Smart Driver for Power Reduction in Next Generation Bistable Electrophoretic Display Technology

Michael A. Baker
Arizona State University
CSE Department
Tempe, AZ 85281
+1 (480) 820-5517
mike.baker@asu.edu

Aviral Shrivastava
Arizona State University
CSE Department
Tempe, AZ 85281
+1 (480) 727-6509
aviral.shrivastava@asu.edu

Karam S. Chatha
Arizona State University
CSE Department
Tempe, AZ 85281
+1 (480) 727-7850
karamvir.chatha@asu.edu

ABSTRACT

Microencapsulated electrophoretic displays (EPDs) are quickly emerging as an important technology for use in battery-powered portable computing devices. Thanks to bistability and their efficient reflective nature, these displays offer power savings on the order of 90% over liquid crystal displays (LCDs) commonly found in today's portable devices. EPD technology is also suitable for use in flexible displays opening the door for integrating much larger displays into small form factors for hand-held devices.

Here we present a method for power reduction in next generation EPD displays with full color and video capability. A "smart driver" for power optimization of next-generation bistable displays is presented which reduces switching power consumption by as much as 50% without affecting quality of service. A more aggressive "lazy driver" capable of achieving significant additional energy savings in exchange for quality of service is also presented.

Finally, important challenges engineers face as they work to advance EPD technology for use in future generation hand-held computing devices are explored.

Categories and Subject Descriptors

C.4 [**Performance of Systems**]: *Design studies, Performance attributes*

General Terms

Performance, Design

Keywords

Electrophoretic Display, Low Power Display, Display Drivers, Bistable Display

1. INTRODUCTION

Today displays represent a significant fraction of the power required by common handheld portable computing devices. Displays often account for anywhere from 30-60% of the power consumption in these devices, primarily due to backlight power consumption in the ubiquitous Liquid Crystal Displays (LCD) [1][2]. A typical QVGA display in a handheld device may consume 220mW of power, 91% of which is directly consumed by the backlight [3]. Maturing alternative technologies such as bistable Electrophoretic Displays (EPD) offer promising possibilities for significant power savings by eliminating the backlight and providing a zero power capability when displaying a static image.

Here we introduce a smart driver concept for next generation full motion and color EPDs which takes advantage of the image stability these displays offer even when the device is turned off. Our smart driver offers substantial power savings of between 30% and 50% of display switching power while displaying video when compared to a naive driver without loss of quality by selectively updating only portions of the image which change from one frame to the next. We also introduce a more aggressive lazy driver which seeks to improve power savings even further in exchange for video quality. Both methods are analogous to inter-frame compression used in common video compression algorithms.

A great deal of effort has gone into optimizing power consumption in LCDs [4], and as battery powered computing devices become increasingly powerful and pervasive, that effort continues to grow in importance. As lower power display technologies like EPDs become more capable, the effort to optimize those technologies for use with handheld devices will also increase. Currently EPDs are the technology of choice for electronic paper due to the small amount of energy required, very high contrast, and suitability for use in flexible displays. As EPD technology improves, this type of display will increase in importance. With handheld computing devices growing more powerful and more versatile, they will require larger lower power displays than those found in portable devices today. Imminent improvements to full color and full motion capability in EPDs justifies looking into optimization of these devices under those conditions. EPD switching power consumption is not directly evaluated in comparison with LCDs here; however, we find that the power consumed in an EPD with a refresh rate comparable to an LCD displaying full motion video are of the same order. The 9% of the LCD's power budget which goes into updating and maintaining the displayed image is comparable to the total energy consumed by an EPD in the same environment.

We start with an overview of EPD technology in Section 2 followed by our method of characterizing pixel switching power in the EPD in Section 3. Section 4 expands on the smart driver and lazy driver concepts before our simulation and results are covered in Section 5. Finally in Section 6 we present the conclusion and cover some key obstacles faced by industry designers and engineers working to improve EPD performance.

CODES+ISSS'07, September 30–October 3, 2007, Salzburg, Austria.

2. EPD TECHNOLOGY

EPDs use the electrophoretic force created by an electric field on charged pigment particles in an encapsulated colloidal suspension to alter the appearance of a display image. When charged pigment particles are forced to the front of the display though electrophoresis, the capsule appears the color of the pigment particles. Two color particle displays use capsules like the one illustrated in Figure 1. Here particles of opposite charge and color are switched between the front and back of the display to produce pixel color. This process can produce color and contrast comparable to printed paper.

An important distinction between LCD and EPD technology is the concept of bistable pixels. In a bistable display, individual pixels are stable in both "on" and "off" orientations so that an image once established on the display will remain there, even if the display is turned off. This is an extremely useful property of EPDs, which is particularly interesting when power conservation is important. LCDs must be refreshed continually in order to maintain an image on the display, even if the image is constant, while an EPD may retain an image for 100 hours after the device has been turned off [5]. It is this distinction which drives the concepts presented in this paper.

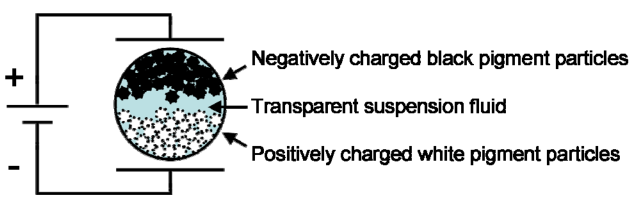

Figure 1. EPD capsule with a transparent electrode at the top making the black pigment particles visible to an observer above after a voltage is applied as shown

Figure 2. Capsules containing colloidal suspension in an EPD display (Flexible Display Center, ASU, E-Ink Corp.)

2.1 Advantages

EPDs have a number of properties which are highly desirable in portable battery powered devices. High contrast in ambient light eliminates the requirement for a backlight found in all transmissive LCD display devices. The bistable nature of EPDs means that once an image is drawn on the display, there is no need to refresh or even power the display until a new image must be drawn. For static viewing applications, such as text viewing, once the image is drawn the display might be powered down for minutes, hours, or even days until the viewer is ready to go to the next page. This bistable property can mean substantial power savings in handheld devices. Figure 2 also demonstrates that display resolution is not limited by microcapsule size. Image resolution is actually dependent only on the size or shape of the electrodes in the backplane.

3. POWER CHARACTERIZATION OF EPD AT THE SUBPIXEL LEVEL

3.1 Electrophoretic capsule

In order to characterize the power consumed by our next generation display, we need to understand the amount of energy required to move a pigment particle in the colloidal solution across an EPD capsule and the amount of leakage current we should expect to occur in the capsule. The physical characteristics of our capsules are based on contemporary examples of EPD display technology. Table 1 lists the fundamental properties chosen for our display for power characterization. Each display pixel is divided into three subpixels corresponding to the RGB color components in the display. Power is characterized at the subpixel level because each color component or subpixel has its own data value and storage capacitor.

Table 1. Simulated EPD's attributes

	Value	Unit
pigment particle radius (*r*) [12]	0.5	μm
pigment particle charge (*q*) [12]	4.8E-16	Coulomb
microcapsule diameter [6]	50	μm
supply voltage [11]	15	Volts
suspension resistivity [5]	1.0E12	Ωm
particle concentration [11]	2E16	part./m^3
microcapsules/subpixel [6]	6	capsules

3.1.1 Capsule switching power

The physical motion of charged pigment particles accounts for most of the power actually consumed in each microcapsule. Here we introduce a method for calculating capsule switching power. For simplification, the amount of power consumed during particle motion is considered to be a constant dependant upon the velocity of the particles as they transit the capsule. Particle motion inside the capsule can be represented as a laminar flow, and the time required to establish laminar flow after the electric field has been applied is very small with respect to the switching timescale, even when we are considering full motion video at 60hz. In [10] this time is calculated at 55ns, while the frame-write period at 60hz is approximately 17ms. For our purposes, we consider the velocity of each particle as it traverses the capsule assuming the particle travels the diameter of the capsule anytime the capsule is switched. The velocity is determined by the distance which must be covered by the particles in the amount of time it takes to write one frame at the driving frequency. From the particle velocity v in meters per second, the applied voltage V, and the capsule diameter in meters d, we can calculate the mobility μ of the pigment particles in solution [10]:

$$\mu = v / \mathrm{E}, \text{ where } \mathrm{E} = \mathrm{V} / d \qquad \textbf{(1)}$$

We consider the 15V driving voltage, capsule diameter, particle radius, and particle charge fixed properties of our next generation EPD. In order to achieve the required mobility, we must identify the viscosity of the suspending fluid. Here we manipulate the equation for mobility in [10]. Applying the charge per pigment particle in Coulombs q , and the radius of the pigment particles r in meters we are able to find the viscosity η necessary to achieve the switching time necessary for our frame refresh rate:

$$\mu = q/12\pi r\eta$$
$$\eta = q/12\pi r\mu \quad \textbf{(2)}$$

Using the values V = 15 volts, $d = 50\mu m$, $r = 0.5\mu m$, $q = 4.8\text{E-}16\text{C}$ [12] and a frame refresh rate of 60hz, we find that we must have a viscosity no greater than 0.00255 Ns/m^2 or 2.55 cP, which is much smaller than value used in [6].

To find the power consumed through physical movement of a single pigment particle, we can determine the force acting on the particle in Newtons: $\text{N} = q\text{E}$ where q is the particle's charge in Coulombs, and E is the electric field inside the capsule as described earlier. Using the pigment particle concentration of $2 \cdot 10^{18} m^{-3}$, and multiplying by the volume per capsule we have approximately 1300 particles in a capsule. The work performed on each particle is this force multiplied by the particle's velocity, in this case $3.00\text{E-}3m/s \cdot 1.44\text{E-}10\ \text{N} = 4.33\text{E-}13\ \text{W}$ per pigment particle. We do not distinguish between the positive and negatively charged pigment particles for a two particle EPD in this calculation, as the work in either case is indistinguishable. To calculate the power consumed at the subpixel level, this number is multiplied by the number of particles per capsule, and the number of capsules per subpixel to find 3.24E-9 W per subpixel during switching.

3.1.2 Capsule leakage power

As long as a voltage is applied across the capsule, a small amount of leakage current will flow through the fluid dependent on the resistivity of the colloidal solution in the capsule. Typical resistivities should be $>10^{12}\Omega \cdot \text{cm}$ [5]. Leakage power is calculated for each capsule based on resistivity *ρ* of the colloidal solution. The height *h* and radius *r* of the capsule are used to determine its resistance:

$$R = \rho h/\pi r^2 \quad \textbf{(3)}$$

Capsule leakage power is found using the capsule's resistance and the operating voltage: $P = V^2/R$. Multiplying this value by the number of capsules per subpixel we get a leakage power of 8.84E-13W per subpixel. Since this value is four orders of magnitude smaller than the power consumed due to particle motion, it can be safely ignored when calculating subpixel power consumption.

Table 2. Subpixel power consumption

	Watts
Steady-state power consumption due to electrophoretic particle motion	3.24E-9
Capsule leakage power	8.84E-13

3.2 Storage Capacitor

To achieve a frame rate acceptable for viewing video, the storage capacitor shown in Figure 3 stores the energy needed to switch a display subpixel between two states, such as black to white or white to black. With a storage capacitor, the display driver can quickly write a row of pixels by charging the capacitor, and then move on while the capsules are driven by the capacitor. The capacitor is charged during the row-write operation, and the particles in the EPD capsules complete their motion under the electric field provided by the charged capacitor during the period of one frame-write operation. At 60 Hz, the frame-write period is approximately 16.7ms. The row-write period is determined by the number of pixel rows in the display. Here we use 320x240 QVGA, where 240 is the number of rows in the image. Dividing the frame-write period by the number of rows gives us a row-write period of 0.0694ms.

The storage capacitor must charge during the row-write period, and then maintain the switching voltage across a subpixel through one frame-write period while performing the work required to switch the subpixel in the same period. The amount of energy lost from the capacitor during a frame-write period is calculated from the amount of work per subpixel derived earlier multiplied by the amount of time the work is performed, in this case the frame-write period: $3.24\text{E-}9\text{W} \cdot 1.67\text{E-}2s = 5.23\text{E-}11j$. Using the spice model shown in Figure 3, we can calculate the amount of energy lost in the storage capacitor based on the voltage drop during the frame-write period. In our model, with an 8.6pF storage capacitor, the subpixel loses 0.47 volts from 14.53V when the capacitor is charged to 14.06V at the end of the frame-write period, expending 5.78E-11j.

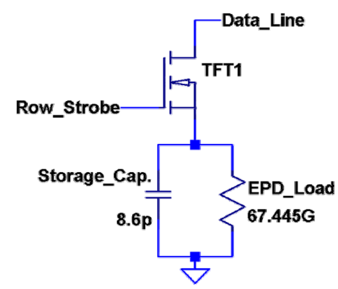

Figure 3. EPD capsule model with TFT gate and component values simulated in LTSpice [7]

The total power consumed in writing to each subpixel is completely dependent on the size of the storage capacitor. At the beginning of each row-write cycle, the storage capacitor is shorted to ground to discharge the remaining energy. This is done because the image information stored in the associated subpixel is assumed to be stable. The next pixel value is also likely to require the opposite charge used to attain the current state, in which case discharging the capacitor reduces the energy required by the driver to charge the capacitor to the opposite polarity [16].

3.3 Thin Film Transistor (TFT)

EPD drivers must use active matrix pixel addressing since the electrophoresis of the pigment particles does not have a threshold voltage. Passive matrix addressing will invariably affect an entire row and column when a single pixel is addressed [5][13][14], while active matrix pixel arrays are switched at the pixel level using a TFT to protect pixels from signals intended for other rows. The EPD driver writes a row of display data at a time by applying the appropriate row image voltage values to the columns in the addressing matrix and applying a separate row strobe to turn on the TFT switches for each row in sequence [15].

4. IMPROVED DRIVER CONCEPT

4.1 Naive driver

Standard display drivers update every pixel on the display each time the frame is refreshed. Constantly refreshing pixels is important to the operation of LCD displays because after a charge has been applied to place an LCD pixel in the desired state, the pixel immediately begins moving back to its quiescent state. As a result, LCD displays must be refreshed constantly even if the image displayed remains static. Similarly, our naive EPD driver updates every pixel in the display according to the frame refresh rate.

Table 3. Driver configurations

Driver	Image degradation	Power savings
Naive	No degradation	0%
Smart	No degradation	3%-50%
Lazy	Selectable degradation	3%-91%

4.2 Smart driver

Without any requirement to refresh a static image, the display driver need only write the image once. An image might remain on the display with the display driver and even the display itself turned off for days. This property enables some possibilities for smarter ways to update moving images. When displaying a video with an EPD, a smart driver would know that it need not update the display faster than the frame rate of the video displayed. Such a scheme results in immediate power savings, as a display capable of updating at 60fps showing a video at 32fps instantly conserves energy by only updating the display when a new frame arrives at half the native rate with no loss of performance.

Common display interfaces present largely static screens such as a user desktop. Interacting with the display interface frequently results in small changes to the displayed image as is the case with drop-down menus and mouse pointer motion. Only a very small fraction of pixels actually change from one frame to the next. In this case a smart driver might very efficiently reduce the amount of work performed at each frame refresh by updating less than 1% of the pixels during each refresh. This concept extends to full motion video and is analogous to inter-frame compression used for MPEG video. Even at 60 fps, some fraction of the pixels on the display will likely remain unchanged from one frame to the next. The smart driver can detect these static portions of the image by comparing RGB values on the display to those in the new frame, and choosing not to address them when the new frame is written. While choosing to update only pixels that have changed from one frame to the next, the display driver will conserve energy without any loss of image quality in a bistable display.

4.3 Lazy driver

The concept of a smart driver for a bistable display can be taken one step further. If power conservation is paramount, the user might be interested in sacrificing image quality for power savings. A lazy driver can further reduce power consumption by loosening the definition of a pixel which is unchanged from one frame to the next. The lazy driver might only compare the most significant part of a pixel's color value and then only update pixels which have changed by some threshold amount before bothering to update them during a frame refresh. For example, the color value of a pixel is represented with a 24 bit number. The three bytes in this number represent the three primary colors in the order red, green, and blue. The lazy driver might compare only the most significant 7, 6, 5, or 4 bits of each byte instead of comparing all 8 as in the smart driver to determine whether a pixel should be updated or not. In effect by doing less work to compare the image on the display with the next frame to be displayed, the lazy driver conserves energy by updating fewer pixels depending on how many bits were compared. The lazy driver might produce significant power savings over a smart driver, but it also degrades the image quality of the displayed video. Image degradation can increase significantly as the number of bits compared decreases.

5. EPD SMART DRIVER SIMULATION

5.1 Bistable display simulator

In order to characterize the potential power savings achieved by upgrading the bistable display driver, we developed a simulator in Java which takes as its input a sequence of bitmap images extracted from video benchmarks. Each image is a frame from the original video. Seven QVGA video segments were extracted from MP4 files provided by Elecard Ltd. [17]. The simulator calculates the power consumed by a naive driver updating every pixel of every frame, the smart driver which updates only pixels that differ from one frame to the next, and six iterations of the lazy driver which compares only the most significant bits of each subpixel value for the next frame with the same bits from the image currently on the display.

5.2 Simulator power characterization

The display is modeled such that the elements in Figure 3 represent a subpixel, or a single RGB component color of each pixel. Power is calculated separately for each subpixel according to the figures in Section 3. The total energy added to the row of capacitors during a row write is used to determine the power consumed during a row write operation. At the beginning of each row write, the storage capacitor is shorted to quickly discharge any stored energy as described in Section 3.2.

The continuous power consumed by the display is determined by the series of row-writes which occur sequentially as each frame is written to the display. The row power is calculated based on the total number of pixels written. The rate of power consumption over the total row during one row write period represents the power during that time period. The total power calculated for the next row represents the power consumed during the next row-write period. When the end of the frame is reached, the next frame begins with the first row.

Power consumption is calculated for every pixel which is written during a frame-write. In the case of the naive driver, every pixel is re-written. The smart driver only updates pixels when any 8 bit RGB component in the next frame is different from the current displayed image. The lazy drivers only compare the first $8-n$ bits of each RGB component for each pixel, where n is the number of least significant bits ignored during the comparison.

5.3 Smart driver vs. naive driver

In Figure 4, the instantaneous simulated display switching power consumption is plotted over 29 frames of "Baroness". The x-axis represents each row written in turn over the course of 29 frames such that every 240 steps along the x-axis represent the instantaneous power over the course of one frame-write. The y-axis gives the power consumed in Watts for each row. The naive driver results in constant power consumption represented by the flat line at 11.3mW. The squares mark the average instantaneous power consumed over the course of each frame by the naive driver. The smart driver produces a display image identical to the naive driver, but with the instantaneous power consumption swinging between 0.0mW and 11.3mW. This video is in a "letterbox" format with a black stripe at the top and bottom of each frame. This constant portion of the image corresponds to zero power consumption by the smart driver at the beginning and end of each frame. The triangles mark the average at the end of each frame for the smart driver. The simulated smart driver resulted in power savings averaging 33% across 7 video clips with savings ranging from 3% to 50% without any degradation to the displayed image.

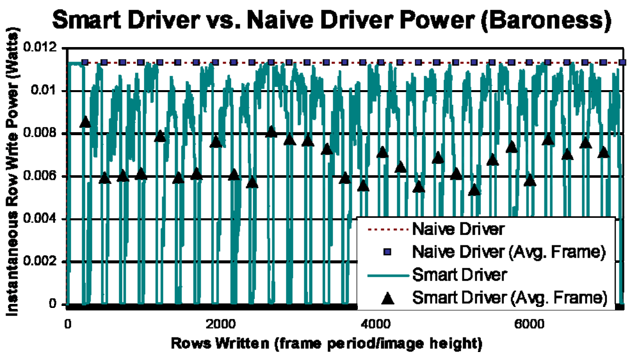

Figure 4. Smart driver reduces power consumption by 40% over the naive driver for "Baroness"

5.4 Lazy driver vs. smart and naive drivers

Figure 5 shows a plot of the average power consumed by each frame over the course of 29 frames of "Baroness" for each driver configuration. Each line plotted represents a different driver configuration for the same video. The relative power consumption using the lazy driver is anywhere from 35-90% less than the naive driver with both drivers updating at 60Hz.

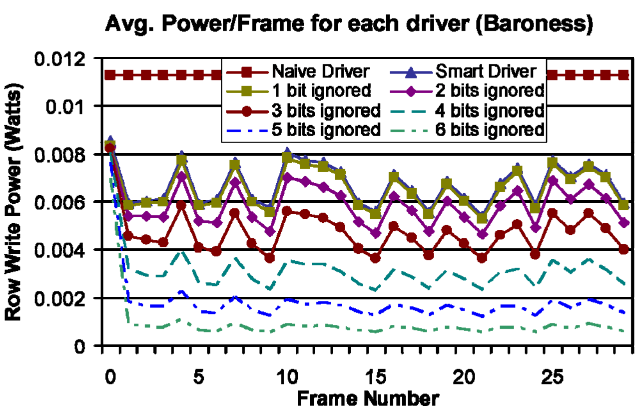

Figure 5. Simulated power consumption for each driver configuration over 29 frames of "Baroness", here the lazy driver produces power savings ranging from 42-91%

In order to characterize the quality of service for each of the drivers, we use the Peak Signal-to-Noise Ratio (PSNR) method to compare the resulting image to the original image. A PSNR value of 100dB indicates no change from the original image. Lower PSNR values represent lower quality images. Typical values for compressed video are 20-40dB. The lazy drivers achieve significant power savings, but at increasing degradation to image quality.

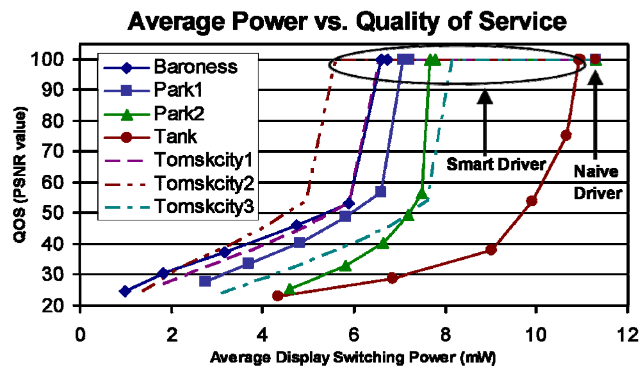

Figure 6. Avg. video power consumption vs. QOS for each video (line) and each driver configuration (point), all videos consume constant power using the naive driver

Figure 6 illustrates the relationship between power savings and loss of image quality. In all cases, the PSNR value of the naive and smart drivers are 100dB indicating no change from the original image. When we ask the lazy driver to compare fewer bits while deciding whether to update a pixel, the power consumption decreases as the image quality declines. Ignoring 1 bit resulted in a very small power savings and no image degradation in all 7 videos. Ignoring 6, 5, 4, 3, or 2 bits corresponds to the first five points plotted on each line with PSNR values ranging from 20dB to 60dB.

a. b. c.

Figure 7. Detail from Baroness frame 29: a. original quality, b. last 5 bits ignored, PSNR value for this frame is 30.5dB c. last 6 bits ignored, trail left by basket moving from left to right is clearly visible, PSNR value is 24.6dB

If we decide that the lowest PSNR value we are willing to accept is 30dB, we find that in all cases ignoring 6 bits results in unacceptable image quality, while all other configurations result in acceptable image quality. In this case we would choose to have the driver ignore 5 bits minimizing power consumption with acceptable loss of image quality. It is also interesting to note that when the lazy driver is configured to ignore 3, 2, or 1 bits, the PSNR values are greater than 40dB, which is better than typical video compression. Figure 7 illustrates the original image quality, compared with degraded video frames ignoring 5 and 6 bits after 29 frames.

6. CONCLUSION AND EPD FUTURE

6.1 Conclusion

We have discussed the advantages of bistable electrophoretic displays in mobile battery powered computing devices. We introduced a method for calculating power consumption in EPD capsules based on the physical motion of pigment particles inside the capsule. We also introduced smart driver and lazy driver schemes which can provide display power savings of up to 50% for these devices without reduction in quality of service with additional savings where reduced quality of service is acceptable. These improved driver schemes are applicable to any bistable or image-stable display. We found that degradation in quality of service was very small in certain lazy driver configurations. Future experiments are expected to show a relationship between lazy driver quality of service and the level of compression in the original video. Additionally, future work will focus on overhead and energy cost within the improved driver, and physical verification of the switching power model for EPD capsules.

6.2 EPD switching time

Slow switching speed remains a dominant issue with EPDs. EPDs typically require relatively high supply voltages to obtain desirable response times. Most EPD pixels today are driven at around 15V which is somewhat high compared to LCD (4.5V-15V) [18]. The switching frequency of the cells is limited by the viscosity of the suspending fluid and the physical motion of charged particles. EPDs historically have switching times on the order of tens to hundreds of milliseconds when driven at reasonable voltages for portable devices with few devices currently operating at the fast end [5][12]. LCDs on the other hand are commonly able to switch on the order of 10 milliseconds [8]. Optimizing the switching speed of EPD capsules is primarily a problem of maximizing the mobility of the pigment particles in suspension. Pigment particle mobility, described in equations (1) and (2), is dependent upon several factors. Increasing the supply voltage can improve response times, but we consider the 15V common to EPDs today an upper limit of what we would like in a battery powered device. Increasing the charge we can attach to pigment particles increases their mobility for a given electric driving field, but engineers must be careful with large charges attached to the pigment particles as associated ions in the solution can screen the electrical field reducing the efficiency of the capsule [19]. Reducing the pigment particle size increases its mobility, but will reduce the charge which can be attached via the surfactant and may increase the risk of agglomeration reducing the lifespan of the capsule [5]. Finally, reducing the viscosity of the suspension fluid increases particle mobility, but viscosity must be considered along with the specific gravity which must be carefully matched with the specific gravity of the pigment particles to stabilize the colloidal solution and enable image retention [5].

6.3 Grayscale in a bistable display

Another important problem with EPDs is the difficulty in achieving grayscale. Because of the bistable nature of these displays, putting a pixel into an intermediate state required to display anything other than black or white can be problematic. The state of the pigment particles inside a capsule is not well defined for interim states required to achieve grayscale. Grayscale can be achieved through area ratio scaling using varying numbers of subpixels to achieve relative lightness or darkness in a pixel; however, the levels of gray achievable through this method are limited by the number of subpixels that can be addressed [6]. It is possible to partially switch a pixel resulting in partial transition from black to white or white to black. This is currently done by erasing or blanking the display, then precisely controlling the amount of energy applied to achieve the desired state. Without first resetting the display to a known state, the amount of energy and the supply voltage polarity required to achieve a specific state is directly dependent upon the current state of the pixel where state is characterized by the location of the pigment particles inside the associated capsules.

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