Backlight Dimming in Power-Aware Mobile Displays

Ali Iranli
Wonbok Lee
Massoud Pedram

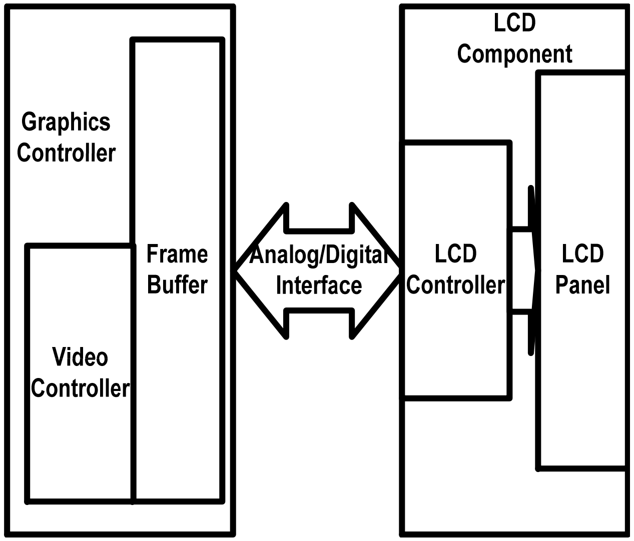
July 26, 2006

Department of Electrical Engineering
University of Southern California

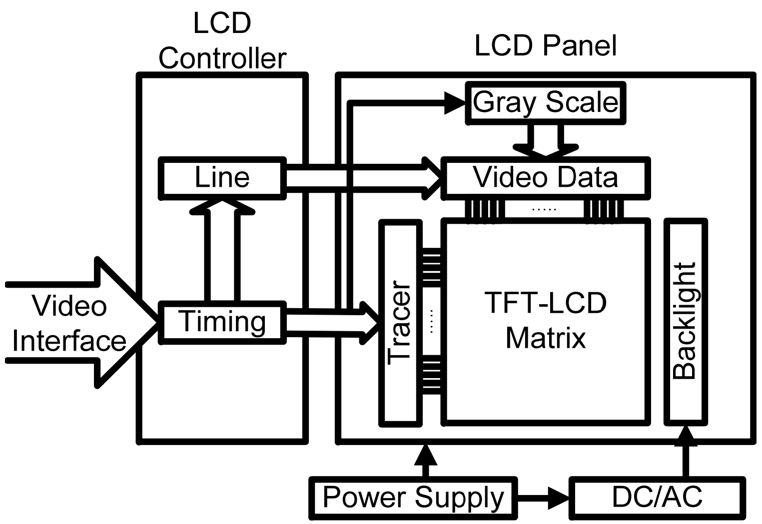
Outline

- Display Systems and LCD Architecture
- Review of Dynamic Backlight Scaling
- Previous Work in Backlight Scaling
- Temporally Aware Backlight Scaling
- Implementation
- Experimental Results
- Conclusions & Future directions

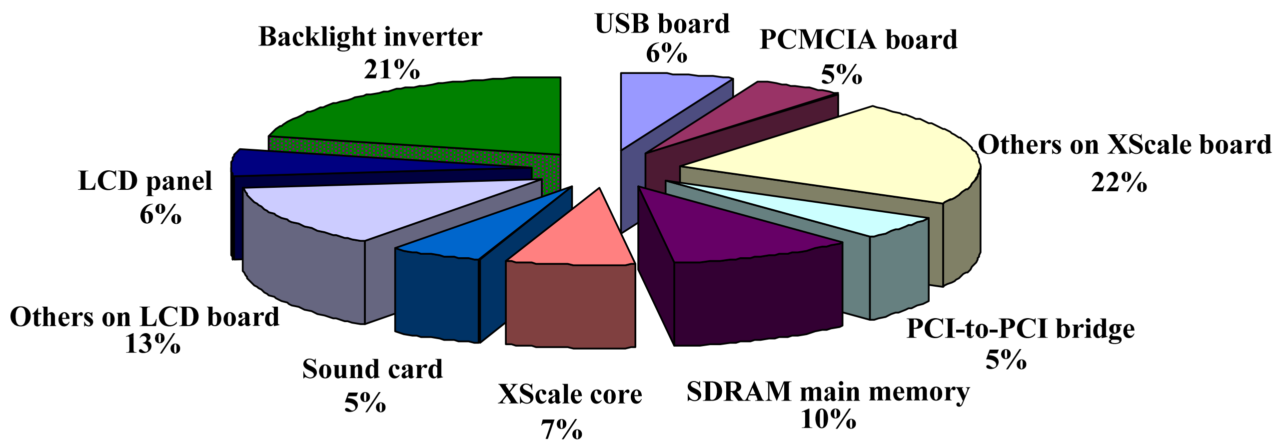
LCD Architecture



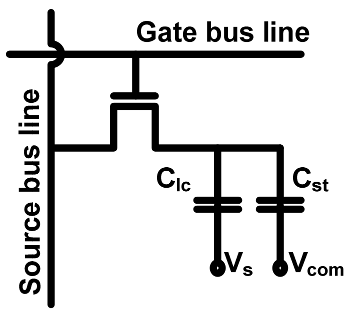
< Display Subsystems >



< LCD Components >



Total Power = 16.8W



< LC Pixel >

Review of Backlight Scaling

- Perceived light emitted from an LCD panel is a function of two parameters
  - Light intensity of the backlight
  - Transmittance of the LCD panel

- Two important observations:
  - We can have the same perception of an image by using different value assignments to the aforesaid parameters
  - Power consumption of the BackLight Unit (BLU) is orders of magnitude larger than the power consumption of the LCD panel

- Backlight Scaling Idea: Dynamically dim the backlight while adjusting the transmittance of the LCD pixels such that the perceived luminance is preserved, yet the overall power consumption is reduced.
  - There is a trade off between the degree of image distortion and the amount of power saving

Precise Problem Statement

- Perceived Luminance ($L(x)$) of a pixel is represented by:

$$\boxed{L(x) = b \times t(x)}$$

$x \in [0:255]$: Grayscale level of a pixel (8 bits)
$t(x)$: Transmittance of a pixel
$b \in [0,1]$: Normalized backlight illumination factor

- Let χ and $\chi' = \Phi(\chi, \beta)$ denote the original and the transformed image data after backlight scaling, respectively
- Moreover, let $D(\chi, \chi')$ and $P(\chi', \beta)$ denote the distortion of the images χ and χ' and the power consumption of the LCD subsystem while displaying image χ' with backlight scaling factor of β
- Dynamic Backlight Scaling Problem: Given the original image χ and the maximum tolerable image distortion D_{max}, find the backlight scaling factor β and the corresponding pixel transformation function $\chi' = \Phi(\chi, \beta)$ such that $P(\chi', \beta)$ is minimized and $D(\chi, \chi') \leq D_{max}$

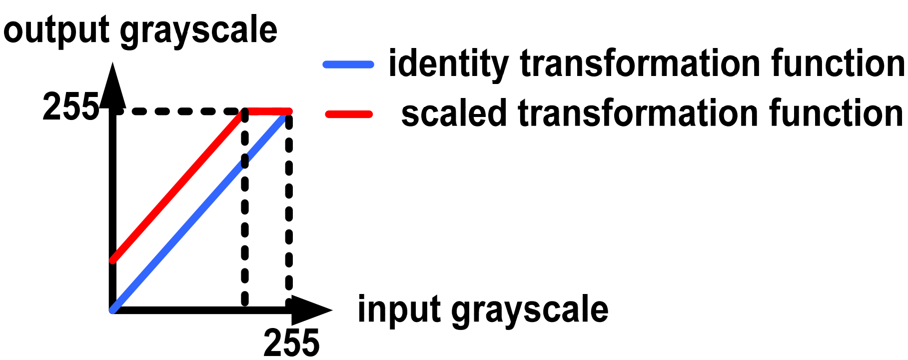
Prior Work

- Dynamic backlight Luminance Scaling (DLS): Chang et al. in 2004 proposed a backlight scaling scheme based on two mechanisms:
  - Grayscale Shifting: concentrate on the brightness loss compensation
  - Grayscale Spreading: concentrate on the contrast enhancement

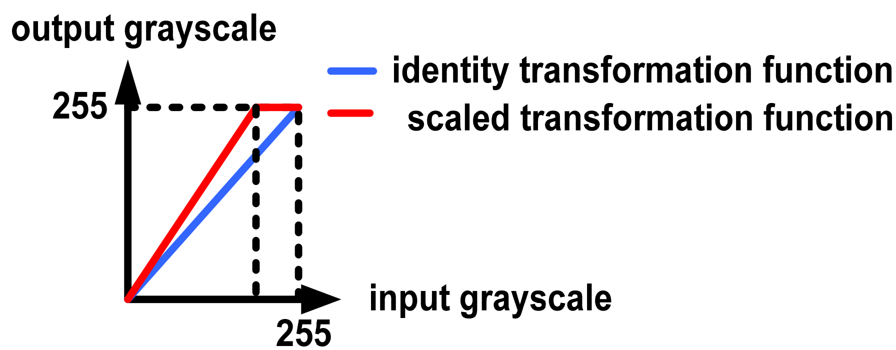
$$\Phi(x,\beta) = \min(1, x + (1-\beta))$$

$$\Phi(x,\beta) = \min(1, \frac{x}{\beta})$$

$\Phi(x,\beta)$: Pixel transformation function
x : Normalized pixel value in 8 bits color depth
β : Backlight scaling factor



< Grayscale Shifting >

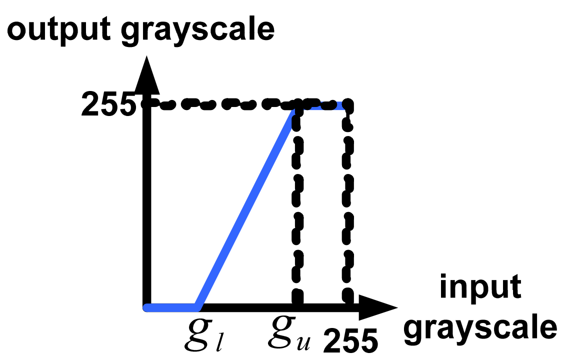


< Grayscale Spreading >

Prior Work (Cont'd)

- Concurrent Brightness and Contrast Scaling (CBCS): Cheng et al. in 2004 proposed two-sided single band grayscale spreading technique in the backlight scaling domain
  - Truncate the image histogram in both ends to obtain a smaller dynamic range and spread out the pixel values within this range
  - Maintain the contrast fidelity and aggressively saves power

$$\Phi(x,\beta)=\begin{Bmatrix} 0, & 0 \le g_l \\ cx+d\,, & g_l \le x \le g_u \\ 1, & g_u \le x \le 1 \end{Bmatrix} where \begin{Bmatrix} c = \dfrac{1}{g_u - g_l} \\ d = \dfrac{-g_l}{g_u - g_l} \end{Bmatrix}$$

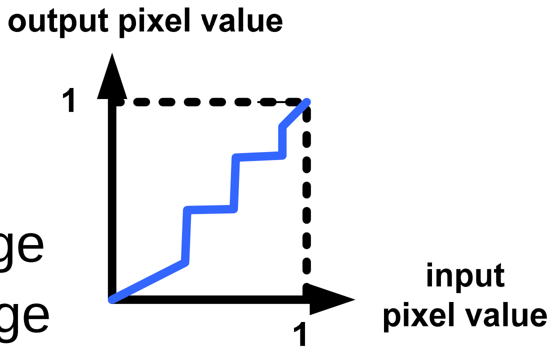


- Pros: Eliminate the pixel-by-pixel transformation of the displayed image in DLS approach through the change of built-in LCD reference driver

Prior Work (Cont'd)

- Histogram Equalization in Backlight Scaling (HEBS): Iranli et al. in 2005 proposed a non-linear grayscale spreading technique
  - Present global histogram equalization algorithm to preserve visual information in spite of image transformation

$$\boxed{\int_0^1 \left| U(\Phi(x)) - H(x) \right| dx}$$



$H(x)$: Original cumulative histogram of an image

$U(x)$: Cumulative uniform histogram of an image

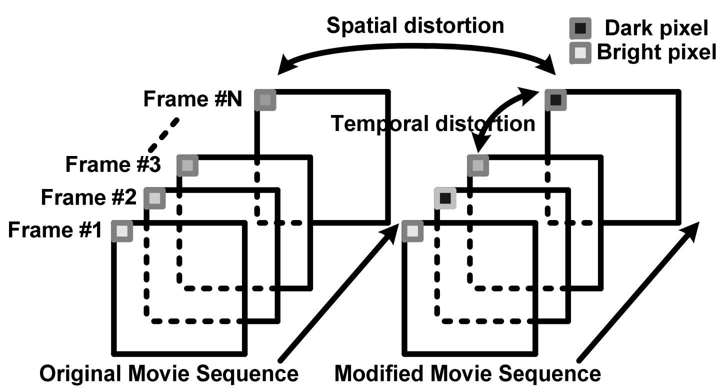
$\Phi(x)$: Monotonic pixel transformation function

- Histogram Equalization Problem: Find the monotonic transformation function that minimizes the above formula

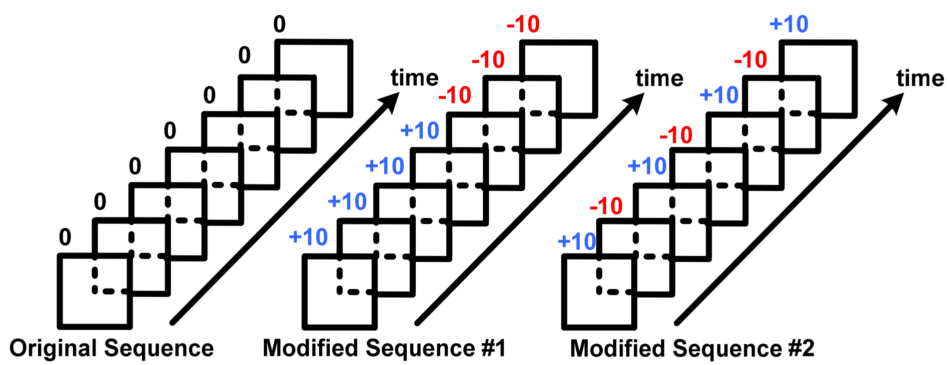
- Need modification in the built-in LCD reference driver to produce piece-wise linear image transformation function

Temporally-Aware Backlit Scaling (TABS)

- No backlight scaling technique has considered temporal distortion
  - Human visual system is quite sensitive to the temporal variation
- Decompose distortion in two components:
  - Spatial : intra-frame luminance distortion btw. respective frames of the original and backlight scaled video
  - Temporal : inter-frame luminance distortion due to large scale change in luminance
- Defining an objective video quality measure (VQM) is difficult
  - Images that have the same MSE may be perceived quite differently by different individuals



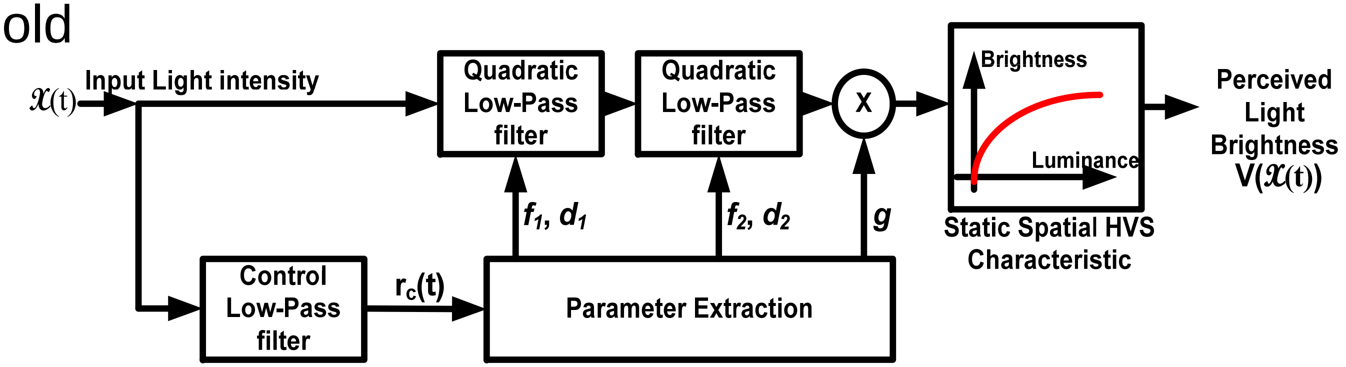
< Spatial & Temporal Distortions >



< Examples of temporal distortion>

Temporal Response Models

- Two models of the dynamics of light perception in temporal domain
  - Aperiodic stimuli:
    - Measure the impulse response of human visual system (HVS)
  - Periodic stimuli:
    - Measure the *critical fusion frequency* (CFF) at various *amplitude sensitivity* (AS) values
    - CFF: Minimum frequency above which an observer cannot detect flickering effect when a series of light flashes at that frequency is presented to him/her
- We adopt a computational temporal response model of HVS due to Weigand et al. proposed in 1995, which can be used to determine the AS threshold



< Temporal Response Model of the HVS >

Spatial and Temporal Distortions

- Two types of distortions:
  - Spatial:
    - Upper bounded by user-given maximum value
  - Temporal:
    - Not given but captures flickering, i.e., time-varying luminance
    - MSE between spectral power density of brightness

$$\begin{aligned} D(x,x') &= \alpha \cdot D_{spatial}(x,x') + (1-\alpha)\cdot D_{temporal}(x,x') \\ &= \alpha \cdot \max_i (D_{spatial}(x_i, x_i')) + (1-\alpha)\cdot \frac{\sum_j (F\{V(x)\}_j - F\{V(x')\}_j)^2}{\sum_j (F\{V(x)\}_j)^2} \end{aligned}$$

x, x' : Original and backlight scaled video sequences, respectively

$D_{spatial}(x,x')$: Spatial distortion between respective frames in two video

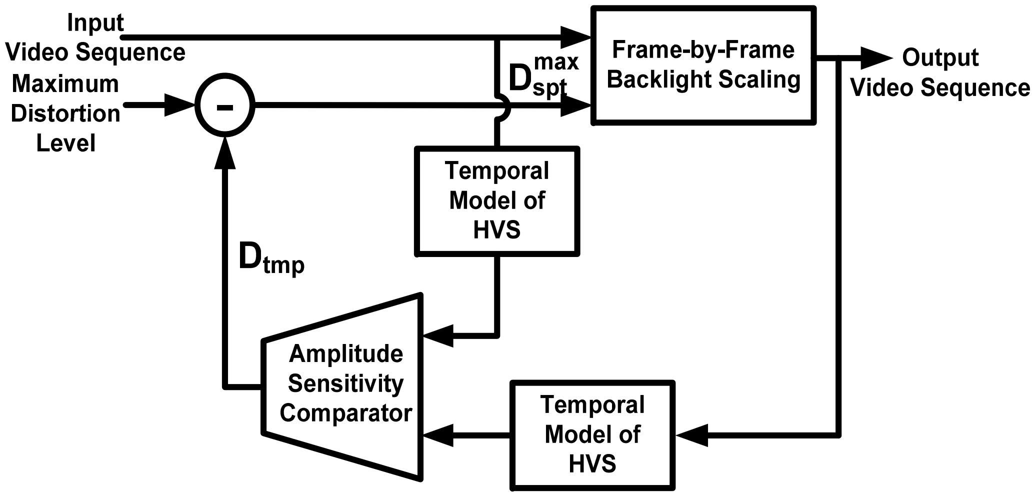
$D_{temporal}(x,x')$: Temporal distortion in some consecutive frames

$V(x)$: Perceived brightness α : Weighting factor

$F\{\}$: Fourier transform operator

Distortions (Cont'd)

- Spatial distortion is in time domain
- Temporal distortion is in frequency domain: Use Parseval's theorem
  - Integral of squared signal equals integral of its spectral power density



< TABS Model >

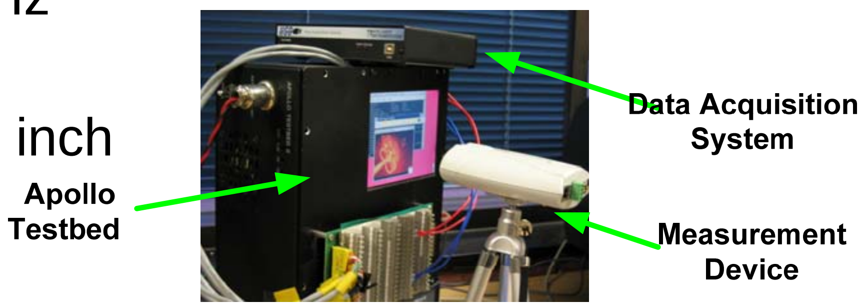
- TABS approach: Measure the temporal distortion of backlight scaled video and utilize this information to change the maximum allowed spatial distortion of frames

1. For each video frame at time t, calculate the mean brightness value of all pixels, $\bar{X}(t)$, $\bar{Y}(t)$
2. Filter signals $\bar{X}(t)$, $\bar{Y}(t)$ using temporal response model to get perceived luminance signals
3. Calculate $D_{tmp}(x, y)$
4. Using $D_{tmp}(x, y)$ above, modify the maximum allowed spatial distortion, D_{spt}^{max}

< TABS Algorithm >

Implementation

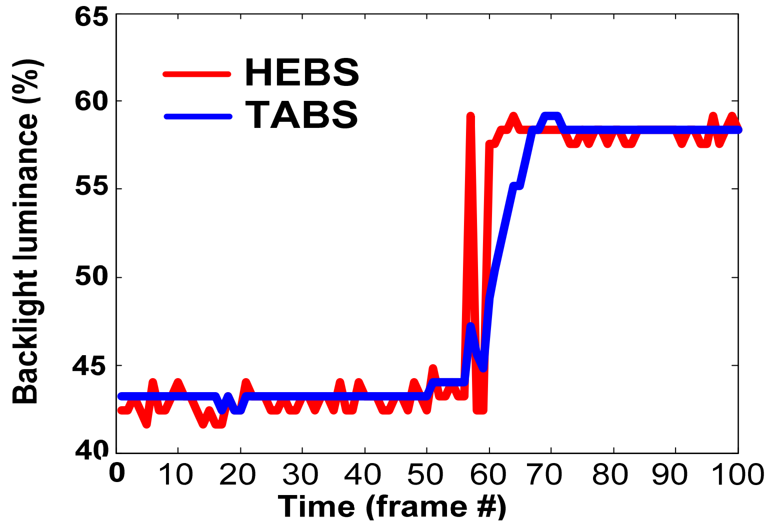
- Platform used for the experiments: Apollo Test-bed II (Custom-made)
  - Processor: XScale 80200 733MHz
  - Linux Kernel 2.4.18
  - LCD: NEC NL6448BC33-50, 6.4 inch
  - CCFL Backlight



- Implementation: MPEG-1 program
  - RGB <-> YUV conversion and Handle Y values
  - Intercept YUV values before dithering step and modify them
  - To suppress temporal abruptness, use a moving average scheme
- Application Programs: 5 Movie Clips
  - Little Mermaid, Incredible, Lord of the Rings, Toy-story and 007
  - Each movie clip has 600 frames
- Measurement:
  - Data Acquisition System (DAQ)
  - Three runs of a clip: Original, HEBS version and TABS version

Experimental Results

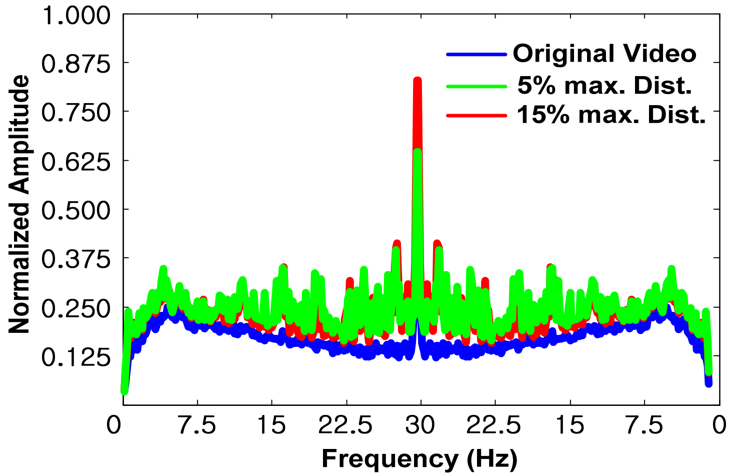
- Backlight luminance changes

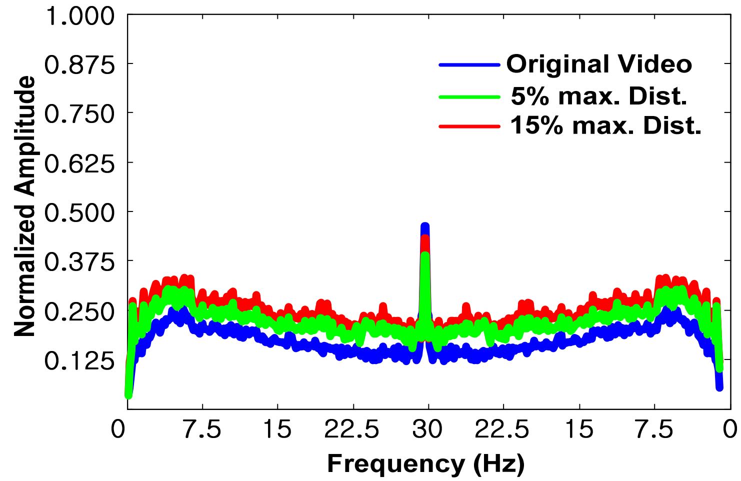


- Flickering in HEBS occurs due to abrupt and frequent changes in the backlight intensity

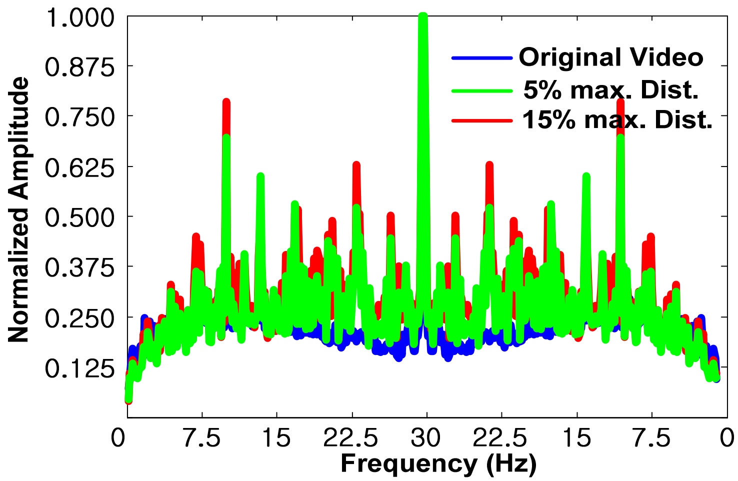
- To avoid this flickering, HEBS should be changed such that luminance changes are suppressed and smoothed out

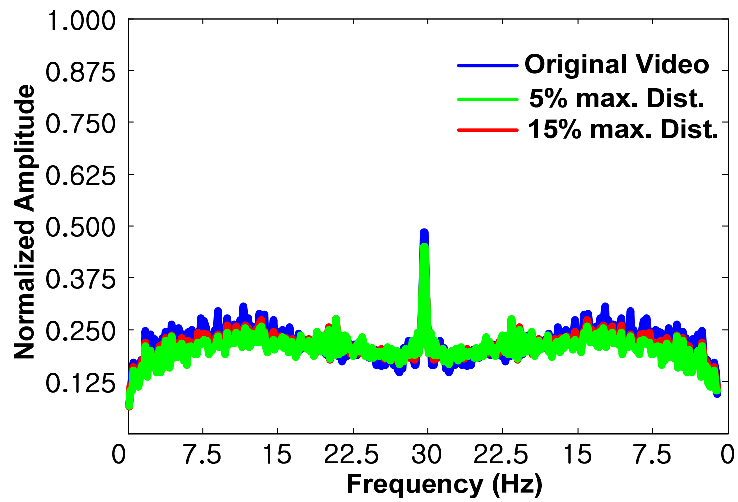
Experimental Results (Cont'd)





< A little mermaid >

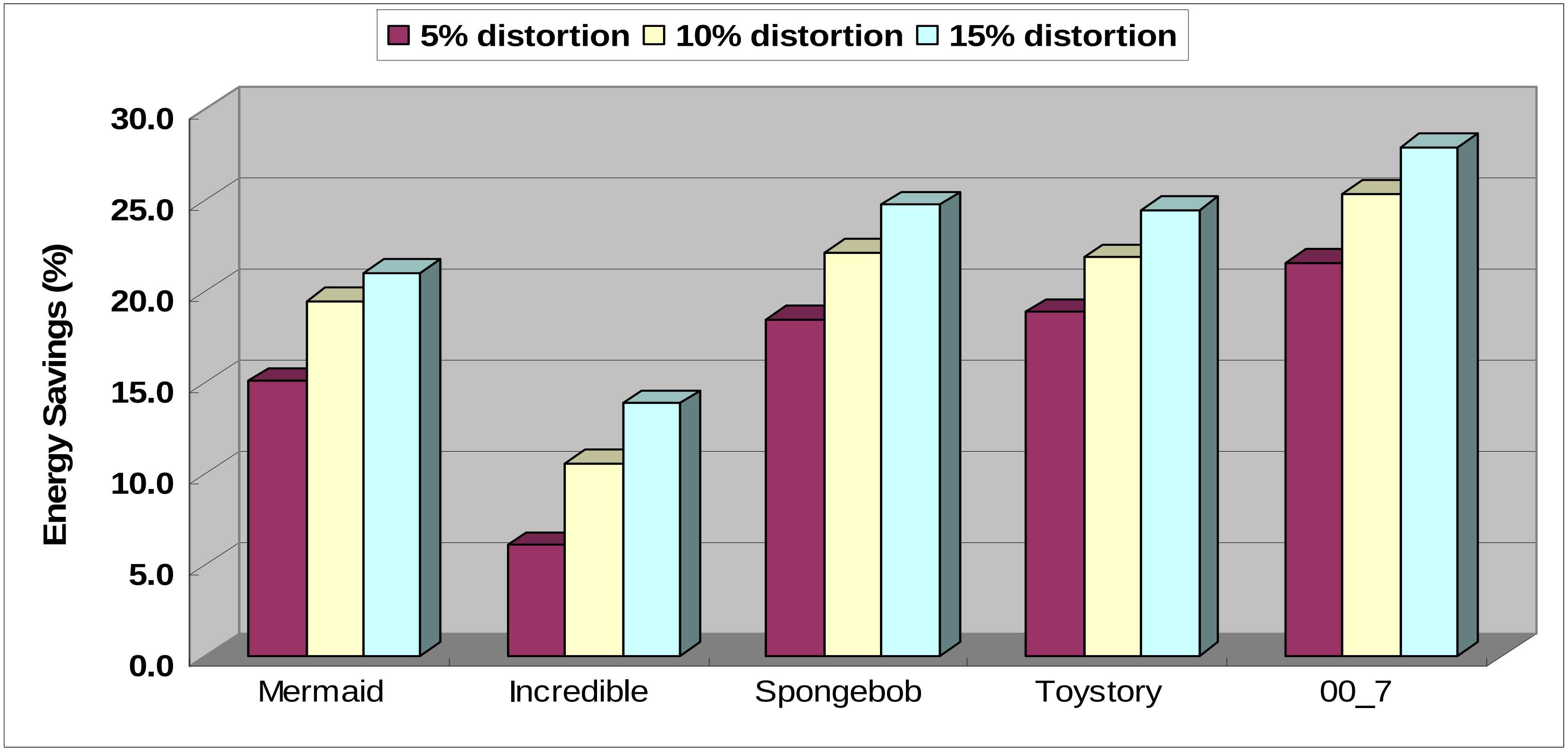




< The Incredibles >

Experimental Results (Cont'd)

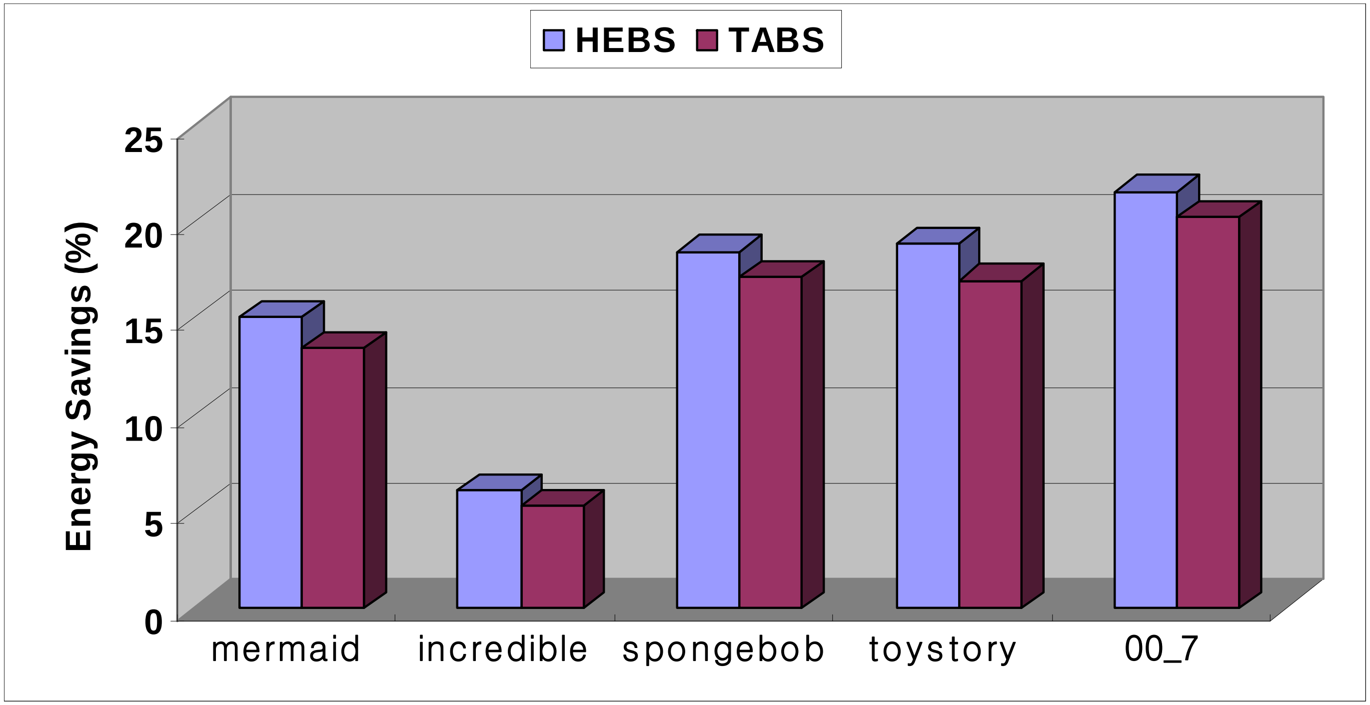
- Energy Savings with human visual system awareness
  - Savings become smaller when distortion goes up



< Energy Savings in TABS >

Experimental Results (Cont'd)

- Energy Savings in two backlight scaling techniques
  - Without temporal distortion awareness, more energy is saved
  - With temporal distortion awareness, quality becomes a lot better

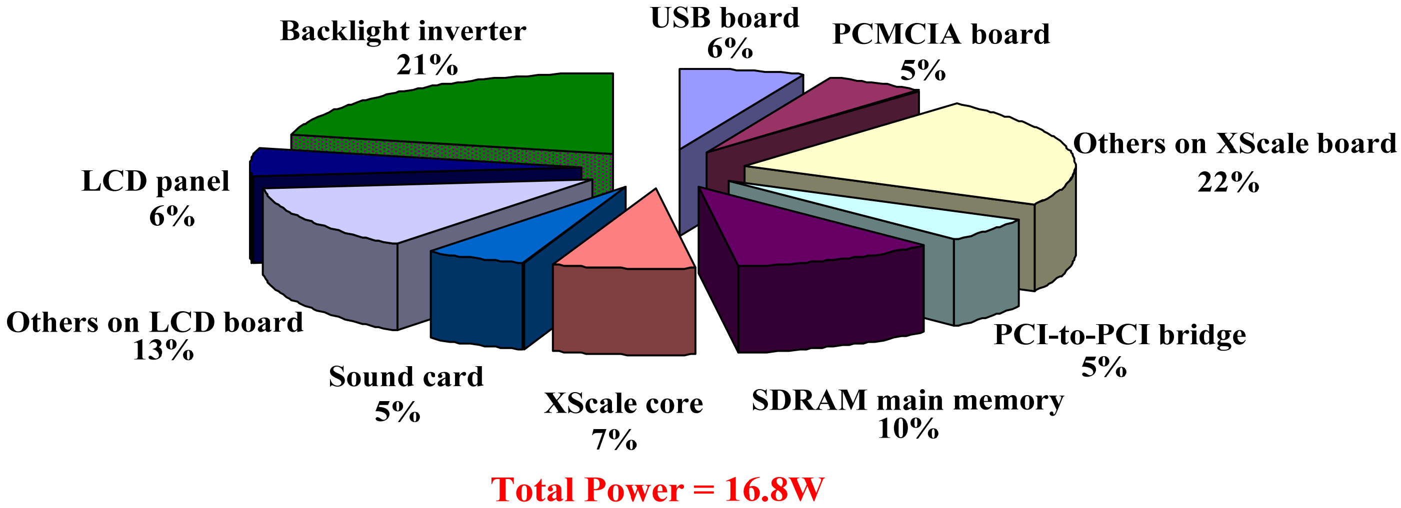


< Energy Savings in HEBS vs. TABS under 5% distortion >

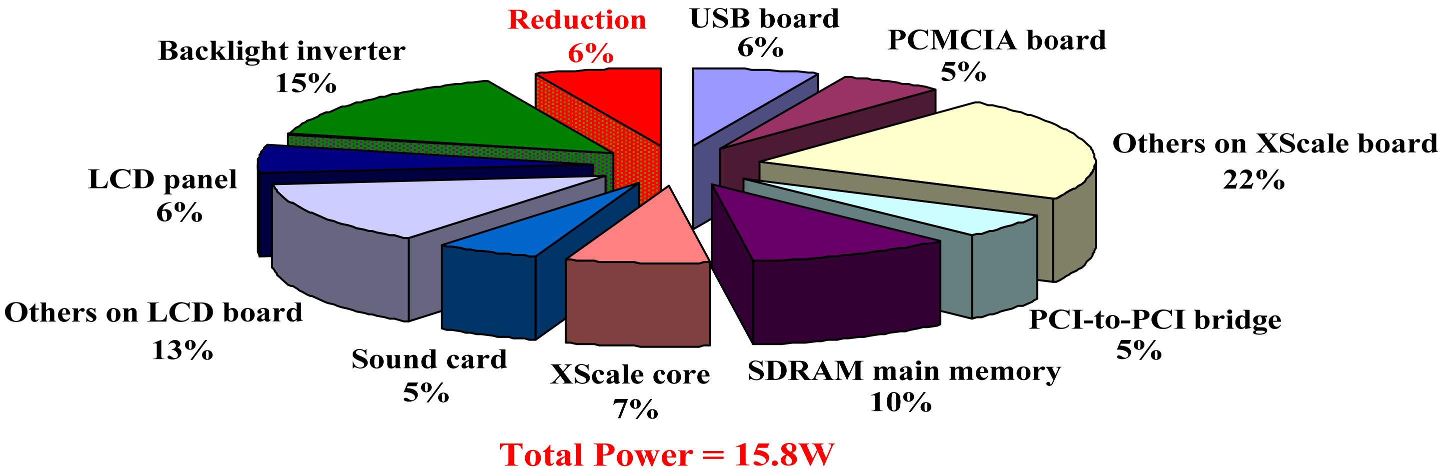
Experimental Results (Cont'd)

- System-wide Power Savings with 5% distortion in Apollo Test-bed II

< Before >



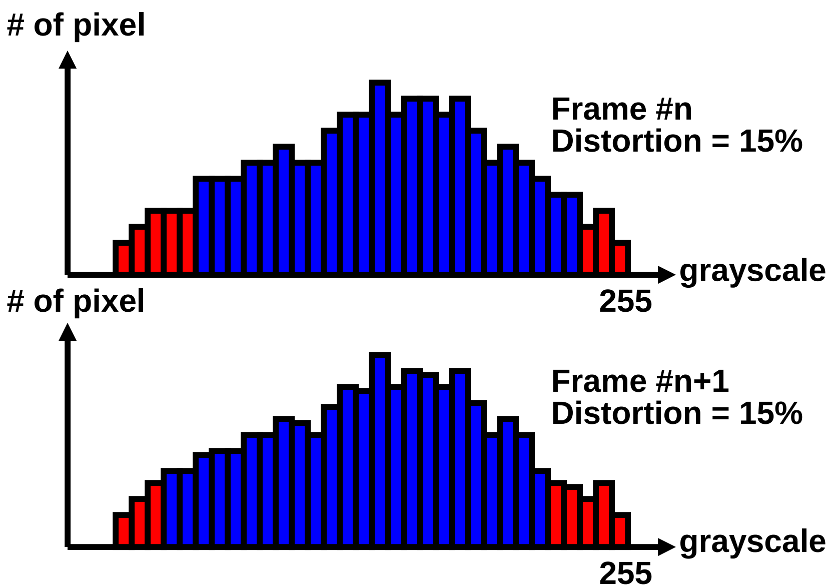
< After >



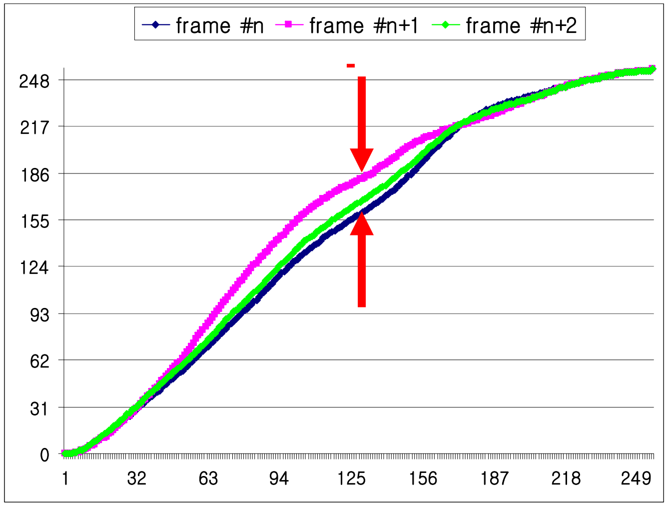
Conclusions and Future Directions

- For backlight scaling technique in video, consideration of both spatial and temporal distortion are quite important to video quality
- Consideration of temporal distortion as well as spatial distortion lead to less energy savings (compared to the spatial distortion only method), but it achieve high quality gains. Simulation results show that 15 ~ 25% of energy savings are achieved in display systems with almost negligible perceivable flickering
- Future Work:
  - Manage the color shift problem in backlight scaling
  - Account for the effect of ambient light on backlight scaling
  - Consider other types of display technology

Backup Slide: Why Flickering Occurs



< Histogram >



< Transformation functions >

- From one frame to the next in HEBS, many grayscale levels have similar pixel distributions
- When we reduce the dynamic range of each frame, the chosen grayscale levels in the two histogram may become different (see above)
- As a result, different dimming values will be used for the two frames and flickering occurs