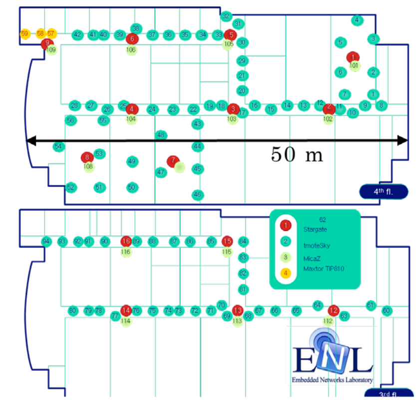
Map of 2nd floor nodes only; blue circles represent nodes

Example: MoteLab Testbed

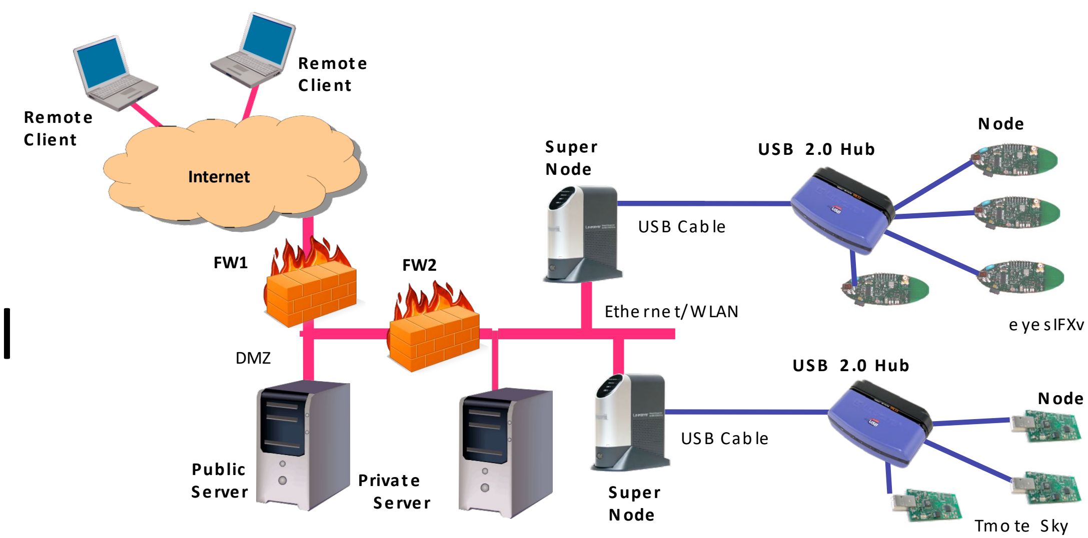


Many Testbed Variants Exist

- Campus/Office distribution
  - Indriya
  - Kansei
  - TWIST
  - TUTORNET



- Web-based access
- Wired backchannel to central server

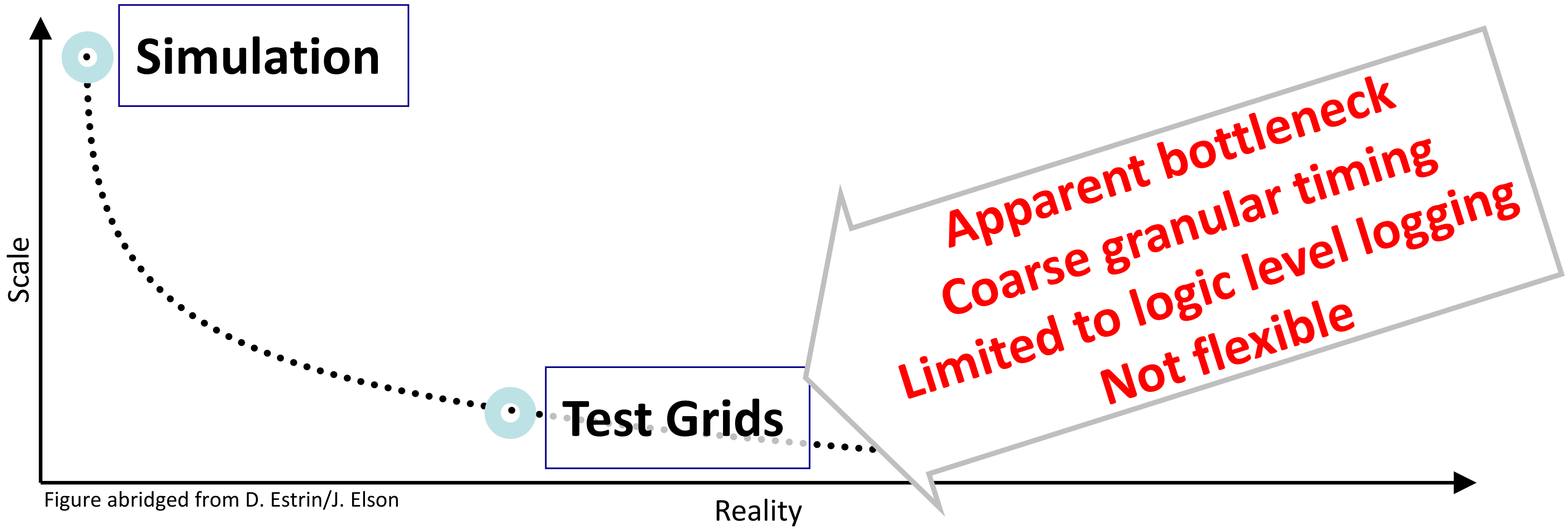


TWIST Testbed @ TU Berlin

Diverse Landscape of Testbeds

Basic support	Node programming	Motelab *IPSN '05*, DSN *EWSN '07*, …
	Support for multiple platforms	TWIST *REALMAN '06*
	Large testbeds	Kansei *IPSN '06*
Observations	Serial I/O	…
	Distributed power measurements	PowerBench *IWSNE '08*, SANDbed *ARCS '10*, w-iLab.t *TridentCom '10*
Controlled environment	Mobility support	Jiménez-González et al. *IROS '10*
	Temperature emulation	TempLab *IPSN '14*
	Interference generation	JamLab *IPSN '11*

WSN Design and Development Tools



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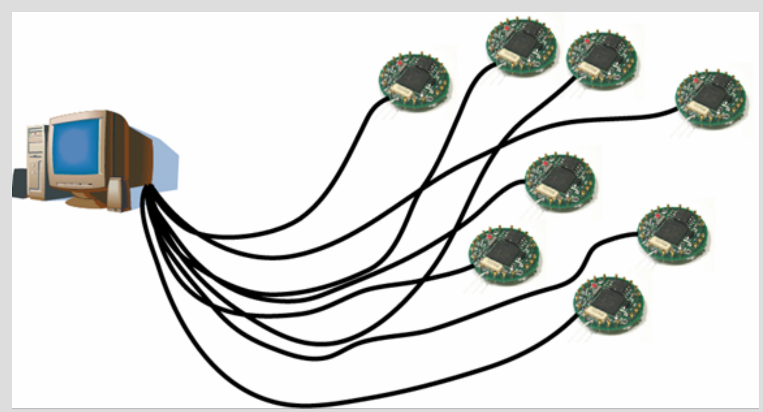
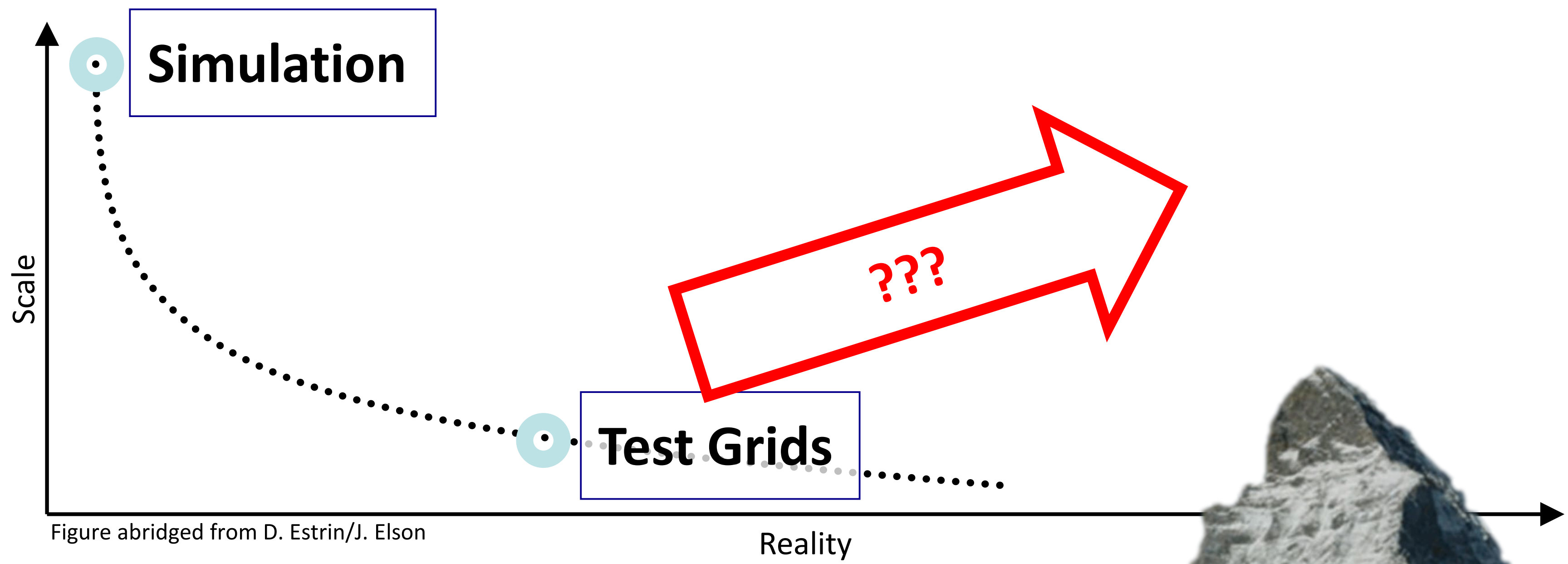
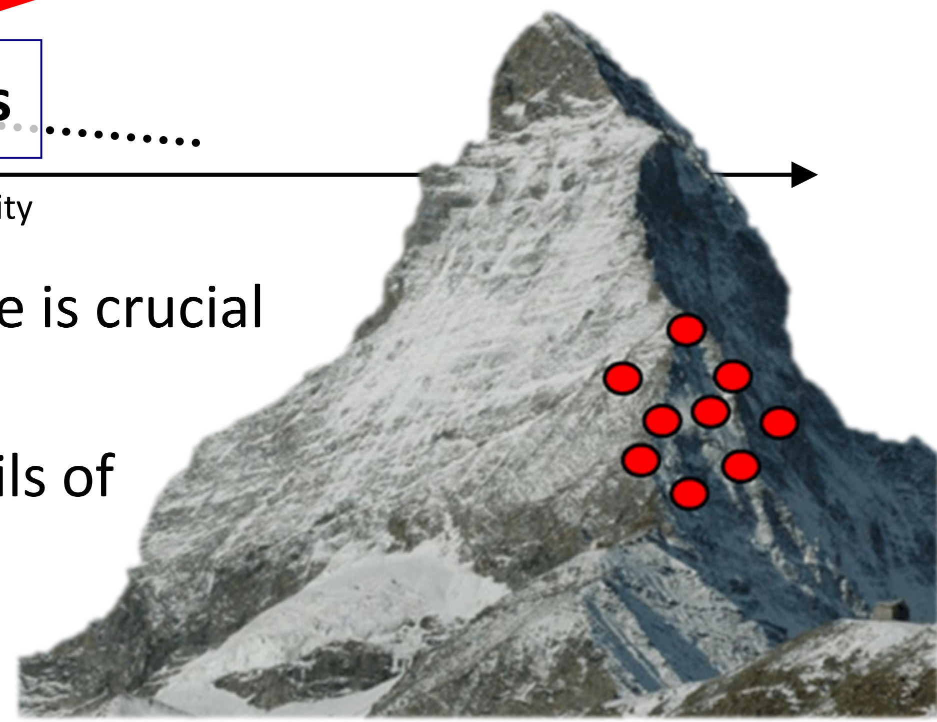


WSN Design and Development Tools



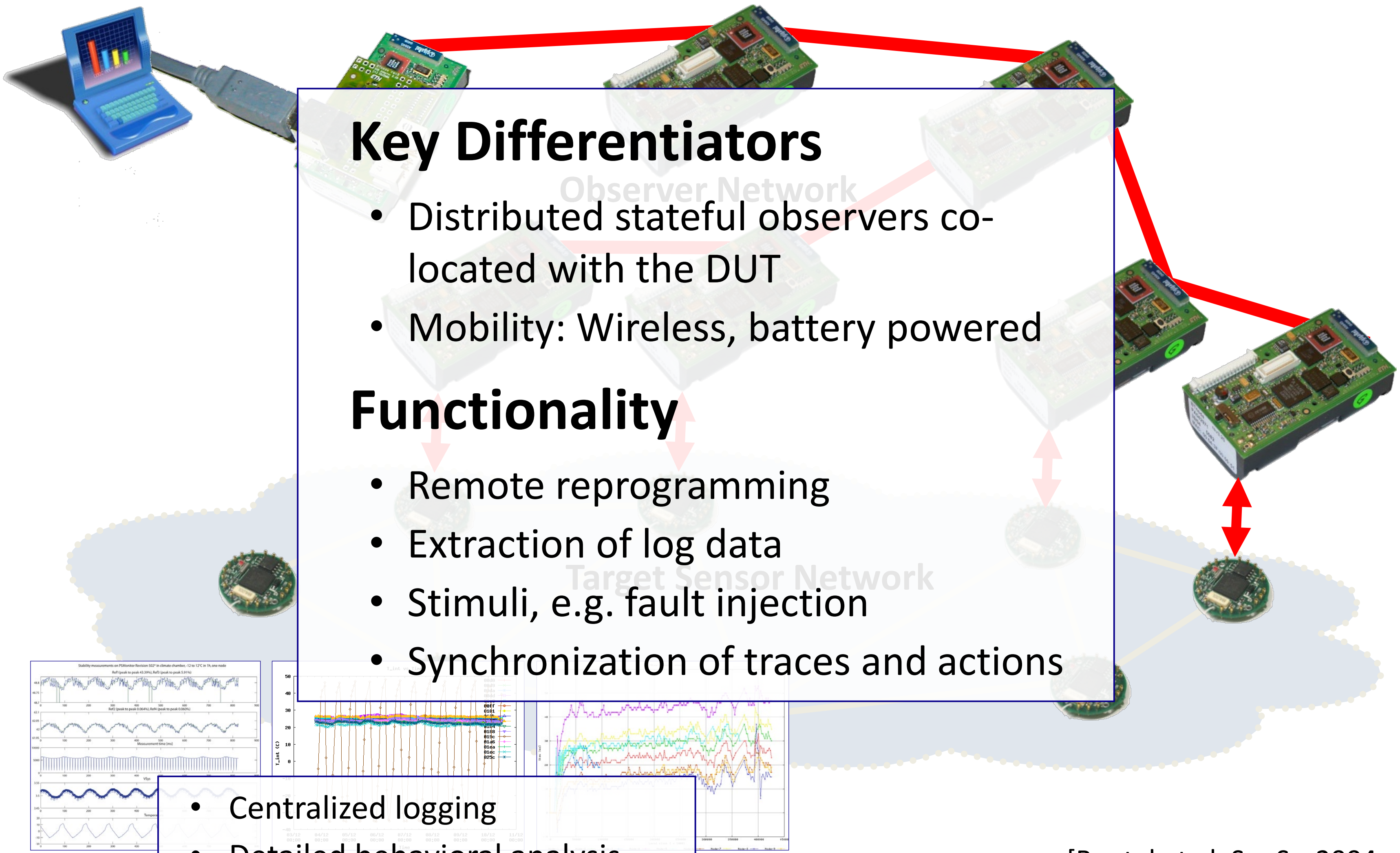


- Correctness at deployment time is crucial
- Validation tools are needed
- Testbeds capture intricate details of the behavior of devices and the environment

Multiple Modalities, Fine Grained Resolution

		FlockLab
Basic support	Node programming	Less intrusive state extraction
	Support for multiple platforms	Precise time measurements
	Large testbeds	High resolution distributed power measurements
Observations	Serial I/O	Time triggered actions
	Distributed power measurements	
Controlled environment	Mobility support	
	Temperature emulation	
	Interference generation	

DSN Testbed: Distributed Observers



Key Differentiators

- Distributed stateful observers co-located with the DUT
- Mobility: Wireless, battery powered

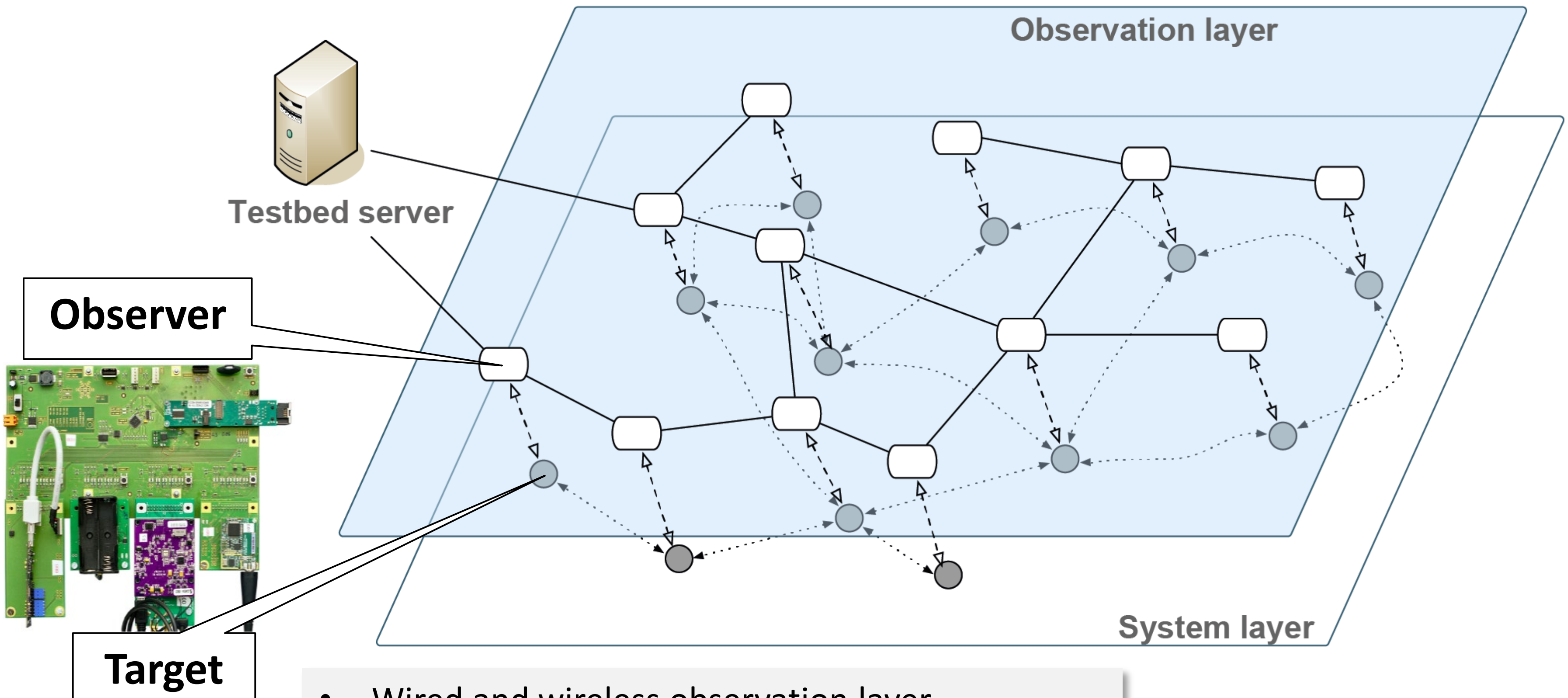
Functionality

- Remote reprogramming
- Extraction of log data
- Stimuli, e.g. fault injection
- Synchronization of traces and actions

- Centralized logging
- Detailed behavioral analysis

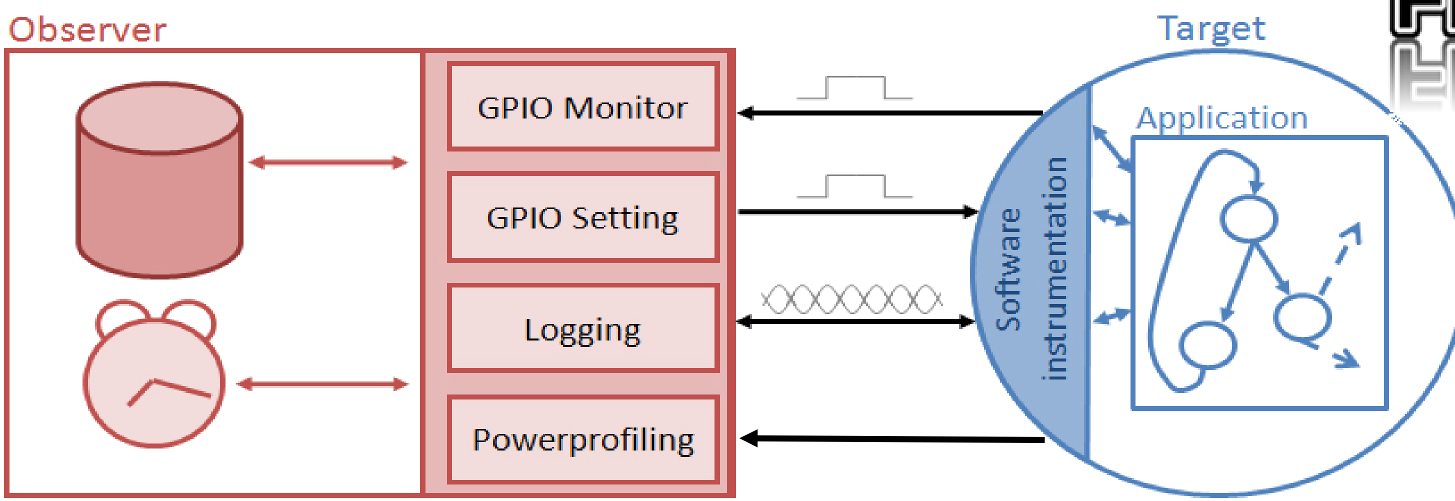
[Beutel et al. SenSys2004, IPSN2005, EWSN2007]

FlockLab Testbed



- Wired and wireless observation layer
- Fast, distributed tracing and actuation of ***logic***
- Synchronized ***power*** tracing
- ***Sensor*** stimuli and references
- ***Time*** synchronization to ~µs

Extending the Target-Observer Model



- Stateful observer supporting multiple services
  - Fast, distributed tracing and actuation of logic
  - Deep local storage
  - Synchronized power tracing
  - Sensor stimuli and references
- Time synchronization to ~20 µs (NTP)

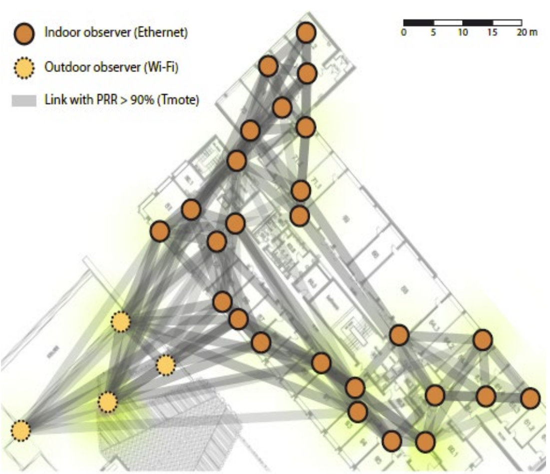
scalability (fast, distributed tracing and actuation of logic; deep local storage)

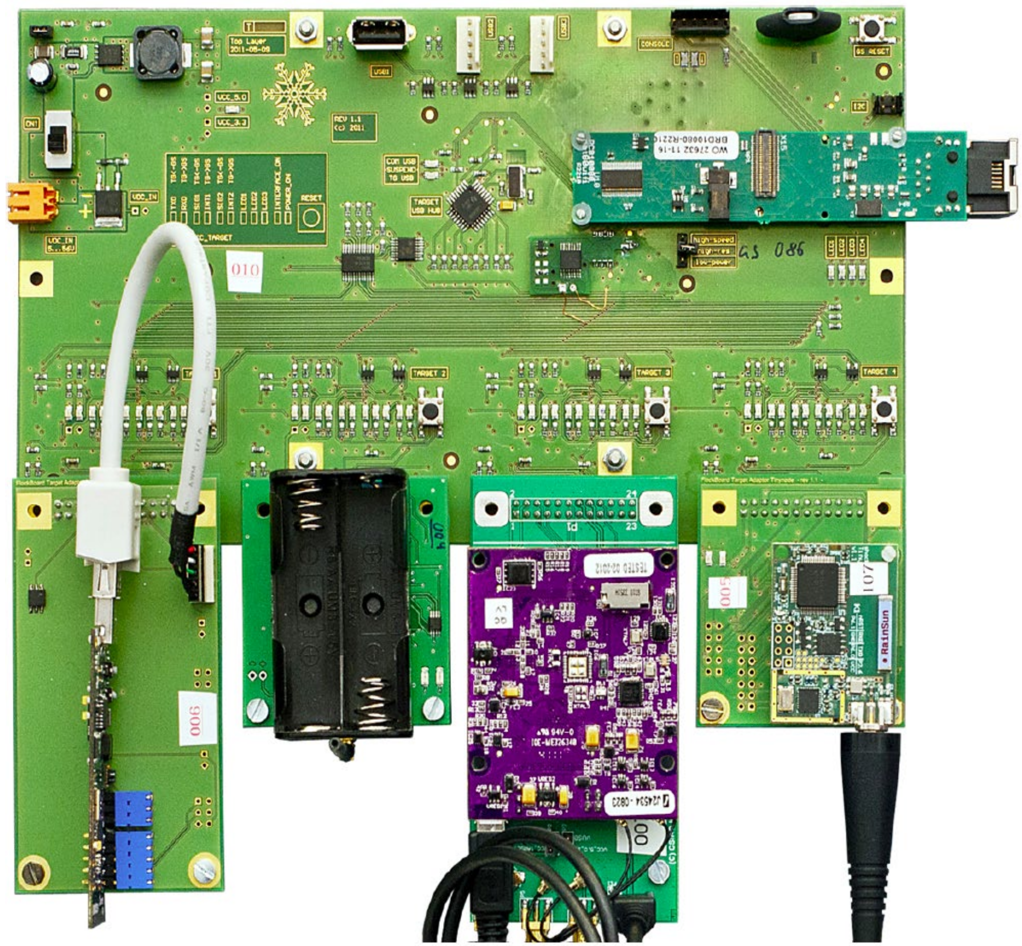
modalities (synchronized power tracing; sensor stimuli and references; time synchronization)

[Woehrle SenSys2009, Lim IPSN2013]

FlockLab Testbed @ ETHZ

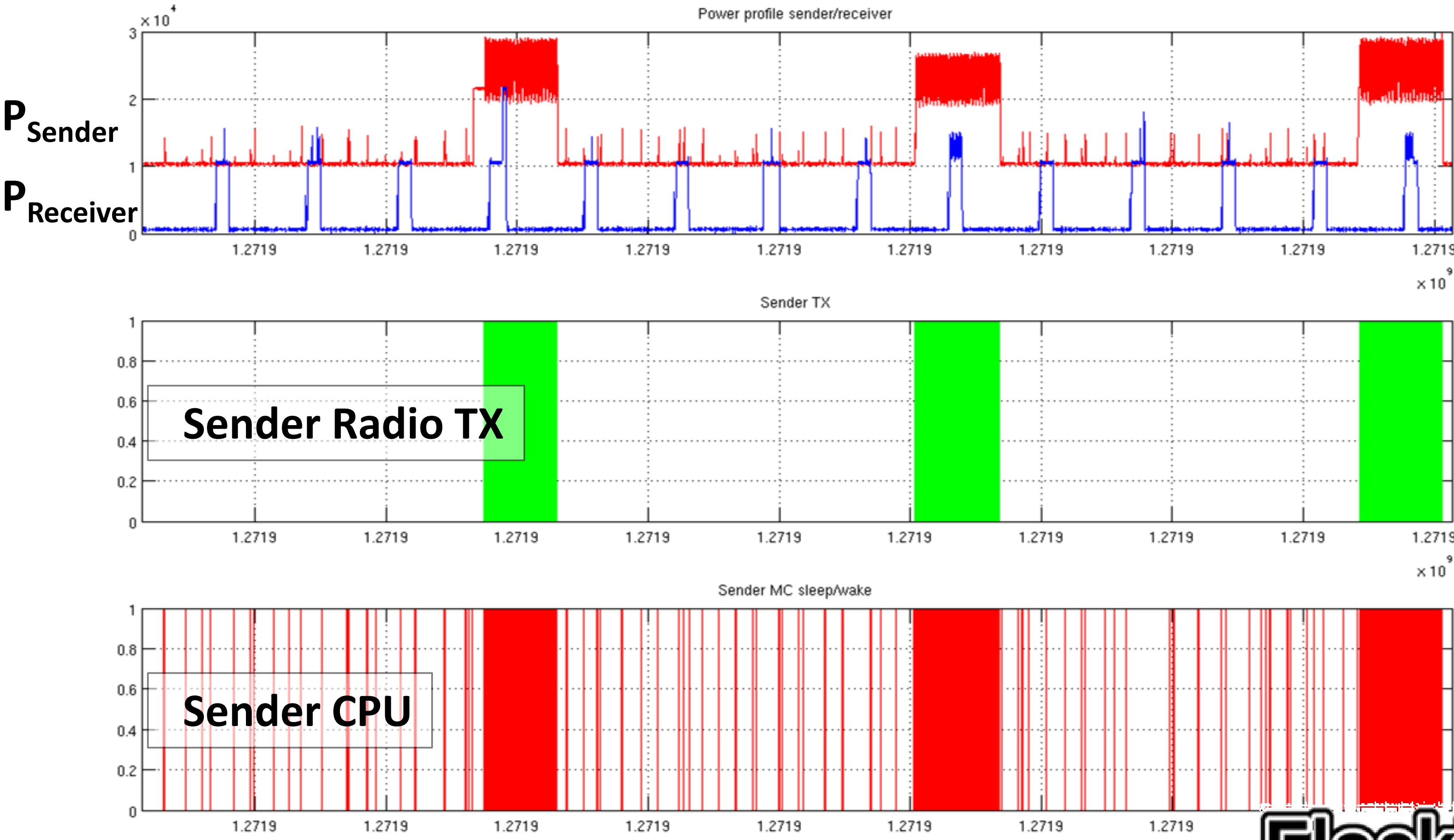
- 4 Target Architectures
  - Tmote Sky
  - TinyNode
  - Iris
  - Opal
- 30 Node Testbed
  - Ethernet/WLAN backbone
  - In- & Outdoor





Get your account @ www.flocklab.ethz.ch

Synchronized Power and State Traces from Distributed Nodes



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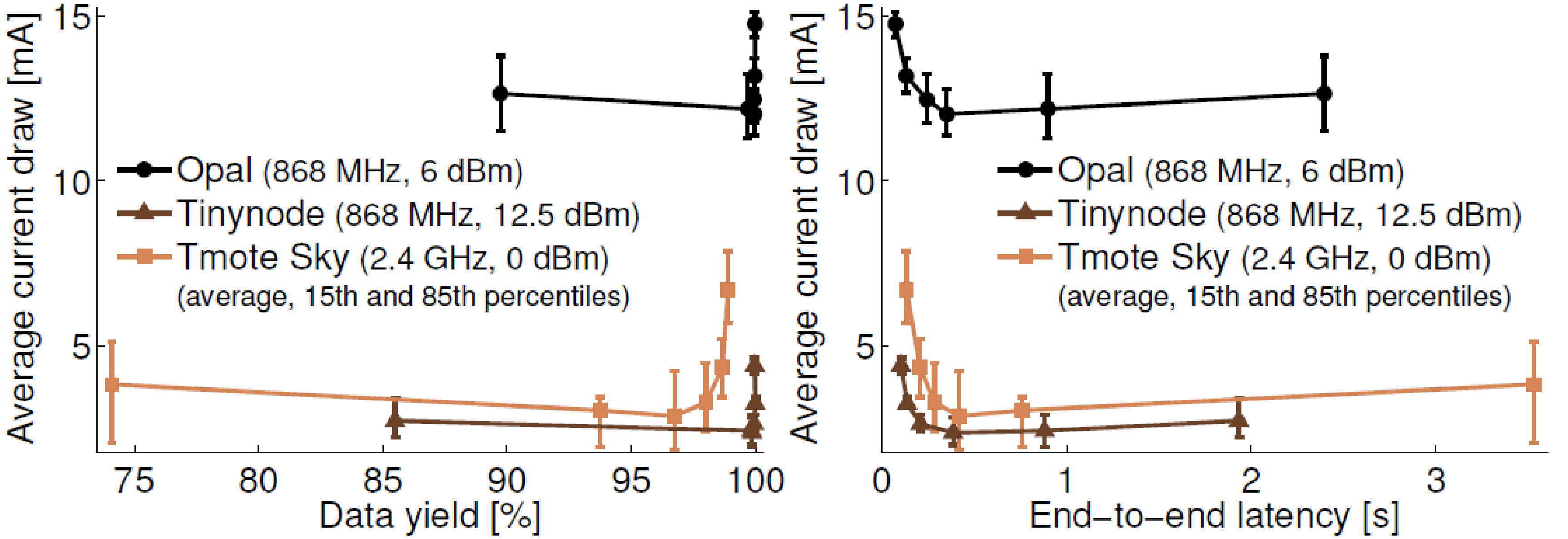
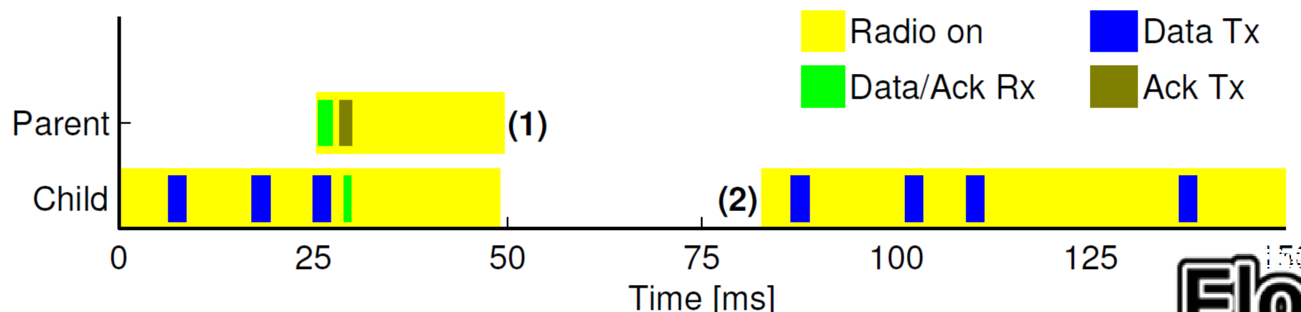
FlockLab

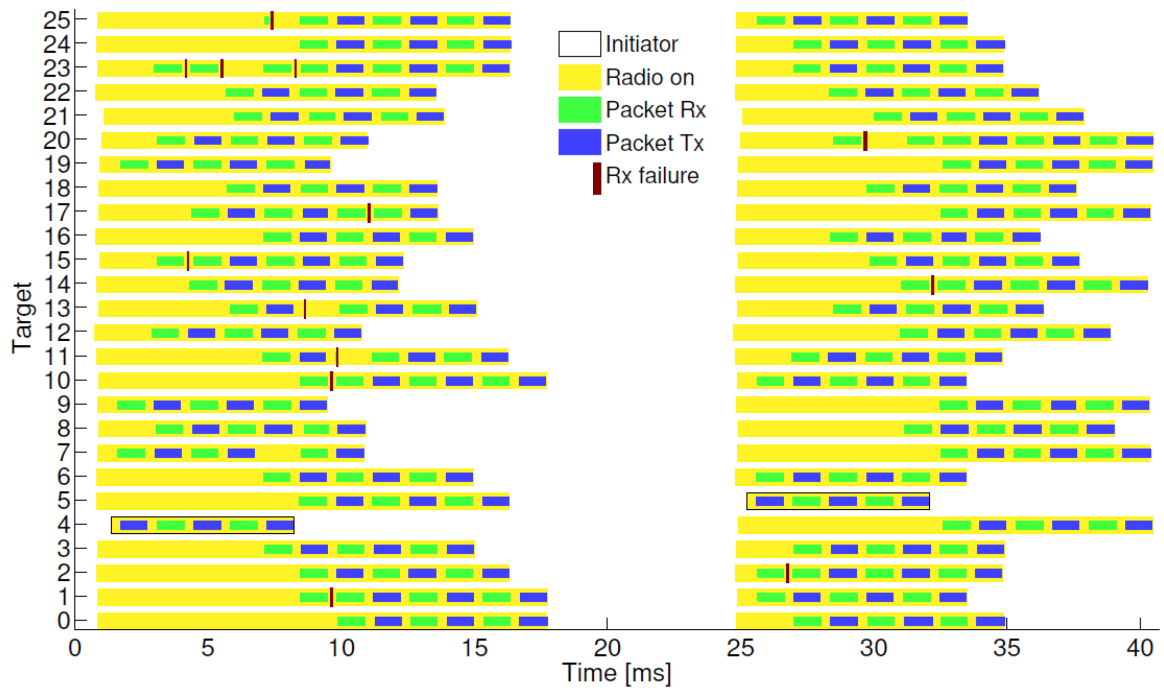
Test Case: Analysis of CTP/LPL



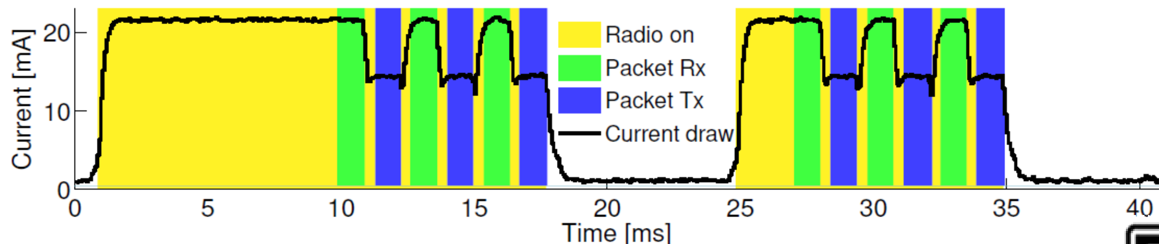


FlockLab

Test Case: Synchronized Glossy Floods



(a) Radio states of 26 Tmote targets obtained from GPIO tracing.



(b) Radio state and current draw of target 0 in (a).

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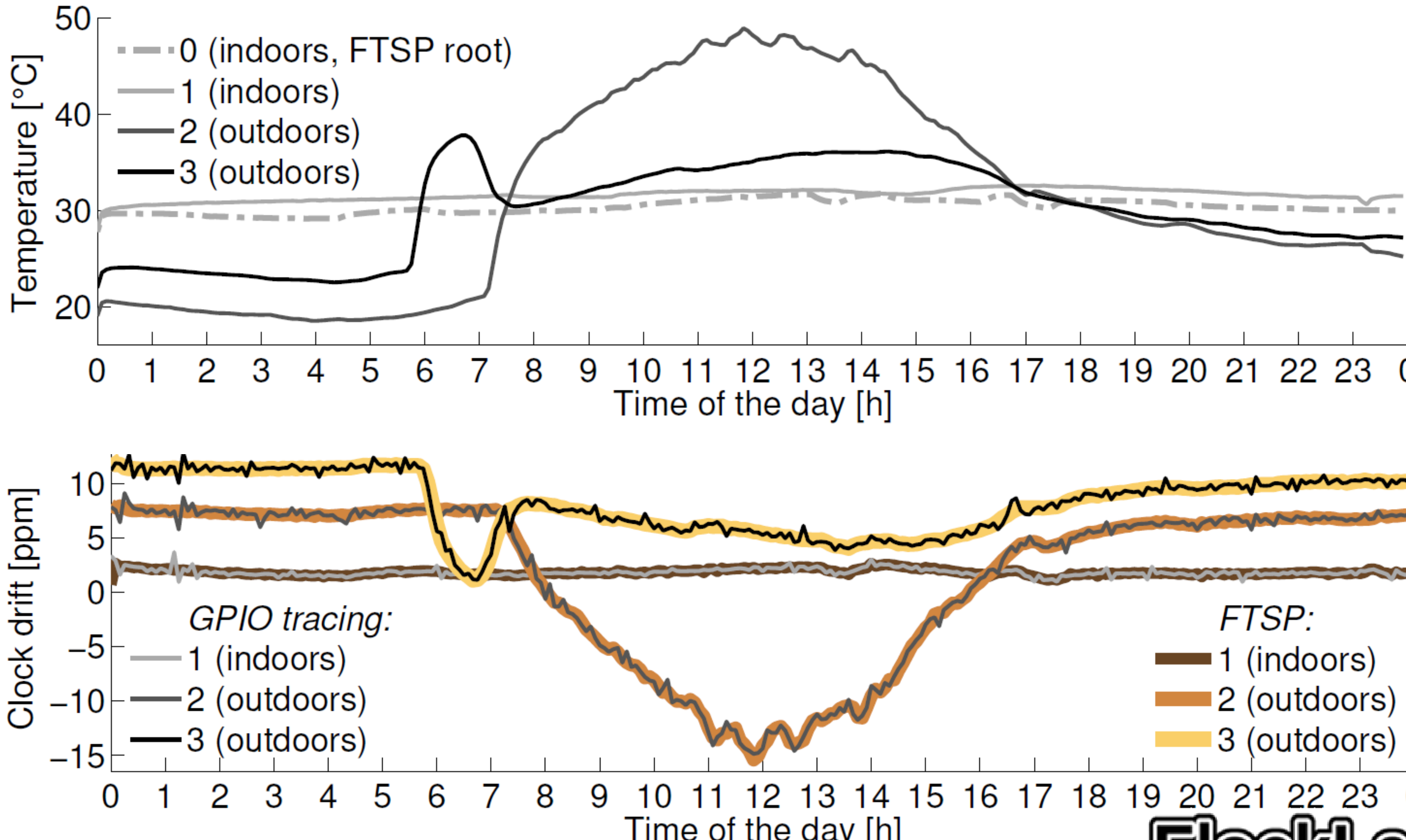
Test Case: FTSP Clock Accuracy



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FlockLab Testbed Statistics

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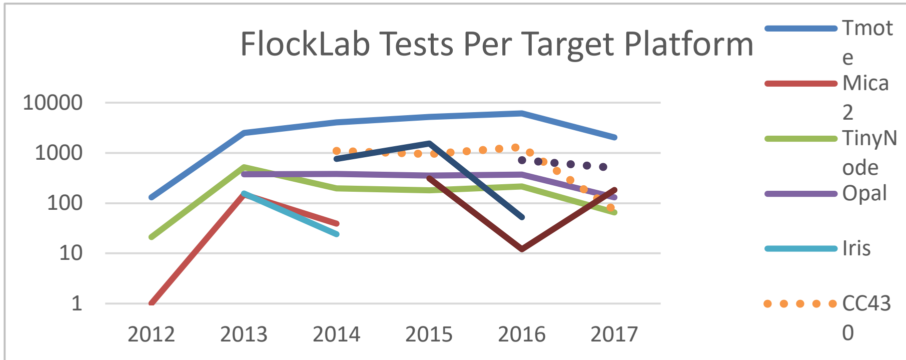
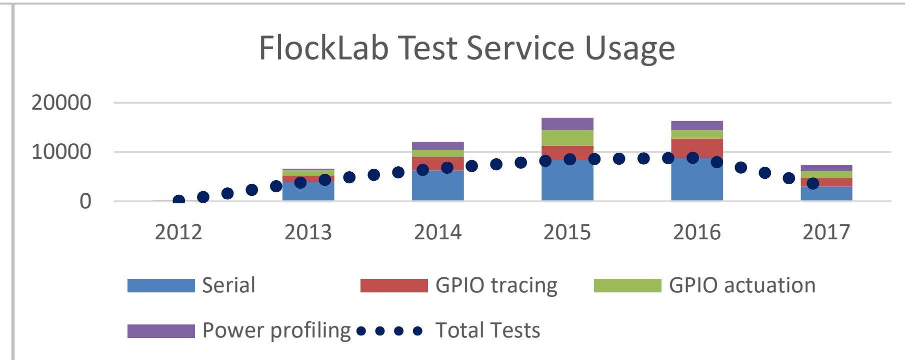
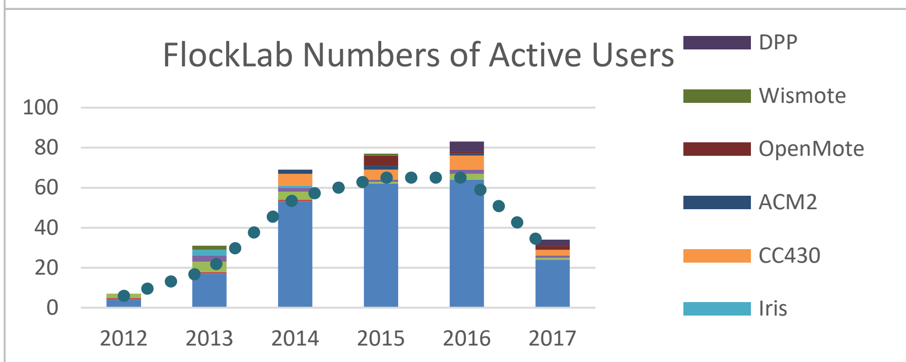
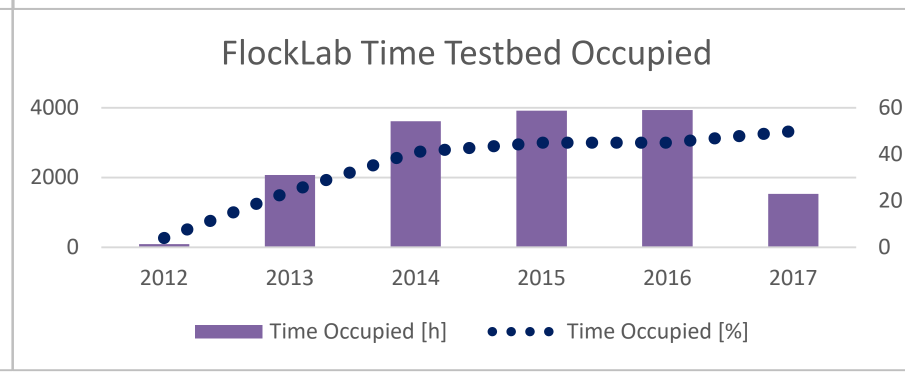


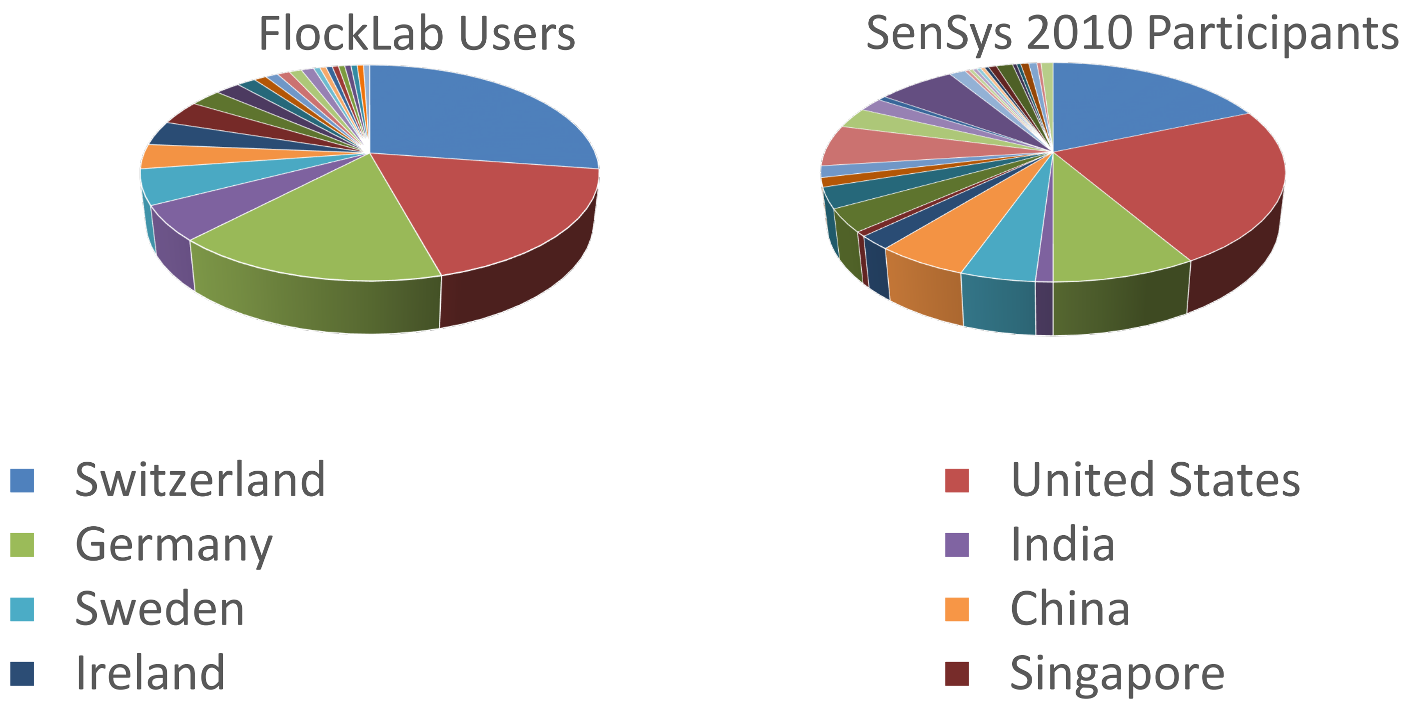






Data taken 2017-05-09

FlockLab Testbed User Demographics



A Big Success – The Rise of WSN Testbeds

Motelab: A wireless sensor network testbed

Authors	Geoffrey Werner-Allen, Patrick Swieskowski, Matt Welsh
Publication date	2005/4/24
Conference	Proceedings of the 4th international symposium on Information processing in sensor networks
Pages	68
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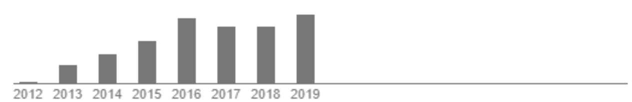

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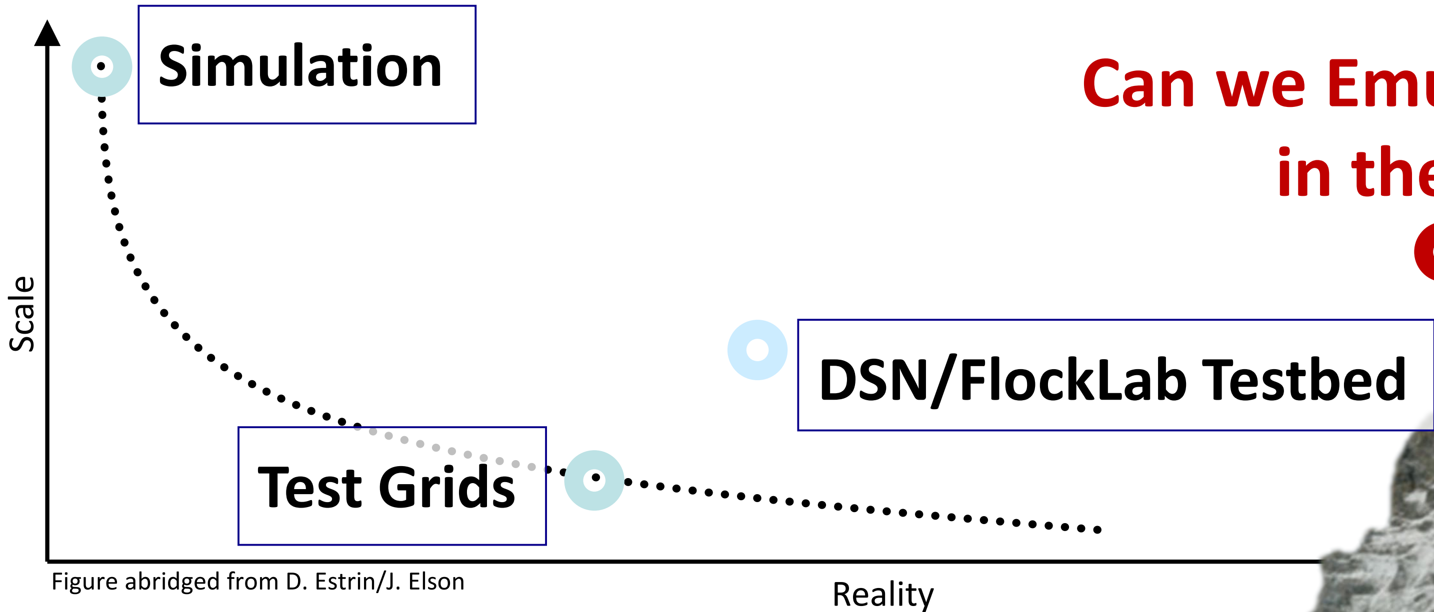
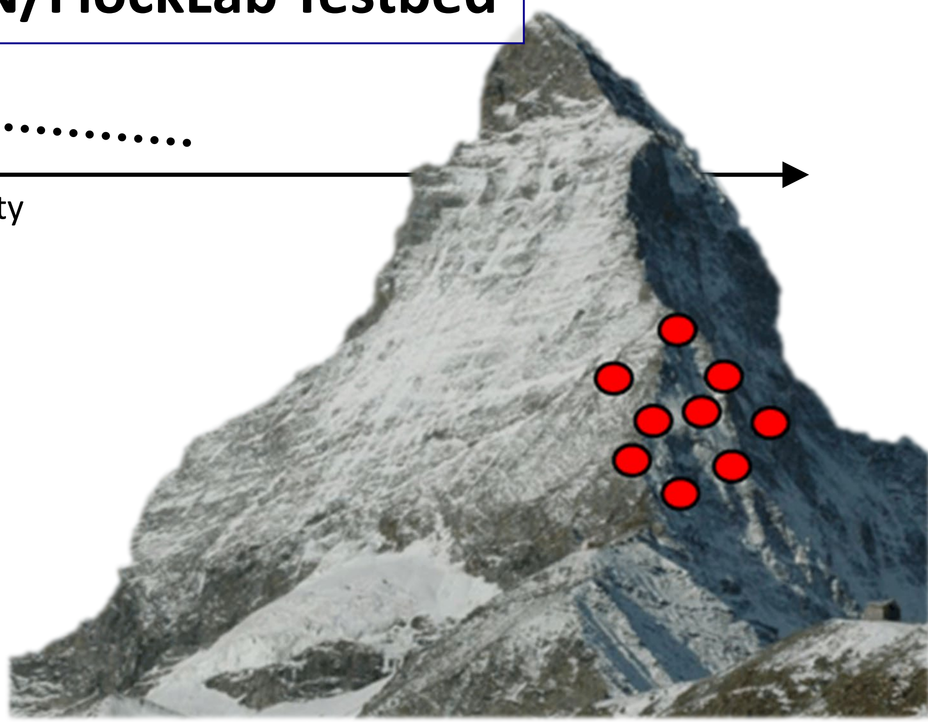


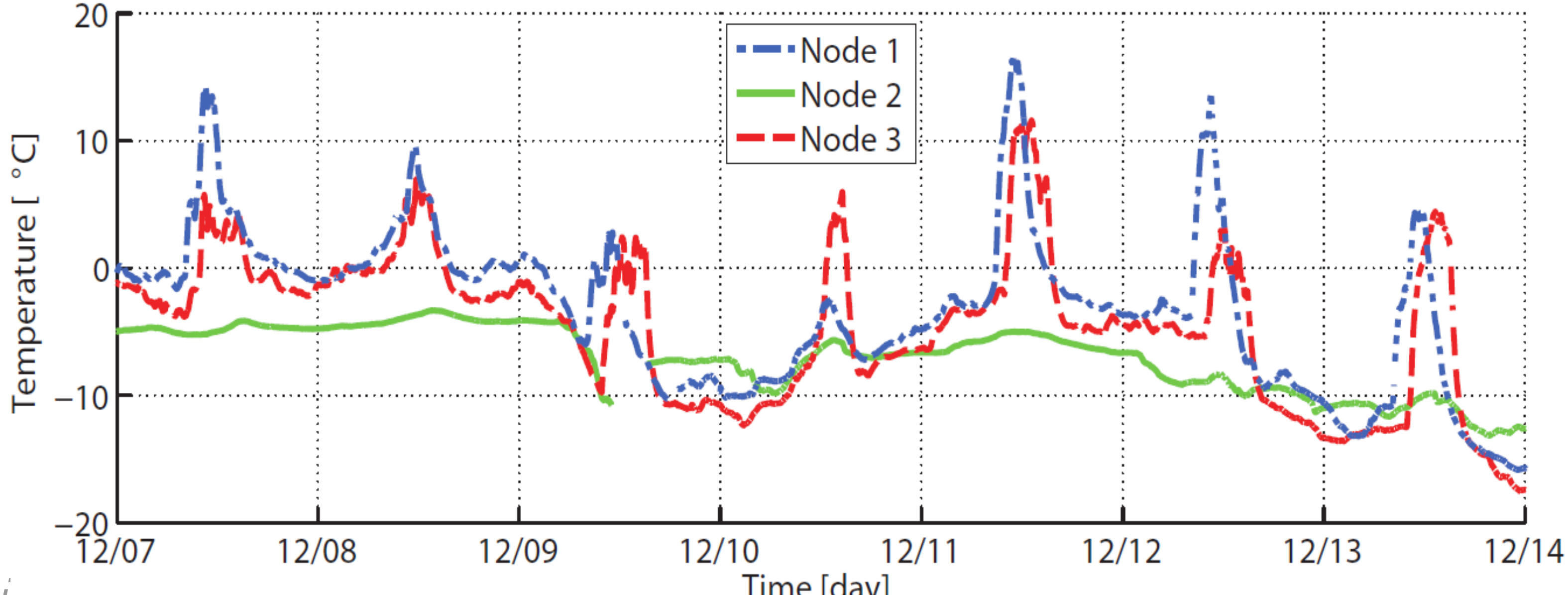
Can we Emulate Reality in the Lab?



- Testbeds are **not** the real target environment
  - RF environment
  - Stimuli from physical processes
  - Weather
  - Scale

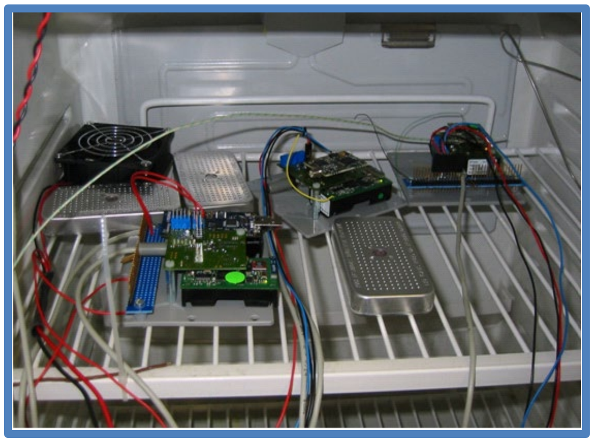
Challenge: The Physical Environment

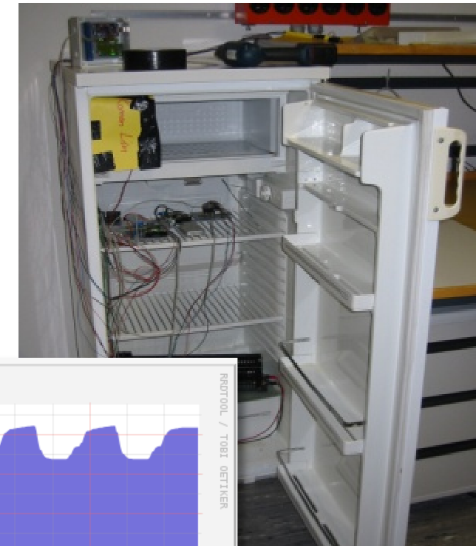
- Strong daily variation of temperature
  - −30°C to +40°C
  - ΔT ≦ 20°C/hour
- Impact on
  - timing, energy availability, fatigue, …

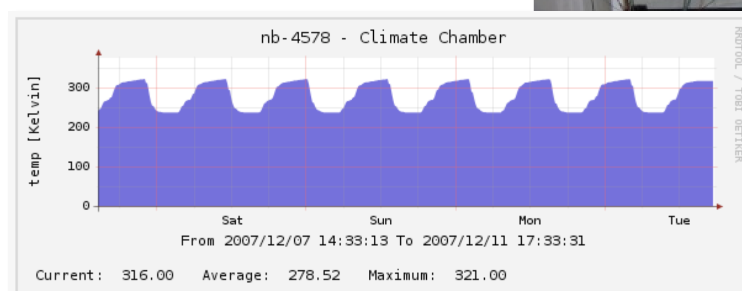


Extending Physical Characterization

- Emulating the environment...
  - temperature cycle testing (TCT)



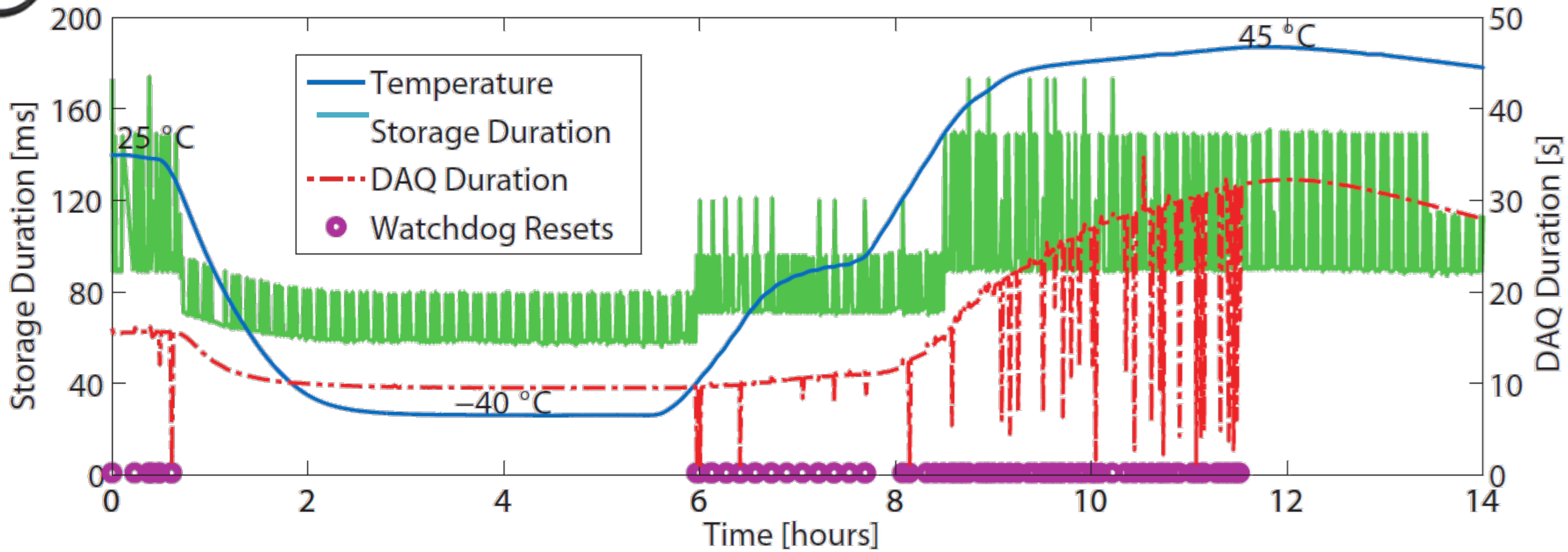




- ... and resource usage
  - different power sources: Batteries, rechargeable cells, solar, fixed DC power...

Impact of Environmental Extremes

- Tighter guard times increase energy efficiency
- Software testing in a climate chamber
  - Clock drift compensation yields ± 5ppm
- Validation of correct function



[Beutel DATE 2011]

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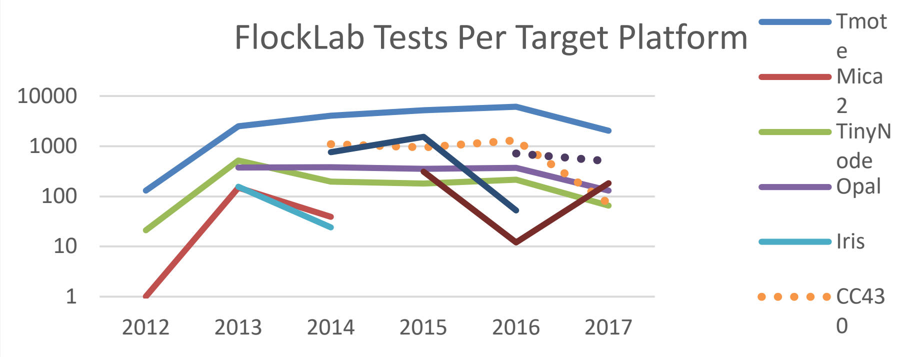

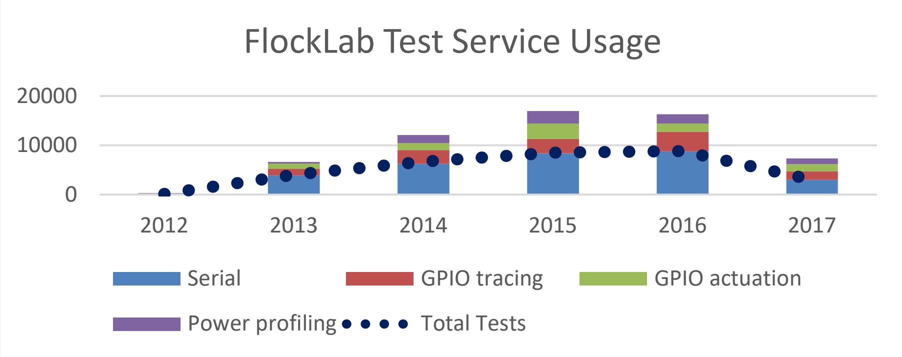

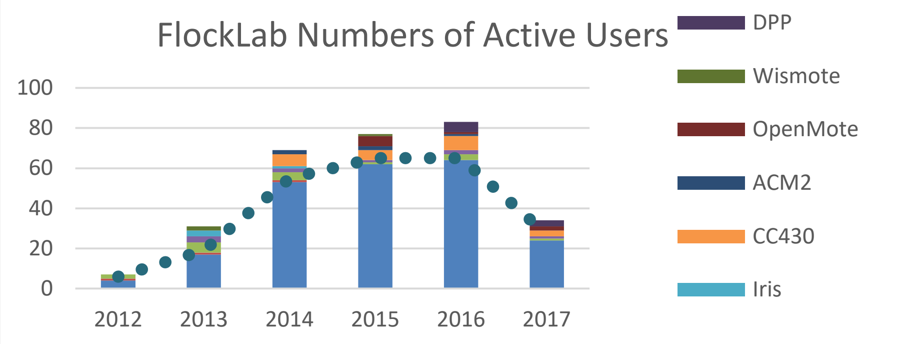

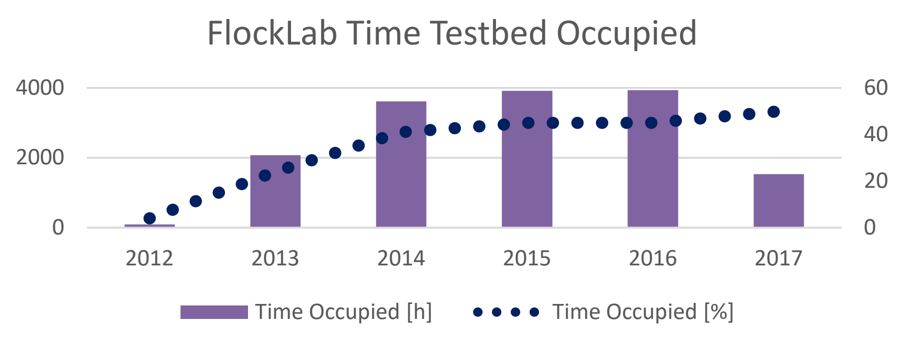

Data taken 2017-05-09

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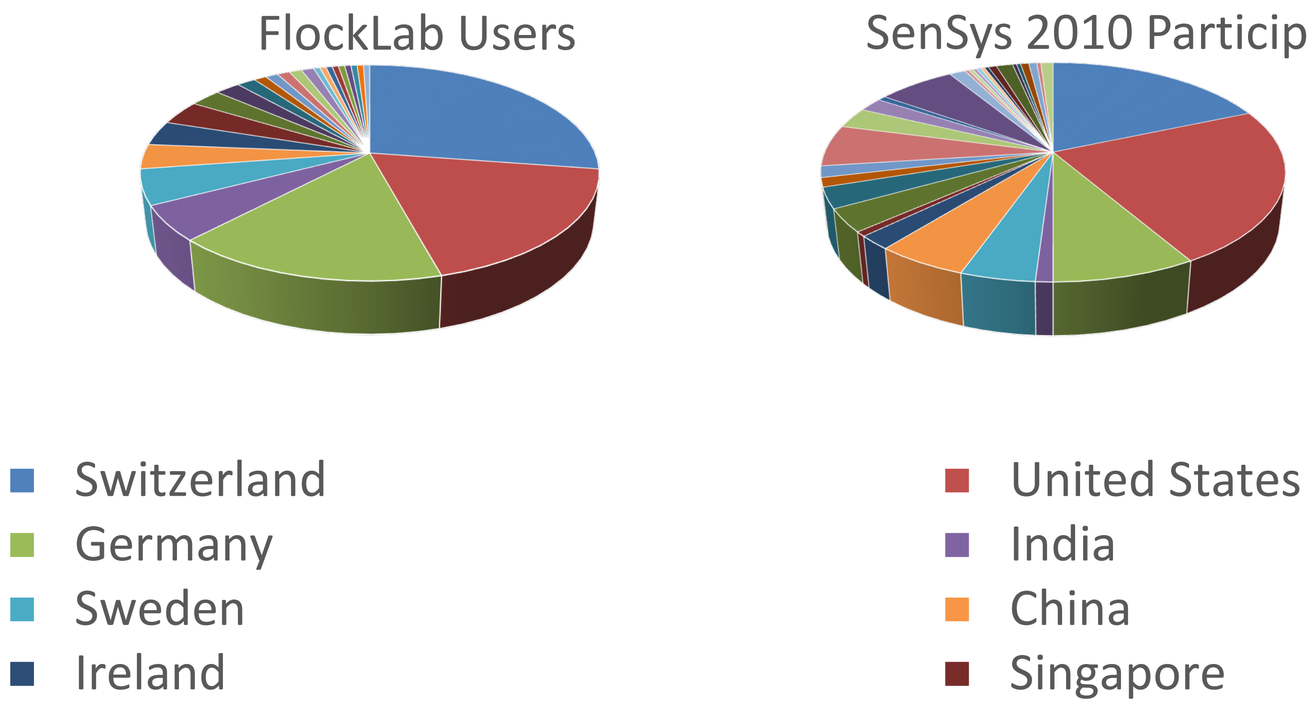

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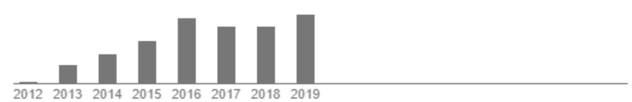


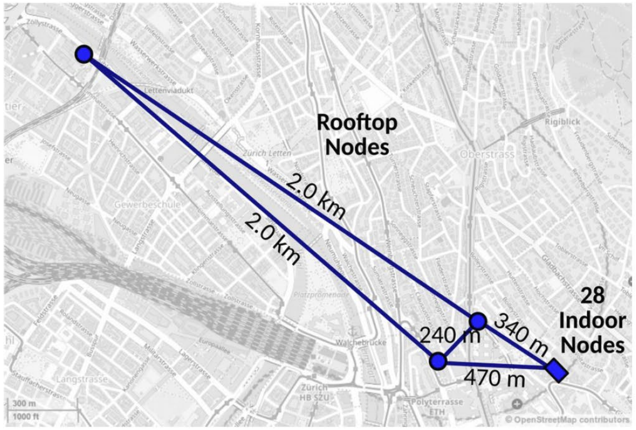
Low-Power System Design

FLOCKLAB RECENT DEVELOPMENTS

Long-Range Extension

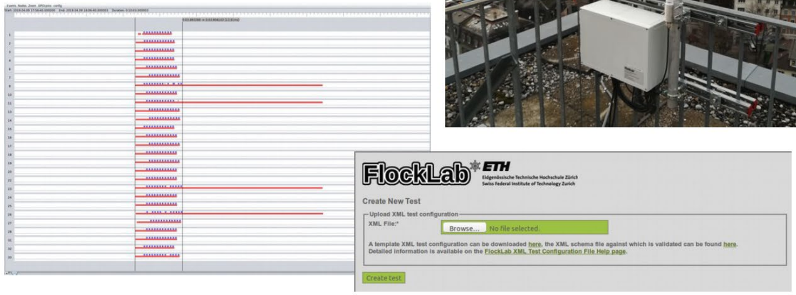
Network Topology

- **Goal**: City-wide long-range testbed
- **Current network**: 3 rooftop nodes, 28 indoor nodes
- **Antenna options**: Identical targets with different antennas (e.g. high-gain, low-gain)



Demo

- FlockLab **observer hardware** exhibit
- Demonstration of running a **FlockLab test** on the **rooftop nodes**
  - Web interface
  - Tracing results (GPIO, serial, power)

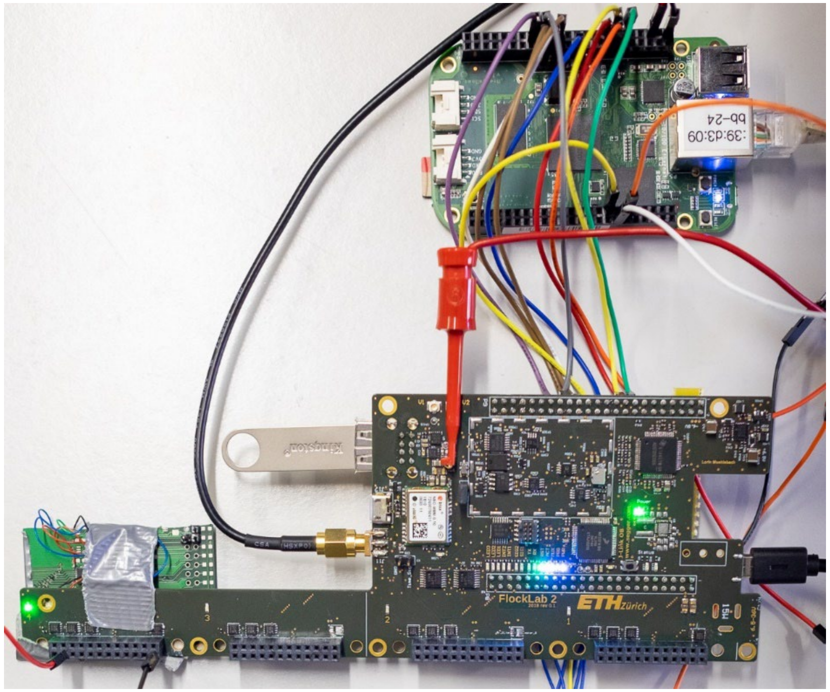


FlockLab v2.0

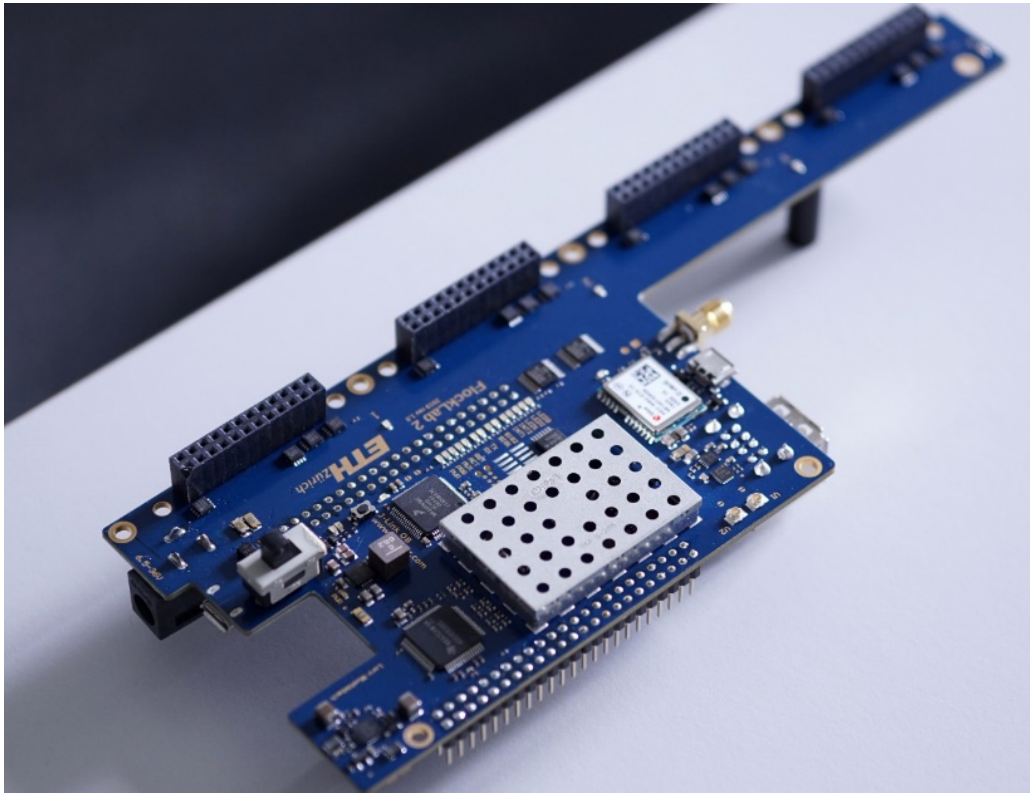
- **Why:** End-of-life of components

- GPIO tracing with 10Mhz
- Serial logging
- Controllable target voltage
- Serial Wire Debugging using SEGGER J-Link/J-Trace
- High dynamic range current measurement
- GPS time synchronisation
- Support for multiple targets
- Compatibility to existing targets

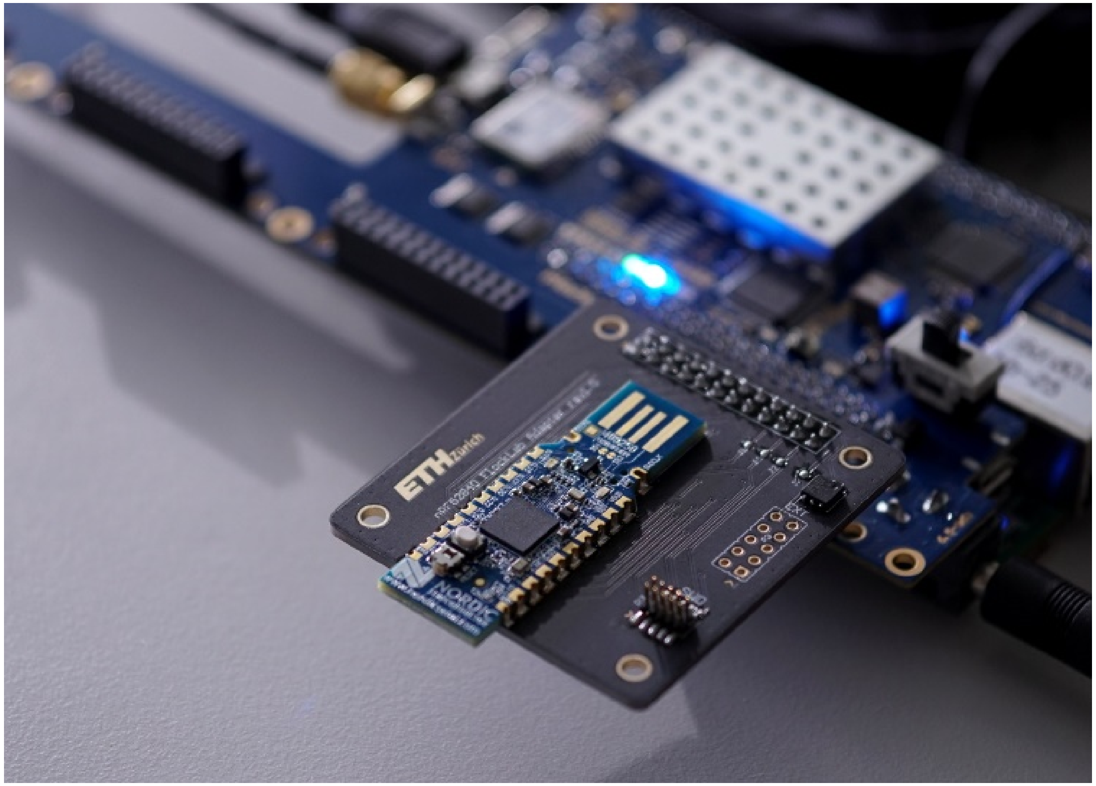
FlockLab V2.0 Prototype



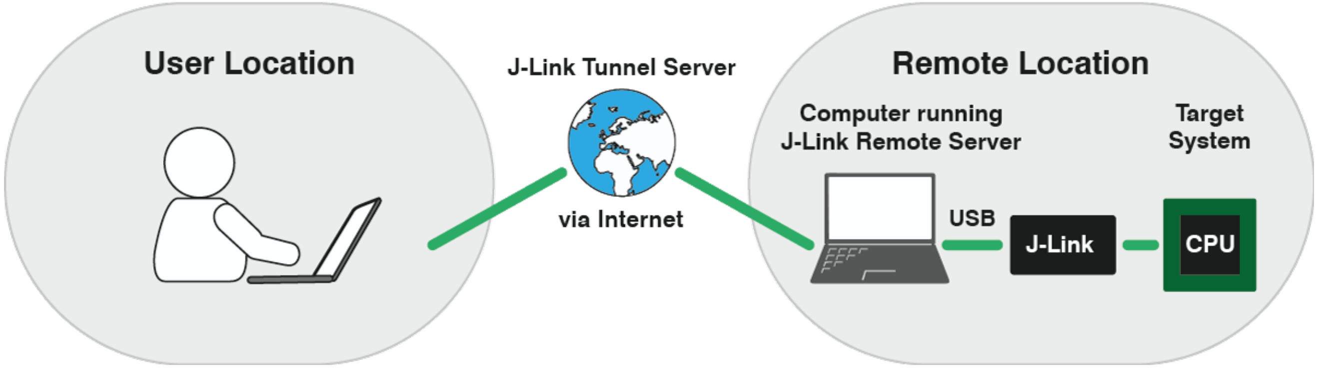
FlockLab V2.0 Pre-Series



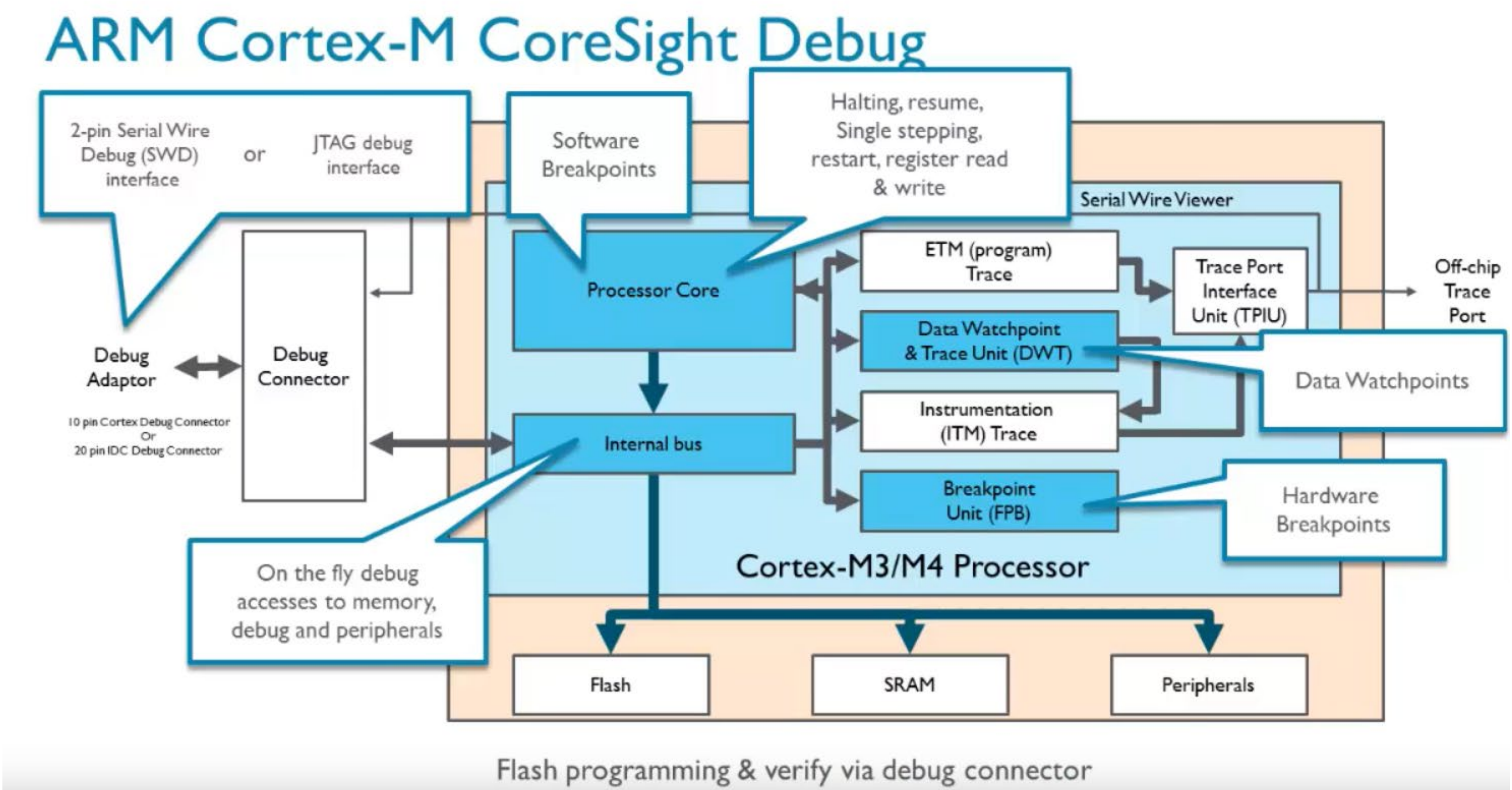
Side Effect – nRF52810



Less Instrumentation using J-Link/J-Trace



Leveraging Full ARM Debug/Trace Support



Low-Power System Design

TESTING METHODS – MODELING TECHNIQUE – VALIDATION

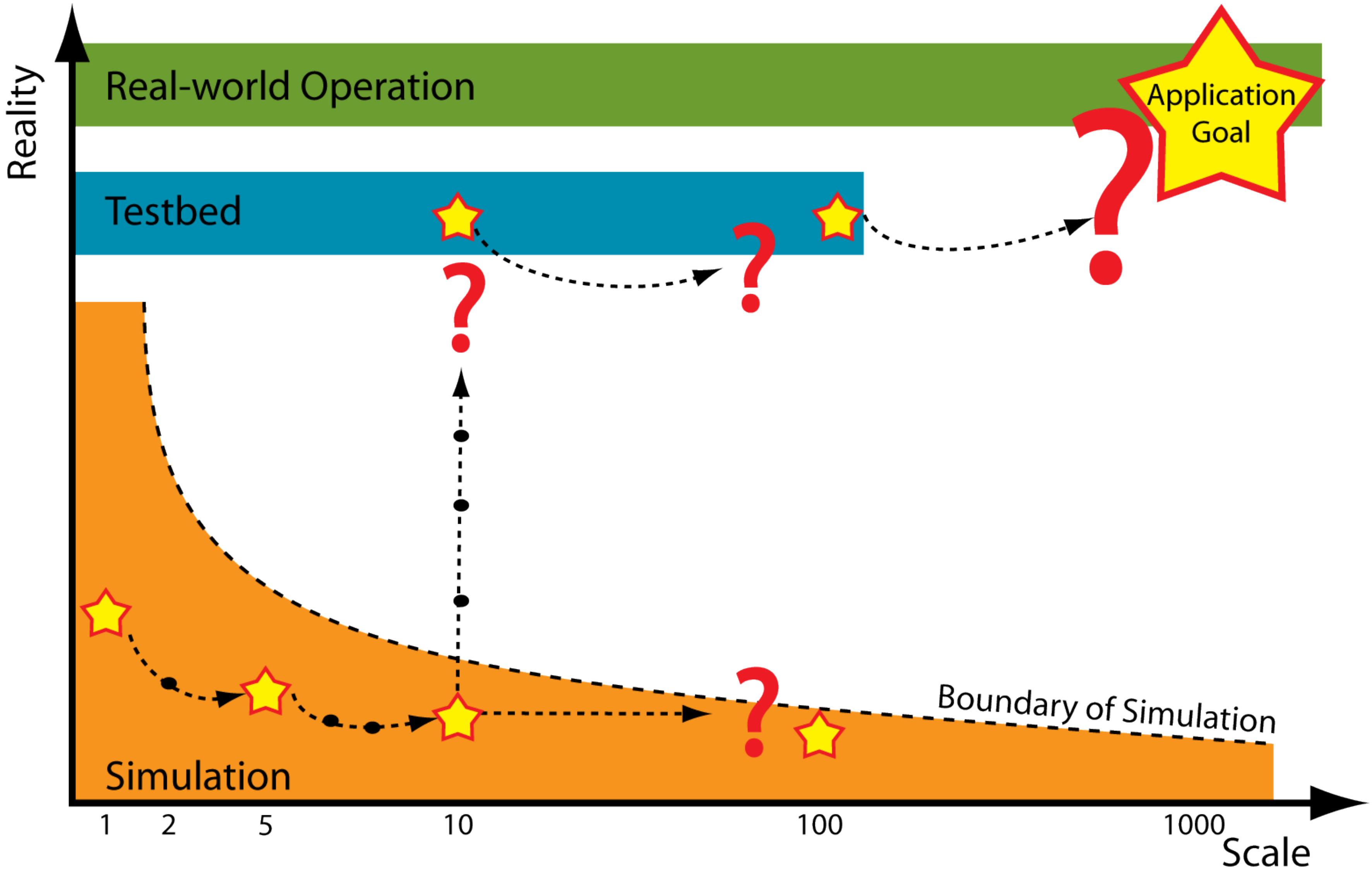
WSN Validation Methods

- Threats to predictability
  - non-deterministic environment (energy harvesting, availability of communication)
  - working close to resource limits (energy, memory, bandwidth) makes systems extremely fragile

- **Formal methods**
  - verification
  - correct by construction

- **Testing**
  - increase observability
  - distributed and scalable
  - different modalities

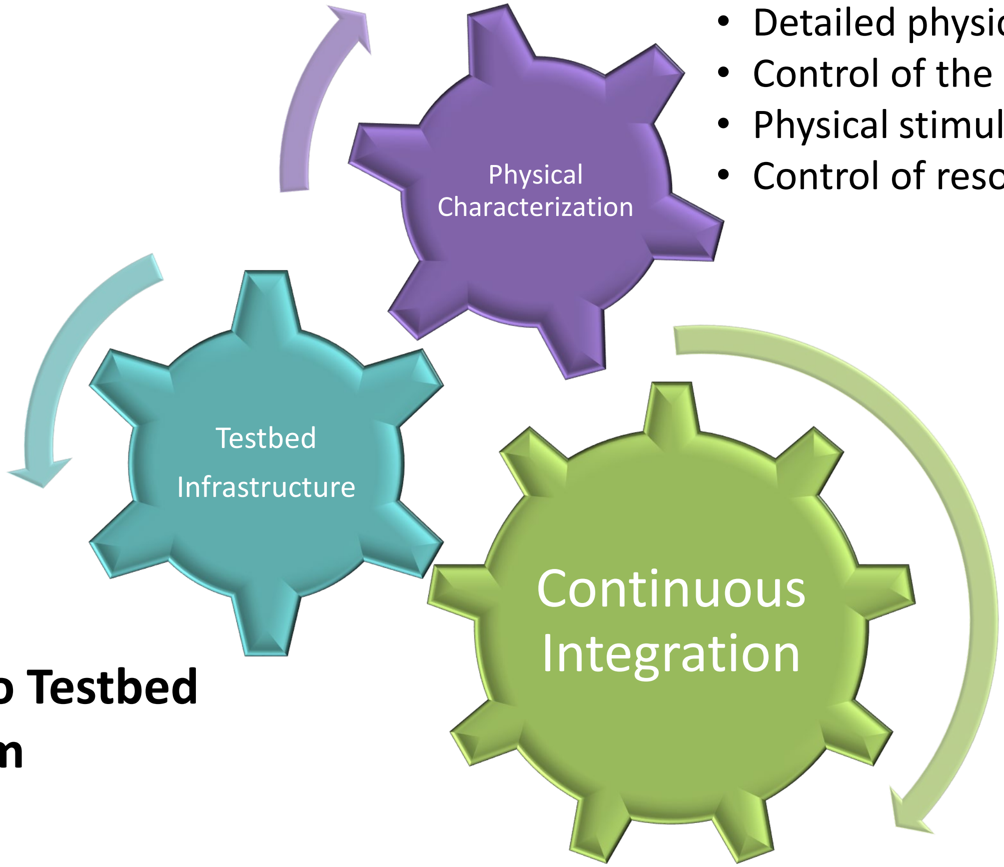
Testing – A Step Towards Reality



Methodology and Development Tools

Extending the Logical View

- Detailed physical monitoring
- Control of the environment
- Physical stimulation
- Control of resources

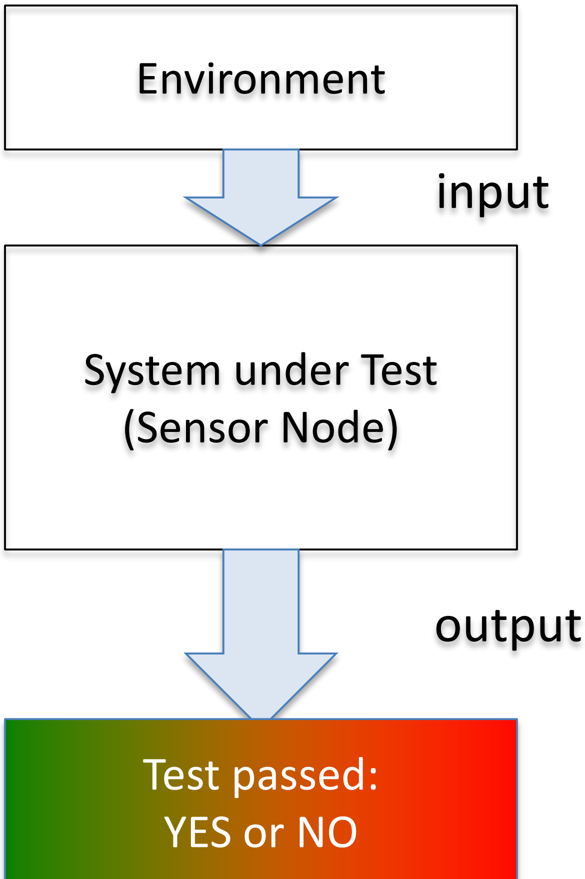


From Platform to Testbed to Multi-Platform

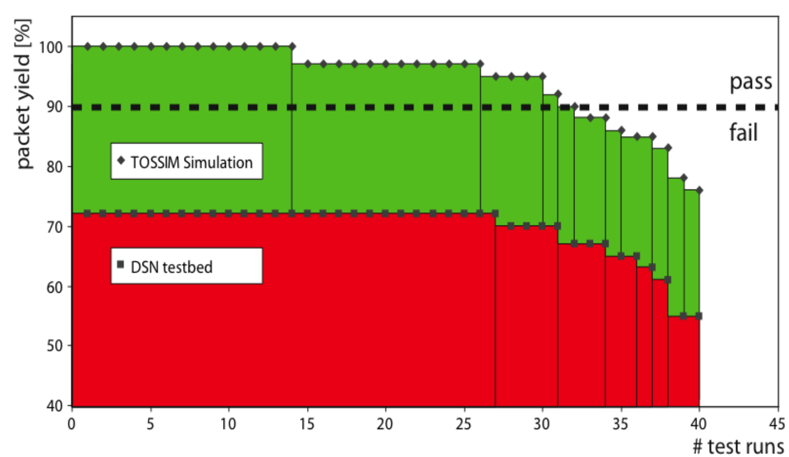
- Native execution
- Log file analysis
- Influence of the environment

Advanced Software Engineering Practices

Coordinated Testing



- Formalize testing procedure
  - Given some test case, an environment and corresponding outputs.
  - Based on the outputs check whether the system works as expected
  - Repeat this…

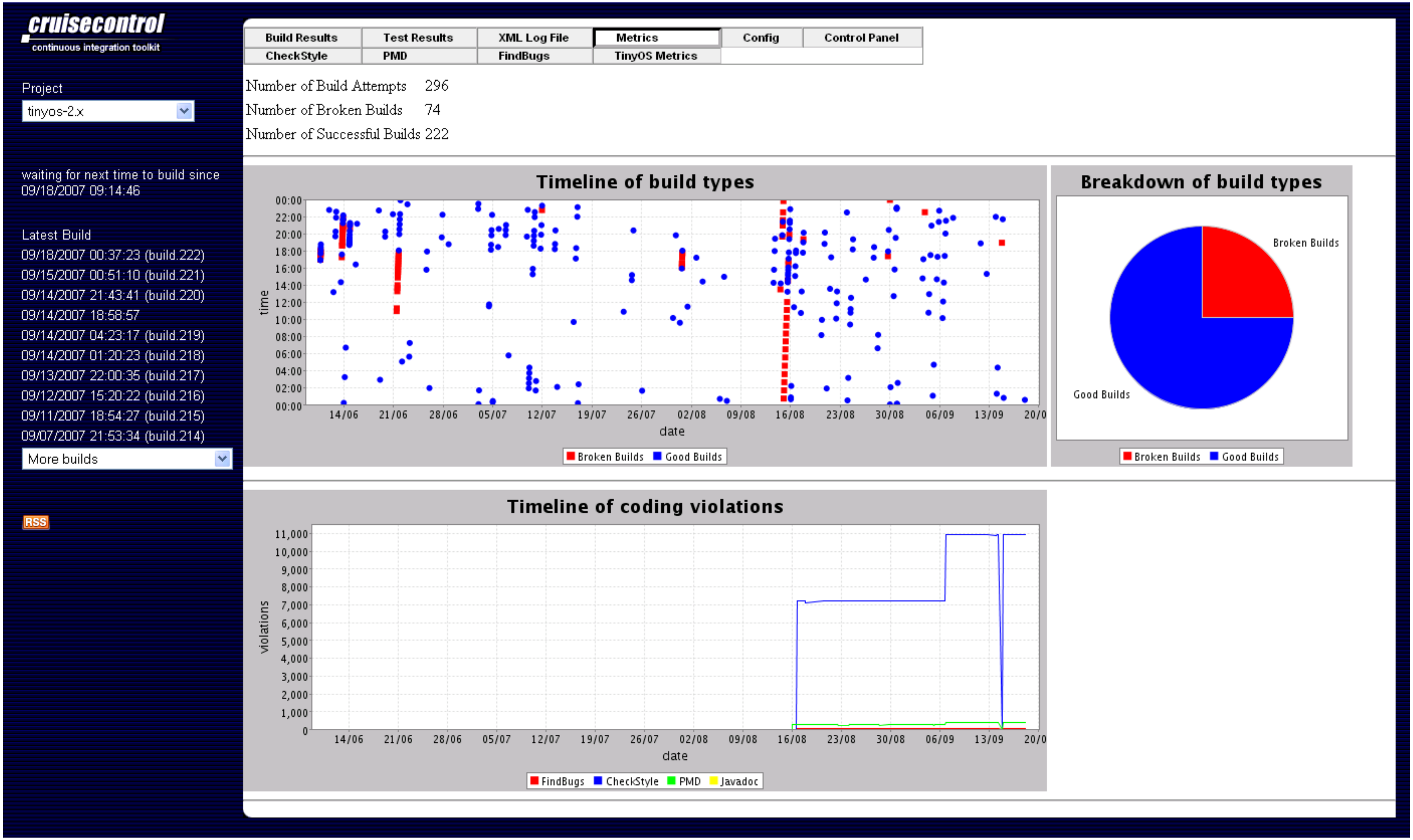


Automation: Continuous Integration

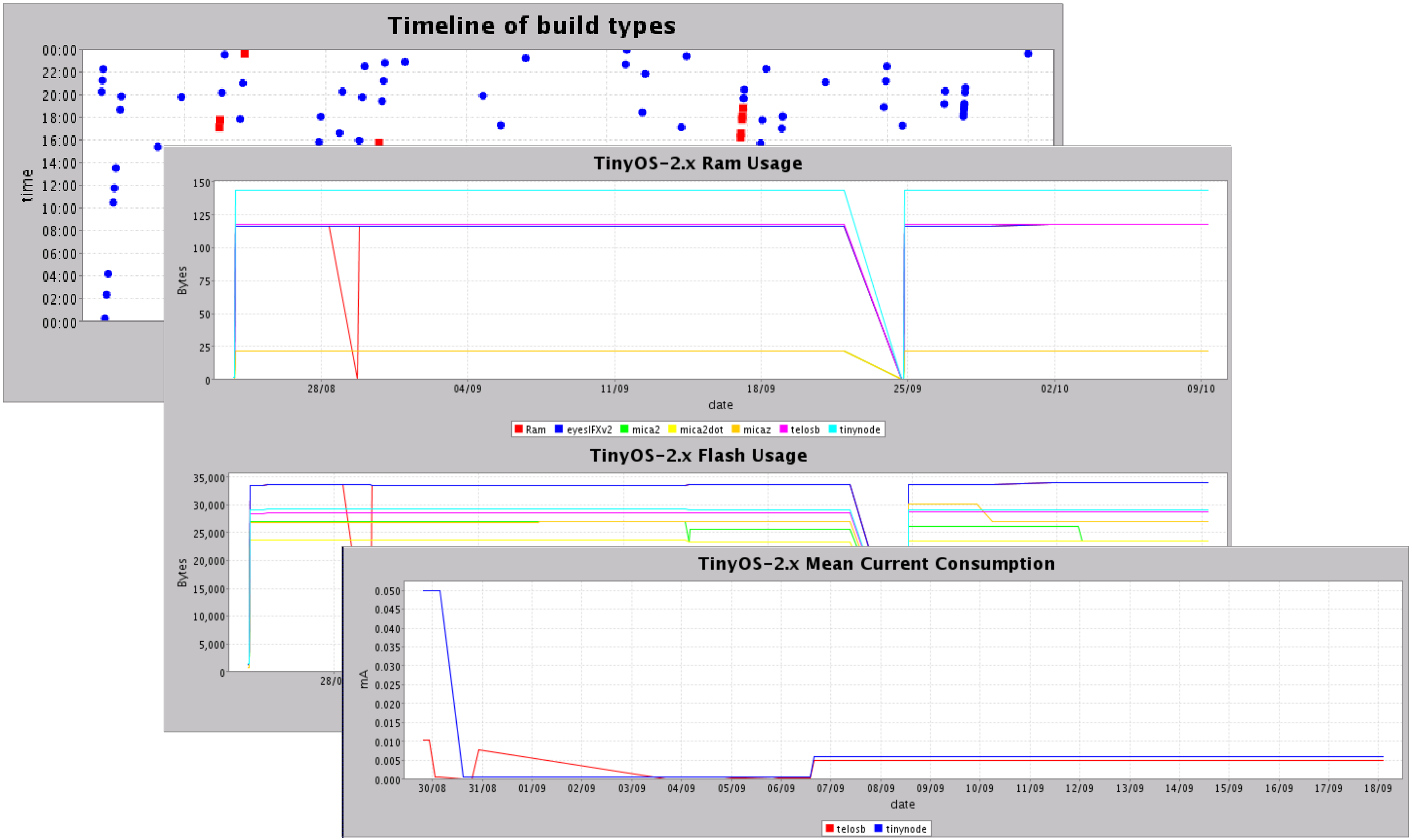
- Run Build and Test Loop Continuously
  - Watch repository for changes
  - Run build and tests
  - Publish status of the build and tests to developers

- Benefits
  - Detect errors early
  - Monitor code quality over time
  - Prevent integration problems

Example Tool Cruisecontrol



Detailed Statistics over Development Time



WSN Validation Methods

- Threats to predictability
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- **Testing**
  - increase observability
  - distributed and scalable
  - different modalities

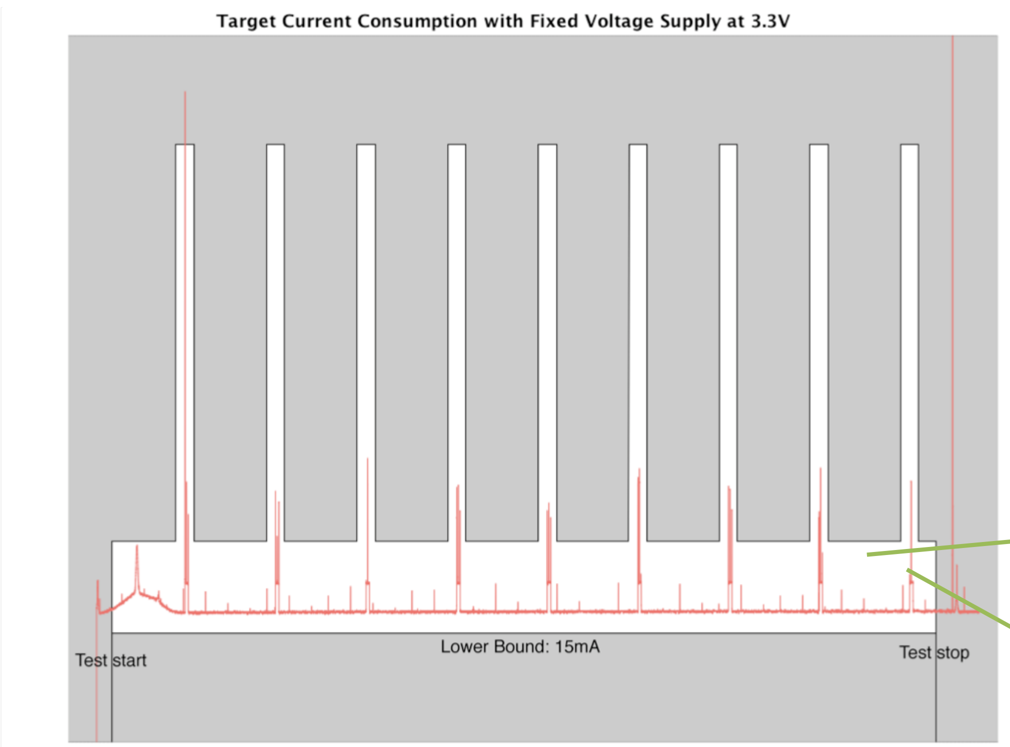
Power Trace Verification

- Generate a (formal) model of the system
  - Model of the hardware and software, including ***dynamic behavior***
  - Model of the measured power traces
  - Model of the test cases

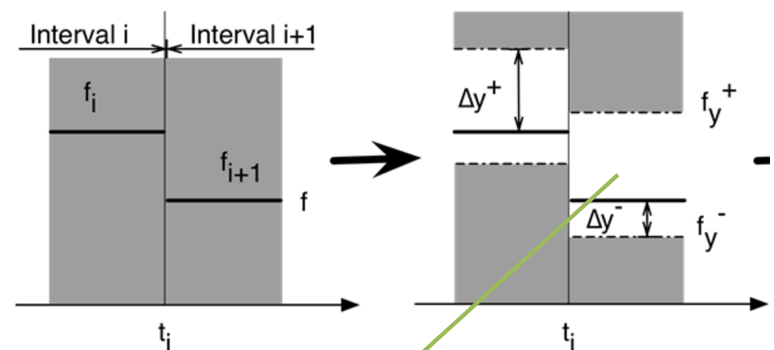
- Conformance test for power measurements
  - Can the measured power consumption be explained by the hardware/software/test specification?
  - Failures may be due to model or implementation errors

“Naïve” Trace Bounds

Bounds for allowed power consumption



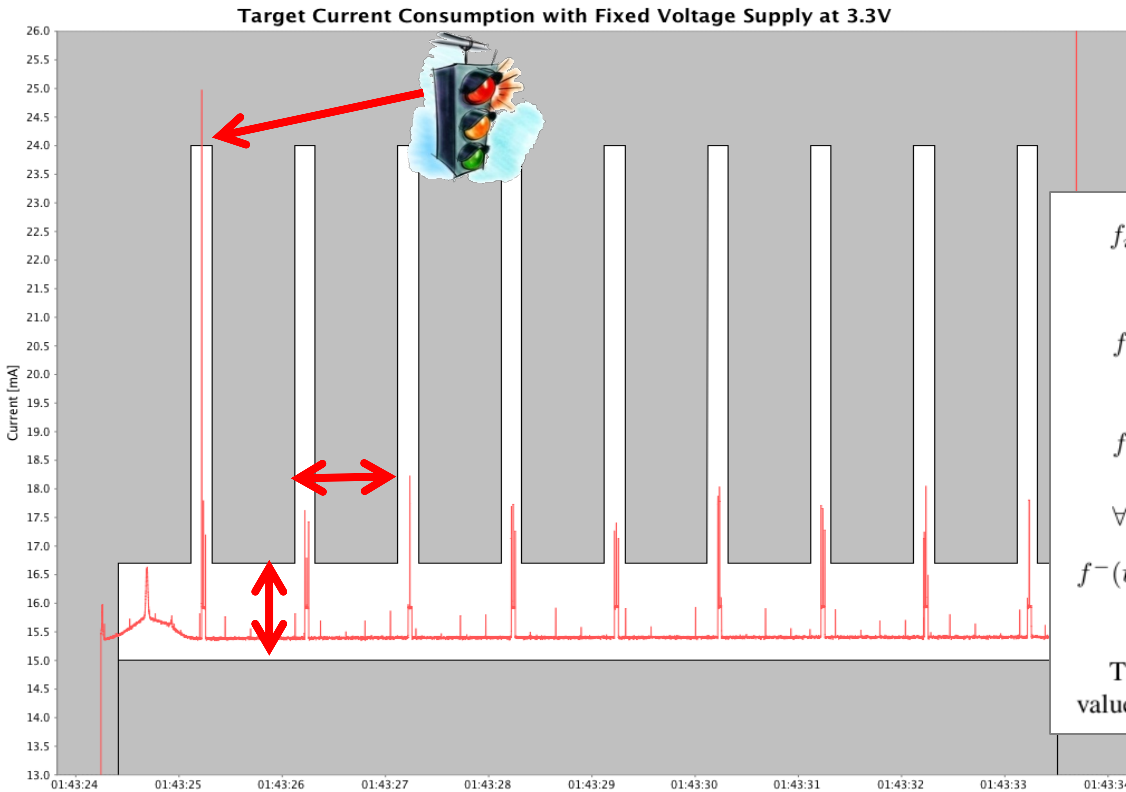
Determine static bounds given a deterministic reference



acceptance region

measurements

Validation of Traces using Formal Bounds



$$f_i(t) = \begin{cases} a_0 + a_1 \cdot x + \dots & \text{if } t \in [t_{i-1}, t_i) \\ 0 & \text{if } t \notin [t_{i-1}, t_i) \end{cases}$$

$$f_i^-(t) = \begin{cases} f_i(t) - \Delta y^- & \text{if } t \in [t_{i-1}, t_i) \\ 0 & \text{if } t \notin [t_{i-1}, t_i) \end{cases}$$

$$f^-(t) = \sum_{i=1}^{n} f_i^-(t)$$

$$\forall \tilde{t} \in [-\Delta t, \Delta t], \forall i \in \mathbb{N} :$$

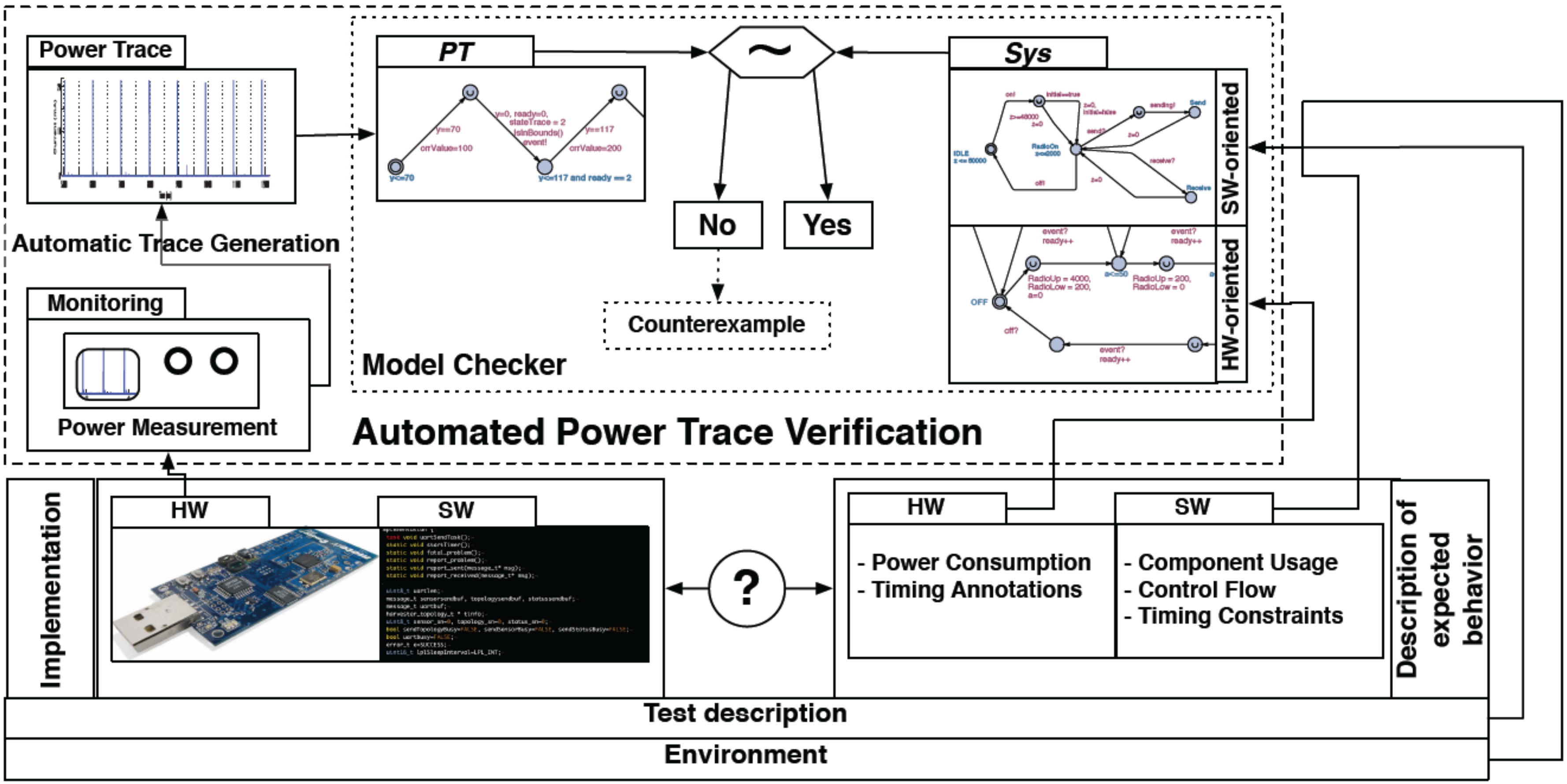
$$f^-(t + \tilde{(t_k)}) = \begin{cases} f^-(t_i^-) & \text{if } -f(ti^-) + f(t_{i+})) \leq 0 \\ f^-(t_i^+) & \text{if } -f(ti^-) + f(t_{i+})) > 0 \end{cases}$$

The upper bound f^+ follows accordingly with a bound value Δy^+.

- Assertions based on reference traces/specification
- Integrated with each build (regression testing)

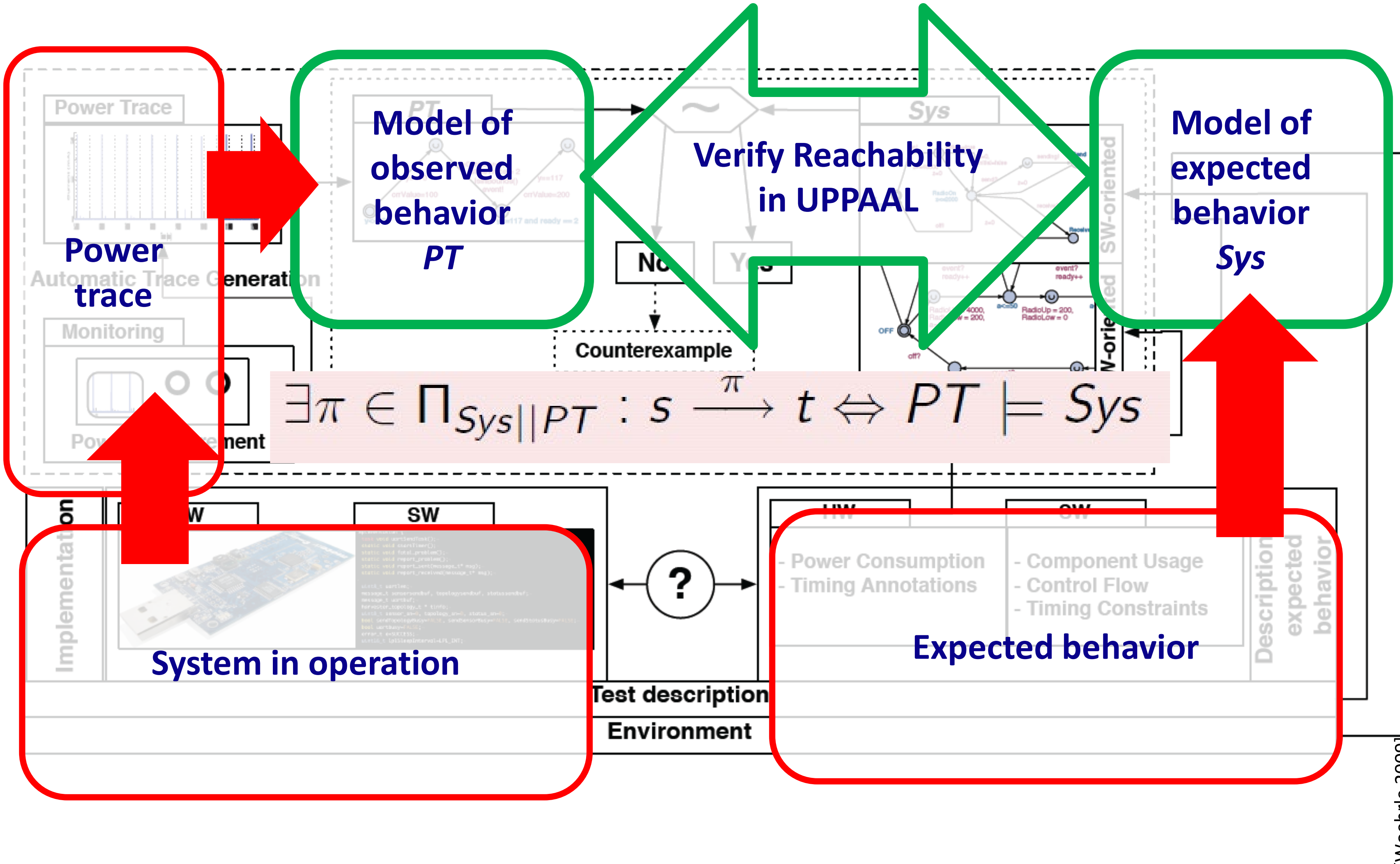
[Woehrle 2007, WEWSN2008, SUTC2008]

Conformance Testing of Power Traces



[Matthias Woehrle, Kai Lampka and Lothar Thiele: Exploiting timed automata for conformance testing of power measurements. Proc. Formal Modeling and Analysis of Timed Systems 2009, p. 275-290, September 2009.]

Conformance Testing of Power Traces



Conformance Testing

- Composition of trace and specification: *PT* || *Sys*
  - Trace automaton *PT* (Sequential measurements)
  - System specification automaton *Sys*
  - Q: Is the power consumption measured explained by the specification?

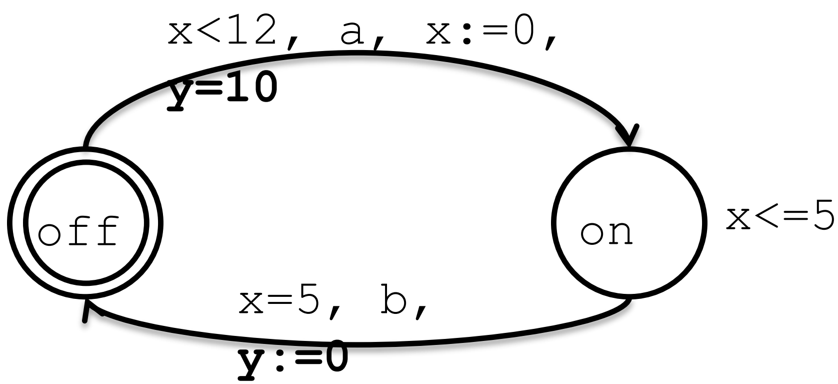
- Example tool: Uppaal Model Checker
  - Offline conformance test
  - Reachability of final trace location

- Possible to test real-time systems on-line: Tron

Basic Timed Automata Model

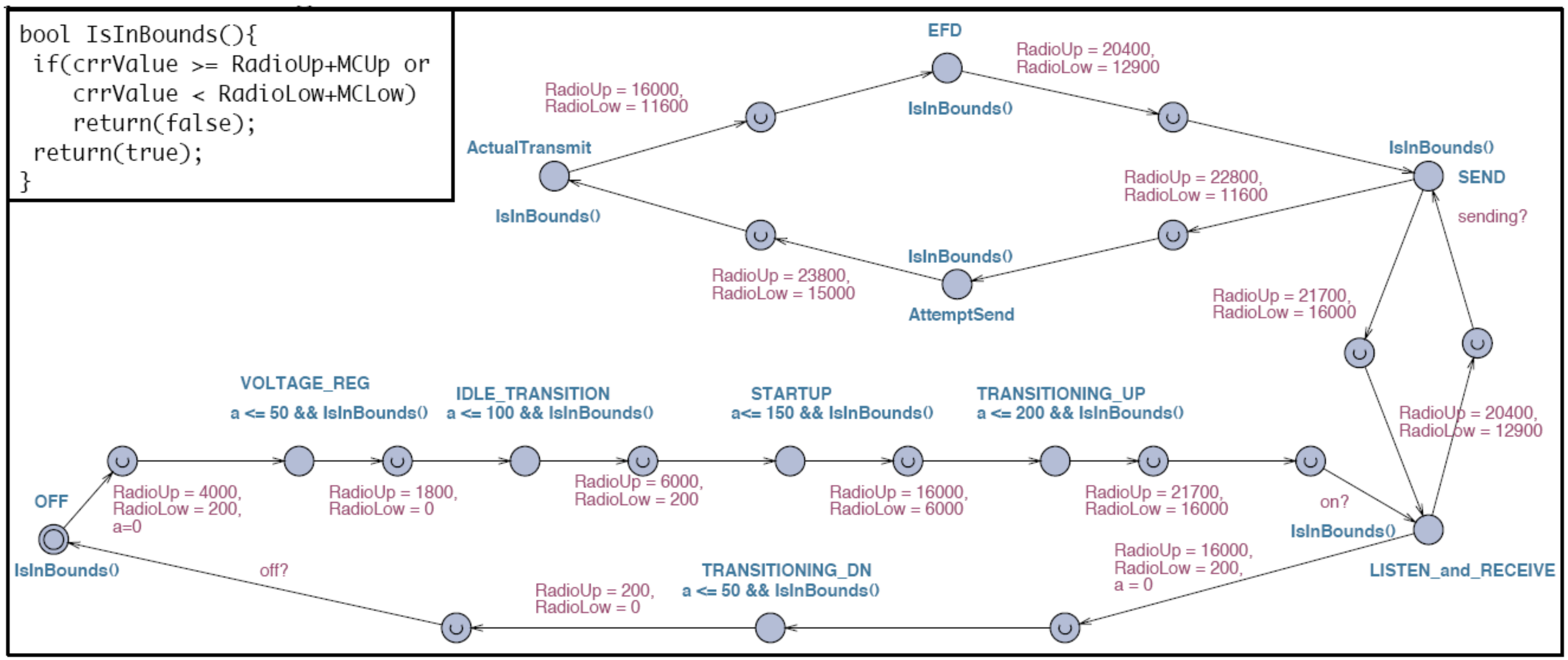
- Infinite state system
- But, reachability is decidable
- Mature tools are available (Uppaal, Kronos)
- **Power consumption as data variable extension**

```
clock x;
label a,b;
int y=0;
```



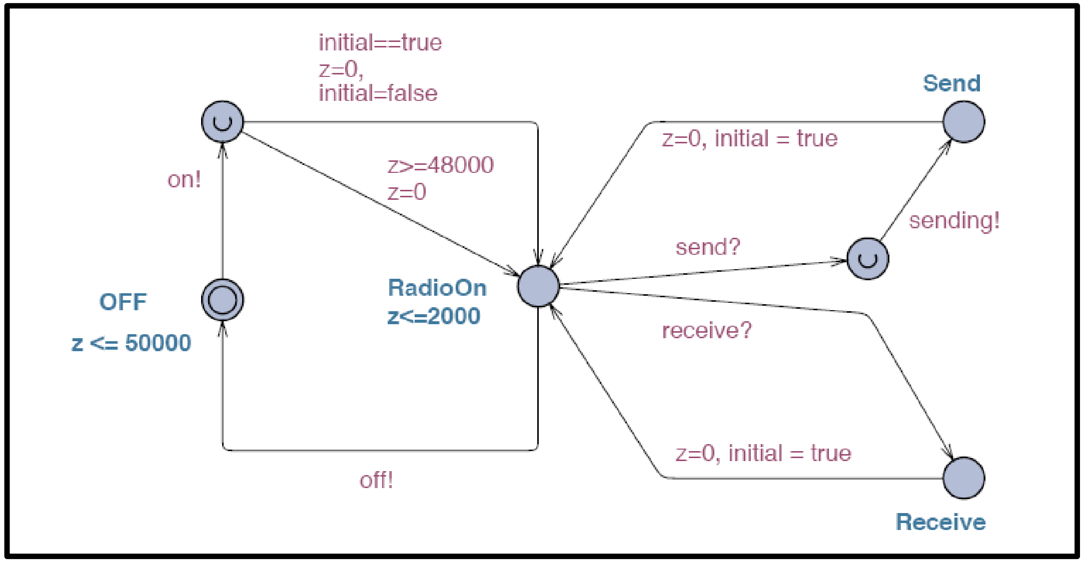
Example Hardware Model

Hardware Model

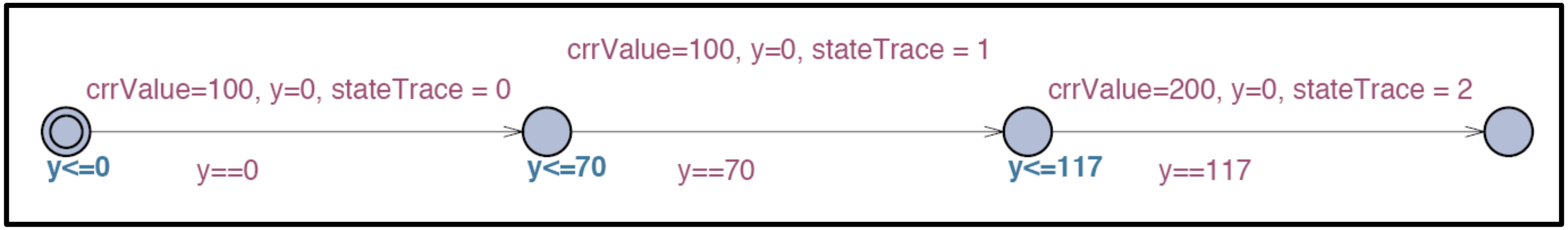


Example Software and Trace Model

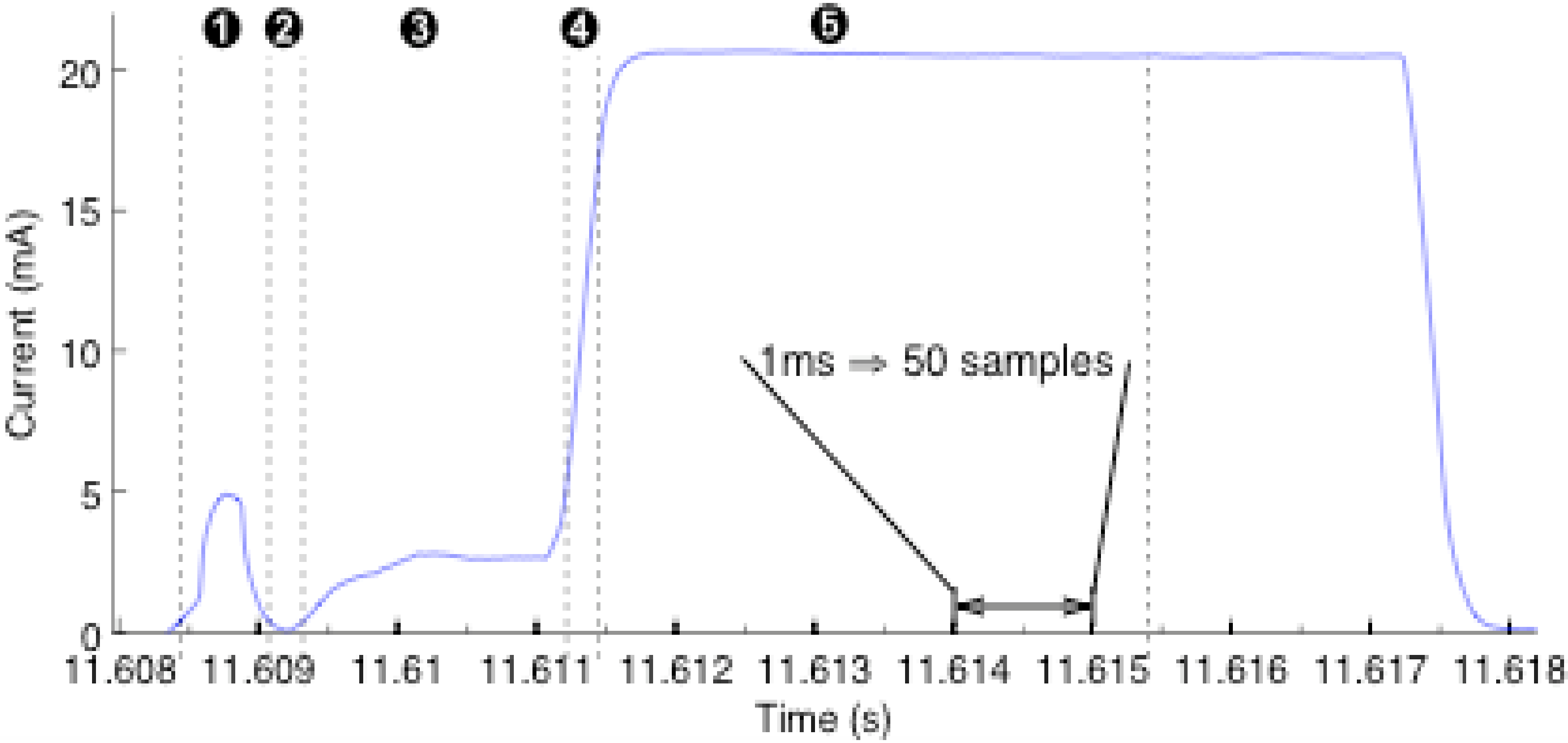
Software Model



Trace Automaton



Power States and Power Traces

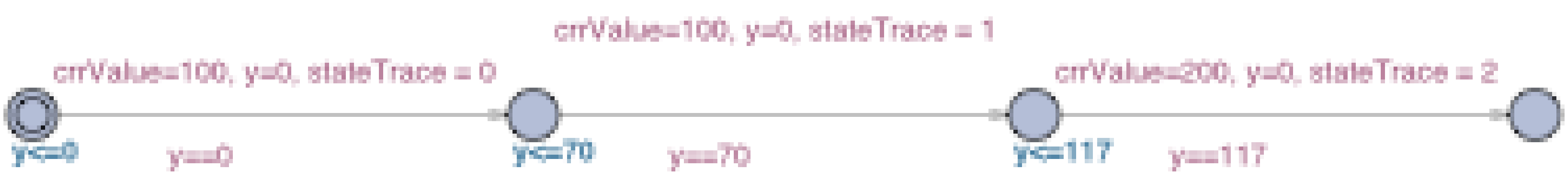


Generating a Power Trace Automaton

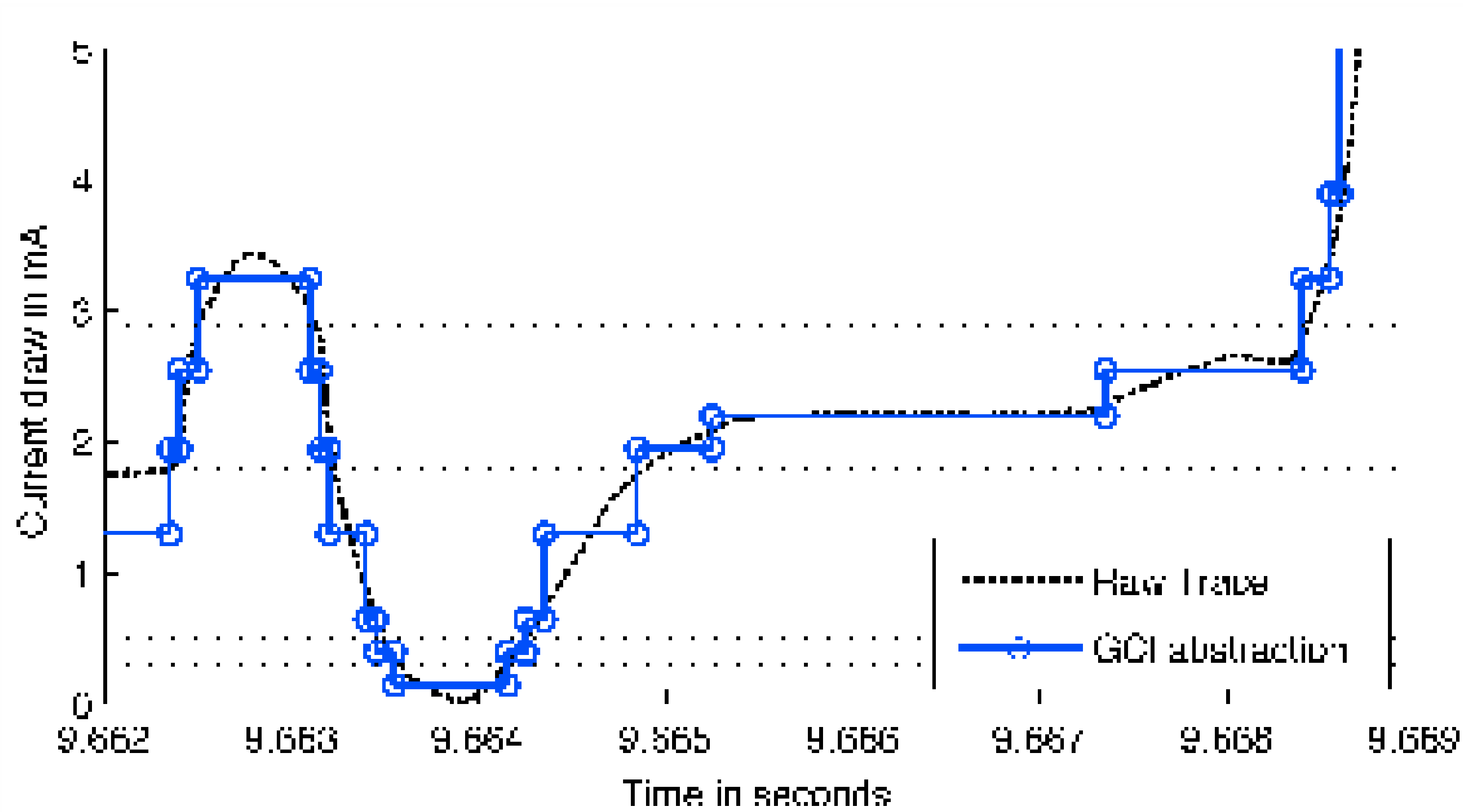
1.79204827
2.32205325
0.288717749
0.0842842821
1.57702206
2.0505207
2.25958169
2.8585387
2.94728409
2.70120291
2.55394464
2.59723726

There are millions of power measurements…

System is indifferent when P ∈ [2mW,3mW]
⇒
Piecewise compression into one value,
e.g. representation by its average value



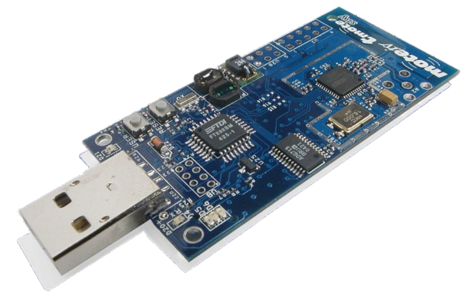
Example Power Trace Compression

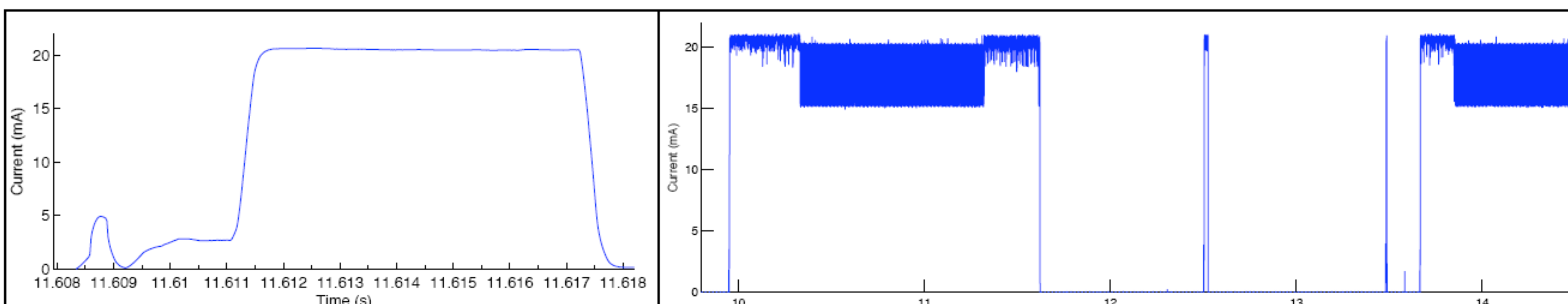


ETH zürich

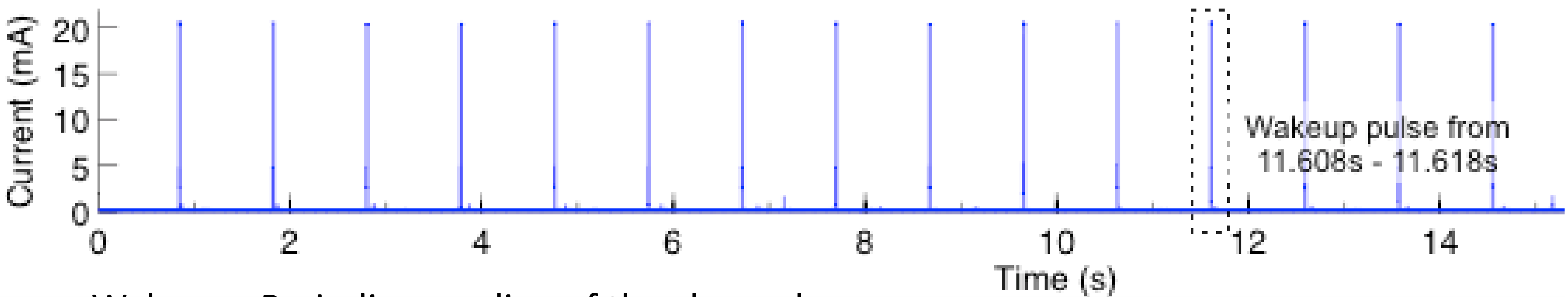
Experimental Evaluation

- Experiment
  - TMOTE Sky (MSP 430, TI CC2420) running TinyOS2
  - Harvester application, LPL MAC data gathering
  - Besides testing a correct run (complex trace)
  - Several errors have been introduced
    - Missing wake-up
    - Inject error in low power scheduler
    - Wrong low power state of MC
    - Specification error).

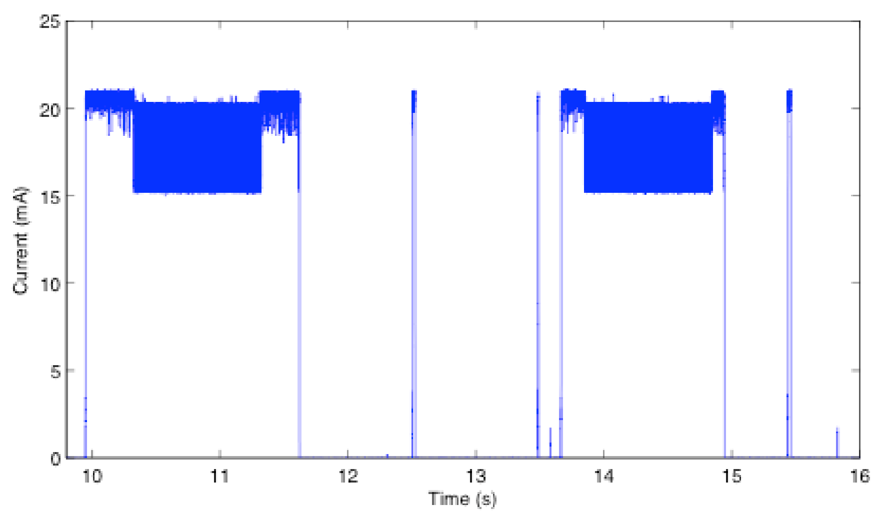




Case Study on Various Traces

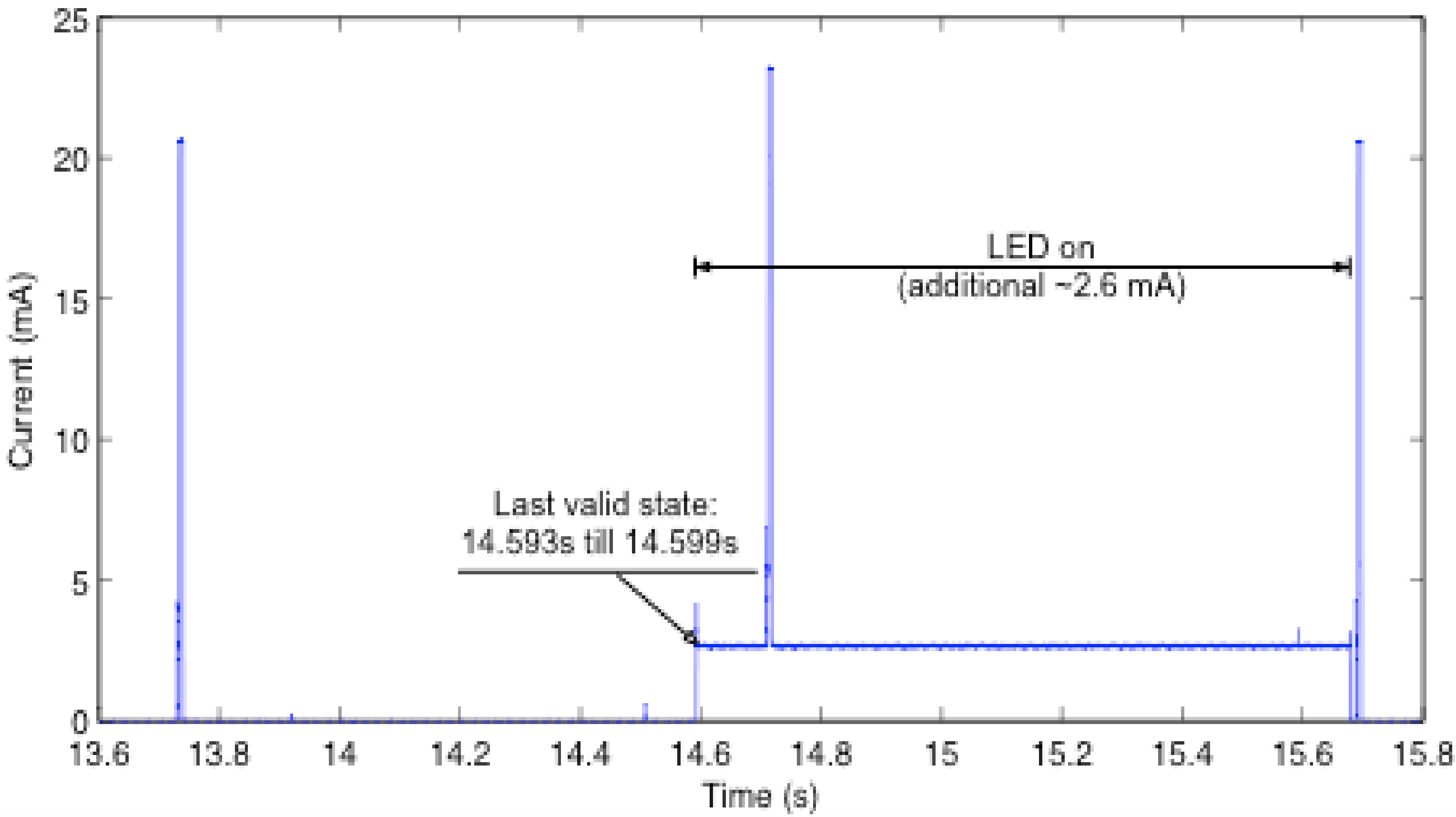


Wake-up: Periodic sampling of the channel
Inject: Extended period error



Complex: Send/receive operations with lots of non-determinism

Explicit Modeling of Defects



Some Runtime Results

Verification Results

Model	Samples	Compression		Runtime	
		Intervals	100uA steps	Intervals	100uA steps
Wake-up	1000000	2089	13812	8s	182s
Inject	990000	2040	13666	5s	167s
Complex Trace	310000	21811	89678	15min	Fails
MC state	1000000	1086	5539	4s	22s
Specification	1000000	1478	4578	7s	22s

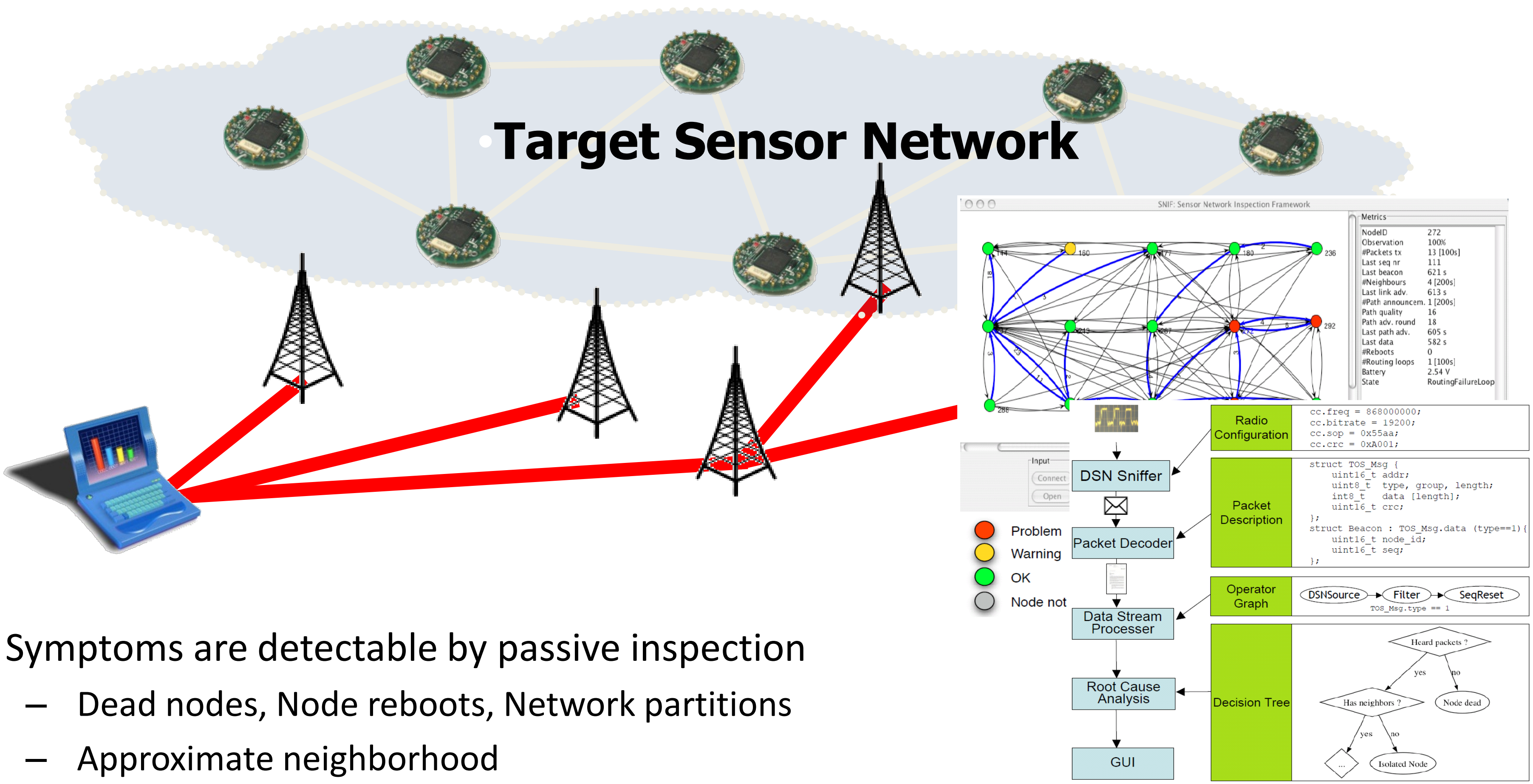
Improvements have been done in terms of scalability.
But a complexity issue remains.

[Matthias Woehrle, Kai Lampka and Lothar Thiele: Conformance testing for cyber-physical systems ACM Transactions in Embedded Computing Systems (TECS). Volume 11, Issue 4, p. 84, December 2012.]

Low-Power System Design

IN-BAND/IN-SYSTEM VALIDATION USING ASSERTIONS

Other Approaches – Packet Level Overhearing



- Symptoms are detectable by passive inspection
  - Dead nodes, Node reboots, Network partitions
  - Approximate neighborhood
- Failure root causes remain unclear

[Ringwald DCOSS 2007, Roemer IPSN 2009]

Evaluation With Passive Distributed Assertions

- Assertions: express belief that a condition holds

```
int i;
...
assert(i > 50);
```

- Assertions over distributed program variables
  - Value of variable i should equal value of variable k at node 100

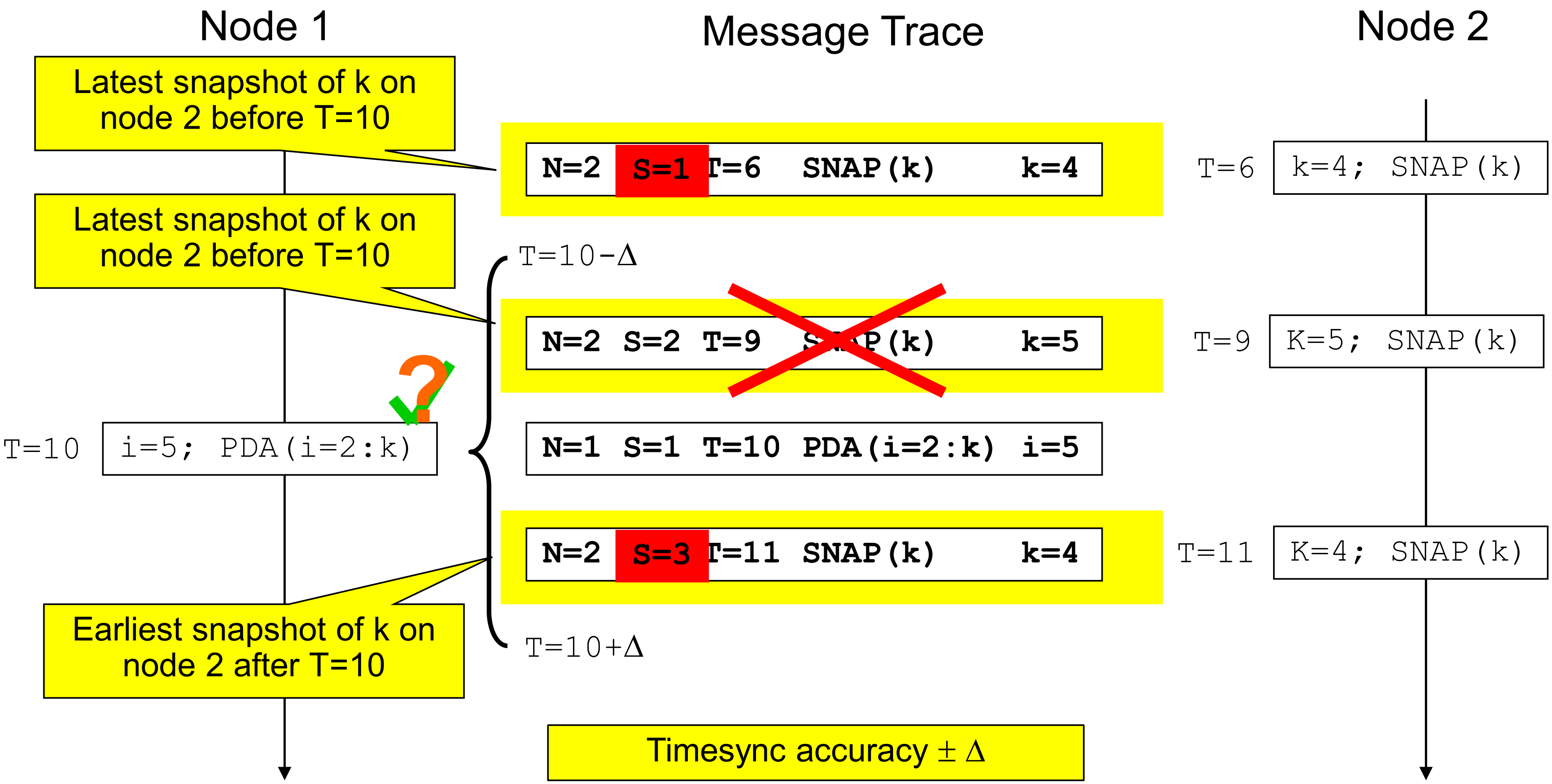
```
int i;
...
PDA(i = 100:k);
```

Variable k on node 100

- Checked by passive inspection
  - Nodes only broadcast assertions (**PDA msg**) , changes of relevant variables (**SNAP msg**)
  - Overheard by sniffer network
  - Minimize interference

```
k = ...;
SNAP(k);
```

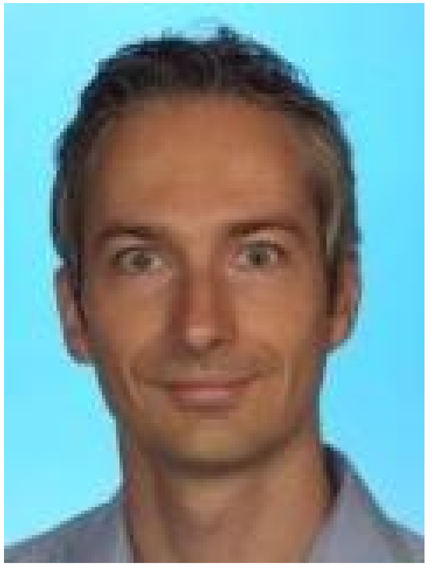
Assertion Evaluation Example



Today's Hot Researcher & Paper

- Kay Roemer
  - Faculty at TU Graz

- Distributed systems background (ETH Zurich)
  - Early influence on Internet of Things
  - Early contributions to sensor/ad-hoc network time sync
  - Recently more focus on dependability/reliability and embedded systems



K. Römer, F. Mattern: **The design space of wireless sensor networks**. Wireless Communications, IEEE 11 (6), 54-61, 2004.