Aalto University
School of Science

A First Look at Power Consumption of Smartphones

T-110.6120 Spring 2014

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15.4.2014

Agenda

- **Something you should know about smartphone batteries**
- **Overview of energy causes**
- **How to measure and analyze power consumption**
  - Metrics
  - Hardware-based vs. software-based measurement
  - Case studies
- **Basics of power modeling**

- **Smartphones are powered by batteries**
- **Battery Life: the time your phone will run before it must be recharged**
- **Battery lifespan: the amount of time your battery will last until it must be replaced**
- **A key target of energy-efficient mobile computing: *extending battery life***

Smartphone Batteries

- **Rechargable Lithium-ion(Li-ion) or Lithium-polymer (Li-Po) batteries**

Samsung Galaxy S4

Nokia Lumia 1520

Battery Parameters

- **Nominal Voltage: 3.8V**
- **Typical/Minimum Capacity: Wh(Watt Hour), mAh(milli-amper hour)**

$$Q_{(mAh)} \times \frac{V_{(V)}}{1000} = E_{(Wh)}$$

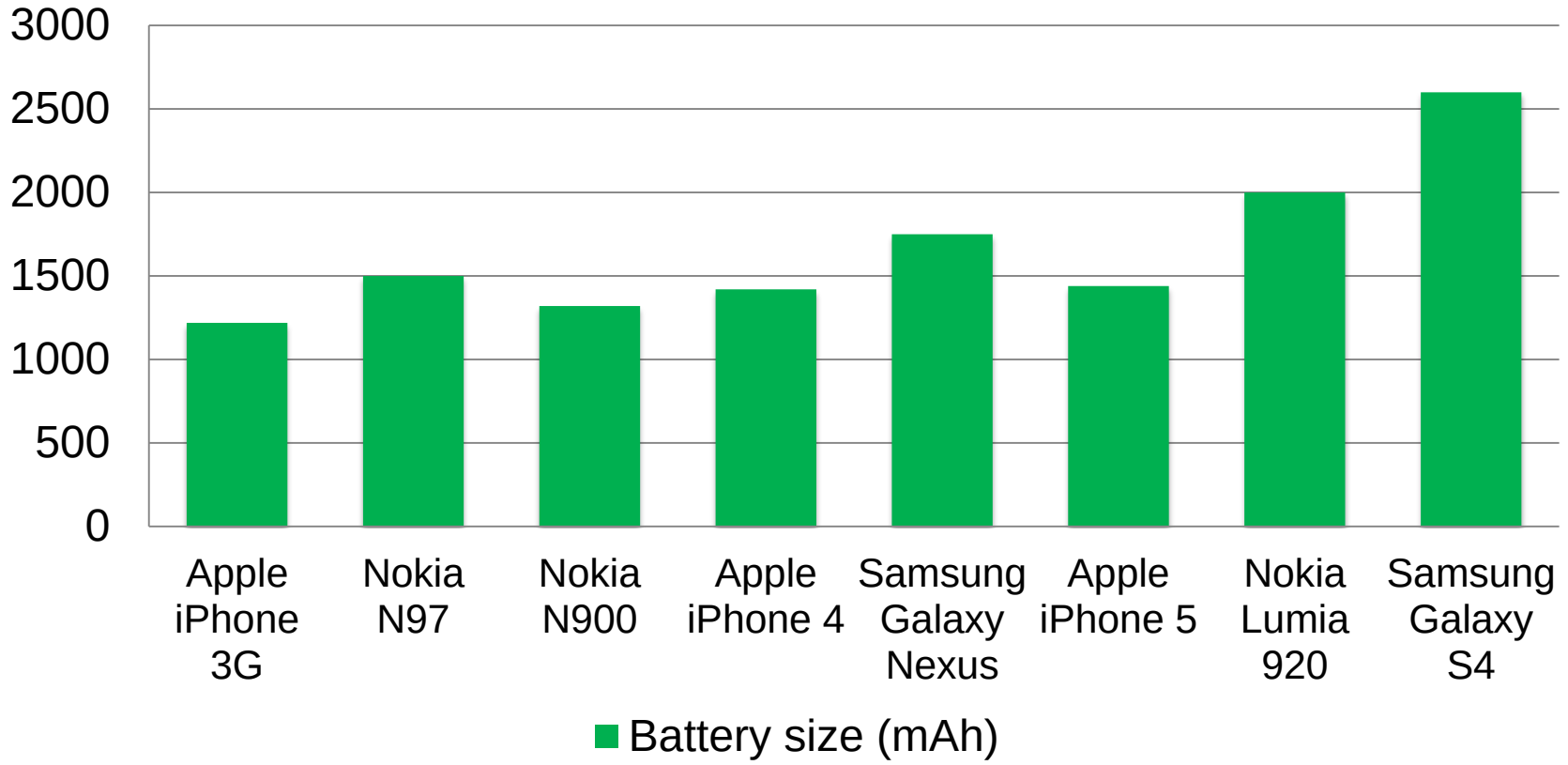
For example,

3400mAh x 3.8V / 1000 = 12.92Wh

1Wh = 3600 Joules

- **Maximum Charging Voltage: 4.35V**

Battery Capacity is Growing, but Not Fast Enough



- **There is no Moore's Law for batteries**
- **Improvement in energy storage density of lithium batteries has been only incremental for the past decade**
- **Smartphones batteries must be**
  - Light
  - Small
  - Thin

Battery Life (Product Specifications)

Usage	Samsung Galaxy S4	Apple iPhone 5	Nokia Lumia 1520
Battery Capacity	2600mAh	1440mAh	3400mAh
Stand-by	Up to 370h(3G), up to 320h(LTE)	Up to 225h	Up to 768h
Talk time	Up to 17h(3G)	Up to 8h(3G)	Up to 27.4h(2G) Up to 25.1h(3G)
Audio playback	Up to 62h	Up to 40h	Up to 124h
Video playback		Up to 10h	Up to 10.8h
Internet use	Up to 8h(3G) Up to 8h (4G) Up to 10h(WiFi)	Up to 8h(3G) Up to 8h(LTE) Up to 10h(WiFi)	Up to 13.6h(WiFi, Browser)

"Up to" : fully charged battery, single app

What you cannot tell from the specs

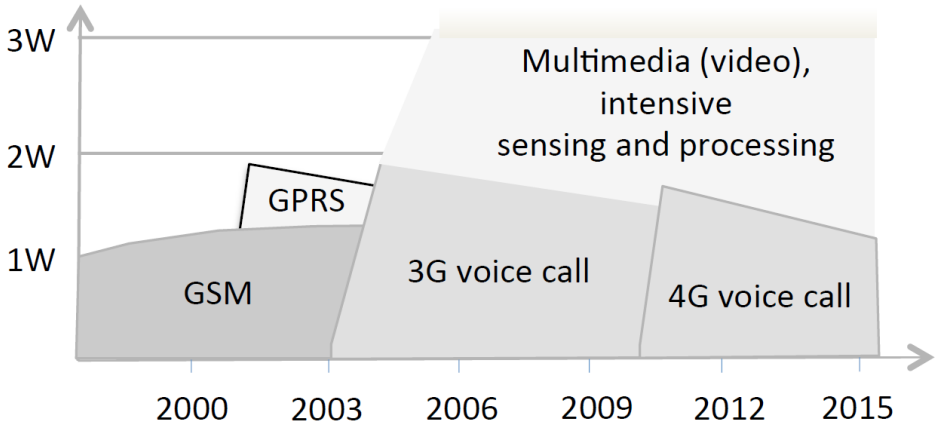
- **Minimum battery life**
- **Under what conditions the battery life can be maximized**
- **The difference in energy usage between Internet apps**
- **Energy usage of sensing applications**

What We Learn from Product Specs

- **Higher battery capacity → Longer battery life**
- **Battery life depends on which app you use, and which network your phone connects to**

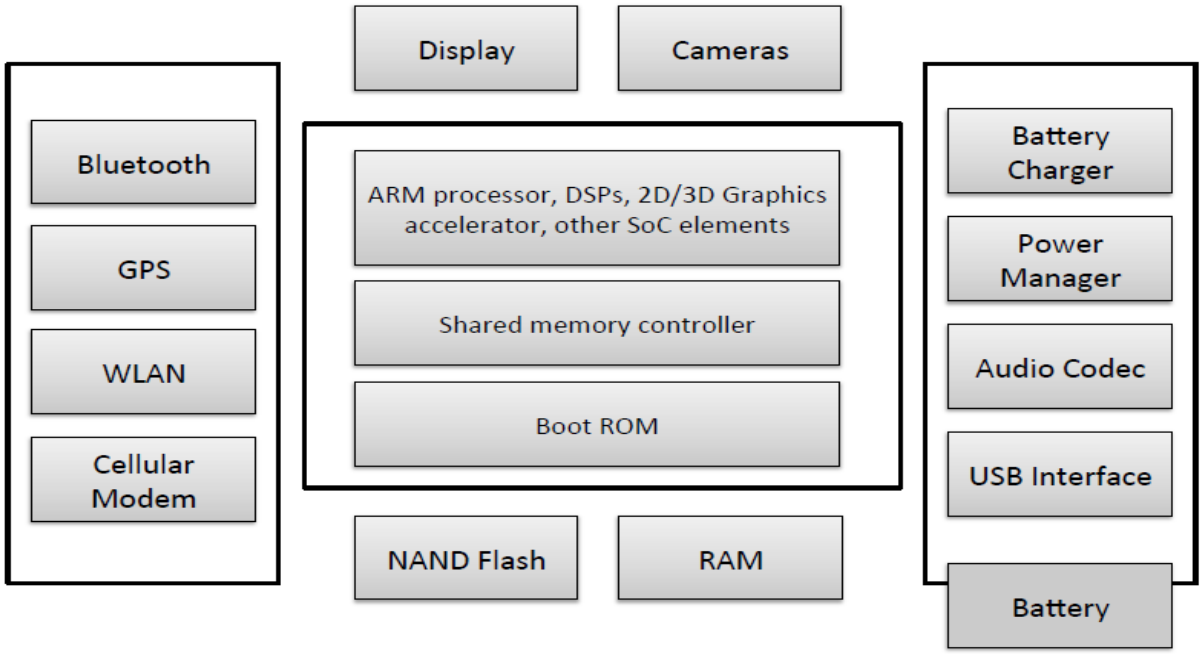
We are seeing an increase in energy consumption

- **Growing usage of Internet**
- **Bigger display and higher resolution**
- **Popularity of mobile sensing applications**
- **More compute-intensive applications (e.g. computer vision, 3D gaming)**



To save energy, you must first understand how energy is consumed

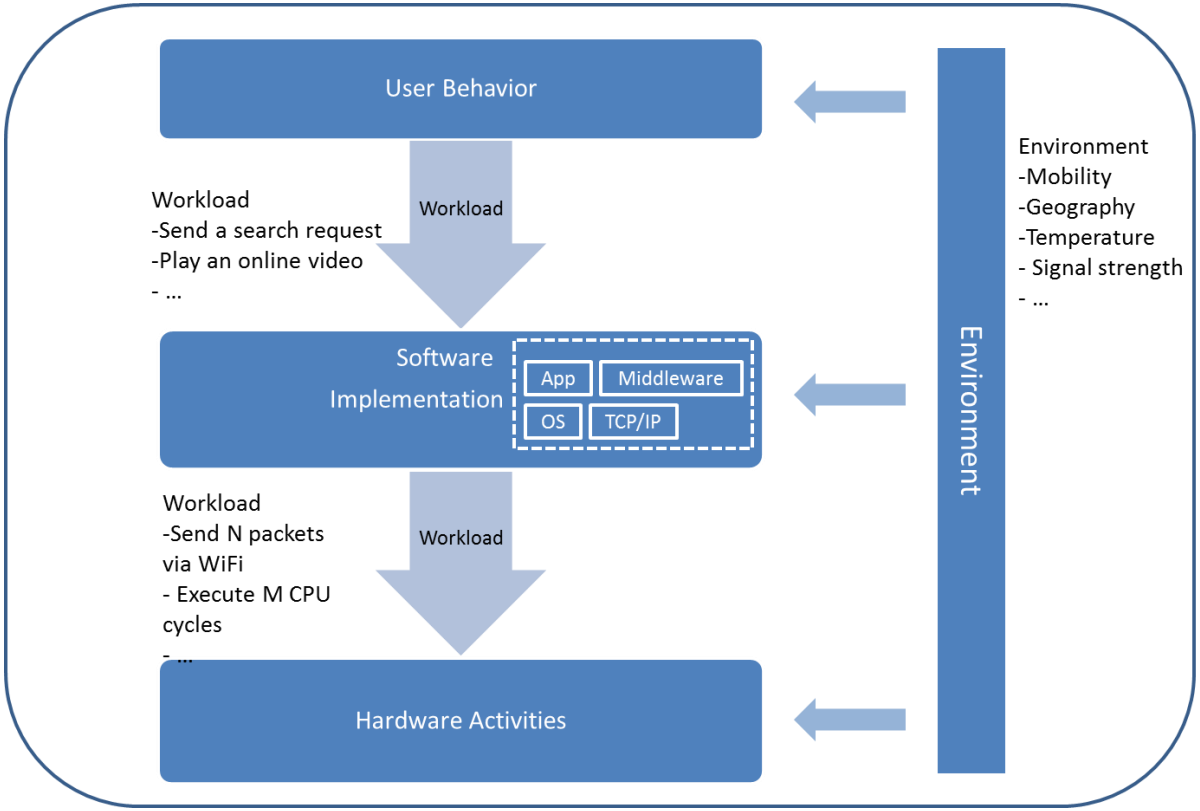
- **Hardware components are real energy consumers**



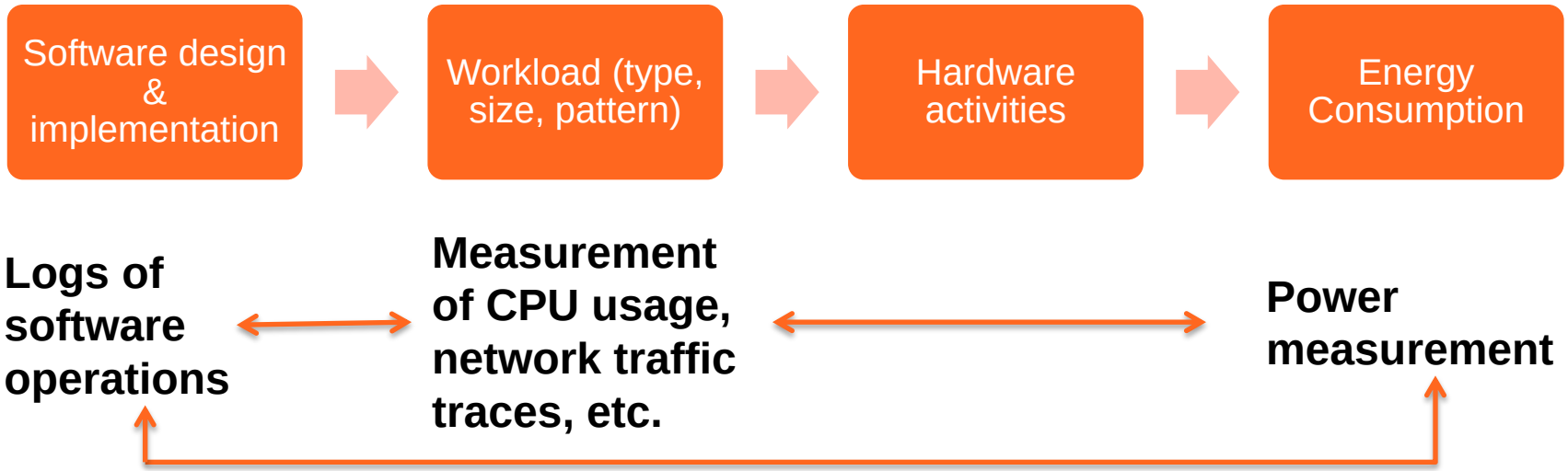
- **In this course, we focus on software solutions, not low-power hardware design**

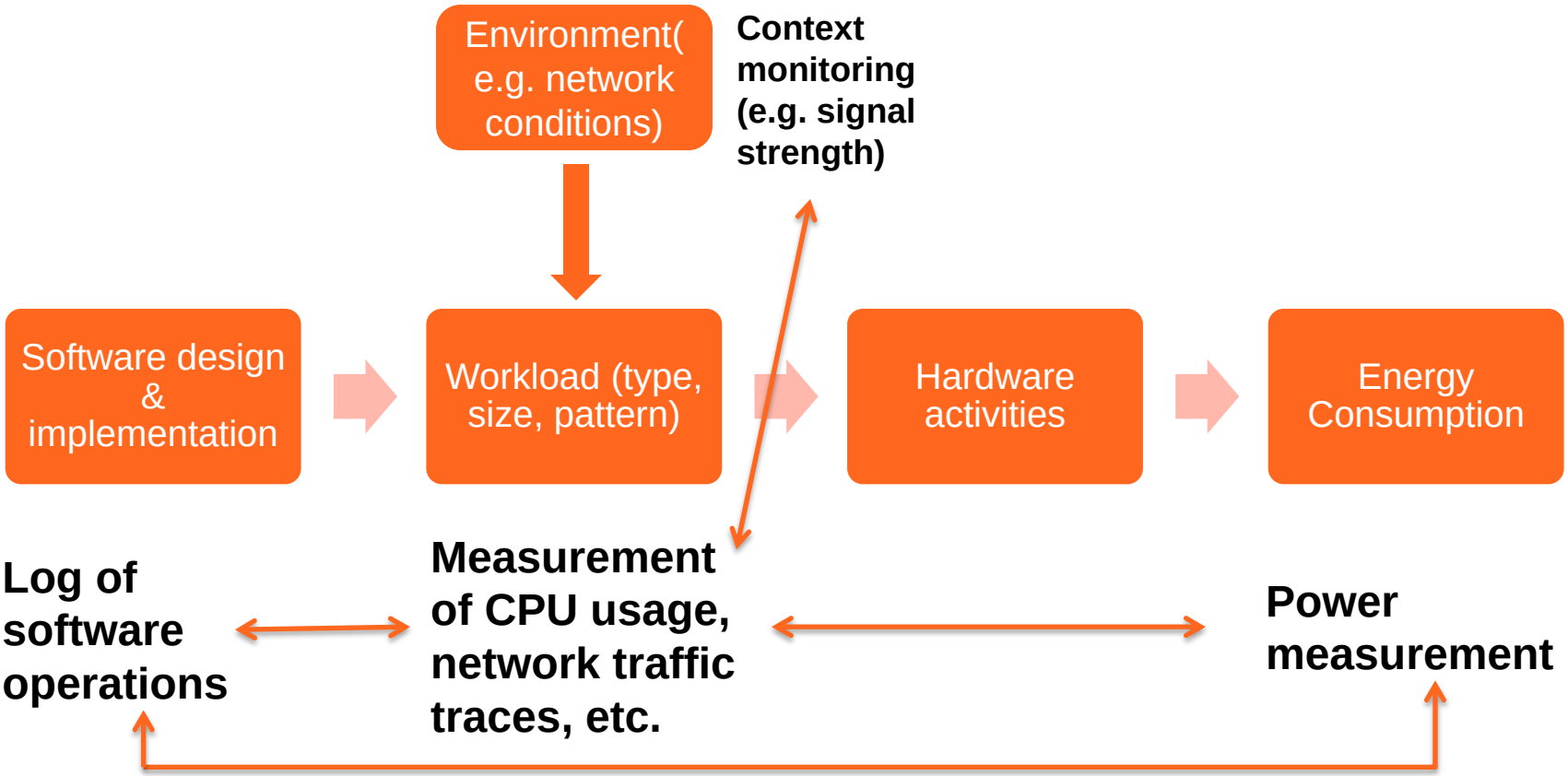
- **Why do we need to take energy-efficiency into account while designing and implementing software? How is that related to energy consumption of the underlying hardware?**

Overview of Energy Causes



- **Hardware components are the real energy consumers**
- **Software including the OS and applications generate the workload of computing, I/O access, encoding/decoding, and other hardware operations.**
- **The work is transformed into a set of circuit activities on the corresponding hardware components, and the circuit activities consume energy.**


Software design & implementation
Workload (type, size, pattern)
Hardware activities
Energy Consumption
Logs of software operations
Measurement of CPU usage, network traffic traces, etc.
Power measurement


Environment(e.g. network conditions)
Context monitoring (e.g. signal strength)
Software design & implementation
Workload (type, size, pattern)
Hardware activities
Energy Consumption
Log of software operations
Measurement of CPU usage, network traffic traces, etc.
Power measurement

Given an app, we would like to know

- How much energy is being consumed by the phone while running the application?
- Which operations are power hungry? Why are they power hungry? Is it due to heavy CPU processing, wireless networking, always-on display, intensive sensing, or other factors?
- Does the energy consumption vary with the operating status of the phone, the networking environment, the order of the user operations, and the location?

To answer these questions, power measurement is very much needed.

Power Measurement

Metrics

- **Power(W): energy transferred per unit time**

  P = IV

  1W = 1A x 1

- **Energy(J): the amount of energy consumed over time**

  E = PT

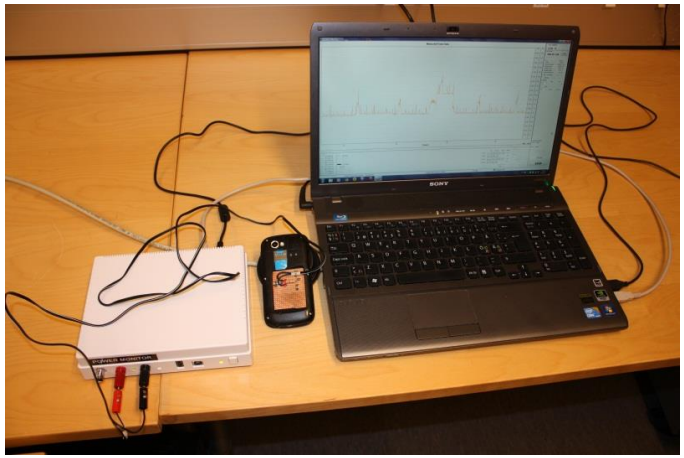
  1J = 1W x 1s

- **Energy Utility**

  For example, for data transmission, energy utility(KB/J) shows how many KB can be transmitted/received using 1 Joule

Measurement Methods

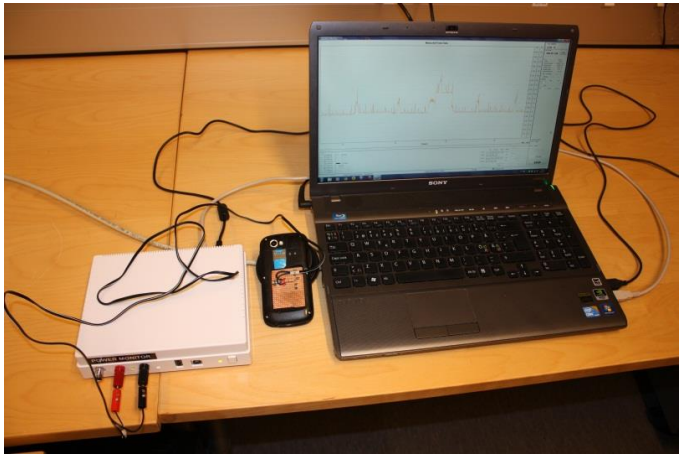
- **Hardware-based: using physical power meters**



- **Software-based: getting battery usage information through APIs**

Hardware-based Power Measurement

- **Physical power meters**
  - Metrics: voltage, current, watt
  - Sampling frequency
  - Logging software



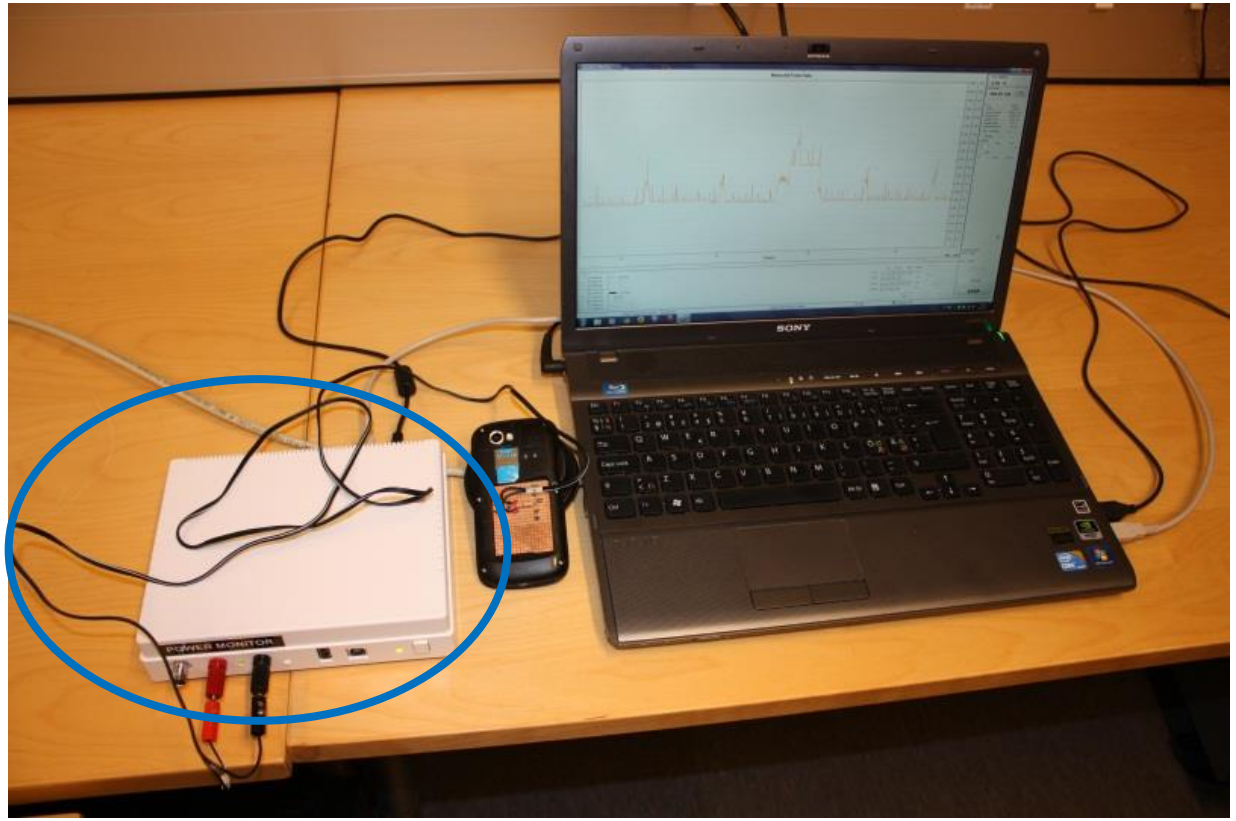
- **External DC power supply vs. battery power supply**

- **Circuit design**

Example Setup: Power Meter

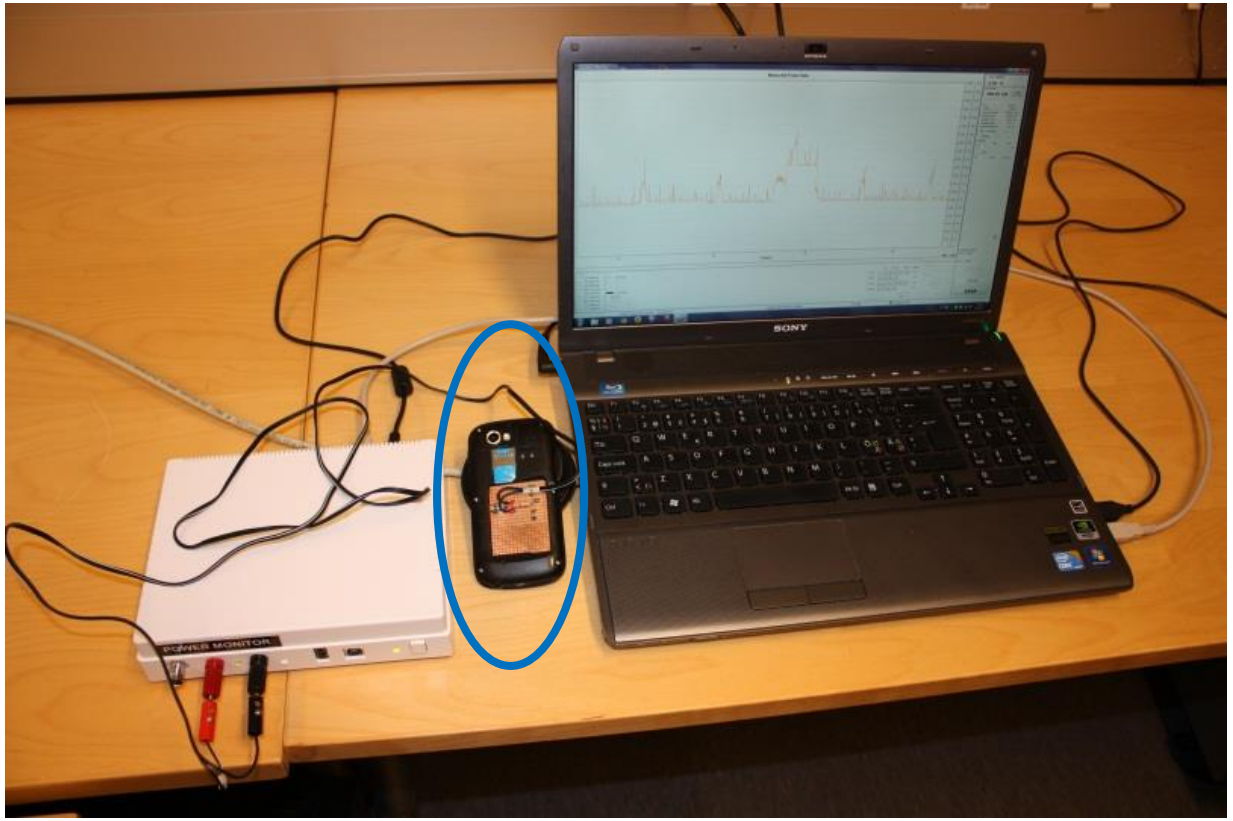
Monsoon Power Monitor (DC power supply, meter)

Sampling frequency: 5000Hz

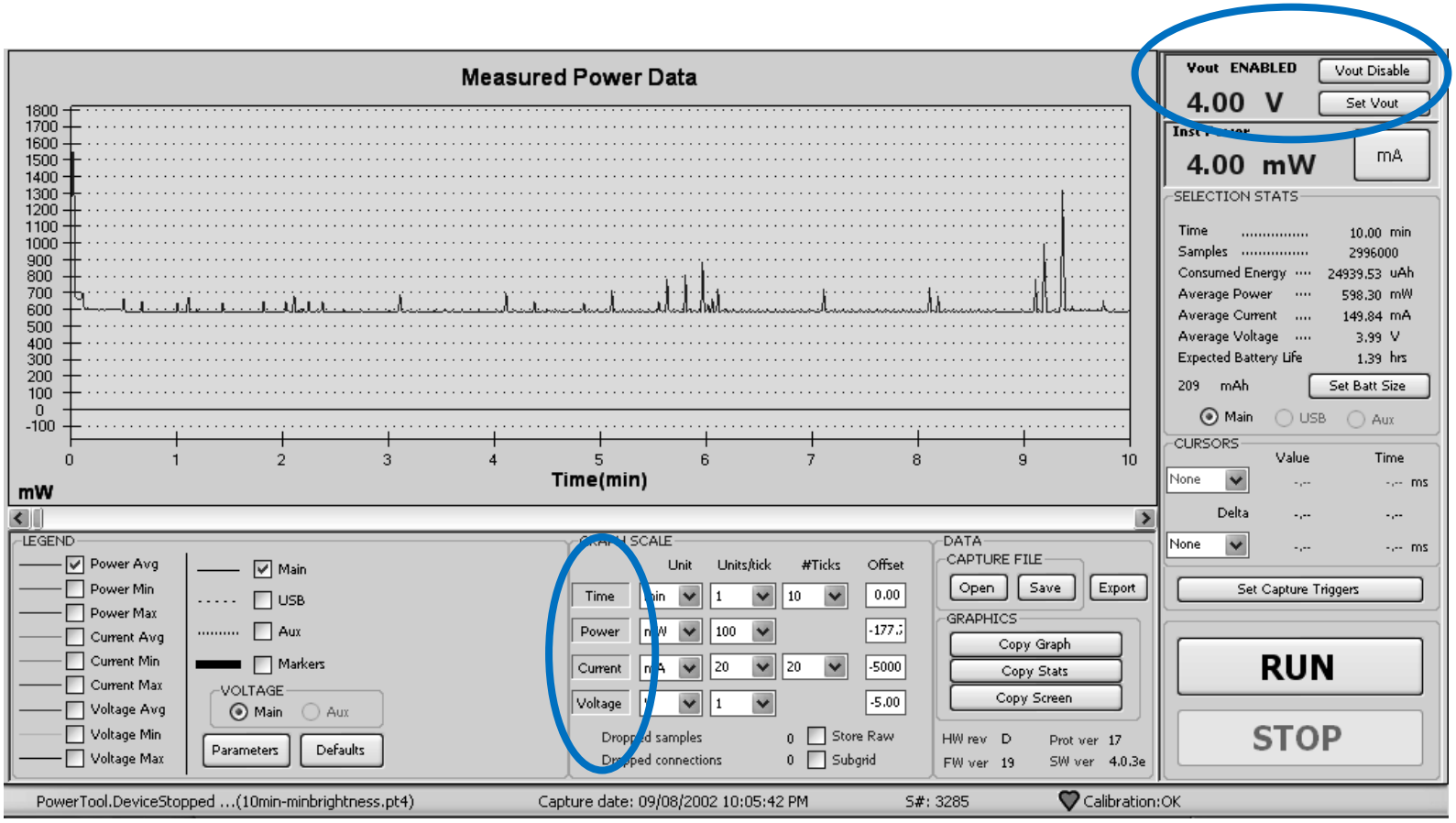


Example Setup: Fake Battery

Fake Battery

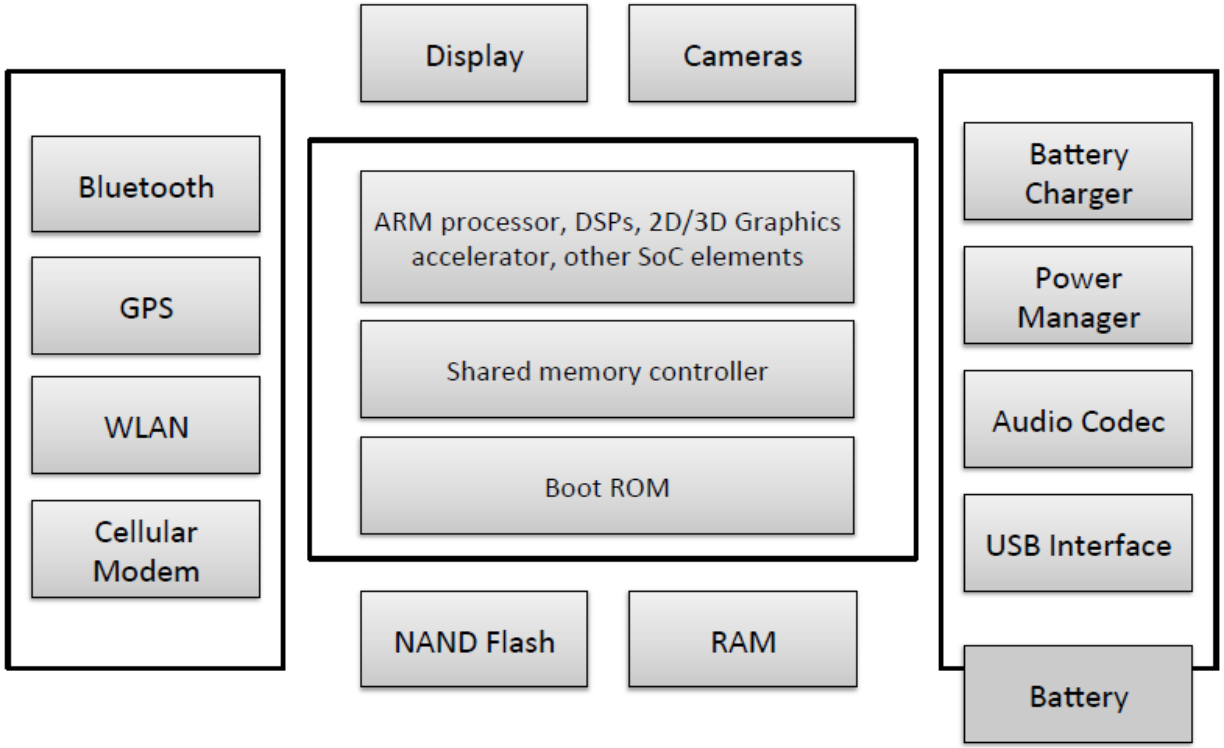


Example Setup: Logging Software



For more details, please attend the tutorial on 15.4.2014 and read the instructions given by course assistant.

Can I measure the power consumption of each hardware component?



Component-level Power Measurement

- **Requires information about power distribution network at the circuit level**

- **Only a few off-the-shelf devices can be measured on component-level**

  e.g. Openmoko Neo Freerunner

  It has a debug port with complete access to low-level hardware.

Hardware-based Power Measurement

Strengths:

- **High sampling frequency**
- **Does not cause energy overhead**

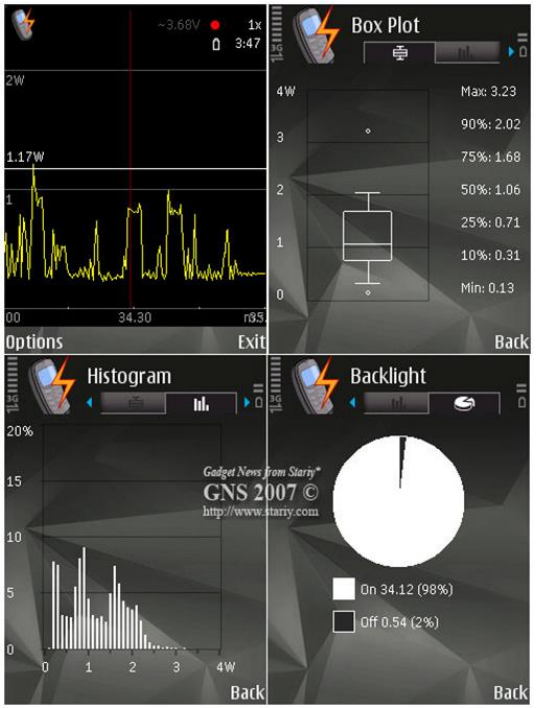
Weakness:

- **Not feasible for power measurement in mobility scenarios**
- **Require special hardware**

Software-based Power Measurement

- **Nokia Energy Profiler (for Symbian)**

- **Trepn Profiler for Android devices featuring Qualcomm Snapdragon processors**



Software-based Power Measurement

- **Smart battery APIs**
  - ✓ *A smart battery is a battery that has special hardware for monitoring its internal state and environment*
  - ✓ *The monitoring hardware usually estimates* ***voltage, current, and temperature of the battery***
  - ✓ *Smartphone OS and its drivers can access these values through a low-power serial bus*

Overview of Smartphone Battery APIs

API	SOC	Health	Battery capacity	Cycle count	Voltage	Current	Temperature
Android	Yes, 1% granularity	Yes (categories)	Not in the API (some devices support / sys/ access)	No	Yes	Not in the API (some devices support / sys/ access)	Yes
iOS	Yes, 5% granularity	No	No	No	No	No	No
Windows Phone	Yes	No	No	No	No	No	No
Blackberry	Yes	Yes (categories)	Yes	Yes	Yes	No	Yes
W3C Battery status API	Yes, 1% granularity	No	No	No	No	No	No

SOC: state of charge which gives the remained battery capacity in percentage.
Cycle count: the number of charge/discharge cycles

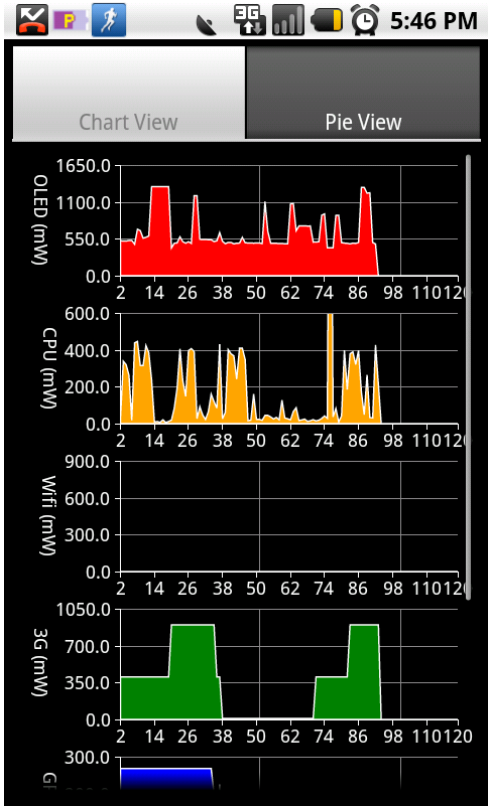
Example Smart Battery Interfaces

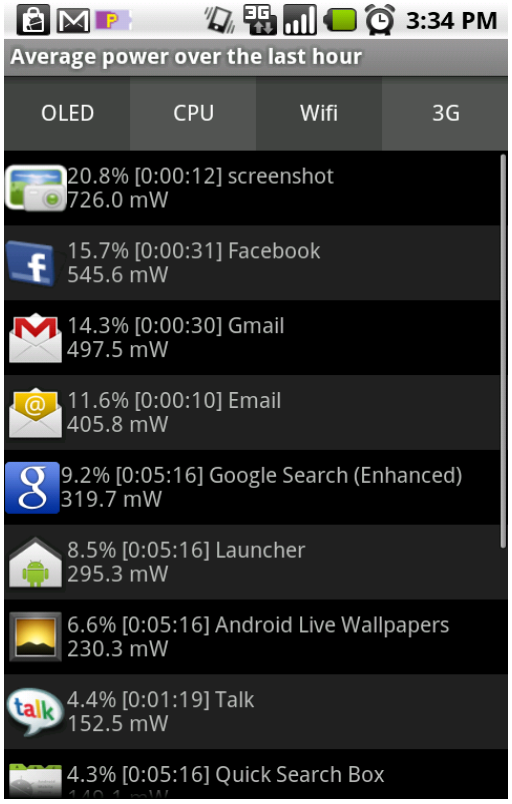
Battery unit	Update rate	Sampling rate	Resolution	Error
Maxim DS2784 (Google Nexus One)	0.28 Hz	18.6 kHz	104 µA	±1%.
Maxim MAX17040 (Samsung Galaxy Nexus)	2 Hz	32 kHz internal clock	Voltage: 1.25mV SOC: 1/256%.	±12.5mV
TI BQ27200 (Nokia N900)	0.39 Hz	100 kHz internal clock	2.7mv	±25 mV, Current gain variability ±0.5%

Limitations of Software-based Power Measurement

- The required information may not be available, namely the current.
- Update rate of the battery status is low
- The readings of the smart battery interface are not accurate

Can Apps like PowerTutor be used for power measurement?





- **Not all energy profiling software can provide ground truth of power consumption**
- **Accuracy of model-based energy profilers like PowerTutor depends on the accuracy of the power models in use**
- **Power models are usually hardware specific, which means the models built for Phone Model A may not be applied to Phone Model B**

Case Study

Case 1: Idle Power

- **How do you define an idle or standby state?**

Wi-Fi scanning	Off
Wi-Fi	1) Off 2) On(no traffic)*
3G/LTE	1) Remove SIM card 2) Idle(no traffic)*
Display	1)Turn off 2)Turn on with a fixed brightness level*
Background Services	Stopped
Sensors(e.g. GPS)	Off
CPU frequency	Fixed (no change in frequency during measurement)

Idle Power of Samsung Nexus S

Samsung Nexus S (Wi-Fi IDLE)

CPU Freq	Display	Power(W)
100MHz	Off	0.213
200MHz	Off	0.435
100MHz	On	0.742
200MHz	On	0.800
400MHz	On	0.890

In a study of Wi-Fi transmission cost, we notice
-- when the display is off, the CPU freq increases from 100MHz to 200MHz whenever the data sending rate increases from 256KBps to 512KBps.
-- due to CPU partial wakelock, the data rate cannot go over 512KBps if the display is off.

Case 2: watch YouTube video online

How would you analzye the power consumption of a YouTube client? Assume that the client is open source and you can use either Wi-Fi, 3G or LTE network. You can use the physical power meter in our lab for power measurement.

Group Discussion(4 persons per group, 20min)

Guideline for Group Discussion

1) Overview of the selected application(e.g. functionality, requirement for network connectivity, access to local sensors)
2) Design criteria and description of test cases (e.g. what kind of power consumption behavior do you want to study through these test cases? Are your test cases sufficient?)
3) Measurement metrics you choose(e.g. Power(W), Energy(J), unit cost, energy utility)
4) Experiment setup (e.g. how do you measure power consumption? How do you set up network connection? How do you monitor network traffic?)
5) Experiment results (you can use figures and tables to present your results)
6) Discussion(e.g. findings from your study, lessons you learn)

Case 2: watch YouTube video online

- **Step 1**
  - ✓ What happen after a video request is sent from the phone?
  - ✓ How is video delivered from YouTube server to the phone?
  - ✓ When can playback start?

Case 2: watch YouTube video online

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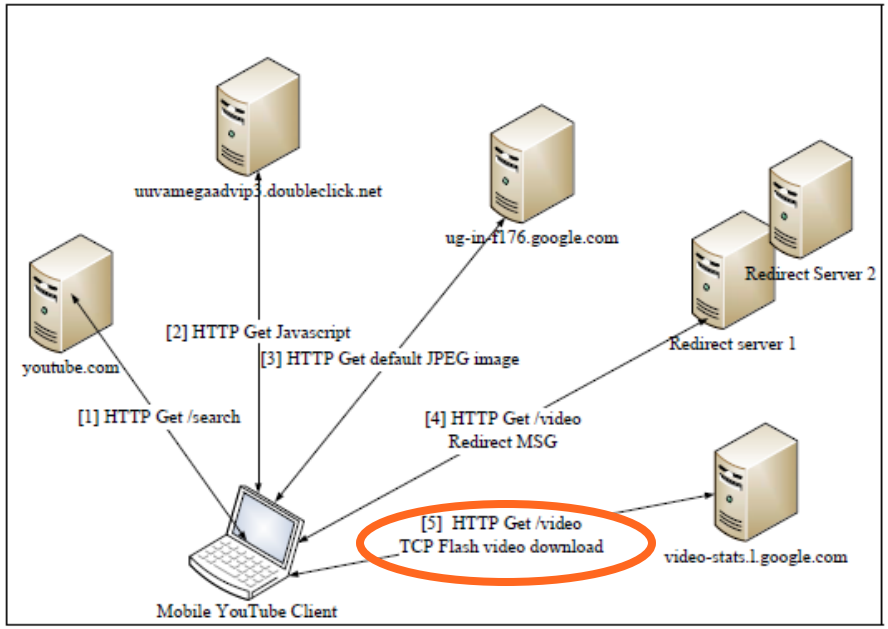


Case 2: watch YouTube video online

- **Step 1**
  - ✓ How is video delivered from YouTube server to the phone?
  - ✓ When can playback start?

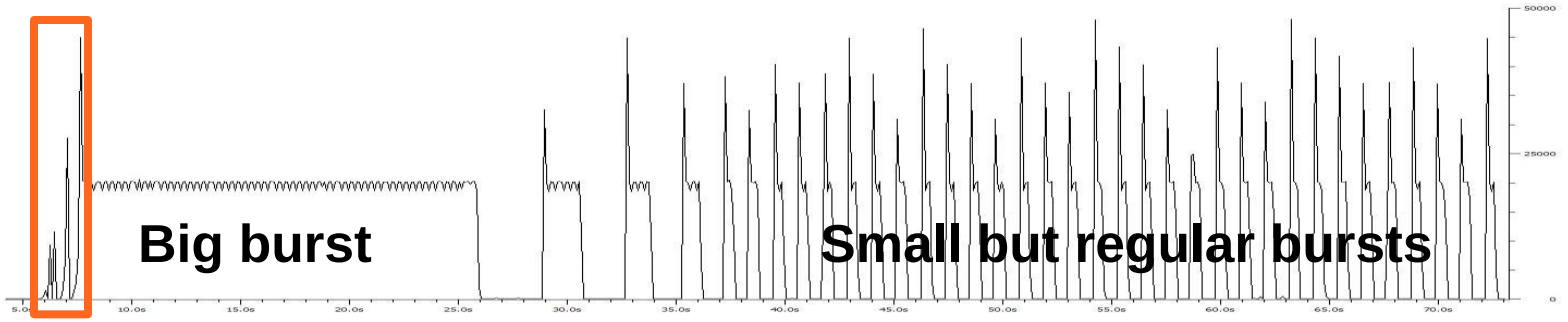


Figure: I/O graph of YouTube traffic (Byte/tick)

Case 2: watch YouTube video online

- **Online YouTube viewing includes 3 stages: download only, download+playback, playback only**

- **Step 2: design test cases**
  - ✓ How much energy is consumed by video download? How much is cost by video playback?
  - ✓ Is it more energy-efficient to use WiFi than 3G?

Example Test Cases

Test Case	Network	Storage
Online view via WCDMA	3G	Cache
Online view via 802.11g	Wi-Fi	Cache
Download-and-play via WCDMA	3G	Phone memory
Download-and-play via 802.11g	Wi-Fi	Phone memory
Playback from phone memory	Disabled	Phone memory
Playback from flash drive	Disabled	Flash drive
Replay	Disabled	Cache

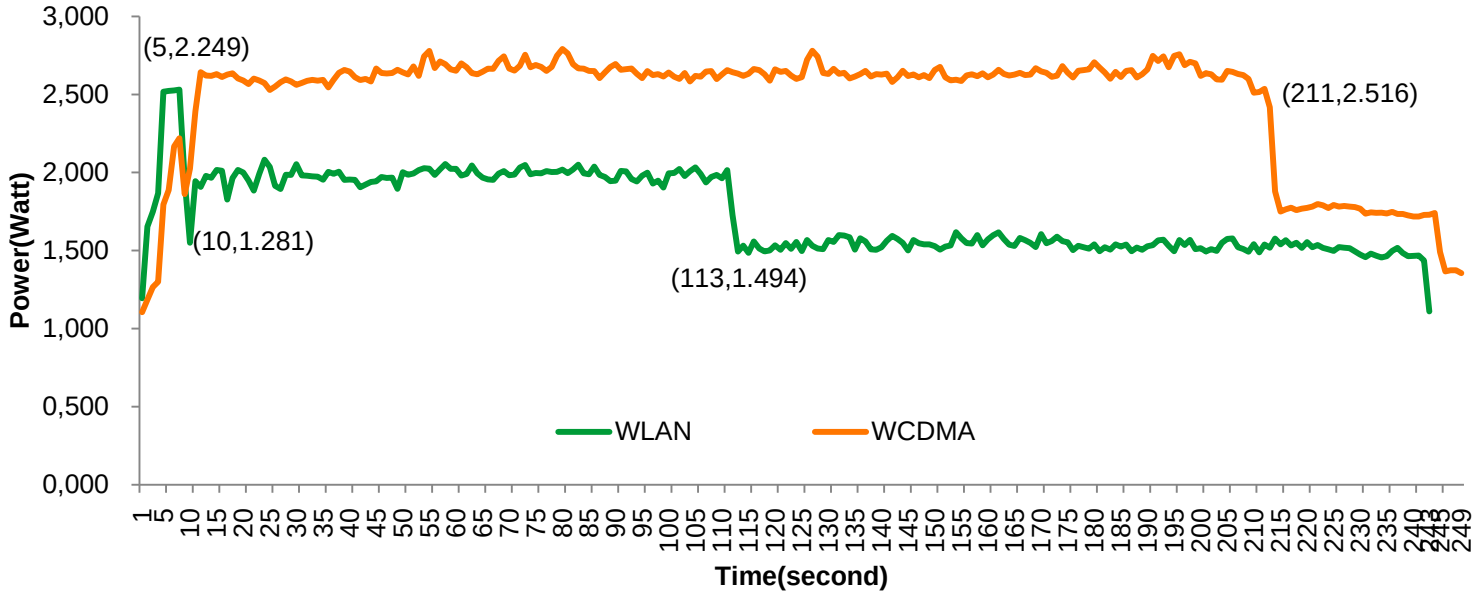
Case 2: watch YouTube video online

- **Step 3: Metrics**
  - ✓ Energy cost (J)
  - ✓ Average Power(W) during each stage
  - ✓ Duration(s)

- **Step 4: Experiment Setup**
  - ✓ Network connectivity
  - ✓ Software-based power measurement
  - ✓ Settings of Wi-Fi AP
  - ✓ Logging of software operations
  - ✓ Monitoring of network signal strength

Case 2: watch YouTube video online

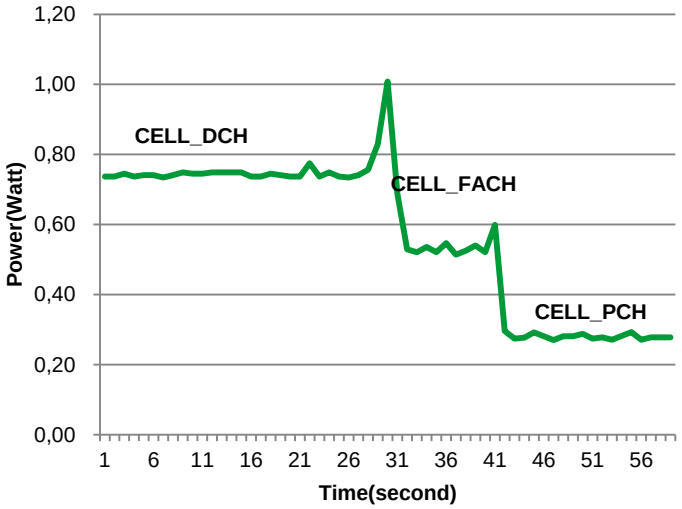
- **Step 5: Results**



Results of Test Case 1&2 show that it is more energy-efficient to use WiFi than 3G

Case 2: watch YouTube video online

- **Step 6: Discussions**
- ✓ **3G Tail Energy**



If you would like to learn more about this case, please refer to

Yu Xiao; Kalyanaraman, R.S.; Yla-Jaaski, A., "Energy Consumption of Mobile YouTube: Quantitative Measurement and Analysis," *NGMAST '08.* pp.61,69, 16-19 Sept. 2008

Case 2: watch YouTube video online

- ✓ geographic and temporal variation

Table 1: Performance and power consumption of watching a YouTube video through WLAN.

	AP1	AP2
No. of users	1	multiple
SNR	63	41
Download duration(s)	147	172
Power consumption of video downloading+playback (mW)	1487	1563
Power consumption of playback alone (mW)	1265	1277

- ✓ Video codec/encoding rate/resolution ~ playback cost
- ✓ Location of the YouTube server ~ download cost

Basics of Power Modelling

What is a power model?

It is a mathematical model that describes the relationship between power consumption and …

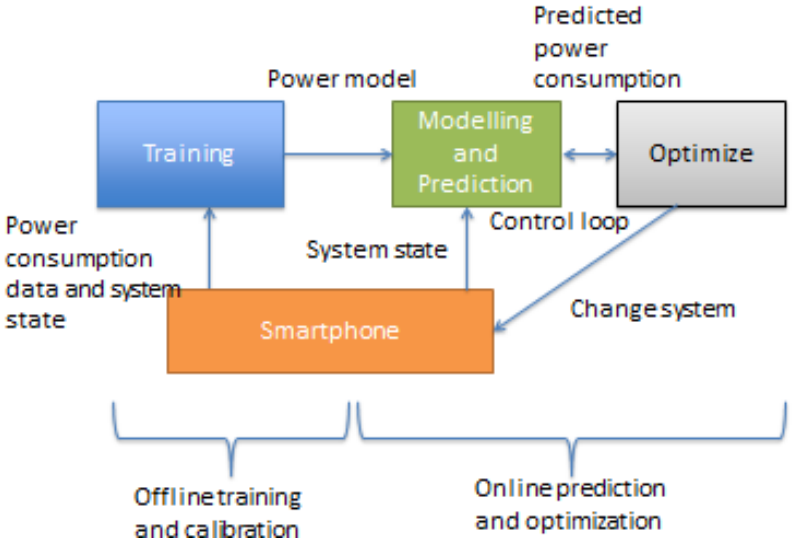
Examples:

- Processor power ~ instruction (V.Tiwari et al.)
- Processor power ~ Hardware performance counters(HPC) (K.Singh et al., B.C.Lee et al. , C. Isci et al., B. Goel et al., D.Brooks et al.)
- Wireless transmission cost ~ network throughput (Y.Xiao et al.)
- …

A power model can be built for a whole device, a certain hardware component, or a software component.

Why do we need power models?

- **Power models can be used for estimating power consumption**
- **Power models quantify the impact of different influcing factors. They can provide hints on how to reduce energy consumption.**



Example Energy Model

An energy model can be formulated as follows for a component based system:

$$y(t) = f(x_1(t), x_2(t), \dots, x_n(t)),$$

where *y(t)* represents the energy draw in the time interval *t*, and the functions $x_1(t), x_2(t), \dots, x_n(t)$ represent the component level behaviors.

The function *f* can be linear or non-linear.

The overall energy drain for a given time period can be obtained by integrating *y(t)* over the period.

Example Energy Model: Nokia N810

C_0: CPU_CYCLES

C_1:DCACHE_WB

C_2: TLB_MISS

$$Power(W) = 0.7655 + 0.2474 \times g_0(x_0) + 0.0815 \times g_1(x_1) + 0.0606 \times g_2(x_2) + 0.0011 \times g_{17}(x_{17}) + 0.0015 \times g_{18}(x_{18}) + 0.3822 \times g_{19}(x_{19}) + 0.125 \times g_{20}(x_{20}).$$

$$g_0(x_0) = \frac{x_0 - 1316.84}{1349.423}, x_0 = \frac{c_0}{d},$$

$$g_1(x_1) = \frac{x_1 - 0.000901}{0.00045}, x_1 = \frac{c_1}{c_0},$$

$$g_2(x_2) = \frac{x_2 - 0.000513}{0.000365}, x_2 = \frac{c_2}{c_0},$$

$$g_{17}(x_{17}) = x_{17}, x_{17} : download \quad data \quad rate(KB/s),$$

$$g_{18}(x_{18}) = x_{18}, x_{18} : upload \quad data \quad rate(KB/s),$$

$$g_{19}(x_{19}) = x_{19}, x_{19} : CAM \quad switch,$$

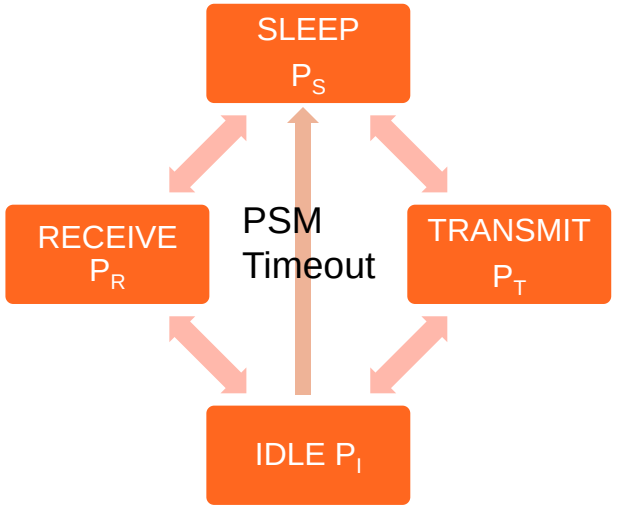
$$g_{20}(x_{20}) = x_{20}, x_{20} : brightness \quad level.$$

How to build a power model?

- **Deterministic power modelling**
  - ✓ map software operations to hardware activities based on expert knowledge and to estimate the power consumed by the hardware components involved based on their activities

For example, power consumption behavior of a Wi-Fi interface can be described with a power state machine.

The Power(W) in each state is measured and used for calculating the variable coefficient.



How to build a power model?

- **Statistical power modelling**

✓ Finding out the relationship between power consumption and the model variables based on statistical models like linear regression.

✓ The variables of statistical power models can be application-specific parameters, hardware performance metrics, and other variables that are related to power consumption.

$$\begin{aligned} Power(W) = {} & 0.7655 + 0.2474 \times g_0(x_0) + 0.0815 \times g_1(x_1) \\ & + 0.0606 \times g_2(x_2) + 0.0011 \times g_{17}(x_{17}) \\ & + 0.0015 \times g_{18}(x_{18}) + 0.3822 \times g_{19}(x_{19}) \\ & + 0.125 \times g_{20}(x_{20}). \end{aligned}$$

Summary

- **Battery Life**
- **Hardware-based vs. Software-based Power Measurement**
- **Case Study: How to analyze power consumption of YouTube**
- **Basics of Power Modelling**