Towards Edge Power Measurement: A Low-Cost, Programmable Power Meter

Master's Thesis Presentation

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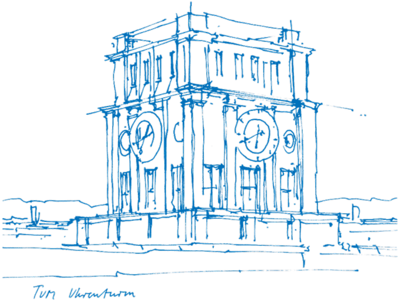


Outline

Motivation

An offload decision needs task accuracy, latency, and **input energy.**
Software measures the first two. Can the devices report their own energy?

No power data

routers · network switches · many microcontroller boards

no software method available

Partial coverage

software counters

the counters read only some power rails

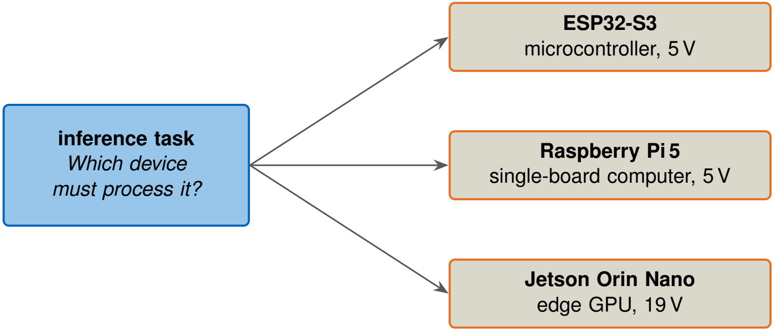
Load dependent

onboard sensors

values deviate by up to
50 %
(Jetson study, IEEE EDGE 2023)

Many edge devices report no input energy, or values that deviate with the load.

Devices Under Test



no power data

PMIC: **69–80 %**
of the input power

sensor: **78–85 %**
changes with the load

DUT: device under test. Ratios measured in this work, idle $\rightarrow$ full load, against a calibrated sensor at the power input. PMIC: power-management integrated circuit.

The three DUT report no power data or 69–85 % of the input power.

Measurement Gap

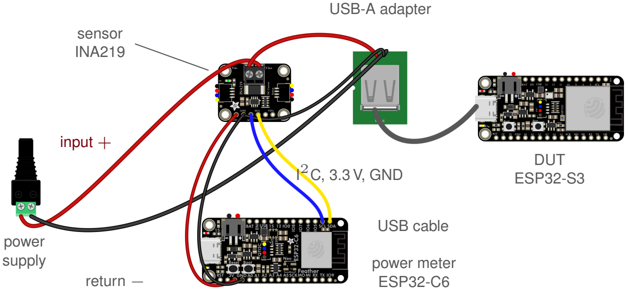
Instrument	Voltage	Channels	Connection
RocketLogger (DATE'17)	$\pm$5.5 V	2 current, 4 voltage	portable logger
Shepherd Nova (MobiSys'25)	$\leq$4.8 V, 50 mA	testbed node	testbed
Monsoon HVPM	$\leq$13.5 V	1	USB host
Otii Ace Pro	$\leq$25 V	1	USB host
PowerSensor3 (ISPASS'25)	$\leq$20 V	4 modules	USB host
this work	**5–19 V**	**3, common timestamp**	**Wi-Fi network**

PowerSensor3 supports four modules at 20 kHz. This work uses three networked channels for 5–19 V device inputs. 5–19 V is the tested range; the sensor inputs accept up to 36 V (INA226) and 85 V (INA228).

No reviewed instrument combines 5–19 V, three channels, and network control.

Outline

Three Input Channels



One channel shown: the INA219 sensor on the ESP32-S3 power input.

Power input	Sensor	Shunt	Current range
ESP32-S3, 5 V	INA219	100 mΩ	2 A
Raspberry Pi 5, 5 V	INA226	2 mΩ	20 A
Jetson Orin Nano, 19 V	INA228	15 mΩ	2.7 A

One shunt sensor per power input; the sensor type matches the current range.

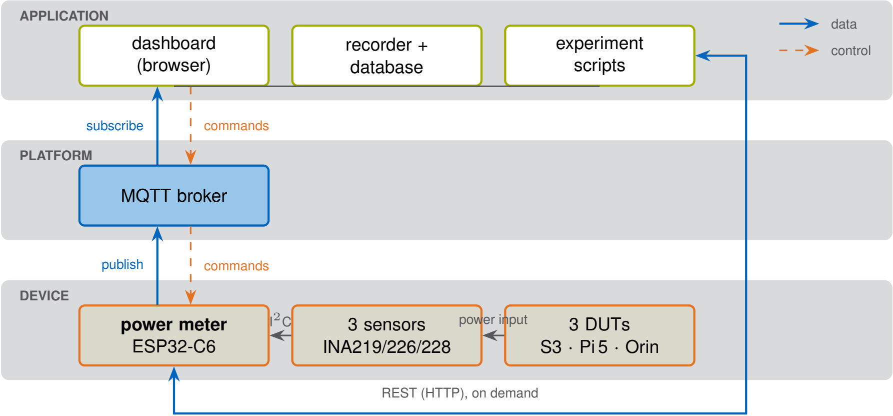
Parts Cost

Part	Quantity	Retail price
ESP32-C6 board with display	1	$\sim$12 €
INA219 sensor module	1	1.5 €
INA226 sensor module	1	3.0 €
INA228 sensor module	1	5.5 €
Adapter boards and cables	6	$\sim$5.0 €
Total for three channels		**$\sim$27 €**

Retail prices from August 2026. The parts cost does not include the reference instrument that is necessary for calibration.

The approximate parts cost is 27 € for three measurement channels.

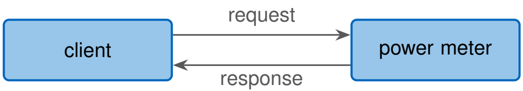
System Overview



The power meter sends data only to the broker; the broker sends the data to all applications.

Two Communication Patterns

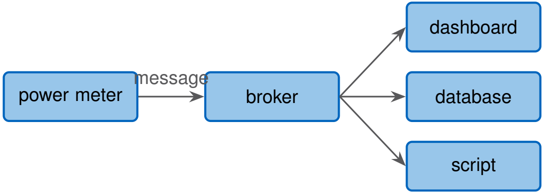
request-response



REST interface

one value or one control command

publish-subscribe

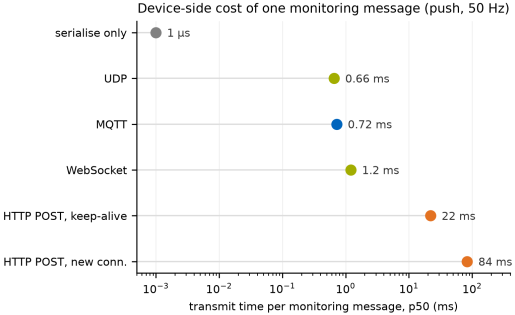


MQTT interface

the continuous data stream to many clients

REST controls the power meter; MQTT sends the continuous data stream to many clients.

Protocol Trade-off



Same board, same payload, 48 runs of 20 s. p50: median.

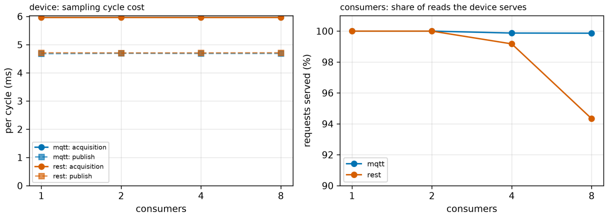
	handling time	rate
MQTT PUBLISH	**0.7 ms**	**50 Hz**
POST, keep-alive	22 ms	34 Hz
POST, new connection	84 ms	11.5 Hz
GET polling	4.5 ms	43 Hz

handling time: the median time the power meter is busy with one message. The benchmark excludes sensor acquisition.

An MQTT PUBLISH operation does not wait for an application response. Each HTTP POST waits for a response. A new connection also requires a TCP handshake.

MQTT occupies the power meter for only 0.7 ms per message, leaving sufficient time for 50 Hz

Scalability



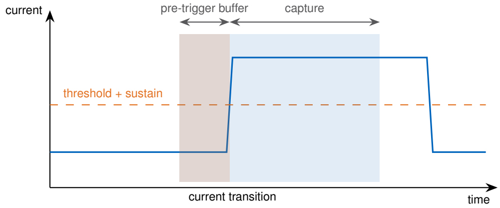
The monitoring rate is 10 Hz. Each test has 1–8 consumers and a duration of 120 s.

- Each of eight MQTT subscribers receives 10.0 Hz.
- The device publish time remains 4.7 ms.
- With eight REST clients, the 95th-percentile response time is 1084 ms and 5.6 % of requests fail.

Eight subscribers add no device load; eight REST clients cause failed requests.

Two Acquisition Modes

	averaged monitoring	transition capture
operation	continuous	when a current transition is expected
rate	1–50 Hz	up to 2.4 kHz
granularity	coarse	fine
output	live power curve	one event window

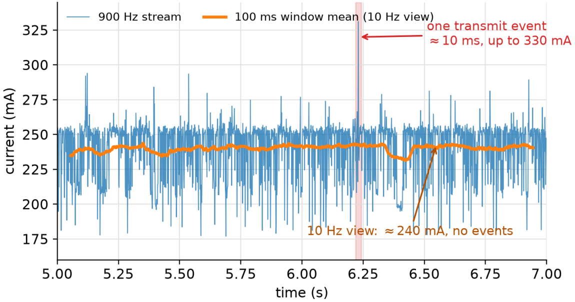


The pre-trigger buffer includes data from before the current transition.

Averaged monitoring shows the mean power; transition capture records the detail of a current transition.

Millisecond Events

An event lasting 10 ms has a negligible impact on the average monitoring. To record the event itself, the power meter must sample at kilohertz rates.

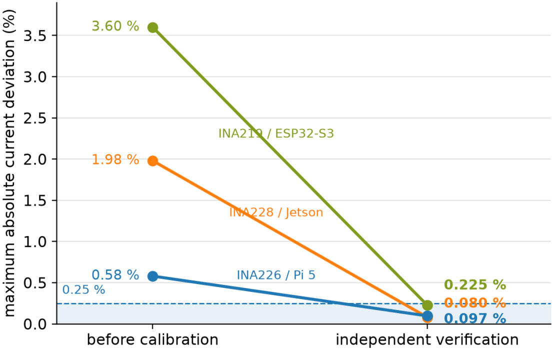


ESP32-S3 input during Wi-Fi transmission: 900 Hz stream and its 100 ms window means, same capture.

A 10 Hz mean does not show 10 ms events; a kilohertz sampling rate shows them.

Outline

Calibration

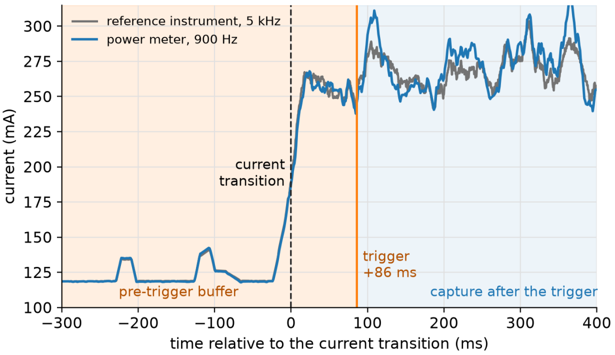


Maximum absolute current deviation from the reference value over the tested load range.

1. Connect the reference instrument in series.
2. Calculate one gain and one offset for each channel.
3. Verify the calibration in an independent run.

After calibration, the maximum absolute current deviation is 0.25 % or less.

Transition Capture



One captured event: power meter and reference instrument on the same 5 V input, 20 ms moving mean.

- each capture contains the current transition itself and, through the pre-trigger buffer, the data from before it
- events captured: **20 of 20** (ESP32-S3) and **25 of 25** (Jetson)
- current levels: within **0.4 %** of the reference values

Transition capture records the current transition itself: 45 of 45 events captured.

Task Energy

Does the calibrated power meter stay accurate on real inference tasks?

	ESP32-S3	Raspberry Pi 5	Jetson Orin Nano
model	ResNet-8 int8 (MLPerf Tiny)		Faster R-CNN (MobileNetV3)
runtime	int8 C firmware	LiteRT (XNNPACK)	PyTorch (CUDA)
one task	1 inference	3574 inferences	1 inference
task duration	1.4 s	1.0 s	0.23 s
task energy above idle	172 mJ	1997 mJ	1309 mJ
difference from the reference instrument	−1.5 %	−2.8 %	−1.9 %

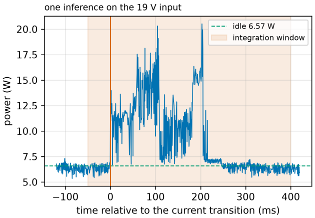
One task every 3 s (ESP32-S3, Pi 5) or every 1 s (Jetson). The two instruments are in the same series circuit but measure voltage at different points. The Jetson runs at 12 V here, because the reference instrument accepts 13.5 V or less; all other Jetson results use 19 V.

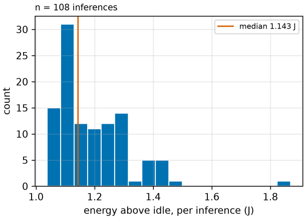
For real tasks, the power meter and the reference instrument agree within 3 % on all three devices under test.

Outline

Inference Energy

Task energy is a mean over seconds — can the platform measure one single inference?





Jetson Orin Nano object detector. One image every 500 ms. Capture rate: 2 kHz.

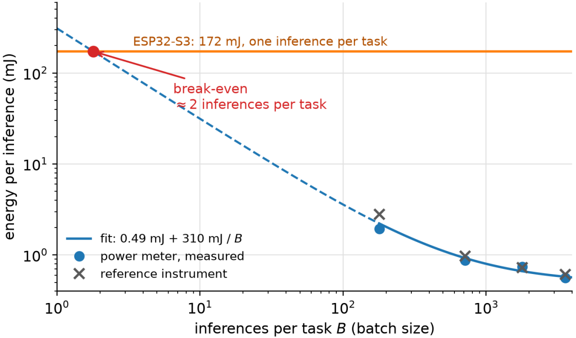
1.14 J

median incremental energy

number of inferences	$n = 108$
inference time	216 ms
idle power	6.6 W

The platform measures the energy of one inference: 1.14 J on the Jetson.

Offload Energy



Points: measured; dashed part: extrapolation. Computation energy only; the int8 kernels differ.

- ESP32-S3: **172 mJ** per inference, one inference per task
- Pi 5: **0.49 mJ** per inference, plus a fixed task overhead of ≈310 mJ
- both instruments give the same marginal energy within 2.2 %
- break-even against the ESP32-S3: ≈2 inferences per task

Energy per inference depends on the batch size, not only on the device under test.

Outline

Limitations

Limit	Value
smallest resolved current (20 A channel)	$\sim$5 mA
voltage path	datasheet $\pm$0.1 %, not calibrated
delivered sampling rate at the 50 Hz setting	$\sim$43 Hz
averaged monitoring while the DUT transmits	samples lost (Wi-Fi contention)
latency	no upper bound (maximum observed: 1.11 s)

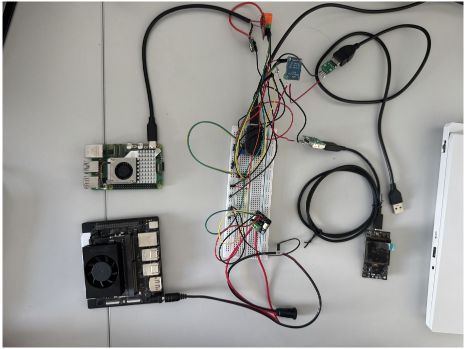
Use the platform above 5 mA; do not use it for sleep currents or hard real time.

Conclusion

1	We build a power meter with publish/subscribe and REST access: three 5–19 V channels, one common timestamp, $\sim$27 € parts cost.
2	We evaluate it against a reference instrument: current deviation 0.25 % or less, task energy within 3 %.
3	We apply it to inference tasks on three devices under test: energy per inference, and the offload break-even at $\approx$2 inferences per task.

The platform provides input energy data, evaluated against a reference instrument.

Demonstration



The browser demonstration shows:

- the power traces of all three devices
- the workload start and stop controls
- one transition capture

Questions

Thank you.

3 channels · 5–19 V · current deviation 0.08–0.25 % · 1.14 J per inference · ~27 € parts