CLOUD-BASED VIDEO STREAMING WITH SYSTEMATIC MOBILE DISPLAY ENERGY SAVING: RATE-DISTORTION-DISPLAY ENERGY PROFILING

Qian Liu[+], Zhisheng Yan[*], and Chang Wen Chen[*]*

[+] Dept. of Computer Science and Technology,
Dalian University of Technology, China
Email: qianliu@dlut.edu.cn

[*] Dept. of Computer Science and Engineering,
State University of New York at Buffalo, USA
Email: {zyan3, chencw}@buffalo.edu

ABSTRACT

Mobile display has been considered as the major contributor to the energy consumption of the ever-increasing mobile video services. Current practices in display energy reduction (DER) utilize local computing resources to analyze the video content before DER strategies can be applied in a per-device fashion. For a given video, same analytical computations are repeated in millions of individual devices. In this paper, we demonstrate that a paradigm shifting framework can be designed to systematically move the common DER local processing to the streaming server with the emergence of cloud-based video services. This framework has the potential to replace the massive per-device DER computation by a one-time global video processing in the cloud. To accomplish this ultimate goal in DER, a new family of video rate-distortion (R-D) profile with embedded DER strategies shall be properly generated. This family of rate-distortion-display energy (R-D-DE) profiles contains a set of common DER parameters to be directly extracted and employed by individual mobile devices to achieve desired display energy saving without repeated local computation. Performance evaluations of the proposed design are carried out to show that this family of R-D-DE profiles is indeed able to command the systematic DER design based on the intrinsic relationships among bitrate, video quality and display energy saving.

Index Terms—Rate-distortion, display energy reduction, OLED, video streaming, video encoding

1. INTRODUCTION

Recently, video-rich mobile communication has become the major driving force of the global communication and mobile industry. One major problem of the current video communication systems is the battery-hungry nature of continuous video streaming services at the mobile user end. A recent study illustrates that the longest battery life of top smartphones in the market only lasts for 11.1 hours [1] with continuous video streaming applications.

It has been well demonstrated that the mobile display accounts for a very significant percentage of total energy consumption of mobile devices [2], and therefore becomes a main contributor of total power consumption in the global mobile video communication infrastructure. As a result, various display energy reduction (DER) algorithms [2]-[12] have been developed for the new generation of mobile devices. However, all these DER strategies utilize local computing resources to carry out on-the-fly media processing in order to implement proper display energy reduction. Upon receiving the video stream, additional pixel-by-pixel processing is needed for each device and the same computation shall be repeated among thousands or millions of mobile devices that request the same video content. Such repeated computation on a per-device base is absolutely inefficient from the overall systematic point of view. Therefore, a systematic strategy for mobile DER scheme is vitally needed in order to achieve global scale energy saving for the massive mobile video streaming services.

Fortunately, the emergence of cloud computing and storage platforms provides a golden opportunity to achieve the desired global-scale energy saving. The virtualization of computation and storage resources in the cloud offers a fundamentally different design space for preparing the video streams for millions of mobile users. It is now possible to afford extra processing and storage resources during the video encoding process to embed video analytic parameters into the video stream. These embedded parameters can be directly extracted and applied at individual mobile devices for DER in order to save the processing energy for repeated computation on each mobile devices.

It is based on this principle that we propose in this paper a novel cloud-based video streaming infrastructure with systematic mobile display energy saving capability. In particular, a new video encoder is developed in the cloud servers aiming at integrating mobile DER into the global video processing for delivery to individual mobile users. In contrast to the conventional video streaming systems that adopt the classical rate-distortion (R-D) principle to optimize the bandwidth efficiency and video quality, the proposed new framework creates a family of rate-distortion-display energy (R-D-DE) profiles to exploit the intrinsic tradeoffs among bitrate, video quality and mobile energy saving. A unique contribution of the proposed framework lies in its exquisite design of global energy saving driven video streaming services by shifting massive numbers of per-device DER computation to the one-time R-D-DE profiling in the cloud.

2. ANALYSIS OF THE CURRENT DER STRATEGY

The current mobile DER mechanism can be considered as a post-processing strategy attached to the current video streaming infrastructure, as shown in Fig. 1.

In the current research, we focus on active-matrix OLED (AMOLED) displays with voltage scaling (VS) based DER mechanism. AMOLOED is currently the most popular display for mobile devices (e.g. AMOLED panels are utilized in Apple iWatch, Samsung Galaxy series, and Motorola Moto X series [13]). For VS-based DER, it is a hardware-based DER mechanism which reduces the mobile display energy by decreasing the supply voltage of the OLED panels. The lower the voltage, the darker the display luminance, and the more energy can be saved. In addition, this DER mechanism has already been adopted by smartphones in the market. For example, the display power saving strategies of "automatic brightness" in Samsung Galaxy S4,

This research is supported by US NSF Grants 1405594 and 0915842.

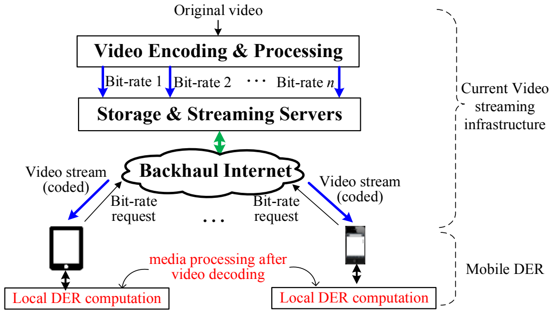


Fig. 1. The current practice.

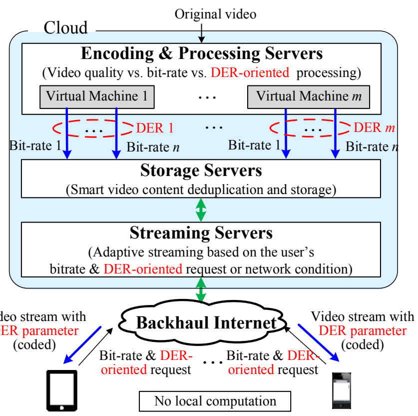


Fig. 2. The proposed cloud-based video streaming infrastructure with systematic mobile DER strategy.

S5 and S6, which allows the mobile device to select the brightness or voltage levels based on the remaining battery life.

In general, DER algorithms [4], [10]-[12] were developed mainly aiming at reducing the video quality degradation caused by VS-based DER. However, all these algorithms need sophisticated local computations for distortion compensation which generally requires video frame statistics and delicate mapping parameters. Such per-device DER strategies lead to two fundamental drawbacks:

(1) It is highly energy-inefficient from the global video service perspective: The same display-oriented media processing computation needs to be repeated by thousands or millions of mobile devices that receive the same video stream.

(2) It cannot just merely minimize display energy consumption: The reduction of display energy consumption inevitably comes at the penalty of processor energy consumption for carrying out display-oriented media processing.

3. THE OPPORTUNITY TO ACHIEVE SYSTEMATIC DER IN THE CLOUD

In order to overcome the drawbacks of the current mobile DER mechanism, a novel cloud-based video streaming infrastructure as shown in Fig. 2 is developed by moving the per-device DER computation to the global video processing in the cloud. Comparing Fig. 1 and Fig. 2, we can observe that the proposed framework is of paradigm shifting nature in that m families of video streams with different bitrates need to be generated and stored for m DER levels. With the emerging cloud computing and storage platforms, these streams can be prepared effectively in parallel in the cloud. This DER-aware video streaming infrastructure provides a double-fold benefits:

(1) It is able to accomplish the shift of local DER analysis to the cloud: for a specific class of mobile devices, the massive repeated local computations can be replaced by a one-time global video processing in the cloud.

(2) It is also feasible even though multiple streams need to be generated and stored in the cloud as this will be accomplished via the virtualization of cloud resources.

4. CREATING R-D-DE PROFILES TO ENABLE SYSTEMATIC DISPLAY ENERGY SAVINGS

From Fig. 2, it is clear that the realization of the systematic mobile DER strategy can be achieved by developing a novel augmented video encoding scheme by incorporating an additional dimension, display energy, to the classic R-D profile and creating a new R-D-DE profiles. In this section, we shall present the details on how this new R-D-DE profiles can be generated.

4.1. An Overview of the Proposed Video Encoder

The framework of the proposed new video encoding engine is shown in Fig. 3. This engine consists of two major components: DER-aware video encoding and R-D-DE profiling. Comparing with the regular video encoder, two new modules are added to this video encoding engine: Luminance compensation (LC) and VS-based luminance model. It is the introduction of these two new modules that enables the proposed video encoding engine to generate the R-D-DE profiles so as to accomplish the desired shifting of per-device computation to the cloud-based global computation for massive display energy saving.

For a given raw video sequence and a specific bit-rate requested by the user, the proposed encoding engine first prepares the video encoding parameters for the raw video sequence, e.g. quantization parameters (QPs, determined by the bit-rate). This process is the same as the regular video encoding.

In order to minimize the distortion in terms of luminance degradation caused by VS of mobile display, a proactive LC algorithm is applied in the proposed encoder by "mapping up" the luminance value of the raw video data based on the requested DER voltage level. The luminance compensated raw video sequences are then encoded with the voltage levels embedded in the bitstreams. In mobile devices, these embedded voltage parameters are first extracted from the bitstreams and then directly applied to VS-based DER. This way, the proposed framework releases individual mobile devices from the repeated local media processing and computation.

Meanwhile, the VS-based luminance model is applied to the intermediate results of video encoding, or the reconstructed video frames, in order to mimic the displayed video contents after VS-based DER at the mobile user end. The R-D-DE profiles can now be obtained by comparing the original video content with the displayed video content. An example of the R-D-DE profiles created by the proposed video encoding engine is shown in Fig. 4. Since VS-based DER mechanism introduces distortions to the video content, a given R-D curve will move down indicating that additional distortion is introduced at the mobile device. The more energy saving is intended, the worse the video quality will be on the mobile display. Such a phenomenon is illustrated as the blue curves in Fig. 4. Since the proactive LC algorithm is adopted in the proposed encoder, this color re-mapping strategy can effectively reduce the distortion induced by VS. Such a phenomenon is illustrated as the red curves in Fig. 4. It is evident that the red curves have higher quality then the corresponding blue ones.

4.2. VS-based Luminance Model

One of the key components of the proposed new video encoding engine is the VS-based luminance model which mimics the luminance behavior of OLED displays after applying VS-based DER

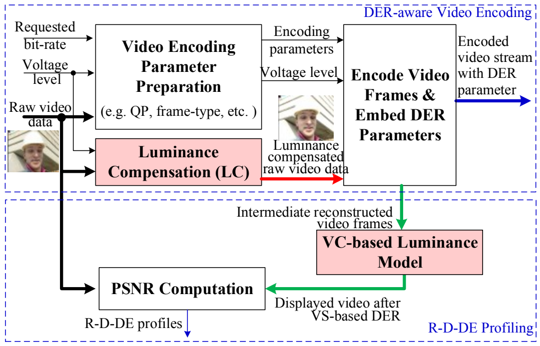


Fig.3. The proposed video encoder in the cloud servers

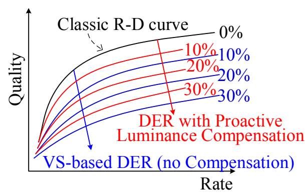


Fig.4. An illustration of R-D-DE profiles.

mechanism. In plain words, this model demonstrates the mapping of "before" and "after" pixel luminance values of video frames after applying VS on the mobile device.

In [8], Shin et al. measured the luminance of AMOLED display panel under different voltage levels and demonstrated the relationship between the measured display luminance (in cd/mm2) and the gray level (%) of an image (ref. Fig. 7 in [8]). We assume that no voltage scaling distortion is introduced into the displayed content when operating at the maximal supply voltage (15 V) [8]. Therefore, the original luminance value is assumed equal to the distorted luminance value with a voltage of 15 V (the "diagonal" lines in Fig. 5). Then we apply curve fitting and linear interpolation to characterize the relationship between the measured display luminance (in cd/mm^2) and the gray level (%) of an image in [8]. Finally, we scale the original axis into the range of [0 255] in proportion and obtain the relationship between the original pixel luminance value and the distorted pixel luminance value under various voltage levels. We named this model as VS-based luminance model in this research.

With this model, the voltage level can be adjusted in the range of 10~15 V. For any given pixel luminance value x and supply voltage level V_{DD}, the expected display luminance value (y^*) can be calculated through Eqs. (1)-(2).

$$y = \begin{cases} -0.21875x + 0.08125\, xV_{DD}), & 13 \le V_{DD} \le 15 \\ -1.1944x + 0.1563\, xV_{DD}), & 12 \le V_{DD} < 13 \\ -0.1588x + 0.07\, xV_{DD}), & 10 \le V_{DD} < 12 \end{cases} \quad (1)$$

$$y^* = I(y) \quad (2)$$

where $I(\cdot)$ represents the nearest integer of a real number.

Fig. 5 (a) provides an illustration of the VS-based luminance model. We can observe that the scaling distortion occurs as long as the voltage level is below 15 V.

4.3. LC Module

The core innovation of the proposed LC module lies in the proactive distortion compensation strategy, which can be derived from the VS-based luminance model in the previous section.

From Fig. 5 (a), we can see that the OLED display achieves the same distorted luminance value (i.e. 100) when the original luminance value is 100, 119,145 and 185 for a different values of V_{DD} in 15 V, 13 V, 12 V and 10 V, respectively. As a result, we

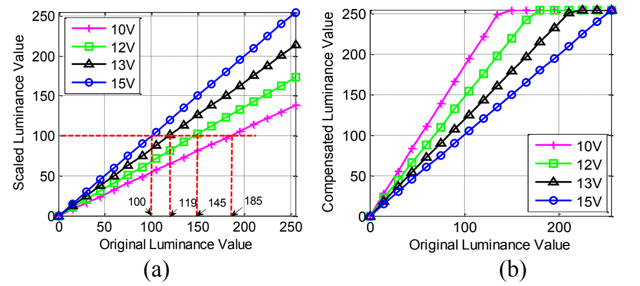


Fig. 5 (a) Illustration of original luminance value vs. distorted luminance value (after VS) in the proposed VS-based pixel luminance model (derived from the Fig. 7 in [8]). (b) Illustration of original luminance value vs. compensated luminance value in proposed luminance compensation algorithm.

can conclude that when V_{DD} is equal to 10 V, no scaling distortion will occur if we pre-compensate the original luminance value from 100 to 185. Based on such analysis and discovery, we propose a luminance compensation algorithm to restore the distorted luminance value when the scaled voltage level is to be applied.

For any given pixel luminance value x and a supply voltage level V_{DD}, the compensated luminance value (z^*) can be calculated through (3)-(4). We shall point out that z^* is actually the inverse function of y with a maximal value constraint (i.e. 255).

$$z = \begin{cases} x/(-0.21875 + 0.08125\, V_{DD}), & 13 \le V_{DD} \le 15 \\ x/(-1.1944 + 0.1563\, V_{DD}), & 12 \le V_{DD} < 13 \\ x/(-0.1588 + 0.07\, V_{DD}), & 10 \le V_{DD} < 12 \end{cases} \quad (3)$$

$$z^* = \min\{I(z), 255\} \quad (4)$$

Fig. 3 (b) provides an illustration of the proposed luminance compensation algorithm. The pre-saturation range of the curves indicates that the proposed algorithm fails to compensate the distorted luminance values.

5. R-D-DE PROFILE CONSTRUCTION AND RESULTS

5.1. R-D-DE Profile

In this section, we demonstrate the construction of the R-D-DE profiles for AMOLED displays with VS-based DER. Due to the page limit, we only include the R-D-DE profiles for test video sequence "Ice" at the resolution of CIF. More simulation results can be accessed via http://www.cse.buffalo.edu/UBMM/Media/Qian/sup_icip16.pdf. The video sequences are encoded by JM 18.5 reference software with a GoP size of 16. For VS-based DER strategy, the maximal voltage level V_{max} is set as 15 V, and the minimal voltage level V_{min} is set as 10 V.

The results of profile construction are shown in Fig. 6. The red curves denote the classic R-D performance without embedding VS parameters for mobile devices (the baseline or upper bound of R-D-DE curves). The black curves represent the R-D-DE profile of VS-based DER approach without luminance compensation while the blue curves illustrate the R-D-DE performance of the proposed scheme with DER and proactive luminance compensation included in the video encoding engine.

From Fig. 6, we can observe that when the scaled voltage is 13 V or 14 V, the R-D-DE curves of the proposed algorithm are pushed close to the ideal case (i.e. no DER). In other words, we are able to reduce the scaling distortion to a minimal level with substantial power savings by using the proposed compensation algorithm. In addition, we can observe that the curves are nearly flat even when the bit-rate increases. This means that higher bit-rate does not provide additional benefit in improving video quality in the R-D-DE profile. This is quite different from conventional R-D characteristics when higher bitrate would improve video quality. Therefore, this new R-D-DE profiles can indeed provide new insights in quality management than the conventional R-D curves because the DER strategy based on such R-D-DE profile can improve the quality of video displayed on mobile devices.

Note that the DER analysis and processing can be computed offline via parallel computing in the cloud. In contrast, conventional per-device approach would need to periodically compute the DER analysis online, which would introduce additional processing time and energy in the device. Furthermore, the storage of additional 5 versions of video for the sequence can be easily accommodated by the abundant storage capability of the cloud.

5.2. Percentage of Display Power Saving

The luminance of an OLED cell is proportional to the value of the cell current. Therefore, the percentage of display power saving can be expressed as:

$$\eta = \frac{L'_{AVG}(V'_{DD} - V_f)}{L_{AVG}(V_{DD} - V_f)} \quad (5)$$

where L_{AVG} denotes the average luminance of the original video content without display VS, and L'_{AVG} denotes the average luminance of the displayed video content after VS. Therefore, Equation (5) can be used to calculate the average percentage of power saving for OLED display. In Table 1, we demonstrate the average percentage of power saving for tested video sequence with different scaled voltages.

5.3. Visual Results Illustration

In this section, we present several visual results of some snapshots of the video sequence in order to demonstrate the characteristics and performance enhancement of the R-D-DE profiles:

(1) The proposed algorithm can proactively compensate for the luminance distortion caused by VS, and achieve satisfactory viewing performance on mobile devices (as shown in Fig. 7).

(2) Different amount of power can be saved under different scaled voltages in the proposed video streaming scheme. However, the more energy saving we seek, the worse the displayed video quality (as shown in Fig.8).

From the snapshots of the "ice" sequence shown in Fig.7, we can observe that the proposed scheme can achieve substantial DER without noticeable distortion at the mobile devices. This performance measure comes from the adoption of proactive LC during the video encoding process in the cloud.

Fig. 8 shows the snapshots of video content at different scaled voltages delivered by the proposed video encoding engine. We can also observe that a noticeable quality degradation occurs when the voltage level is 10 V. This indicates that the proactive LC algorithm is still unable to compensate for the large distortion caused by the VS-based DER when the voltage level is too low.

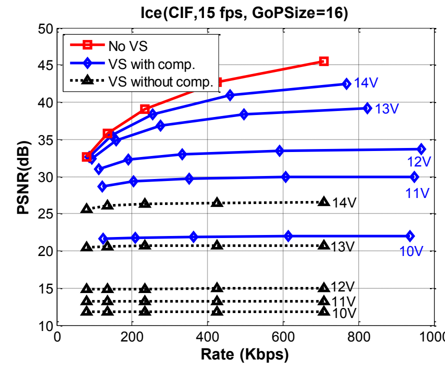


Fig. 6. R-D-DE curves of video sequence "Ice".

Table 1. Percentage of display power saving

Scaled Voltage	14 V	13 V	12 V	11 V	10 V
% of Power Saving	13.79	26.85	39.92	53.93	69.80

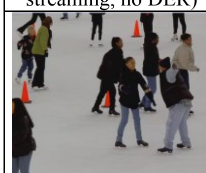
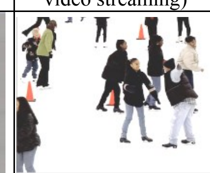
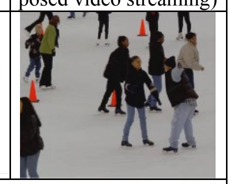
Received video frame (Conventional video streaming, no DER)	Received video frame before VS (Proposed video streaming)	Displayed video frame at mobile device (Proposed video streaming)
		
Rate: 709.18 Kbps; PSNR: 45.54 dB	Rate: 824.34 Kbps; PSNR: 39.19 dB; Power Saving: 26.85%	

Fig. 7. Illustration of the proposed scheme with fixed scaled supply voltage (Scaled V_{DD}: 13 V).

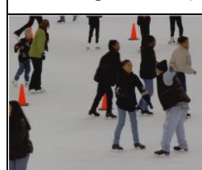
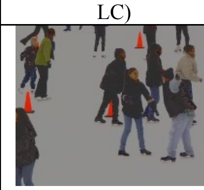
Received video frame (Conventional video streaming, no DER)	Displayed video frame after VS (Proposed video streaming with proactive LC)	Displayed video frame after VS (Proposed video streaming with proactive LC)
		
Rate : 709.18 Kbps; SNR: 45.54 dB	Scaled V_{DD}: 14 V; PSNR: 42.49 dB; Power Saving: 13.79%	Scaled V_{DD}: 10 V; PSNR: 21.95dB; Power Saving: 69.80%

Fig. 8. Illustration of the proposed scheme with different voltage levels.

6. CONCLUSION

In this paper, we presented a comprehensive R-D-DE analysis in the cloud aiming at integrating display energy reduction strategy with the video encoding. Based on such analysis, we developed a new video encoding engine capable of trading-off between bitrate, video quality and display energy for various video contents. This video encoding engine generates a new family of R-D-DE profile to implement the desired trade-off in order to achieve cloud-based display energy saving over the conventional per-device based display energy reduction.

In addition, we focus on the power reduction of AMOLED in this research. For the conventional Liquid Crystal Display (LCD), several DER schemes were developed in [14]-[17]. Although the operational mechanisms of LCD are fundamentally different from that of OLED displays investigated in this research, the design principles for OLED can be adopted for the power reduction of LCD displays with proper adjustments. We shall study the DER of LCD separately in the future research.

We shall point out that the R-D-DE profiles generated by this new video encoding can be directly applied to the current HTTP streaming infrastructure [18], [19] for display energy saving. In addition, the current research on quality-of-service (QoS) based R-D-DE exploration can be extended to Quality-of-Experience (QoE)-aware DER design by taking advantage of the existing research in practical QoE models [20], [21]. For example, the proposed scheme can be further improved when considering different lighting backgrounds of the mobile users as in a dark room or under sunlight. In summary, the proposed new video encoding engine, together with the R-D-DE profiles generated by it, offers a new opportunity for the users to save display energy of their mobile device in a global scale in this video-rich mobile era.

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