Support for Power Efficient Mobile Video Playback on Simultaneous Hybrid Display

Yuanfeng Wen¹, Ziyi Liu¹, Weidong Shi¹, Yifei Jiang², Albert M.K. Cheng¹, Feng Yang³, Abhinav Kohar⁴
1.Department of Computer Science, University of Houston, Houston, TX 77004, U.S.A
2.Department of Computer Science, University of Colorado at Boulder, CO 80309, U.S.A.
3.School of Computer and Communication Sciences, EPFL, Switzerland
4.Department of Computer Science, IIT-Patna, India
Email: {wyf,ziyiliu,larryshi,cheng}@cs.uh.edu, yifei.jiang@colorado.edu, feng.yang@epfl.ch, abhinav2@iitp.ac.in

Abstract—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 displays on those devices put more tensions on this situation as the displays consume a large portion of the total battery power. A TOLED–EPD hybrid display that integrates a transparent OLED (TOLED) with an electrophoretic display (EPD) has been emerging to reduce the energy usage of displays. The technology displays information selectively on one of the displays based on the update rate of content, thus reduces the energy usage.

In this paper, we propose a design of mobile video playback, Decoder4Hybrid, for the hybrid displays. The proposed approach supports encoded video playback based on the update frequency of each block, which is exploited by the hybrid display controller to determine which display should be used to show a MPEG encoded block. A fast DCT-based heuristic algorithm is proposed to detect the changes between frames at block level with minimal computation cost. Experimental results show that the proposed approach can save up to 40% power with acceptable video quality.

I. INTRODUCTION

Recent study [1] shows 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[2] 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[3]. 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.

To address the increasing energy demand, mobile displays have been developed based on a variety of technologies including flat-panel LCD displays, light-emitting diode based displays such as active-matrix OLEDs, or electrophoretic displays (EPD) such as e-paper. Those techniques are designed for different application environments. They have various energy characteristics when used with mobile devices. And they exhibit different trade-offs between user experiences and energy consumption. Thus, a display technique that is suited for one application context may not apply to other application and usage scenarios.

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 as 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, the EPD consumes 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 unsuited for certain application contexts such as playing a video.

More recently, researchers and engineers propose the concept of hybrid mobile display [4] that integrates multiple displays of different techniques in one system to support display adaptation based on the usage context and contents. One such hybrid display design is to combine transparent OLED (TOLED) and color EPD with the color EPD beneath the transparent OLED. When used in hybrid mode, both the EPD and the OLED can be turned on at the same time with slow contents displayed on the EPD and fast contents on the OLED.

Based on the characteristics of the hybrid display, we 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.

The main contributions of our work include: (i) a design of...
mobile video playback, Decoder4Hybrid, for mobile hybrid displays, (ii) a fast DCT-based heuristic algorithm to detect changes between different blocks, and (iii) energy and optical evaluation of video quality and power consumption when using hybrid display to playback cartoon videos.

The rest of this paper is organized as follows. Section II describes background of mobile hybrid displays and MPEG, and motivates the research. Details of the video decoder for hybrid displays are presented in Section III. Experimental results on power savings and video qualities using the new design are in Section IV. Related works are discussed in Section V, and the final conclusions of the paper are presented in Section VI.

II. BACKGROUND

A. Mobile Hybrid Displays

A simultaneous mobile hybrid display was first proposed in [4] for achieving better energy efficiency. By overlaying a TOLED module layer over a color EPD module, an energy efficient hybrid display can be implemented. Such hybrid display is feasible to realize and the total display size can be as thin as 3mm. In detail, a TOLED display can be only 1.5mm. The thickness of a color EPD film is 1.5mm or even less in the coming future. Each display has its own active matrix TFT backplane. Both the EPD and the TOLED module must have the same pixel density to support simultaneous hybrid mode. This would not be an issue because EPD today can exceed pixel density of 200DPI and the 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. Low cost mass produced TOLED is already available in the market such as the TOLED mobile phone shown in figure 1.

The design of a TOLED–EPD hybrid display is shown in Figure 2. Generally, a display controller will be used to control both the TOLED module and the EPD module by sending the data from a local RAM, where decoded frames, lookup tables, signal waveform data are saved, to the corresponding display modules. Hybrid display uses a display mask to determine where to show each part of the frames. There are three kinds of marks for each pixel, OLEDONLY, EPDONLY, and MIXED. The MIXED means showing contents on both displays. Based on how fast contents are updated during video playback, the controller will dispatch parts of each decoded frame to either the EPD module or the TOLED module. In addition, the design comprises of one or multiple light dependent resistors. The resistor, functioning as an illuminance level sensor, is connected to the display controller. Because contents shown on the EPD and the TOLED may look different, calibrations are applied to the displayed pixels such that pixels displayed on the EPD and the TOLED will have similar visual effects to the users. The calibrations can be either done by the display controller or applications. After calibration, frames displayed on the hybrid display simultaneously appear as a whole and the users are not aware that different parts of the frames are actually shown on different displays. The calibration approach takes environment and ambient illuminance into consideration using the light sensitive resistors. A power circuit controls both the TOLED and the EPD. Typically, an EPD display requires 15V power supply.

B. MPEG Video

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).

1According to our measurement, the TOLED phone in figure 1 has a transmission rate of about 60%. However, TOLED prototypes with transmission rate over 80% have been demonstrated in many labs around the world.
The interface compression depends on the previous frames or the 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 versa.

C. Videos with Lower FPS

Frame per second (FPS), is the rate a device produces consecutive images per second. 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/carousels 12 frames are shown per second [5], which is still acceptable. There are a large amount of areas change infrequently in animations/carousels. 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 [4], 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.

III. Decoder4Hybrid System Design

A. 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.

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 3 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 3.

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 MPEG, 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 the contents shown on the TOLED and EPD look similar by modifying TOLED’s color space.

B. 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/macroblox, 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, [6]. 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 the blocks.

1) MSE: The mean squared error (MSE) [7] 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:

\[
MSE = \frac{1}{64} \sum_{i=0}^{7} \sum_{j=0}^{7} (BLK_1(i,j) - BLK_2(i,j))^2 \quad (1)
\]

\( BLK_m(i,j) \) 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) [7] is also frequently used as a quality metric. The computation cost of PSNR is even higher than MSE.
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 [8], one can use a mean squared error of DCT coefficients (MSE-DCT) as an objective quality metric. The MSE-DCT is defined as:

\[
MSE-DCT = \sum_{i=0}^{7} \sum_{j=0}^{7} (QD_1(i, j) - QD_2(i, j))^2
\]  

Where \(QD_m(i, j)\) 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.

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),

\[
SAD-DCT = \sum_{i=0}^{7} \sum_{j=0}^{7} |QD_1(i, j) - QD_2(i, j)|
\]  

SAD-DCT is a reasonable indicator because SAD can be used as a good estimator of motion [8]. 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) **SSDCT Heuristic**: If time and resource constraints are stringent on mobile systems, one can approximate the SAD-DCT metric by a selective-SAD-DCT (SSDCT) heuristic algorithm that only picks up fewer DCT coefficients 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. The 10 coefficients in the upper-left triangle are selected.

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

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 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 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 1 illustrates how the Change Detector works.

**Algorithm 1 SSDCT Change Detection Algorithm**

1: for EACH block, \( BLK \), in the current frame do
2: if a motion vector is associated with it then
3: Change-Detector mark it as a change;
4: else
5: calculate SSDCT using Eq 3 with selective coefficient
6: if SSDCT > th_{SSDCT} then
7: Change-Detector mark it as a change;
8: end if
9: end if
10: end for

C. 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 \( \frac{240}{1000/66} = 16 \).

To update a pixel to a new gray level, it takes two steps:  
1) pulling back the pixel to full white state;  
2) setting the pixel to the given gray level.

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.

The Display-Chooser uses a dynamic programming algorithm to collect the change information of each block. The computation cost is \( O(1) \) only.

D. Calibrator Module

The Calibrator makes contents displayed on the EPDs and TOLEDs having similar visual effects. The Calibrator is needed because i) TOLED has a larger color gamut to show more colors; and ii) EPDs only reflect lights so that contents shown on the EPDs are usually darker than those shown on the OLEDs. Therefore, for better user experience, the Calibrator makes calibrations on blocks shown on the TOLEDs to ensure that contents visually similar on different displays.

The Calibrator takes four factors into account: gamut mapping between EPDs and OLEDs, reflectance rates of the EPDs, transmission rates of the TOLEDs, and ambient luminance.

1) Color Gamut Mapping: We use real AMOLED and color AMEPD devices to compare the color gamut of TOLED and color EPD. The measurement is conducted by using the Konica Minolta Spectroradiometer as shown in Figure 5(a). CS-1000, a, is usually used for absolute measurement of TFT displays, LED’s, reflective displays, etc. A ring light source was used as light source. The measured data are tristimulus values for a two-degree observer under D65. The measurement results in Figure 5 shows the color gamut of an AMOLED vs. a color AMEPD based on measurements of the primary \((R, G, B)\). Clearly, the color EPD gamut is dominated by the OLED color gamut so that it is plausible to use gamut mapping to let an OLED panel simulate the color appearance of a color EPD panel using an OLED. We use perceptual rendering intents [10] to handle the outrage gamut. That is, mapping the full OLED color space into the EPD gamut [10]. This can be also implemented by using a lookup table, which has only \( O(1) \) cost to finish the mapping.

2) EPD Reflectance: The optical reflectance of an EPD device is a non-linear function of gray levels [11], [12], which is shown in Figure 6. The average reflectance is about 21%.

3) TOLED Transmission Rate: The modeled TOLED exhibits an average transmittance rate of over 80% in the visible spectral region. The visible red, green, and blue light has a wavelength of about 650 nm, 510nm, and 475nm. The
transmittance rates of RGB in our model are set to 84%, 90% and 86% separately.

4) **Calibration Process:** The calibrator can get the ambient luminance from the hybrid display’ illuminance level sensor and then adjust the luminance of the pixels in the blocks to be shown on TOLED. Considering that YCrCb [10] is used in MPEG standards, where $Y$ indicates the luminance, it is easy to adjust the luminance by modifying $Y$. The calibration algorithm is shown in Alg 2

**Algorithm 2** Calibration Process Algorithm

1: SET $L_{\text{EPDmax}}$ = the max luminance (under full white), which the EPD can have under current ambient illumination;
2: SET $L_{\text{TOLEDmax}}$ = the max luminance the TOLED can emit;
3: for EACH pixel shown on OLED do
4: Map $(Y, C_r, C_b)$ to $(Y', C_r', C_b')$ using perceptual rendering intent if necessary, where $(Y', C_r', C_b')$ is within EPD gamut;
5: SET $Y' = Y' * (L_{\text{EPDmax}}/L_{\text{TOLEDmax}})$
6: end for

Figure 8 shows examples of display appearance for the hybrid display. Figure 8(a) shows a frame displayed on the TOLED; figure 8(b) shows the same frame displayed on both the TOLED and the EPD but without TOLED calibration. Here, there is only one area with a cartoon character is shown on the EPD, while others are on TOLED. Therefore the contents on the TOLED are brighter than those displayed on the EPD; figure 8(c) shows the appearance after the adjustment of the Calibrator. Contents on both displays look similar. The cost of calibration is also reduced by using color profile file and taking advantage of the usage YCrCb colorspace in MPEG.

**IV. Evaluation**

**A. Experimental Setup**

To test our algorithm, 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 [13] to compare the videos. We use the same power model in [4] to measure power consumption. The simulation parameters for the power model are listed in Table I.

B. Experimental Results

In figure 9, we collected 12 frames from a cartoon video, South Park. Figure 9 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 threshold, i.e. 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. SSDCT = 50. There may be delay in frame display time when larger threshold is used. For example, in frame 4, 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 9 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 [17], on average, PSNR is typically between 30 dB and 50 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 10, 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 the SSDCT threshold is larger than 100.

In figure 11, 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 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 12. Even though more power saving can be achieved by increasing the SSDCT threshold value, however, as mentioned video quality becomes unacceptable if the SSDCT threshold exceeds 100.

Figure 13 shows the percentage of pixels during video

<table>
<thead>
<tr>
<th>EPD parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>microcapsule diameter</td>
<td>10</td>
<td>μm</td>
</tr>
<tr>
<td>pigments per capsule</td>
<td>1300</td>
<td></td>
</tr>
<tr>
<td>supply voltage</td>
<td>15</td>
<td>Volts</td>
</tr>
<tr>
<td>suspension resistivity</td>
<td>1.0E12</td>
<td>Ωm</td>
</tr>
<tr>
<td>particle concentration</td>
<td>2*10^3</td>
<td>m^-3</td>
</tr>
<tr>
<td>EPD TFT Rate</td>
<td>66</td>
<td>frames/s</td>
</tr>
<tr>
<td>EPD Color Levels</td>
<td>16<em>16</em>16</td>
<td></td>
</tr>
<tr>
<td>EPD response time</td>
<td>300</td>
<td>ms</td>
</tr>
<tr>
<td>EPD update time</td>
<td>1.2</td>
<td>s</td>
</tr>
<tr>
<td>Capsule leakage power</td>
<td>8.84E-13</td>
<td>Watts</td>
</tr>
<tr>
<td>Steady-state power consu</td>
<td>3.24E-9</td>
<td>Watts</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOLED parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOLED Vdd</td>
<td>13.8</td>
<td>Volts</td>
</tr>
<tr>
<td>TOLED Max Luminance</td>
<td>90</td>
<td>cd/m²</td>
</tr>
<tr>
<td>TOLED transmission rate</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>TOLED pixel area</td>
<td>15028</td>
<td>μm²</td>
</tr>
</tbody>
</table>

Fig. 10. Average PSNR under Different SSDCT Thresholds

Fig. 11. Average Power Saving under Different SSDCT Thresholds (0 to 100, step = 10)

Fig. 12. Average Power Saving under Larger SSDCT Thresholds (0 to 350, step=50)
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 be displayed in MIXED mode according to Display-Chooser so that more video contents are shown on both the OLED and the EPD.

Figure 14 shows relationship between PSNR and power saving. The figure suggests that when $\theta=50$, 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 15 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).

V. RELATED WORK

In this section, we survey the previous research studies that are most relevant to ours. The related work can be grouped into three categories, (i) energy efficient mobile video; (ii) optimization of mobile display power consumption, and (iii) design of low power mobile displays.

Much of the attention on energy efficient mobile videos has been directed towards efforts such as optimization of mobile video delivery (e.g., [18], [19], [20]) and energy-aware video coding (e.g., [21], [22]). Energy efficiency research focusing on reduction of display power consumption of mobile video playback is comparably less. In [23], 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.

Display power reduction for mobile devices has been actively researched in the recent years. Solutions for achieving display energy efficiency have been proposed for LCD, EPD, and OLED displays. In [24], the authors find that the display idle time is following certain distribution. For reducing LCD power consumption, they propose 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.

For EPD, in [14], 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 in their works, which set a threshold on the changes of pixel’s 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.

For reducing OLED power consumption, in [25], the authors study 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 [26], 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.

The third group of related work includes approaches that combine multiple display techniques into one system for optimizing display power consumption. Recently, mobile device companies have started to explore ways to mix different display technologies. Apple Inc. filed a patent by incorporating EPD technology into iPhone, iPad and iPod touch [27]. In their model, the display system would switch between different modes by displaying mobile content either on an EPD device or on an OLED device, but not both. Samsung also implemented a prototype which 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 simultaneously show frame content on both transparent OLED and EPD, at the same time. In addition, we propose adaptive control approaches that can take into account content update rates and decide at subframe level which display should be used for attaining the best tradeoff between energy reduction and support for video playback. Furthermore, we evaluated performance of the proposed video playback approach using high fidelity simulations derived from reported measurements of actual EPD and TOLED devices.

VI. CONCLUSIONS

In this paper, we propose a solution of mobile video playback, named Decoder4Hybrid, for supporting mobile hybrid displays that integrate a color EPD with a transparent OLED. 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. A pixel calibrator is implemented to ensure that contents shown on different displays are visually similar. Experimental results show that using the proposed approach, up to 40% power can be saved with acceptable video quality.

VII. ACKNOWLEDGEMENT

The authors are grateful to anonymous reviewers for providing many valuable comments to improve the quality of this paper. The authors would also like to thank Dr. Heidi Hofer at College of Optometry, University of Houston, for providing Konica Minolta Spectroradiometer.
REFERENCES
