Linaro CONNECT EUROPE 2012 (LCE12)

How to measure SoC power

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Introduction

- I lead Linaro TI Landing Team at Linaro
- Mainly been working on hardware the last 25 years
- TI very interested in power optimization
- SoCs have a lot of schemes needing software support
- So there's a lot of things we work with that might, or should impact system power
- We need to observe and measure those expected impacts
- Many people working in different areas can benefit from looking at power as they change things...

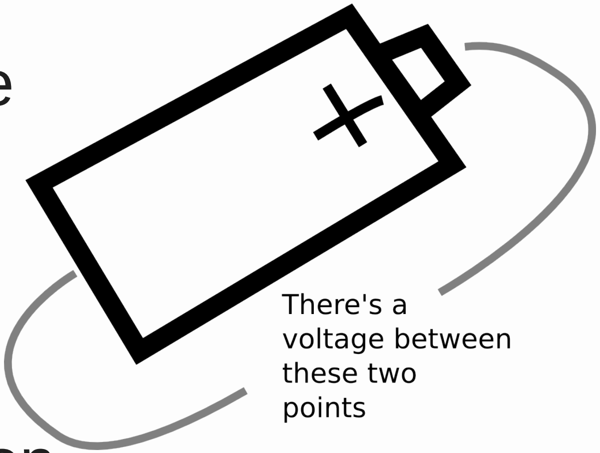
Sections

- 1: Minimum Electronics Primer
- 2: Measuring voltage and current
- 3: Arm Energy Probe hardware
- 4: Practical Board instrumentation
- 5: Error Sources
- 6: Commandline Linux AEP app
- 7: aepd and HTML5 UI

Section 1: Minimum Electronics primer

What is voltage?

- Voltage is like the “pressure” electrons have to go somewhere
- They might not be going anywhere at any particular time, but the pressure is still there
- In a battery, electrons are chemically separated out to the – side and prevented from leaking on to the + side through the inside
- So there's “pressure” built up for electrons on the – side to want to go to the + side

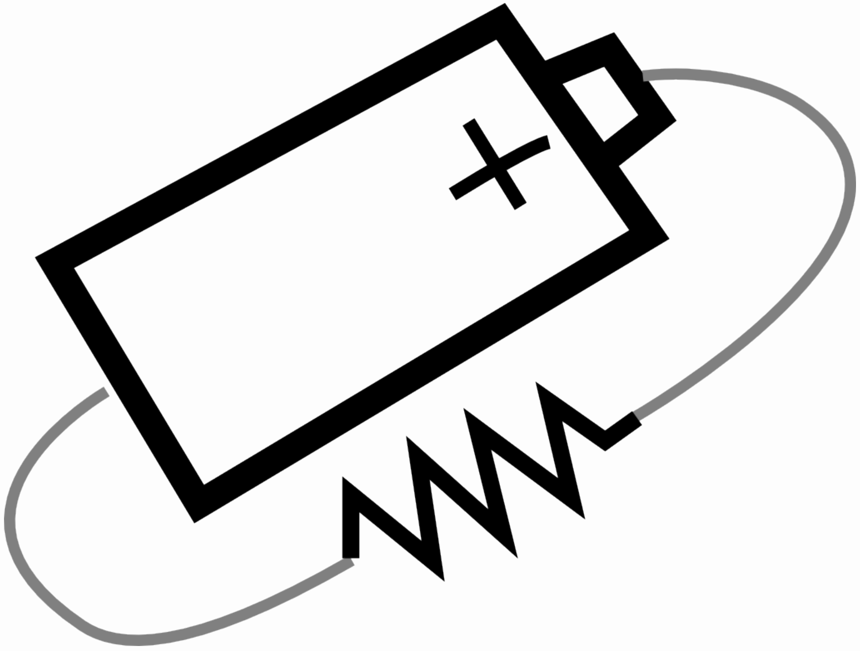


What is voltage?

- Voltage is measured in Volts / **V**
- In SoCs we usually deal with 0.9 – 5V range
  - Typical transistors want to switch around 700mV
- We can measure voltage using a voltmeter of some kind

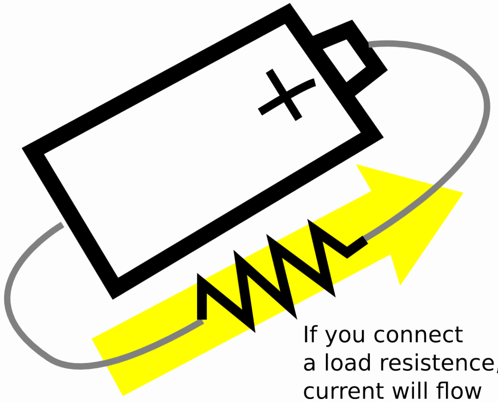
What is load?

- **Load** is the thing we put between a voltage to make current flow and get work done
- It has a **resistance**, measured in Ohms / **R**



What is current?

- Current is a measure of electrons flowing through the circuit
- It's measured in Ampere / A
  - Sometimes the symbol I is used to talk about current
- How much current flows is a function of voltage and load resistance (I = V / R)
- A “short circuit” is ~0R load, maximum current flows



So...what is power?

- Power = current x voltage... **P=IV**
- Voltage or current tends to increase or decrease == power is increasing or decreasing accordingly
- P=IV == $\mathbf{V^2/R}$ == halving the voltage reduces the power by a factor of 4!
  - This is why DVFS is so interesting...
- Measured in Watts / **W**

Why talk about power and not current?

- By converting voltage & current measurements to power, you can compare power from different voltages or parts of the system
- For that reason, although V and A may be interesting **all power reporting should be done in W, so the numbers are comparable**
- In the end you always want to compare individual rail power to overall system power, which is definitely at a different voltage... **Watts only!**

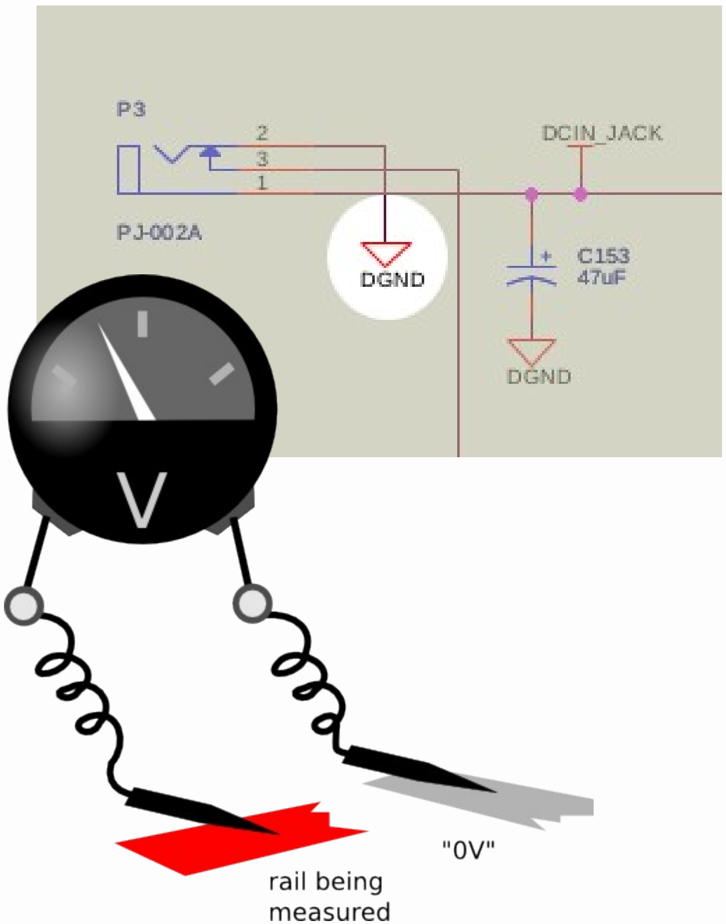
Summary

- Voltage (V) is “pressure” for electricty to flow
- Current (A) measures the flow of electricity
- Load (R) is what the current flows through
- Power (W) is the Voltage x the Current, or pressure x flow

Section 2: Measuring voltage and current

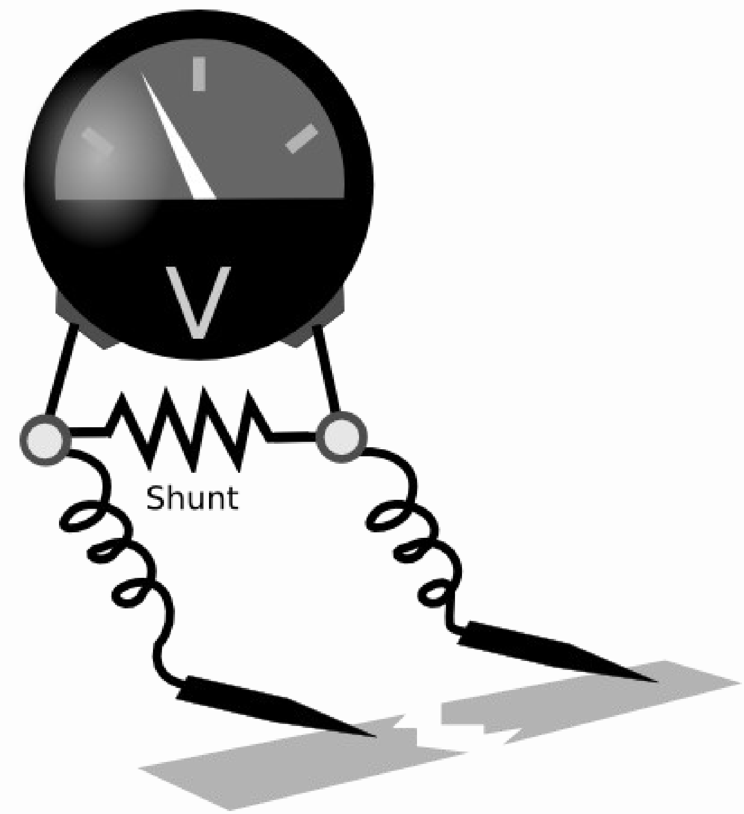
Common-mode voltage measurement

- Voltage is relative between two points
- One side of the input voltage is decreed "0V" reference to which all the other voltages are compared (it's the – side of the DC input by convention).
- Common-mode voltage is the difference between your rail and "0V"



Measuring current with an Ammeter

- An Ammeter (current meter) can be implemented as a sensitive voltmeter measuring the difference in voltage across an internal series shunt resistor
- You interrupt the circuit to add the meter in series
- This is how your multimeter works in A range



Measuring current with a voltmeter

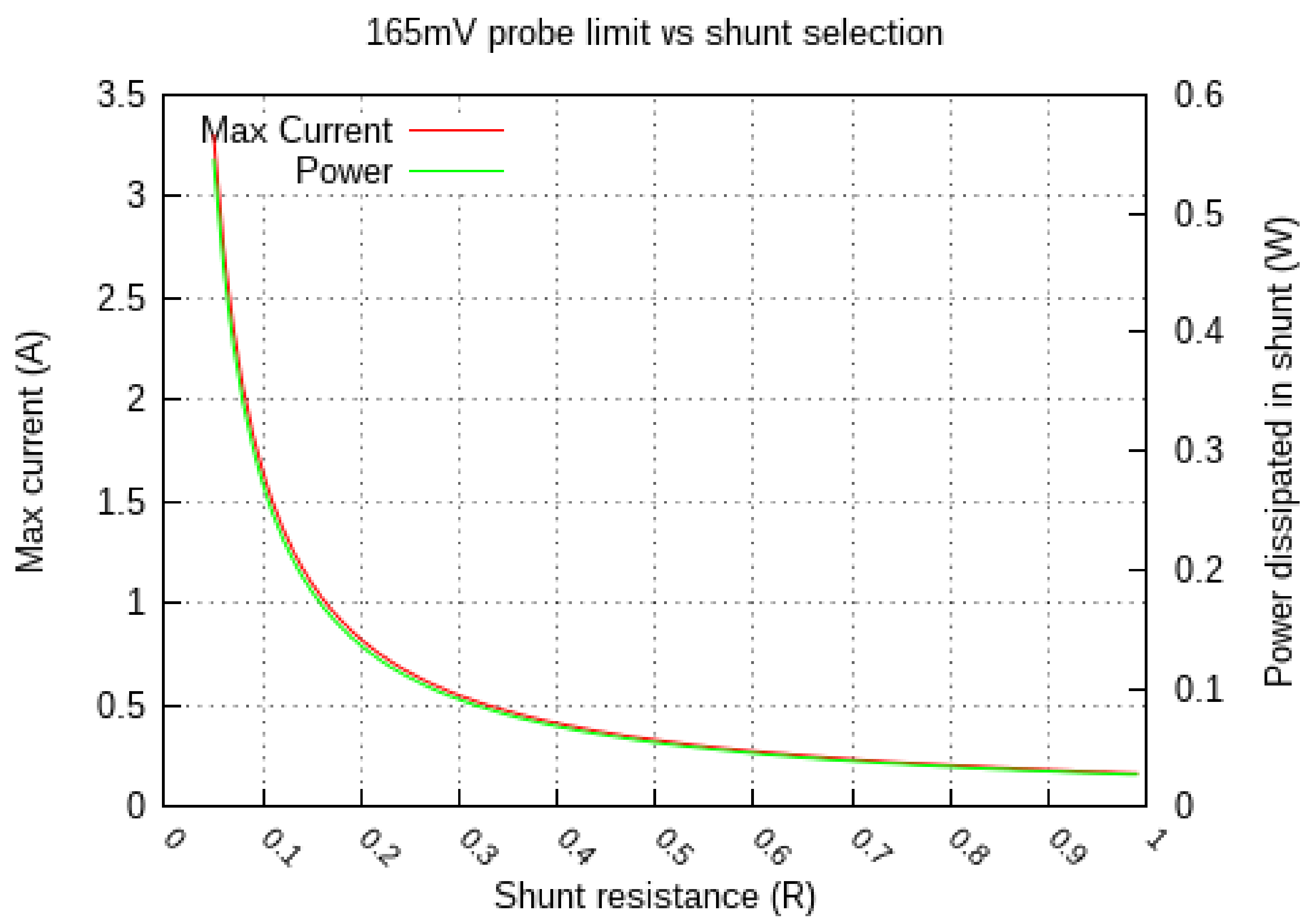
- Actually you could just add the shunt resistor yourself and use a sensitive voltmeter
- That has advantages that the high current path does not go via the meter cables any more, just straight through the resistor
- How do we choose which shunt resistor to use?

Shunt Resistance Selection

- The main criteria is voltmeter sensitivity
- For AEP, shunt measurements top out at 165mV, so that is the voltage drop over the shunt we want for worst case current
- For larger currents, we also have to take care that the shunt can cope with the power it dissipates as heat
- Here is the shunt selection chart for 165mV drop at various maximum currents

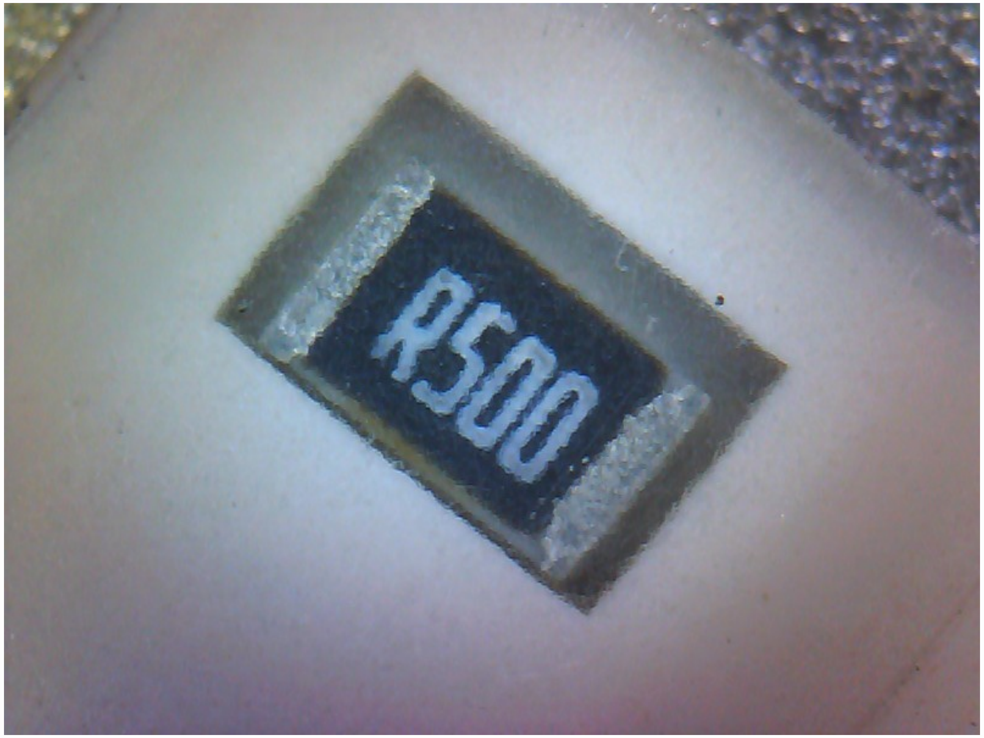
Shunt power dissipation selection

- Eg, 1.5A max --> 100mR shunt, 1/4W rated



Rule of thumb for shunts

- For AEP usage (165mV shunt range)
  - Many Watts like DC jack, or high power rails use 0.22R or 0.1R 1W or more
  - For normal rails, 0.47R 0.5W

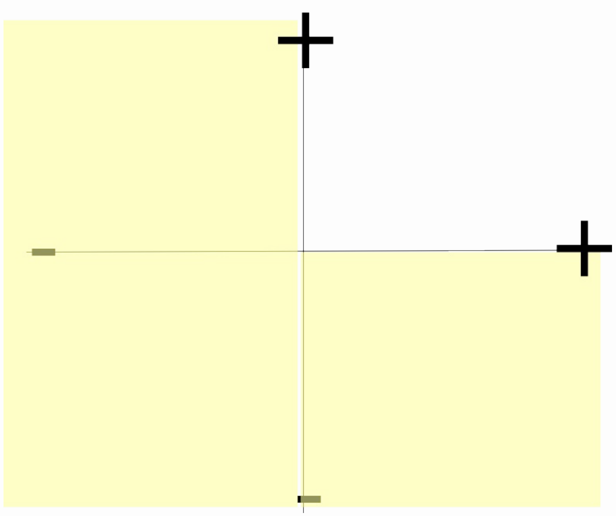


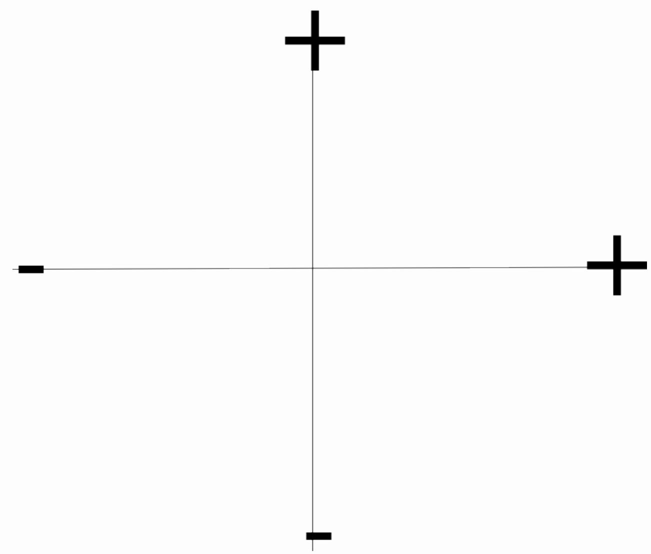
Choosing lower value shunt than necessary

- For some rails, like CPU DVFS rails, shunt loss at full scale of voltmeter may be too much to lose
  - Eg, 165mV of 900mV rail is 18% loss
- You can select a shunt that drops less than full scale at the highest expected current
  - Eg, only drop 50mV of 900mV rail worst case
- It works, but because you only use part of the range the measurement ADC step size is larger, noise goes up and precision goes down
- Trick... if you didn't plan on lower value shunt needed, you can double-up two or more in parallel to get R/n

Unipolar vs Bipolar voltmeters

- Unipolar or “1-quadrant” can just measure positive voltage or current
- Bipolar or “4-quadrant” can measure +/- common-mode voltage and +/- current
- +/- current very useful for battery, +/- voltage less so
- Bipolar may have problems determining what “zero” looks like
- Unipolar should do better with “zero” but doesn't always



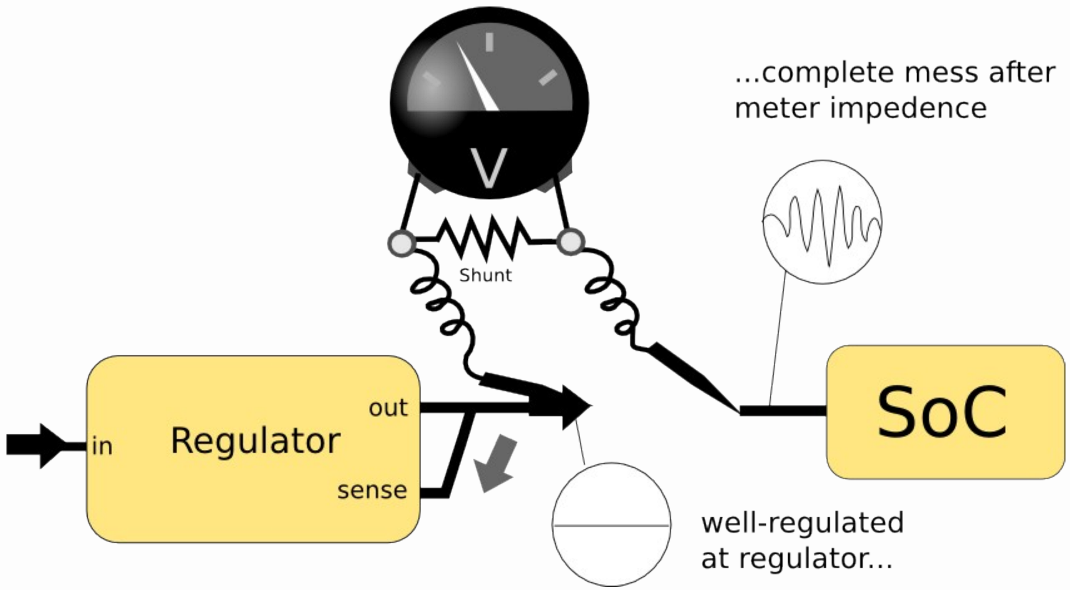


Difficulties with regulation

- Regulators operate in a loop
- They allow more or less input to the output according to what it senses at the output
- They have an internal or external “sense” pin which lets them watch the output and then act to make sure it stays at the right voltage

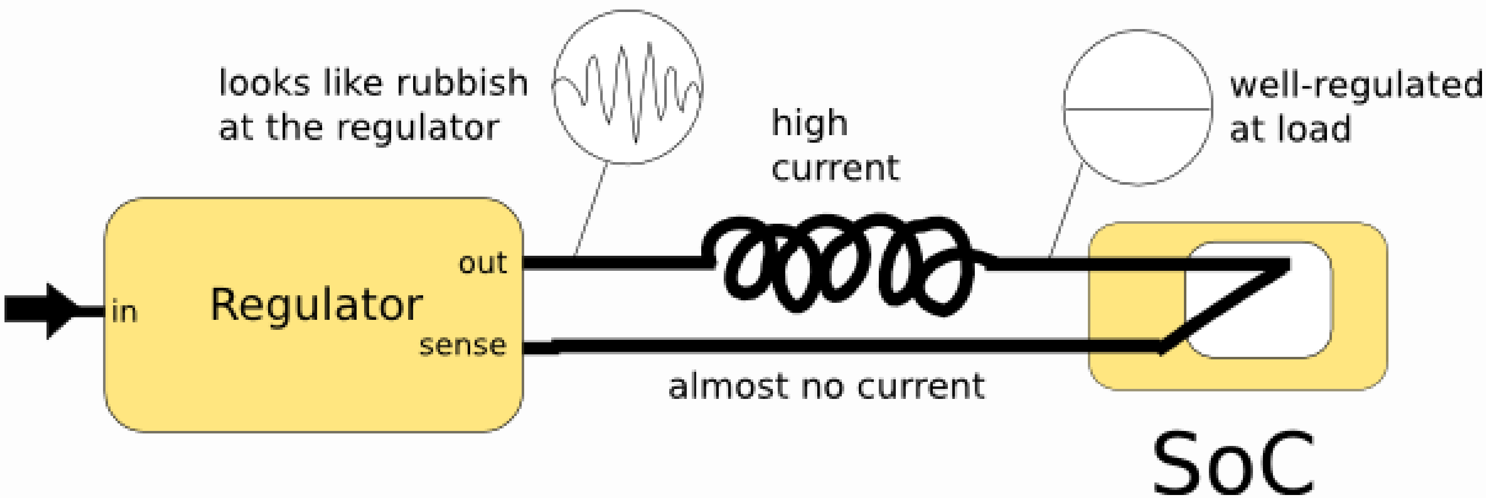
Difficulties with regulation

- Wiring has “inductance” which affects the signal or power as the load changes
- Additional inductance of meter and wiring mean the regulator cannot sense load changes properly
- SoC will crash



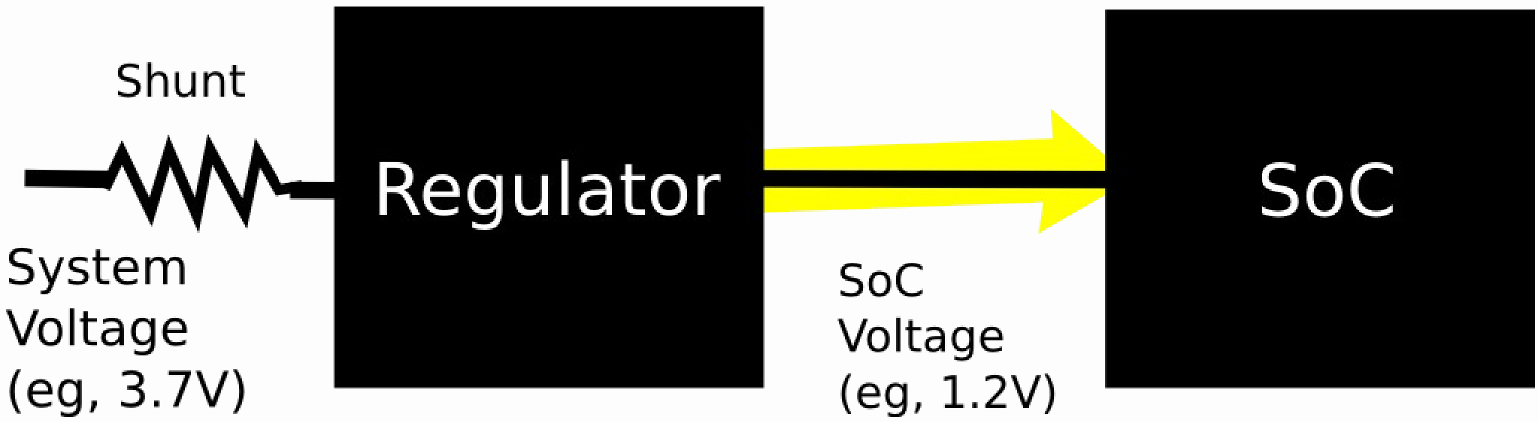
Modern Regulation strategies help

- For high power, dynamic loads, SoCs provides a separate “sense” pin for the regulator
  - connected right at the load, on the die
- Regulator does what's needed to keep that regulated



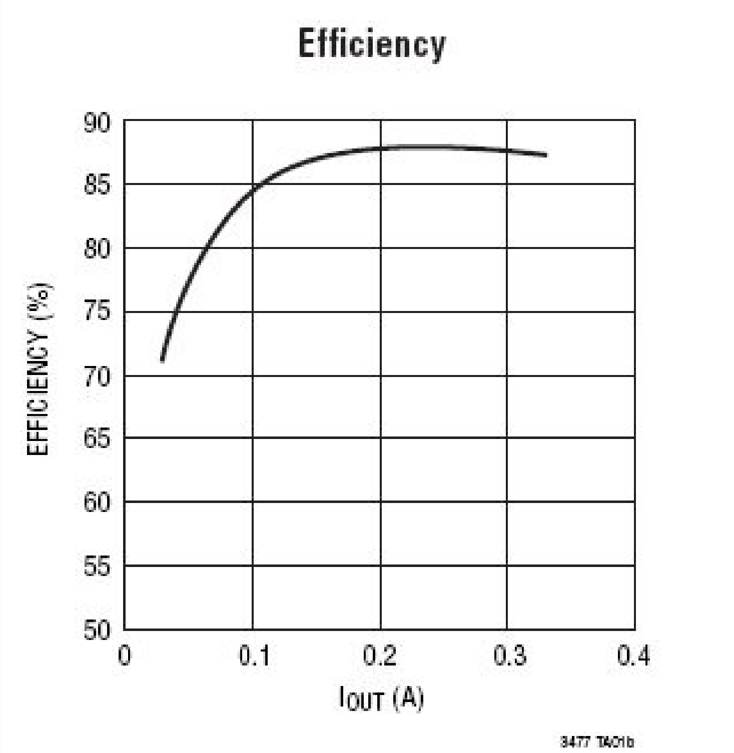
Input-side measurements

- The extra impedence is one problem
- Another is the voltage drop from the shunt, 150mV is not much but on a 900mV DVFS rail, it will stop the SoC working
- Both problems can be avoided by measuring the input side of the regulator instead
  - You don't see output voltage then though
  - Your power measurement include regulator losses



Regulator efficiency

- **Switching** regulators are designed for peak efficiency (up to 95%) at a particular load
  - For different loads, efficiency may decline below 50%
- **Linear** regulators are simpler but can be grossly inefficient
  - Current at input side same as the output side
  - If input side voltage is much higher than output, large power losses as heat result
    - Input – output delta is called “dropout voltage”
  - Only useful at low dropout voltage and low currents
  - Used in sensitive analogue circuits though, since they do not introduce switching noise

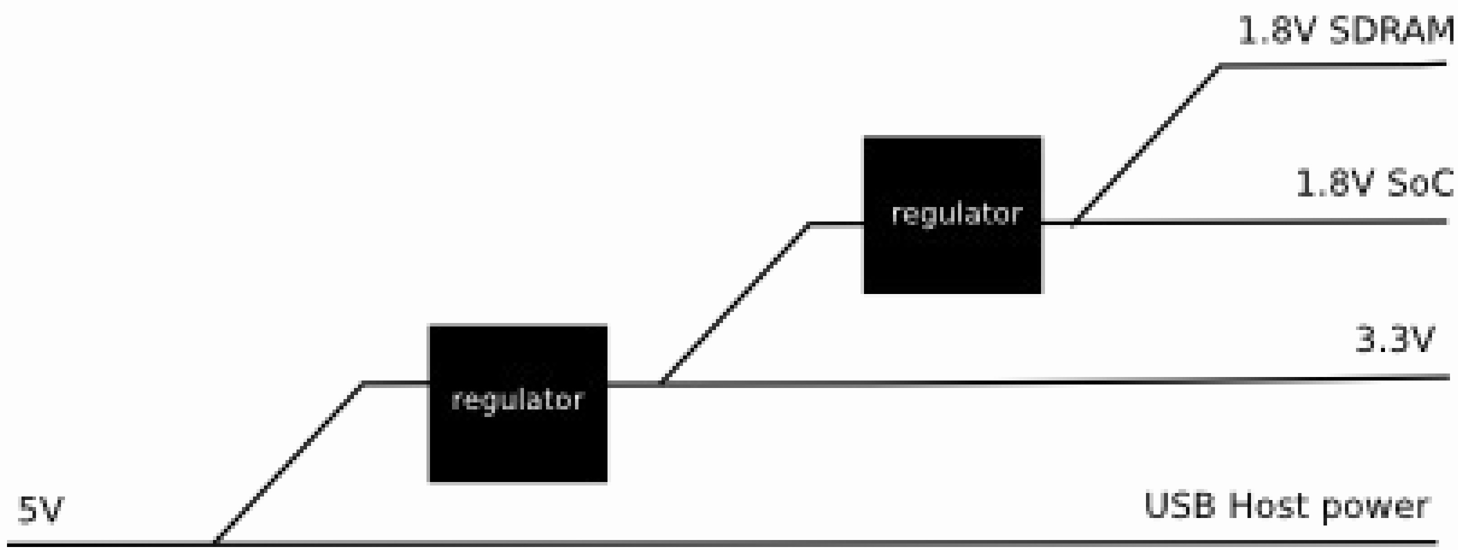


Measurement bandwidth

- How many samples per second do you need to analyze current used by an SoC regulator?
- Modern regulator switching frequency tends towards a few MHz, if you measure input of regulator this is its “clock frequency”
  - Higher switching frequency allows use of smaller inductors
  - Load only visible at input for part of switching cycle --> load is typically modulated at a few MHz. So sample rate > ~5Msps not useful
  - Spread spectrum and duty-cycle modulation also in use
- Smoothing and reservoir capacitors hide short load bursts, but all **output load must appear at input,** perhaps delayed
- You can see **plenty** at 10ksps

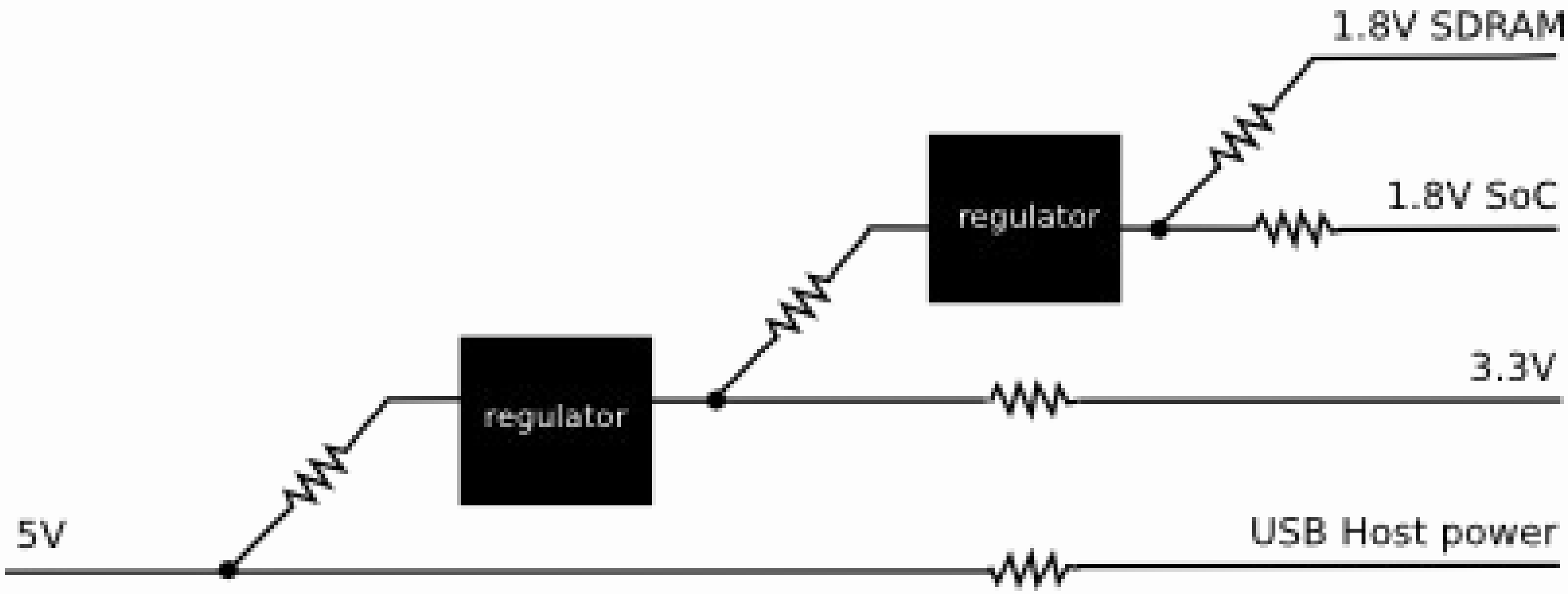
Power tree

- The DC input jack and each regulator supplies a “rail”
  - Some designs still use a metal “rail” or “bus bar” to distribute the power around the circuit, hence the name
- One or more device connects to the rail to consume power from it
  - Sometimes it is other regulators to produce a new rail supplied by the parent one, ie, a power tree



Power tree vs regulator efficiency

- Ideally you add shunts and measure power on all rails
- If rails go to several interesting places, you would want to add individual shunts for power to each device
- You can also measure the input side of the regulator that supplies the rails
  - If you have power measurements on both sides of the regulator, you can easily see its efficiency



Four basic measurement strategies

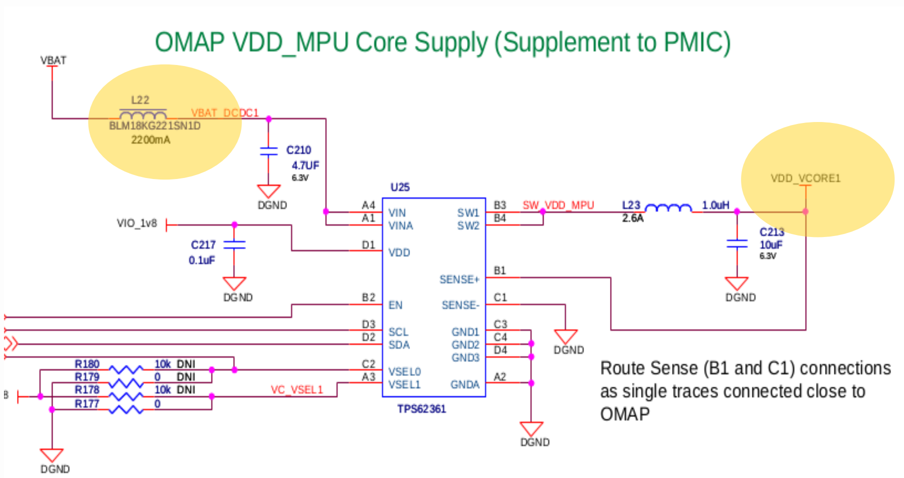
- There are four basic approaches to instrumenting your board for getting power data
  - Monitor the DC input to the whole system
  - Monitor V and A on input side, and V on output side
  - Monitor all SoC rails
  - “Eye of Sauron”

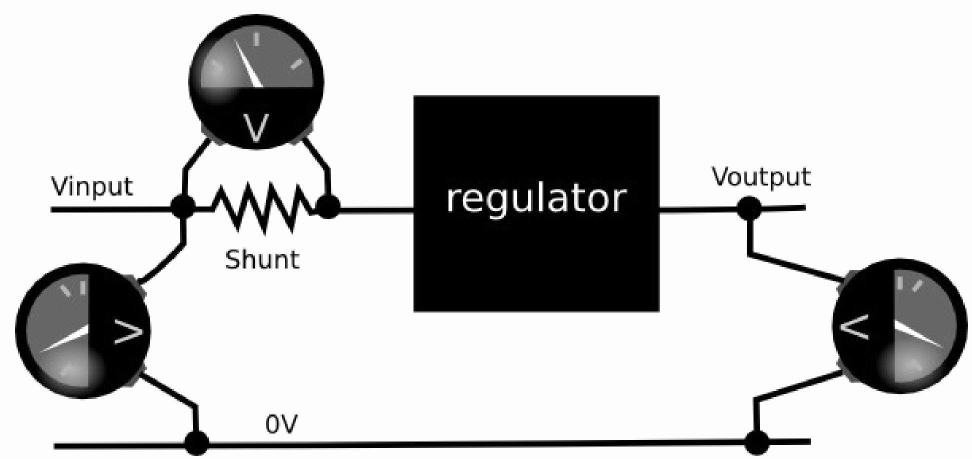
Plan A: DC input

- Ultimately everything that consumed power got it from the power input, by one route or another
  - Every activity on the board consumes power
- But it can be hard to interpret “why” or where the power was used if all you can see is one total number
  - If multiple activities are ongoing, you can't tell between them
- But it's an easy and quick way to start
- You can use it for “delta” comparison, same setup before and after a change you want to test
  - But take note of the error sources section later

Plan B: Input side and output side voltage only

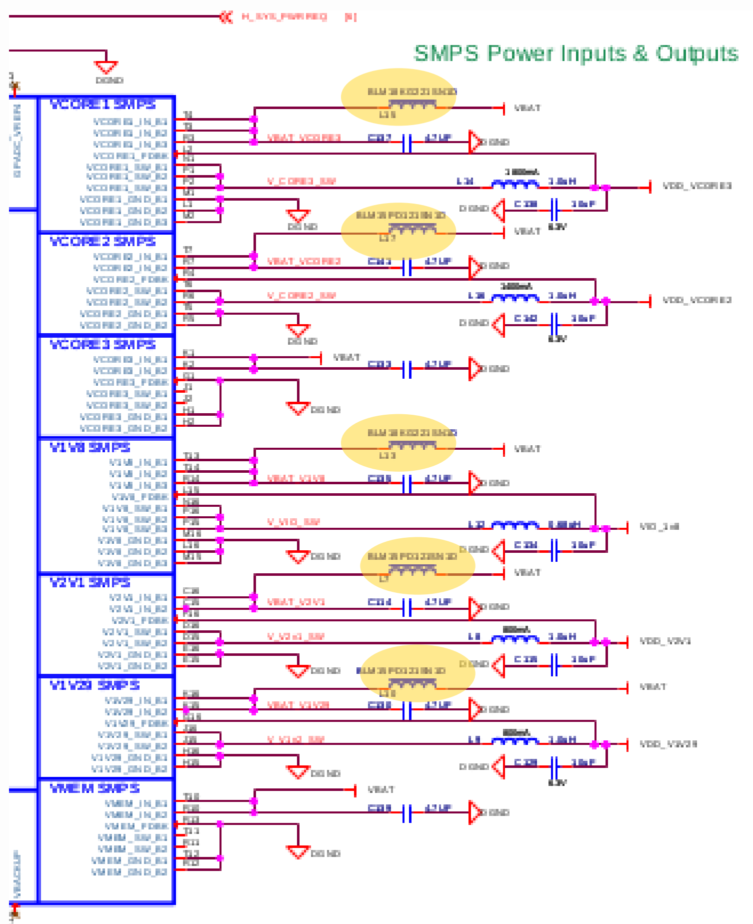
- Some SoC rails that have adaptive voltages are interesting, but it might not be possible to instrument them directly
- Instead you can instrument the input side of their regulator as discussed, and find the current (including regulator overhead)
- You can use a second channel then to monitor just the common-mode voltage on the output side
- In that way you can infer output-side current and voltage information without changing the output side





Plan C: shunts on all SoC rails (input side)

- SoC vendor primarily interested in SoC power consumption
- Programmers should be very interested also in how their code affects each SoC Rail



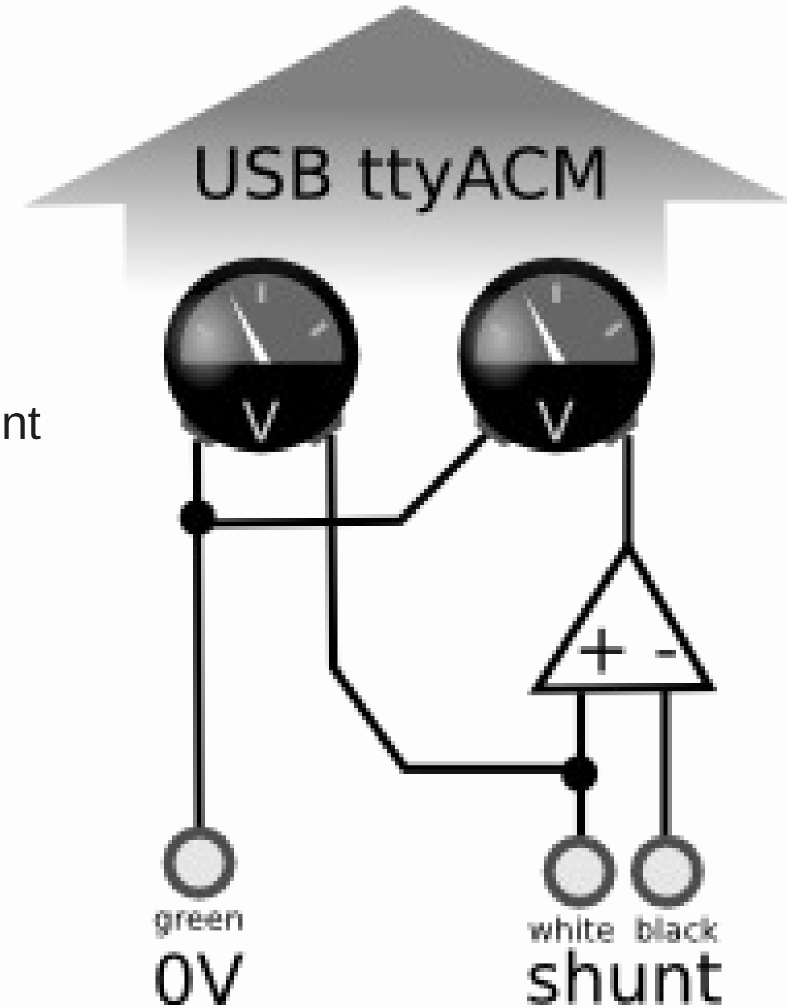
Plan D: shunts on everything

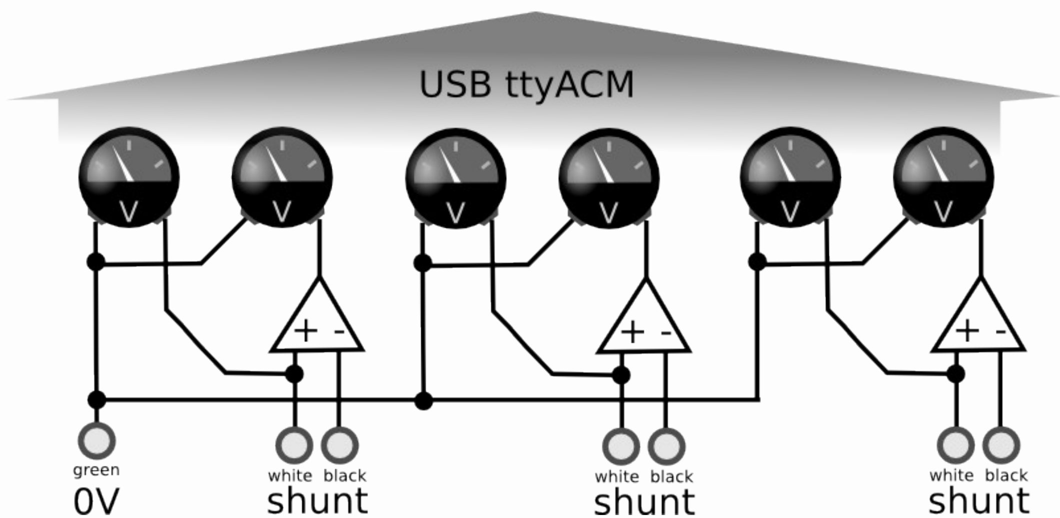
- Most ideal scenario, “Eye of Sauron” on all power consumption in exact detail, using many channels
- Samsung Origen breaks power tree into 14 shunts... perfect
- This lets you answer questions like, “exactly how much power is consumed by xxx?”, where XXX might be
  - GPS in standby
  - 3G module when connected to tower but not in use
  - WLAN module over various power modes
  - HDMI PHY in use and standby
  - USB PHY, USB 5V generator etc etc

Section 3: Arm Energy Probe hardware

Arm Energy Probe architecture

- Three channels of 2 voltmeters each
  - 0 – 30V range
    - Common-mode voltage
  - 0 – 165mV range
    - Amplified (x20) to increase sensitivity
    - cross-shunt voltage measurement
    - To turn into current value, need to know Rshunt





Scaleable USB connectivity

- 3 channels per probe
- As many probes as you need
- Appear as ttyACM serial ports automatically
- No built-in serial number or other way to tell them apart... care needed to make sure the right probe maps to the right ttyACM number
- Have a known protocol

Section 3: Practical board instrumentation

Steps to instrument a board

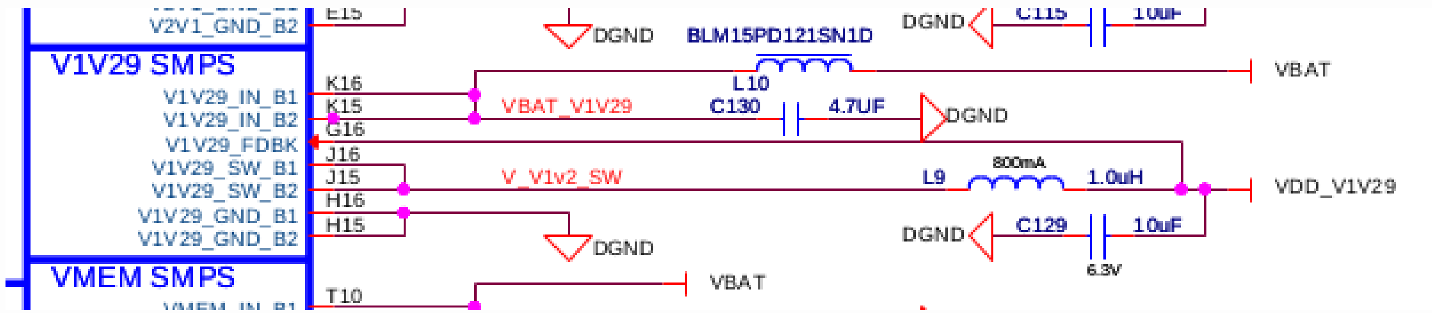
- Study schematic to find where to place shunts
- Estimate correct shunt size and resistance
- Place one 7-pin header per AEP
- Wire up ground pins
- Place shunts
- Wire up shunts to header pins

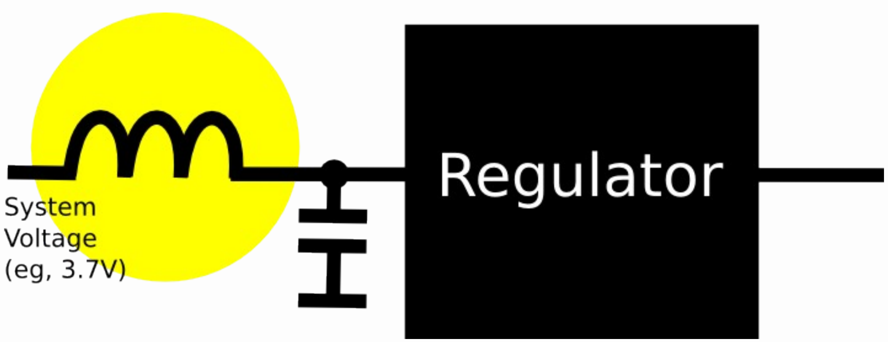
Reading Schematics

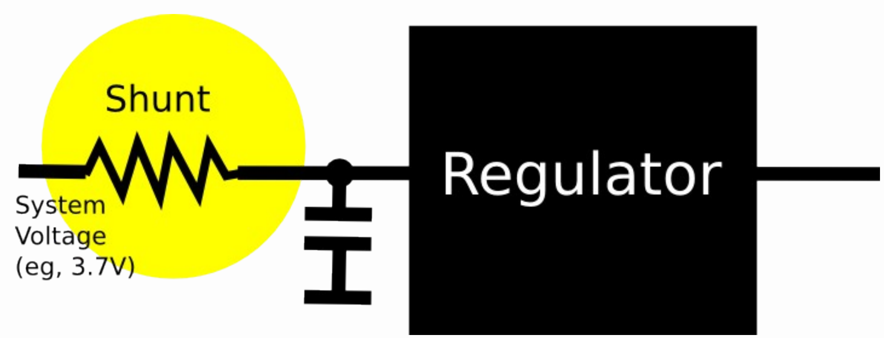
- Schematics are drawings of how the components of the electronic design are connected
- Boxy things might be a chip, or part of a chip
- Boxy things have a name, like U5 (IC 5) or R7 (Resistor 7)
- On the PCB, the device will have the matching name nearby
- Lines are connections, made into copper lines on the PCB
- Lines can be named, wherever the same name is seen will be connected together on the PCB
- If you provide the board schematic to an EE, he can tell you where it's possible to place your shunts

Input-side inductors

- Used to attenuate regulator RF switching emissions leaking on to power cable, not critical for operation
- Ideal series break point to introduce shunt







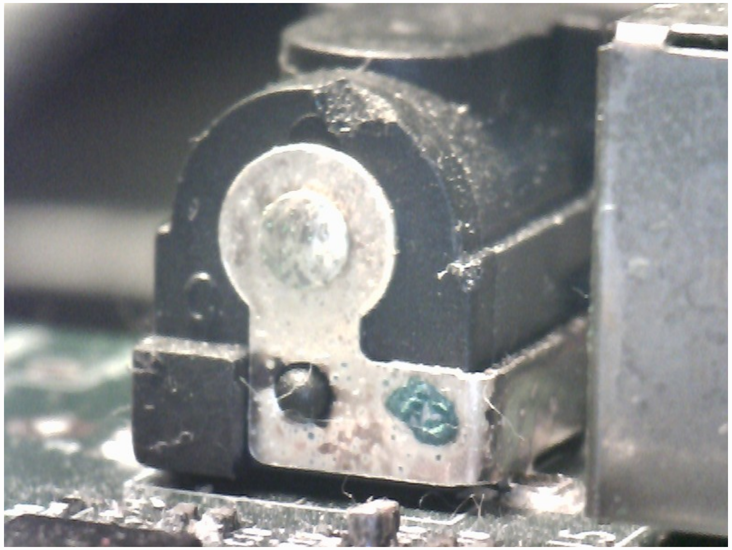
AEP connector

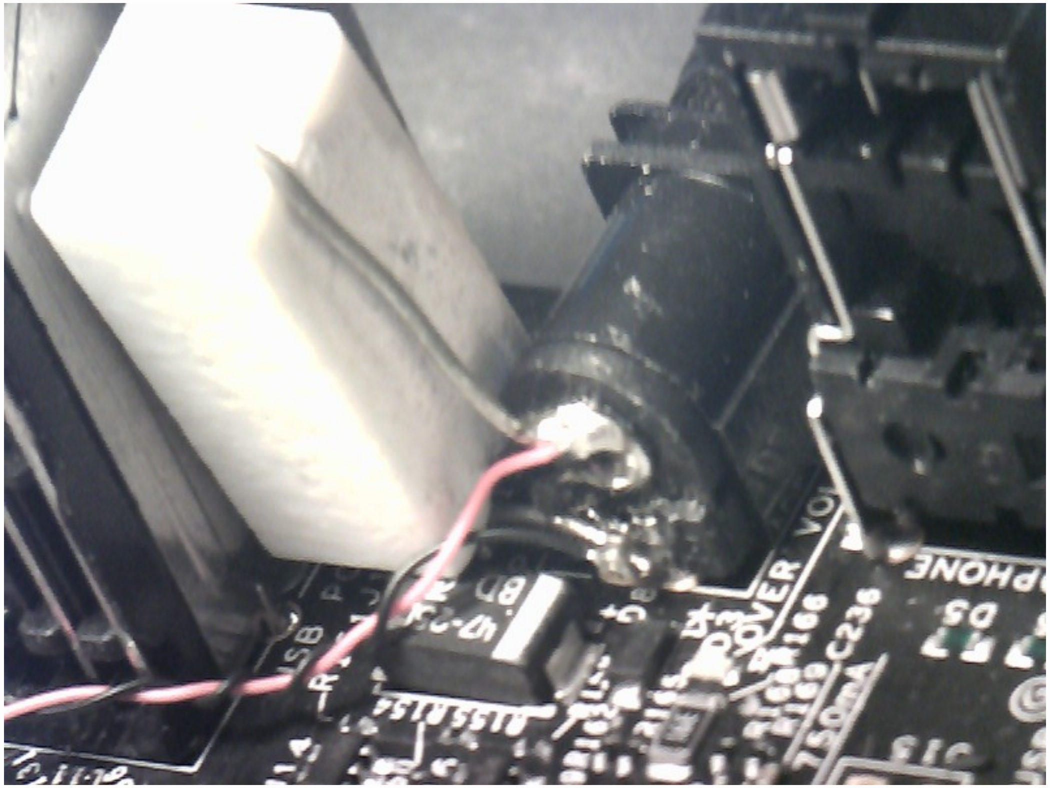
- 7-pin: 3 x 2 sense leads, 1 x 0V reference lead
- Orientation of sense leads on shunt matters
- White lead needs to go on “before” side of shunt

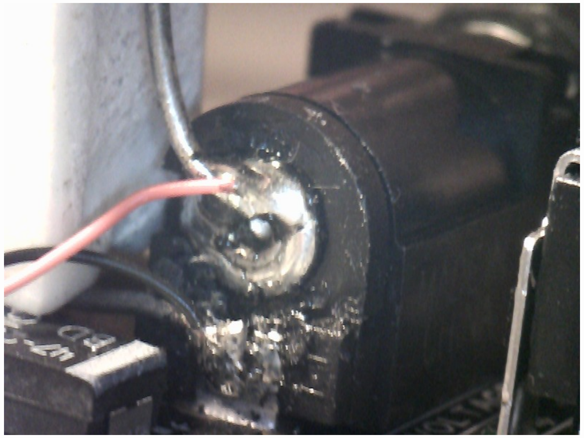
Adding shunt to DC jack externally

Adding shunt to DC jack internally

- Usually your DC jack exposes the + power
- You can cut it and bridge the cut with your shunt

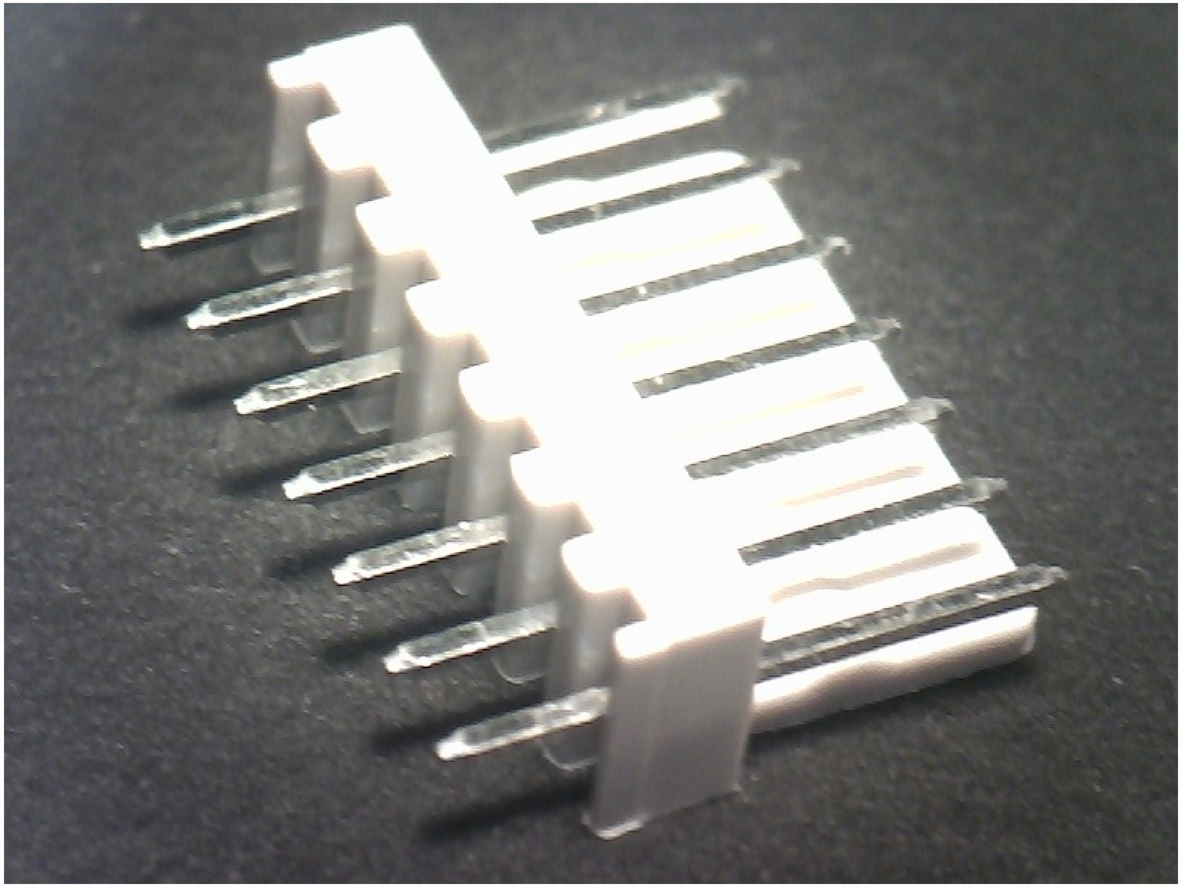






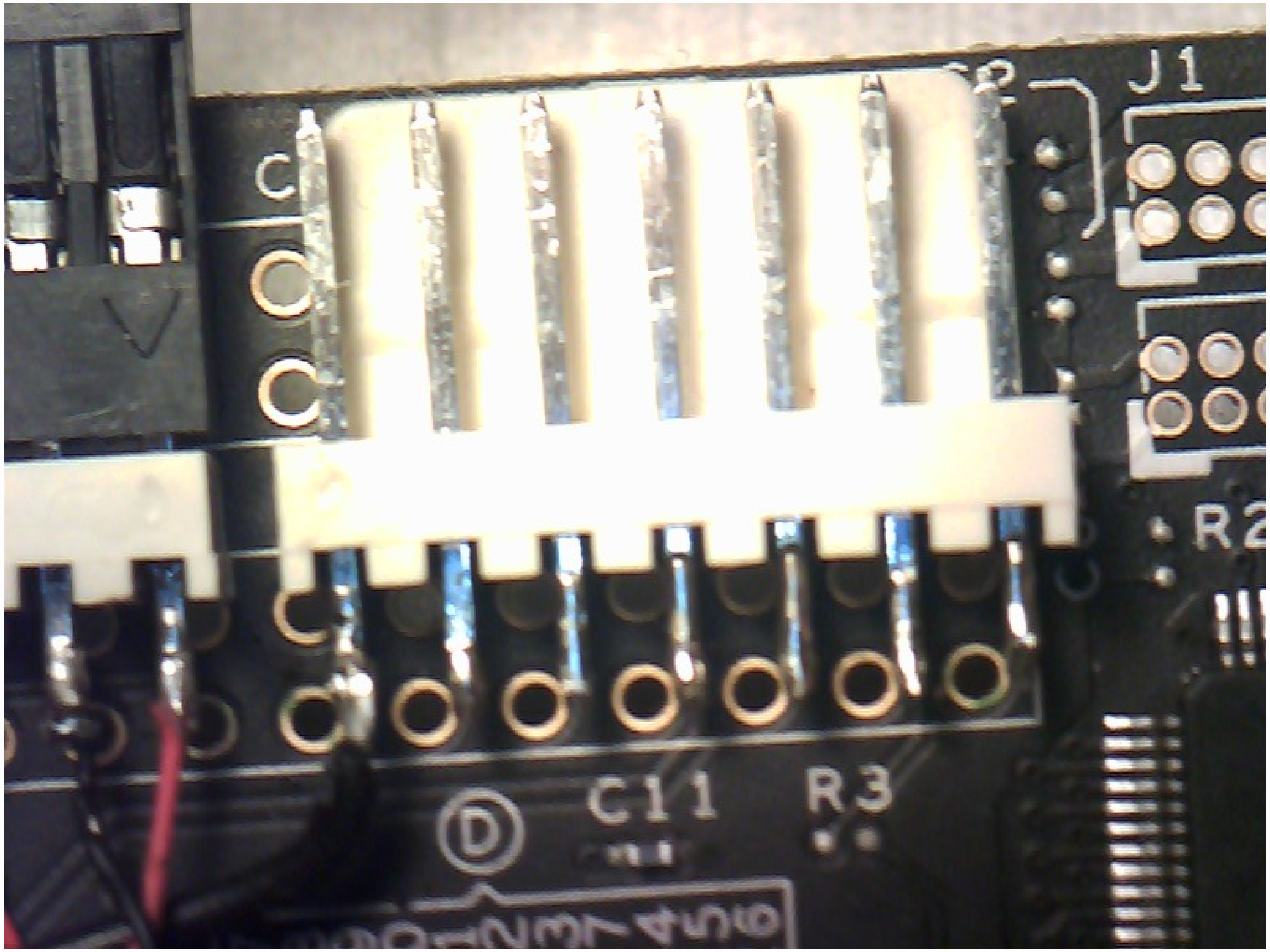
Preparing your board for measurements

- Use a 7-way 0.1" header for each probe (3 channels)



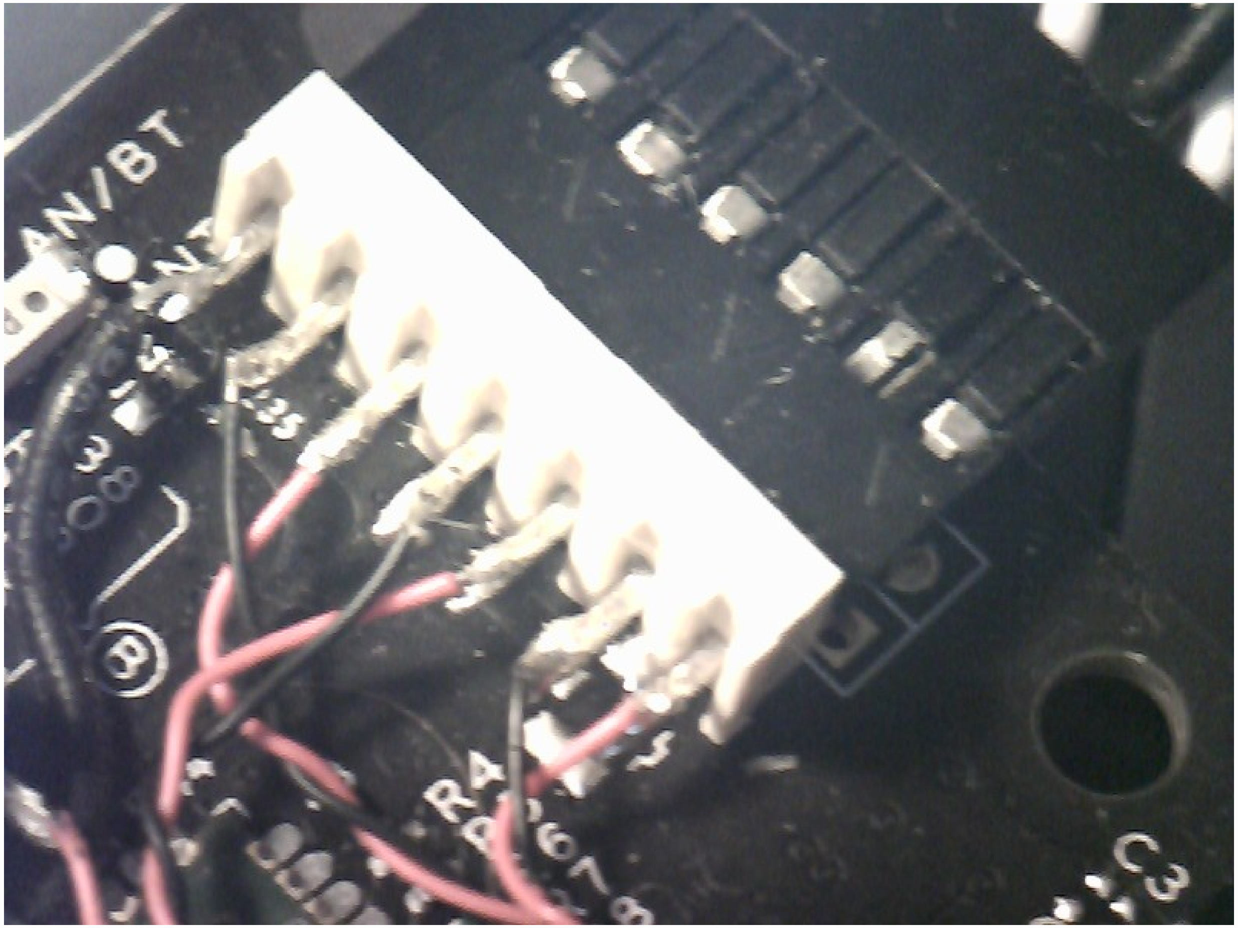
Adding SMT shunts

- Superglue the back to a spare region of the board



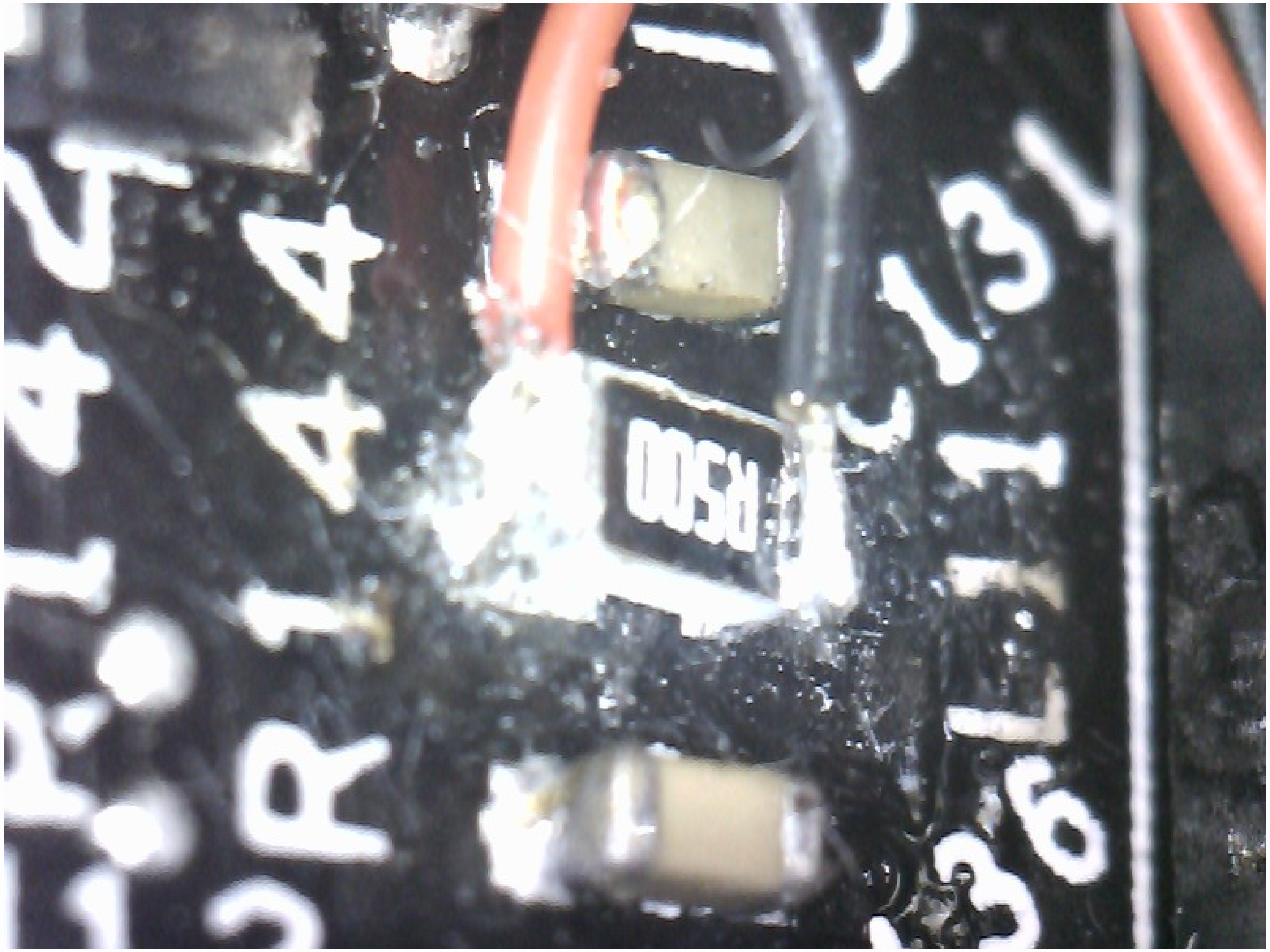
Adding SMT shunts

- Add 0V connection
- Add twisted pairs back to the shunt



Adding SMT shunts

- Solder the shunt in place
- Add the other end of the wires to the shunt



Adding high power shunt on high current path

- Same deal just bigger resistor

Section 4: Error sources

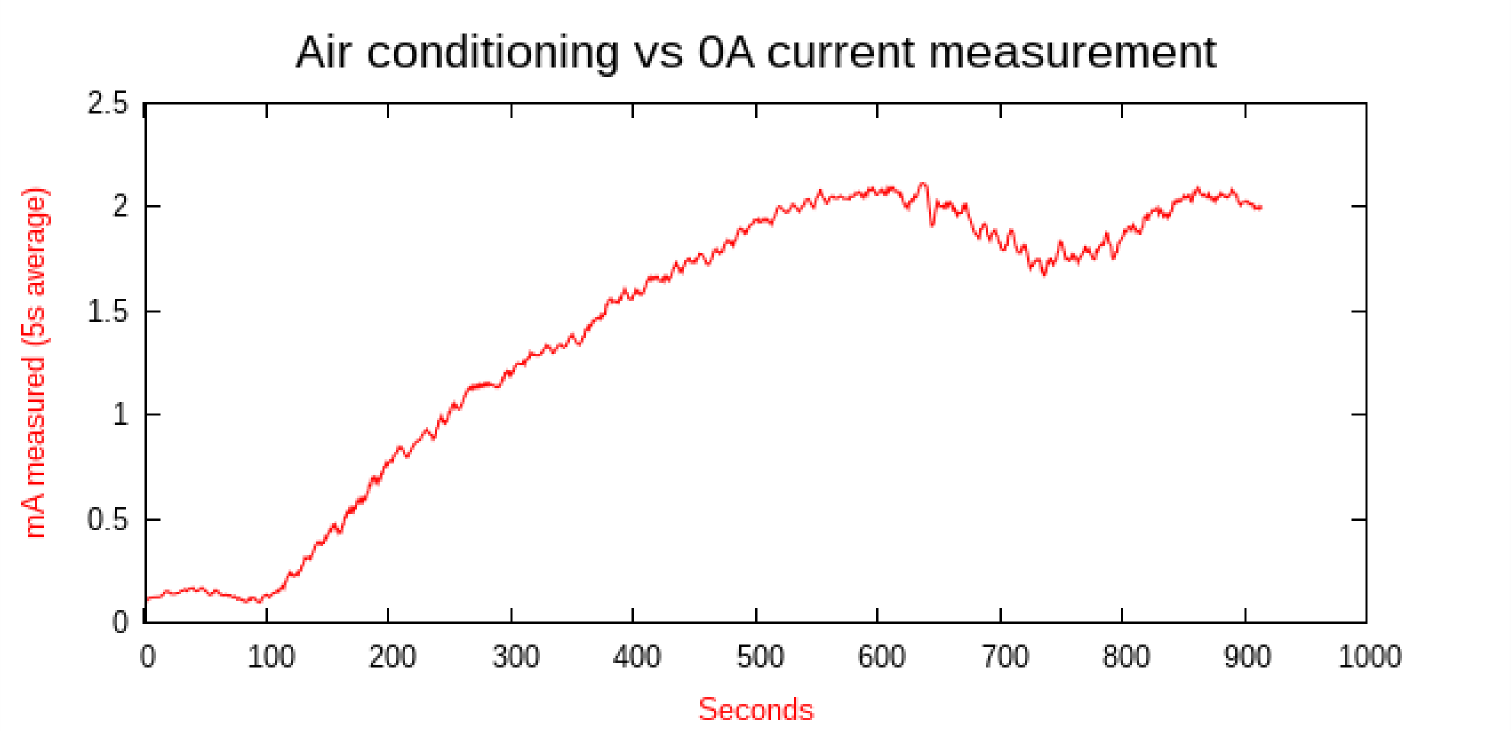
- All measured numbers are just bullshit until:
  - You know what they are supposed to measure / mean
  - You can repeat the meaurements
    - Different day / test channel / board / temperature
  - They are sane
    - If you measure total system power and one rail measurement is higher, something is broken
    - If you know zero power is in use, does it say 0.000W?
  - You have a rough error budget for how the numbers were arrived at
    - Even when the numbers have a pedigree, +/- 20% vs absolute accuracy is a reasonable assumption
    - If you have access to lab-calibrated, absolutely accurate equipment to compare them with, you can trust them more

Concept of repeatability

- Numbers that cannot be repeated under similar test conditions contain error
  - Need to understand why and how much, can still be usable
- Ultimately if it's not repeatable, it's not a useful measurement

Zero offset

- Bits of the circuit, the shunt, the measuring device drift with age and temperature
- Here's what happened to “0mA” when I turned the air conditioning on, over 15 minutes



Effect of temperature on measuring device

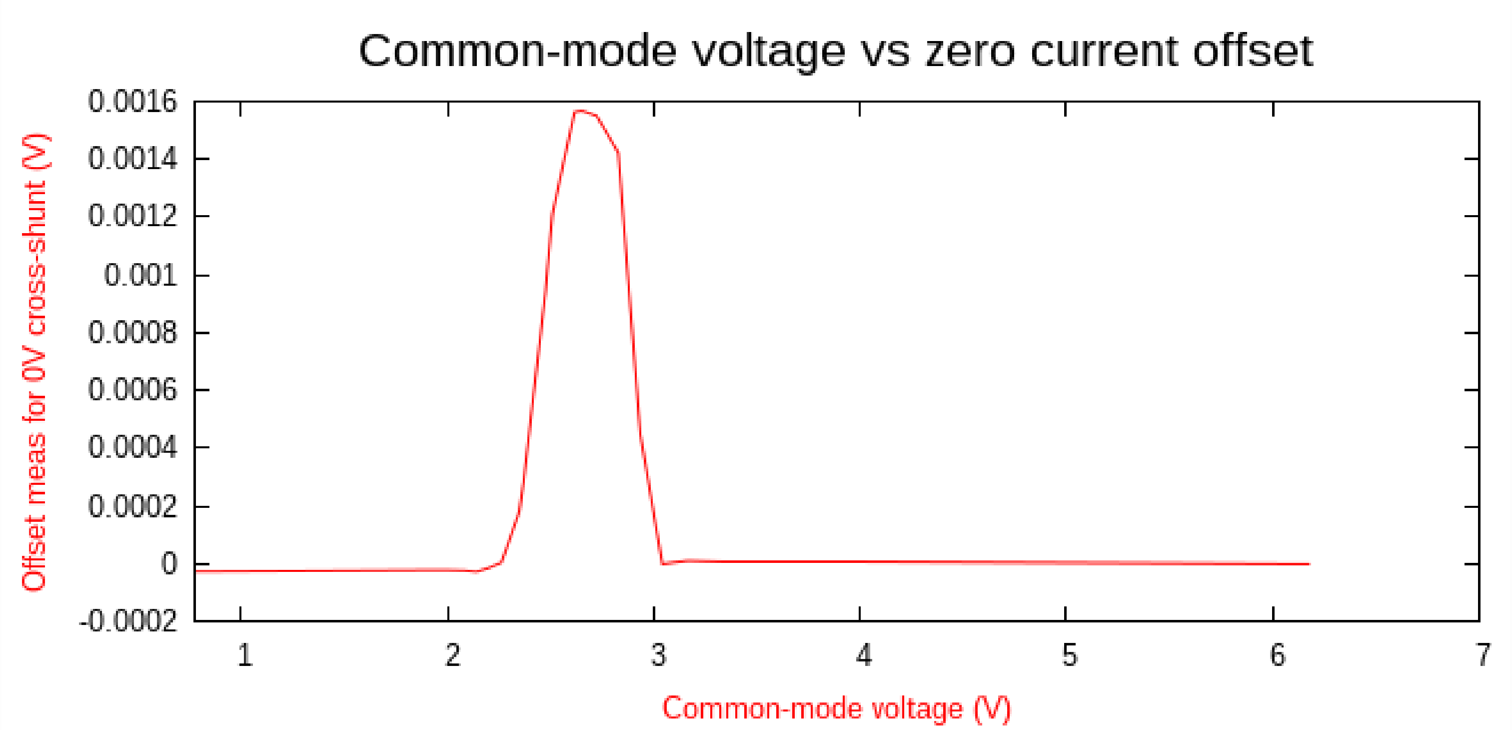
- Shunt resistance is sensitive to temperature
  - Take care about self-heating at high currents too
  - Different resistor chemistries act different, SMT ones seem better
- Adc
- Shunt voltage amplifier
- Resistor reaction to temperature
  - Ntc / ptc networks

Measurement bandwidth

- The rate of sampling can also impact results
- At 10Ksps, events significantly faster than 100uS may be missed or under-reported
- If you're unlucky load changes at a rate that is a multiple of the sample rate can lead to aliasing
- When measuring at the input side of the regulator, these load changes are themselves sampled by the switching action of the regulator
- Generally even fast load changes are averaged fairly well

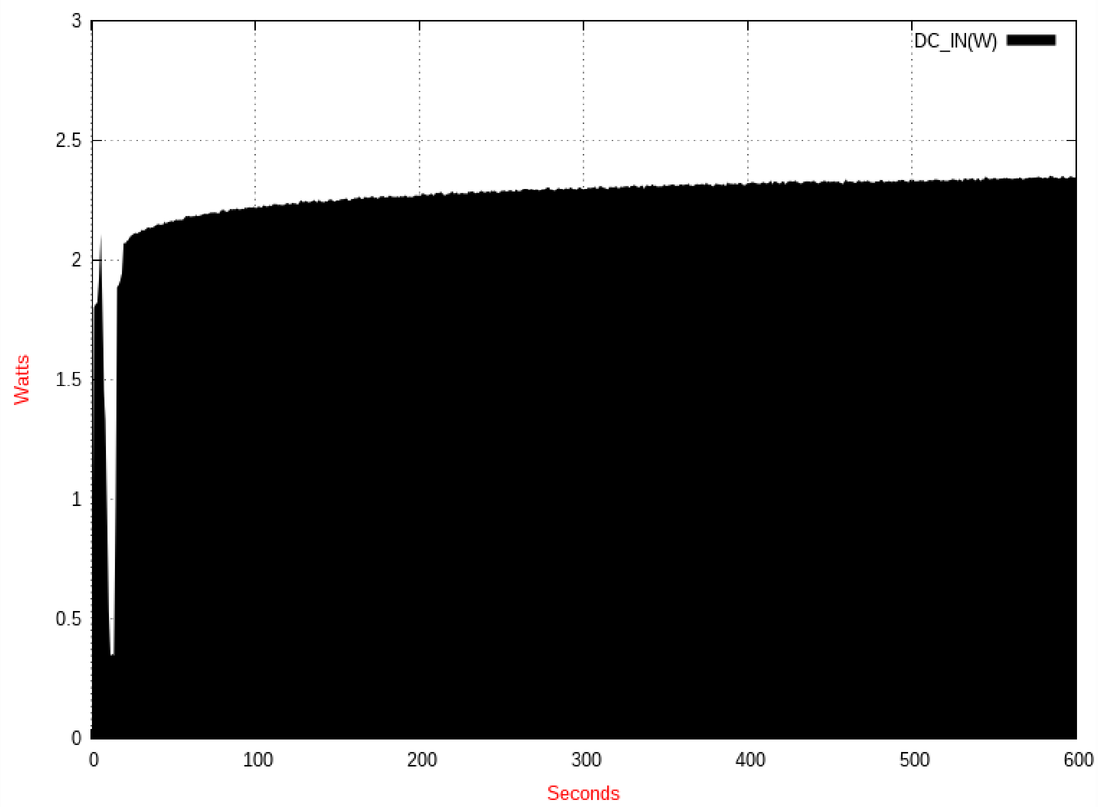
Linearity of ADC + shunt amp

- Supposed to ignore common-mode voltage
  - Measure the same 2mA for 2mA at 1V, as 2mA at 5V
- But this is “0mA” measured at different common-mode voltages...



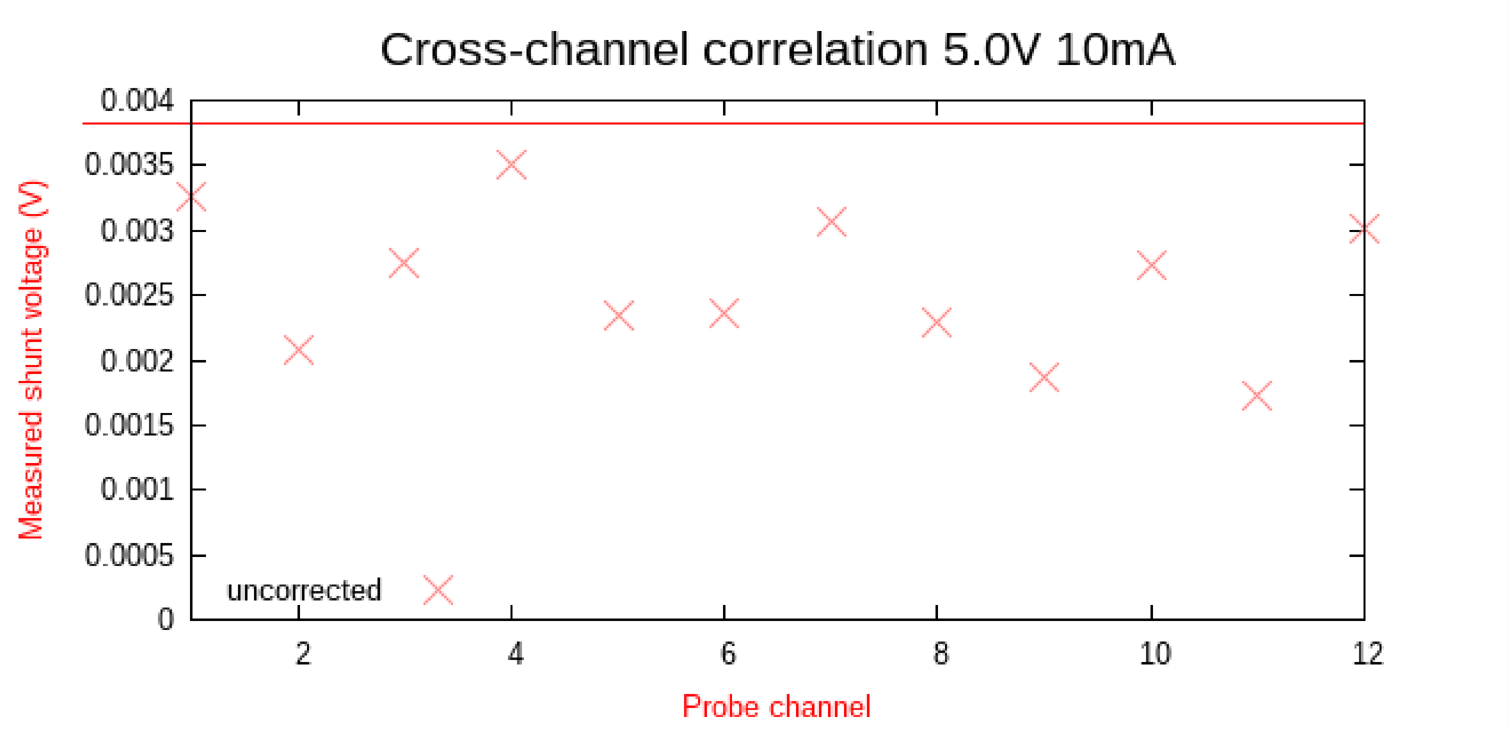
Silicon power consumption over temperature

- Silicon switching efficiency is a function of temperature
- 23% (1.9W – 2.34W) increase in consumption for same cpuburn just from die temperature rise from 30°C – 60°C
- Repeatability...



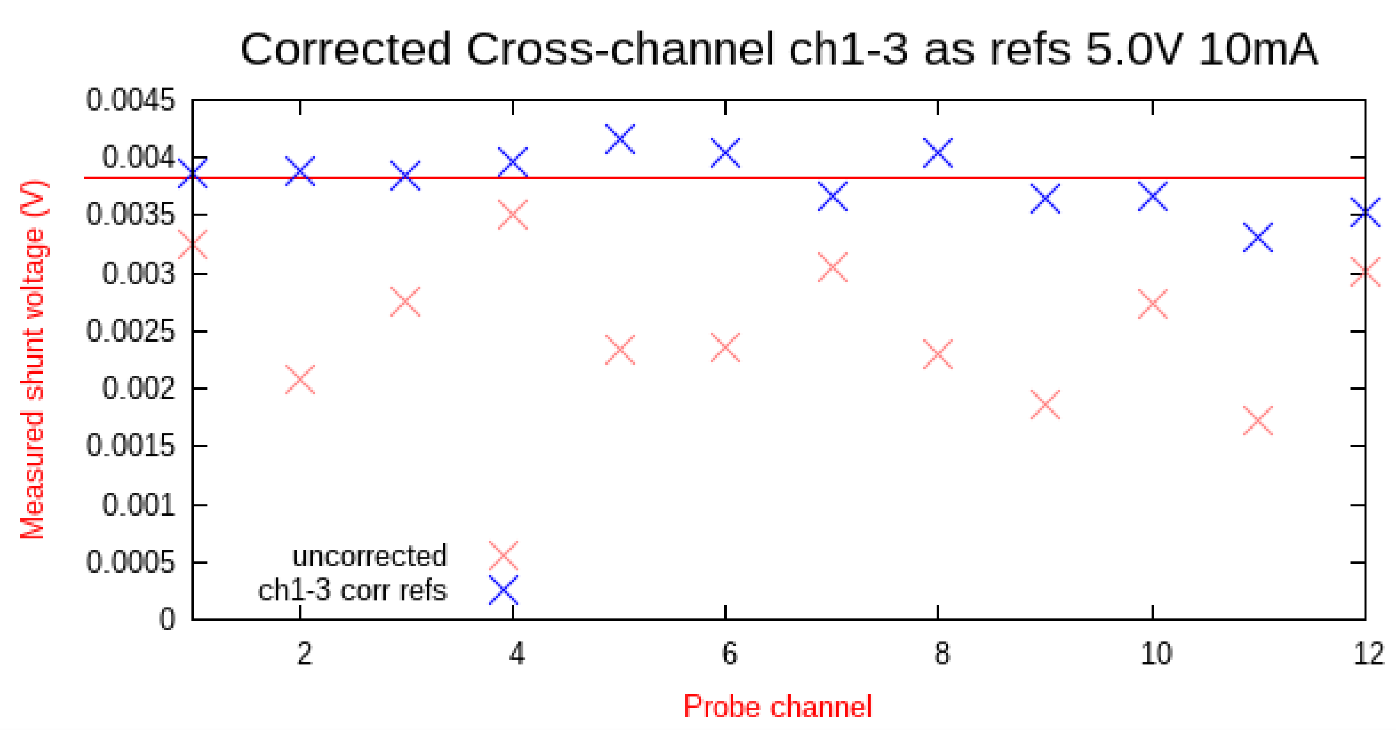
Differences between channels

- Uncorrected (except zero offset) measurement of same 3.8mV shunt voltage (red line) using 12 channels in turn
- Huge variation of reported numbers by channel



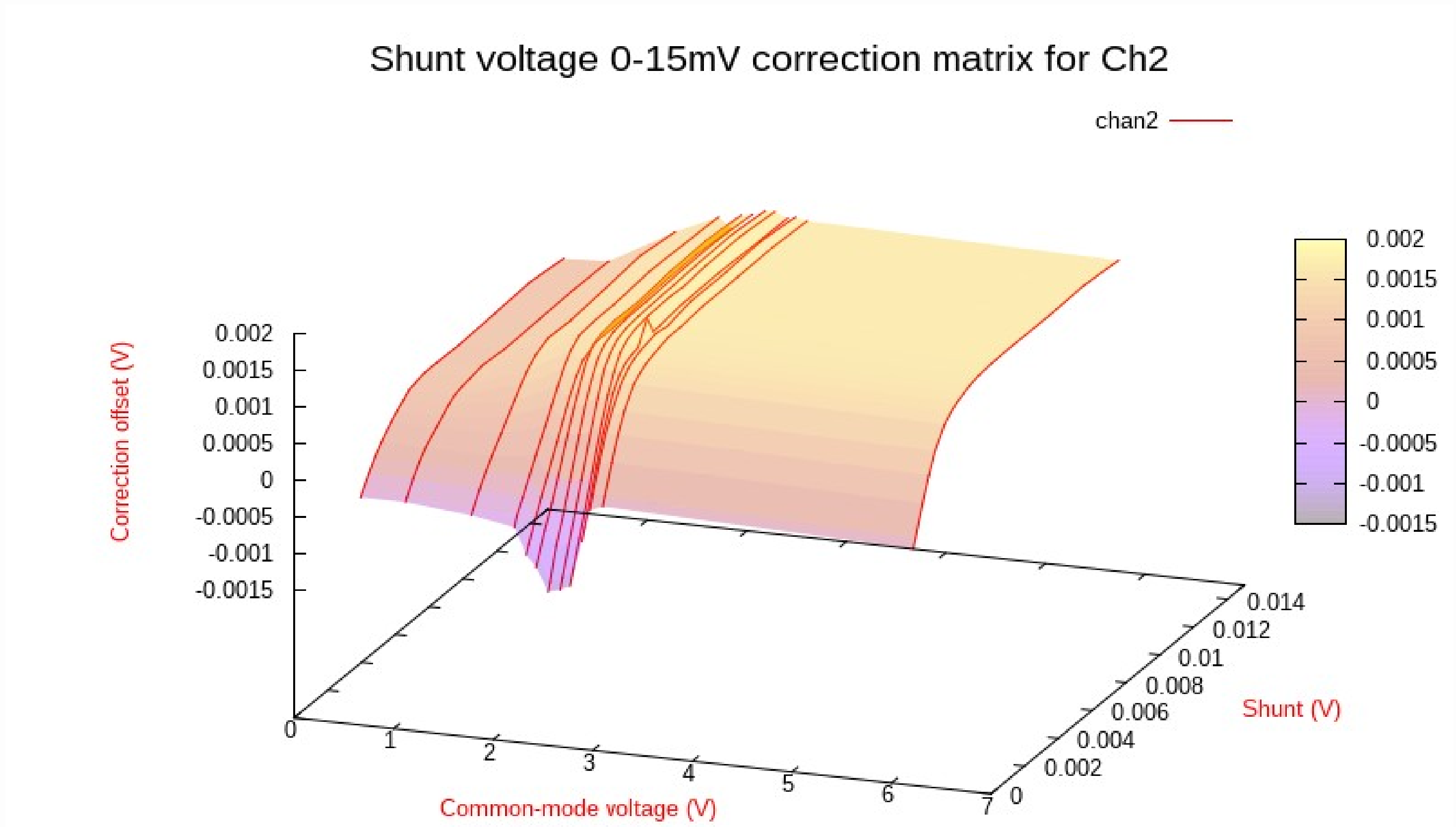
Channel correlation correction effectiveness

- After software correction (blue X)
  - Error less than -13%/+9% at 3.8mV



AEP-specific problems with low voltage range

- Considering all the sources of error, I applied "2D" correction tables (adjustments across common-mode voltage and current)



Error budget estimation

- Actual resistance of shunt is not what is marked on the resistor due to manufacturing process spread
  - Typ +/- 5%, +/- 1% available
- ...and it varies by temperature...
  - Typical SMT (Yaego RL0805) 470mR changes by +300ppm / °C
  - 10°C change is +1.4mR (0.3%)
- ... so conversion of shunt voltage to current has ~+/- 6% (2% for 1% resistors) uncertainty
- Channel current differences are around +/- 10% (at 10mA) even after correction
- Unknown ADC offset and linearity errors
- In AEP case, numbers below a few mA are almost certainly wrong due to linearity problems...

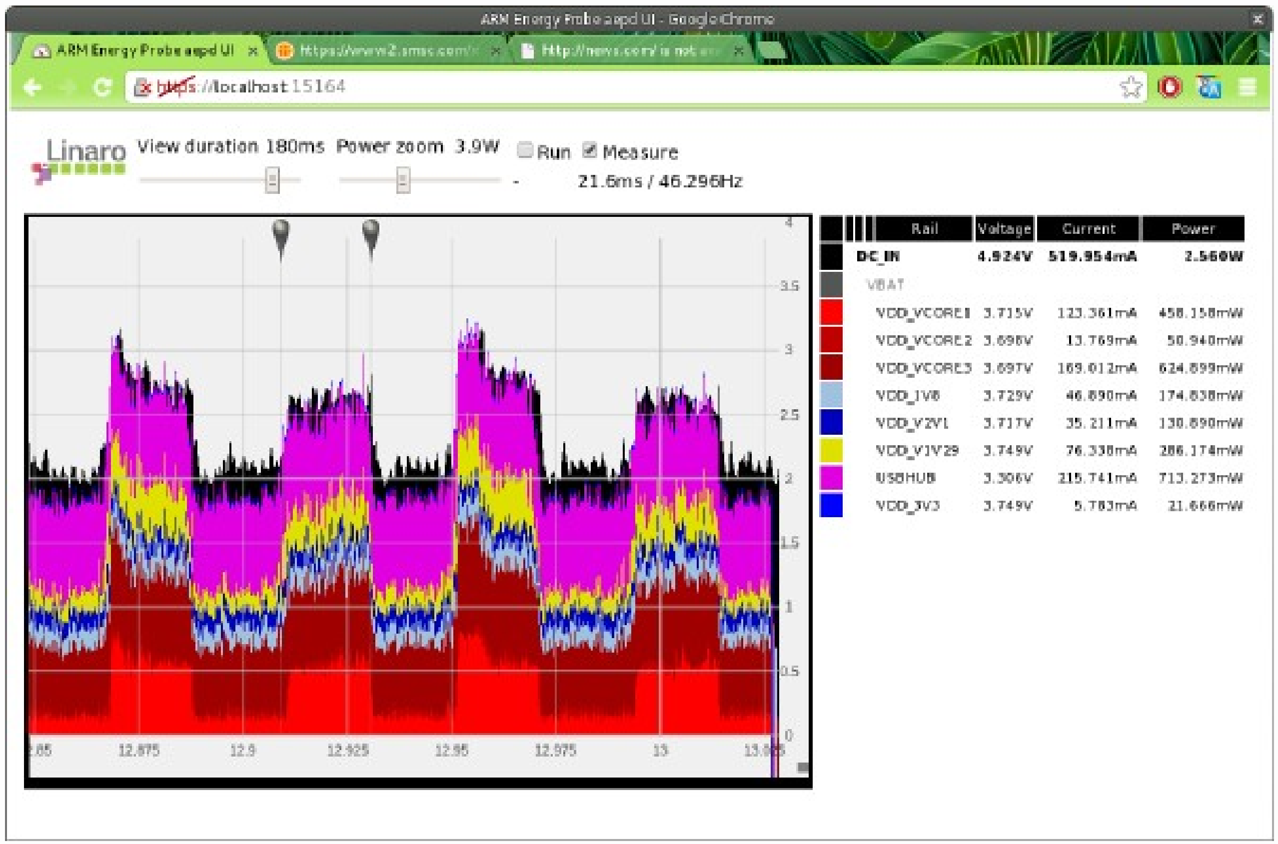
Section 5: Commandline Linux AEP app

Architecture

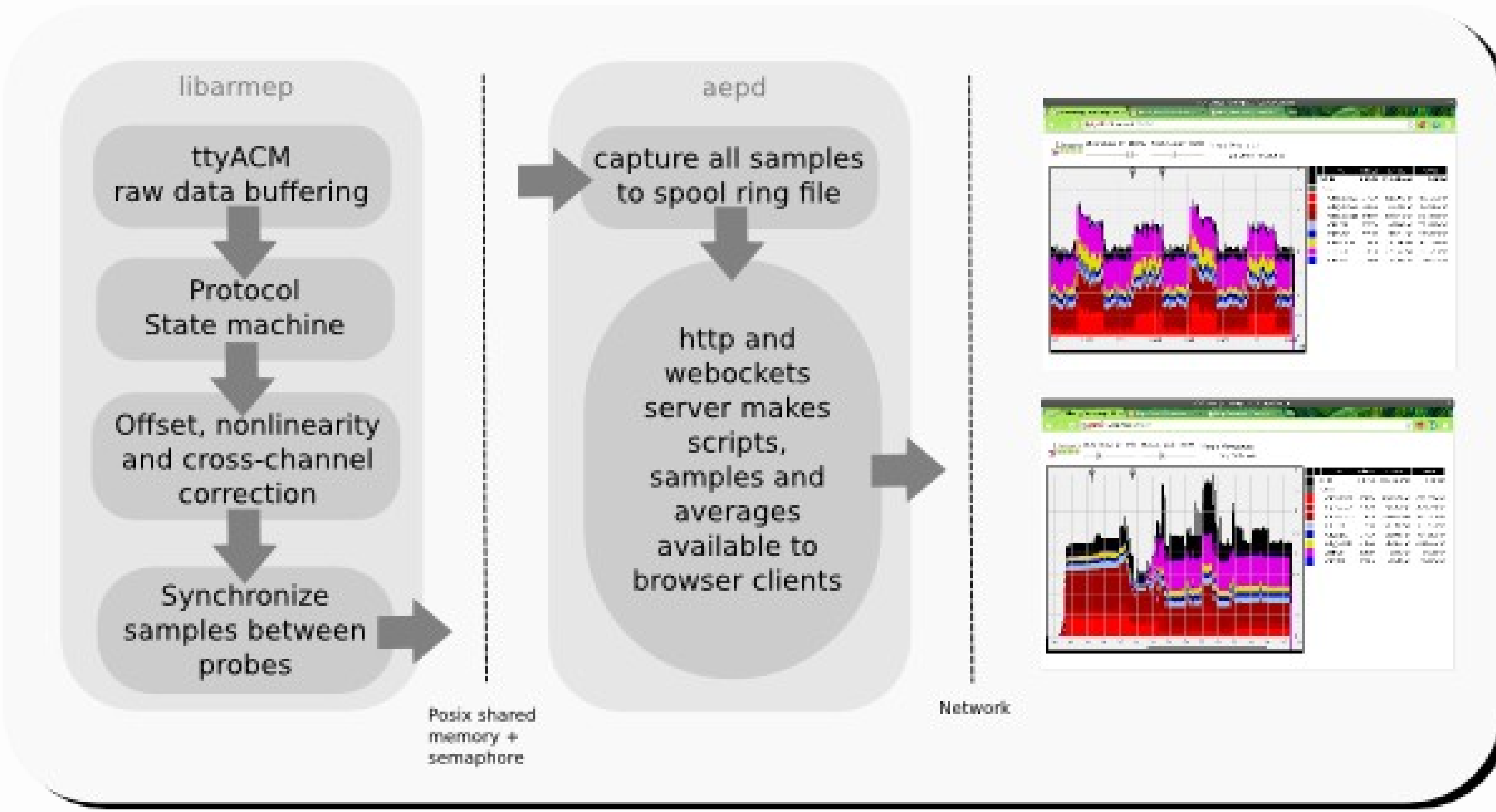
- Synchronizes sampling across multiple energy probes
- Outputs ascii numbers in column format
- Appends columns to stdin if present
- Gnuplot-friendly output
- Autozero support

Example interface to gnuplot

Section 6: aepd and HTML5 UI



Aepd architecture



Websockets advantages

- Realtime, immediate graphical update from aepd link
- 600px, up to 24fps == see all 10Ksps samples
- “power scope”

Generic sample interface

- Allows integration of alternate measurement hardware
- Floating-point voltage and current

Averaging scheme in the storage ringbuffer

Smart comparing of power tree

- Combined / additive channel view

Calipers

- Get averaged stats on region of interest

“Search”

- Different paradigm than oscilloscope, since operates on deep, complete buffer post-capture
- “fade out” different parts of dataset based on power level search criteria
- Determine duty cycle of matching / non-matching regions
- Get power averages just for matching regions

Uses of deep buffer 100% capture

- True analysis of boot timing from first power to various activities in boot
  - Can't be replicated by “from inside” measurements

All software GPL'd and available today

- **git://git.linaro.org/tools/arm-probe.git**
- Need AEP
- Instrument your board with shunts
- Linux box to host AEPs on USB and aepd
- Google Chrome (best HTML5 implementation)
  - Works on Android Chrome as well
- Expected to be useful as basis for vendor in-house power monitoring tools in future

Linaro CONNECT EUROPE 2012 (LCE12)

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