An Analysis of Power Consumption in a Smartphone

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Introduction

- Mobile devices derive the energy required to operate from batteries that are limited by the size of the device.
- The ability to manage energy usage requires a good understanding of where and how the energy is being used.
- The advancing functionality of modern smartphones is increasing the pressure on battery lifetime, and increases the need for effective energy management.
- Goal is to break down a modern smartphone and measure the power consumption of the devices major subsystems, under a range of usage scenarios.
- Results from the breakdown of energy consumption will be validated against two additional mobile devices.
- Finally, an analysis of the energy consumption will be performed, and an energy model will be created to allow us to model usage patterns.

Methodology / Device Under Test

- The approach is to take physical power measurements at the component level on a piece of real hardware.
- Three elements to the experimental setup, the device under test, a hardware data acquisition (DAQ) system, and a host computer.
- Device under test is the Openmoko Neo Freerunner 2.5G smartphone.

Component	Specification
SoC	Samsung S3C2442
CPU	ARM 920T @ 400 MHz
RAM	128 MiB SDRAM
Flash	256 MiB NAND
Cellular radio	TI Calypso GSM+GPRS
GPS	u-blox ANTARIS 4
Graphics	Smedia Glamo 3362
LCD	Topploy 480 × 640
SD Card	SanDisk 2 GB
Bluetooth	Delta DFBM-CS320
WiFi	Accton 3236AQ
Audio codec	Wolfson WM8753
Audio amplifier	National Semiconductor LM4853
Power controller	NXP PCF50633
Battery	1200 mAh, 3.7 V Li-Ion

Table 1: Freerunner hardware specifications.

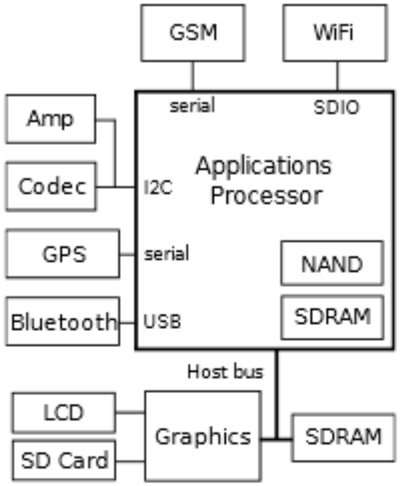


Figure 1: Architecture of the Freerunner device, showing the important components and their interconnects.

Experimental Setup

- To measure power to each component, supply voltage and current must be measured.
- Current is measured by placing sense resistors on the power supply rails of each component. Resistors were selected such that the voltage drop did not exceed 10mV, less than 1% of the supply voltage.
- Voltages were measured using a National Instruments PCI-6229 DAQ.

Characteristic	Value
Max. sample rate	250 kS/s
Input ranges	$\pm$0.2 V, $\pm$1 V, $\pm$5 V and $\pm$10 V
Resolution	16 b
Accuracy	112 μV @ $\pm$0.2 V range
	1.62 mV @ $\pm$5 V range
Sensitivity	5.2 μV @ $\pm$0.2 V range
	48.8 μV @ $\pm$5 V range
Input impedance	10 GΩ

Table 2: National Instruments PCI-6229 DAQ specifications [6].

Software

- The device was running the Freerunner port of Android 1.5, using the Linux v2.6.29 kernel.
- Kernel was configured to run at 100 MHz and 400MHz, the only frequencies supported by both the OS and the hardware.
- The host computer ran the power-data collection software which interfaced with the DAQmxBase 3.3 library to collect raw data, aggregate it, and then write the results to a file for post-processing.
- Each data point was an average of 2000 consecutive voltage samples.
- A complete snapshot of the system was generated approximately every 400ms.

Benchmarks

- Two types of benchmarks, micro-benchmarks, which independently measured different components, and macro-benchmarks, which measured total system power during usage scenarios.
- Low interactivity scenarios were launched from the command line.
- Interactive scenarios were simulated using a trace of input events. This does bypass the power consumed by the hardware and interrupt paths, however this additional power is negligible.
- Majority of energy in handling a touchscreen event is consumed in delivering it from the kernel to the software.

Baseline Cases / Suspended Device

- Need to establish the baseline power of the device, when no applications are running.
- Phones spend the majority of their time in the suspended state.
- Application processor is idle, communications processor performs low levels of activity.
- Results are shown as an average of 10 separate 120 second intervals.
- Standard deviation was 8.2%.
- Deviations were mainly from GSM and graphics.

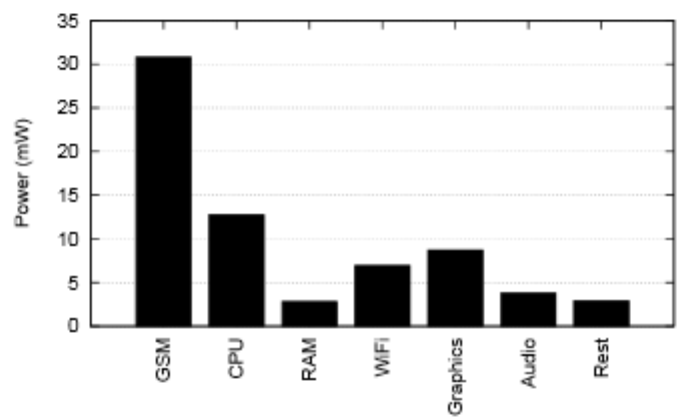


Figure 2: Power breakdown in the suspended state. The aggregate power consumed is 68.6 mW.

Idle Device

- Phone is fully awake, but no applications are active.
- The backlight is turned off for these measurements, but the rest of the display subsystem is enabled.
- Standard deviation of 2.6%.
- Display related subsystems consuming around 50% from graphics and LCD alone.
- Backlight would increase this to around 80%.

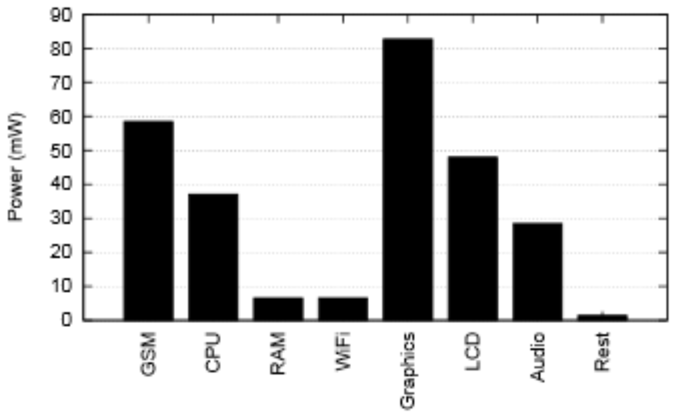


Figure 3: Average power consumption while in the idle state with backlight off. Aggregate power is 268.8 mW.

Display

- Display brightness is controlled through a linear integer between 30 and 255.
- The minimum power is approximately 7.8 mW, the maximum 414 mW.
- Content displayed on the LCD affects the LCD's power consumption, 33.1 mW for a white screen, and 74.2 mW for a black screen.

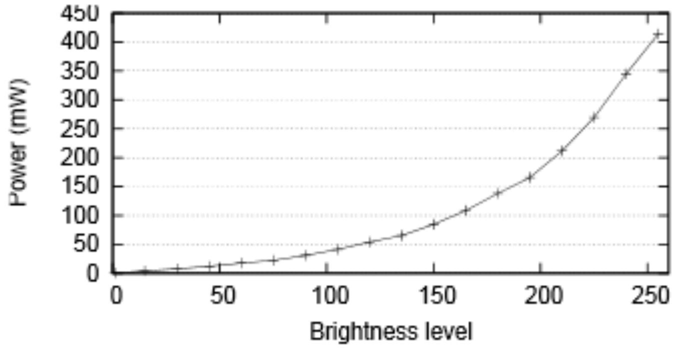


Figure 4: Display backlight power for varying brightness levels.

Micro-benchmarks / CPU and RAM

- A subset of the SPEC CPU2000 suite was ran to measure CPU and RAM power.
- Benchmarks selected were equake, vpr, crafty, and mcf.
- Benchmarks needed to run on Android OS, fit the phones memory, and have a reasonable turn around.

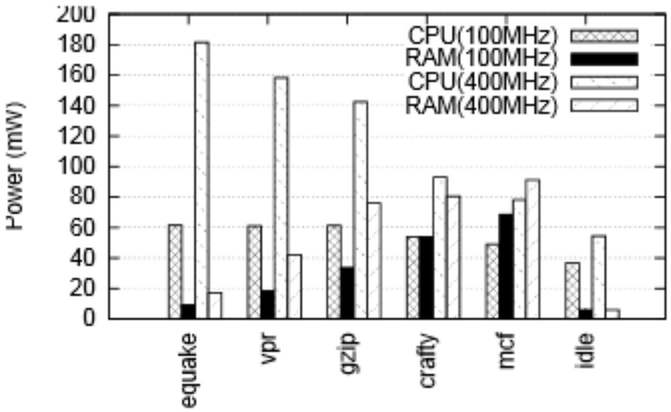


Figure 5: CPU and RAM power when running SPEC CPU2000 micro-benchmarks, sorted by CPU power.

Benchmark	Performance	Power	Energy
equake	26 %	36 %	135 %
vpr	31 %	40 %	125 %
gzip	38 %	43 %	112 %
crafty	63 %	62 %	100 %
mcf	74 %	69 %	93 %
idle	-	71 %	-

Table 3: SPEC CPU2000 performance, power and energy of 100 MHz relative to 400 MHz. Both CPU and RAM power/energy are included.

Flash Storage

- Storage provided by 256 MB of internal NAND flash, and an external SD card slot.
- Linux 'dd' program was used to perform streaming reads and writes.
- Reads copied a 64 MB file, writes wrote an 8 MB file of random data.

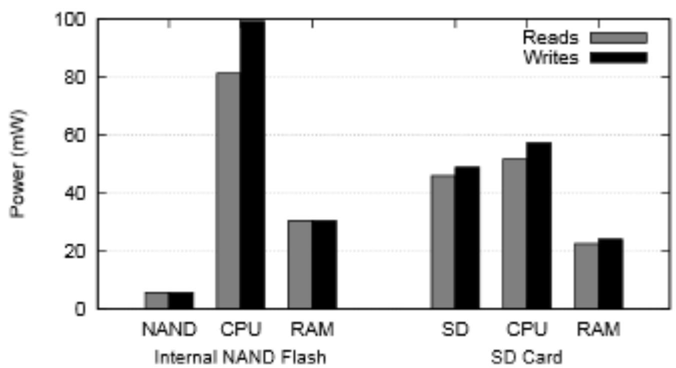


Figure 6: SD, NAND, CPU and RAM power for flash storage read and write benchmarks.

Metric	NAND	SD
Idle (mW)	0.4	1.4
Read		
throughput (MiB/s)	4.85	2.36
efficiency (MiB/J)	65.0	31.0
Write		
throughput (KiB/s)	927.1	298.1
efficiency (MiB/J)	10.0	5.2

Table 4: Flash storage power and performance.

Network

- In this test, the two main networking components: WiFi and GPRS (provided by the GSM subsystem) are benchmarked.
- Files were downloaded via HTTP using 'wget'.
- Files contained random data, and were 15 MB for WiFi, and 50 KB for GPRS.
- Increased CPU / RAM power consumption for WiFi reflects the higher throughput.
- To test the effect of signal strength on power, the phone was placed in a 2mm thick metal box. GSM power increased by 30%.

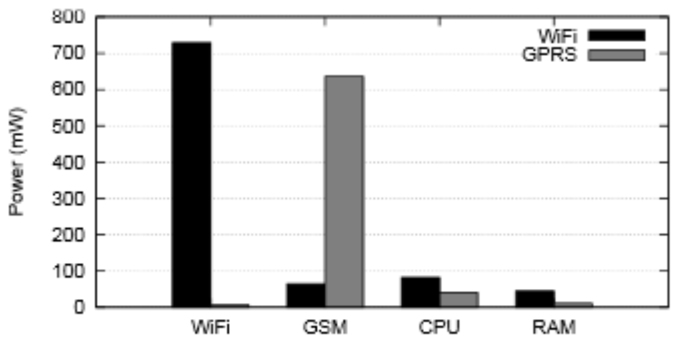


Figure 7: Power consumption of WiFi and GSM modems, CPU, and RAM for the network micro-benchmark.

GPS

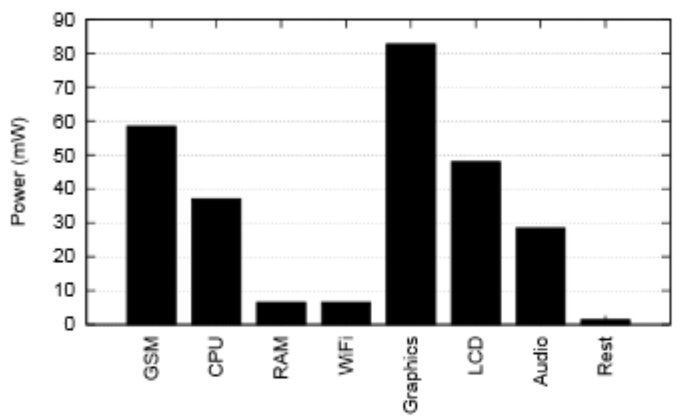
- The 'GPSStatus2' Android application was run to measure the power consumption of the GPS subsystem.
- The energy consumption is largely independent of the received signal, neither number of satellites nor signal strength had much effect.
- This is contrary to the parts data sheet, which specifies that power consumption should drop by around 30% after satellites are acquired.

State	Power (mW)
Enabled (internal antenna)	$143.1 \pm 0.05\,\%$
Enabled (external antenna)	$166.1 \pm 0.04\,\%$
Disabled	0.0

Table 5: GPS energy consumption.

Usage Scenarios / Audio Playback

- Sample music is a 12.3 MB, 537 second stereo 44.1 kHz MP3, outputting to a pair of stereo headphones.
- Backlight is off, simulating the typical case of someone listening to music while carrying the phone in their pocket.
- Idle case was 268.8 mW, this shows an increase of 51.2 mW.
- Volume will change the audio subsystem power by about 14%.



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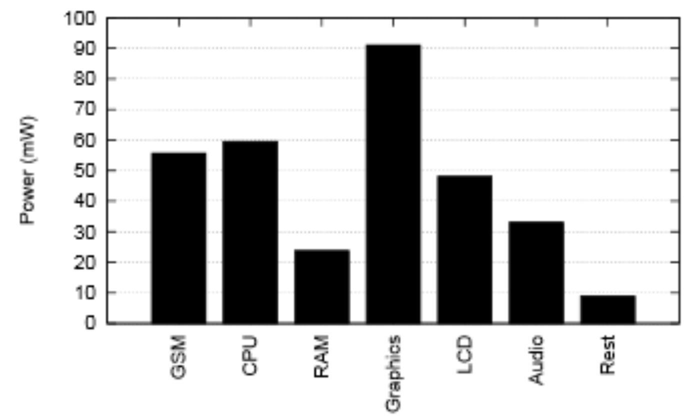


Figure 8: Audio playback power breakdown. Aggregate power consumed is 320.0 mW.

Video Playback

- A 5 minute, 12.3 MB H.263 – encoded video clip with no sound was played to test power consumption.
- Backlight power has been included in these results at 0%, 33%, 66% and 100%.

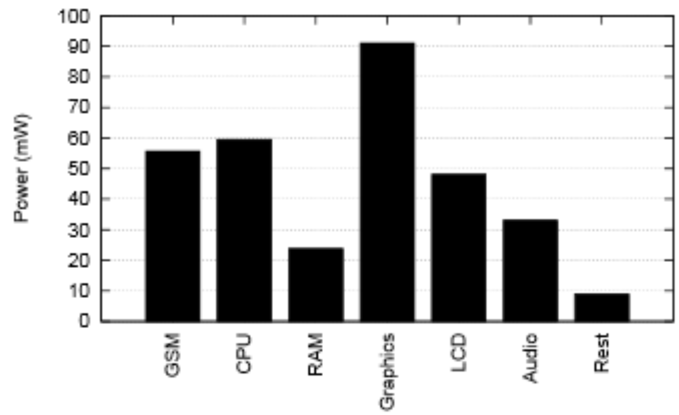


Figure 8: Audio playback power breakdown. Aggregate power consumed is 320.0 mW.

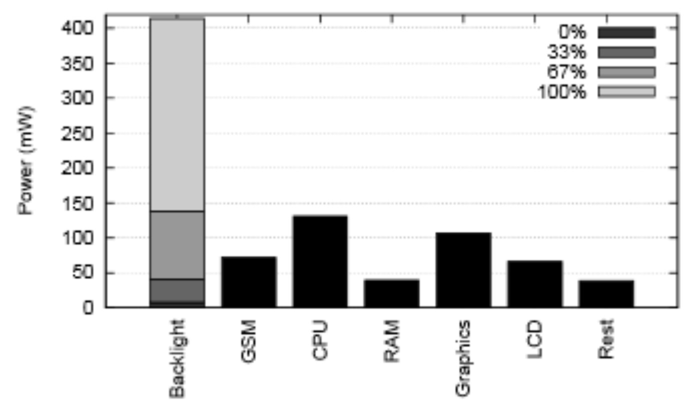
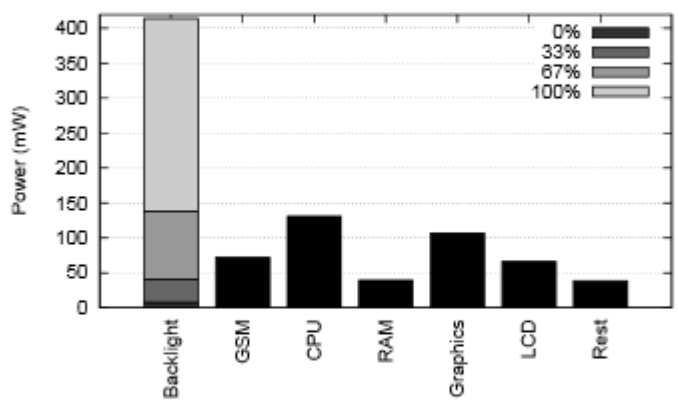


Figure 9: Video playback power breakdown. Aggregate power excluding backlight is 453.5 mW.

Text Messaging

- A trace of real phone usage was used to simulate a 55 character message being typed over 62 seconds. GSM was monitored for an additional 20 seconds.
- GSM only 7.9 mW greater than idle over the full duration of the benchmark.



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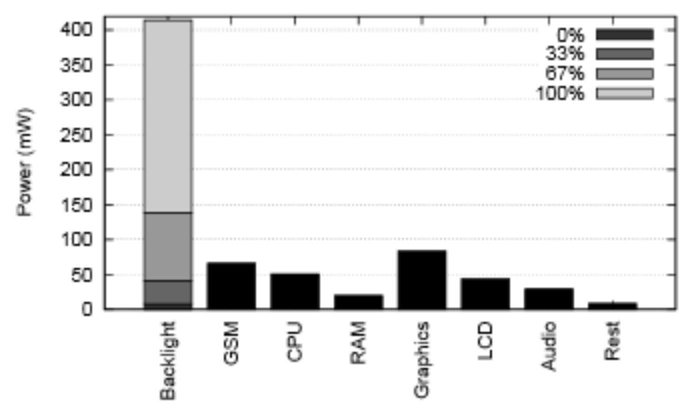
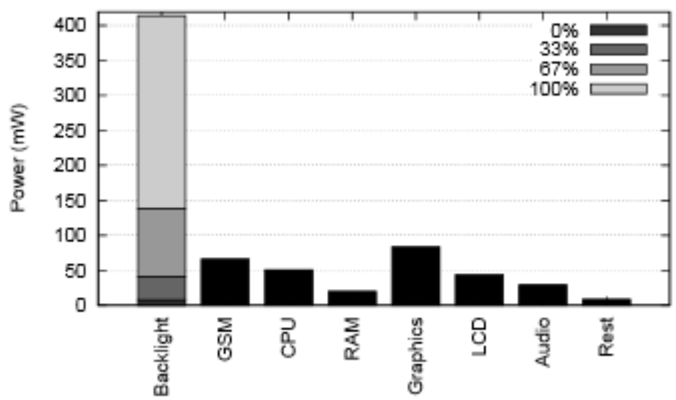


Figure 10: Power breakdown for sending an SMS. Aggregate power consumed is 302.2 mW, excluding backlight.

Phone Call

- A trace was used to simulate loading the dialer application, dialing a number, and making a 57 second call. The total benchmark was 77 seconds.
- The receiving phone was configured to automatically accept the call after 10 seconds.
- Backlight only active for around 45% of the benchmark, due to Android automatically disabling it during a call.



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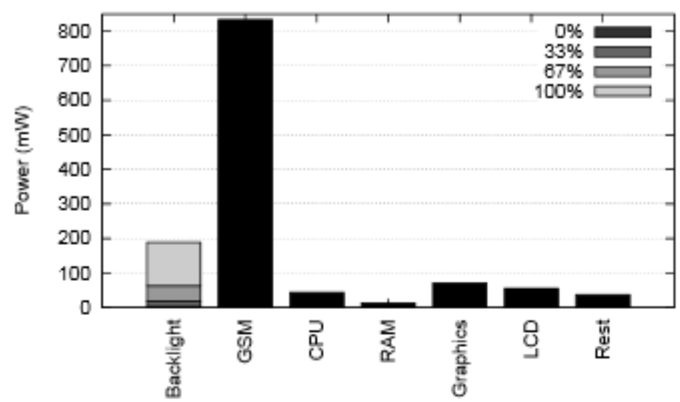
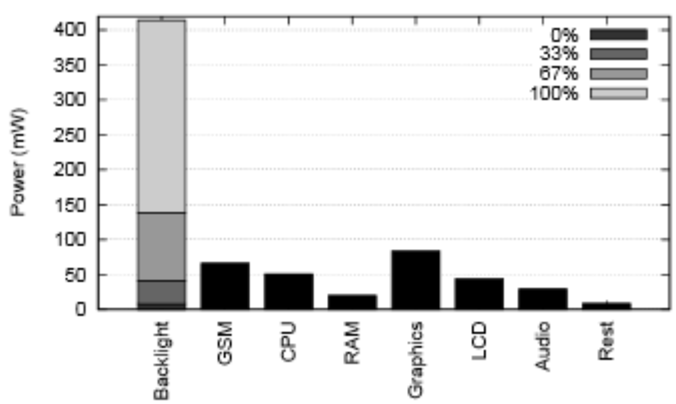


Figure 11: GSM phone call average power. Excluding backlight, the aggregate power is 1054.3 mW.

Emailing

- Workload consisted of downloading and reading 5 emails and responding to 2 of them.



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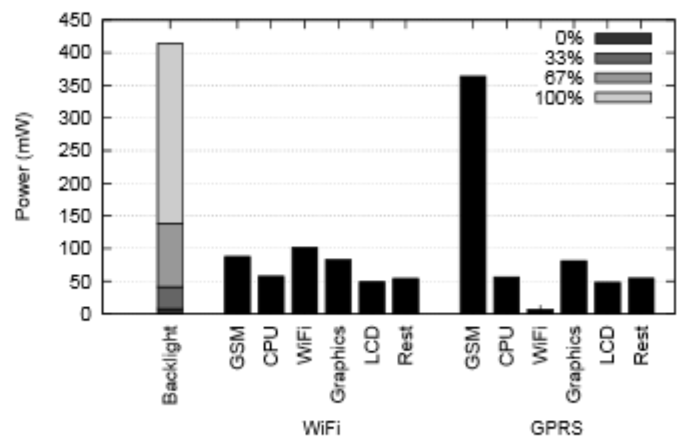

Figure 12: Power consumption for the email macro-benchmark. Aggregate power consumption (excluding backlight) is 610.0 mW over GPRS, and 432.4 mW for WiFi.

Web Browsing

- A web browsing workload using both GPRS and WiFi connections was used.
- Benchmark was trace based, lasted 490 seconds, and consisted of opening the browser application, selecting a bookmarked website, and browsing several pages.
- More modern phones can be expected to show different results. The higher bandwidth of 3G / 4G is likely to result in them being more power hungry.

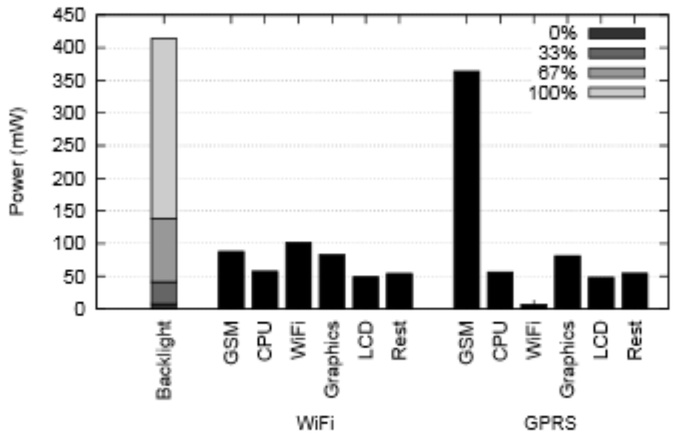

Figure 12: Power consumption for the email macro-benchmark. Aggregate power consumption (excluding backlight) is 610.0 mW over GPRS, and 432.4 mW for WiFi.

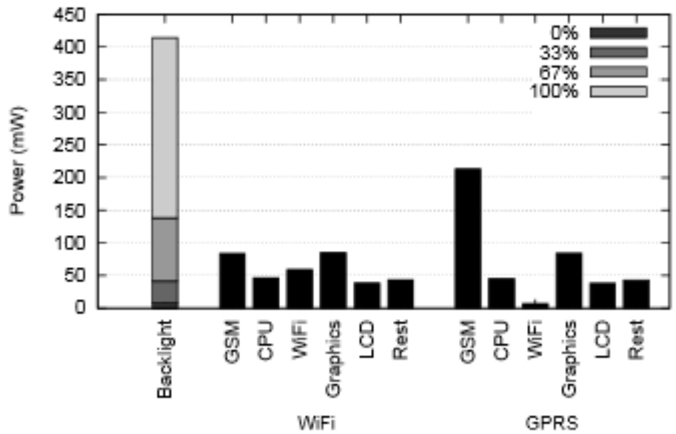

Figure 13: Web browsing average power over WiFi and GPRS. Aggregate power consumption is 352.8 mW for WiFi, and 429.0 mW for GPRS, excluding backlight.

Validation

- The power consumption of two additional phones will be measured; the HTC Dream (G1), and the Google Nexus One (N1).
- Full system power is measured at the battery, the necessary documentation for per-component measurements is not available.

Component	Specification
SoC	Samsung S3C2442
CPU	ARM 920T @ 400 MHz
RAM	128 MiB SDRAM
Flash	256 MiB NAND
Cellular radio	TI Calypso GSM+GPRS
GPS	u-blox ANTARIS 4
Graphics	Smedia Glamo 3362
LCD	Topploy 480 × 640
SD Card	SanDisk 2 GB
Bluetooth	Delta DFBM-CS320
WiFi	Accton 3236AQ
Audio codec	Wolfson WM8753
Audio amplifier	National Semiconductor LM4853
Power controller	NXP PCF50633
Battery	1200 mAh, 3.7 V Li-Ion

Table 1: Freerunner hardware specifications.

	G1	N1
SoC	Qualcomm MSM7201	Qualcomm QSD 8250
CPU	ARM 11 @ 528 MHz	ARMv7 @ 1 GHz
RAM	192 MiB	512 MiB
Display	3.2" TFT, 320x480	3.7" OLED, 480x800
Radio	UMTS+HSPA	UMTS+HSPA
OS	Android 1.6	Android 2.1
Kernel	Linux 2.6.29	Linux 2.6.29

Table 6: G1 and Nexus One specifications.

Display and Backlight

- The HTC phone also features a backlight for the keyboard and buttons. These are plotted along with the display brightness at different settings.
- The Google Nexus features an OLED display, and does not require a separate backlight, however the power consumption is tightly coupled to what is displayed on the screen.
- For a white screen at minimum brightness 194 mW is consumed, and at maximum brightness, 1313 mW.

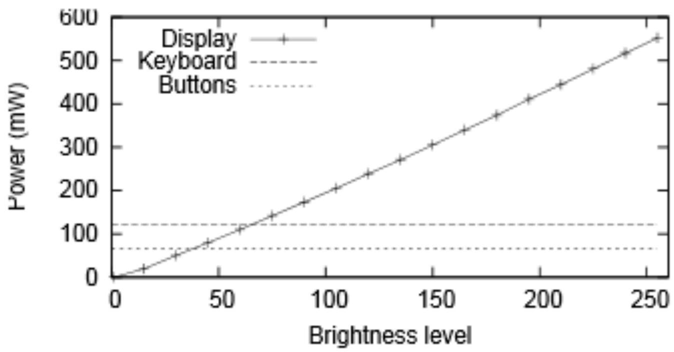

Figure 14: Display, button and keyboard backlight power on the G1.

CPU

- The SPEC CPU2000 benchmarks were once again used.
- HTC frequency was from 246 to 384 MHz.
- Google Nexus frequency was from 245 to 998 MHz.

	Performance (%)		Power (%)	
Benchmark	G1	N1	G1	N1
equake	67	25	87	26
vpr	68	25	87	26
gzip	71	25	86	27
crafty	76	25	89	28
mcf	84	54	91	41

Table 7: SPEC CPU2000 performance and average system power of 246 MHz relative to 384 MHz on the G1, and 245 MHz relative to 998 MHz on the N1.

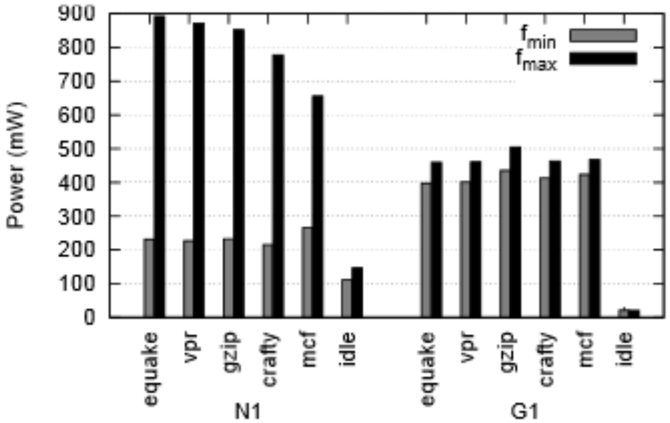

Figure 15: N1 and G1 system power for SPEC CPU2000 benchmarks.

Bluetooth

- A baseline audio benchmark was ran, and then another audio test was ran using a bluetooth headset at different ranges.
- In the near benchmark, the headset was 30 cm from the phone, and in the far benchmark it was about 10 m from the phone.

Benchmark	Power (mW)	
	Total	Bluetooth
Audio baseline	459.7	-
Bluetooth (near)	495.7	36.0
Bluetooth (far)	504.7	44.9

Table 8: G1 Bluetooth power under the audio benchmark.

Benchmarks

- Power consumption shown from a variety of earlier benchmarks. Power consumed from the backlight has been subtracted out.
- The additional power from the Google Nexus OLED screen is shown.
- Low power consumption of the HTC in idle, web, and email attributed to excellent low power state of the SoC.
- The Google and HTC phones enter a suspended state during a phone call, reducing their power consumption.

	OLED Power (mW)	
Benchmark	Min.	Max.
Idle	38.0	257.3
Phone call	16.7	112.9
Web	164.2	1111.7
Video	15.1	102.0

Table 10: Additional power consumed by the N1 OLED display at maximum and minimum brightness.

	Average System Power (mW)		
Benchmark	Freerunner	G1	N1
Suspend	103.2	26.6	24.9
Idle	333.7	161.2	333.9
Phone call	1135.4	822.4	746.8
Email (cell)	690.7	599.4	-
Email (WiFi)	505.6	349.2	-
Web (cell)	500.0	430.4	538.0
Web (WiFi)	430.4	270.6	412.2
Network (cell)	929.7	1016.4	825.9
Network (WiFi)	1053.7	1355.8	884.1
Video	558.8	568.3	526.3
Audio	419.0	459.7	322.4

Table 9: Freerunner, G1 and N1 system power (excluding backlight) for a number of micro- and macro-benchmarks.

Analysis / Where does the Energy Go?

- The majority of power consumption attributed to the GSM module, the display, the graphics accelerator / driver, and the backlight.
- In all tests except the GSM intensive ones, the brightness of the backlight is the most critical factor.
- Selecting a light-on-dark color scheme and dimming the backlight can significantly improve battery life.
- The GSM module constantly requires power to maintain connection with the network, and can spike in excess of 800 mW during a phone call. Unfortunately, a phone-call heavy workload is difficult for software-level power management.
- RAM, audio, and flash subsystems consistently showed the lowest power consumption and offer little potential for energy optimization
- Video playback showed SD card power consumption of <1% of total power.

Dynamic Voltage and Frequency Scaling

- CPU benchmarks have shown that dynamically scaling the frequency scaling can significantly reduce power consumption, however this also causes a longer run-time.
- Results show that only highly memory-based work exhibit a net reduction in energy.
- After completing the test, the device still consumes power, to correct for this the measurements are padded with idle power to equalize the run times.
- DVFS is very effective on the Google Nexus due to its high efficiency at low frequencies.

$$E = Pt + P_{\text{idle}}(t_{\max} - t)$$

Benchmark	% Energy		
	Freerunner	G1	N1
equake	95.5	126.0	75.6
vpr	95.8	124.5	75.9
gzip	95.8	120.1	77.7
crafty	95.5	115.6	77.3
mcf	94.9	105.3	65.9

Table 11: SPEC CPU2000 percentage total system energy consumption of the minimum frequency compared with the maximum frequency, padded with idle power.

Energy Model

- The results from the Freerunner device can be used to create an energy model showing energy for each usage scenario as a function of time.
- The equations give the energy consumed in Joules when the time is entered in seconds.
- P_{BL} is the backlight power in watts.
- Equations without a P_{BL} are assumed to be run with the backlight off.

$$
\begin{aligned}
E_{\text{audio}}(t) &= 0.32W \times t \\
E_{\text{video}}(t) &= (0.45W + P_{\text{BL}}) \times t \\
E_{\text{sms}}(t) &= (0.3W + P_{\text{BL}}) \times t \\
E_{\text{call}}(t) &= 1.05W \times t \\
E_{\text{web}}(t) &= (0.43W + P_{\text{BL}}) \times t \\
E_{\text{email}}(t) &= (0.61W + P_{\text{BL}}) \times t
\end{aligned}
$$

Modeling Usage Patterns

- A number of usage patterns are defined to simulate day to day use.
- GSM used for all data networking, opposed to WiFi.
- Backlight assumed to be at 66%, corresponding to 140 mW power consumption.

Workload	SMS	Video	Audio	Phone call	Web browsing	Email
Suspend	-	-	-	-	-	-
Casual	15	-	-	15	-	-
Regular	30	-	60	30	15	15
Business	30	-	-	60	30	60
PMD	-	60	180	-	-	-

Table 12: Usage patterns, showing total time for each activity in minutes.

Workload	Power (% of total)							Battery life [hours]
	GSM	CPU	RAM	Graphics	LCD	Backlight	Rest	
Suspend	45	19	4	13	1	0	19	49
Casual	47	16	4	12	2	3	16	40
Regular	44	14	4	14	4	7	13	27
Business	51	11	3	11	4	11	10	21
PMD	31	19	5	17	6	6	14	29

Table 13: Daily energy use and battery life under a number of usage patterns.

Limitations

- The biggest limitation with this analysis is that the Freerunner is not a current generation phone. It lacks a 3G / 4G interface, which supports much higher data rates than the 2.5G GPRS used on the device.
- The application processor is based on an older ARMv4 architecture. The power consumption difference between this and more modern processors is largely attributed to idle power, in other aspects it is not a substantial difference.

Conclusions

- A detailed analysis of energy consumption was performed, based on measurements from a physical device.
- It was shown how the different components of the device contribute to overall power consumption.
- An energy model of the phone was created, and it was shown how the battery life of the phone is affected by different usage patterns.
- The open source information and nature of the Openmoko Neo Freerunner phone is what allowed such a detailed analysis of its power consumption.
- The detailed measurements were compaired with a coarser analysis of more modern phones, and the results were comparable.
- The aim of this work is to enable a systematic approach to improving power management of mobile devices.

Thank you for listening