A Complete Picture of the Energy Consumption of a Portable Computer

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Abstract

High battery lifetime is important to the usability and acceptance of portable computers. In order to develop strategies to minimize power consumption, designers need a good picture of the total power consumption of a system. For this purpose, we indicate the power consumptions of a set of portable computers and how they are broken down among the components of those computers. Then, we use user profiles to show how the use of power-saving features currently implemented serves to reduce these power consumptions by 35–56%. We also show how these power-saving features affect the breakdown of overall power consumption, so that we can evaluate how successful certain new software techniques and hardware changes would be at reducing power consumption. The results of this paper point out the most promising avenues for further work in the reduction of power consumption, and indicate some strategies that can provide an immediate power benefit to the class of machines studied.

1 Introduction

One of the most important features of a portable computer system is its battery lifetime. Users would like a portable computer to last for a day, or even a week, without needing to be recharged, but a typical modern portable computer can only operate in this way for two to four hours [25]. Recognizing this, component and operating systems designers have had to consider ways to increase battery lifetime through special consideration of the portable environment.

One way to increase battery lifetime is to design and use components that consume less power. For instance, some companies are working on diode-type active-matrix LCDs that can consume less power than the currently used thin-film transistor active-matrix panels [9]. Also, Bertsch et al. have shown how selective scaling, i.e. reduction of only the threshold voltage and gate oxide thickness, can be used to reduce the power consumption of the PowerPC 601 microprocessor by about 73% while only reducing its performance by 25% [7]. Recently available disk drives made for the portable market, such as the HP Kittyhawk C3014A and the Caviar Ultralite CU140, also exhibit noticeable power reduction compared to their predecessors. A final example is due to Douglis et al. [13], who suggest using a type of nonvolatile storage called flash memory as a low-power substitute for the hard drive.

Another way to increase battery lifetime is to take better advantage of the low-power states of portable system components. For example, most hard drives made for portable computers can be made to stop spinning in order to save power, and operating systems can take advantage of this by spinning down the hard drive when it is not in use. Li et al. [19] describe an aggressive strategy for doing just that to eliminate as much as 90% of hard drive power. Another low-power state that can be taken advantage of is running the CPU at a lower voltage. CPU energy consumption per clock cycle is proportional to the square of the operating voltage. Since the number of clocks the CPU must run is invariant with the voltage, one can minimize CPU power consumption by minimizing CPU voltage. Weiser et al. [28] point out that in order to operate properly at a lower voltage, the clock rate must be simultaneously reduced. They propose a method for the operating system to reduce the clock rate dynamically so that it can be reduced as often as possible while still allowing the CPU to meet its task completion deadlines. In this way, the voltage can be reduced while the clock rate is reduced, in order to reduce the total power consumption of the CPU. They indicate that their techniques can re-

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duce CPU power consumption by as much as 50% or 70%, depending on how low a voltage is supported by the hardware. Note that taking advantage of low-power states means making trade-offs between power and performance, since low-power states have associated disadvantages. For instance, spinning down the disk causes the subsequent disk access to have a high latency, and decreasing the CPU rate can raise response time.

However, knowing how much a technique reduces the power consumption of a component is not sufficient to evaluate the effectiveness of that technique. The increase in battery lifetime due to a reduction in the power consumption of a component depends on the fraction of total system power due to that component. Therefore, to evaluate the effectiveness of power-saving hardware and software, one must know how total system power is divided among the system components. Furthermore, it is not realistic to use a power consumption breakdown consisting of the normal power consumption of each component. One must use, for each component, an average power consumption figure that takes into account how often the component is in a low-power mode. For instance, if a breakdown does not take into account how much energy is saved from spinning down the hard drive, then it will attribute too high a percentage of total power to the hard drive. This, in turn, can lead to an inflated figure for the effectiveness of a new disk power-saving technique.

To evaluate the effect of existing, proposed, and potential power-saving techniques, we have designed software tools to collect data on the power use of Macintosh portable computer components, and on the frequency of use of their low-power states. We use these tools to determine, for each machine studied, what its maximum power consumption is and how this is divided among its components. We then show how the use of power-saving modes reduces, and changes the breakdown of, this power consumption. Then, we show how this power consumption could be reduced even further through the use of additional software power-saving techniques. Finally, we show how power consumption could be reduced further by changing the hardware configuration.

The paper is divided as follows. Section 2 gives some background about the computers being studied: their components, their power-saving features, and their power-reporting features. Section 3 describes how our analysis tools work and how we used them. Section 4 presents the results of using these tools and some information that we collected from other sources. Then, Section 5 uses these results to perform the analyses described in the previous paragraph. Section 6 discuss avenues for future research and development to extend and apply the results of the paper. Finally, Section 7 concludes.

2 Background

Machines studied

The Macintosh PowerBook Duos 230, 270c, and 280c are part of a line of portable computers produced by Apple Computer, Inc. They are currently in wide use, and so provide an excellent testbed for realistic modeling. Table 1 shows the major features of the Duos studied here [2].

Each of these computers uses a single battery. The battery currently manufactured by Apple that can operate on all three of these machines and has the greatest capacity is called a PowerBook Duo Battery Type III.

Figure 1 shows a block diagram of the main logic board functions of the Duo 280c [5]. The Duo 270c differs from this in that the MC68LC040 is replaced by an MC68030 and a 68882 coprocessor [4]. The Duo 230 differs in that the CSC is replaced by the GSC (gray-scale controller), and the MC68LC040 is replaced by an MC68030 [3]. Also, in the Duo 230 and 270c, the processor is connected directly to the main bus, so the PLL and MBT are not present [3, 4].

We can use this block diagram to divide the computer into the following main components:

- Processor
- Hard drive (hard drive and SCSI controller)
- Backlight
- Display
- Modem (modem, DAA, and RJ-11)
- Sound (DFAC, microphone, and speaker)
- FPU, if present
- Video (CSC/GSC and VRAM)
- Power management (power management chip and SRAM)
- Memory (DRAM and expansion DRAM)
- Serial communications (SCC and serial port)
- Input (keyboard and trackball)

Machine	Features
Duo 230	68030 processor; 33 MHz top speed; supports 16 MHz operation; internal hard drive either 80 MB, 120 MB, or 160 MB; 9" backlit supertwist monochrome display with 16 levels of gray; optional internal modem; trackball; keyboard; 4MB RAM expandable to 24 MB
Duo 270c	68030 processor with 68882 math co-processor; 33 MHz top speed; supports 16 MHz operation; internal 240 MB hard drive; 8.4" backlit active-matrix color display; optional internal modem; trackball; keyboard; 4 MB RAM expandable to 32 MB
Duo 280c	68LC040 processor; 33 MHz top speed; internal 320 MB hard drive; 8.4" backlit active-matrix color display; optional internal modem; trackball; keyboard; 4 MB RAM expandable to 40 MB

Table 1: Features of the PowerBook Duos studied [2]

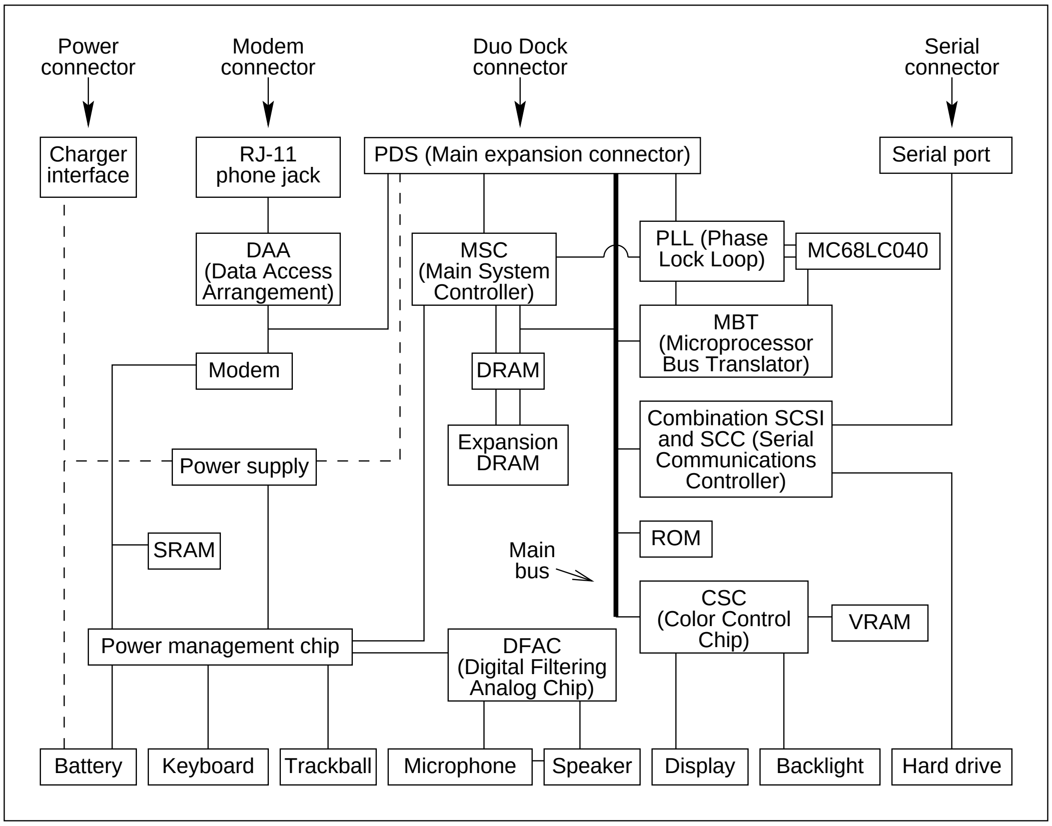

Figure 1: Block diagram of the Duo 280c main logic board functions [5]

- Power supply
- Miscellaneous glue logic and components (PDS, MSC, PLL, MBT, main bus, etc.)

When we talk about the power consumption breakdown of a machine, we will mean how much power is consumed by each of these main components. Since the serial communications and input components consume a negligible amount of power, they will not be mentioned in such contexts.

A few words should be said about power supply inefficiency. The power supply of a laptop computer taxes all power coming from the battery at a rate of about 15% [26]. In our breakdowns of power consumption, we could therefore say that the power supply consumes 15% of total power. However, we instead take the approach of attributing the power supply inefficiency to the components that use the power. This makes the interpretation of our measurements straightforward, since if we see a power difference when a component shuts off we can attribute all this power to the component itself rather than concerning ourselves with how much of it is due to the lower load on the power supply. Furthermore, this approach makes interpretation of our results more straightforward. For instance, if we say that 10% of the power consumption is attributable to the hard drive, and that there is a method of reducing the hard drive power consumption by 50%, one can conclude that the total power reduction would be 5%. The computations become unnecessarily complex when one must also take into account the reduction in power supply power consumption resulting from the power reduction of another component.

It will turn out to be useful to break down the power consumption slightly further, for the following reason. When the processor is turned off, as it is during a power-saving mode to be described later, there is a consequent reduction in the power consumption of many motherboard parts other than the CPU and FPU. For example, when the CPU is inactive, the main bus has less to do and consequently consumes less power. It is thus useful to make a distinction between *reducible* and *nonreducible* components, where the reducible components are those whose power is reduced to zero when the processor is off. Note that if a component has its power reduced by 50% when the processor is off, we are considering half of this component to be reducible and the other half to be nonreducible. Most components do not have their work reduced when the processor is off, and so are assumed to be nonreducible. However, the FPU and, of course, the CPU are entirely reducible. Also, the miscellaneous component has both reducible and nonreducible parts. We therefore further break down the miscellaneous component into a reducible miscellaneous component and a nonreducible miscellaneous component.

Power-saving features

We now discuss the low-power modes available on the Duos, and how the operating system takes advantage of them.

First, on each machine, the hard drive is capable of being spun down. The user specifies an interval between 30 seconds and 15 minutes; if the specified amount of time goes by without any disk accesses, the operating system will spin down the disk. It will not spin the disk back up until the next disk access is requested. The user may also set the interval to infinity, i.e. elect to have the hard drive never spin down.

The backlight on each of the Duos can be set to many different levels, ranging from 0% to 100% of its maximum possible brightness. The user adjusts this brightness using buttons next to the screen. Furthermore, the user specifies an interval between 30 seconds and 5 minutes, after which amount of inactivity the operating system will begin to progressively dim the backlight, stopping when it eventually reaches 0% illumination. Note that here and in later contexts, activity is defined as any input, any indication by a process that it is busy, or any access of the disk, sound chip, or modem. When activity occurs again, the operating system will return the backlight immediately to the brightness level it was at before progressive dimming began. The user may also set the interval to infinity, i.e. elect to have the backlight never automatically dim.

The processor on the Duo 230 or the Duo 270c can be made to run at a lower speed; each supports 16 MHz operation in addition to the typical 33 MHz operation. The user indicates at what speed the processor should run, but any changes he or she makes do not take effect until the machine shuts down and restarts.

The processor on the Duos supports another low-power mode, called cycling. The operating system causes the machine to enter this mode by executing the processor cycling procedure, described in Table 2. We use the term *halt cycle* to denote a single iteration of this loop. Thus, a halt cycle consists of an *on interval*, during which the machine checks for activity, followed by an *off interval*, during which the CPU is off. Note that when the

```
save CPU state
loop
   check for user or network activity
   if there is activity
      exit the loop
   else
      turn off CPU until next interrupt
restore CPU state
```

Table 2: Procedure for processor cycling

CPU turns off, its cache is flushed. Also, as mentioned before, when the processor is off, not only is its power consumption reduced, but the power consumption of the rest of the motherboard is also significantly reduced. Usually, when the processor is cycling, the only interrupts that occur are the vertical-retrace interrupts. Since these interrupts occur roughly 120 times a second, a halt cycle typically takes about 8 ms. Since checking for activity takes a short amount of time, most of this 8 ms is spent in the off interval.

The user indicates whether or not processor cycling should be used. If it is to be used, the operating system will initiate the processor cycling procedure whenever no activity has occurred in the last two seconds and no disk activity has occurred in the last 15 seconds. The procedure will stop whenever activity is once again detected. This technique is somewhat conservative, firstly because it is difficult to determine when the processor is doing useful work and one does not want to turn it off while it is doing such work, and secondly because even if one cycles the processor only when it is not doing useful work, there will still be a performance degradation from flushing the cache.

The sound chip on the Duos can be turned off. The operating system ensures that the sound chip is turned on when it is needed, and that it is shut off after about eight seconds pass with no sound being produced. The user has no control over the strategy used to turn the chip on and off.

The modem on the Duos can be turned on and off, but only explicitly by the user or by the applications he or she runs. The operating system standard user interface provides no mechanism for automatically shutting the modem off when not in use.

Finally, the system can have its power reduced as a whole by putting it in sleep mode. When the machine is asleep, all its components are off except for the DRAM. The user specifies an interval between 30 seconds and 15 minutes, after which period of inactivity the machine will be put in sleep mode. The machine automatically exits sleep mode whenever a key is pressed, taking about 12–15 seconds to return to normal operating mode. Note that the user may indicate an interval of infinity, i.e. make the machine never sleep.

Power-reporting features

The Duos have built-in hardware and software for monitoring their energy consumption. The software can be queried for the instantaneous power consumption, as well as the total energy consumption since the last time the battery was charged. These values are given in units of 0.06426 W and 0.06426 W-s, respectively.

3 Methodology

There are two aspects to measuring the breakdown of power consumption on a portable computer: measuring how much power is consumed by each component in each state, and profiling how often each component is in each state. We designed a program called PowerMeasure to perform the former task and one called StateProfiler to perform the latter one.

The operation of PowerMeasure is as follows. For each component c, and for each pair of states s_1 and s_2 of c, it computes the difference in instantaneous total power consumption between when component c is in state s_1, and when all other component states remain the same but c is in state s_2. Note that this approach automatically accounts for power supply inefficiency as a part of each other component's power consumption, as discussed before. PowerMeasure also computes the energy savings from one halt cycle by subtracting the total energy consumption over a period of five minutes with processor cycling enabled from the total energy consumption over a period of five minutes with processor cycling disabled, then dividing by the number of halt cycles that occurred during those five minutes. Finally, it computes the energy consumption of spinning up the hard drive by subtracting the energy consumption over an 8-second period from the energy consumption during another 8-second period which is identical except that the hard drive is spun up once.

To validate the software power monitoring routines, we performed some measurements with hardware. A Duo 230 was instrumented with a voltmeter and ammeter so that battery current and voltage, and thus power consumption, could be observed while the PowerBook was running. The percentage differences found between software and hardware power figures ranged from 0.1% to 5.6%. These differences seem small enough to warrant confidence in the values we obtained from PowerMeasure.

StateProfiler operates as follows. Every five seconds, it examines the state of each component and increments a counter for each such component state it finds as well as a global time counter. In addition, it arranges to be notified each time certain events of significant energy consumption take place so that it can count them. These events include the hard drive spinning down, the machine entering or leaving sleep mode, and a halt cycle starting.

Note that PowerMeasure needs to be run only once per machine type, while StateProfiler runs as a background application for a user throughout his or her participation in the study. Several users were selected for this study and asked to run StateProfiler on their machines for about a week. Each of them works as an engineer or researcher at Apple Computer, Inc. and uses his or her own PowerBook. Because power consumption is largely unimportant when running on wall power, most results presented in this paper use only data collected while users were running on battery power. We further restricted consideration to time the machines spent not asleep, since battery lifetime typically only refers to this kind of time. In the users studied, the percentages of time spent running on battery power were 14% for the Duo 230, 29% for the Duo 270c, and 13% for the Duo 280c. Furthermore, eight other users, who spent less than an hour each running on battery power and were thus excluded from the analysis, spent a total of almost 243 hours running on wall power. We see, unfortunately, that the user community studied does not make heavy use of battery power.

4 Results

Component power consumption

PowerMeasure was run on three different machines to determine power and energy consumption figures. They were a Duo 230 with 80 MB hard drive, a Duo 270c with 240 MB hard drive, and a Duo 280c with 320 MB hard drive. The top half of Table 3 shows, for each of these machines, the total power consumption in the absence of power-saving modes, the power saved by entering various power-saving component states, the energy saved or consumed by certain transient events, and the rate at which halt cycles occur during extended idle periods. Different machines generally use different components with different power consumptions; however, since the same modem is used for all three machines, the fact that we find a slightly lower modem power consumption on the Duo 270c is probably due to product variation or measurement error. Note that it is normal for different machines, even with the same processor, to have different maximum cycling rates, since these rates depend on how often interrupts occur. However, the rate differences observed between different CPU speeds on the same machine are probably due to measurement error.

We performed an additional experiment to determine the usable capacity of a Type III battery. The battery was run down from fully charged to the point at which the operating system forced the machine to sleep in order to preserve the contents of memory. Immediately before the machine went to sleep, the software was queried for the total energy consumption since charging. In this way, the usable capacity was determined to be 16.94 W-h.

Power of motherboard components

Since PowerMeasure cannot obtain power figures for machine states not currently supported, some data must be obtained through other means. To allow us to break down the power consumption of the motherboard, we obtained the following estimates from an engineer at Apple Computer [26]:

- 68030 at 33 MHz consumes 1.15 W.
- Duo 270c FPU, in typical operation, consumes 460 mW.
- 68LC040 at 33 MHz consumes 3.33 W.
- Power-management chip consumes 120 mW.
- On interval duration is roughly 6600 clock cycles.
- Duo 230 display consumes 200 mW.
- Duo 230 video controller and VRAM consume 350 mW.
- Duo 270c/280c display consumes 750 mW.
- Duo 270c/280c video controller consumes 370 mW.
- Duo 270c/280c VRAM consumes 90 mW.

Item measured	Duo 230	Duo 270c	Duo 280c
...by PowerMeasure			
Maximum power consumption	7.84 W	10.08 W	12.08 W
Power saved by spinning hard drive down	0.96 W	1.22 W	1.48 W
Power saved by turning modem off	0.58 W	0.51 W	0.58 W
Power saved by turning sound system off	0.19 W	0.19 W	0.19 W
Power difference between CPU at 16 MHz and at 33 MHz	1.09 W	1.35 W	N/A
Power difference between backlight off and at full	2.38 W	3.21 W	3.40 W
Energy saved by cycling CPU once during 16 MHz operation	0.013 W-s	0.014 W-s	N/A
Energy saved by cycling CPU once during 33 MHz operation	0.019 W-s	0.022 W-s	0.028 W-s
Energy consumed by spinning hard drive up	11 W-s	8.8 W-s	4.4 W-s
Maximum CPU cycling rate observed at 16 MHz	116 Hz	125 Hz	N/A
Maximum CPU cycling rate observed at 33 MHz	120 Hz	126 Hz	130 Hz
...by means other than PowerMeasure			
CPU power at 33 MHz	1.15 W	1.15 W	3.33 W
FPU power in typical operation	N/A	0.46 W	N/A
Power management power	0.12 W	0.12 W	0.12 W
Display power	0.20 W	0.75 W	0.75 W
Video power	0.35 W	0.46 W	0.46 W
Memory power	0.06 W	0.06 W	0.06 W
Reducible misc power at 33 MHz	1.19 W	1.23 W	0.41 W
Nonreducible misc power at 33 MHz	0.66 W	0.72 W	1.30 W

Table 3: Power consumption results obtained for all three machines

We also used our hardware instrumentation of a Duo 230 to measure its power consumption while asleep. Since only the 12 MB of DRAM is active while the machine is asleep, we attribute the 0.06 W we measured to the memory. We use the same result for the Duo 270c and Duo 280c, since they typically have the same amount of DRAM.

There are two additional things we must know in order to fully break down power consumption. First, we must know how to compute the power consumption of a reducible component given the rate at which halt cycles occur. Second, we must know how much of the miscellaneous component is reducible and how much is nonreducible.

We can compute the average power consumption of a reducible component by multiplying its full power consumption by the fraction of time the processor is on. One can compute the fraction of time the processor is off by multiplying the rate at which halt cycles occur by the amount of time the processor spends off per halt cycle. In summary, if the full power consumption of a reducible component is p, the cycling rate is r, and the duration of an off interval is d_{off}, then its average power consumption is

$$(1 - d_{\mathrm{off}} r)\, p.$$

If we assume that the maximum cycling rate observed is the maximum achievable on the machine, i.e. the result of beginning a halt cycle as soon as the previous one has ended, then the reciprocal of this rate must be the sum of the on and off interval durations. Thus, we can compute the duration of an off interval from the maximum possible cycling rate possible r_{max} and the duration of an on interval d_{on} with the following equation:

$$d_{\mathrm{off}} = 1/r_{\mathrm{max}} - d_{\mathrm{on}}.$$

The energy savings e attained from each halt cycle are due to saving the power of all reducible components for a period of time equal to d_{off}. Thus, the full power consumption of all reducible components together is e/d_{off}. We can obtain the power consumption of the reducible miscellaneous component by subtracting from this value the power consumptions of the CPU and FPU.

The bottom half of Table 3 summarizes the results of our estimates and computations for the motherboard components of each machine.

An interesting result of these computations is that the Duo 280c differs greatly from the other machines in the fraction of miscellaneous power consumption that is reducible. This fraction is 64% on the Duo 230 and 63% on the Duo 270c, but only

24% on the Duo 280c. This may be because on the Duo 280c, the MBT lies between the processor and the rest of the motherboard, making less apparent to the rest of the motherboard when the processor is off. The result of this lower fraction on the Duo 280c is that it gets significantly less non-CPU power savings from processor cycling than the other Duos. Perhaps, if the motherboard were designed differently, more power could be saved during processor cycling on the Duo 280c.

Frequency of component states

StateProfiler profiled seven users while their machines were running on battery power and awake, and the resulting data are shown in Table 4. Users 1–6 were engineers; user 7 was a researcher. In this table, backlight levels are expressed as percentages of the maximum possible power consumption of the backlight. In addition, cycling rates are expressed in Hz, or times per second. Note that there was no use of the 16 MHz setting of the processor. Also, users 1 and 7 had different hard disk sizes than the machines we measured with PowerMeasure. For the purposes of later calculations, we will overlook this fact, since it seems likely that had these users been using the same hard disk sizes as the machines we studied, their usage patterns would not have changed. Similarly, users 3 and 5 had different memory sizes than the machines we measured, but hopefully this did not have a noticeable effect on their usage patterns.

For future calculations, we will aggregate all the users on each machine into a composite. We form the composite profile of a set of users by simply concatenating their profiles. We never aggregate users who worked on different machines, because usage patterns are probably highly dependent on the machine used. For instance, a user might prefer a different backlight level on a color machine than on a black-and-white one. Also, a user with a faster processor will begin tasks that are dependent on the results of previous processing sooner.

5 Discussion

Maximum power consumption

The figures obtained by PowerMeasure and by other means allow us to break down the total power consumption of each machine when each component is in its highest-power state. Table 5 shows these breakdowns. We see that, when all components are active, the components consuming the most power are the backlight, the processor, and the hard drive. These three components account for 57% of the Duo 230 power, 55% of the Duo 270c power, and 68% of the Duo 280c power.

We can compare these results with an estimate of the power consumption breakdown of a hypothetical 33 MHz Am386 DXL system described by MacDonald [22]. This system is generally similar in architecture to the Duo 230, except that it has a floppy drive but no sound or modem. The estimates given by MacDonald for the machine with all components in their highest-power states, based on actual and estimated data for various components, indicate that out of a total power consumption of 13.03 W, 13% is due to the processor, 14% is due to the hard drive, 13% is due to the backlight, 4% is due to the display, 1% is due to the FPU, 16% is due to the video system, 1% is due to power management, 2% is due to memory, and 1% is due to the floppy drive. These percentages are similar to those given for the Duo 230, although the backlight on the Duo 230 consumes a noticeably greater percentage of total power and the video system consumes a noticeably lower percentage. Also, the Duo 230 has a total maximum power consumption 40% less than that of the hypothetical Am386 DXL system.

Effect of current power-saving features

The power consumption and user profile data can be combined to give a power consumption breakdown for each machine that takes into account the power-saving modes used in real environments. These breakdowns are presented numerically in Table 6. They are also shown graphically in Figure 2, in which they are compared to the corresponding breakdowns given no use of power-saving modes.

Comparison of Tables 5 and 6 reveals that users make large use of the power-saving modes available when running on battery power. Power reduction attained from these methods amounts to 42% on the Duo 230, 56% on the Duo 270c, and 35% on the Duo 280c. Roughly 35% of these savings are due to backlight savings, 20% are due to hard drive savings, and 35% (25% on the Duo 230) are due to processor cycling. Thus, the power-saving modes provided are together quite effective, with spinning down the hard drive, backlight dimming, and processor cycling each accounting for a significant portion of the savings attained.

Not only does the total power consumption of

Item measured	User 1	User 2	User 3	User 4	User 5	User 6	User 7
Machine used	230	270c	270c	280c	280c	280c	280c
Hard disk size	120 MB	240 MB	240 MB	320 MB	320 MB	320 MB	240 MB
DRAM size	12 MB	12 MB	24 MB	12 MB	24 MB	12 MB	12 MB
Time profiled (h:m:s)	8:45:40	11:36:25	3:24:10	5:09:00	1:41:10	2:29:45	14:14:44
% time hard drive off	62.20%	91.27%	63.88%	77.02%	85.17%	54.03%	53.38%
% time modem off	88.43%	100.00%	97.06%	95.90%	0.00%	100.00%	0.26%
% time sound off	98.30%	99.92%	98.73%	99.35%	99.01%	95.10%	76.90%
Mean backlight level	48%	36%	32%	41%	46%	32%	67%
Max backlight level	100%	100%	50%	100%	77%	100%	100%
CPU cycling rate	42.33 Hz	111.75 Hz	0.00 Hz	101.52 Hz	130.01 Hz	41.71 Hz	31.71 Hz
Avg time b/n spindowns	6.41 min	23.1 min	6.80 min	6.31 min	12.6 min	3.94 min	5.27 min

Table 4: Profile data for users

Component	Duo 230		Duo 270c		Duo 280c	
Processor	1.15 W	(14.67%)	1.15 W	(11.41%)	3.33 W	(27.57%)
Hard drive	0.96 W	(12.24%)	1.22 W	(12.10%)	1.48 W	(12.25%)
Backlight	2.38 W	(30.36%)	3.21 W	(31.85%)	3.40 W	(28.15%)
Display	0.20 W	(2.55%)	0.75 W	(7.44%)	0.75 W	(6.21%)
Modem	0.58 W	(7.40%)	0.51 W	(5.06%)	0.58 W	(4.80%)
Sound	0.19 W	(2.42%)	0.19 W	(1.88%)	0.19 W	(1.57%)
FPU	N/A	(0.00%)	0.46 W	(4.56%)	N/A	(0.00%)
Video	0.35 W	(4.46%)	0.46 W	(4.56%)	0.46 W	(3.81%)
Power management	0.12 W	(1.53%)	0.12 W	(1.19%)	0.12 W	(0.99%)
Memory	0.06 W	(0.77%)	0.06 W	(0.60%)	0.06 W	(0.50%)
Reducible miscellaneous	1.19 W	(15.13%)	1.23 W	(12.24%)	0.41 W	(3.37%)
Nonreducible miscellaneous	0.66 W	(8.47%)	0.72 W	(7.11%)	1.30 W	(10.79%)
Total (Type III battery life)	7.84 W	(2.16 hr)	10.08 W	(1.68 hr)	12.08 W	(1.40 hr)

Table 5: What the power consumption breakdown for each machine would be if power-saving modes were never used

Component	Duo 230		Duo 270c		Duo 280c	
Processor	0.75 W	(16.65%)	0.38 W	(8.66%)	1.96 W	(24.94%)
Hard drive	0.39 W	(8.64%)	0.19 W	(4.36%)	0.59 W	(7.55%)
Backlight	1.14 W	(25.22%)	1.16 W	(26.31%)	1.94 W	(24.75%)
Display	0.20 W	(4.42%)	0.75 W	(17.03%)	0.75 W	(9.56%)
Modem	0.07 W	(1.48%)	0.00 W	(0.08%)	0.40 W	(5.05%)
Sound	0.00 W	(0.07%)	0.00 W	(0.02%)	0.02 W	(0.36%)
FPU	N/A	(0.00%)	0.15 W	(3.46%)	N/A	(0.00%)
Video	0.35 W	(7.73%)	0.46 W	(10.45%)	0.46 W	(5.86%)
Power management	0.12 W	(2.65%)	0.12 W	(2.73%)	0.12 W	(1.53%)
Memory	0.06 W	(1.32%)	0.06 W	(1.36%)	0.06 W	(0.76%)
Reducible miscellaneous	0.78 W	(17.17%)	0.41 W	(9.29%)	0.24 W	(3.05%)
Nonreducible miscellaneous	0.66 W	(14.66%)	0.72 W	(16.27%)	1.30 W	(16.60%)
Total (Type III battery life)	4.53 W	(3.74 hr)	4.40 W	(3.85 hr)	7.85 W	(2.16 hr)

Table 6: Power consumption breakdown for each machine, taking into account observed use of power-saving modes

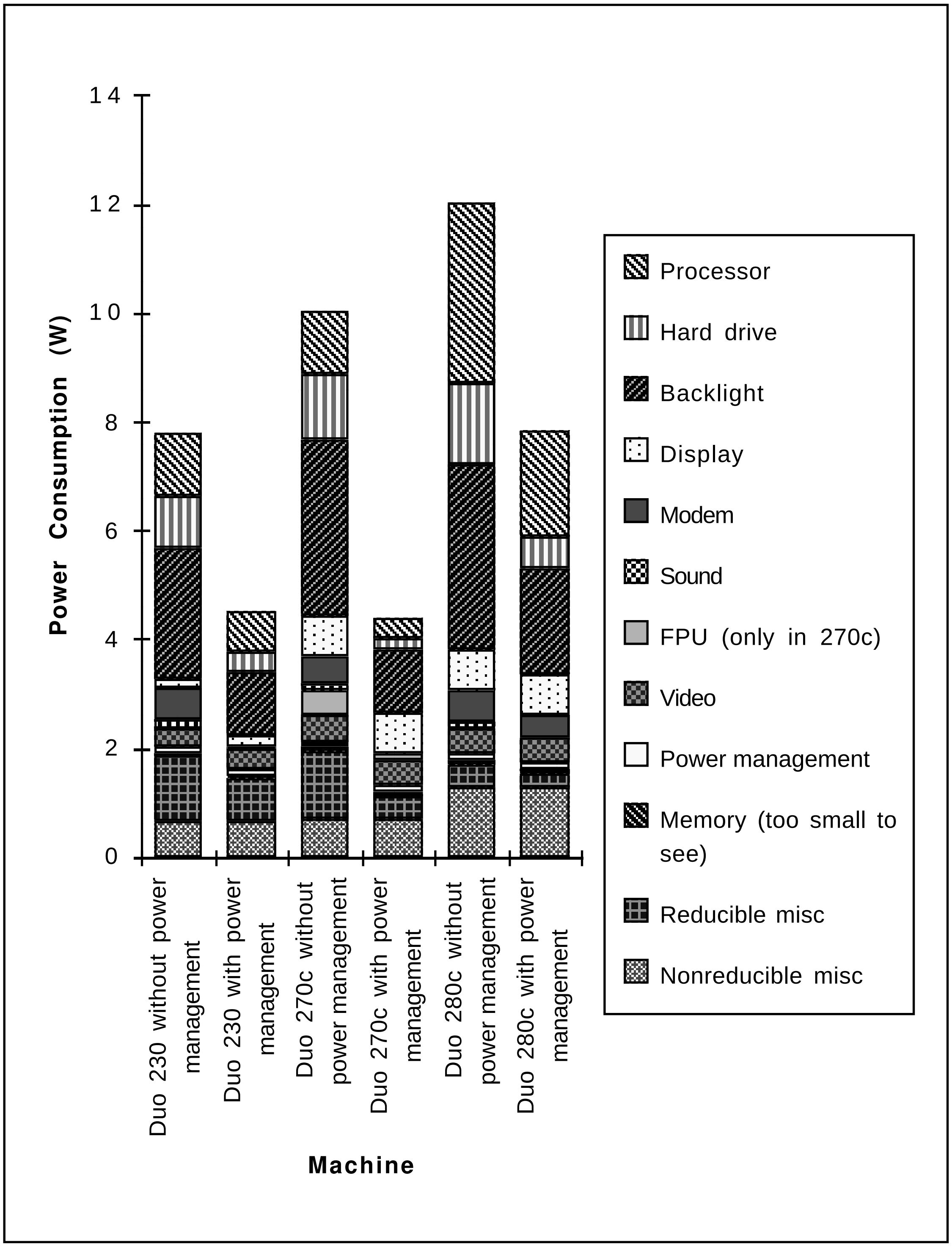

Figure 2: Power consumption breakdowns for each machine, given no use of power-saving modes and observed use of power-saving modes

each machine decrease when power-saving modes are used, but the breakdown of this power consumption changes. For instance, the hard drive, which normally accounts for about 12% of total power consumption, only accounts for 4–9% of this power consumption when power savings are taken into account.

We must be cautious when interpreting all of these figures, because as Table 4 shows, different users have widely different usage patterns for each power-saving feature. Although we present results about composites of users, we must keep in mind that different users will have different total power consumptions and different breakdowns of power consumption. We can therefore expect the influence of a power-saving strategy to be different for different users.

One interesting finding is that users completely avoided the 16 MHz CPU speed. This seems to indicate that they do not think the power savings this feature provides are worth its performance penalty. This is not surprising, considering that halving the CPU speed, although it halves the power consumption, also doubles the time it takes to complete the CPU portion of a task. Thus, the total energy needed to complete the CPU portion of a task is invariant with CPU speed. As long as the processor does not run when it has no tasks to perform, there is no benefit to reduced speed; since processor cycling attempts to restrict processor-on times in just this way, 16 MHz operation should not yield large power savings. Note, however, that if the voltage were reduced when CPU speed was reduced, as Weiser et al. [28] suggest, then we could expect larger power savings.

We can compare these Duo results with those of the hypothetical Am386 DXL system described earlier, by taking into account MacDonald's estimates of the usage of low-power states of that machine [22]. These estimates lead to an average power consumption figure of 6.17 W, divided into 4% for the processor, 12% for the hard drive, 17% for the backlight, 4% for the display, 1% for the FPU, 26% for video, 3% for power management, 3% for memory, and 2% for the floppy drive. The main differences between these figures and those of the Duo 230 are that the Duo 230 has a significantly greater percentage of its power going to the processor, hard drive, and backlight, while the hypothetical Am386 DXL system has a greater percentage of its power going to video. Also, the Duo 230 consumes 27% less power under average conditions than the hypothetical Am386 DXL system.

Although this study concerns the power consumption of machines while they are running on battery power, a comparison of these results with what happens when wall power is used may be interesting. Table 7 shows the power consumption breakdown of each machine given the use of power-saving modes by our seven users while their machines were running on wall power. Note that the results on which these figures are based are not presented in this paper. We observe, unsurprisingly, that users use power management features less when they are running on wall power. Generally, the hard drive and CPU are allowed to consume nearly their maximum possible power, although roughly the same level of backlight savings are attained as when running on battery power. This may imply that users are especially bothered by the processor cycling and hard drive spindown features. We also find that the lesser use of power-saving modes leads to a greater proportion of power consumption being attributable to the hard drive, CPU, FPU, and reducible miscellaneous components. Therefore, any new power-saving feature will have a different impact on a machine when it is running on wall power than when it is running on battery power.

Effect of different software techniques

Our figures allow us to evaluate the effect of other power-saving techniques on total power consumption. For example, Li et al. [19] suggest a way to reduce total hard drive power consumption by 90%. Our studies show that the average Duo 280c user already saves about 60% of hard drive power. Furthermore, currently about 7.6% of total power is due to the hard drive. Combining these figures, we find that Li et al.'s technique would reduce total Duo 280c power consumption by about 5.7%, increasing battery lifetime by about 6%. Of course, for different machines and for individual users these figures may be different; to get answers for such situations one must appropriately replace figures in the above calculation.

Weiser et al. [28] indicate that if their algorithms are used to reduce CPU speed and voltage simultaneously, they can save as much as 50% or 70% of CPU power, depending on whether the minimum voltage available is 3.3 V or 2.2 V. Let us assume that all reducible components, not just the CPU, would exhibit this 50% or 70% power reduction using Weiser et al.'s method. As the reducible components account for 28.0% of the total Duo 280c power consumption, the new method could save as

Component	Duo 230		Duo 270c		Duo 280c	
Processor	1.15 W	(23.79%)	0.65 W	(10.71%)	3.13 W	(31.98%)
Hard drive	0.96 W	(19.86%)	1.22 W	(20.18%)	1.19 W	(12.12%)
Backlight	0.14 W	(2.95%)	1.12 W	(18.55%)	2.09 W	(21.39%)
Display	0.20 W	(4.14%)	0.75 W	(12.38%)	0.75 W	(7.66%)
Modem	0.00 W	(0.00%)	0.00 W	(0.00%)	0.30 W	(3.05%)
Sound	0.00 W	(0.01%)	0.00 W	(0.01%)	0.00 W	(0.04%)
FPU	N/A	(0.00%)	0.26 W	(4.29%)	N/A	(0.00%)
Video	0.35 W	(7.24%)	0.46 W	(7.59%)	0.46 W	(4.70%)
Power management	0.12 W	(2.48%)	0.12 W	(1.98%)	0.12 W	(1.23%)
Memory	0.06 W	(1.24%)	0.06 W	(0.99%)	0.06 W	(0.61%)
Reducible miscellaneous	1.19 W	(24.54%)	0.70 W	(11.49%)	0.38 W	(3.91%)
Nonreducible miscellaneous	0.66 W	(13.74%)	0.72 W	(11.83%)	1.30 W	(13.31%)
Total (Type III battery life)	4.83 W	(3.51 hr)	6.06 W	(2.80 hr)	9.79 W	(1.73 hr)

Table 7: Power consumption breakdown for each machine given the composite usage pattern of the set of users who used that machine while they were running on wall power

much as 14% or 20% of total power consumption, increasing battery lifetime by 16% or 24%.

Not only can we determine how much power savings are achievable through various new software techniques, we can determine upper bounds on how much savings could be achieved through such techniques. The percentages shown in Table 6 give upper bounds on the potential power savings achievable through better power-saving techniques for a given component. For example, since the hard drive on the Duo 280c only accounts for 7.6% of the total power consumption, the most reduction in power consumption possible through better hard drive power-saving techniques is 7.6%. We observe then, that more hard drive power reduction can save at most 4–9%, backlight power reduction 25–26%, and modem power reduction 0–5%. Greater processor cycling could save at most 33.8% on the Duo 230, 18.0% on the Duo 270c, and 28.1% on the Duo 280c. Reducing the video power consumption, perhaps by turning off the display when it is not in use, could save at most 7.7% on the Duo 230, 10.5% on the Duo 270c, and 5.9% on the Duo 280c. Note that different machines are affected differently by the power reduction of a given component.

Effect of different hardware

Our breakdowns of power consumption can also be used to estimate the impact of hardware changes, as long as one knows the power consumption of the alternative components to be used. Some examples of such information are presented in Table 8, which gives power consumption figures for a variety of components. These figures allow us to estimate how much power consumption would be reduced by switching to other components.

We have discussed how reducing the speed of the CPU to reduce power consumption does not work well, since the reduction in power consumption is offset by the fact that the CPU will have to run longer and thus consume power for a longer period of time. A better strategy for reducing the power consumption of the CPU is to use a processor with a better ratio of performance to power consumption. For example, if we could accept a reduction in the CPU performance of the Duo 280c of about 60%, we could switch from the 34.8 MIPS, 3.33 W, 33 MHz 68LC040 [8] to the 13.5 MIPS, 0.29 W, 20 MHz 92010 Hobbit [6], thus increasing MIPS per watt from 10.5 to 47. Since the Hobbit has about 40% of the performance of the 68LC040, and the 68LC040 only spends about 40% of its time off due to processor cycling, let us pessimistically assume that the Hobbit would never get a chance to use processor cycling. Thus, the reducible miscellaneous power consumption would always be at its maximum level. However, this maximum level should be lower than that of the Duo 280c, since the processor is doing less work per unit time. Let us assume, then, that maximum reducible miscellaneous power consumption is proportional to CPU performance. Thus, in this new scenario, it would be

$$\frac{13.5 \text{ MIPS}}{34.8 \text{ MIPS}} \times 0.41 \text{ W} = 0.16 \text{ W}.$$

Thus, CPU power consumption would decrease

Type	Description	Power	Source
Processor	20 MHz 92010 Hobbit, 3.3 V	0.29 W*	[6]
	Motorola 68349	0.35 W*	[28]
	20 MHz ARM610, 5 V	0.58 W*	[17]
	25 MHz Intel486 SL	1.15 W*	[15]
	33 MHz Motorola 68030	1.15 W	This paper
	33 MHz PA-RISC PA/50L	1.50 W*	[24]
	33 MHz Am386 DXL	1.59 W*	[22]
	40/80 MHz MIPS R4200	1.73 W*	[29]
	50 MHz PowerPC 603 with dynamic power management	1.75 W*	[27]
	66 MHz PowerPC 603 with dynamic power management	2.17 W*	[27]
	60 MHz experimental 2.0-V PowerPC 601	2.30 W*	[7]
	80 MHz PowerPC 603 with dynamic power management	2.53 W*	[27]
	25 MHz Intel386 SL	2.88 W*	[15]
	33 MHz Motorola 68LC040	3.33 W	This paper
	25/50 MHz MicroSPARC	4.60 W*	[29]
FPU	Cyrix 83D87	0.15 W*	[22]
	Motorola 68882	0.46 W	This paper
Display (mono)	Used in Duo 230: 9"	0.20 W	This paper
	Used in Sharp PC 6785	0.32 W	[16]
	Suggested for Intel386 SL system	0.35 W	[14]
	Suggested for Am386 DXL system	0.46 W*	[22]
	Toshiba reflective 7.9" TFD AMLCD prototype†	0.46 W*	[9]
(color)	Used in Duo 270c/280c: 8.4"	0.75 W	This paper
	Sharp "typical" color display	3.45 W*	[9]
	Micron Display Technology estimate of a 10" FED†	< 5.75 W*	[10]
Backlight (mono)	Used in Sharp PC 6785	1.43 W	[16]
	Suggested for Am386 SL system	1.56 W*	[22]
	Suggested for Intel386 SL system	2.00 W	[14]
	Used in Duo 230: 9", intensity 70 cd/m^2	2.38 W	This paper
(color)	Used in Duo 270c: 8.4", intensity 70 cd/m^2	3.21 W	This paper
	Used in Duo 280c: 8.4", intensity 70 cd/m^2	3.40 W	This paper
	Toshiba 9.5", intensity 60 cd/m^2	3.45 W*	[9]
	Toshiba 9.5", intensity 70 cd/m^2	4.14 W*	[9]
Hard drive	HP Kittyhawk C3014A	0.72 W*	[23]
	Caviar Ultralite CU140	0.81 W*	[13]
	Used in Dell 320SLi	0.90 W	[12]
	Used in Duo 230	0.96 W	This paper
	Used in Zenith Mastersport SLe	1.00 W	[12]
	IBM DB0A-2720	1.09 W*	[18]
	Used in Sharp PC 6785	1.10 W	[16]
	Quantum Go•Drive	1.15 W*	[12]
	Maxtor MXL-105 III	1.15 W*	[19]
	Suggested for Intel386 system	1.20 W	[14]
	Used in Toshiba T3300SL	1.20 W	[12]
	Used in Duo 270c	1.22 W	This paper
	Suggested for Am386 system	1.38 W*	[22]
	Used in Duo 280c	1.48 W	This paper

* indicates a figure that we have inflated by 15% to account for power supply inefficiency
† indicates a display not needing a backlight

Table 8: Comparison of power consumption of components studied in this paper to power consumption of components described elsewhere

from 1.96 W to 0.29 W and the reducible miscellaneous power consumption would decrease from 0.24 W to 0.16 W, for a total decrease in power consumption of 1.75 W, or 22%. This would increase battery lifetime by 29%, which would be 0.62 hr on a Type III battery. Note, however, that the switch to a lower-power, lower-speed processor could wind up increasing the power consumption of other components. For instance, if it caused the user to spend more time looking at the screen and thus needing the backlight at its maximum level, the backlight power consumption could increase from 1.94 W to as much as 3.40 W, offsetting much of the power consumption advantages of the lower-power processor. The lower speed of the processor might also spread out disk accesses, reducing the amount of time the hard drive spends spun down. Note, finally, that the lower performance of the processor would mean that the user might have to leave the machine on for longer to accomplish a given set of tasks, leading to an even higher standard for acceptable length of battery lifetime.

Another way to get a higher ratio of performance to power consumption out of the processor is to use the 80 MHz PowerPC 603. This chip has an estimated performance of 75 SPECint92, roughly 92 MIPS, but consumes only 2.53 W, for a ratio of about 36 MIPS per watt. If we switched from the Duo 280c to the PowerPC 603, we could expect processor cycling to occur at a greater rate since the processor would complete its tasks sooner. Currently, the processor spends only 59% of its time on due to processor cycling. Since processor performance would increase by a factor of about 2.64, we may estimate that the processor would only have to spend $59\% \div 2.64 = 22\%$ of its time on. Thus, the power consumption of the CPU would be 22% of 2.53 W, or 0.56 W. If we make the same assumption as before, namely that the maximum reducible miscellaneous power is proportional to the performance of the CPU, then we can estimate that the new machine would have a maximum reducible miscellaneous power of

$$\frac{92 \text{ MIPS}}{34.8 \text{ MIPS}} \times 0.41 \text{ W} = 1.08 \text{ W}.$$

Since the reducible miscellaneous component would only be consuming power 22% of the time, its average power consumption would be 0.24 W. Total power savings would be

$$(1.96 \text{ W} + 0.24 \text{ W}) - (0.56 \text{ W} + 0.24 \text{ W}) = 1.40 \text{ W},$$

or 18%. This would yield a battery lifetime increase of 22%, which would be 0.47 hr on a Type III battery. Note that using a higher-performance processor might also cause the power consumption of other components to be reduced. For example, the user may spend less time waiting for the CPU and needing the backlight on.

We can also estimate the impact of using other peripherals that consume less power. For instance, using the more modern IBM DB0A-2720 720-MB hard drive on the Duo 280c would save roughly

$$\frac{0.59 \text{ W}}{1.48 \text{ W}} \times (1.48 \text{ W} - 1.09 \text{ W}) = 0.16 \text{ W},$$

or 2.0% of total power. Note, however, that other features of a different hard drive could change this analysis. For instance, if the new hard drive had bigger track buffers, and thus needed to seek less often, its power consumption might be even further reduced.

Another technique for reducing the power consumption of the disk is to replace it with flash memory, as suggested by Douglis et al. [13]. They indicate that one such product can save 90% of hard drive power, even in the presence of disk power management. Given our figures, this would represent a total system power reduction for the Duo 280c of about 6.8%. Furthermore, our figures show an upper bound on the effectiveness of flash memory in this regard: if it eliminated 100% of hard drive power and consumed negligible power itself, then total Duo 280c power consumption would decrease by about 7.6%.

Limitations of the study

The following factors limit the results of this study. First, the model of power consumption we use does not account for transient events such as sound emissions, disk seeks, memory accesses, modem use, and bus activity. Second, PowerMeasure cannot separate the power consumption of two component states that are always coexistent in the computers studied; therefore we had to use unverified estimates for the power consumption of individual motherboard components. Third, the results obtained from PowerMeasure have limited accuracy, as evidenced by the hardware validation and by the differences in values obtained for the same component in different trials. Fourth, we do not account for power savings achieved through use of the sleep mode.

6 Future Work

Research

There are at least four categories of further study emanating from this research. First, there is study which extends the results. Our model should be extended to take into account the energy consumed during such transient events as sound emissions, disk accesses, waking from sleep, and modem transmissions. We also need a better model for the breakdown of motherboard power consumption. We would like to obtain more diverse user profiles, since the current set comes only from employees at Apple Computer, Inc., and these users did not use battery power often. In addition, more work is needed to apply the principles of this paper to desktop machines. Power consumption is increasingly becoming an important issue for desktop machines, as the government and consumers demand machines consuming less power and dissipating less heat. The most visible evidence of this trend is the Environmental Protection Agency's Energy Star program, which is setting standards for low power consumption on the desktop.

The second category is research that analyzes the relationship between the parameters of power-saving strategies, component power consumption, and system performance. For instance, more research is needed to describe how different hard drive inactivity time-out values simultaneously affect both the access latency and power consumption of the hard drive. Once such a relationship is known, it can be used along with the results of this paper to show a user what trade-off between battery lifetime and performance he would be making for each time-out value he could select. It is important to let the user indicate his preferences about power consumption, and to get the maximum benefit from his input one must provide him with enough information to make an informed decision.

The third category of further study is the development and evaluation of new software techniques for reducing the power consumption of laptops. Such study requires tools that obtain detailed, time-stamped traces of those user and system activities that have potential impact on the states of the system components. As described before, work has already been done on strategies to reduce disk power consumption by more frequent spinning down or replacement with flash memory, and on strategies to reduce processor power using voltage scaling and dynamic speed adjustment. We hope that the results presented in this paper serve both as an indication of what power-saving techniques are most promising for future study and as a tool in the analysis of such techniques. We are currently working on improved techniques to make use of processor cycling on Macintosh portables, as it seems from this study that this is the most promising avenue for these machines.

The fourth category of further study is in how to design hardware components that consume less power. Since the processor and backlight account for the largest percentage of total power, these are the components of which it is most important to develop lower-power versions. Other components whose power consumptions are significant are the hard drive and display.

Product development

The findings of this paper also suggest things that can be done immediately to improve the type of products studied. First, support for multiple CPU speeds, all with the same operating voltage, does not seem to be worth the cost and effort of the technology and operating systems support for them. Lower CPU speeds are generally only worthwhile if they allow simultaneous reduction in the operating voltage. Second, we have seen that the Duo 280c shows much less reduction in miscellaneous power consumption as a result of processor cycling than the Duo 230 and the Duo 270c. This suggests that the Duo 280c motherboard could be redesigned to improve the effect of processor cycling on the power reduction of other components. In general, when designing a motherboard, it is important to keep in mind how power reduction of the CPU will translate into power reduction of other components. Third, we have seen that the greatest sources of power consumption are the processor and backlight. Therefore, designers of new products should be especially eager to take advantage of new versions of these components that provide greater ratios of performance to power consumption, such as the PowerPC 603.

7 Conclusions

This paper illustrates, using the Duo line of portable computers, how power consumption in portable computers can be and is reduced by software and hardware techniques. The first part of this illustration is how power consumption is reduced by power-saving features currently available. Without power-saving modes, the Duo 230 consumes 7.84 W, the Duo 270c consumes 10.08 W, and the Duo 280c consumes 12.08 W. However, using the power-saving features currently provided reduces these to 4.53 W for the Duo 230, 4.40 W for the Duo 270c, and 7.85 W for the Duo 280c. About 35% of these savings come from dimming the backlight, 20% from spinning down the hard disk, and 35% (25% on the Duo 230) from processor cycling.

The next part of our discussion demonstrates how power consumption could be further reduced by additional software techniques. We find that aggressive spinning down of the hard disk, as suggested by Li et al. [19], could reduce power consumption of the Duo 280c by about 5.7%. We also find that using Weiser et al.'s technique [28] for reducing the speed and voltage of the CPU simultaneously could reduce Duo 280c power consumption by as much as 14% or 20%, depending on how low a limit on voltage was imposed by the hardware. Finally, we show that there are upper bounds on the potential savings from additional software techniques, dictated by the percentages of total power attributable to each component. We see that depending on which machine he uses, the average user cannot hope to get more than an additional 18–34% from CPU cycling, 25–26% from backlight power reduction, 4–9% from hard drive power reduction, or 0–5% from modem power reduction.

Power consumption can also be reduced by substituting different components for those currently used. Using the lower-performance 20 MHz 92010 Hobbit could decrease Duo 280c power consumption by as much as 22%, although this figure may be significantly lowered by the fact that non-motherboard components would probably rise in power consumption due to the lower performance. Using the higher-performance PowerPC 603 could decrease Duo 280c power consumption by 18%, although this figure might be higher due to the reduction in non-motherboard power consumption we can expect from a higher-performance processor. We also show how using a lower-power disk drive, the IBM DB0A-2720, may reduce the Duo 280c power consumption by 2% even though it increases the disk capacity by a factor of 2.25.

From our results, we can form some general conclusions about how the efforts to reduce portable computer power consumption should proceed. First, since the processor and backlight consume the highest percentages of total power, development of software and hardware techniques to reduce their power consumptions is especially crucial. The hard drive and display also consume large percentages of total power, so the reduction of their power consumptions is also important. Second, designers of portable computers should consider the effect of the power consumption of one component on the power consumption of others, e.g. how much motherboard power can be saved when the processor power is reduced. Finally, since the effect of a power-saving strategy can be strongly dependent on the user environment in which it is applied, user variability must be taken into account when evaluating such a strategy, and a system that implements such a strategy should measure and consider user preferences and activity patterns during its operation.

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