8-1-1996

Power Management in Mobile Computing (a Survey)

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University of Pennsylvania Department of Computer and Information Science Technical Report No. MS-CIS-98-26.

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Disciplines

Computer Sciences

Comments

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1998

Power Management in Mobile Computing*

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August 1996

Abstract

Rapid advances in technology have resulted in laptop (mobile) computers with performance and features comparable to desktop (stationary) machines. Advances in rechargeable battery technology have failed to keep pace, decreasing the usefulness of mobile computers and portable wireless devices.

Several methods of power management can be used to prolong the battery life of a mobile computer. We provide a detailed analysis of power consumption typically encountered in a networked laptop computer and the power management methods currently used. We also outline some novel proposed power management methods.

1 Introduction

Laptop computers have often served as portable word processors or game machines. Such machines were generally two or more generations behind desktop computers in terms of processing power, features and performance. Limitations in display and miniaturization technology prevented laptops from being able to compete with desktops as "real" (i.e. full featured) computers.

Recent advances in technology have dramatically improved laptop performance and it is increasingly common to see software development being done on a laptop. Laptops with a 133 MHz Pentium processor, 1.2 Gigabyte hard disk, modular 6x CD ROM drive and 12.1 inch SVGA display are available in mid-1996, albeit at a price premium over comparable desktops. A survey in Computerworld [7] predicts that the number of workers using portable computers will expand from about one in five today to about one in three by the year 2000, and that 80% of portable users will use their portables as their primary machines, up from the current 30%. This optimistic view is heavily dependent on laptops being able to overcome some key drawbacks. In addition to a price premium, laptops have another significant disadvantage compared to desktops—limited battery life.

1.1 Background

The major components of a typical laptop are the microprocessor (CPU), liquid crystal display (LCD), hard disk, system memory (DRAM), keyboard/mouse, CD ROM drive, floppy drive, I/O subsystem, audio subsystem and in the case of a mobile computer, a wireless network card. There are other components, but these are significant consumers of power. The CPU/motherboard of a laptop poses several design problems not found in a desktop. In addition to the power it consumes, there are also extreme thermal dissipation and space concerns. Because of these issues, laptop CPU's are still typically several months behind desktop CPU's in terms of processing power.

The display is another major power consumer and again poses problems not found in a desktop machine. Unlike the Cathode Ray Tube (CRT) monitors used in all desktops, there are two major types of displays

*This work was supported by the Hewlett-Packard Research Grants Program, the AT&T Foundation, NSF #CDA-92-14924, and DARPA #MDA972-95-1-0013.

used in laptops - passive dual scan (STN - Super Twisted Nematic) and active matrix (TFT - Thin Film Transistor). The dual scan display is cheaper and easier to manufacture but has poorer picture quality, especially when displaying fast-moving images. The active matrix display produces excellent picture quality but at a higher cost and greater power consumption. Active matrix displays are also more difficult to manufacture and very often have several defective pixels in them. Table 1 shows some of the differences between typical desktop and laptop displays[1].

Display type	Display size (diagonal inches)	Weight (lbs)	Power Consumed (Watts)	Resolution (pixels)	Number of colors
Desktop	17"	47.4	190 (max)	1280x1024	unlimited
Laptop	11.3"	1.1	2.7	800x600	262,144

Table 1: Comparison of typical laptop and desktop displays.

In addition to reducing the physical size (i.e. form factor), laptop drive design also requires increased tolerance for mechanical shocks and the ability to spin up faster than desktop drives. The latter is necessary because laptop drives get spun down more often in order to reduce power consumption (this is explained in more detail in Section 4.1). Table 2 shows the contrast between typical[2] desktop and laptop drives. The differences in power consumption are very significant, as we will see later in this paper.

Type	Capacity (MBytes)	Size ($inches^3$)	Weight (lbs)	Power (R/W) (Watts)	Power (Idle) (Watts)	Shock Tolerance (Gs)
Desktop	2113	15.0	1.0	7.0	3.2	2
Laptop	810	8.3	0.4	2.1	1.0	100

Table 2: Comparison of laptop and desktop hard drives

All of the subsystems of the laptop share a single battery as their primary source of power when not plugged into a wall outlet. There is usually an additional small battery for the real time clock and for memory backup, but this is not relevant to our discussion.

A mobile computer (for the purposes of this paper, we define a mobile computer as a laptop computer with wireless networking capabilities) has severe limits on its electrical power usage, and a frequent complaint about mobile computers is the short lifespan of the battery [11]. Battery life is rarely more than 2-3 hours for a heavily-used laptop. Additional features, such as larger color displays, larger and faster hard disks, powerful processors, more memory and CD-ROM drives are becoming common, and result in increased electrical power demands. Unfortunately, laptop batteries are not advancing as rapidly as the other subsystems (for a comparison, see Figure 1). Each new feature, unless managed properly, will only further reduce battery life and inhibit untethered operation.

1.2 Overview

In the next section we discuss laptop batteries and show why batteries are unlikely to improve significantly in the forseeable future. Section 3 examines relative power consumption of the major subsystems of a laptop. In Section 4 we survey currently applied power management techniques for each of the subsystems, and discuss some of the problems associated with them. Section 5 outlines several new power management ideas.

[1]The monitor is a Nanao FlexScan T2-17TS and the laptop display is Fujitsu's FLC29SVC6S Active Matrix LCD
[2]The desktop drive is a Seagate Medalist Pro 2.1 and the laptop drive is a Seagate Marathon 810

2 The Problem with Batteries

A battery's performance can be characterized by the total amount of energy it can store (i.e. power x duration) and the physical dimensions (weight and size) of the battery. The total energy available from a battery is a design issue and is fixed at design time, along with its weight and size. The only value available for manipulation by the user is duration, or battery life. Short battery life plagues mobile computer users to whom the stark contrast between exponential and non-exponential technology improvement rates are particularly evident.

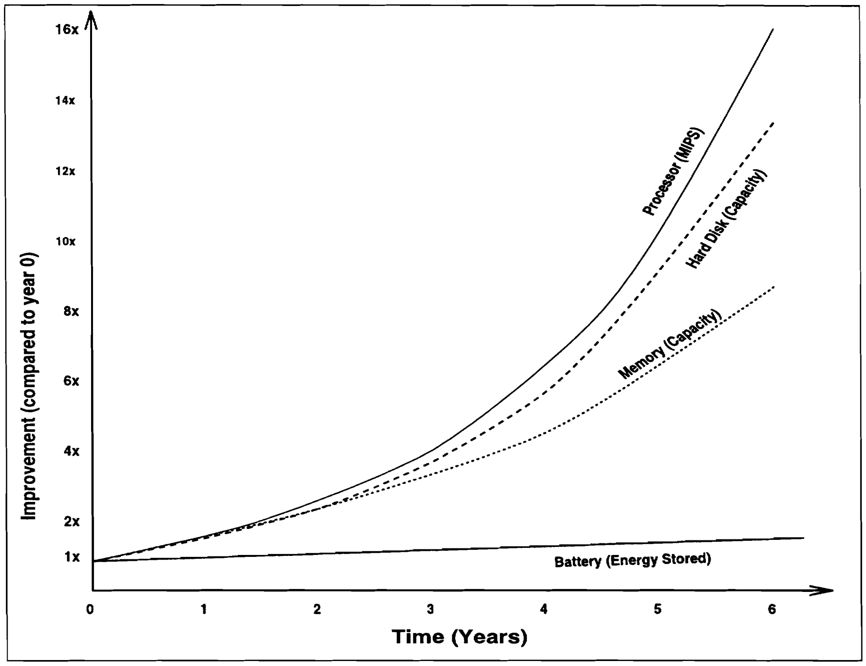

Figure 1: Approximate performance/capacity growth of major laptop components

Figure 1 shows the approximate time it takes for the some of the major subsystems of a laptop to double in performance or capacity [2, 19]. In general, an unmanaged performance or capacity increase also indicates some increase in power consumption. Based on current research, the growth rate of battery power output through the year 2000 is expected to be no more than 20% [19].

Advancements in power storage technology are slow in comparison to the other subsystems of a mobile computer. At present there is a shift from Nickel Cadmium (NiCd) and Nickel Metal Hydride (NiMH) batteries to Lithium Ion (Li-ion), which has a significantly better gravimetric energy density (energy per unit of weight) and longer recharge cycle life, as shown in Table 3. Li-ion batteries took many years to develop and have some disadvantages compared to NiCd batteries—they can require an additional 2-3 hours to reach their maximum charge compared to NiCd batteries, and require much stricter voltage regulation when charging [11]. Significant advances in battery technology take many years and are unable to keep pace with the growth of laptop power consumption.

An important issue in mobile computing is battery weight. One impractical solution to the limited battery life problem would be to carry multiple spare batteries and simply replace them as necessary. There are also laptops that allow a user to install two batteries in the laptop, extending the laptop's usage but at the expense of additional weight and the loss of a modular bay. The most recent advances in laptop batteries are in the form of better "fuel gauging" of the battery, to give a more precise measure of the charge level and to estimate the time left before a recharge is needed. For example, Intel-Duracell's Smart Battery Specifications [15] propose a common information mechanism for laptop rechargeable batteries. Although this is a useful measure, it does not extend battery life from the user's point of view.

Another issue that has been brought up with laptop batteries is that of safety. The current generation of

Battery Characteristic	Li-ion	NiMH	NiCd
Gravimetric Energy Density (Watt-hours/kg)	110	65	55
Volumetric Energy Density (Watt-hours/liter)	260	240	210
Recharge Life (Cycles)	1200	1000	1000
Memory Effect	No	Yes	Yes

Table 3: Some characteristics of common laptop batteries.

Li-ion batteries have had mixed reviews in terms of safety. A laptop that is recharged/used in an insufficiently ventilated area may cause the battery to burn out. Dropping the laptop may cause a short-circuit that could start a fire in the laptop [23]. This is not mere speculation – for example, Apple Computer had to recall their Powerbook 5300 laptops [1] because the batteries ignited under certain conditions. Battery manufacturers claim otherwise – documents from them show that the batteries in laptops can survive significant abuse (short-circuit, puncturing, heat etc.) without any danger of fire or explosion [3]. These contradictory claims make it hard to decide on the safety of Li-ion batteries. It is not clear whether some of the problems are caused by bad design, or misuse by the user.

We believe that these problems will increase as mobile computer use becomes more prevalent and batteries continue to increase in energy density. Again, the indications are that we must learn to use the available power more efficiently. Thus, unless there is a major advance in power management, the mobility of mobile computers is going to be severely restricted by short battery life.

3 The Balance Of Power

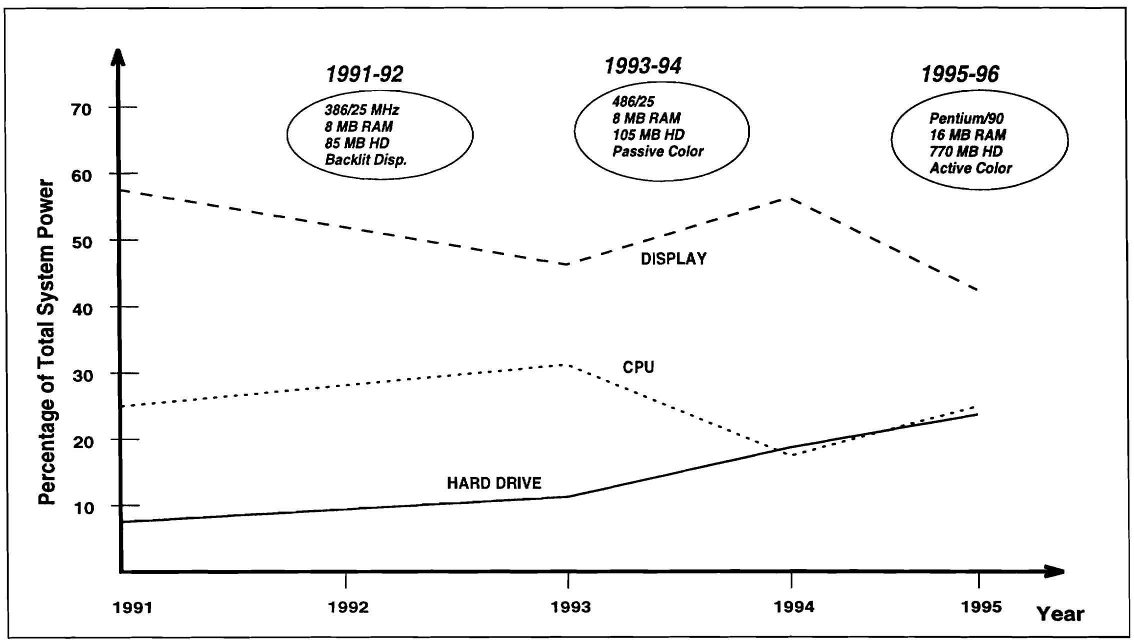

Figure 2: Percentage of total power consumed by major components in a typical laptop computer.

Figure 2 shows the change over the past few years in the fraction of total power consumed by the major subsystems of a laptop computer. The x-axis represents recent years, and the data is for typical laptop[3] computers for that year. The specifications for a laptop we consider typical for that year are included in the bubbles above the graph lines. The values in the graph are mostly experimental values from [9, 16, 18] and measurements by the authors, although some estimations have been made for 1992. The jump in the power consumed by displays (1993 to 1994) is due to the move from grayscale to color displays. It should be noted that although the percentage of total power used by the display for the newest computer has decreased, the actual power used has increased due to the use of active matrix technology.

The reduction in microprocessor power consumption is a result of advanced microprocessors with built-in power management and also the move to lower voltage designs. A more detailed explanation is provided in Section 4.3. Hard disks are consuming an increasing fraction of total system power as manufacturers focus on increasing capacity rather than reducing power consumption. The rest of the components of a typical laptop – keyboard, floppy drive etc. – typically consume less than 15% of the total power and are not shown on the chart. CD ROMs can use a significant amount of power, but are not included in the chart since they are used infrequently.

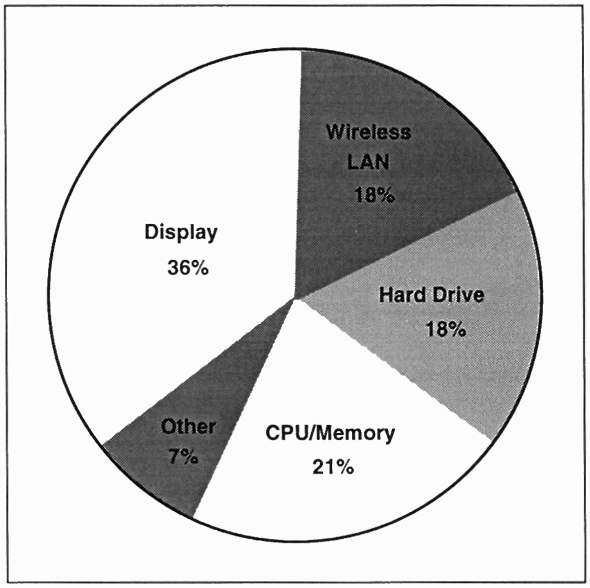

Figure 3: Power consumption by each subsystem of a mobile computer.

Figure 3 gives measured values of the power consumed by the major system components of a Toshiba 410 CDT mobile computer (Pentium 90 with 8 MBytes of EDO RAM and AT&T WaveLAN PC Card). While this figure is based on actual measurements, the results are based on estimates of typical usage. The measured instantaneous power with the system idle (display on, HD spinning, WaveLAN receiving) was 14 Watts which is small compared to a mains-powered appliance (e.g., a light bulb uses 60 Watts) but large for a system that is powered by a battery.

The conclusion is that even though the Features/Dollar (and in some cases Features/Power Consumed) ratios have increased significantly, the overall power consumption of a laptop has also increased. One solution to this problem would be to decrease the capacity and/or performance of the individual components. For example, we could offer a 80286 laptop with 1 MB RAM, small grayscale display and a 10 MB disk that would offer superior battery life, but this machine might not load a current operating system, nor be useful in day-to-day laptop-based tasks. In fact, machines similar to this already exist as palmtop computers or Personal Digital Assistants (PDA) and have their own niche. Since reducing the features available on a computer is not economically feasible we are forced to intelligently manage system power use.

[3] The computers measured were the Zenith MasterSport SLe (1991), Compaq LTE 386 (1993), Compaq 486 (1994) and Toshiba 410 CDT (1995-96)

4 Current Work in Power Management

Currently, power management in laptops is performed in a variety of ways, including custom BIOS implementations, unique device configurations for specific operating systems, and various interpretations of the Advanced Power Management standard [15] (APM - a joint proposal from Intel and Microsoft). The APM BIOS is a layer of software that supports power management in computers with "power manageable" hardware. The APM specification defines the hardware independent software interface between system hardware and an operating system power management policy driver. Unfortunately, most manufacturers incorporate only a small subset of the APM features, and few operating systems actually use the features.

Most laptops have simple power management schemes that allow the CPU to be run in "fast" or "slow" mode to conserve power (described in more detail in Section 4.3). In addition, the display can be blanked after being idle for a set amount of time, and the hard drive can be powered down when idle for several minutes. The user commonly has the option to set each of the parameters individually. The remainder of this section examines each major subsystem of a laptop and discusses the details of currently available management schemes.

4.1 Hard Disk Power Management

The hard disk is one of the three big consumers in a laptop's power budget as can be seen in Figures 2 and 3. Depending on its state, the disk can use up between one and three Watts—approximately 25% of total system power. Although the Power/MByte ratio has fallen rapidly in the past few years, the actual power consumed by a typical drive has remained approximately constant. Since some of the other laptop components have reduced their power consumption, the net effect (Figure 2) is that a laptop hard drive is taking an increasing percentage of total system power. Drive manufacturers driven by consumer demands have focused their efforts on increasing drive capacity, rather than decreasing overall power consumption.

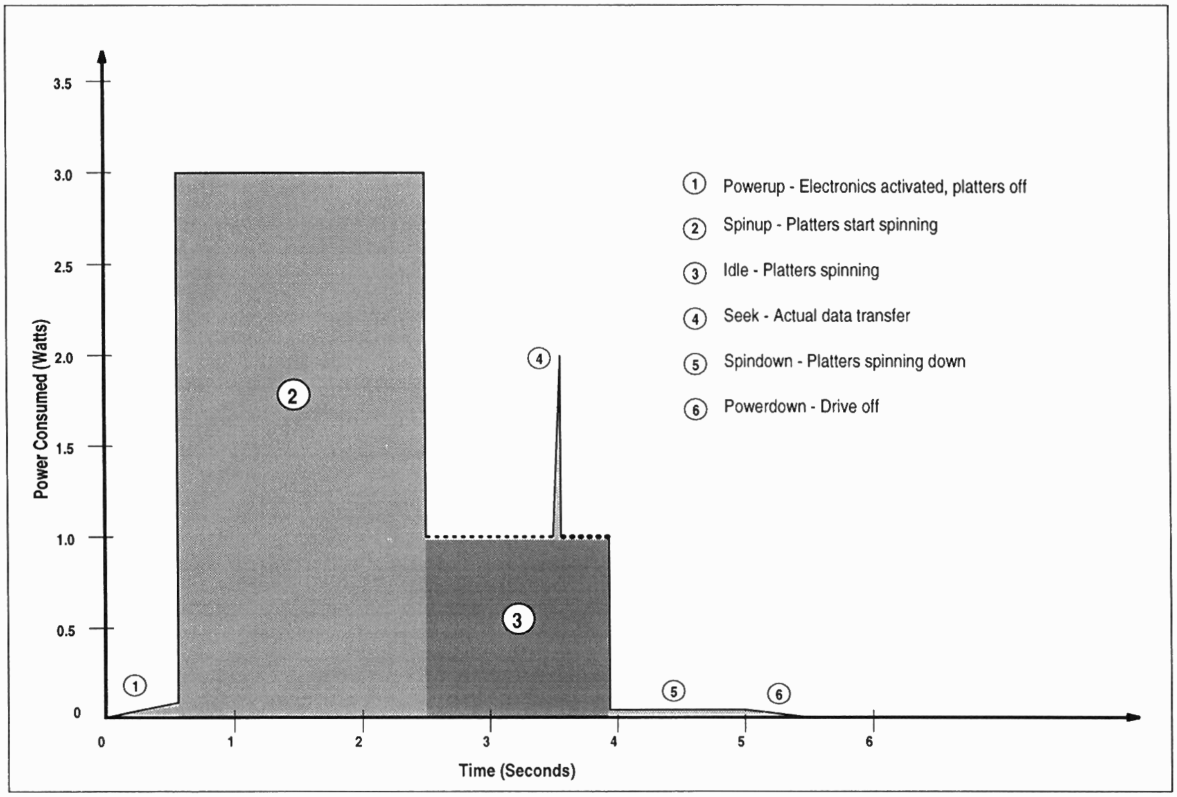

Figure 4: Dynamic power consumption for a typical laptop-optimized hard disk.

Figure 4 is derived from Li, et. al's [16] measurements and illustrates the dynamic power consumption of a typical laptop-optimized hard drive (a Maxtor MXL-105 III). The total energy consumed is equal to the entire shaded area under the curve (i.e. Energy = Watts*Seconds). The largest power drain occurs during spin up, shown as area **2** in the figure. Spinning up a disk requires overcoming the mechanical inertia of the stationary platters of a disk. Once the platters are spinning, the power required to keep them spinning is much lower, as shown in area **3** of the figure. Disks optimized for laptops have a shorter spin up time than disks intended for ordinary PC's, to allow for frequent spin-downs to conserve energy. Of course, spinning-down and spinning-up a disk *too frequently* can result in higher overall power consumption since the energy required to spin up a disk is much higher than that needed to keep the disk spinning. In theory, the best power conservation happens when a disk is spun down if the energy it would spend being idle (i.e. area **3**) is equivalent to or greater than the additional cost of spinning it back up (the area in **2**). As we will see, this isn't always feasible in practice.

Research has been done on reducing the overall amount of energy used by a hard drive. This has ranged from simple algorithms that spin down the drive when it is idle for more than a set length of time (currently the most common method), to adaptive spin down techniques where the drive examines past access patterns to determine a dynamic spin down strategy.

The fixed length spin down policy has one big advantage: it is very simple to implement. If the spinning disk is not accessed for *idle_time* minutes, the assumption is that there will be no disk accesses in the near future and the disk is spun down. It spins up again when there is a read/write request. This is the only widely available disk management method at present. Since the user fixes the value of *idle_time* and rarely readjusts it, the savings are very limited. Setting *idle_time* too low results in the user waiting for the drive to spin up too often. Too high a value of *idle_time* results in minimal power savings since the disk will remain spinning most of the time. A study by [16] has shown that the optimal value (strictly from the power conservation point of view) for *idle_time* is approximately 6 seconds. This may be ideal from the power perspective, but is very inconvenient for the user who will frequently have to wait for the drive to spin up (a spin up takes 2-6 seconds). In addition, since a hard disk is a mechanical device, it typically has a spin-up/spin-down life expectancy of 40,000-60,000 cycles and overly aggressive spin-down techniques will result in premature drive failure. For example, if *idle_time* is set to 6 seconds, the drive could spin-up over 1000 times on a 5 hour cross-country flight, reducing disk life by about 2% in just one flight.

Adaptive disk spin-down attempts to adjust to the user's access patterns. IBM's Adaptive Battery Life Extender (ABLE) [12] looks for temporal locality of reference in drive accesses to put a hard drive in a special *idle* mode that shuts down most of the electronics of the drive but does not spin-down the platters when accesses are not expected. The drive analyzes the frequency distribution of commands over the previous 10-15 seconds and calculates the probability that the current command is the final one in the burst. This method conserves about 15% more power than a regular idle mode disk and is transparent to host software. Some adaptive spin-down schemes [8] propose actually spinning down the drive completely to maximize energy conservation, but are difficult to implement and have only been simulated so far. The caveat for each of these schemes is that savings can vary widely with usage. A more detailed analysis of these techniques can be found in [20].

Another technique is increasing the size of the disk cache to reduce the need for spin-ups. Caching can improve performance, while reducing power consumption. Simulations by Douglis et. al. [8] show that using a 32 Kbyte SRAM write-buffer improves average write response by a factor of 20 or more and reduces energy consumption by between 15%-20%. Their simulations show that increasing the buffer beyond 32 Kbytes does not improve write response time, nor does it save additional energy, although this will probably vary with the operating system environment. Thus there is an upper bound on how useful a disk cache can be, and there are also negative consequences for reliability since SRAM is volatile and there is potential for data loss in the event of a system error.

In summary, hard disk management is still not mature. Currently available algorithms (almost exclusively fixed-length spin down) can help, but are far from optimal. Adaptive algorithms are still in the preliminary research stage, and are difficult to implement. There are other problems inherent to hard disks – since they are mechanical devices, they have limited spin-up/spin-down cycles before drive failure.

4.2 Flash Memory Versus Disks

Flash memory is a form of non-volatile storage that has gained popularity in the past few years. Data is stored in semiconductor memory that is about as compact as DRAM with the added advantage of not needing any refreshing to maintain the data. From the user's point of view, it has the non-volatility of a hard disk (i.e. keeps data even when the power is turned off) and the speed and compactness of DRAM. Flash memory is solid state and thus immune to mechanical shocks, unlike a hard disk. It is about as fast as system memory when doing reads but much slower when doing writes. The other limitations include high cost and a limited number of write cycles [20].

Cost plays a key role in the selection of storage devices in mobile computers. Figure 5 is based on data from [6] and shows the broad range of cost/Mbyte (the y-axis is logarithmic) for the various types of laptop memory. Flash prices are falling as sales volumes increase, but the price of flash relative to hard disk has remained very high, with flash memory costing between 60-100 times more per MByte than hard disks. While we could present a power management scheme that extended battery life to 24 hours and required the use of flash memory to replace a hard disk, it would raise the cost of a laptop (with just 300 MB storage) to about $18 000, far beyond the reach of most users.

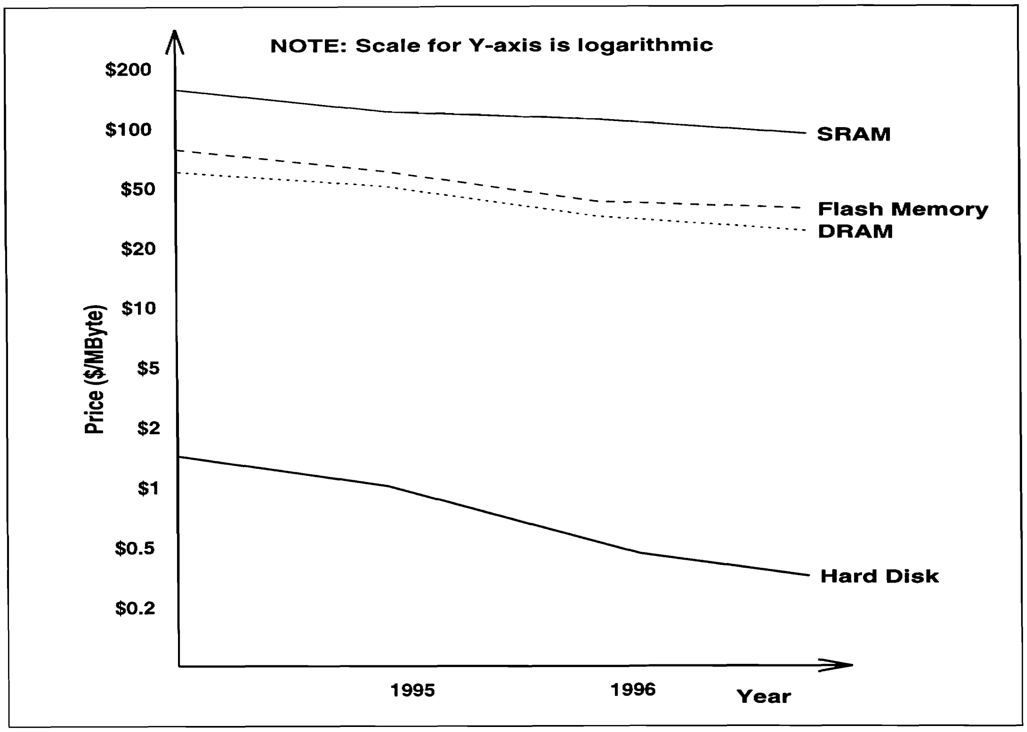

Figure 5: Price comparison of the various laptop storage devices

Since software advances almost always result in larger executable size, mechanical storage devices today are an economic necessity in laptops. Hard disks may consume significant amounts of power, but they are non-volatile and very low cost. Until the price of flash memory (or other non-volatile memory) is nearer to that of a hard disk, the problems of spinning mechanical disks must be dealt with.

4.3 CPU Power Management

The Performance/Power ratio of microprocessors has increased tremendously in the past few years, as can be seen in Table 4 which shows the specifications for various Pentium processors. The performance index (Intel's iCOMP index) and data for Table 4 are from Intel [14].

The key physical changes in the design of microprocessors are reduced feature size (smaller transistor size generally results in lower power consumption) and lower operating voltage, from 5 Volts to 2.9 Volts. The

CPU Frequency (MHz)	Voltage (Volts)	Typical Power (Watts)	Performance (iCOMP/Watt)
Desktop 66	5.0	~10	57
75	3.3	3.0 - 4.0	174
90	2.9	2.5 - 3.5	245
100	2.9	2.0 - 3.0	326
120	2.9	2.5 - 3.5	333
133	2.9	3.0 - 4.0	317

Table 4: Power requirements of Pentium processors for laptops.

amount of power used by a circuit is proportional to the square of the voltage used, so even a small decrease in processor voltage results in a large decrease in the power consumed.

The newer Pentium CPUs also have circuitry that allow the microprocessor to slow down, suspend, or completely shut down various subunits of the processor when they are not in use. This is transparent to the operating system and application software and explains the dramatic drop in power consumption for the more recent processors, as shown in Table 4. As power management schemes internal to the CPU start reaching their limits, the total power consumed will start rising, as is apparent with the fastest processor in the table.

In addition, there are user selectable options to run the CPU at a slower speed to conserve power—this is the most common user choice in most power managed laptops. The problem with user-selectable "slow" or "fast" CPU modes is that the user may actually end up using **more** power with the "slow" power-saving mode than by not using the power save mode at all. For example, if the user is editing a spreadsheet, having the CPU in its slow state is optimal, but if the user is running a calculation in the spreadsheet, having the CPU running slower will result in more power being used since the display and hard disk will be left on longer. It is impractical to expect the user to set the CPU speed manually each time so this inefficiency is common.

4.4 System Memory

One method to reduce the number of times a hard disk has to be spun up is to have a large amount of system memory (i.e. DRAM). This makes intuitive sense—place the current working set in memory and there will be few page faults to cause the disk to spin up. Unfortunately this is not feasible in practice. A study by Li [17] has shown that having as little as 8 MBytes of additional DRAM can use up as much power as a constantly spinning hard disk. To confirm this rather surprising result, we did some calculations based on manufacturers data [5], and found that 8 MBytes of 60ns Extended Data Output (EDO) DRAM uses 2.8 W when active, compared to a typical 500 MByte hard disk which uses about 3 W. Newer memory technologies will probably reduce the power consumption of DRAMs, but it will still remain significant in comparison to a hard disk.

This indicates that adding system memory solely to reduce disk accesses is not a workable solution. In fact, a user wanting to maximize battery life may need to keep system memory to an absolute minimum. We discuss this further in Section 5.

4.5 The Display and Network Interface

The display of a laptop can absorb almost half of the total available system power. Active matrix screens use more power than the older dual scan displays. Displays are improving rapidly in size and resolution, but not in terms of power consumption. Power management of displays is typically restricted to blanking the display after a period of inactivity. Some newer system management software allows a user to set a low power mode that dims the screen. Blanking the screen after a few minutes is effective in saving power but is not optimal.

Wireless network interface cards are becoming more common. The wireless Ethernet card (CSMA/CA) we are using is the AT&T PC Card WaveLAN, which has a claimed consumption of 3 W during transmission, 1.5 W when receiving and 0.2 W in sleep mode [22]. Experiments conducted on PDAs by Gauthier et. al. [10] support these numbers. In addition, they also noted that the time the WaveLAN takes to switch from sleep mode to active mode is about 100 ms – sufficiently short that the user would not notice a lag if the card were put in sleep mode frequently.

The wireless LAN standard (IEEE 802.11) is still being defined and will include some form of built-in power management when finalized. While there has been work on reducing power consumption of wireless network cards [10, 13], most of it is focused on a particular subsystem, not the entire mobile computer.

5 Power-Conscious Memory Management

Since software continues to require more memory it is useful to control the amount of memory actually powered up. For example, if a laptop with 40 MBytes of memory were to use only 16 Mbytes and depower the other 24 Mbytes, there would be very significant power savings, possibly with performance degradation. If a user could set (either at power-up, or dynamically) the amount of memory to be powered down, it would offer a method to tradeoff performance with laptop battery endurance. Since about 8 Mbytes of DRAM can use as much power as a spinning hard disk [17], the additional page faults (and subsequent drive spin-ups) would be offset by the savings from having reduced DRAM. Intel has released a new Pentium PCI chipset (the 82430MX PCI chipset) that has suspend and standby modes which not only put the CPU in low power mode, but also restrict power to system memory. The challenge is to intelligently trade power savings from reducing system memory against performance penalties.

Udani [21] is researching *intelligent* power management where a central "Power Broker" is aware of the global system state and selectively shuts down laptop components based on a rule base for each group of applications. Applications are unmodified. Dependencies between components (e.g. if the the display is off, the hard drive can be immediately spun down) can be used to minimize power consumption without affecting performance.

An idea proposed by the Video Electronics Standards Association (VESA) group is the Unified Memory Architecture (UMA) [4]. They propose a scheme where segments of main memory are dynamically allocated for video and graphics, thus eliminating the need for a separate frame buffer. This proposal is presented primarily as a cost saving measure, but can also be viewed from the power management point of view. Instead of having dedicated memory reserved for graphics (2 MB requires about 0.7 W of power), segments of main memory can be used as needed. This would be more efficient and flexible. For example, a word processing application might need only 512 KBytes whereas photo rendering may need over 2 MBytes. Each of these could be accommodated using the UMA scheme and the memory returned for system use after the application is finished. The claim by VESA is that UMA is transparent to the operating system and is controlled by the core BIOS logic. There are disadvantages however. Since we are using the system bus and system memory for all the traffic, performance degradation is likely and estimated to be between 5-15%. For a desktop machine this may not be acceptable, but if it can extend a laptop's battery life by 10% there is strong incentive to use the scheme.

6 Summary

We have analyzed the various subsystems of a mobile computer from the power management perspective. In summary, we:

1. Looked at technology trends in mobile computing
2. Identified batteries as the key laggard
3. Surveyed possible solutions for power management

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