COVER FEATURE

Energy-Aware User Interfaces and Energy-Adaptive Displays

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Providing mechanisms in hardware and software for the system to gracefully reduce the energy consumed when its full functionality is not used offers the promise of dramatically reducing display power consumption without compromising user acceptance.

Among the various components that contribute to the consumption of electrical energy, the display subsystem—the electronics associated with the visual representation of the data the system generates, particularly the display and the controller—plays an important role, often consuming more than half the laptop[1] or handheld[2] system's total energy. Further, display power consumption has traditionally been invariant across technology updates, making it likely to be a greater fraction of the total power consumed by future systems.

Developers optimize the design of conventional systems' displays for the most aggressive expected usage. For example, a handheld device that supports video playback would typically support a high-color, high-resolution, larger-sized display. Current approaches to reducing the display power for these devices focus on aggressively turning off the entire display when not in use or designing systems with lower-quality or smaller-sized displays, which would compromise the user experience for all applications. In contrast, we address the possibility of controlling the display's *individual subportions* or power-consumption properties based on the end user's or application's specific requirements.

We based our work on the intuition that different workloads and users have varying display needs. Having a one-size-fits-all display that targets the needs of the most aggressive workload or user often leads to energy inefficiencies in the display-energy consumption of other workloads and users. In contrast, an energy-adaptive design that consumes energy only on those portions and characteristics of the screen the application is using and that are relevant to the user can achieve energy benefits consistent with the desired end user experience. For example, the display for a handheld device could adapt to use lower power when the user runs an e-mail application that does not need high-quality color, high resolution, or significant screen area. Such an approach becomes particularly promising with the increased availability of emissive display technologies such as *organic light-emitting diode* (OLED) displays[3] that allow lower power consumption when a reduced portion of the screen is in use.

Our work identifies, quantifies, and analyzes potential mismatch opportunities in workload, user needs, and current display properties. Across different usage classes, we consistently find that users typically do not stress the display's full properties, and they often associate screen usage with content that can be displayed with significantly lower energy consumption. We propose new display subsystems that use energy adaptivity in hardware and energy awareness in software to obtain dramatic display power savings—with typical improvements ranging from factors of 2 to 10 without compromising user acceptance.

Our work shows that user interfaces must be designed with energy in mind, and that such energy-aware interfaces can actually provide a good combination of energy benefits and greater ease of use by leveraging features that improve usability instead of simply providing a tradeoff.

UNDERSTANDING DISPLAY-USAGE BEHAVIOR

We conducted a user study to identify typical display-usage patterns and corresponding opportunities for power reduction.[4]

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				Screen usage for active samples			
User	Display Size and resolution	Log length (hours)	Active samples (hours)	Mean (%)	Std. Dev. (%)	Mean (%)	Std. Dev. (%)
				Window of focus		Background windows	
			Desktop user population				
1	19" 1024 x 768	210	33	62.8	38.5	10.6	21.2
2	21" 1280 x 1024	346	61	57.2	22.3	11.6	28.5
3	19" 1280 x 1024	214	31	46.3	19.7	30.4	19.7
4	19" 1280 x 1024	64	43	36.7	14.5	34.1	8.8
5	19" 1280 x 1024	253	27	44.5	22.7	32.6	21.1
6	21" 1280 x 1024	229	31	55.5	18.4	24.7	17.8
7	21" 1280 x 1024	235	30	57.5	19.2	20.0	18.8
8	17" 1024 x 768	135	13	85.2	26.2	9.7	24.4
			Laptop user population				
9	13" 1280 x 1024	42	23	61.8	21.6	25.1	22.3
10	14" 1024 x 768	98	54	71.1	25.4	22.4	23.9
11	14" 1400 x 1050	57	57	37.4	20.3	7.2	15.1
12	14" 1024 x 768	20	13	93.7	12.3	2.3	12.2
13	15" 1024 x 768	169	154	43.3	38.9	17.5	24.3
14	13" 800 x 600	132	6.2	71.1	37.6	3.0	15.0
15	14" 1024 x 768	9	6.4	44.1	21.4	10.3	15.3
16	14" 1400 x 1050	69	15	54.6	25.9	18.5	17.5
17	14" 1024 x 768	10	6.0	77.3	36.8	5.0	17.0

Average screen usage—window of focus: 58.8%; background windows: 16.7%

Figure 1. Typical display usage. A user study revealed that average screen usage was 58.8 percent for the window of focus and 16.7 percent for the background windows. The data show that most users apply only a small fraction of display properties, such as size, color, and resolution.

Methodology

Figure 1 summarizes the results of the study, which included 17 users chosen to cover a cross section of mobile system usage: administrative tasks, code development, personal productivity, entertainment, and so on.

All participants used a Microsoft Windows environment. An application logger program was run on the users' machines for times ranging from 1 to 14 days to collect data during periods representative of their typical usage. The logger program collected periodic information once a second about the current window of focus and the total screen area used, defined as all nonminimized background windows. These were used as first- and second-order proxies for the areas of user interest and captured information about the currently active application.

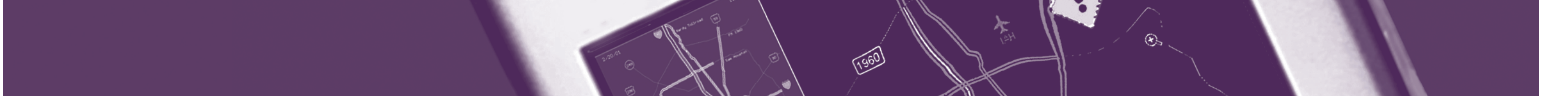
To eliminate incorrect conclusions about periods when users were away from their computers, the screen saver initiation time was set to very small thresholds. Any samples associated with the screen saver were removed to distill the "active samples" that would receive further study. We chose this methodology with the intuition that approaches to turn off the display during user idle times would work well for those scenarios.

Column 3 in Figure 1 summarizes the length of the user traces, which ranged from 9 to 346 hours. The trace variations represent the differences in how individuals used their machines during their participation in the study. Overall, the samples represent close to 100 days of continuous computer time. Column 4 in Figure 1 summarizes the length of the "active" user traces, after factoring out the time used by the screen saver.

Results

Looking at the average screen usage for the window of focus—a first-order indication of the user's area of interest—shows that the test population used anywhere from 37 to 94 percent of the total available screen area. Other background windows that were neither active nor minimized used an additional 2 to 34 percent of the screen. On average, across all users, the window of focus typically used only about 59 percent of the entire screen.

Additionally, in many cases the screen usage involved content that could have been displayed with comparable visual quality on much simpler, lower-power displays. Analysis of the user traces showed that many of these mismatches could be traced to the typical content of the windows as opposed to specific user preferences. For example, we can categorize the screen-usage classes based on the applications to show that the dominant types of smaller-sized windows included those with low



content, such as e-mail composition, terminals, system status and control messages, and menu widgets:

- *Active area of 0 to 25 percent, 23 percent of the time for the typical user:* key applications include task bar, 20 percent; program manager, 15 percent; X-term, 5 percent; and miscellaneous windows, 60 percent.
- *Active area of 25 to 50 percent, 22 percent of the time for the typical user:* key applications include X-term, 19 percent; message composition, 18 percent; Internet Explorer, 6 percent; miscellaneous windows, 57 percent.
- *Active area of 50 to 75 percent, 28 percent of the time for the typical user:* key applications include Internet Explorer, 33 percent; mail composition and reading, 24 percent; and miscellaneous windows, 43 percent.
- *Active area of 75 to 100 percent, 27 percent of the time for the typical user:* key applications include Outlook, 21 percent; Internet Explorer, 20 percent; Excel, 7 percent; and miscellaneous windows, 52 percent.

Windows with relatively higher content, such as those used for Web browsing, miscellaneous applications such as Visual Studio, PowerPoint, or document reading provided the dominant types of larger-sized windows. In some cases, user preference for smaller windows and font sizes translated into a greater use of smaller-sized windows, but in most cases, the screen area's low usage stemmed from windows that typically held little content. The data also showed that the periods when the display's full properties were not used were distributed uniformly across overall system usage. Other researchers have provided more data on user study findings.[4]

Organic Light-Emitting Diode Displays

A key requirement for energy-adaptive designs is support at the display subsystem for variability in the display power based on the properties of the screen output. That is, it should be possible to change the energy consumption of regions of the display independent of each other. Several emerging display technologies support such variable power over different regions of the screen. This is preferable to existing technologies that require making energy tradeoffs for the entire screen.

Organic light-emitting diode displays are a good example of this class. In OLEDs, a pixel's energy consumption is related to its brightness and color. OLED displays are built from small organic molecules that efficiently emit light when stimulated by an electric field. As of 2004, more than 20 vendors were providing OLED displays, with close to a doubling in volume compared to 2003.[1] Samsung, RiT display, Pioneer, LGE, and Philips were among the top suppliers in terms of volume shipments. At trade shows, Kodak, Sanyo, and Sony have shown prototypes from 5.5-inch displays to 13-inch displays.

In general, OLEDs have better image quality compared to conventional LCDs—better horizontal and vertical viewing angles, higher brightness, and faster response times—and do not need a separate backlight, resulting in lower power consumption.

As the technology matures, the biggest challenges are in overcoming yield problems and consequently reducing costs. Oled-info.com's latest information shows more than 80 product offerings using OLED displays in cell phones, PDAs, MP3 and media players, digital cameras, and other applications.[2]

References

1. "Quarterly OLED Shipment and Forecast Report, Q1 05," *Display Search*, Mar. 2005; www.displaysearch.com.
2. "Devices Using OLED Displays," 2005; www.oled-info.com/devices.html.

ENERGY-ADAPTIVE AND ENERGY-AWARE DESIGNS

Results from the preceding analysis indicate that energy-adaptive designs that match display-power consumption to the functionality that the workload or user requires offer the potential of significantly reducing the subsystem display's overall energy consumption. Such designs require specific hardware and software changes.

Hardware support

At the hardware level, our approach requires the design of energy-adaptive displays. Key to enabling energy-adaptive designs is support at the display subsystem for variability in the display power, based on the screen output properties. That is, it should be possible to change the energy consumption of the display's various regions independent of each other. Several emerging display technologies support such variable power across different screen regions. We find this preferable to technologies that require making energy tradeoffs for the entire screen, mainly because of the dominant power from a single backlight.

OLED displays provide a good example of this class, as the "Organic Light-Emitting Diode Displays" sidebar explains. While these displays typically have better image quality than traditional LCDs—better horizontal and vertical viewing angles, higher brightness, and faster response times—their key benefit for our work is their ability to vary energy consumption based on the number of pixels turned on as well as the individual pixels' brightness and color. Figure 2 compares an OLED-display-based prototype and a conventional LCD-based system.

Figure 2. Energy-adaptive display design. The device on the left is a prototype iPAQ with an OLED display. For comparison, a similar device with a conventional LCD is shown on the right. OLED displays provide one way of enabling the fine-grained control of display power needed for an energy-optimized design.

We used an OLED-display-based design to demonstrate the benefits of our approach. However, other display technologies that enable energy adaptivity can also be used. These include other optoelectronic and emissive displays and even conventional cathode ray tube displays, as well as hybrid technologies like LCDs with OLED backlights. With display technologies using LCDs and conventional backlights that do not support energy variability, energy-adaptive display designs can still integrate a multimodal *hierarchy of displays* configuration.[5] For example, a mobile device could have two displays: one with higher quality and consequently higher energy use, and another with lower quality and lower energy use. While the adaptivity in such a design is more coarse-grained than with the OLED systems we consider, the insights from our study apply to these designs as well.

Software support

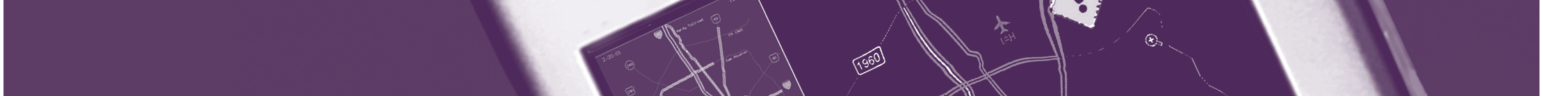
At the software level, our approach involves designing energy-aware user interfaces. We examined the dis-

Materials

E-MAIL	READER	MP3 PLAYER	FLASHLIGHT	INVERSION
0% Gradient baseline battery life	0% Gradient baseline battery life	Blue baseline battery life	0% Flashlight baseline battery life	baseline battery life
40% Gradient x 1.58 Longer	40% Gradient x 2.21 Longer	Gray x 2.86 Longer	40% Flashlight x 1.58 Longer	Inversion x 3.21 Longer
100% Gradient x 2.56 Longer	100% Gradient x 6.06 Longer	Green x 20.96 Longer	100% Flashlight x 8.77 Longer	baseline battery life
				Inversion x 5.50 Longer

- **Examples of screens (with factorial battery life improvement relative to 'Baseline' interfaces)**
  - E-mail Gradients
  - Reader Gradients
  - MP3 Player Screens
  - Flashlight Screens
  - Inversion Screens
- **Simple design rules for lower energy**
  - On/Off Rule: turning pixles off when not in use
  - Brightness Rule: dim pixels that are not in use
  - Colour Rule: primary colours more energy efficiant
- **The prototype energy-adaptive interfaces extended battery life by factors ranging from 1.2 to 20 compared to current baseline designs**

Figure 3. Energy-aware user interfaces. The images labeled "baseline battery life" represent the default interface, while the other images show the energy-aware interfaces. The energy values for various configurations and the rules used to guide the design of the energy-aware interfaces are summarized at the bottom of the picture.



play screens associated with typical mobile tasks—akin to those in our user study—and developed an alternate energy-aware version for each screen.

While still based on standard principles, our designs were more cognizant of the user and technology contexts associated with their usage. We worked from the key design principle of using higher contrast or graded dimming to turn off or reduce the brightness of those screen portions we judged to be of lower interest to the user. We iterated the design process based on feedback from interviews with several experienced users. The individual designs for the various scenarios had different settings for the level of dimming and the size of the dimmed region to enable study of user responsiveness to these parameters.

We studied both simple user interfaces that approximate the area of user interest to the window of focus[4] and more elaborate static and dynamic user interfaces that identify and leverage spatiotemporal trends in screen usage for specific applications.[6,7]

Figure 3 shows five types of dynamic energy-aware user interfaces:[7] the e-mail inbox gradient, Acrobat Reader gradient, MP3 player, flashlight, and inversion.

With the e-mail and Acrobat Reader interfaces, users can highlight only those portions of the screen they are reading. The e-mail application separates the gradients at the individual message level, while the Acrobat Reader application has a gradient associated with the scrollbar. Available size gradient options range from 0 to 100 percent in 20 percent increments. The 0 percent interfaces were not gradients, but rather the conventional Outlook Inbox and Acrobat Reader interfaces, which served as control interfaces in our investigation.

The MP3 player interface represents an alternative way to design energy-aware interfaces. Here, the conventional blue Windows Media Player interface has been replaced with a green and black *skin* that better focuses on the content of interest to the user.

Finally, the flashlight and inversion interfaces represent further options for designing energy-aware user interfaces. While the flashlight interface presents a dimmed interface with a user-movable region illuminated at several levels, the inversion interface passes the pixels in the frame buffer through a simple inversion function when doing so is more energy advantageous.

In all these interfaces, controlling the color of the dimmed area and the shape of the illuminated area permits other variations. Although the complexity at the various levels differs based on the specific interface, these interfaces typically can be implemented at either the application, OS, or device driver level in the software stack. Other publications have written more detailed descriptions of these user interfaces.[4,6,7]

Power savings

Our results show that energy-adaptive displays can dramatically reduce power consumption when compared to baseline designs that do not vary display power with usage.

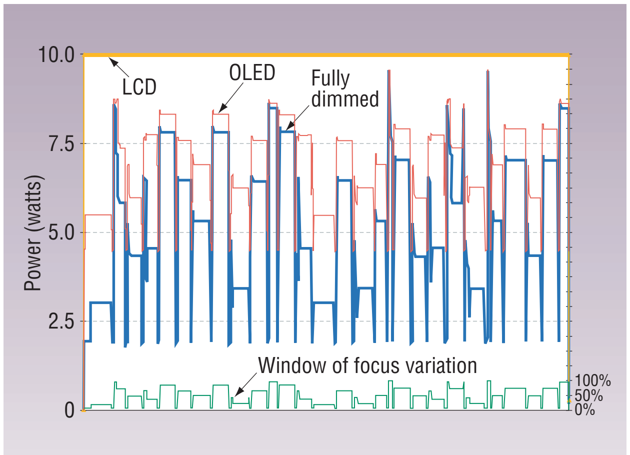


Figure 4. Power benefits from energy-adaptive designs. The LCD line represents conventional displays where power is invariant to display usage. The base energy-adaptive hardware (OLED) and simple energy-adaptive software heuristic (fully dimmed) lines show how power is proportional to the window usage in energy-adaptive cases.

The data in Figure 4 shows the benefits from energy adaptivity by plotting the temporal power consumption for a representative user trace across three systems: a baseline LCD system, an OLED-display-based system that does not use energy-aware interfaces, and a fully dimmed system that uses the energy-adaptive display with a relatively simple energy-aware user interface.[4] The diagram in the bottom half of the graph shows the variation in the window of focus.

Figure 4 shows that energy-adaptive displays can adapt their power consumption based on the content being displayed on the screen and the area of interest to the user. While the base hardware alone captures many of the benefits from this approach, energy-aware software can obtain additional savings.

Overall, our evaluation on laptops showed improvements factors of 1.3 to 10,[4] while our evaluation for handhelds showed improvements of 1.3 to 8[6] and 1.5 to 21.[7] The improvements represent the power savings for individual screens.

A more accurate estimate of the device's total battery life improvement depends on the actual mix of these screen shots in a given usage pattern and the time spent on each interaction. However, our study of screen usage patterns for several typical users over a long period indicates that the chosen scenarios represent the average usage patterns and that the relative time spent on the type of interaction each scenario typifies is likely similar. The specific OLED display's chemistry also influences the power-improvement numbers. However, given the trends in OLED displays, we expect our results to be qualitatively similar for future chemistries as well.

Other Approaches to Reducing Display Power

In addition to our own work on energy-aware user interfaces, other researchers have engaged in various activities intended to optimize display and user interface power.

Turning off the backlight

Industry standards such as *advanced power management* and *advanced configuration and power interface* include an interface for changing the display's power state through software using *display power management signaling*. This lets the display transition to a lower-power state—the display is turned off or the backlight is turned off or dimmed—after a certain period with no user input.

Angela Dalton and Carla Ellis[1] proposed a novel variation that uses sensors to detect user intent and physical content. For example, their FaceOff prototype allows visual tracking of user interest to turn off the display for more user-friendly power savings. In a similar approach, the HP iPAQ PocketPC has an ambient light sensor to allow for adaptable display brightness.

In one of the earliest works to look at display power management, Jason Flinn and M. Satyanarayanan[2] discussed the notion of zoned backlighting to control power at subregions of the screen if hardware support for this becomes viable.

Energy-aware GUI designs

Lin Zhong and Niraj Jha extensively studied the energy efficiency of graphical interfaces and I/O mechanisms in handheld devices. Their work focused on the power the display subsystem consumes in the creation and manipulation of the images in the frame buffer and identified the relative energy tradeoffs with various GUI event-handling and window-creation functions and their sensitivity to size, color depth, color sequence, and platform.[3]

They suggested interfaces that accelerate user interaction, minimize screen changes, minimize text input, reduce redundancy, and allow intelligent overlap of computation to reduce energy. Their work also included a discussion of sensory perception-based limits for visual and auditory output as well as for I/O speed for various interfaces. They proposed the notion of a low-power interface cache that can enable energy savings during interactive tasks.

Varying refresh rates, color depths, and image fidelity for power savings

Inseok Choi and coauthors[4] proposed and evaluated several system-level approaches to manage TFT LCD power. They showed that variable-duty refresh rates can reduce the energy consumption by the frame buffer and the communication bus. An alternate pixel organization for color-depth control can provide additional energy savings by shutting down portions of the memory.

They also proposed image modifications that use contrast enhancement to compensate for the reduced brightness when the backlight is dimmed for power savings. This approach of scaling the backlight with corresponding changes to compensate for any fidelity losses in the image has also been evaluated in other studies.[5-7]

Significant energy savings can often be achieved without perceptible loss in image quality. Jason Flinn and M. Satyanarayanan[2] also discussed in detail the energy benefit of reduced computation with lower fidelity of images for Web browsing and video playback.

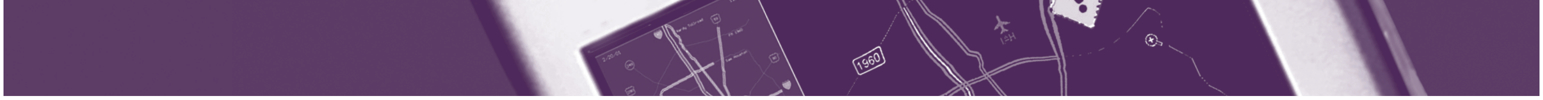
References

1. A. Dalton and C. Ellis, "Sensing User Intention and Context for Energy Management," *Workshop on Hot Topics in Operating Systems* (HOTOS IX), Usenix, 2003, pp. 151-156.
2. J. Flinn and M. Satyanarayanan, "Energy-Aware Adaptation for Mobile Applications," *Proc. Symp. Operating Systems Principles* (SOSP 99), ACM Press, 1999, pp. 48-63.
3. L. Zhong and N.K. Jha, "Graphical User Interface Energy Characterization for Handheld Computers," *Proc. Int'l Conf. Compilers, Architectures & Synthesis for Embedded Systems* (CASES 2003), ACM Press, 2003, pp. 232-242.
4. I. Choi, H. Shim, and N. Chang, "Low-Power Color TFT LCD Display for Handheld Embedded Processors," *Proc. Int'l Symp. Low-Power Electronics and Design*, ACM Press, 2002, pp. 112-117.
5. F. Gatti et al., "Low-Power Control Techniques for TFT LCD Displays," *Proc. Int'l Conf. Compilers, Architecture, and Synthesis for Embedded Systems*, ACM Press, 2002, pp. 218-224.
6. H. Shim, N. Chang, and M. Pedram, "A Backlight Power Management Framework for Battery-Operated Multimedia Systems," *IEEE Design and Test of Computers*, Sept./Oct. 2004, pp. 388-396.
7. W-C. Cheng and M. Pedram, "Power Minimization in a Backlit TFT-LCD Display by Concurrent Brightness and Contrast Scaling," *IEEE Trans. Consumer Electronics*, Feb. 2004, pp. 25-32.

Finally, our results also represent the combined benefits from energy-adaptive software and energy-aware user interfaces. While the base hardware alone captures many of the benefits from this approach, energy-aware software can obtain additional savings over and above the hardware. In general, for systems that allow great flexibility in user choices for background and window colors, it may be preferable to implement software optimizations in addition to the base hardware support for adaptivity.[4]

USER ACCEPTANCE

We assessed user acceptance of the new energy-aware interfaces through three user studies: one that surveyed nine laptop users from within Hewlett-Packard,[4] a sec-



ond that formally studied 12 handheld users from the Houston area,[6] and a third that formally studied 12 experienced PDA users from the Boston area.[7]

In the formal studies, researchers walked participants through scenarios representative of typical day-to-day handheld device use such as e-mail notification, mail checking and reply, note taking, book reading, and checking battery life. Researchers showed participants the default and energy-aware screens in random order and, at the end of the scenario, asked them to fill out a series of quality and acceptance ratings on a nine-point scale ranging from very bad quality at –4 to excellent quality at +4. For each interface, participants engaged the prototype to complete the task, offered verbal remarks, and provided ratings based on interface appearance and usability, both before and after learning about the battery-life improvements.

sanvander@hotmail.com says: Please respond!

Default configuration

Hierarchy-of-windows

Other user interfaces

Figure 5. Energy-adaptive display extensions. The displays can be extended for use in alternate configurations that use multiple displays or in scenarios with tradeoffs between higher-level interfaces.

In general, participants found the energy-aware user-interface designs acceptable. In some cases, they rated the energy-aware designs as highly acceptable and even preferable in specific situations that benefited from helpful contrasts.

Participants indicated that they preferred energy-aware designs because of their improved contrast and more readable text. Most also preferred energy-aware designs that dimmed the background behind popup messages—for example, for mail in notifications or menus—because the added contrast made the popup more salient. Although it occurs for relatively shorter periods, the transient usage of such low-content screens still constitutes a large fraction of total screen usage. With screens for tasks involving a longer duration or requiring greater informational context, study results indicated that users found extremely dark values of gray unacceptable and lighter grays more acceptable. For other high-informational content screens, participants favored the energy-aware inversion and MP3 interfaces and tended to prefer them to their respective contemporary control interfaces.

Participants preferred these interfaces because they greatly reduced energy consumption while making it easy to view all necessary text when completing their tasks. Participants rated a flashlight-based interface lower and preferred alternate single-color backgrounds to save energy.

Overall, our work indicates that energy-aware interfaces can actually provide a good combination of energy benefits and greater ease of use by leveraging features that improve usability instead of simply providing a tradeoff.

From an implementation viewpoint, the interfaces we studied covered a diverse spectrum, from needing support at the application or operating-system level to being transparently implementable at the OEM adaptation layer. Our results indicated significant energy potential and user acceptance for simple interfaces that could be implemented at this layer. However, application and OS-level changes can obtain even greater power savings over and above these interfaces.

FUTURE WORK

Much more can be done to identify and refine interface design principles that support reduced display-battery consumption and offer a positive or enhanced user experience. Some common themes identified from our participant responses include the desire to use contrast to highlight areas of interest, personalize an interface, and view a large amount of context. Because they can enable lower energy consumption while improving user acceptance, all these preferences must be explored further.

For example, interface personalization offers a fertile research area, including an assessment of preexisting display settings so that each setting provides a unique combination of battery consumption and interface color and illumination. Also, interfaces that involve controlling a temporal aspect offer much promise. For example, recently changed areas of the screen could be displayed brightly, then fade as time progresses. When it detects inactivity, an e-mail application could dim its screen area until new mail arrives. Finally, additional work must also be done to determine the amount and nature of power control the system should expose to the end user.

The principles espoused in this work have relevance in

the context of a system with multiple displays—for example, a higher-quality and higher-power primary display and a lower-quality and lower-power secondary display. Researchers could also extend this work to user interfaces beyond displays to include other modes of communication that match output content and intent to the best low-power mechanism for that user. For example, Figure 5 shows how an LED display that blinks when e-mail arrives could replace an e-mail notification on the display that says, "You have mail." A similar notification mechanism, such as speech output or vibrations, could also be used.[8]

Other optimizations have been proposed for display power management, as the "Other Approaches to Reducing Display Power" sidebar describes, and the interactions of all these methods offer compelling evaluation opportunities.

Overall, the philosophy of providing mechanisms in hardware and software for the system to gracefully reduce the energy consumed when the system's full functionality is not used—the *energy scale-down approach*[9]—is likely to be critical in the designs of future systems. This approach offers the promise of reducing display power consumption without compromising user acceptance. Our results indicate that the benefits from this approach are equally promising in other components of the system as well, and we believe that such mechanisms will likely become an important part of future mobile system designs. ■

References

1. S. Udani and J. Smith, *The PowerBroker: Intelligent Power Management for Mobile Computers*, tech. report MS-CIS-96-12, Distributed Systems Laboratory, Dept. Computer Information Science, Univ. of Pennsylvania, 1996.
2. I. Choi, H. Shim, and N. Chang, "Low-Power Color TFT LCD Display for Handheld Embedded Systems," *Proc. 2002 Int'l Symp. Low-Power Electronics and Design*, ACM Press, 2002, pp. 112-117.
3. S. Forrest, "The Roadmap to High-Efficiency Organic Light Emitting Devices," *Organic Electronics*, Sept. 2003, pp. 45-48.
4. S. Iyer et al., "Energy-Adaptive Display System Designs for Future Mobile Environments," *Proc. 1st Int'l Conf. Mobile Systems, Applications and Services,* Usenix, 2003, pp. 245-258.
5. P. Ranganathan et al., *Energy-Aware Software-Controlled Plurality of Displays*, US patent 6,912,664, filed 2001, Patent and Trademark Office, 2005.
6. T. Harter et al., "Energy-Aware User Interfaces: An Evaluation of User Acceptance," *Proc. Conf. Human Factors in Computing Systems* (CHI), ACM Press, 2004, pp. 199-206.
7. L. Bloom et al., "Investigating the Relationship between Battery Life and User Acceptance of Dynamic Energy-Aware Interfaces on Handhelds," *Proc. 6th Int'l Symp. Mobile Human-Computer Interaction* (MobileHCI), LNCS 3160, Springer, 2004, pp. 13-24.
8. P. Ranganathan et al., *Software-Directed, Energy-Aware Control of Display*, US patent 6,801,811, filed 2001, Patent and Trademark Office, 2004.
9. R.N. Mayo and P. Ranganathan, "Energy Consumption in Mobile Devices: Why Future Systems Need Requirements-Aware Energy Scale-Down," *Proc. Power-Aware Computing Systems* (PACS), IEEE Press, 2003, pp. 26-40.

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