PARVAI - HVS Aware Adaptive Display Power Management for Mobile Games

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***Abstract*—Displays are one of the major system energy consumers in smartphones. Power consumption of Organic Light-Emitting Diode (OLED) displays have direct relationship with the colour and intensity of the contents being displayed. Games are one of the most popular smartphone applications that consume relatively more resources and power. In this paper, we present Human Visual System (HVS) aware algorithms and techniques to reduce OLED display power consumption up to 45% while retaining the perceived quality of game content. We have implemented and evaluated our solution in the game Quake III and its Android port Kwaak3.**

I. Introduction & Motivation

In the current generation of mobile smartphones, the three main sources of power consumption are, 1) the CPU, 2) the display, and 3) the network interfaces, among which the display alone consumes more than 45% of the overall system energy [1]. Because of the limited size and capacity of the batteries, how efficient and effective we can utilize the energy becomes crucial in making mobile device more sustainable [2]. We describe the motivations for this work and basic ideas of our solution in the following subsections.

A. Games

Games are one of the prevalent mobile apps in the US [3] and it grows faster than any other application every year. We have noticed that modern 3D networked games are the most power consuming applications in smart phones due to their demand for rich graphics, fast interactions, continuous network communication and high frame rate. For example, our measurements show that the HTC Desire HD Android smartphone battery provides 8 hrs of GSM talk time, while it last for only 1hr 50min when 3D game Kwaak3[4] is played[1].

B. OLED Displays

Organic light-emitting diode (OLED) is an emerging display technology that uses a thin film of organic compounds which emit light in response to electric current. The power consumption of OLED displays depends on the luminance and colour of the content being displayed. We describe the dependencies below at higher level for easier understanding.

- The organic components for each sub-pixel (red, green, blue) on the display are individually powered up to illuminate the pixels. Hence, power consumption of OLED displays depends on the luminance of the content being displayed.
- The OLED material used to produce blue light degrades more rapidly than the materials that produce other colours. This results in a faster decrease of blue light output relative to the other colours. Manufacturers address this issue by optimizing the size of the R, G and B sub-pixels to reduce the current density through the sub-pixels in order to equalize lifetime at full luminance (Figure 1) [6]. For example, a blue sub-pixel may be 100% larger than the green sub-pixel. A red sub-pixel may be 10% smaller than the green sub-pixel. This leads to an uneven power consumption by objects with different colours (while their luminance is constant). In this case, an image with a dominant blue shade consumes more power than an image with a dominant red or green shade.

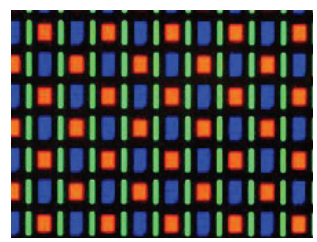


Fig. 1. Google Nexus One Smartphone AMOLED sub-pixels (close-up). RGBG system of PenTile matrix family

C. Human Visual System

Human visual perception is affected by luminance, colour and contrast of the contents. We summarise below the findings from various research works.

- Human vision has a non-linear perceptual response to luminance [7]. For example a source having a luminance only 18% of a reference luminance appears about half as bright [8]. Poynton [8] states that the lightness perception to human eyes is roughly logarithmic. When an image is sufficiently bright, reducing some amount of brightness to the image will result in less noticeable difference as compared to reducing the same amount of brightness to a darker image.
- Bigelow [9] explained how the human eyes are unequally sensitive to different colours due to a kind of photoreceptor in the eyes, called the cones. The majority of the cones present in the eyes are sensitive to green and red, and only a few are sensitive to blue. As shown in Figure 2 below, there are about 30 red and green

[1]Kwaak3 is an Android port of the most popular Quake III [5] game

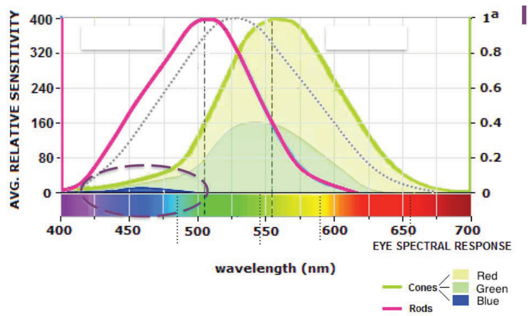


Fig. 2. Spectral Response of the Human Eye in Photopic (bright light) Mode[10]

sensitive cones for every blue one. Red and green cones help in resolving an image (sensing its luminance, edges, and other structural details which also detect colour of course. However, the blue cones detect only colour due to low relative sensitivity 2. Light from the blue subpixels does little to help the eye resolve images, most of it goes to waste. Hence, blue pixels can be removed/reduced in intensity without loosing brightness, contrast and visual quality. To illustrate, Bigelow's gave an example image of a blue circle surrounded by a green square, with both colours of equal brightness. However, the green part of the image is perceived brighter than the blue part. The human eyes are more sensitive towards green than blue, therefore green appears much brighter when in fact both colours are having the same absolute brightness value.

- HVS is more sensitive to local contrast than global contrast as local contrast defines the structural property of the scene [11], [12].

D. Saliency

Obviously, people in high speed interactive virtual environments (eg, such as playing high speed interactive video games) are highly concentrated on the game contents and details but only to the part that is related to interactions such as cross hair pointer of the gun, enemy and the path that player is heading through. There is always a group of salient content that draws players' attention more than the rest, though this group of contents may differ from game to game. Therefore, we keep the salient content as they are and darken those contents that are of less importance. For Quake III, since the aim is fixed in the centre of the screen, we can expect the centre part is more salient than the others. Hence we apply less brightness reduction to the centre part. It is also shown in previous studies [13], the *Locus of Attention (LoA)* (that is, area of interest) is approximately 300x220 pixels at the centre of the screen when the game resolution is 640x480 pixels.

From the observations above, it is obvious that, by HVS aware manipulation of the contents, significant amount of power can be saved without compromising the perceived quality of the contents. As we are interested in maintaining the perceived quality of the game, we eliminate the following category of approaches:

- Approaches that naively trade-off quality for power savings such as turning off, greatly dimming the display at constant intervals, etc. Such approaches reduce the brightness of the contents and reduces the details of the scene that makes important game objects (such as cross hair pointer) hard to differentiate from the background.
- Image processing methods which processes pixel by pixel [14] [15] are computationally intensive and brings down the frame rate to unplayable levels. In addition, any such computationally intensive algorithms in interactive real-time applications will defeat the energy saving objective. Though we can pre-process static game maps, modern games heavily depends on dynamic maps to reduce memory requirements and offer more variations to the users.

E. HVS based approach

For game contents, fidelity of colours is important to provide the expected experience to the player as thought and designed by the game designers. Hence, we cannot abruptly change the colours of these contents. In this paper we present an OLED power management technique for mobile games which is adaptive to the game content (colour and intensity) and Human Visual System (HVS) characteristics.

We have evaluated our approach using a combination of analytical and user testing. Our results show that we are able to save up to 45% of the OLED display power with no perceptible quality loss to the game contents.

Overall contributions of this paper are as follows: 1) We present a novel *power efficient colour mapping technique* that exploits the HVS properties to transform colours of the game contents to power efficient versions without compromising the perceived quality. The method primarily focuses on reducing blue channel as it consumes the most power and at the same time it is less sensitive to HVS. 2) We present *saliency based darkening technique* to save more energy by darkening the areas which seldom receive player attention. 3) We show that power savings can be achieved for almost all type of game maps. We also show that the loss of quality due to content transformations is kept minimum and at an unnoticeable level using industry standard *objective* quality metrics and a relatively large scale *user study*.

II. Related Work

Dong et al. [16] describes two approaches of reducing power consumption of OLED-based displays on mobile phones through structured colour transformation of standard background and foreground GUI objects, or unstructured transformation of individual pixel colours of arbitrary GUI elements. The approach dramatically alters the original colour of the displayed objects, again making it unsuitable for contents which are sensitive to colour fidelity changes, such as images, games and videos.

Chuang et al. [17] proposes a colour-mapping algorithm that swaps current colours with an iso-lightness colour set within a certain restrictions, so that the overall lightness of the final display is still the same with the original display.

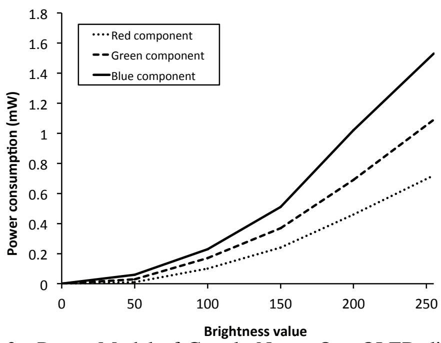


Fig. 3. Power Model of Google Nexus One OLED display

The original colours are significantly changed in the process and not suitable to be applied to photos, games and videos, in which colour accuracy is important.

Chulwoo et al. [18] describes a power-constrained contrast enhancement algorithm for organic light-emitting diode (OLED) displays using log-modified histogram equalization (LMHE) scheme, which reduces overstretching artefacts of the conventional histogram equalization technique. The algorithm is constrained by OLED power model. With their approach, the power saving is not significant for most common images.

There are various works on backlight scaling for conserving display energy [19] [20] [21] [22] [23]. In all these works the content is dynamically brightened and the backlight is dimmed. A more efficient way of backlight scaling using HVS aware tone mapping is proposed by Iranli et al. [7]. However, these methods cannot be applied to OLED displays as these display techniques don't use backlight. Each pixel in OLED display and its variants such as, AMOLED (Active Matrix OLED) is directly illuminated.

In general, these works target non-real-time contents and applications and are not applicable for games.

III. PARVAI System Design

PARVAI system reads the frames from the frame-buffer and transforms the contents of each frame to power efficient versions as explained below.

A. Grid Based Transformations

As processing colour transformation pixel by pixel is computationally intensive for real-time application such as games, we divide the frame contents into *virtual grids* and apply changes grid by grid. By dividing it in to grids we also retain the local contrast while applying any colour transformation.

B. Power Efficient Colour Mapping

As described in previous sections, OLEDs are *inefficient in displaying blue dominant colours*. As shown in Figure 3, blue colour consumes more power than red and green in Google Nexus One OLED display. It is also true for most other OLED phone models including Galaxy S and Nokia N85 [24]. As a compliment, HVS is very less sensitive towards blue colour. *Hence, small changes in blue colour are not easily observable by human eyes* [9]. By combining these two, we have designed a power mapping algorithm that transforms colours to power efficient colours. The colour mapping algorithm is explained below.

1) Generation of bLUT: Our objective is to map a given colour to its power efficient version with some constraints on hue, saturation and lightness. In order to speed up the colour mapping process in a real-time application, we precompute and generate a bLUT (Look Up Table ordered by Blue) that gives power efficient colour (C') for any given colour (C_0) in R,G,B colour space. As a look-up table for the entire colour space is impossible, we quantise the colour space to 32-bit colours as most mobile displays support up to 32-bit colours. As blue is the most power consuming colour and the least sensitive to our human eyes, we have arranged the bLUT in increasing order of blue channel first then followed by red and green channels.

The mapping for each colour is decided by solving an optimisation problem as follows. For each colour C_0, we want to map it to a $C' = (r', g', b')$ with *minimum power consumption* and *lowest* b' subjected to some constraints on the differences between C' and C_0. Specifically, given $C_0 = (r_0, g_0, b_0)$ we want to

$$\begin{aligned} \text{minimise} \quad & E(C^{'}), b' \\ \text{subject to} \quad & L(C^{'}) \geq L(C_0) \\ & |H(C^{'}) - H(C_0)| \leq \alpha \\ & (1-\beta)\cdot S(C_0) \leq S(C^{'}) \leq (1+\beta)\cdot S(C_0) \end{aligned}$$

where α, β are configurable parameters that controls the strictness of the constraints. In our implementation, $\alpha = 9$ and $\beta = 0.25$ provides the optimal balance between power saving and image distortion.

The function to minimises the power consumption (in microwatts) of the colour $C^{'}$ (that is, minimum $E(C^{'})$) is determined from the power model in Figure (3)).

Luminance, $L(C)$ is the perceived brightness of colour C.

$$L(C) = 0.299\ r' + 0.587\ g' + 0.114\ b' \quad (1)$$

where, r', g' and b' are gamma corrected values of the red, green and blue sub pixels.

$H(C)$ and $S(C)$ is based on the hue and saturation component of the HSV colour space.

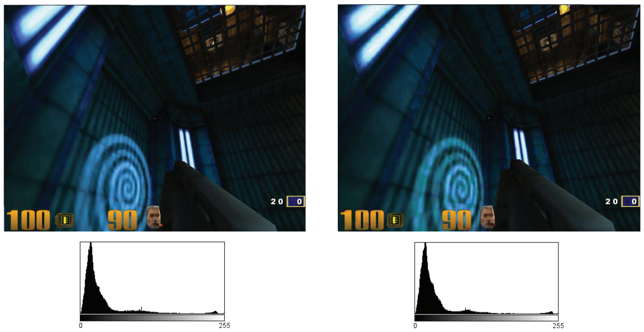
Hue, $H(C)$, measures the similarity of colour C to well described colour such as red, green and blue.

$$H(C) = \arctan 2(\sqrt{3}\cdot(g-b), 2\cdot(r-g-b)) \quad (2)$$

Saturation, $S(C)$, describes the colourfulness of colour C from greyscale to pure colour.

$$S(C) = \frac{\max(r,g,b) - \min(r,g,b)}{\max(r,g,b)} \quad (3)$$

2) Efficient Run-Time Colour Mapping with Blending: In this section we describe about how we use the bLUT to change the colours of the game content during runtime to power efficient colours in an efficient way using *blending function*. For each virtual grid, we will calculate and store the average RGB value upon reading the pixel values from the frame buffer. After rounding the average RGB to its nearest colour in the bLUT, we find its power efficient colour. Using the power efficient colour, we apply the blending function to every pixel in the grid. The best result will be achieved by matching the colour to its power efficient colour pixel-by-pixel for all pixels in the content. However, this will be computationally intensive



a. Original Image:63 mW   b. Colour Mapped:57 mW

Fig. 4. Power efficient colour mapping - Quake III Map: Chiropteradm - Power Model:Figure 3

in real-time applications. Hence, we use blending function. The cost of the blending function is same as drawing few more triangles into a 3D graphics. As modern 3D scenes in the games have millions of triangles, the cost of blending function is negligible [25]. We used OpenGL blending function,

$$glBlendFunc(GL\_DST\_COLOR, GL\_ZERO),$$

which takes a source colour C_s and multiplies it with the destination colour *GL_DST_COLOR* (the original colour of the content) to achieve blending. *GL_ZERO* is simply a constant with value 0.

By selecting appropriate C_s we can change original colours of all pixels to power efficient colours. We obtained C_s using Equation 4.

$$C_s(r,g,b) = \frac{C'(r,g,b)}{C_0(r,g,b)} \qquad (4)$$

where C_0 is the original colour and C' is its power efficient colour.

Hence, when C_s is multiplied with *GL_DST_COLOR*, only the C' (power efficient colour) remains and becomes the colour that is finally displayed.

Since we process a grid at a time, there will be some distortion to pixels in that grid. However, for smaller grid sizes the distortion is not noticeable.

Figure 4b shows the result of applying power efficient colour mapping to the original image in Figure 4a. With this approach we can save around 10% of energy with quality of the image comparable to the original image.

C. Saliency Based Darkening

In games the user's view always focused on a small area in the screen, known as *LoA region* as described in Section I. Hence, in PARVAI darkening is applied only to the areas outside this LoA region in multiple levels, gradually darkening more as we move towards the edges of the screen. Human eyes will encounter greater pressure when the sight angle is moving vertically and less pressure when it is moving horizontally [26]. A conclusion of this is that we are less reluctant to browse horizontally, which means the horizontal strip in the centre of the screen is much more important than the vertical strip. Based on this argument, we assign each grid a value that shows how far it locates from the centre of the screen

a. Original Image (187 mW)   b. Saliency Darkening (151 mW)

Fig. 5. Saliency Based Darkening - Quake III Map: REQBATH - Power Model:Figure 3

and since the ratio between height and width is 480 divided by 640 which is 0.75, the vertical distance gets only 75 percentage importance of the horizontal distance.

For every grid, distance to the centre grid is calculated using the Equation 5.

$$Distance = abs(x + 0.5 - x_c) * 0.75 + abs(y + 0.5 - y_c) \qquad (5)$$

where x, y are coordinates of the bottom left pixel and x_c, y_c are the coordinates of the centre point. abs() returns the absolute value of the expression

Figure 5b shows the result of applying saliency based darkening on the original image in Figure 5a for 0% to 50% of darkening. The range (0% to 50%) is adjusted non-linearly based on the overall lightness of the frame [7] [8]. Darker frames have lower upper bound than brighter frames. With this simple approach we can save around 20% of energy without distorting the perceived quality.

D. Final Run-Time Algorithm

The final run-time algorithm has two modes, *Conservative* and *Aggressive*. *Conservative* mode applies only 'power efficient colour mapping' to save energy and retains the quality of the contents close to the original contents. *Aggressive* mode applies both 'power efficient colour mapping' and 'saliency based darkening' for saving higher amount of energy with minimum loss to the quality of the contents. The modes provide trade off between quality and power efficiency. The user can select the mode according to the quality requirements. The final algorithm is given below (Algorithm 1).

Algorithm 1 Final Run-Time Algorithm

input: Frame from the frame-buffer, mode (aggressive or conservative)
output: Power efficient version of the Frame

Segment the Frame to virtual grids
for each grid **do**
  Compute average Red (R_{ave}), average Green (G_{ave}) and average Blue (B_{ave}) of the grid
  if B_{ave} significantly higher than R_{ave} and G_{ave} **then**
    With average R,G,B values, search the bLUT to get the power efficient colour and apply
    if $mode = aggressive$ **then**
      Calculate the distance of the gird to the centre of the screen
      Apply saliency based darkening
    end if
  end if
end for

Implementation. We used the commercially successful Quake III Arena [5] 3D FPS game as our test game. It is open sourced and provides tough challenges in frame rate performance as it is an FPS game. In addition, Quake III has all the basic features (maps with different colour combinations and brightness levels) required for testing our algorithms.

IV. EVALUATION

In this section, we present our evaluation methodology and evaluation results. We compare output of Conservative and Aggressive modes of our approach with simple darkening approach which is most common for OLED power saving (available in most phones as a user adjustable parameter). Simple darkening approach, simply reduces all pixel values by a constant percentage.

A. Evaluation Metrics

Objective Metrics. To calculate the amount of power saved, we measured the power consumed by the original content and the modified content. We present the objective evaluation using the industry standard metrics - Global Contrast Loss (GCL) [1] and Structural Similarity Index (SSIM) [27] for game scenes to show that our approach retains the quality of the content to be close to the original content. The results are presented in Section IV-B.

Quality Measurements - User Study. As our content transformation techniques are HVS based, the study on the perceived quality with actual human subjects is essential to validate the approach. We did two user studies with 76 student users with different backgrounds. As our algorithms are developed for mobile devices, we let the users view the original and modified pictures and videos of the game play over the WWW (accessible by any internet connected devices including smartphones) in various lighting conditions. The pictures and videos are captured with original, simple darkening, conservative and aggressive modes with three different maps (dark, bright and blue dominant colours). The user demography is shown in Table IV-A.

TABLE I
DEMOGRAPHICS STATISTICS FOR THE USER STUDY

Total Number	76 (in age group 19-28)
Gender	Male (57), Female(19)
Photography Experience	Beginner (41), Amateur (28), Semi-professional (6), Professional (1)
Photo Editing Tool	Photoshop (46), Paintshop Pro (2), CameraSW (16), Others (31).[some use morethan 1]
Game Experience	Beginner (48), Amateur (24), Semi-professional (3), Professional (1)
Video Editing Tool	Premiere(22), Video Studio (4), Movie Maker(28), Others (37)

Our first user study compares the original and the modified versions of game images (screen capture). We gave a pair of images from a pool of original and power optimised versions. The users were asked to select the most visually appealing image in each pair. The second user study asked the users to rank the game play videos based on its colour and brightness with three options - 0 (hard to distinguish), 1(need additional efforts), 2 (clearly distinguishable).

B. Evaluation Results

The power and quality measurement for three game scenes and their power optimised versions are shown in Figure 6.

We start by analysing the GCL and MSSIM among these images. The power consumption of simple darkening and aggressive version are set to be equal. In almost all the maps, our aggressive approach gives better MSSIM and GCL. This shows that our aggressive approach provides better quality under the same power saving levels.

The GCL in our conservative approach is almost negligible and its MSSIM is high. Its quality is comparable to the original image. However, power saving is only up to 10%.

User study results after removing biased entries are shown in Figure 7. Normalised performance count is a ratio between total number of times the image appeared in the pair for selection and number of times it is selected as the best. As expected, the conservative approach have got the best score (irrespective of the map type). Aggressive approach performs slightly better than simple darkening approach for most maps. However, for brighter maps, it outperforms simple darkening approach by a significant margin. The user study on game play videos also show similar trend.

V. CONCLUSION

We have presented a novel real-time in-game content transformation algorithm for energy efficiency which directly process the contents in the frame-buffer and exploits the properties of HVS to retain the perceived quality. With our implementation, users can save up to 45% of energy depending on the game map. As display is the dominant power consuming component, this translates to about 20% of overall system power saving.

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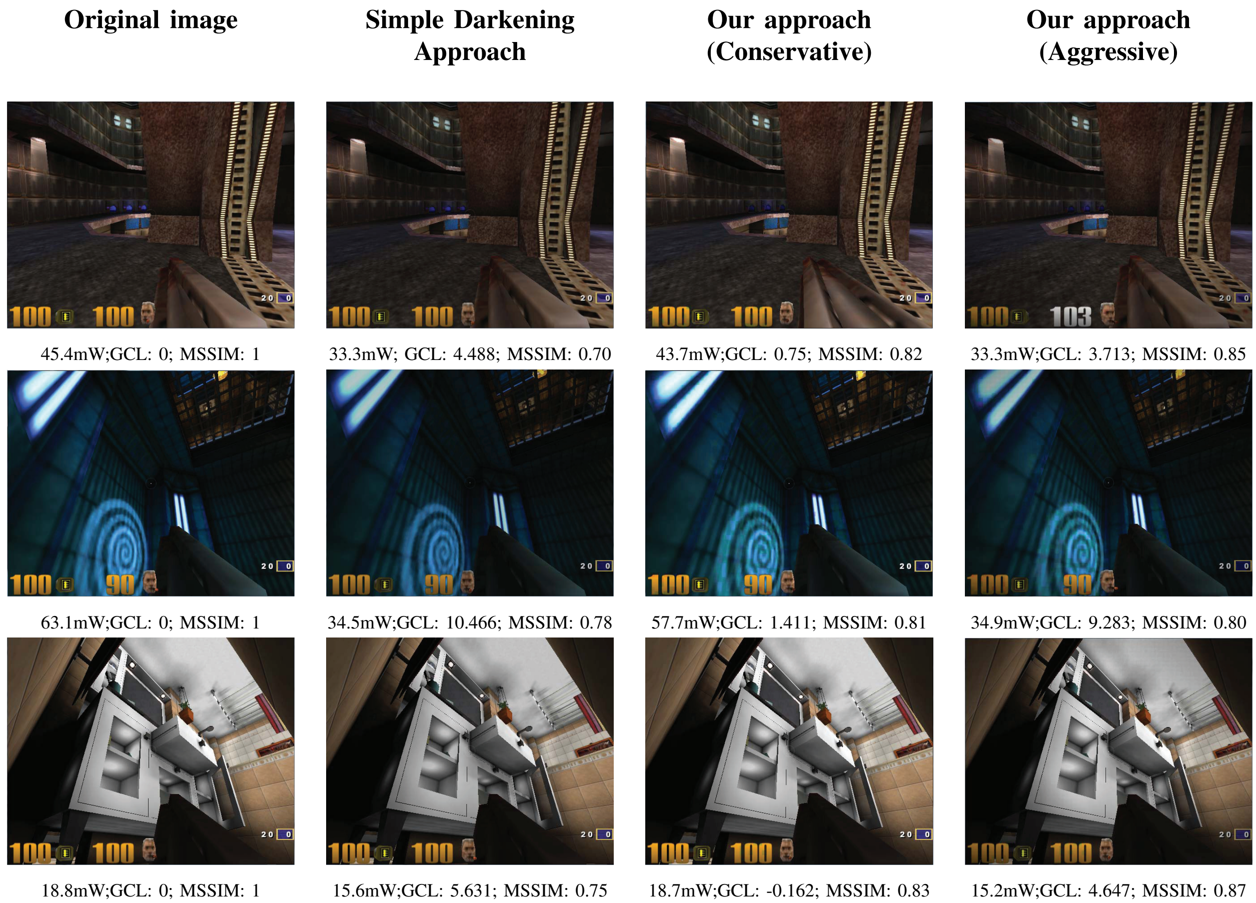
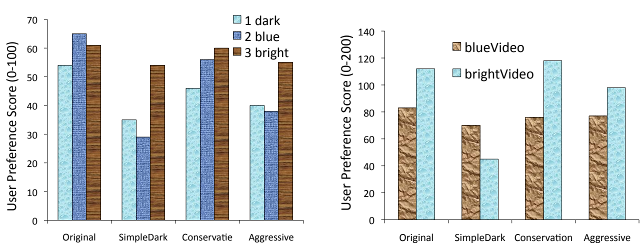


Fig. 6. Power and quality measurement



a. Image Transformation b. Game Play Video

Fig. 7. User Study

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