Low-Power Color TFT LCD Display for Hand-Held Embedded Systems

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ABSTRACT

An LCD (Liquid Crystal Display) is a standard display device for hand-held embedded systems. Today, color TFT (Thin-Film Transistor) LCDs are common even in cost-effective equipments. An LCD display system is composed of an LCD panel, a frame buffer memory, an LCD and frame buffer controller, and a backlight inverter and lamp. All of them are heavy power consumers, and their portion becomes much more dominant when running interactive applications. This is because interactive applications are often triggered by human inputs and thus result in a lot of slack time in the CPU and memory system, which can be effectively used for dynamic power management.

In this paper, we introduce low-power LCD display schemes as a system-level approach. We accurately characterize the energy consumption at the component level and minimize energy consumption of each component without appreciable display quality degradation. We develop several techniques such as variable-duty-ratio refresh, dynamic-color-depth control and backlight luminance dimming with brightness compensation or contrast enhancement. Each method exhibits power reduction of 260mW, 250mW and 480mW, respectively. The aggregate energy reduction ratio is 28% out of total energy consumption including the CPU and the main memory system when we execute a document viewer. We also demonstrate that we can extend the battery life about 38% and 20% for a text editor and an MPEG4 player, respectively.

Categories and Subject Descriptors

C.5 [**Computer Systems Organization**]: Computer System Implementation; I.3.1 [**Computer Graphics**]: Hardware Architecture; B.4.2 [**Input/Output And Data Communications**]: Input/Output Devices—*Image Display*

General Terms

Design

Keywords

low power, low energy, LCD, embedded system

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1. INTRODUCTION

As demand on multi-media applications increases, modern hand-held embedded systems are equipped with a high-quality man-machine interface as well as a high-performance CPU and a high-bandwidth, large capacity memory system. While power-efficient STN (Super-Twisted Nematic) LCD (Liquid Crystal Display) is suitable for long battery life, backlight TFT (Thin-Film Transistor) color LCDs are the norm for today's embedded systems.

So, the display system is a major energy consumer even though current embedded systems are equipped with a 32bit RISC CPUs running at hundreds of MHz and with a tens of megabytes of SDRAM as a memory system. Hand-held embedded systems usually execute interactive programs which often results in very low utilization of CPU and memory, and thus lots of slack time. Taking actual energy consumption into account, the display system is more dominant because slack time can be used to reduce the energy consumption of the CPU and the memory but no such advantage exists for displays. Dynamic power management and dynamic supply voltage scaling have been developed for this purpose [1, 2, 3, 4, 5]. In most cases, users cannot recognize the energy saving actions of the computing part, the CPU and the memory, as long as the I/O devices for man-machine interface stay awake. In accordance with this context, previous energy reduction has focused on CPUs and memory systems [6, 7]. Range of software and hardware techniques have been introduced to reduce their energy consumption.

The display system is depended on as the interface to the operator on a nearly full-time basis and as such does not have the luxury of sleeping, at least not without significantly degrading the user experience. Indeed, shutting down the display system, even only for a short period, should be the last choice to extend the battery life, *i.e.* only in an emergency situation. In this paper, we introduce new energy saving techniques for the color TFT LCD display system taking the display quality into account.

From the device to the software level the internals of embedded systems have been subject to diverse energy reduction techniques, but energy reduction for display technology is still immature. Energy reduction has been performed for individual component for the display systems [8, 9, 10, 11]. Consequently, today's LCD panels and backlight tubes become much more energy efficient but it is still difficult to find consistent system-level approaches to reducing the energy consumption of the display systems. The system-level approach has been proven to be more promising than the individual device-level approach in work focused on other components of embedded systems; offering more opportunities to achieve global optimizations. Therefore, in this paper, we focus on energy reduction of the display system at the system-level.

Unlike the computing part, there is no slack time in the display system. Shutting down the LCD panel or turning off the back-

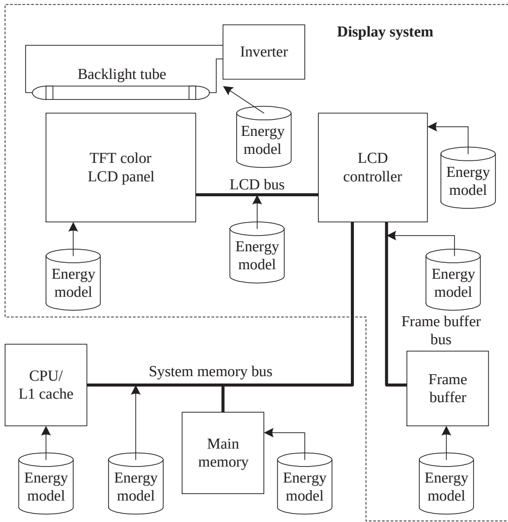

Figure 1: Energy model of a hand-held embedded system with a high-quality LCD display.

Table 1: Power consumption of commercial 32bit embedded CPUs.

Mode	Power (mW)		
	StrongARM	SH3	MIPS
Run	400.00	454.50	660.00
Idle	100.00	68.00	297.00
Sleep	0.17	0.11	N/A

Table 2: Power consumption of main memory (K4S280832B-TC1L) and frame buffer memory (KM48S2020BT-G10) at memory clock frequency of 66MHz.

Leakage energy (nJ/clock)			
State		Main memory	Frame buffer
Active		2.76	2.40
Idle		0.88	1.20
Power-down		0.08	0.08
Dynamic energy (nJ)			
Operation		Main memory	Frame buffer
Column read	Initial	68.24	22.05
	Successive	64.64	21.84
Column write	Initial	29.69	11.01
	Successive	26.35	10.80
Row activate		55.91	31.26
Row precharge		4.76	9.92
Auto refresh		144.40	48.81

Table 3: Power consumption of main memory bus and frame buffer memory bus at memory clock frequency of 66MHz.

Leakage energy (nJ/clock)				
State	Main memory		Frame buffer	
	data bus	address bus	data bus	address bus
High	0.08	0.08	0.08	0.08
Low	0.53	0.58	0.53	0.58
Dynamic energy (nJ)				
Operation	Main memory		Frame buffer	
	data bus	address bus	data bus	address bus
High to low	0.08	0.08	0.08	0.08
Low to high	0.53	0.58	0.53	0.58

light are trivial but result in unacceptable display quality degradation. Even dimming the backlight without appropriate compensation also degrades the display quality. Nevertheless, some commercial LCD controllers have power management functions for low power consumption that shut down the whole display system because currently there is no other systematic techniques that efficiently save energy in view of the whole display system.

A system-level approach or a high-level approach, must start from precise energy models. We fully utilize the detailed energy consumption characteristics of each display component with cycle-accurate measurement. In addition, we organize a system-level energy simulator, which directly reflects detailed hardware operation, with a deep understanding of the hardware design. This paper takes into account real display components and application programs to ensure these methods are applicable in practice. We also demonstrate the energy reduction in view of the total system including the CPU and the memory system. First, we locate major energy consuming components in the color TFT LCD display system by accurate measurement. Secondly, we suggest accepting minor display quality loss for great energy saving since lossy approaches are often much more efficient than lossless approaches. However, we do not allow appreciable display quality degradation. This is possible because we fully utilize detailed energy consumption models, characteristics of application programs such as text-based and graphics-based ones, and human cognition. As a result, we introduce the following techniques: variable-duty-ratio refresh, which is substantially different from variable dot clock, dynamic-color-depth control and backlight luminance dimming with brightness compensation or contrast enhancement.

The rest of paper is organized as follows. Section 2 introduces a system model of modern hand-held devices with a high-quality display system. We also introduce the energy models of following components: a CPU, a main memory, an LCD controller, a frame buffer memory, an LCD panel, a backlight inverter and lamp, and associated system buses. And we illustrate that display system is a dominant power consumer in view of the whole system. In Section 3, we introduce new energy reduction techniques for color TFT LCD display systems. Section 4 shows performance evaluation results, and finally, we conclude the paper in Section 5.

2. SYSTEM AND ENERGY MODEL

Fig. 1 shows a reference platform of a modern hand-held embedded systems with a high-quality display. Energy models are associated with dominant energy consumers. Among the components, the display system is shown in the dash-lined box. We are interested in the energy consumption of the display system. But, we also include the energy consumption of the computing part in order to calculate the total energy consumption since we claim the energy reduction ratio is in view of the whole system to emphasize the contribution.

2.1 CPU and main memory

The reference platform is in the range of high-performance PDAs and Hand-held PCs running WinCE or Linux operating systems: a 32bit RISC CPU @206MHz, 32bit 64MB SDRAM main memory @66MHz and 8KB 2-way-set-associative data cache and instruction cache. StrongARM [12], SH3 [13] and MIPS [14] are all in this category. We estimate energy consumption of the CPU, main memory and memory buses to demonstrate the energy reduction of the display system in view of the whole embedded system. We may use an average power consumption of the CPU without loss of generality (Table 1) as far as we accurately estimate the actual execution time. This is because we use the energy model of the

Table 4: Power consumption of an LCD panel.

# of blocked colors	Color	Power (mW)	Δ Power (mW)
0	white	830.5	0
1	red + green	858.5	28.0
	red + blue	857.5	27.0
	green + blue	856.0	25.5
2	red	885.5	55.0
	green	887.0	56.5
	blue	882.5	52.0
3	black	908.0	77.5

CPU for estimation only. We use energy values of the StrongARM running at 206MHz for the CPU while assuming that the cache size is 8K each for the instruction and data for more generality.

The reference platform is equipped with four K4S280832B-TC1L [15] from Samsung whose bus length is 2″ and its equivalent capacitance is 2.7pF. The memory data bus is buffered with 74LVT245 from Fairchild whose I/O capacitance is 4pF. The bus-hold circuit in the buffer has additional 0.5pF equivalent capacitance. The I/O capacitance of the K4S280832B-TC1L data ports is 5.3pF. The memory address bus is driven by 74LVT244 from Fairchild whose output capacitance is 4.0pF. The input capacitance of the address port is 15.0pF because four K4S280832B-TC1L chips are connected together. The correct estimation of the main memory system's behavior is very important because the execution time of CPU and the energy consumption of the memory system are highly dependent on it. We characterize the SDRAM devices by the cycle-accurate measurement introduced in [16]. Tables 2 and 3 show energy characterization of the SDRAM devices for the main memory and the frame buffer, and their associated buses. Due to the limited space, we have data for the two devices together. We build a cycle-accurate cache and main-memory simulator and estimate the energy consumption as well as the execution time of the CPU.

2.2 LCD controller and frame buffer memory

Years ago, when STN LCDs were popular in embedded systems, the size of the frame buffer memory was less than a few KB, and the bus width was only 8bit. Today, 32bit frame buffers are popular even in embedded systems as the number of colors, the size of screen (including virtual screen) and the number of pages increase. We implement an LCD and a frame buffer controller with Xilinx Spartan II XC2S150-5PQ208. The controller occupies one GCLKIOB, 128 IOBs, 181 SLICEs and three GCLKs. We estimate the power consumption with XPower [17], a new power estimation tool in the Xilinx FPGA development tool kit. The XPower reports 136.7mW at 2.5V VCC_{int} (core supply voltage), 3.3V VCC_{out} (I/O supply voltage) at 25°C, 66MHz and 10pF output load.

We compose a 32bit, 8MB frame buffer with four KM48S2020BT-G10 from Samsung. The bus length is 2″ and energy models are shown in Tables 2 and 3. Other parameters are the same as the main memory.

2.3 LCD panel and LCD bus

The reference platform is equipped with 640×480, 6.4″, 18bit color, transmissive, color TFT LCD panel, LP064V1 from LG-Philips. It is a low-power display and supports 60Hz refresh and VGA (Video Graphic Array) compatible input timing [18]. The power consumption of the LCD panel is sensitive to the display color as shown in Table 4. White consumes the least power as the amount of the light blocked by the cell is the minimum. Since the power consumption of the LCD panel is not variable as far as the cells do not change, we measure the power consumption by a digital multimeter. LCD bus is generally a flat cable whose energy consumption is larger than that of signals on a printed circuit board. We have also performed cycle-accurate measurement for the LCD bus (Table 5).

Table 5: Power consumption of LCD bus at pixel clock frequency of 25MHz.

State	Leakage energy (nJ/clock)
High	0.21
Low	0.21
Operation	**Dynamic energy (nJ)**
High to low	0.54
Low to high	0.54

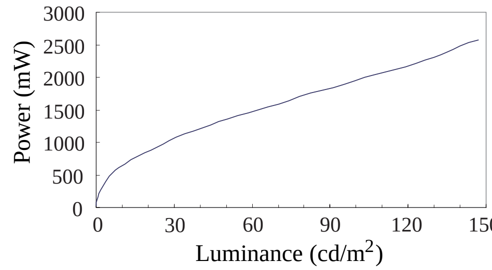

Figure 2: Steady-state power consumption versus luminance of the CCFL backlight system

2.4 LCD backlight and inverter

The backlight tube is a CCFT (Cold Cathode Fluorescent Tube) and thus requires a high-voltage inverter. We use an illuminometer (Minolta LS-100) and a digital multimeter to characterize the power consumption of the backlight lamp and inverter by changing the luminance. Since the backlight is not for embedded systems only, the maximum luminance is over 150cd/m^2. Typically, the luminance of the backlight for embedded applications is less than 45cd/m^2. So, we operate the backlight lamp from 15cd/m^2 to 45cd/m^2. The backlight inverter has 12V supply voltage, and we need another DC-DC converter when we use a single battery. However, we do not consider the energy loss of the additional DC-DC converter in this paper, for more generality.

2.5 System-wide energy consumption

Fig. 3 shows the energy consumption of each major component when we run an MPEG4 player. The CPU and the memory are in power-down mode during the slack time while the display component is being in active mode the whole time. This results in the LCD backlight being the most dominant power consumer, and the LCD panel and the frame buffer being the second and the third dominant power consumers, respectively. The MPEG4 player is a somewhat computing intensive application, so when we run a document viewer or a word processor, all most all the energy is consumed by the display components.

3. LOW-POWER LCD DISPLAY SYSTEMS

3.1 Variable-duty-ratio refresh

Although CRT (Cathode Ray Tube) displays and LCDs are substantially different from each other, commercial LCD panels commonly support virtually compatible interface with the CRT display except for the final signal format. This section introduces an en-

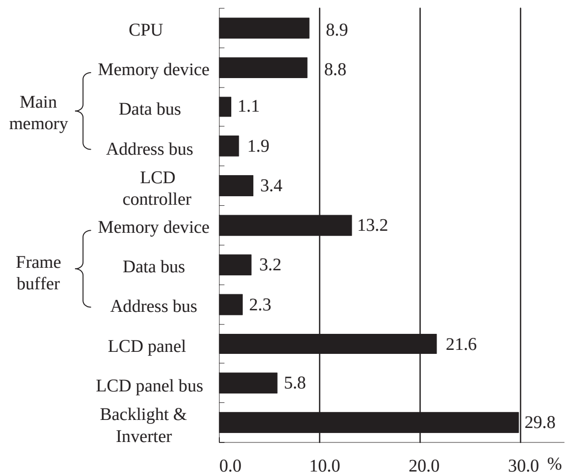

Figure 3: Energy portion of conventional system component (MPEG4 player).

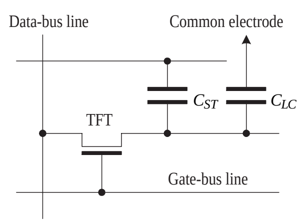

Figure 4: LCD sub-pixel equivalent circuit.

ergy reduction technique that utilizes the fundamental difference between the CRT and the LCD display.

Fig. 4 shows an equivalent circuit of a sub-pixel on the TFT LCD panel [19]. There are two capacitive components C_{LC} and C_{ST}. The equivalent capacitance of the liquid crystal is denoted by C_{LC}. There is an explicit capacitor, named storage capacitor, C_{ST}, that sustains the signal voltage. The storage capacitor needs to be refreshed, much like dynamic memory.

CRT display is based on an afterimage of human eyes. As we reduce the refresh rate of the CRT display that exceeds the minimum period for an afterimage on the human eye, we start to feel flicker. In other words, the image on the CRT display is always flickering; but human eyes do not recognize it as long as the flickering frequency is high enough. Meanwhile, the image on the TFT LCD panel also flickers, but the flicker on the LCD panel is of a different nature. As far as the refresh rate is higher than the time constant of the storage capacitors, the image on the LCD display does not flicker at all. Consequently, we can reduce the refresh rate of the LCD display as long as it is shorter than the time constant of the storage capacitors. Actually, modern LCD displays adopt flicker-free techniques, and the time constant is much longer than that of the CRT display. In addition, as we increase the refresh rate of the CRT display far exceeding the minimum period for the afterimage, we do feel better quality; so we often use 120Hz or higher refresh rate for high quality image. However, once the refresh rate is higher than the time constant of the storage capacitors, the image quality of the LCD display is not enhanced further. So, most LCD panels support fixed refresh rate, unlike CRT displays.

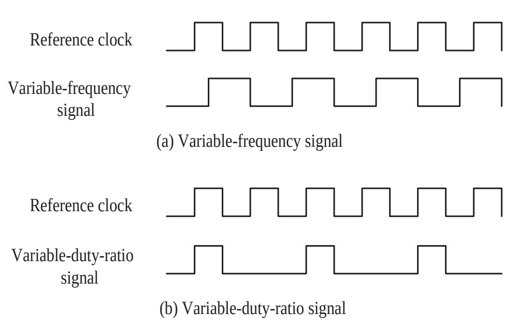

Figure 5: Variable-frequency versus variable-duty-ratio signals.

Reducing the refresh rate saves energy consumption of the frame buffer and the associated bus. As shown in Fig. 3, more than 19% of energy is consumed in the frame buffer and the bus. We can use two different methods to change the refresh rate. Fig. 5 illustrates variable-frequency and variable-duty-ratio methods. It is not desirable to use variable-frequency method because we need a programmable PLL (Phase Lock Loop) with no dead time. On the other hand, variable-duty-ratio is easily implemented with the use of a DTMG signal. Fig. 6 shows 100% and 50% duty refresh. Again, we do not change the H-sync., V-Sync. and thus dot clock; V-sync. is 60Hz.

As a result, at 75% duty, we save 129.8mW observing no flicker at all. At 50% duty, we save 259.7mW without flicker, either. At 33% duty, we save 346.2mW observing minor flicker. At 25% duty, we save 389.5mW, but noticeable flicker is observed.

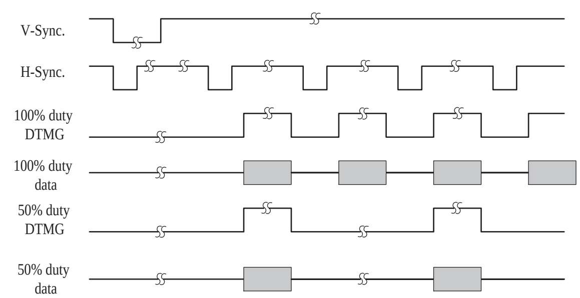

Figure 6: Implementation of the variable-duty-ratio refresh for VGA-compatible TFT LCDs.

3.2 Dynamic-color-depth control

Most commercial color display systems support color-depth control. When we reduce the color depth, the frame buffer memory offers wider screen or a larger number of pages. However, we do not expect energy savings. The LP064V1, the LCD panel for the reference platform, supports the maximum 18bit color depth. So, desirable pixel size is 16bit. Fig. 7 (a) shows typical pixel organization for 16bit color depth. In this paper, we modify the pixel organization as Fig. 7 (b).

The purpose of the new pixel organization is to save energy when we decrease the color depth. Instead, we do not expect larger screen or a larger number of pages. During the rendering process, the CPU draws image or text in full color depth. During the sweep process, the LCD controller adjusts the color depth to save energy. The new pixel organization enables the shut down of the LSD (Least Significant Device) when we use 8bit depth. Modern LCD controllers, including the controller in the reference platform, have bus arbitration logic inside, and thus the CPU does not have the control over the frame buffer. So, the new pixel organization does not need to modify any existing software, meaning this causes no compatibility issues.

Since the power down of the SDRAM is done at device level, *i.e.* only the whole chip can be sent to the power-down mode, we can control the color depth in two levels under 16bit pixel with an 8bit SDRAM configuration.

The energy gain is somewhat application dependent. As a result, we save 315.7mW, 250.2mW, 253.0mW, 251.8mW and 250.1mW for an MPEG4 player, an MP3 player, an image viewer, a document viewer and a text editor, respectively.

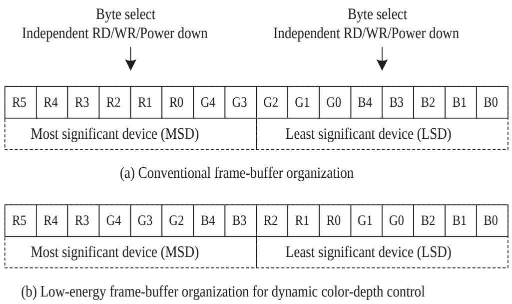

Figure 7: Low-energy frame-buffer structure for dynamic color-depth control.

3.3 Brightness compensation and contrast enhancement with backlight luminance dimming

Since the backlight lamp and inverter are the most dominant power consumers, we can save a lot of energy if we dim or turn off the backlight. However, transmissive TFT LCDs do not allow the backlight to be turned off; only transflective and reflective TFT LCDs are still functional without the backlight. Most importantly, even a small amount of dimming of the backlight results in significant quality degradation of the display system without proper compensation. In this section, we propose to use backlight dimming followed by proper brightness or contrast enhancement. As the luminance of the backlight decreases slightly, the quality does not reduce a noticeable amount. Slightly more is tolerable, but causes the user to strain their eyes. Still more dimming can cause the display to be illegible. The bottom line is that we must compensate the brightness or enhance the contrast of the image on the LCD panel for the luminance lost from backlight dimming. The brightness means perceived intensity by human eyes. Let the luminance of the backlight and image be L and Y, respectively. The perceived intensity, I, is given by

$$I = \rho L Y \tag{1}$$

where ρ is the transmittance of the LCD panel. Now, we reduce the luminance of the backlight to L' such that $L' \leq L$. We may maintain the perceived intensity, I', such that $I' \approx I$ by enhancing the luminance of the image where $Y' \geq Y$.

Brightness compensation does not distort the original image appreciable as far as the number of saturated pixels is minor. Usually the amount of possible enhancement is not much, and thus relatively small amount of energy gain is expected. On the other hand, contrast enhancement does distort the original image. But more aggressive compensation is possible as long as we are not concerned about preserving the original color such as high-contrast color setting is used for visually handicapped people in PC Windows systems.

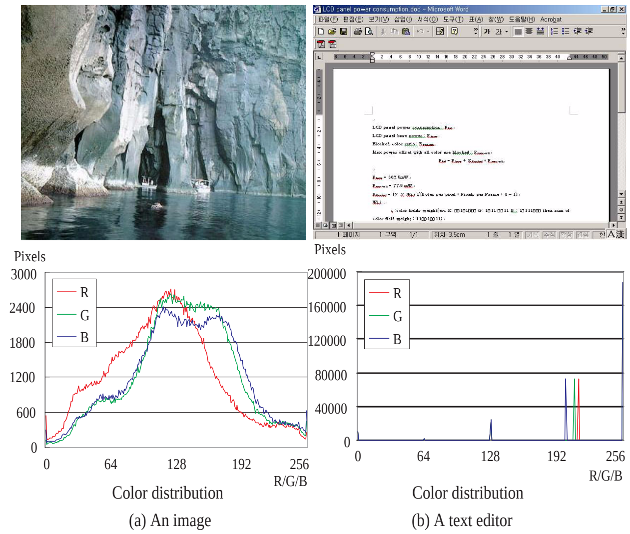

Figure 8: Color distribution of a text editor and an image.

Fig. 8 shows two different styles of images and their color distributions. The color spectrum of Fig. 8 (a) shows possibility to enhance the brightness because no distinct spectrum appears at the both ends. Fig. 8 (b) is suitable for contrast enhancement because the image contains no significant continuous color spectrum. However, contrast enhancement may also change naturally different colors to the same color, which makes the image even more difficult to recognize when the image contains continuous color spectrum (Fig. 8 (a)).

Table 2 shows 12mW power saving by lowering 1cd/m^2 of luminance. Brightness compensation is denoted by

$$C' = min(1, C + \Delta C) \tag{2}$$

such that,

$$\Delta C = 1 - \frac{L'}{L} \tag{3}$$

where C and C' are each normalized RGB values before and after brightness compensation, respectively. Note that, each RGB value needs to be compensated by the same amount to maintain the original color. L and L' are luminance of backlight before and after brightness compensation. We save 200mW of power by reducing the backlight luminance from 45cd/m^2 to 32cd/m^2. We can dim the backlight more aggressively with the contrast enhancement. Contrast enhancement is denoted by

$$C' = min(1, \frac{CL}{L'}) \tag{4}$$

where C and C' are each normalized RGB values before and after the contrast enhancement, respectively. We achieve 480mW power saving by reducing the backlight luminance from 45cd/m^2 to 15cd/m^2.

4. EXPERIMENTAL RESULTS

This section demonstrates the aggregate energy reduction ratio by the use of techniques introduced in Section 3. The aggregate energy reduction will be virtually the summation of each reduction amount because each reduction technique is orthogonal.

The behavior of the frame buffer is divided into two categories. One is the sweep operation by the LCD controller, and the other

Table 6: Application specific parameters.

Application program	Cache hit (%)	CPU usage (%)	Display Pixels/sec
MPEG4 player	99.5	87.4	2,304,000
MP3 player	99.8	35.9	5,000
Image viewer	98.9	10.0	102,400
Document viewer	99.9	1.0	61,440
Text editor	99.9	1.0	1,500

Table 7: Aggregate power reduction .

Application	Original (mW)	Reduction (mW)	%
MPEG4 player	4028	3358	16.6
MP3 player	3430	2545	25.7
Image viewer	4015	3408	15.1
Document viewer	3202	2315	27.6
Text editor	3197	2313	27.6

one is the access from the CPU. The energy consumption due to the sweep operation is accurately simulated. Since the CPU access is performed by the auto-precharge mode, sending the SDRAM to idle mode after every burst-mode transaction, we may simply add the energy consumption due to the CPU access. Eventually, the energy reduction ratio is dependent on the application program. We experiment with five different popular embedded applications. Table 6 shows the cache-hit ratios and the CPU activities extracted by the cycle-accurate simulation. The MPEG4 player has 320×240 screen resolution with the frame rate of 30Hz. The MP3 player has an interface[1] whose size is 100×50 pixels. The update period of the skin is one second. The image viewer shows 640×480 still images. It moves to the next image every three seconds automatically. The document viewer has 640×480 screen size and precedes to the next page every five seconds. Finally, the text editor updates three new characters a second, and cursor is updated two times a second.

Table 7 shows the aggregate power reduction ratios. Note that the reduction ratios are not for the display system only, but for the whole embedded system including the CPU and memory system. We apply the variable-duty-ratio, dynamic-color-depth control and brightness compensation methods for the MPEG4 player and the image viewer. The variable-duty-ratio, dynamic-color-depth control and contrast enhancement methods are applied to the MP3 player, the document viewer and the text editor. The amount of power savings is the same as the amount of energy savings because the total run time is not variable due to the reduction techniques. We apply power reduction techniques only to the display system, however, we save around 25% of the total power consumption of the embedded system.

5. CONCLUSIONS

Modern embedded systems are being equipped with high-quality display systems as demand for multi-media applications increases. This results in more power consumption in the display systems when compared to the requirements of the rest of the embedded system. This becomes more significant when we run interactive applications such as a document viewer and a text editor. However, we cannot use a simple power down scheme for the display system and not cause unacceptable display quality degradation.

This paper introduces new low-power techniques, which are system-level approaches, taking into account detailed physical energy models of the components, characteristics of application programs, and human behavior and cognition. We introduce variable-duty-ratio refresh, dynamic-color-depth control and backlight luminance dimming with brightness compensation or contrast enhancement. This enables us to achieve vertical optimization of system hardware and thus dramatic reduction without appreciable display quality degradation.

We illustrate the energy reduction including the CPU and the memory system to emphasize the power of these techniques in practice. We demonstrate the 16.6%, 25.7%, 15.1%, 27.6% and 27.6% energy reduction of the total embedded systems with an MPEG4 player, an MP3 player, an image viewer, a document viewer and a text editor, respectively.

[1] A user interface display that looks like a real MP3 player.

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