Power Consumption Breakdown on a Modern Laptop

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Abstract
The purpose of this work was to obtain a component-wise breakdown of the power consumption a modern laptop. We measured the power usage of the key components in an IBM ThinkPad R40 laptop using an Agilent Oscilloscope and current probes. We obtained the power consumption for the CPU, optical drive, hard disk, display, graphics card, memory, and wireless card subsystems--either through direct measurement or subtractive measurement and calculation. Moreover, we measured the power consumption of each component for a variety of workloads. We found that total system power consumption varies a lot (8 W to 30 W) depending on the workload, and moreover that the distribution of power consumption among the components varies even more widely. We also found that though power saving techniques such as DVS can reduce CPU power considerably, the total system power is still dominated by CPU power in the case of CPU intensive workloads. The display is the other main source of power consumption in a laptop; it dominates when the CPU is idle. We also found that reducing the backlight brightness can reduce the system power significantly, more than any other display power saving techniques. Finally, we observed OS differences in the power consumption.

Keywords: portable systems, power measurement, power breakdown, power reduction, dynamic voltage scaling

1 Introduction

Mobile systems have become increasingly more powerful, but they depend on a battery, which can only power it for a limited time. To extend the battery life, we need to reduce system power without compromising performance. This has motivated newer portable computers to feature components that support several power modes. Examples include processor Dynamic Voltage Scaling (DVS), low power modes in RAMBUS DRAM, wireless card radio power modes, and others. Moreover, there is a big research initiative to exploit these component level power management features for reducing power consumption. For instance, the GRACE-OS scheduler sets the CPU speed based on application demand [1], power aware page allocation puts active pages on a minimal set of memory chips [2], and cooperative I/O queues hard disk accesses to maximize the standby time [3].

A component-wise power consumption breakdown is necessary for evaluating the actual effectiveness of these power management techniques. In some cases, component level power management techniques can potentially lead to increase in system power consumption. For example, a component that uses small fraction of total system power may be managed in a way that increases energy usage by other components. Moreover, a breakdown of power consumption is essential for guiding future research in power management. Researchers will want to target those components that are currently using the most power.

Our work sought to obtain this breakdown of power consumption. We obtained the power usage of the CPU, optical drive, hard disk, display, graphics card, memory, and wireless card subsystems. We further compiled this breakdown for each of a variety of workloads, to reflect how such numbers would differ for laptops being used in different environments.

To obtain the power consumption breakdown, we performed measurements in several phases. The first phase involved stripping the system to the minimum configuration that would still be usable. The next was measuring, either directly or subtractively, the power consumption of each component in all possible power modes. The third step was to run several benchmarks, and determine the component-wise power consumption. The fourth step was to determine the power consumption of the components not in the stripped system. The final step was to determine the component-wise power consumption for the workloads that used these additional components.

The main results of this study are:

- Total system power varies considerably depending on workloads.
- CPU power dominates, in spite of DVS, for many applications.
- Display power, which is affected most by backlight brightness, dominates when system is idle.
- Graphics, wireless and optical drives are major power consumers only in specific workloads.

The rest of the paper is organized as follows: Section 2 describes the experimental setup. Section 3 presents the methodology in detail. Section 4 compiles the results of our experiments and Section 5 discusses them. Section 6 examines related work and we conclude in Section 7.

2 Experimental Setup

The experimental setup consisted of three main elements, the testing platform (a laptop), the measurement apparatus, and the software to be run while doing the measurement.

2.1 Testing Platform

The measurements were performed on an IBM ThinkPad R40 laptop. The laptop was ideal for this study as it is representative of the current breed of laptops in performance and battery life (nearly five hours on a single battery). Table 1 shows the major features of this laptop.

Component	Details
Processor	1.3 GHz Pentium M
Memory	256 MB
Hard Drive	40 GB @ 4200 RPM
Optical Drive	CD-R/RW, DVD
Wireless Networking	Intel Pro Wireless 2100
Screen	14.1" 1048 x 768

Table 1: Test platform details.

2.2 Measurement Apparatus

The main element of the measurement apparatus was a 50 MHz, Agilent 54621A analog oscilloscope. This oscilloscope had some very handy features such as MegaZoom, and math functions. To measure the voltage, we used a standard voltage probe. To measure current we used the Agilent N2774A current probe. This probe allowed us to measure current without breaking circuits. A limitation of this probe is that it needs to be clamped around the wire for which it is measuring current. As a result, we could not directly measure current used by devices that are directly soldered on, or are slotted into the motherboard. For most of the measurements presented, we averaged our measurements over five seconds and repeated multiple times.

2.3 Software

Since major goal of this project was to examine the workload-dependent nature of a laptop's power consumption, we used a variety of workloads to represent a wide range of tasks that may be performed on the machine. Moreover we needed several measurements for obtaining a component-wise breakdown of power consumption, and thus each workload had to be completely reproducible. Our workloads included the PCMark and 3DMark benchmarks, as well as multimedia playback and an FTP download and upload.

PCMark2002 consists of separate CPU, memory, and hard drive performance tests, as well as a combined "crunch test." These tests, while synthetic, are representative of the CPU, memory, and hard drive intensive tasks performed by typical home and office applications.

A stress test for any machine is 3D games. To measure the power consumption that might be typical during gameplay, we used the 3DMark2001 SE benchmark. This benchmark tests the performance of the CPU, memory system, and graphics controller by rendering 3D scenes representative of modern 3D games.

For measuring the power consumption that could be expected during Internet usage, we used FTP over a wireless LAN. FTP stresses the wireless LAN card and the hard drive, as is typical during Internet downloads.

For measuring the power consumed by multimedia applications, we played an audio CD. This stresses the optical drive, as well as some I/O subsystems.

3 Methodology

We initially envisioned performing direct measurements for power consumption of all components, but the limitations of the setup made this difficult. So, we divided the components into categories by the method by which they were measured:

1. Directly measurable – Hard drive, LCD/backlight, Speakers, Cooling Fan.
2. Indirectly measurable
   i. Non-removable – Processor, Memory, Graphics.
   ii. Removable – Wireless card, Optical Drive, Modem, USB/1394 Ports (turned off)

The power consumption for the components in the first category, as well as the system power, was obtained using direct measurement with the current probe. For the second category, we used subtractive measurement. The basic idea is that for each benchmark we obtained the power consumption of the entire system with a given component in several different modes. The difference between these measurements gives the power consumption of the component.

The power measurement was conducted in several phases. The first was to strip the system to the minimum configuration that would still be usable, i.e. containing only the directly measurable and non-removable components. The next was to measure either directly or subtractively, the power consumption of these components in each possible state. The third step was to run the PCMark and 3DMark benchmarks, determining the component-wise power consumption. The fourth step was to determine the power consumption of the components not in the stripped system, including the DVD drive and the wireless LAN card. The final step was to determine the component-wise power consumption for the workloads that used these additional components.

The first phase of the power measurement was to strip the system to its minimal configuration and gaining access to the directly measurable components, which required disassembling the laptop. This disassembly was done following the steps in the notebook service manual [9]. This process was time-consuming, as we had to keep track of all the disassembled parts, and avoid static discharge once the outer case was removed. The modular design of modern notebooks has made them easier to open, but it has also them difficult to use for power measurement, as most of the modules are connected without wires (they plug into sockets that are soldered on to the motherboard).

Once the laptop was disassembled, the power supplies for the directly measurable components had to be identified and isolated. One of these components was the LCD display system. The LCD assembly on the R40 consists of two major components: the LCD panel and the inverter card that powers the backlight. The connector between the motherboard and the LCD assembly consisted of nearly 40 wires bundled together. This together with the unavailability of datasheets for the LCD panel and the backlight made the task of identifying the power supply wires challenging. However, the wires coming out of the sockets on the inverter card and LCD panel were laid out separately in a transparent ribbon cable behind the LCD panel, and so after unbundling the wires we could separate them into smaller bundles by whether they went to the inverter for the backlight or to the LCD panel, and further separate these wires by the voltages we measured at their ends.

Another measurable component that did not have a separate power connector was the hard drive. In fact the hard drive was connected directly to a female connector on the motherboard, with 4 of the pins on the connector used for the power supply. To isolate these, we made an intermediate connector from two series-connected 44-pin laptop IDE cables, with the four power supply wires separated from the main cable.

We made an additional intermediate connector for the system power supply; this intermediate connector exposed the terminals of the connector to enable voltage measurement and separated the plus and minus wires to allow easy connection to the current probe.

Once we had access to the measurable component power supplies, we proceeded to measuring the power consumption of the components in the stripped system, specifically the hard drive, display, CPU, memory, and graphics controller, as well as the power loss through the system power supply.

The hard drive power was measured using the direct measurement method. The HDD on the R40 laptop had three power states, namely standby, idle and active. The standby state is the lowest power state in which the HDD motor is not spinning. Next is the idle state in which the HDD is spinning but no data is being transferred. Finally, the HDD is in the active state when data is being read or written. The power options in Windows OS allows setting the time after which the hard drive should be put to standby power mode. This value was set to three minutes, and the current going into the HDD was measured over a period of 500 seconds. The measurements showed the power state transitions, and the values obtained are summarized in the top rows of Table 2. To measure the active state power, the read, write and copy tests of the PCMark2002 benchmark suite were used. The power consumption averaged over a fixed number of reads, writes and copies is summarized in the bottom rows of Table 2.

Hard Drive State	Power Consumption
Idle	.575 W
Standby	.173 W
Read	2.78 W
Write	2.19 W
Copy	2.29 W

Table 2: HDD power consumption

The LCD panel operating voltage and current were directly measured using the probes. The initial measurements were done with the typical Windows background. The LCD panel current showed no variation while the backlight brightness was changed. Measurements were also obtained when LCD panel displayed a completely white, and a completely black background. Finally, color bit-depth for the pixel was varied from 16 bit to 32 bit in Windows, and from 8 bit to 16 bit to 32 bit in Linux for all the three backgrounds. The results obtained from the measurements are summarized in Table 3.

Background Color	Power Consumption
Black	1.01 W
White	0.93 W
Windows default background	0.99 W

Table 3: Effect of display color on LCD power

No measurable difference was seen either at the LCD panel, backlight or the system power consumption when the color bit-depth was changed.

The power consumption of the LCD backlight was obtained by performing a direct measurement on the current used by the backlight. The measurement was repeated for each of the eight available brightness levels, and the values obtained are summarized in Figure 1. The backlight current showed no variation with changes in external factors such as the color being displayed on the LCD and the color bit-depth.

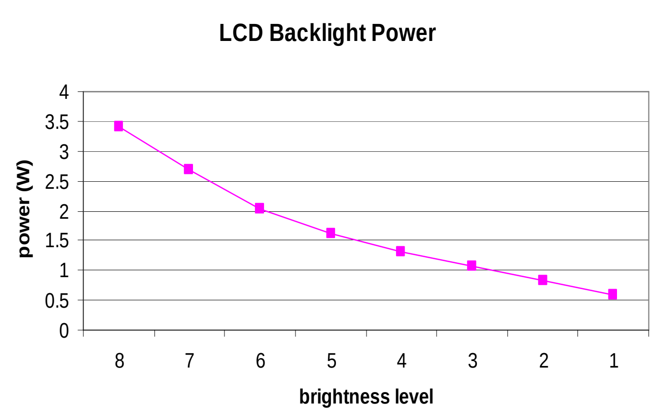

Figure 1: Backlight power versus brightness level

The CPU power measurement depended on the formula for power in terms of frequency and voltage, $P_{CPU} = \alpha CV^2 f$, where C is dependent on the capacitance of the chip and α the level of activity. Given two power measurements for P_{CPU}, we can calculate:

$$P_{CPU1} - P_{CPU2} = \alpha C V_1^2 f_1 - \alpha C V_2^2 f_2$$
$$= \alpha C (V_1^2 f_1 - V_2^2 f_2)$$
$$\alpha C = \frac{P_{CPU1} - P_{CPU2}}{V_1^2 f_1 - V_2^2 f_2}$$

Since $P_{CPU} = P_{system} - P_{other}$, holding P_{other} constant implies $\Delta P_{CPU} = \Delta P_{system}$. P_{other} cannot be held exactly constant, but it can be held approximately constant by either leaving the system idle or running a program that stresses only the CPU, without touching main memory or I/O. For this measurement we created a synthetic benchmark that computes several functions and stores the results in an array. The total memory usage of this program is 470KB as measured using top, so it exercises the 1MB cache in the Pentium M, but does not access main memory after an initial phase.

Frequency (MHz)	Linux Idle	Linux Max	Windows Idle	Windows Max
600	14.31	16.54	11.24	14.85
800	15.69	20.98		
1000	15.88	22.71		
1200	16.47	25.71		
1300	16.9	27.45	12.84	25.53

Table 4: System power consumption (Watts) under Linux and Windows with CPU idle and maximized.

αC	Linux	Windows
Lowest Idle	9.601×10^{-10}	8.18×10^{-10}
Highest Idle	1.321×10^{-9}	
Lowest Busy	5.578×10^{-9}	5.46×10^{-9}
Highest Busy	5.052×10^{-9}	

Table 5: Calculated values for αC

The system power was measured under Linux and Windows, both with the CPU idle and running the cpu-maximizer, at a variety of different CPU frequencies. The results are shown table 4. From these numbers, the value of αC for an idle CPU can be calculated using the formula; the results are shown in table 5. Figure 2 gives the CPU power consumption obtained by using these values of αC. We compared our results to processor power consumption number from Intel [4].

One limitation of this approach is the assumption that α is constant for different applications, which is not necessarily the case.

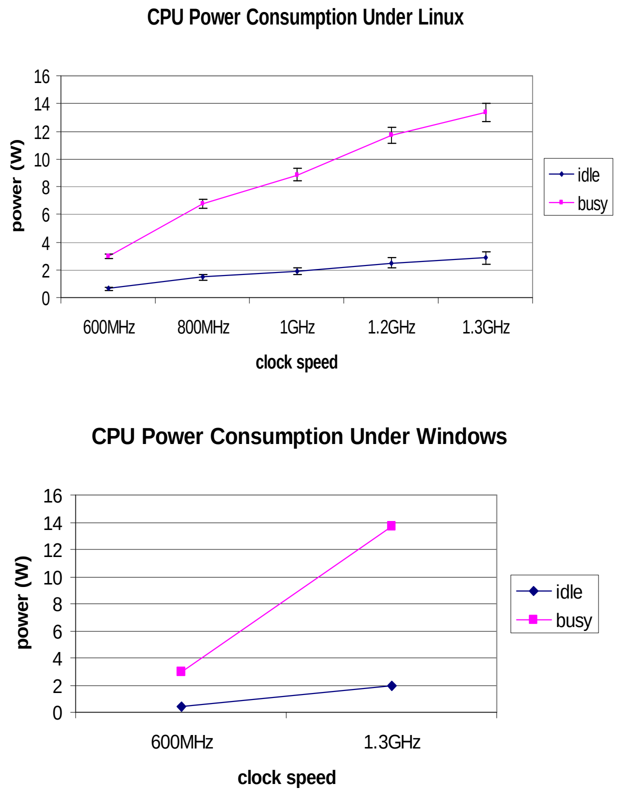

Figure 2: CPU power consumption under Linux and Windows using calculated αC.

The remaining components of the stripped system were the memory and graphics chipset. The graphics card power consumption was also obtained using the subtractive method. There were two main problems that we had to deal with. Firstly, ATI has not published the electrical specifications or the power states of the device. Secondly, there was no means of turning off the device or putting it into different power states. Thus, we assumed a base power of 1.09 W based on the values given in the Intel paper [4]. We obtained the active power use by subtracting the system power for the CPU maximizer from the system power for the 3DMark2001 benchmark. The resulting maximum power consumption was 5.1 W.

The memory power consumption was obtained by the subtractive method in the same manner as the graphics power. We obtained a baseline measure of its power consumption, 0.45 W, from the manufacturer's data sheet [8]. We then obtained system power from a memory test, and subtracted from it the idle system power and the difference in CPU power, yielding 1.42 W. For each of the benchmarks, we computed a memory power figure in between these two by determining the number of memory accesses each benchmark did.

One final power loss we noticed was a baseline 0.65 W loss in the power supply. This was found by measuring the power consumption of the system when nothing is turned on. This figure is just a baseline, and we expect that the true power supply loss under load is substantially higher.

Once the power consumption of each of the components of the stripped system was determined, we proceeded to measure the power consumed by the removable components. Amongst these, we were specifically interested in the power consumption of the wireless LAN card and the optical drive, as the ports on the computer usually consume too small an amount of power to measure accurately with the current probe.

The power consumption of the wireless LAN card was measured using the subtractive method. The wireless card has numerous power states when enabled. To measure these, we measured the system power with the wireless card disabled, enabled but idle, in a power-saving state, while receiving via FTP, and while transmitting via FTP. The power consumption of the system and of the wireless card alone is shown in Table 6. The wireless card power is the difference between the system in the given state minus the system power with the card disabled; for the receive and transmit, we also subtracted the additional power consumed by the CPU and hard drive.

Wireless Card States	Power Consumption
Power Saver (Idle)	0.14 W
Base (Idle)	1.0 W
Transmit	3.12 W total at 4.2 Mb/s
Receive	2.55 W total at 2.9 Mb/s

Table 6: Wireless LAN card power consumption

The power consumption of the optical drive was also measured using the subtractive method. First, the system power was measured with the optical drive removed from the system. Then, the system power was measured with the optical drive inserted but idle, while inserting a CD into the optical drive, while the optical drive is spinning steadily, and while the optical drive is reading data. The power consumed by the optical drive in each of these states is the system power in that state minus the system power with no optical drive minus any additional hard drive or CPU usage. Table 7 shows the results:

Optical drive state	Power (W)
Initial spin up	3.34
Steady spin	2.78
Reading data	5.31

Table 7: Power consumption of optical drive

4 Results

We used several benchmarks described in the experimental setup section to analyze the component-wise breakdown of power consumption. As can be seen in Figure 3, the total system power varies by a factor of four depending upon the workload. In the next section we will see the component-wise breakdown of the system wide power, and some of the reasons that contributed to such a large range of total system power consumption.

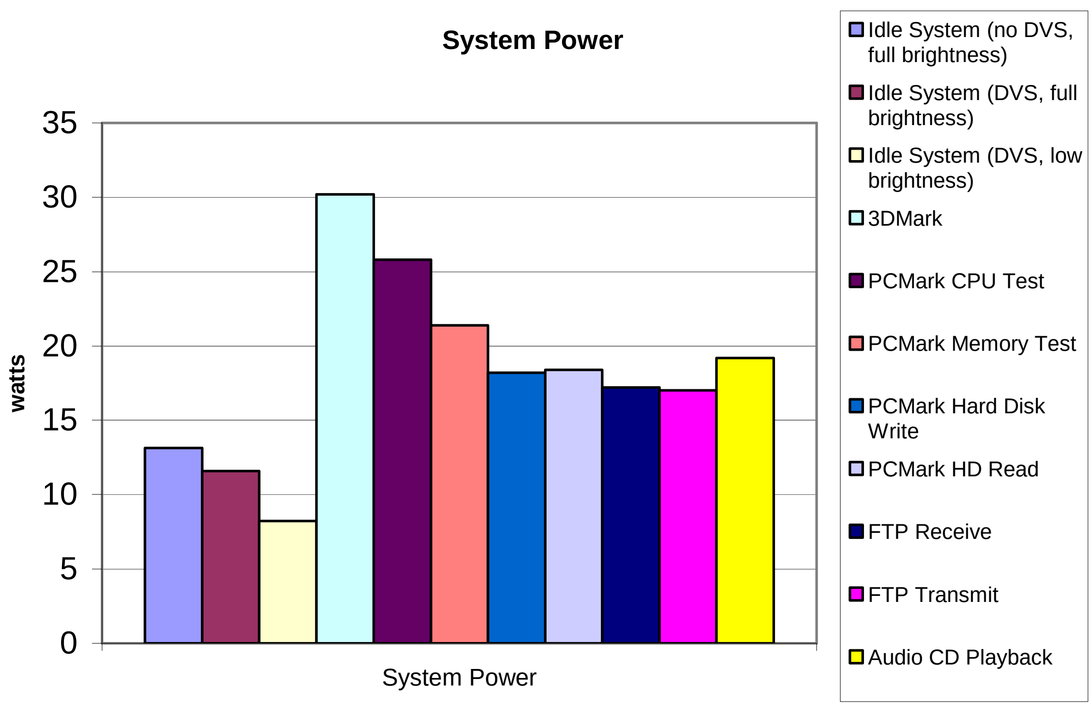

Figure 3: Power consumption of system under various workloads

Figures 4 - 7 show the component wise breakdown of the total system power. We have categorized the power consumption into 10 categories, some of which were described in the previous section. These include CPU, hard drive, base power supply loss, wireless card, LCD, backlight, optical drive, memory system, graphics card. We were unable to categorize all of the power consumption, and so we include a rest of system category that consists of memory and interrupt controller hub (Northbridge and Southbridge), rest of the system power supply loss, and miscellaneous components on the motherboard.

Figure 4 shows the breakdown of idle system power consumption. The power consumption breakdown for an idle system running without DVS and at full backlight brightness is dominated by the display system (34%). When the CPU is running at 600 MHz, it uses one-tenth the power used by the display system. Dimming the backlight does reduce the backlight power, but the display system still accounts for one-fifth of the system power, mainly due to the one-Watt fixed power consumption of the LCD panel.

Next, in Figure 5 we look at the breakdown for PCMark2002. During the course of the CPU tests, the CPU power consumption dominated the total system power consumption. Similarly, in the Memory test, CPU was used a lot for reading, and writing different size blocks. Though the share of memory power consumption went up, it still was small compared to the CPU or Display power. Finally, the breakdown of power consumption for the Hard Drive tests shows equal power consumption by the Hard Drive and the CPU. This is not surprising as most of the time was spent in reading/writing to the disk. Also, we note the power consumed by the rest of the system increases dramatically; this may be because of the increased IDE controller activity that is included in this category.

Figure 6 shows the breakdown for power consumed during a wireless FTP upload and download of the same file. This breakdown is very similar to the Hard Drive tests, as both loaded the CPU by around 6%, and both devices use around 2-3 W of power when active. Transmit was slightly more expensive than receive, but comparison is not fair as the transmit speed through TCP was slightly higher than the receive speed.

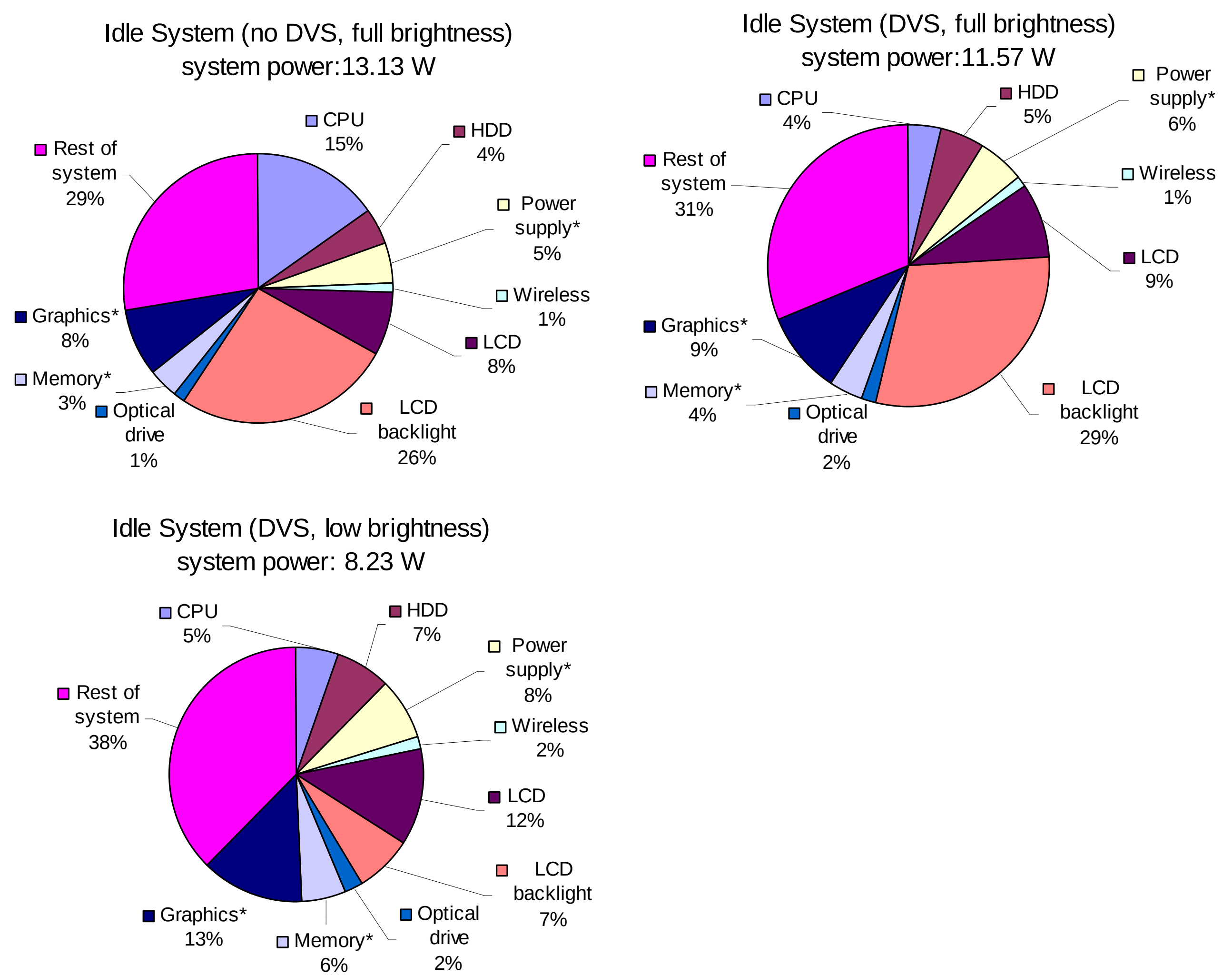

Figure 4: Breakdown of idle system power conversion with various CPU speeds and display brightness levels

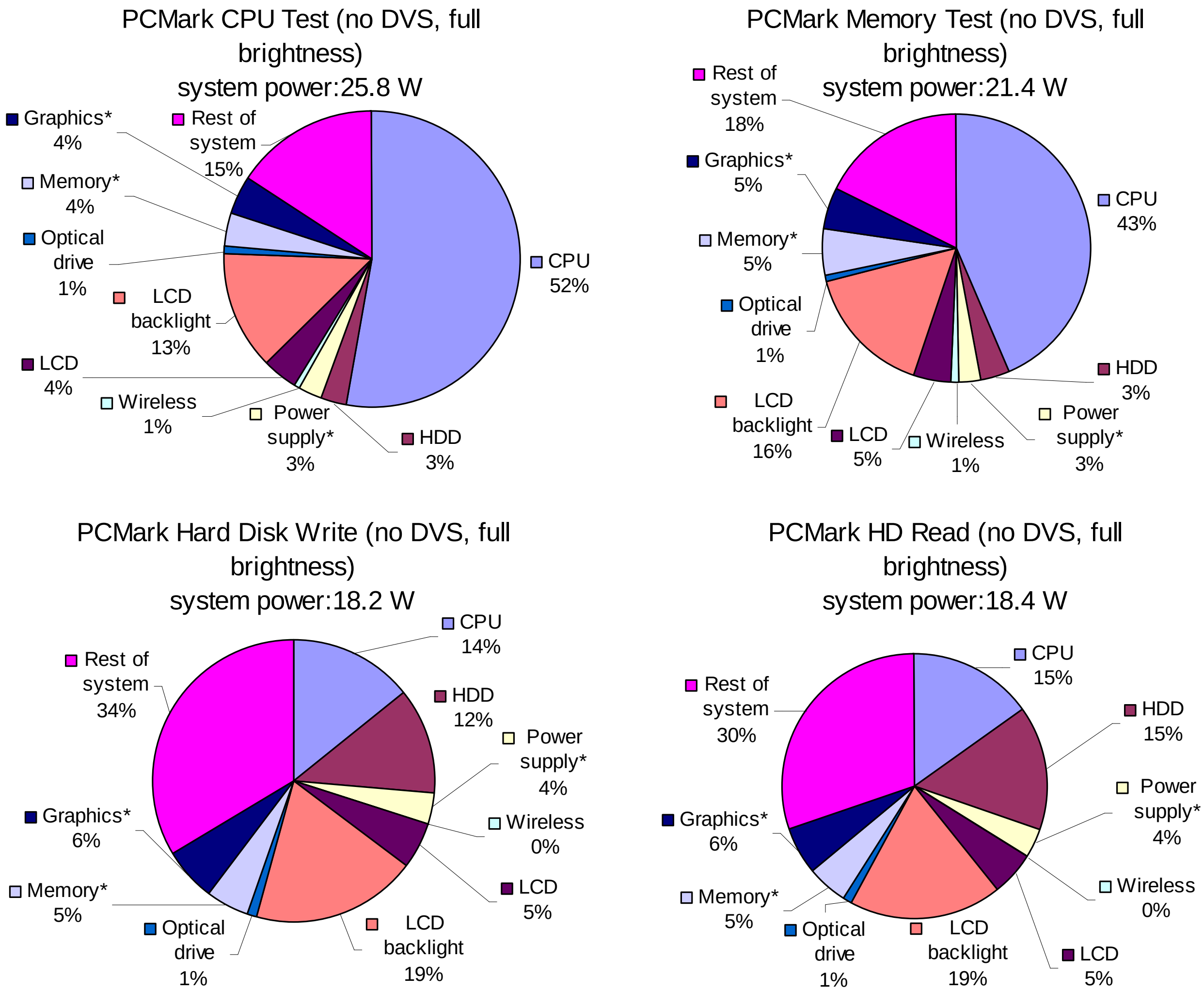

Figure 5: Breakdown of power consumption under different PCMark2002 benchmarks

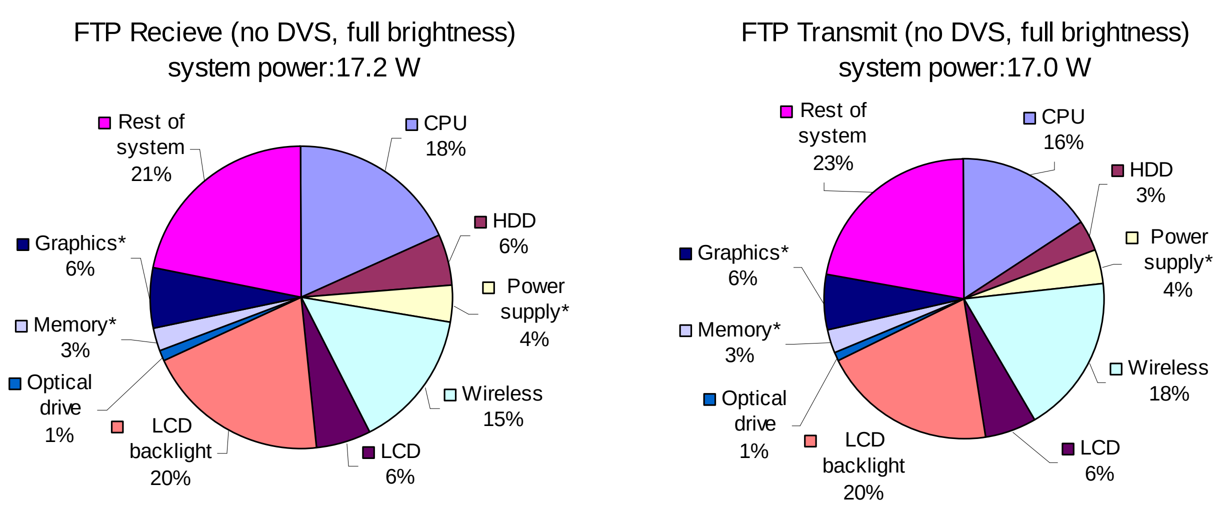

Figure 6: Power consumption breakdown of FTP

We can see in Figure 7 that the optical drive uses a lot of power, even more than the processor, during an audio CD playback. This is because the CD was spinning at full speed for the whole duration of the track.

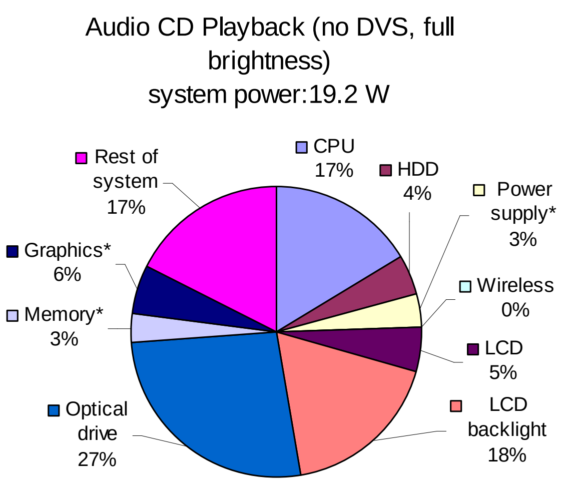

Figure 7: Power consumption breakdown of audio CD playback

Figure 8 shows the breakdown of power consumption during 3DMark. Not surprisingly, CPU dominates, while graphics comes in a distant second.

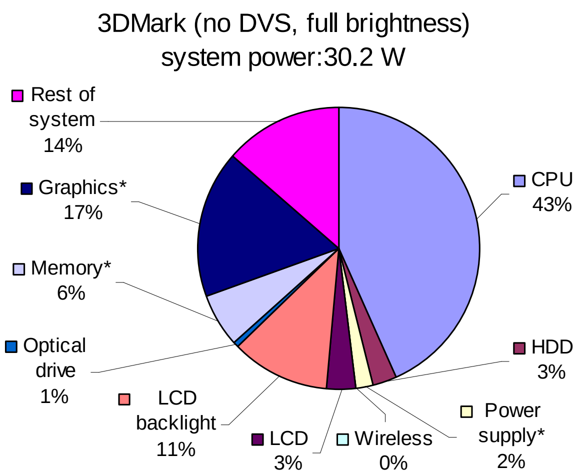

Figure 8: Power consumption breakdown of 3DMark01

5 Discussion

This study provided some useful insights into the power consumption behavior of the individual components, and the manner in which the OS uses these components.

5.1 CPU

This study showed empirical evidence for the fact that DVS saves power, and that these savings are significant enough to contribute to a lower total system power.

A power aware OS can reduce component wise power consumption by exploiting the various low power states supported by a device. In our study we found that the total Idle System power consumption went up when we were running Linux OS compared to the power consumption under Windows OS. This can be attributed to the fact that Linux Kernel we were using did not have support for ACPI, and even after upgrading the kernel we were not able to get ACPI working under Linux. Windows OS on the other hand provides user with a GUI to set the power preferences.

Even though DVS reduces CPU power consumption, CPU still dominates whenever it is extensively used by an application. Using DVS can reduce the CPU power, but lowered frequency and thereby increased execution time may not be acceptable to all users. This implies that there is a lot more room for work in the area of CPU power reduction.

5.2 Hard Drive

One of the interesting observations made during this study was the mysterious Hard Drive accesses made by Windows OS when the drive was in Idle state. These accesses had a frequency of 150 ms and they increased the power consumption of the disk by 0.2 W. Linux OS did not show any such behavior.

5.3 LCD

The relation between LCD power and the color being displayed validates similar findings in adaptive display literature [10]. This also makes a case for light colored screensavers, as the traditional Windows XP screensaver increased the system power consumption by 0.5 W. We also tested the idea of reducing color bit-depth to save power, as proposed in the display system community [10]. We found that for our platform such a scheme did not save any power, either at the LCD panel or the system level.

The power reduction that we observed by reducing the backlight brightness level strongly supports automatic brightness reduction as performed by Display Power Saving Technology [11].

5.4 Graphics

From the results, the graphics chipset does not consume a large fraction of the system power except when using 3D acceleration, and even then the graphics chipset only consumes about 17% of the total system power. However, the machine we are measuring contains an older Radeon 7500 chip; newer, faster chips such as the Radeon 9600 may use considerably more power.

Some of the new areas for power savings are certainly at the circuit level, for example the chipset power consumption, and the power supply loss are a major portion of the Idle System power.

5.5 Limitations

The accuracy of our results is limited by several factors. One important limitation is the limits of the power measurement apparatus, particularly the current probe. Agilent's own documentation notes that the probe has a margin of error of +/- 2 mA. Moreover, because the probe works by detecting the magnetic field generated by current flow rather than by directly measuring the current flow, it is susceptible to influence by external magnetic fields. Strong magnetic fields can raise the error margin as high as 20 mA, though the fields in our test environment were fairly small.

Another factor limiting the accuracy of our results was the subtractive method. Because of this method, small errors (< 1%) in the system power measurement can translate to very large errors measuring low-power components, as 1% of system power is about 0.15 W. Moreover, because of the inexact methods used to get subtractive measurements of memory, graphics, and the power supply, the measurements in those categories should be regarded as estimates.

A major limitation of this project is that we were unable to get a component-wise breakdown of much of the power consumed by the system. From 14% to 38% of the system power is classified as "rest of platform." Although the information we have discovered is useful, a breakdown of this unclassified power consumption would allow even more insight.

Finally, this project has focused only on the power consumption of the electronic and mechanical parts of the computer, and has completely neglected the idiosyncrasies of the battery. Proper battery management is as crucial to good battery life as reduced power consumption. A future project of this type should also try to assess how much energy the battery wastes under various workloads and drain rates.

6 Related Work

There have been few other studies on breakdown of laptop's power consumption. Intel recently published a paper describing the reduced power consumption of Centrino platform [4][12]. This paper also included a power consumption breakdown, but it does not give much detail on the methodology or the system and the workload that was measured. The breakdown that we obtained for the Idle System with DVS is very similar to the breakdown given in that paper. Another work related to ours is [5], which uses a combination of software profiler and data obtained from industry to come up with a similar breakdown. Although this work is very detailed and informative, it was done a long time ago, and the hardware has since become outdated. Comparing our breakdown numbers to those given in Lorch's paper, we found that the total system power has nearly doubled, but the share of each component has not changed drastically. Our work is different from Lorch's work as we explore the application-dependent nature of a laptop's power consumption whereas his work measures the power consumption under a representative or average set of power states obtained through profiling. There have been several recent studies on power consumption of a hand-held device [6] [7], but these numbers are not representative of a laptop. Some of the notable differences are that hand-held devices do not have hard drive or graphics card.

7 Conclusions

The purpose of this work was to obtain a component-wise breakdown of the power consumption in a modern laptop. We measured the power usage of the key components in an IBM ThinkPad R40 laptop using an Agilent Oscilloscope and current probes. We obtained the system wide power consumption breakdown for the following components: CPU, optical drive, hard disk, display, graphics card, memory, and wireless card subsystems. Due to the limitations of our measurement equipment, we had to use a combination of direct measurement and subtractive measurement approaches.

We found that total system power consumption varies a lot (8 W – 30 W) depending on the workload. We also found that, although power saving techniques such as DVS can reduce CPU power considerably, the total system power is still dominated by CPU power in the case of CPU intensive benchmarks. The display is the other main source of power consumption in a laptop. We found that reducing the backlight brightness can reduce the system power significantly, more than any other display power saving techniques. The graphics, wireless networking, and disk drives can all consume a substantial amount of power when they are active, but when they are idle, as is the case most of the time, they do not consume too much. Finally, we observed that power consumption under Windows OS differs from power consumption under Linux, probably due to differences in ACPI support.

Last but not the least, we were successful in not destroying the laptop (a fear of all our colleagues).

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