ENERGY EFFICIENT HYBRID DISPLAY FOR EMBEDDED AND MOBILE SYSTEMS

A Thesis

Presented to

the Faculty of the Department of Computer Science

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Yuanfeng Wen

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If it is easy, it won't be amazing. Let's celebrate, when the day comes!

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Abstract

Embedded and mobile devices, such as smartphones, e-books, and tablets, have limited battery capability because of the constraint of battery size and mobility requirement. However the large color display on those devices put more tensions on this situation as the display consumes a large portion of the total battery power. Electrophoretic displays (EPDs) and organic light-emitting diodes (OLEDs) are two key technologies used on embedded and mobile devices. We propose the design of an integrated hybrid display combining a transparent OLED (TOLED) and a low-power EPD, which is adaptive to show contents of a frame partially on either the TOLED or the EPD. A windows-based predictive model and a calibration algorithm on TOLED are introduced to decide how frame contents can be split between the two displays for achieving the best tradeoff between power reduction and user experiences.

In addition to regular contents, we also propose a design of mobile video playback, *Decoder4Hybrid*, for the hybrid displays to play realtime videos. A fast DCT(Discrete Cosine Transform)-based heuristic algorithm is proposed to detect the changes between frames at block level with minimal computation cost.

A simulation environment that can estimate both the energy consumption and optical properties of the proposed hybrid display is set up based on actual physical measurements. Simulation results show that the predictive model can make right decisions on choosing proper displays in over 90% of the test cases, and this new display design can save over 70% power under many mobile application contexts and still support contents that require fast update rates. Experimental results show that the proposed approach can save up to 40% power with acceptable video quality.

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Chapter 1

Introduction

Mobile electronic devices, especially smartphones, e-reader, tablets, and netbooks are powered from batteries which are limited in size and capacity. Thus power management has been and will continue to be an essential aspect of technology for designing mobile electronic devices. Today, high-end mobile gadgets are rich devices that can support a wide range of functionality and experiences such as voice communication, audio and video playback, email communication and online chat, web browsing, social networking, gaming, and more. With the popularity of mobile applications, more functionality will be integrated with mobile devices and increase the pressure on the battery life, and exacerbate the need for efficient power management. As mobile devices need to provide more PC-like capabilities, many of them integrate a large color display for supporting mobile applications. A high-end smartphone can provide the same screen resolution as workstations a few years back. The large mobile displays play an important role as human-machine interface and support media-rich applications. At the same time, they are energy-hungry components, often consuming significant percentage of total battery power.

In addition, the display makes a non-negligible contribution to the greenhouse gas emissions. According to market analysis and prediction, in 2015, all around the globe, there will be 640 million laptops, 1.5 billion smartphones, and 966 million laptops. Based on analysis of current laptop, smartphone, and tablet usage patterns, display energy consumed by those mobile devices will be equivalent to burning 2.53E+08 gallon gasoline, which accounts for 2.22E+06 tons of CO_2 eq. emissions per year.

OLEDs are envisaged to offer more brilliant images with higher levels of contrast than LCD panels and at the same time provide a significant reduction in energy consumption. The electrophoretic display has the advantages of being the best candidate for electronic paper. With the properties of being invariably reflective and bistable, it is more comfortable to read than conventional displays. EPD has no need to be refreshed constantly and it reflects ambient light rather than emitting its own light such as OLEDs. Moreover, the power supply of an EPD can be turned off after updating images. As a result, EPD consumes an order of magnitude less power than LCD panels and OLEDs. However, EPD has a very low refresh rate compared with other low-power display technologies. Therefore, EPD is unsuitable for certain application contexts such as playing a video. Furthermore, due to technology limitation, it is a great challenge to support a large number of colors in EPD. Currently, EPD can support only 4K colors.

We propose the concept of a hybrid mobile display, which is to integrate multiple displays of different techniques in one system to support display adaptation based on the usage context and contents. The result is improved trade-off between user experiences and energy management. In this paper, we propose and evaluate a mobile hybrid display design that integrates transparent see-through OLED with EPD in a stack structure. The hybrid display allows context-based display adaptation by supporting two operation modes. In switch mode, a mobile system or user can adaptively switch between OLED and EPD based on the application context. In hybrid mode, both the EPD and the OLED can be turned on at the same time, in different display areas, with slow contents displayed on the EPD and fast contents on the OLED. When used in the hybrid mode, OLED can be adapted to the color space of EPD, thus creating consistent viewing experiences. Transparent OLED is a key technique that makes such a hybrid display a reality. If switched off, a transparent OLED display may appear as an ordinary window which allows a clear view on everything behind it. When combined with a low power reflective based display such as EPD, a highly adaptive and low power hybrid display design can be created as one of the candidates for achieving the best trade-off between power efficiency and user experiences.

Recent studies [1, 16] also show that 48% smartphone users watch videos on their phones and one in every ten tablet users views video content almost daily on their devices. Those numbers keep increasing because of the popularity of online video services. However, video playback on mobile devices is power hungry [9] because of the requirement of display activation and long duration of the activation, e.g., average length of a YouTube video is 4 minutes and 12 seconds [2]. High power consumption of video playback may drain battery on mobile devices quickly and undermine the usability of the mobile devices. This situation becomes even worse with modern large size and high resolution displays on mobile handheld devices.

However, designing such a hybrid display is a challenging task because it is hard to decide which parts of the displayed contents should be shown on the OLED panel and which parts should be shown on the EPD, which can achieve energy reduction and guarantee user experience at the same time. Users should not notice that two displays are being used. In addition, the ambient luminance is a dominating factor when using EPD since if the luminance level is low, EPD can be barely seen. To further study energy reduction and user experience, we need to establish both a power model and optical model to evaluate the design of the proposed hybrid display.

Based on the characteristics of the hybrid display, we also propose a novel video decoder for the EPD−TOLED hybrid-display in order to reduce the energy consumption of video playback and at the same time keep the high quality of video playback on mobile devices. Our design is based on the observation that many pixels during video playback change less frequently than others, and can be displayed on the EPD with slow refresh rate. Other frequently updated pixels during video playback can be displayed on the TOLED.

Mobile video playback can benefit from such EPD−TOLED hybrid displays, especially for certain types of videos such as cartoon movies because the cartoon contents are often simpler and the frame rate is slower than other types of video contents. To the best of our knowledge, no related works use both TOLED and EPD for energy efficient video playback on handheld devices.

Main Contributions

The main contributions of this thesis include:

- a design of an integrated hybrid display stack combining TOLED and EPD for supporting context−based display adaptation;
- a windows-based predictive model and a calibration algorithm on TOLED that allow frame contents to be shown on both TOLED and EPD at the same time for supporting improved trade-off between energy reduction and user experience;
- a design of mobile video playback, Decoder4Hybrid, for mobile hybrid displays;
- a fast DCT-based heuristic algorithm to detect changes between different blocks;
- energy and optical evaluations of the hybrid display using models exhibiting physical characteristics resembling measurements of actual EPDs, an actual OLED, and fabricated transparent OLED devices;
- energy and optical evaluations of video quality and power consumption when using hybrid display to playback cartoon videos.

Organization

The rest of this thesis is organized as follows. Chapter 2 describes the related technologies and the state-of-art researches, then motivates the research. Chapter 3 presents the design of the proposed hybrid display, including the hardware design, the prediction model and the calibration module. Details of the video decoder for hybrid displays are presented in Chapter 4. Experimental results on power savings and video qualities using the new design are in Chapter 5. The final conclusions of the thesis are presented in Chapter 6.

Chapter 2

Related Work

In this chapter, we first study the related technologies, including EPD, OLED, Transparent OLED (TOLED), and MPEG video compression. Then we present the state-of-art research related to our work, including the research on the display power reduction, the mixed-display technology and the energy efficient mobile video. At the end of this chapter, we present the motivations of our work.

2.1 Related Technology

Display technology plays a critical role in the mobile industry. Most mobile devices own a screen with a specific display technology. Currently, handheld electronics have increased demand for displays in multiple areas, such as picture quality, size, and power consumption. The most common display technologies used in mobile devices are LCD and OLED screens which consume about half the amount of the

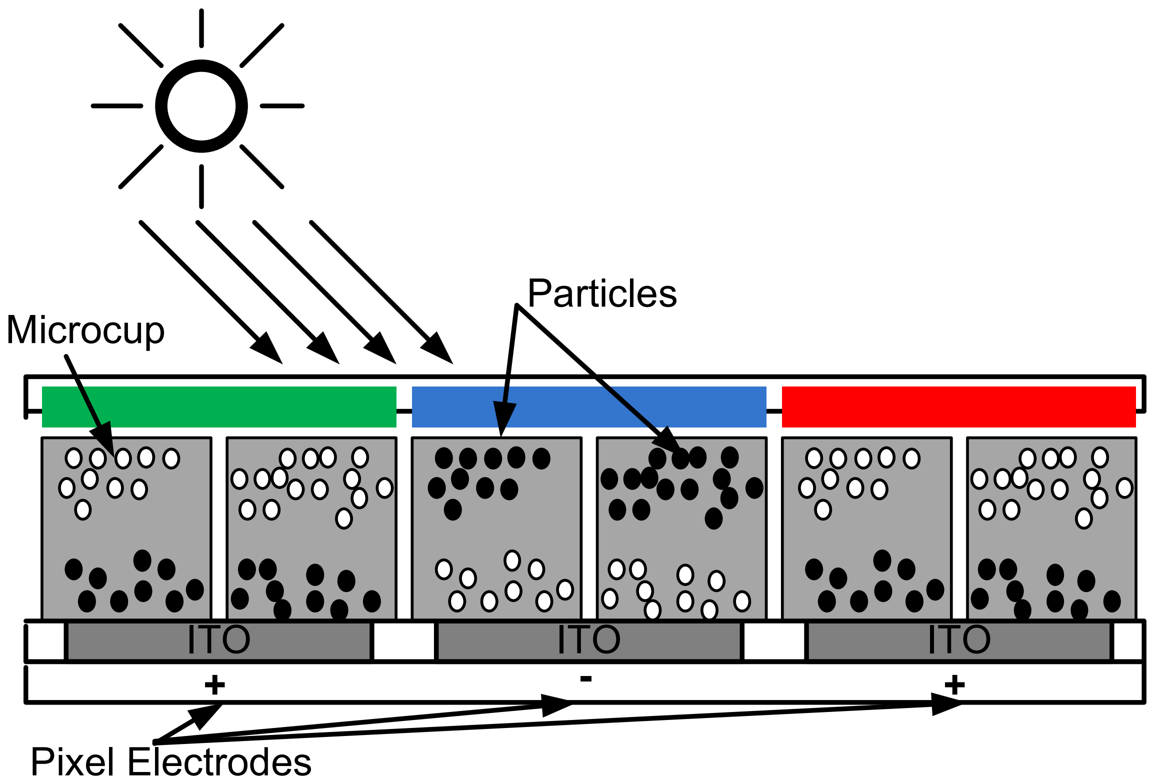

Figure 2.1: EPD

battery power. A new trend in handheld devices like the Kindle, is to integrate an electrophoretic display that offers possibility for significant energy savings.

2.1.1 EPD

Electrophoretic display is a display technology design which imitates the ordinary ink on paper. This technology works by using millions of tiny microcapsules that are held between two arrays of electrodes as shown in Figure 2.1. The microcapsule contains positively charged color pigment particles and negatively charged color pigment particles suspended in a specific liquid layer. Since the particles are of opposite charge, the color pigment particles will switch between front and bottom of the film, allowing users to see different views of color.

The most important feature of these capsules is that the individual microcapsule is stable in its state. Even with the power turn-off, the display content remains visible. This bistate nature benefits some applications with low refresh rate such as reading books. Once the display is shown to the user, it can last a couple of hours with very little leakage power consumption. However the EPD technique has limitation for the device's refresh rate, thus only few reading devices utilize this technology.

2.1.2 OLED

When compared to the narrow usage of electrophoretic display, OLED displays dominant the recent smartphone display market. In Figure 2.2(a), we can see that a typical OLED display consists of multiple layers, a cathode layer, an electron transport layer, an organic layer made of light-emitting materials (e.g., Alq3), a hole transporting layer, an anode layer, and a substrate layer. When the voltage supplies to the OLED display, an electrical current flow is generated from the cathode to the anode. The cathode gives electrons to the organic layers. At the same time, the anode removes electrons from the organic layers. The photons, which are generated when the electrons move across the different organic layers, provide the light for the OLED display. Since OLEDs can emit light, without the need for a backlight, the

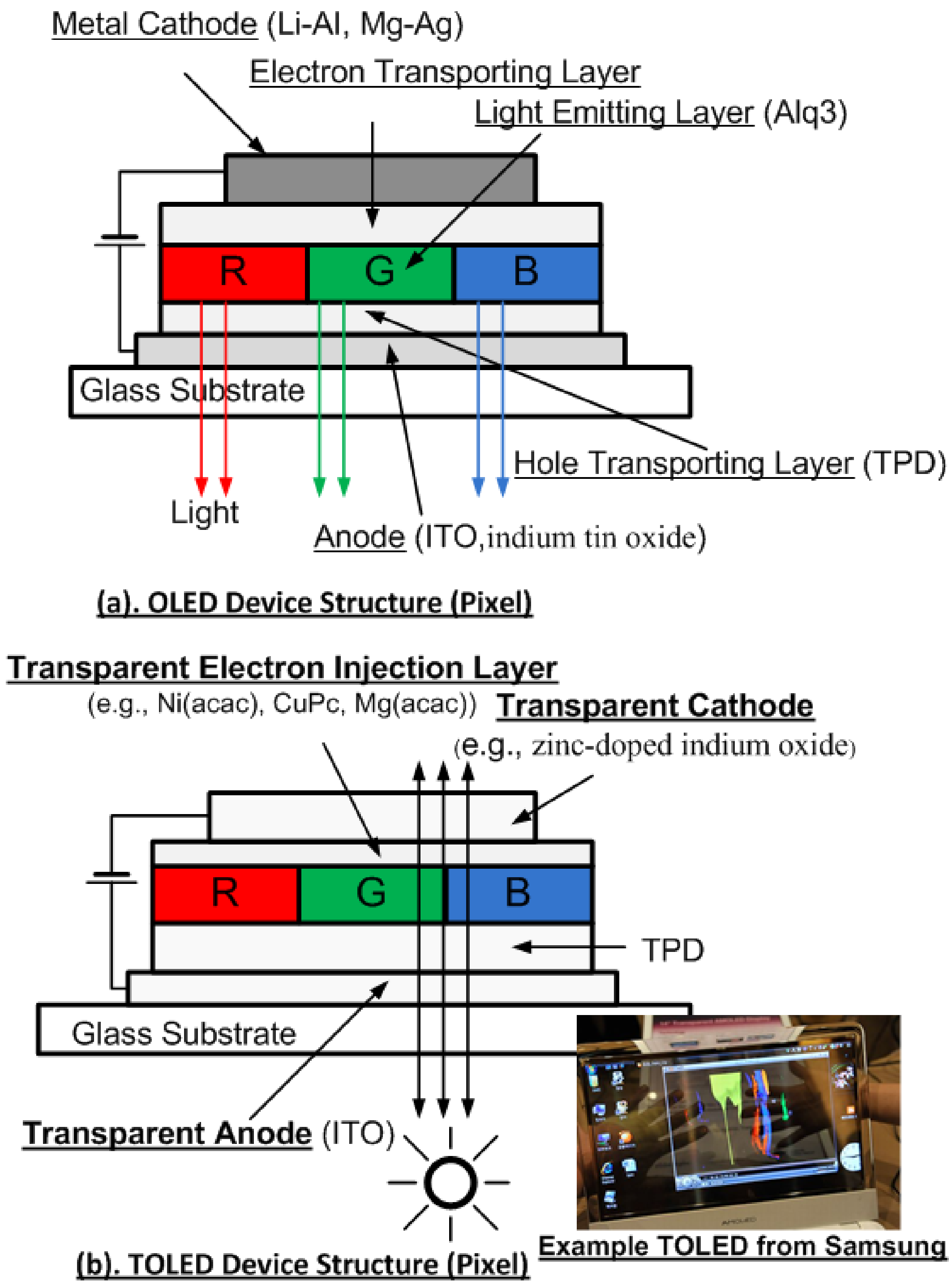

Figure 2.2: OLED

OLED technique requires less power than the conventional LCD technique. However, displays using OLEDs consume order of magnitude of more power than the EPD-based displays.

2.1.3 Transparent OLED

A unique property of many organic molecules is that most OLEDs are highly transparent over their own emission spectrum, and throughout most of the visible region of the spectrum. This property enables a new type of organic electroluminescent display (TOLEDs) that are greater than 80% transparent when turned off. TOLEDs [38, 33, 36, 26] use only transparent components as substrate, cathode and anode. A TOLED structure is shown in Figure 2.2(b), in comparison with the conventional OLED structure. The high transparency of the device is achieved by replacing the non-transparent cathode (e.g., thick MgAg alloy) with a thin layer of transparent electrode. A transparent OLED display can be either active or passive-matrix. However, sometimes TOLED panels may require slightly higher voltage bias than the non-transparent ones for attaining the same current level or brightness.

2.1.4 MPEG Video Compression

In order to produce the standard method of video compression, a group of experts known as motion picture expert group (MPEG) established a standard for coded representation of moving picture and associated audio on digital storage media. Since the first MPEG-1 ((Motion Picture Expert Group) standard proposed in 1988, several standards such as MPEG-2, MPEG-4, etc. have been developed for video as well as audio compression. For achieving maximum compression rate, MPEG uses two primary techniques: intraframe compression and interframe compression. Intraframe coding can provide access points to the coded sequences where decoding can begin and continue correctly. Intraframe coding uses various spatial prediction modes to reduce spatial redundancy in the source of signals in a single picture (e.g., DCT-based compression to reduce spatial redundancy).

The interframe compression depends on the previous frames or later frames. There are two types of frames, intraframe (I frames) and inter-frame (P or B frames). To compress a P frame, there is a reference frame before it. The P frame is divided into 8 x 8 pixel blocks. The blocks will be quantized, scanned, and encoded after applying DCT transformation. Interframe coding (predictive or bi-predictive) exploits information redundancy using inter-prediction of each block of sample values from some previously decoded pictures. The Interframe encoder computes motion vectors and residual blocks. Motion vectors are used for block-based inter prediction to reduce temporal redundancy among different pictures. The encoder compresses the residuals and motion vectors. At the decoder, P frame is reconstructed using the residual block, motion vectors, and the reference frame. The residual information and motion vectors are available at the decoder stage. Additional power saving features are adopted by H.264. For example, there are frames called SI and SP frames in the H.264 which support bitstream switching, i.e., one can easily switch bitstream from high refresh rate to low refresh rate and vice verse.

Frame per second (FPS), is the rate a device produces consecutive images. The human eyes and brain can process 10 to 12 images per second. The modern movies usually runs at 24 frames per second, while animations/cartoons 12 frames are shown per second [5], which is still acceptable. There are a large amount of areas change infrequently in animations/cartoons. Therefore, displaying these unchanged fragments on EPD will lead to significant power savings. This motivates to show those parts on EPD if a hybrid display is used. Different from the work in [37], to determine whether a block is changed or not, one can use not only the history or the previous frames, but also the frames to be shown in the future. The lookahead knowledge helps to make better decision on where to show the blocks.

2.2 Related Research

In this section, we survey works that are most related to ours, focusing on approaches of power consumption reduction for different display technologies, including LCD, EPD, and OLED. We also discuss the existing hybrid display technologies that aim to reducing the power usage and maintaining high display quality at same time.

2.2.1 Display Power Reduction

Display power reduction for mobile devices has been actively researched in the recent years. In [14], the authors find that the display idle time is following certain distribution. For reducing LCD power consumption, they proposed two schedules to turn the LCD screen dim or off. One is called deterministic schedule and the other one is called probabilistic schedule. Either algorithm contributes 50% energy savings of the default schedule on E71.

In 2005, Ghent University [8] presents a complete model for internal particle distribution of EPD. Electrical and optical features can be calculated based on independent physical parameters. The model is simplified in [8]. Technical details on EPD controller design and EPD image quality enhancement can be found in [10, 24, 22].

For EPD, in [7], the authors present a smart driver approach for saving EPD energy. The driver only updates changed pixels between frames, ignoring the ones with only minor changes. Furthermore, a lazy driver is also proposed, which sets a threshold on the changes of pixel colors. Only those with changes exceeding the threshold are updated. The lazy driver is more aggressive in conserving power. However it may provide worse quality of images.

In [12], the authors provide three-level models for power consumption for OLED displays. The three levels are pixel level, image level, and code level respectively. Their models can achieve over 90% accuracy in estimation for 300 benchmark images. They also provided power modeling and optimization for OLED displays, which helps energy-efficient GUI design on the OLED.

For reducing OLED power consumption, in [21], the authors studied OLED power modeling and power consumption optimization. A partial screen darken method, namely dark windows, is proposed to save power and in the meanwhile preserving the quality of user experiences. In [34], the authors present a dynamic voltage scaling-based technique for OLEDs. Their method reduces the power consumption by scaling down the supply voltage, which saves the energy used on driver transistor and internal resistance. The authors claim up to 50% power savings while keeping the same human-perceived quality.

2.2.2 Mixed-display Technology

In [13], the authors provide the design and implementation of Chameleon, a color-adaptive mobile web browser that renders web pages with reduced energy consumption by OLED mobile systems. Chameleon only performs the absolutely necessary tasks that are needed in real-time. It finishes the color maps calculation offline. According to the measurements, Chameleon saves power consumption by 41% for web browsing without noticeable delay.

Recently, mobile device companies have started to explore ways to mix different display technologies. Apple Inc. filed a patent about hybrid display by incorporating EPD technology into iPhone, iPad, and iPod touch [28]. In their model, the hybrid system would switch different modes by displaying the content either on an EPD device or on an OLED device, but not both. Samsung also implemented a prototype that combines e-paper and a LCD screen. The display panel can switch between the two display modes: the “memory mode”, which is similar to the Kindle; the “dynamic mode”, which can playback color video. Our design distinguishes from those works by being able to show frame contents on both transparent OLED and EPD at the same time. In addition, we propose an adaptive control approach that can take into account content update rates and decide at window or subframe level which display should be used for attaining the best tradeoff between energy reduction and support for contents. Furthermore, we evaluate performance of the proposed hybrid display system using high fidelity simulations derived from reported measurements of actual EPD and TOLED devices.

2.2.3 Energy Efficient Mobile Video

Much of the attention on energy efficient mobile videos has been directed towards efforts such as optimization of mobile video delivery (e.g., [35, 19, 39]) and energy-aware video decoding (e.g., [31, 27]). Energy efficiency research focusing on reduction of display power consumption of mobile video playback is comparably less. In [32], the authors propose an adaptive middleware for optimizing the backlight power consumption for mobile handheld devices when playing streaming MPEG-1 video. Their study results show that the approach can save significant amount of energy consumed by backlight without significantly compromising on video quality. To our knowledge, our paper is the first one that minimizes mobile video power consumption via innovative hybrid display techniques and a video playback heuristic suited for the hybrid mobile display.

In [32], the authors proposed and studied a low power mobile video technique that reduces backlight consumptions of mobile handheld devices. Without significantly compromising on video quality, their technique can save up to 60% of the power consumed by the backlight when playing streaming MPEG-1 video.

2.3 Motivation

Energy consumption is a key factor for recently mobile devices. The battery life is usually less than one day with users' daily activities for most of the smartphone. Meanwhile, the e-reader which applies EPD technique could last a couple weeks but no guarantee on displaying with high frame rate application. A natural idea is how to get benefit from different display technologies while avoiding the limitation from them.

Our work is motivated by the observation that in the OLED and TOLED system, some applications require a high refresh rate to be functional (e.g., video player) but some applications do not require that (e.g., book reader). In addition, the applications that require high refresh rate may only need frequent changes in subareas of a screen instead of the whole screen. For example, the video area of a movie player requires a higher refresh rate but the area of the playlist does not. In order to verify our hypothesis, we collected update frequencies at pixel level when running some of the most common applications using iPhone4. As shown in Figure 2.3, the pixel update frequencies are drastically different for different applications. In text-based applications such as iBooks, messaging, and email, most of the pixels don't update for over 6 seconds. In contrast, some media types of applications such as Angry Bird, most of the pixels update over 20 times per second.

The usage pattern analysis suggests that an adaptive and flexible approach that can optimally at subimage or pixel level choose display settings according to the content or application contexts is beneficial. In pursuit of this goal, we proposed

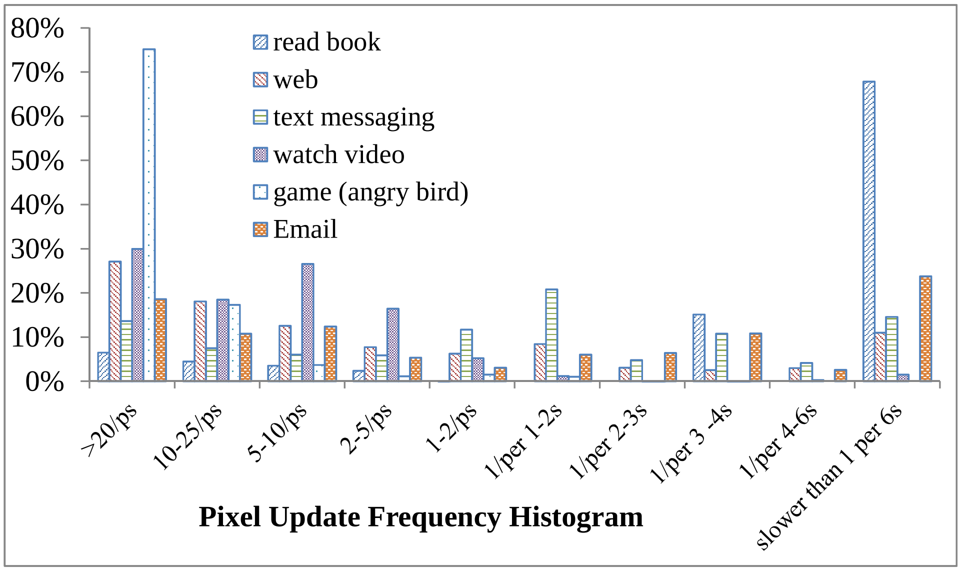

Figure 2.3: Histogram of Pixel Update Frequencies

a TOLED and EPD hybrid display that allows pixel contents to switch between a TOLED screen and an EPD screen.

Such a hybrid display enables adaptive selection of displays based on the contexts and contents. For applications where slow image update rate suffices such as reading books, a system can send display output to the slow and more energy efficient EPD screen. In the context of multimedia applications that demand rich colors and faster updates, the system can switch to the TOLED screen more suitable for showing the rich and faster content. Such display adaptivity can provide a new venue for attaining better tradeoff between user experiences and energy efficiency.

Figure 2.4 illustrates the potential energy savings for a mobile device that supports switch between the two displays based on the contexts. The X-axis shows hypothetical percentage of display time where content is displayed on the EPD screen

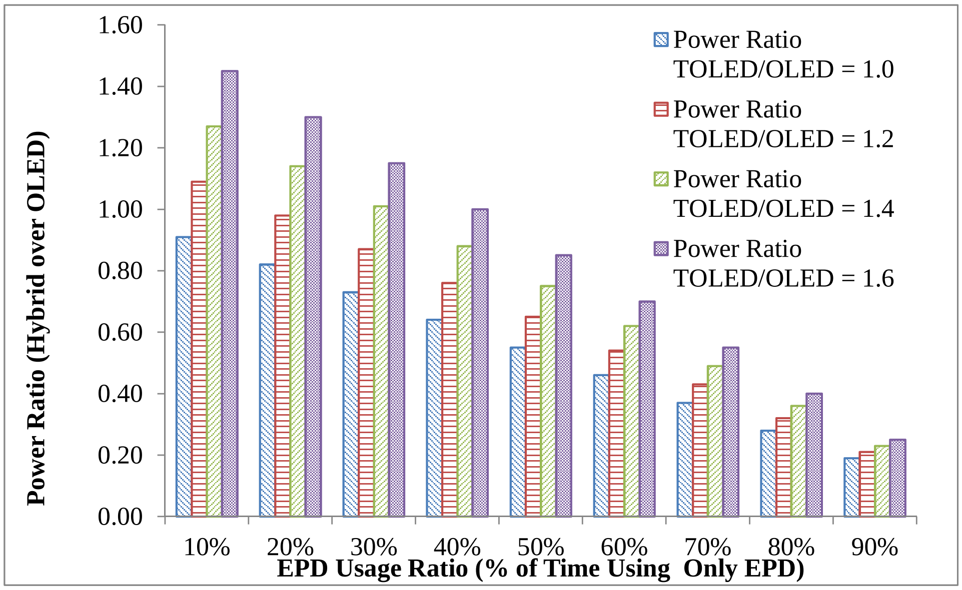

Figure 2.4: Power Saving Estimation When Switching Between EPD and TOLED

and the Y-axis indicates power consumption ratio using the TOLED and EPD hybrid display over a conventional OLED only display.

An OLED display and the equivalent TOLED display may not have the same energy profile even when the TOLED uses materials and fabrication process as close as possible to the OLED. To take this factor into account, we use the TOLED versus OLED power consumption ratio as a parameter. Figure 2.4 evaluates four scenarios where the ratio between TOLED vs. OLED power consumption is 1, 1.2, 1.4, and 1.6. As shown in Figure 2.4, even in an unlikely pessimistic case, when the TOLED consumes 1.4 times more power than an equivalent OLED, a TOLED−EPD hybrid display can still attain the same overall power consumption if around 32% display usage can be done using the EPD.

In addition to the switch mode that supports choosing one output screen at a time,

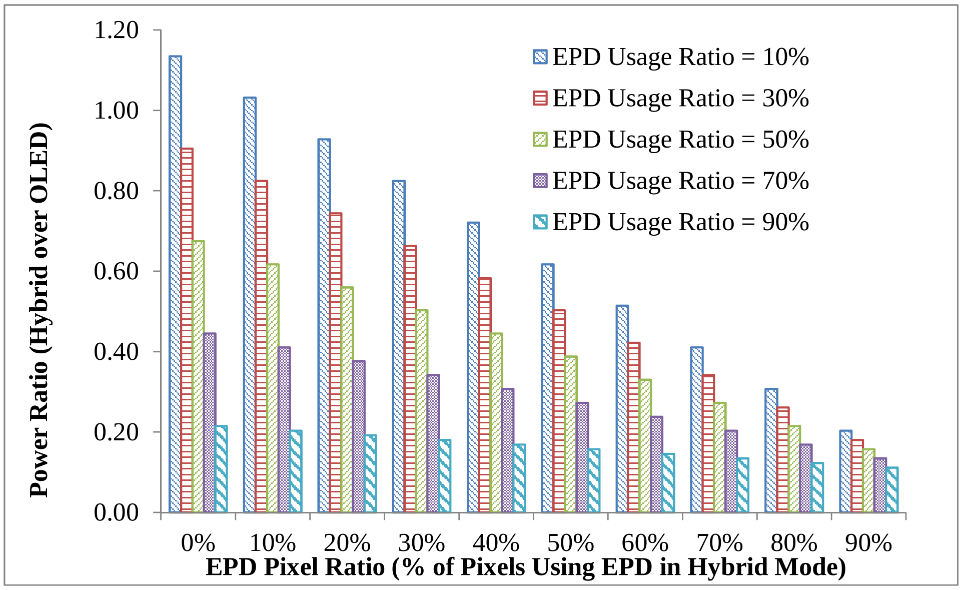

Figure 2.5: Power Saving Estimation When Using Both Displays at the Same Time

a TOLED−EPD hybrid display can support a second usage mode that allows both displays to be used simultaneously. Based on the content, a system can decide that which regions or pixels of an image are suitable to be displayed on the EPD screen, and which regions or pixels should be displayed on the TOLED screen. Consequently, using this hybrid display mode, we can attain even greater energy efficiency.

Figure 2.5 shows power consumption ratio of the TOLED-EPD hybrid display over an OLED only display when both the switch mode and the hybrid mode are used. The X-axis shows, what percentage of the pixels of an image can be displayed on the EPD screen in a hybrid usage mode. For example, 40% means that in the hybrid mode, on average, 40% of the image pixels can be displayed on the EPD and the rest of them are shown on the TOLED. The Y-axis indicates the power consumption ratio of the TOLED−EPD hybrid display that uses both the switch mode and the hybrid mode over an OLED only display. In addition, Figure 2.5 includes data of five application scenarios where the average EPD usage in the switch mode is 10%, 30%, 50%, 70%, and 90%. We assume that power consumption of the TOLED itself is about 1.25 times of an equivalent OLED display using materials and fabrication process as close as possible. Figure 2.5 suggests that we can achieve even greater power savings using a TOLED−EPD hybrid on top of the switch mode by supporting selectively showing image content on both displays at the same time. For instance, counting the total amount of time spent by a person running applications that require a display, if half amount of the total time is spent on the applications whose contents can be displayed exclusively on the EPD screen using the switch mode. The maximum power saving is about 38% under the switch mode. For the rest amount of time, when the TOLED is used, if on average, for each frame, 40% of the pixels can be further displayed on the EPD screen, additional 14% power can be saved.

Chapter 3

Hybrid Display Design

In this chapter, we first present the hardware design of the proposed EPD−TOLED hybrid display. Then we discuss a windows-based predictive model and a calibration algorithm on TOLED that allow frame contents to be shown on both TOLED and EPD at the same time for supporting improved trade-off between energy reduction and user experience. The EPD and TOLED power models are also proposed in this chapter.

3.1 EPD−TOLED Hybrid Display Design

A mobile hybrid display can be realized by overlaying a TOLED module layer over an EPD module. Generally a TOLED display can be as thin as 1.5mm. The thickness of a color EPD film is 1.5mm or even less in future. As a result, the hybrid display can be only 3mm thick. Each display has its own active matrix TFT backplane. To

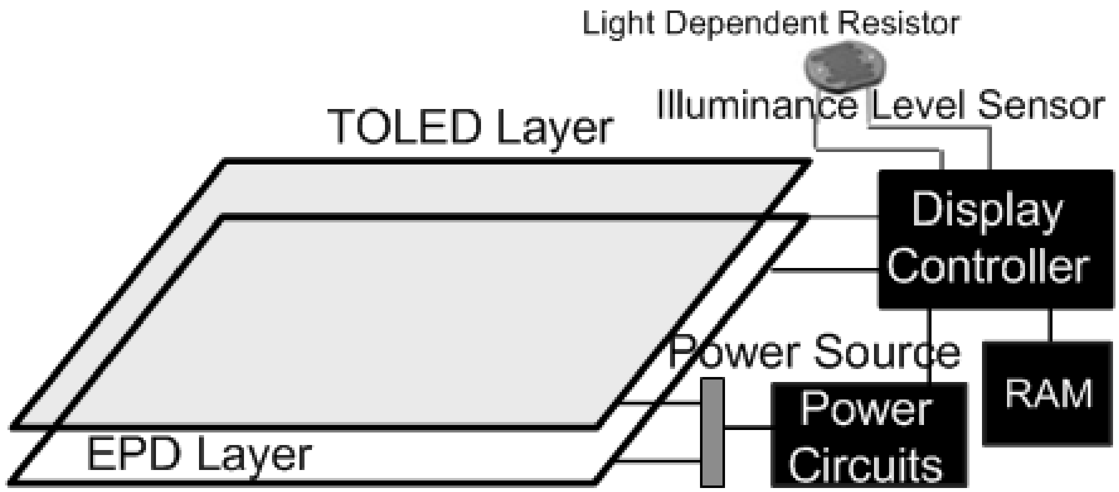

Figure 3.1: TOLED-EPD Hybrid Display

support the hybrid mode, the EPD and the TOLED module must have the same pixel density. This would not be an issue because EPD display today can exceed pixel density of 200DPI and the pixel density continues to improve. Transparent AMOLED (active matrix OLED) with 200DPI was demonstrated. Some high-end non-transparent AMOLED can support up to 300DPI pixel density. Over time, technology scaling will support a hybrid display with both high resolution EPD and TOLED of the exact same size and pixel density.

Figure 3.1 shows the design of the EPD-TOLED hybrid display. Instead of having two controllers, one for the EPD module and the other one for the TOLED module, one combined controller can be employed to control both the EPD and the TOLED module. This combined controller sends signals to drive both the EPD module and the TOLED module. When using a combined controller, we can easily support the hybrid display mode. The combined controller connects to a local RAM where images/frames, lookup tables, and signal waveform data can be stored. The displayer controller determines where to show each part of images/frames. This decision is made by a predictive model. The predictive model is discussed in section 3.2. A light-dependent resistor is equipped in the design. The resistor, functioning as an illuminance level sensor, is connected to the display controller. Because contents shown on EPD and TOLED displays may look different, the display controller is responsible for calibrating the TOLED and EPD modules to let them have similar visual appearances so that users can use the hybrid display as a whole without being aware parts are shown on different displays. Section 3.3 details this design. A power circuit controls both the TOLED and the EPD. Typically, an EPD display module requires 15V power input. For evaluating power reduction, power models for EPD and TOLED displays are constructed in section 3.4.

3.2 Predictive Model

A predictive model, as a component of the display controller, determines the display mode (EPD or TOLED) for each pixel of a display screen, e.g., one or several subareas of the screen be displayed on the EPD module and the rest subarea(s) be displayed on the TOLED module. The prediction is based on the facts: 1) parts that are likely to change should be displayed on the TOLED; 2) More recent update history (changed or unchanged) of a display region has more impacts on the prediction. We use X windows system [20], or simply called X, the most widely used protocol as the reference windows system for graphical user interfaces (GUIs). Subareas in our prediction model are referred as windows or sub-windows in X windows system, i.e.,

Table 3.1: Selected Events Used on X-Windows Systems

Event Category	**Event Type**
Keyboard events	KeyPress, KeyRelease
Pointer events	ButtonPress, ButtonRelease
Exposure events	Expose, GraphicsExpose
Structure control events	ConfigRequest, ResizeRequest
State notification events	CreateNotify, DestroyNotify

our model makes predictions on where each window is going to be displayed.

X windows system uses a client-server model and is device-independent. The current major version is X11. As shown in Figure 3.2(a), X server can collect user input from keyboards, mouses or touch screens, and send the changes of GUIs to clients, which can be either local or network connected as long as target computers implement X. Events are the packets sent to a client indicating that some changes happened. The client first registers its interested events on the server. Table 3.1 lists selected events in X windows system. Once specified events occur, the X server will send event notifications to the client. Figure 3.2(b) shows the process. Notice that, even though some Unix-like systems doesn't use X for graphics, the principle of their graphics designs is similar. For example, Android uses a windows manager over Surface Manager. These systems all create a hardware abstraction layer (HAL). Display changes are notified by events. Therefore, our predictive model can be generalized and easily applied to other graphics systems other than X. In this paper, we state the predictive model based on X windows system.

Before stating the core prediction algorithm, the following things have to be mentioned.

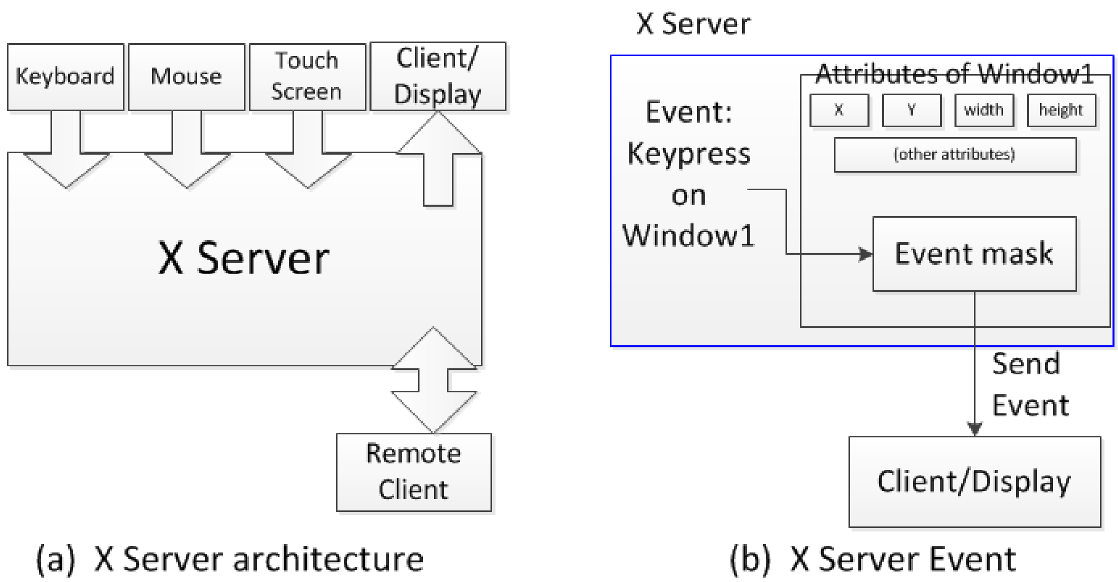

Figure 3.2: X Windows System

1. Not all windows on X are visible. For example, Input-Only windows are not visible, neither are those fully covered by some others. They are not considered in our prediction.

2. The ambient illuminance is a dominant factor. If the ambient illuminance is low, all the windows are shown on the TOLED. Because EPD can only reflect lights, EPD is barely visible under this situation. Therefore, all windows of current frame are shown on the TOLED.

3. Some programs have a direct access to the frame-buffer to update graphics. For example, Direct Graphics Access (DGA) is an extension for X Windows System, which makes client programs can manipulate frame-buffer directly. Those client programs usually need high refresh rate, such as video players, or games. Windows of this kind of program are shown on TOLED.

4. If users/developers set a preference on where to show a program, windows of the program are shown on the user-specified display.

5. Newly created windows are always shown on TOLED.

The prediction is based on histories. Let $P(t)$, be the estimated probability that a window is going to change at frame t, where $0 \leq P(t) \leq 1$; the bigger P(t), the more likely that the window will change; at the beginning, P(1) is set to 1.

Let $A(t)$, be the actual status whether the window is changed or not between frame $t-1$ and frame t, where $A(t) \in \{0, 1\}$, and A(t) = 1 means that the window at frame t is different from that at frame $t-1$, i.e. specified events are received;

$P(t+1)$ is synthesis of the most recent status and historical prediction by using exponentially weighted moving average (EWMA):

$$P(t+1) = \alpha * A(t) + (1-\alpha) * P(t), 0 \leq \alpha \leq 1$$

The coefficient α is an influence factor that indicates how the most recent status impacts on the prediction. A higher α discounts older statuses faster.

To determine which display to use, let θ_1 and θ_2 be the lower and upper threshold respectively, then

- if $P(t) \leq \theta_1$, predict that the window is shown on the EPD;
- if $P(t) \geq \theta_2$, predict that the window is shown on the TOLED;
- if $\theta_1 < P(t) < \theta_2$, predict that the window remains on the same display as it was at the previous frame.

Algorithm 1 History Based Prediction

for each $frame_t$ to display **do**
  /* prediction*/
  if the ambient illuminance is low **then**
    Show all the windows on TOLED
    CONTINUE
  end if

  for each window,w, in current X **do**
    if w is INPUT-ONLY windows or INVISIBLE **then**
      CONTINUE
    end if
    if w has a user preference **then**
      Show w on user-specified display
      CONTINUE
    end if
    if w is using DGA extension **then**
      Show w on TOLED
      CONTINUE
    end if
    if $w.P(t) \leq \theta_1$ **then**
      Show w on the EPD
    else if $w.P(t) \geq \theta_2$ **then**
      Show w on the TOLED
    else
      Show w on the same display as it was at the previous frame.
    end if
    /* regular update*/
    if No events related to w are received between current frame and previous frame **then**
      SET $w.P(t) = (1 - \alpha) * w.P(t) + \alpha * 0$
    end if
  end for
end for

α, θ_1, and θ_2 can be determined in this way:

- The k-step-back status has a relative small weight, δ, such as 0.0001, on P(t), then α is estimated by $(1-\alpha)^k \leq \delta$. In our model, α is set to 0.85.

- If a window is shown on the EPD and it keeps changing in the next m contiguous frames, it is moved to the TOLED. Therefore, θ_2 is chosen by considering $\theta_2 \geq \alpha * \sum_{i=0}^{m-1}(1-\alpha)^i$. In our model, to get better user experience, that is, the system can rapidly reflect the changes. Once there is a change in a certain window, the window is switched to TOLED. θ_2 is chosen by setting m=1, i.e., $\theta_2 = 0.85$.

- If a window is shown on the TOLED and it remains the same in the next n contiguous frames, it is moved to the EPD, therefore θ_1 can be determined by $\theta_1 \leq (1-\alpha)^n$. In our model, θ_1 is chosen by setting n=5, i.e., $\theta_1 = 0.00007$.

The meta data, $P(t)$ and other information associated with each window, w, is stored in display controller RAM indexed by windows ID. $P(t)$ is either updated from frame to frame regularly, or updated immediately if events of changes are received. Algorithm 1 shows the prediction algorithm. Algorithm 2 shows the event-driven update process of the meta data.

Algorithm 2 Event-driven Update

while TRUE **do**

  if an event in the selected event list is received **then**

    Retrieve window id, wID, and other information from event message

    if the window is newly created **then**

      Add new meta data w_{new}

      $w_{new}.P(t) = 1$, $w_{new}.id = wID$

    else if the window is destroyed **then**

      Remove the meta data, whose windows id is wID

    else

      Find the window, w, where $w.id = wID$

      SET $w.P(t) = (1 - \alpha) * w.P(t) + \alpha * 1$

    end if

  end if

end while

3.3 Hybrid Display Calibration

Calibrations are used to make contents displayed on the EPD and TOLED modules to have similar visual appearances. There are three modes in the hybrid display, i.e. EPD-only mode, TOLED-only mode, and hybrid mode. Calibrations are needed in the hybrid mode, because i) TOLEDs can present more colors than EPDs, i.e. TOLEDs have a larger gamut; and ii) unlike TOLEDs, EPDs only reflect lights.

Figure 3.3: Konica Minolta Spectroradiometer and Color EPD

Contents shown on the EPDs are usually less colorful and darker than those shown on the OLEDs. Therefore, for better user experiences, the calibration is mainly performed for the TOLEDs so that they will show contents as close as possible to the EPDs. When calibration is applied, factors including gamut mapping between EPDs and OLEDs, EPDs' reflectance, TOLEDs' transmission, and ambient luminance have to be taken into consideration.

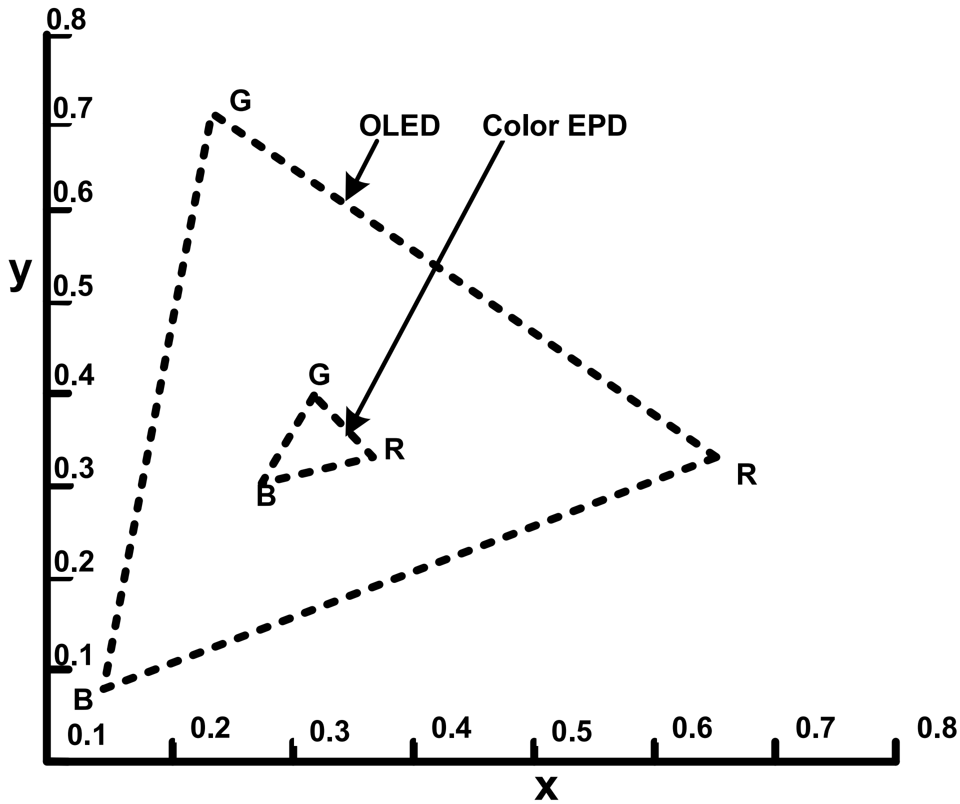

Figure 3.4: Color Gamut for OLED and Color EPD

3.3.1 Color Gamut

To compare the color gamut of TOLEDs and color EPDs, we conducted measurements using real AMOLED and color AMEPD devices. The AMEPD can support 4096 colors. The measurement of the mono colors of the AMEPD and AMOLED was conducted by using the Konica Minolta Spectroradiometer, CS-1000 (Figure 3.3). CS-1000 gives the measurement of spectral power distribution, luminance, chromaticity, and correlated color temperature of light sources, display devices and the non-contact measurement of reflective subjects. It can be used for absolute measurement of TFT displays, LEDs, reflective displays, etc. A ring light source was used as light source. The measured data were tristimulus values for a two-degree observer under D65. Figure 3.4 shows the color gamut of an AMOLED vs. a color AMEPD based on measurements of the primary (R, G, B). The color gamut is shown on device-independent stand color space, CIExyY color space. The color gamut area of the measured color EPD is much less the color gamut of the measured OLED panel. Note that the color EPD gamut is covered by the OLED color gamut. This means that it is plausible to simulate the color appearance of a color EPD panel using an OLED display panel by adapting gamut mapping [15]. In our experiments, we also measured the reflectance ratio of the color AMEPD. Given illumination levels of an environment, we can estimate color EPD luminance for each displayed color value.

Given a color (R, G, B) in RGB color space, we can use a conversion matrix to transform it to the standard CIExyY color space. The conversion for RGB to XYZ can use the matrix in [18].

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Then, $x = \frac{X}{X+Y+Z}$ and $y = \frac{Y}{X+Y+Z}$. Different devices have different conversion matrix. To minimize the conversion computation cost, a color profile file [15] is maintained. A color profile file contains a transformation from EPD or TOLED color space to the standard CIExyY color space, which makes the transform with a small constant time. We have built the color profile file for the EPD and TOLED based on our measurement.

In Figure 3.4, it already shows that TOLED has a larger color gamut than EPD

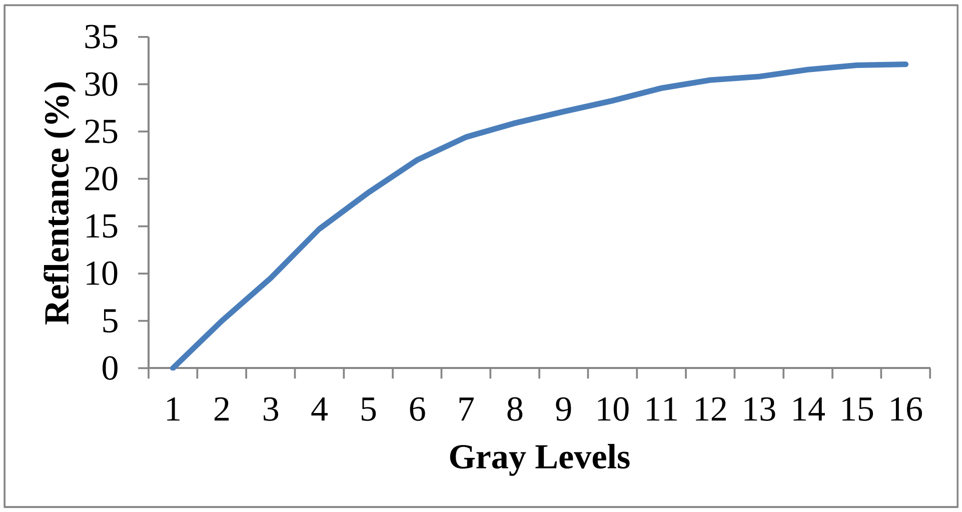

Figure 3.5: EPD Reflectance at Room Temperature

does. We use perceptual rendering intents [15] to handle the outrange gamut. That is, compress the full CIExyY color space into the EPD gamut [15]. This can be also implemented by using a lookup table, which only cost O(1) to finish the compression.

By using the color profile file and perceptual colorimetry, the hybrid display can show the contents similar in colorfulness. Next, we need to adjust the brightness by considering the EPD reflectance and OLED transmission rate, both of which are modeled in the next two subsections.

3.3.2 EPD Reflectance

The optical reflectance of an EPD device is a non-linear function of gray levels [23, 30]. The number of gray levels is determined by the frame scan rate and the response time, which is the time to change the optical state from black to white or from white to black. The response time is sensitive to the ambient temperature. The higher the temperature is, the faster the EPD updates, which results in the reduction of selectable gray levels that is defined as the number of scanning frames in the time duration of one response. For example, if the response time is about 240ms at the temperature of 25°C and the frame scanning rate is 66 frames/s, the selectable gray levels are at most $\frac{240}{1000/66} = 16$. Usually, to achieve 16 gray levels, it needs more time than 240ms. In our model, we set it to 300ms. Consequently, our EPD takes total 1.2s to update (300ms * 4 for the four required steps to drive an EPD pixel to a new gray level, [24, 30]). Furthermore, in our color EPD model, reflectance at different color is based on real measurements.

Figure 3.5 shows the EPD reflectance function curve at different gray levels at room temperature(25°C). For an EPD device, to update a pixel to a new gray level, it takes four steps [24]: 1) pulling back the pixel to full white state; 2) changing the pixel from full white to full black, 3) changing the pixel from full black to full white; and 4) setting the pixel to the given gray level. Those four steps are performed by the EPD controller via sending corresponding waveforms to the TFT driver. The steps of resetting a pixel to full white and black are necessary because they prevent particles from sticking. Therefore, for supporting 16 gray levels for each color dimension and the above four steps, updating a pixel takes 1.2s.

3.3.3 TOLED Transmission Rate

The modeled TOLED exhibits an average transmittance rate of over 70% the visible spectral region. According to [38], TOLED has a relatively low transmission rate

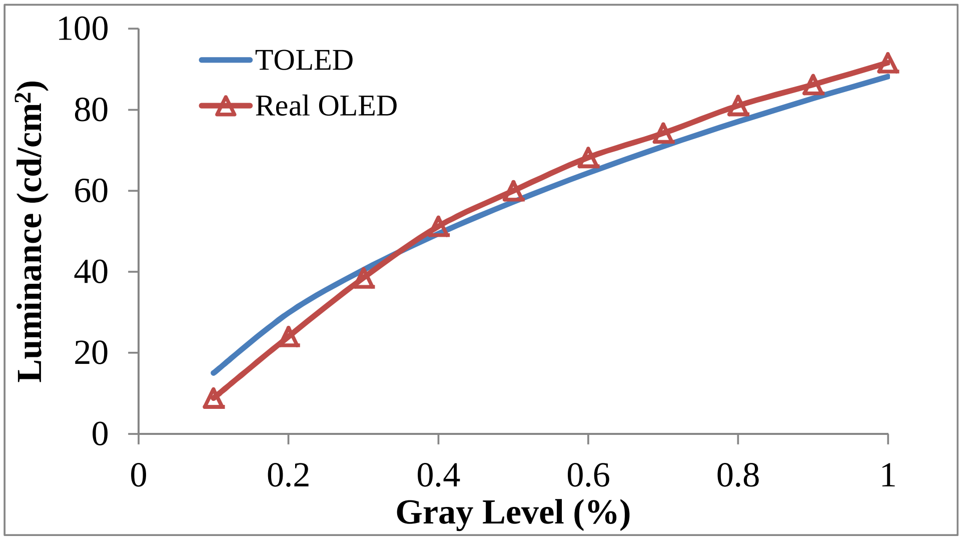

Figure 3.6: Gray Level - Luminance Characteristics (Actual OLED Measurement vs. Our Simulated TOLED Model)

when the wavelength is less than 450nm, and reaches the peak at around a wavelength of 500nm. With a wavelength larger than that, the transmission rate remains above 80%. The visible red, green, and blue light has a wavelength of about 650 nm, 510nm, and 475nm respectively. The transmittance rate of RGB in our model are set to 84%, 90%, and 86% respectively. Further, to model how an image displayed on the EPD appears under the TOLED, we have to estimate the impact of EPD's reflectance and TOLED's transmission rate on the luminance of color. For this purpose, a model of EPD reflectance under different gray levels based on the actual measurement [23] is combined with the TOLED transmittance model [38]. The CIE XYZ color space is designed for color evaluation, the Y parameter of which is a measure of the luminance. The conversion for RGB to XYZ can use the matrix in [18]. Contributions of RGB components to the luminance level can be evaluated using $Y_L = 0.2126 * R^{2.2} + 0.7152G^{2.2} + 0.0724B^{2.2}$. The coefficients are valid for

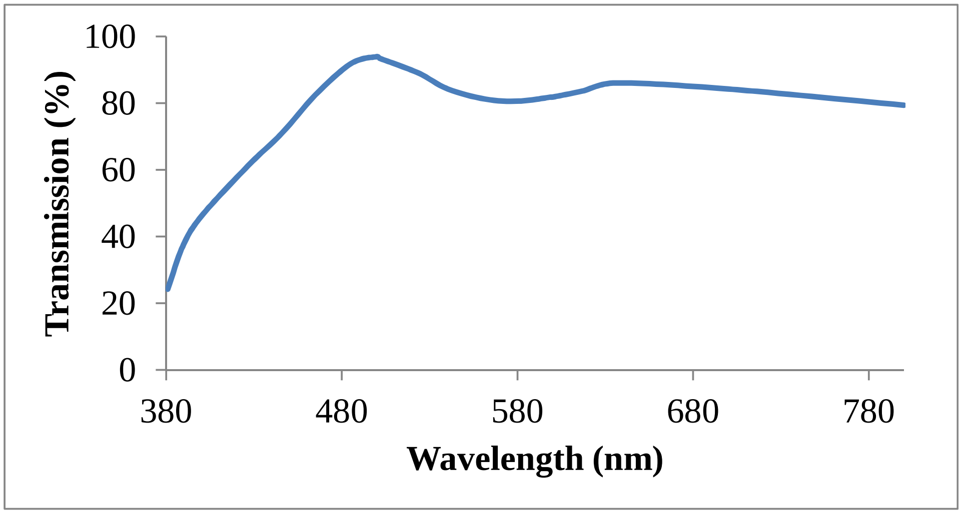

Figure 3.7: Transmission Rate of an Actual TOLED Device)

using D65 white point.

3.3.4 Illuminance Level Sensing and Calibration

The hybrid display controller can sense the ambient luminance, which determines EPD's brightness. The hybrid display controller can adjust the TOLED's luminance level according to the ambient light, which completes the calibration process. The calibration algorithm is shown in Alg 3.

Figure 3.8 shows examples of display appearances using the hybrid display. Figure 3.8(a) shows a frame displayed on the TOLED; Figure 3.8(b) shows the same frame displayed on both the TOLED and the EPD panel but without TOLED calibration. Therefore the pixels on the TOLED panel are brighter than those displayed on the EPD panel; Figure 3.8(c) shows the appearance after TOLED adjustment. Contents on both displays look similar. Note that calibration is only used in the hybrid mode.

3.3.5 Prediction and Calibration Overhead

The overhead of our design comes from two sources, i.e. to determine on which display panel a window should be shown and calibration of these pixels shown on the TOLED panel. Both of them are small. Firstly, the total number of windows in one frame is usually less than 20. The overhead for tracking these components is minimal. Secondly, according to our measurement, in the hybrid display mode, the percentage of frame contents shown on the TOLED is typically less than 20%. The cost of calibration is also reduced by using color profile file. Our study shows that the predictor only has an energy cost of 3.4 miliwatts.

Algorithm 3 Hybrid Display Calibration

Convert $I = (R, G, B)$ in RGB color space to (x, y, Y) in xyY color space;

Compress (x, y, Y) to (x', y', Y) using perceptual rendering intent if necessary, where (x', y') is within the EPD gamut;

SET L_{EPDmax} = the max luminance (under full white), which the EPD can have under the current ambient illuminance;

SET $L_{TOLEDmax}$ = the max luminance the TOLED can emit;

SET $Y' = Y * (L_{EPDmax}/L_{TOLEDmax})$

Show (x', y', Y') on the TOLED;

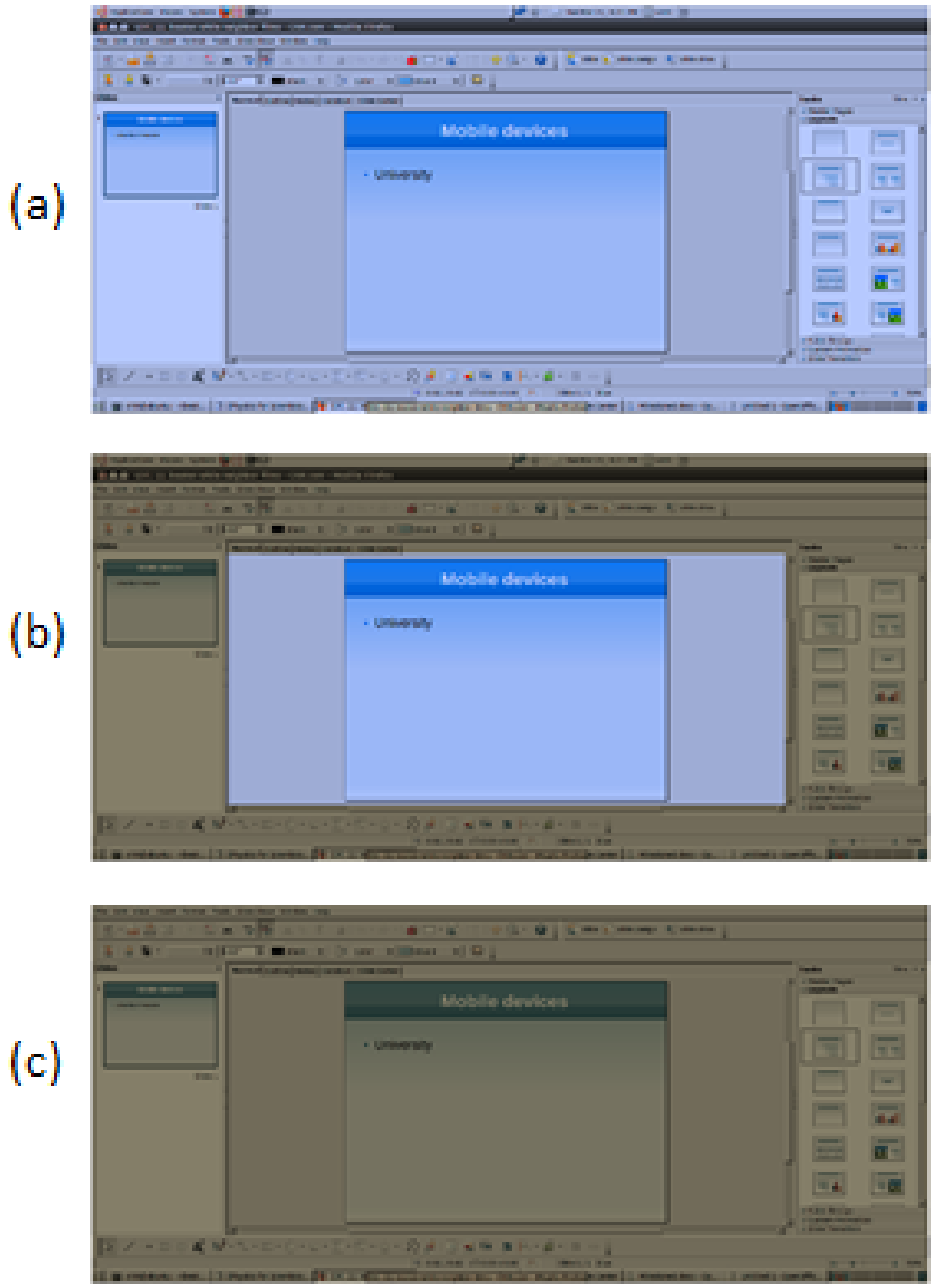

Figure 3.8: Calibration Results (Contents shown on EPD may look darker when printed)

3.4 Power Model

In order to evaluate the power efficiency of the hybrid display, power models for EPD and TOLED are discussed in this section.

3.4.1 EPD Power Model

Figure 3.9(b) shows an equivalent circuit model for driving an EPD pixel. According to [8, 7], the total power consumption for an EPD pixel consists of three parts, capsule switching power, capsule leakage power, and storage capacitor charge power.

Capsule switching power is the power cost for pigment particles moving through the capsule. The power consumption for each particle could be estimated by multiplying the force imposed on the particle (N) with the particle travel distance (s) [8, 7]. We can determine the force F by Newton's Law: $N = qE$ where q stands for the particle's charge, and E is the electric field inside the capsule. Electric field equals to voltage divided by capsule diameter. In this case, for each capsule switching, it will cost 3.24E-9W power [7].

A small amount of current will leak through the fluid when the power supplies the capsule. The capsule leakage power can be calculated using the supply voltage and resistance of the capsule: $P = V^2/R$. By applying the capsules height, radius and resistivity, we get resistance of the capsule: $R = \rho h/\pi r^2$. Each subpixel leaks 8.84E-13W power which is negligible because it is several thousands of times smaller than the capsule switching power.

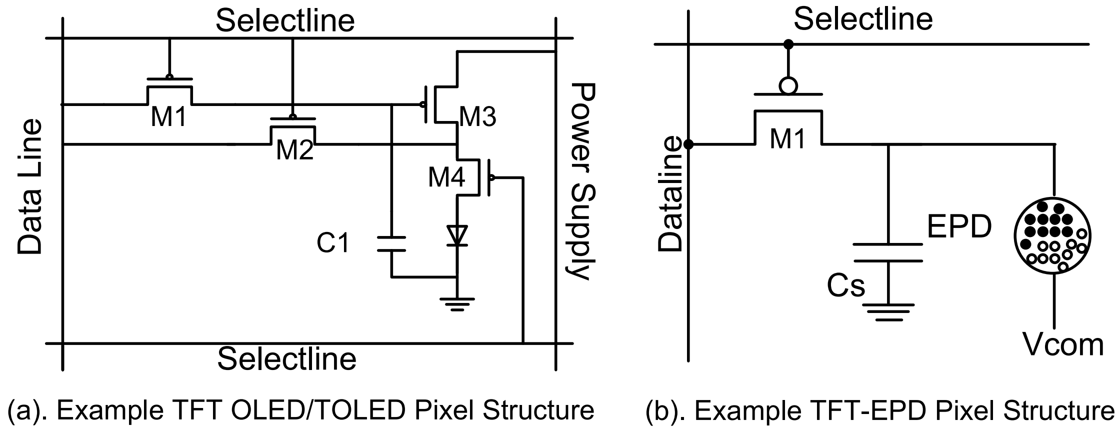

Figure 3.9: EPD and OLED Equivalent Circuit Models

In order to store the required energy for switching color states, we need a storage capacitor shorted to ground shown in Figure 3.9. The charged capacitor will provides electric field which enables the color pigment particles to move through the fluid. The storage capacitor will be charged during the row-write stage. Multiplying the row-write time with the capsule switching power, we get the capacitor storage energy lost for an entire row. Normally by dividing the row number of screen from frame-write rate, the row-write time is relatively small. As calculated, this energy loss is much smaller as well when compared with the switching power.

For our TOLED−EPD hybrid, a subpixel based color EPD with 4K colors is used. In this color EPD display, each pixel consists of three RGB component color subpixels. The structure for these subpixels are the same, but filled with different color pigment.

Using the detailed model described in [7], for each capsule switching, it usually costs 3.24E-9W power [7]. A small amount of current will leak through the fluid when the power supplies the capsule. Based on [7], the leakage power of subpixel can be safely neglected because it is several thousands of times smaller than the capsule switching power. In order to stores the required energy for switching color states, we need a storage capacitor shorted to ground as shown in Figure 3.9. The storage capacitor will be charged during the row-write stage. Normally by dividing the row number of screen from frame-write rate, the row-write time is relatively small. As calculated, this energy loss is much smaller as well when compared with the switching power.

For our TOLED−EPD hybrid display, we use a subpixel based color EPD with 4K colors. In this color EPD, each pixel consists of three basic capsules with RGB filter covered respectively (see Figure 2.2(a)). The structure for these subpixels are the same, but filled with different color pigment. Each capsule displays one of the 16 graylevels using a driving waveform [30].

3.4.2 TOLED Power Model

OLED power consumption models have been studied recently [6, 34, 12]. As shown in Figure 2.2, TOLEDs have similar structure with the OLEDs but made of transparent components (e.g., transparent anode and cathode). Both of them use light emitting materials. Typically, electrical and optical characteristics of the OLEDs and TOLEDs can be specified using the current density−voltage characteristic (J-V) and current density−luminance characteristic (J-L). Given these electrical and optical characteristics of an OLED film, one can estimate its energy efficiency. Due to differences in materials and fabrication process, different OLED devices may have

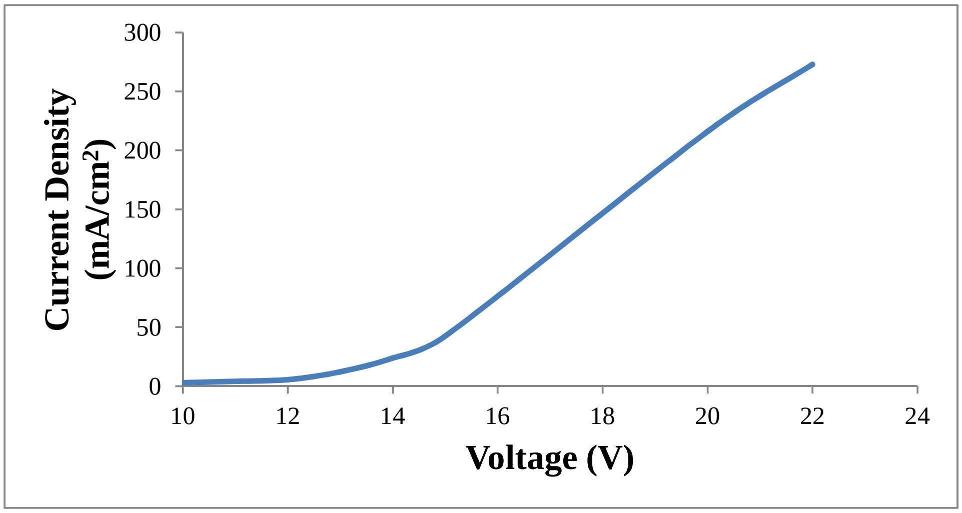

Figure 3.10: Physical Characteristics of an Actual TOLED Device (V-J Characteristic)

different electrical and optical characteristics. In the past several years, a great deal of efforts have been spent on searching solutions that can lead to increase in device efficiency (obtaining the same luminance by using less energy).

In [6], the authors described a detailed model and design for active matrix OLED display based on organic TFT. According to [6], the current across each pixel, I_{pix}, is proportional to the luminance, L_{pix}, and to the area of the pixel,A_{pix}, i.e., $I_{pix} = KL_{pix}A_{pix}$. Using measured electrical optical characteristics of an actually fabricated TOLED device [38] and [6], we create a TOLED model that has the same current density−voltage characteristic and current density−luminance characteristic as the actual TOLED reported in [38], see Figure 3.10 - Figure 3.12.

We use the TOLED in [38] because it requires low input voltage and has good voltage − luminance performance, more suitable to be used as mobile device display. The coefficient, K, is set to $2.5A/cd$ according to the published results in [38]. The

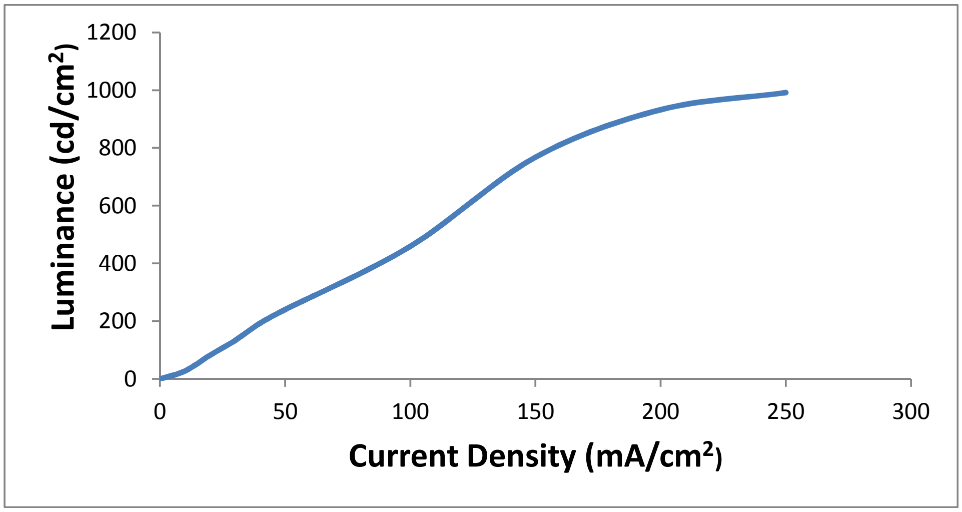

Figure 3.11: Physical Characteristics of an Actual TOLED Device (J-L Characteristic)

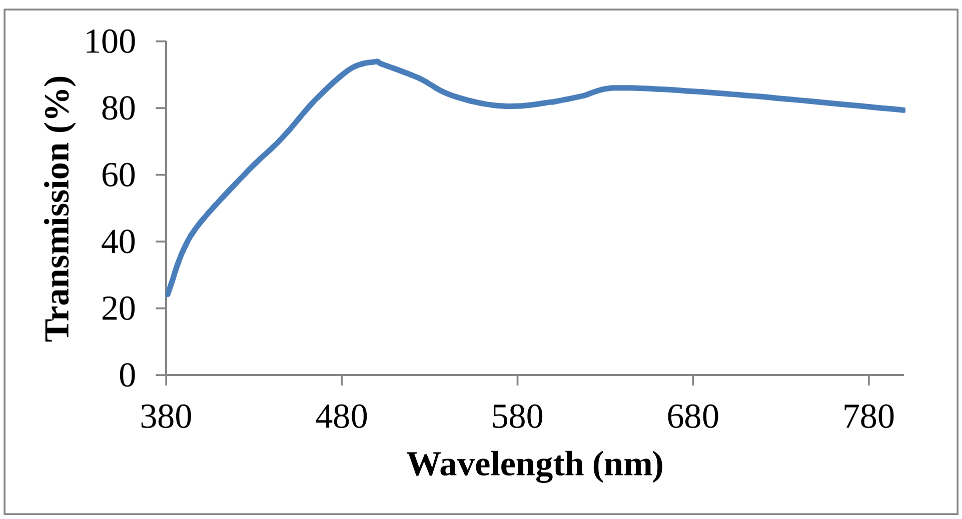

Figure 3.12: Physical Characteristics of an Actual TOLED Device (Transmittance)

pixel area is $15028 \mu m^2$ ($221 \mu m * 68 \mu m$). The device has six layers consisting of glass-ITO-TPD-Alq3-Ni (acac)2-IDIXO (transparent cathode). It has close to 90% transparency in the visible region. Actual measurement of its optical transmission spectrum is shown in Figure 3.12.

The modeled TOLED uses 13.8V power supply and the corresponding current density is 21.42mA/cm^2. It achieves luminance level close to 90cd/m^2. Same as [34], the TOLED power model is based on estimating the current going through a single OLED cell.

For TOLEDs and OLEDs, luminance level changes with pixel gray level. Since luminance is proportional to the current value, we validate our TOLED model by calculating luminance level at different gray levels. The result luminance−gray level relationship is plotted in Figure 3.9(a) together with the luminance−gray level results from the actual measurements of a real OLED device [34]. The blue curve corresponds to the modeled TOLED and the red one is based on the reported results of actual measurements [34]. The figure indicates that our TOLED model has an input−luminance profile consistent with the profile of an actual OLED device.

Chapter 4

Video Playback for Hybrid Display

In this chapter, we first present the design of the video playback, Decoder4Hybrid, for hybrid displays. The we discuss the Change-Detector module and the Display-Chooser module in Decoder4Hybrid in details. A fast DCT-based heuristic algorithm to detect changes between different blocks and help to choose the display is proposed in this chapter.

4.1 Decoder4Hybrid Design Overview

Decoder4Hybrid is specifically designed for hybrid display systems to save power and provide acceptable video quality as well. There are two key issues that should be considered.

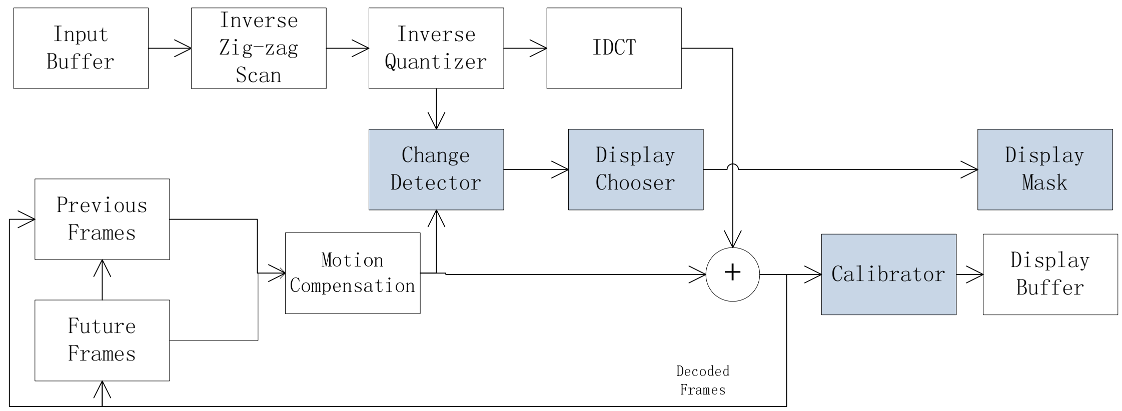

Figure 4.1: System Design Overview

First, to support hybrid displays, display masks should be generated by Decoder4Hybrid. Second, Decoder4Hybrid should provide backward compatibility and support legacy display modes, which means that it should work when the system uses only one display device. For example, mobile users can set preferences to use OLED only for video playback. Therefore Decoder4Hybrid is designed to support traditional video decoder. Figure 4.1 shows the design of Decoder4Hybrid at high level. Modules in gray are newly added to support Decoder4Hybrid. The display mask is one of the Decoder4Hybrid outputs. It is highlighted in gray color in Figure 4.1.

In Decoder4Hybrid, besides the decoding modules that one can find in traditional decoders, three extra modules are introduced: Change-Detector Module, Display-Chooser Module, and Calibrator Module.

The Change-Detector Module is responsible for detecting changes between current frames/pixels and the previous ones. In practice, a 8*8 pixel block is the minimal unit used by Change-Detector. Because DCT is usually performed on 8*8 blocks in MEPG, the Change-Detector leverages the DCT-based computation for achieving accuracy and speed.

The Display-Chooser Module takes on the job of generating the display masks, which are needed by the hybrid display controller to determine which display module should be used for showing pixels/blocks. The Display-Chooser collects block update frequency information generated by the Change-Detector Module to make the decisions.

The Calibrator Module modifies the pixels dispatched to the TOLED. Calibrator ensures that contents shown on the TOLED and EPD look similar by modifying TOLED's color space.

4.2 Change-Detector Module

The Change-Detector compares current blocks with the previous blocks to tell whether they are different. Subframe/block update information is used by the Display-Chooser that calculates the update frequency of each block and directs the hybrid display system to show blocks with high update rates on the TOLED and the others on the EPD.

If a non-zero motion vector is associated with blocks/macroblocks, there is definitely a change. If motion vectors are not specified, considering the limited computation resources of mobile systems, it is preferred that the Change-Detector uses fast video difference detection metrics. Those metrics should be perceptually relevant, or capture the human visual system (HVS) properties, [29]. In this section, three objective metrics are proposed and compared. In addition, a quantized-DCT-based heuristic algorithm is proposed for performing even faster comparison between blocks.

4.2.1 MSE

The mean squared error (MSE) [25] is one of the most widely used metrics that measure the deviation between the original and compressed version of pixels. For two 8*8 black-white blocks, BLK_1 and BLK_2, the MSE is defined as:

$$MSE = \frac{1}{64}\sum_{i=0}^{7}\sum_{j=0}^{7}(BLK_1(i,j) - BLK_2(i,j))^2 \tag{4.1}$$

$BLK_m(i,j)$ is the $(i,j)^{th}$ pixel in the block. If each pixel is represented in (R,G,B) or other color space, for calculating MSE, one has to sum over all the squared value differences and then divide the result by 3. The MSE metric correlates with the HVS. It can be used as a good distortion indicator. However, the computation cost of calculating the square for each pixel is relatively high on mobile systems, which is undesirable. Peak signal-to-noise ratio (PSNR) [25] is also frequently used as a quality metric. The computation cost of PSNR is even higher than MSE.

4.2.2 MSE-DCT

In MPEG, each block is transformed by DCT. In the DCT-domain, the quantized DCT has already taken into consideration of HVS properties. Therefore, direct apply of DCT coefficients for calculating the MSE is also a good approximate difference metric. Similar to what is proposed in [17], one can use a mean squared error of DCT coefficients (MSE-DCT) as an objective quality metric.

The MSE-DCT is defined as:

$$MSE\text{–}DCT = \sum_{i=0}^{7}\sum_{j=0}^{7}(QD_1(i,j) - QD_2(i,j))^2 \tag{4.2}$$

where $DQ_m(i,j)$ is the $(i,j)^{th}$ coefficient in a quantized DCT block. Technically speaking, MSE and MSE-DCT have the same computational complexity. However, since DCT high frequency coefficient are likely to be zeros, calculating MSE-DCT is faster than MSE.

4.2.3 SAD-DCT

To support even faster detection of video change, instead of calculating the square of errors, one can use the sum of absolute difference for DCT coefficients (SAD-DCT),

$$SAD\text{–}DCT = \sum_{i=0}^{7}\sum_{j=0}^{7}|QD_1(i,j) - QD_2(i,j)| \tag{4.3}$$

SAD-DCT is a reasonable indicator because SAD can be used as a good estimator of motion citeSAD. Instead of using SAD to estimate motion, we use SAD to track whether there are any changes between DCT coefficients. At the decoding phase, P frame is reconstructed using the residual information, motion vectors and the reference frame. Therefore, differences between DCT coefficients can be obtained directly from the residual information, which further reduces the cost.

4.2.4 SSDCT Heuristic

If time and resource constraints are stringent on mobile systems, one can approximate the SAD-DCT metric bu a selective-SAD-DCT (SSDCT) heuristic algorithm that only picks up fewer DCT coefficient for SAD. The selection approach is inspired by the design of quantization matrix in MPEG, which provides more resolution on lower frequencies over high frequencies because human are more sensitive to the lower frequencies. The quantization matrix also helps to determine which coefficients are to be picked up. Those coefficients with smaller quantization steps have higher priority to be selected. Usually, those coefficients are at the upper-left triangle area. For example, a common standard quantization matrix is shown as QM in Eq 4.4. The 10 coefficients in the upper-left triangle are selected.

$$QM = \begin{pmatrix} 16 & 11 & 10 & 16 & 24 & 40 & 51 & 61 \\ 12 & 12 & 14 & 19 & 26 & 58 & 60 & 55 \\ 14 & 13 & 16 & 24 & 40 & 57 & 69 & 56 \\ 14 & 17 & 22 & 29 & 51 & 87 & 80 & 62 \\ 18 & 22 & 37 & 56 & 68 & 109 & 103 & 77 \\ 24 & 35 & 55 & 64 & 81 & 104 & 113 & 92 \\ 49 & 64 & 78 & 87 & 103 & 121 & 120 & 101 \\ 72 & 92 & 95 & 98 & 112 & 100 & 103 & 99 \end{pmatrix} \tag{4.4}$$

We collect data from sample video clips and compare the four metrics for measuring the changes between blocks. The clips are 384*512, which has 48*64 blocks per frame. We calculate MSE, MSE-DCT, SAD-DCT, and SSDCT of each block in each frame. Using MSE as baseline, the correlation coefficient between MSE and

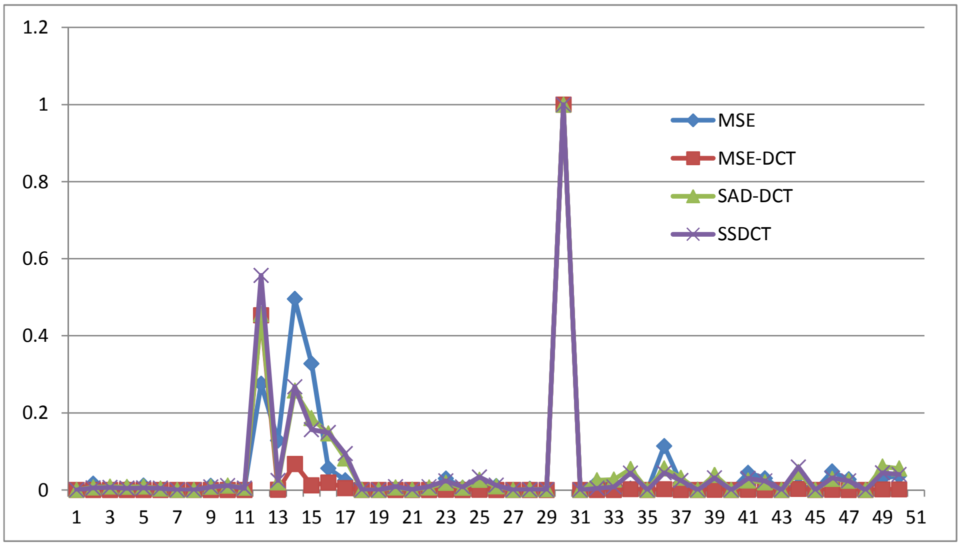

Figure 4.2: A Specific Block's Changes between Frames Measured by Different Metrics

MSE-DCT is 0.59. While the correlation between MSE and SAD-DCT is 0.79, and that between MSE and SSDCT is 0.76. Therefore SAD-DCT and SSDCT are similar and are much better than MSE-DST as difference indicators.

Figure 4.2 shows values of the four metrics for a specific block of 50 sample frames. Each metric is normalized to be inside a scale of 0 to 1. There are three significant changes during this 50 frame period. All the four metrics can tell these changes accurately.

Considering the accuracy and the computation cost, the Change-Detector uses the SSDCT as the difference metric for change detection. In order to detect only significant changes, a SSDCT threshold, th_{SSDCT}, is defined. When $SSDCT < th_{SSDCT}$, the change is ignored. When $th_{SSDCT} = -1$, it means that every tiny change is tracked. Alg 4 illustrates how the Change-Detector works.

Algorithm 4 SSDCT Change-Detection Algorithm

for EACH block, BLK, in the current frame **do**
  if a motion vector is associated with it **then**
    Change-Detector mark it as a change;
  else
    calculate SSDCT using Eq 4.3 with selective coefficient
    if SSDCT $> th_{SSDCT}$ **then**
      Change-Detector mark it as a change;
    end if
  end if
end for

4.3 Display-Chooser Module

For each block, the Display-Chooser uses block change frequency information to determine which display module should be used for showing the block, generates the corresponding display mask, and sends it to the hybrid display controller.

The Display-Chooser is able to examine all the upcoming frames in the decoder buffer and make the decisions. In our design, the Display-Chooser can buffer 10 frames. If a block is shown on the TOLED and unchanged in the next k frames, then it should be moved on the EPD. The K is related to the update rate of the EPD module, and fps of the video. The update rate of an EPD module is determined by the frame scan rate and the response time, which is the time to change the optical state from black to white or from white to black. For example, if the response time is about 240ms at the temperature of 25°C and the frame scanning rate is 66 frames/s, the selectable gray levels are at most $\frac{240}{1000/66} = 16$. According to [5], fps of a cartoon video is usually 12. Therefore, if a block is unchanged in the next 480/(1000/12)=6 frames, it can be considered to be shown on the EPD. In our design, we set $K = 7$.

In the hybrid display, when a block is shown on the TOLED, the corresponding area on the EPD is set to white. Therefore, only 240ms are needed to show the new contents.

The hybrid display supports simultaneous display of a certain frame area on both the TOLED and EPD. The decisions are encoded by a mask using MIXED flag. The Display-Chooser can take advantage of the mask to improve video quality. When a block is updated on the EPD, the TOLED also shows the same contents for 3 frames. The Display-Chooser will set the flag values of the display mask to MIXED mode so the pixels will be shown on both displays. Therefore, users will not notice that the EPD is updating.

Chapter 5

Results

5.1 Simulation Setup

We simulate our hybrid display approach using the models described in Chapter 3 and study its performance. For the proposed TOLED−EPD hybrid display, we model both its power and optical behavior. The EPD model parameters are based on real physical measurement. The TOLDE model parameters are based on physical measurements obtained from a fabricated TOLED and cross-validated by measured results from an actual OLED device. The simulation parameters are listed in Table 5.1. In our simulation, we assume size of a pixel on the OLED panel is around 15k μm^2. The color pixel on the EPD panel contains 6 capsule, the diameter of the capsule is $50\mu m$. Thus the area of the pixel on the OLED panel is same as on the EPD panel. Since we have the same DPI and the same size, the user wouldn't feel resolution difference by using our hybrid display. In order to calculate the display power consumed in the hybrid display mode, we collect data from different usage scenarios using a netbook running Ubuntu Linux system with X-windows server installed. The netbook has an Intel Atom N450 processor at 1.66GHz and 1 GB memory. Six video segments of one hour and a half are recorded, corresponding to reading books, web browsing, programming in Eclipse, email, making PPT, and card gaming (without DGA extension). Those video segments are used as data set for the display test.

To test the Decoder4Hybrid, we select video clips with resolution 384*512 at 12 frames per second with 8 bits per channel (red, green, and blue). We capture 20-minute sequences of each video clip to evaluate how much energy could be saved under different circumstances. The video streams are encoded with the frame pattern: IBBPBBPBBPBBPI. The video quality is measured by PSNR. We use MSU Video Quality Measurement Tool [3] to compare the videos.

5.2 Experimental Results

5.2.1 Prediction Miss

There are two types of prediction misses in our model. One corresponds to the case that a window that should be placed on the TOLED panel is predicted to be shown on the EPD panel. This is called a *type*1 miss. The other corresponds to the case that a window should be placed on the EPD panel is predicted to be shown on the TOLED panel. This is called a *type*2 miss. The *type*2 miss will not bother users, because the TOLED panel is more powerful than the EPD in terms of both color

Table 5.1: Simulation Parameters

EPD parameters	Value	Unit
microcapsule diameter (d) [7, 11]	50	μm
particles per capsule [7]	1300	–
pigment particle charge (q) [8]	4.8E-16	Coulomb
supply voltage [7]	15	Volts
suspension resistivity [7]	1.0E12	Ωm
particle concentration [7]	$2*10^8$	m^{-3}
EPD TFT Rate	66	frames/s
EPD Color Levels	16*16*16	
EPD response time	300	ms
EPD update time	1.2	s
Capsule leakage power [7]	8.84E-13	Watts
Steady-state power consume [7]	3.24E-9	Watts
TOLED parameters	Value	Unit
TOLED Vdd	13.8	Volts
TOLED Max Luminace	90	cd/m^2
TOLED transmission rate	80%	
TOLED pixel area	15028	μm^2

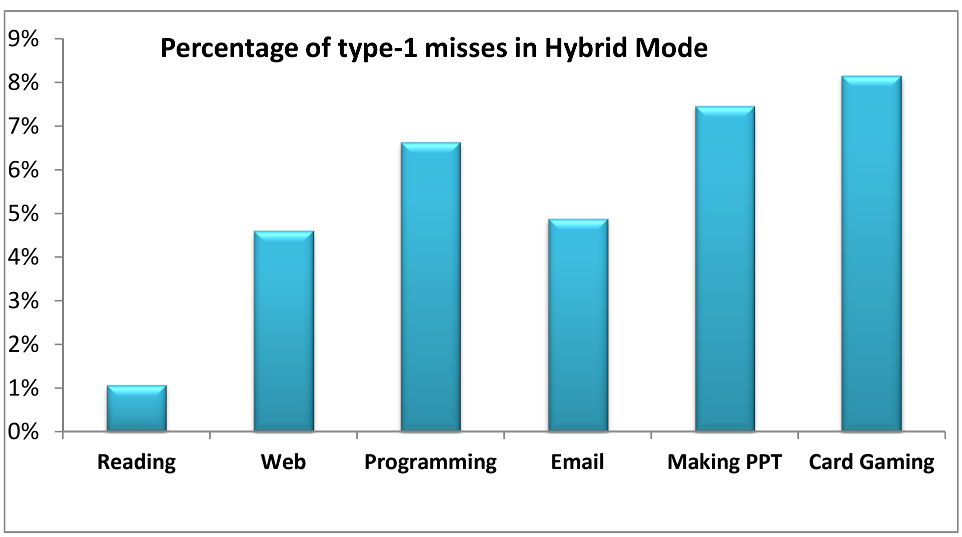

Figure 5.1: Percentage of *type*1 Prediction Misses

space and update rate. However, the *type*1 miss has a more significant negative impact on the user experiences because the refresh rate of the EPD panel is much lower. The *type*1 miss of the hybrid display is evaluated in Figure 5.1. Reading has the lowest *type*1 misses, which is less than 1%, while card gaming and PPT−making has the highest, which are over 7%. However, the average percentage of *type*1 miss in the prediction model is only 5.46%, which means the predictive mode can make the right decisions on choosing a proper display in over 90% of the cases. Furthermore, according to our prediction model, windows with updates are going to be switched to the TOLED panel one frame right after update events are detected. Therefore, user experiences can be guaranteed.

5.2.2 Energy Simulation

The six application scenarios are studied to show performance of the hybrid display mode. We compare with the results of a traditional OLED. Notice that card games are written without DGA extensions. Games using DGA extensions are to be shown on the TOLED directly. Figure 5.2 shows the results. Overall, when using the hybrid mode, the results show at least 60% savings in power consumption. Reading books has the most power reduction, which saves 84.61%. While programming and card gaming only save 59.04%. This is because that the contents are static during most reading time. By contrast, more frequent changes are expected during programming (constantly compiling and testing) and playing games. Energy reduction in the cases of web browsing, Email, and PPT creation are 77.11%, 80.68%, and 67.62% respectively. The average is 71.44% for the six application contexts. In those cases,

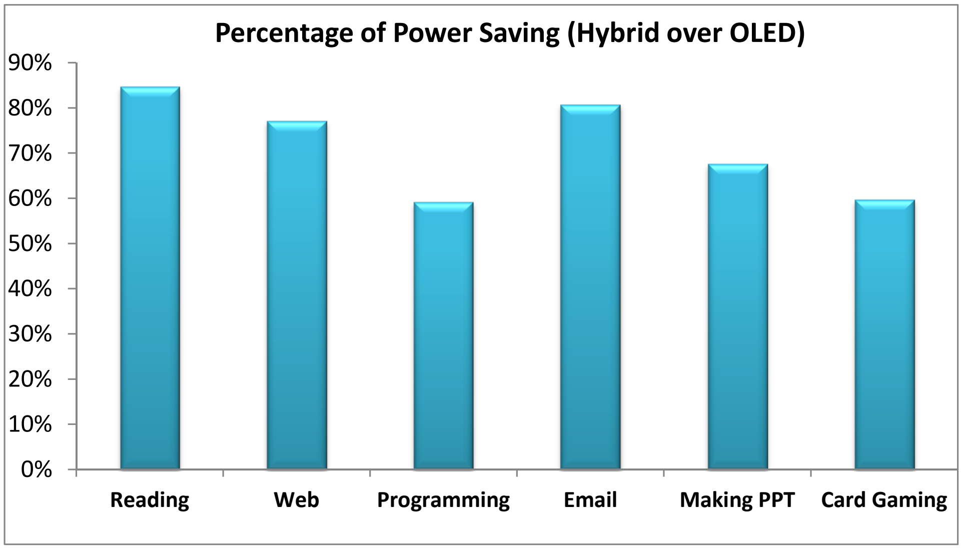

Figure 5.2: Power Saving in Different Contexts

one can achieve significant amount of energy savings.

To further study how the frame contents are actually displayed, we collect percentage of pixels shown on the EPD panel. We count the usage at the pixel level instead of at the windows level. This is because sizes of windows vary from each other. Pixel display statistics at the pixel level are more accurate. Our results in Figure 5.3 show that about 97% of the displayed contents are shown on the EPD panel during reading, compared with 79% of the contents during programming and 75% of the contents during playing games shown on the EPD panel. Web browsing, Email, and PPT creation have percentages of 92.49%, 93.38% and 75.11%, respectively.

The results in Figure 5.2 and Figure 5.3 also indicate that energy reduction is dependent of the displayed pixel contents. Since white pixels consume the most power on the OLED panel, when they are relocated to be shown on the EPD panel

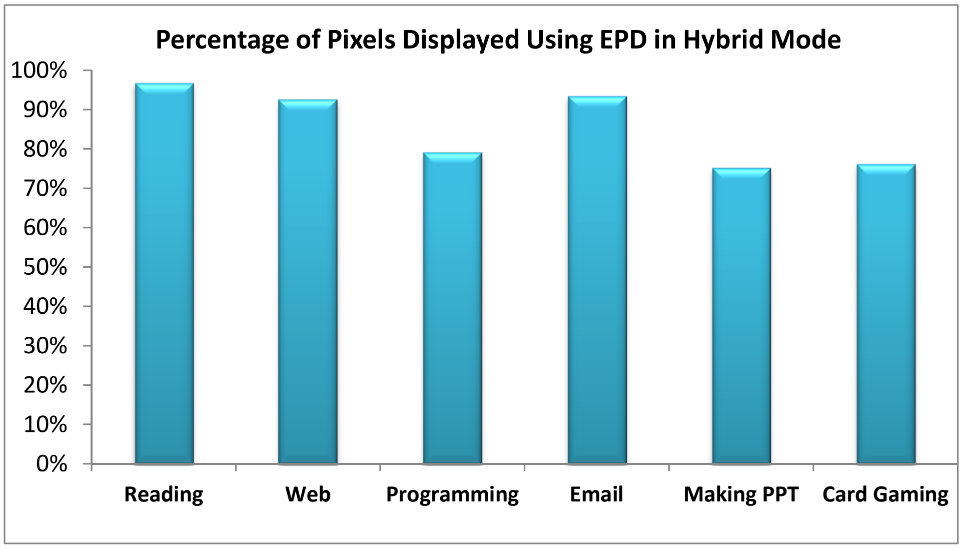

Figure 5.3: Percentage of Pixels Using EPD in Hybrid Mode

in the hybrid mode, the amount of energy reduction is larger than moving colored pixels to the EPD panel. This explains why when comparing energy reduction of PPT creation test against tests of programming and card gaming, PPT creation has slightly less percentage of pixels shown on the EPD panel but has the most energy reduction. When creating PPT, the display background has more background pixels in white than other tested scenarios.

5.2.3 Decoder4Hybrid Results

In Figure 5.4, we collected 12 frames from a cartoon video, South Park. Figure 5.4 compares the frames side by side. The frames in the left column are display results of showing each frame on the OLED only; frames in the middle column are display results of showing the frames simultaneously on the hybrid display with small SSDCT

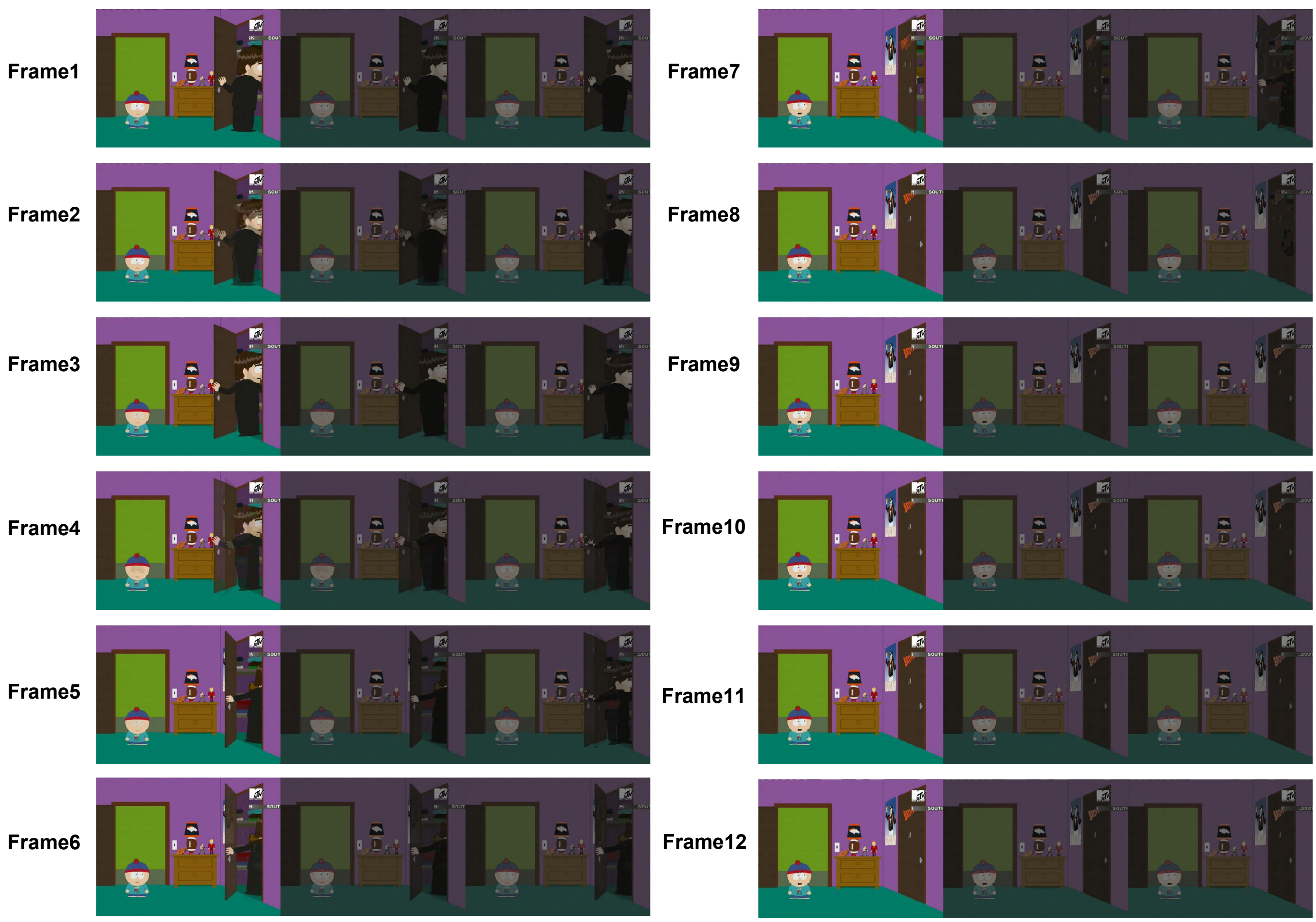

Figure 5.4: Experimental Test Video Sequences: (1) the left column is captured from a video shown on OLED; (2)the middle column is captured from the same video shown on the hybrid display with $th_{SSDCT} = 0$; (3)the right column is captured from the same video shown on the hybrid display with $th_{SSDCT} = 50$

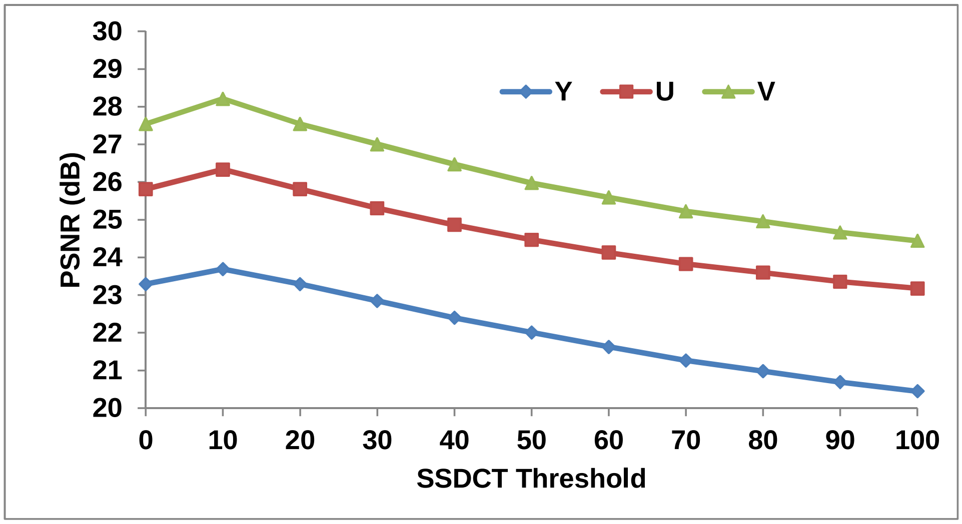

Figure 5.5: Average PSNR under Different SSDCT Thresholds

threshold, i.e. $th_{SSDCT} = 0$; the frames in the right column are display results of showing the frames on hybrid display simultaneously with a larger threshold, i.e. $th_{SSDCT} = 50$. There may be delay in frame display time when larger threshold is used. For example, in frame4, the boy has his eyes open, while he should be blinking according to the original frames. Because of the larger threshold, changes around the eyes are ignored by the Change-Detector. Those blocks are treated as unchanged. Figure 5.4 shows that with a small or reasonable threshold, the video quality can be preserved.

In the following experiments, we compare the video quality and power consumption under different thresholds.

We use PSNR for measuring video quality. PSNR is a widely used measure of quality for lossy compression codec. The higher the PSNR value, the better the quality. According to [4], on average, PSNR is typically between 30 dB and 50

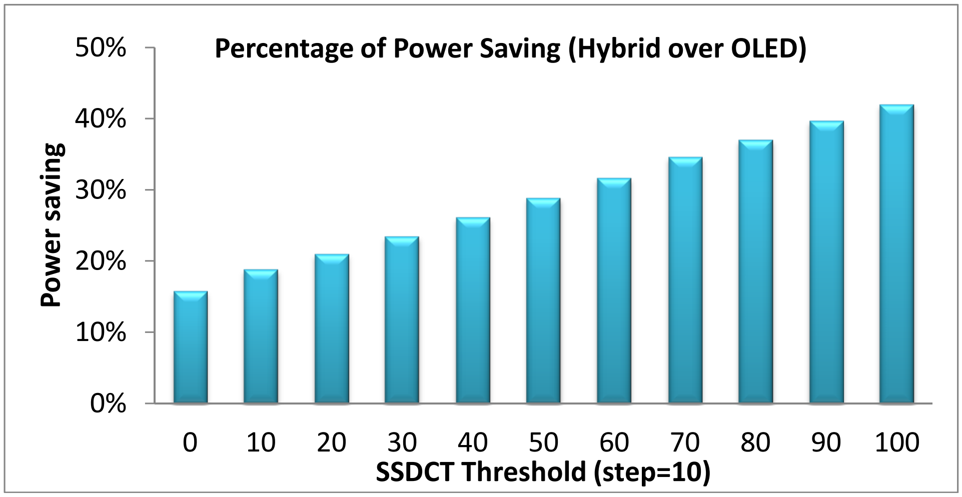

Figure 5.6: Average Power Saving under Different SSDCT Thresholds (0 to 100, step = 10)

dB for compressed videos. Acceptable values are from 20 dB to 25 dB. For color videos, PSNR is measured in YUV color space. In Figure 5.5, we measure the video quality by PSNR, it shows that when the SSDCT threshold increases, PSNRs of Y,U,V decrease, i.e. video quality drops. Video quality becomes unacceptable when the threshold is greater than 100. Sampling clips shown on hybrid displays under different SSDCt thresholds are also presented to different testers to collect subjective feedbacks on the video quality. Similarly, video quality is unacceptable when a SSDCT threshold larger than 100.

In Figure 5.6, power savings under different SSDCT thresholds are measured. One can achieve at least 10% power reduction when SSDCT threshold is zero. While about 40% of power can be saved when SSDCT threshold is 100. The power saving results show a quasi-linear relationship between power reduction and small SSDCT

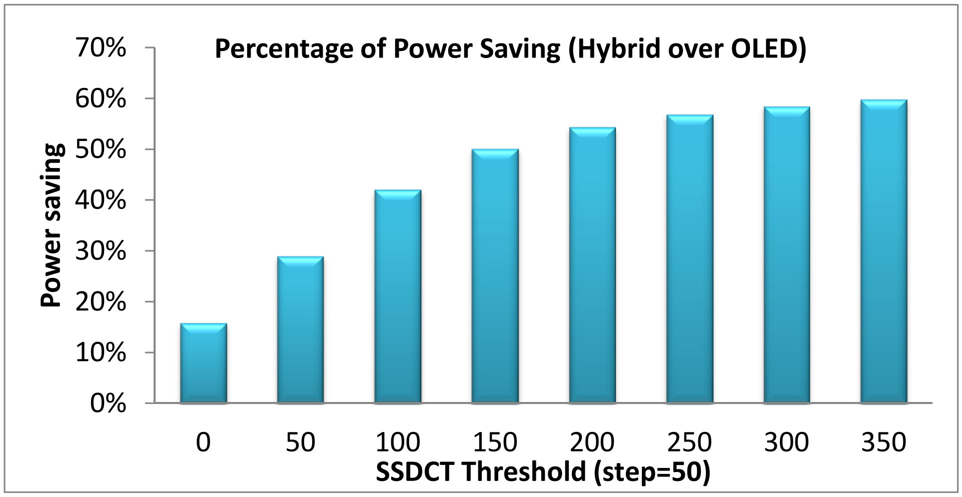

Figure 5.7: Average Power Saving under Larger SSDCT Thresholds (0 to 350, step=50)

thresholds (smaller than 100). However, if the SSDCT threshold continues to increase, the power saving starts to saturate with a maximum value around 45% as shown in Figure 5.7. Even though more power saving can be achieved by increasing the SSDCT threshold value, however, as mentioned video quality is unacceptable if the SSDCT threshold exceeds 100.

Figure 5.8 shows the percentage of pixels during video playback that are shown on the EPD. When SSDCT threshold is zero, there are only about 10% pixels displayed on the EPD. While there are about 50% pixels shown on the EPD when SSDCT=100. Even though half of the pixels are shown on the EPD, the energy savings are not half. This is because when SSDCT is larger, more pixels may have MIXED mask generated by Display-Chooser so that more video contents are shown on both the OLED and the EPD.

Figure 5.9 shows relationship between PSNR and power saving. The figure

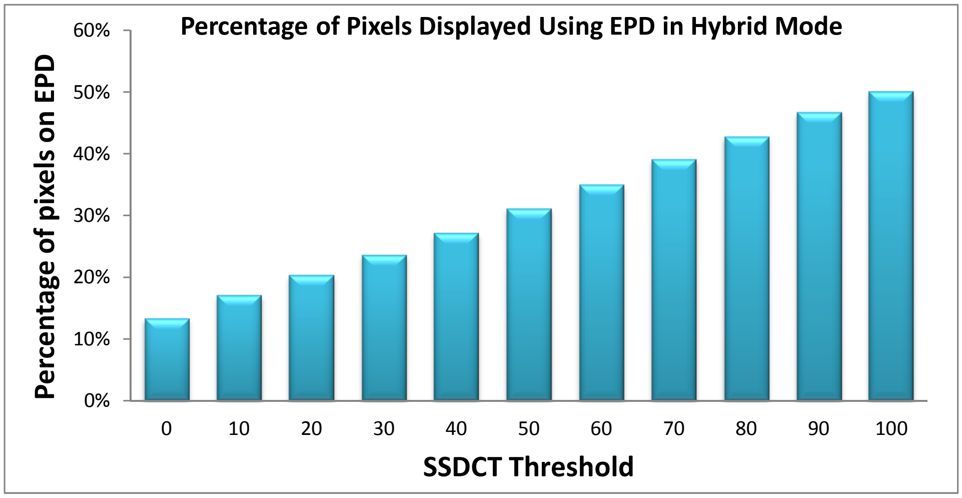

Figure 5.8: Percentage of Pixels Shown on EPD under Different SSDCT Thresholds

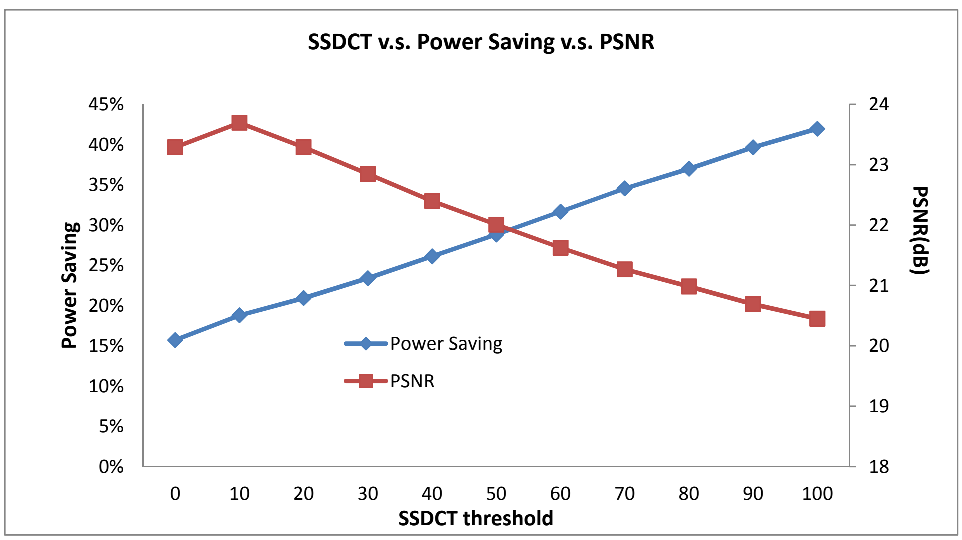

Figure 5.9: Relationship between PSNR and Power Saving under Different SSDCT Thresholds

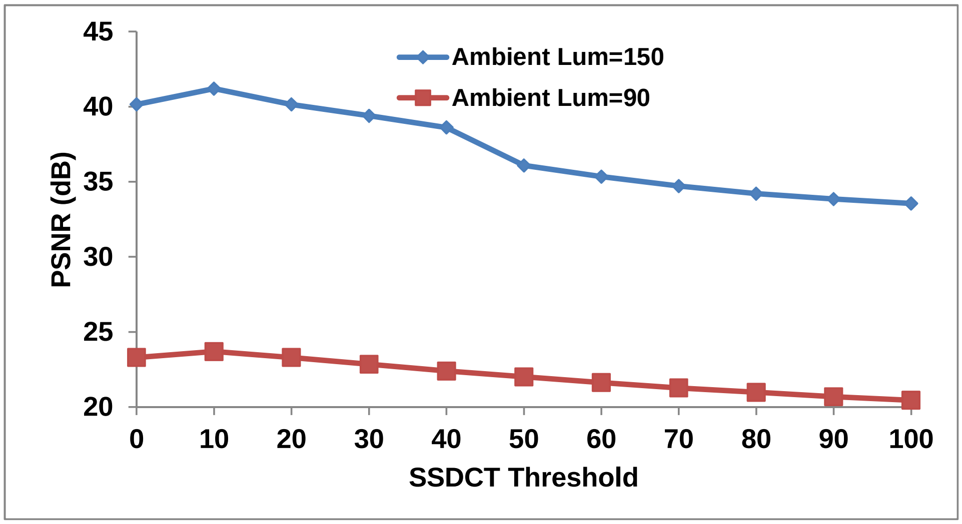

Figure 5.10: PSNR (Video Quality) under Different Luminance Levels

suggests that when th=50, one can achieve the best trade off between video quality and power reduction.

Since EPD only reflects lights, the ambient luminance is also a critical factor when using hybrid display systems for video playback. Figure 5.10 shows PSNR results under different ambient luminance. When ambient light intensity is 90lux, (the luminance level in a regular room without lights in the day time), the video quality is much lower than the video quality when ambient light level is 150lux, (the luminance level in a room with lights on).

Chapter 6

Conclusion

In this paper, we describe the design and evaluation of an integrated hybrid display for embedded and mobile devices, which combines a transparent OLED (TOLED) module and a color EPD module. In addition to EPD only and OLED only display mode, the TOLED−EPD display supports a hybrid display mode where both the EPD module and the TOLED module are used for displaying contents of a frame at the same time. Display contents that need to be refreshed quickly are shown on the OLED module while slow update or static contents are displayed over the low power color EPD module. This hybrid display uses a windows-based predictive model to choose which display should be used for a piece of display content for achieving energy reduction. A calibration approach for the TOLED pixels is also applied to make sure that the hybrid display can present visually consistent views on both display modules simultaneously. Based on actual measurements of the physical characteristics of fabricated TOLED devices, published EPD and OLED power models, and reflectance measurements of actual color EPDs, we set up a simulation environment that can estimate both the energy consumption and optical properties of the proposed hybrid display. Simulation results show that in the hybrid mode, the predictive mode can make correct decisions on choosing the proper displays in over 90% of the cases. The results also show that the average power saving is 71.44% for many mobile application contexts.

We also propose a solution of mobile video playback, named Decoder4Hybrid, for supporting hybrid displays. Decoder4Hybrid uses a fast DCT-based heuristic algorithm to detect changed blocks and generates display masks that can be used by the hybrid display controller to dispatch pixel blocks to display modules. Experimental results show that using the proposed approach, up to 40% power can be saved with acceptable video quality.

In the future work, different predictive algorithms will be studied and compared for the regular windows-based applications. More videos with higher FPS will be selected to evaluate the performance, accuracy and user experience of Decoder4Hybrid. In addition, we also plan to implement the hybrid display with real hardware devices. Currently, the main challenge for the hands-on implementation is that there are no EPDs and TOLEDs of the same resolutions available in the market. When the technologies become more mature, the real hybrid display will be built. Then similar experiments, which are studied in the simulation, can be applied on the hardware, which will bring us a lot of new insights leading to the further improvements of the design.

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