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Sorted Sector Covering Combined with Image Condensation — An Efficient Method for Local Dimming of Direct-Lit and Edge-Lit LCDs

Marc ALBRECHT[†a)], **Andreas KARRENBAUER**[††], **Tobias JUNG**[†], ***and*** **Chihao XU**[†], ***Nonmembers***

SUMMARY We consider the backlight calculation of local dimming as an optimization problem. The luminance produced by many LEDs at each pixel considered is calculated which should cover the gray value of each pixel, while the sum of LED currents is to be minimized. For this purpose a specific approach called as "Sorted Sector Covering" (SSC) was developed and is described in this paper. In our pre-processing unit called condenser the source image is reduced to a matrix of much lower resolution so that the computation effort of the SSC algorithm is drastically reduced. During this preprocessing phase, filter functions can be integrated so that a further reduction of the power consumption is achieved. Our processing system allows high power saving and high visual quality at low processor cost. We approach the local dimming problem in the physical viewing direction — from LED to pixel. The luminance for the pixel is based on the light spread function (LSF) and the PWM values of the LEDs. As the physical viewing direction is chosen, this method is universal and can be applied for any kind of LED arrangement — direct-lit as well as edge-lit. It is validated on prototypes, e.g., a locally dimmed edge-lit TV.

key words: *local dimming, backlight, algorithm, LED, edge-lit, side-lit, direct-lit, interaction between LEDs, crosstalk, optimization, high power saving, efficient processor*

1. Introduction

The reduction of power consumption is one of today's most important topics of the LCD industry. With about 80% of LCDs' total power consumption, the backlight is the main consumer. In conventional displays the backlight acts as a constant light source and consumes the same power for dark as well as for bright images. The idea of local dimming is to adapt the locally distributed backlight to the image content so that the power consumption is reduced. The challenge is to find a proper solution for the LED duty cycles. State of the art algorithms are based on image processing methods. The image resolution is reduced to the LED resolution, as for direct-lit the LEDs are placed in a rectangle grid structure. The interaction between the LEDs is not properly considered. The result is that some LEDs are too dark causing clipping artifacts and some LEDs are too bright consuming unnecessary power.

The presented method uses an optimization approach, so that each pixel gets sufficient backlight and the optimizer is combined with further imaging processing methods so that the total power is considerably reduced, the visual quality of the LCD remains high and the processor cost for the local dimming functionality is low.

First of all, we show the mathematical model of Local Dimming Backlight. Based on this model we present in Sect. 3 our SSC algorithm for the calculation of local dimming backlight. The novel pre-processor named as condenser will be described in the fourth section. In Sect. 5 the complete HW system including pre-processor, SSC optimizer and post-processor will be discussed. Our prototypes for edge-lit and direct-lit local dimming will be presented in the sixth section followed by some visual and statistical results for both backlight types. Finally we give an outlook to further research activities in the field of local dimming backlight.

2. Mathematical Model of Local Dimming Backlight

We consider an LCD screen with an LED backlight. Let us denote the number of subpixels by P, i.e. for full HD we have $P = 1920 \times 1080 \times 3 \approx 6$ millions. For the ease of explanation, we use the term LED not only for a single LED device. It is to be considered as a serial connection of single diodes (at least one diode) which are controlled with the same electrical signal. Let the number of those groups be L. Note that we do not make any assumptions on the location of the LEDs.

Our mathematical model is based on the following facts.

1. We can obtain the contribution of each LED to the luminance of each pixel by a measurement and/or simulation where all the TFT values are set to their maxima and the corresponding LEDs shine constantly in time. This gives the so-called Light-Spread-Function (LSF) denoted by $a_{ij}(\ell)$ which assigns the contribution of light source l to pixel ij.
2. Pulse width modulation (PWM) of the driving signals allows us to set the duty cycle of each LED ℓ to any fraction $0 \leq x(\ell) \leq 1$. Thereby, pixel ij receives only the corresponding fraction $a_{ij}(\ell) \cdot x(\ell)$.
3. The contributions of LEDs are added up at a pixel. That is, the total luminance of pixel ij behind the TFT is given by

$$b_{ij} = \sum_{\ell=1}^{L} a_{ij}(\ell) \cdot x(\ell) \tag{1}$$

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[†]The authors are with Institute of Microelectronics at Saarland University, Germany.
[††]The author is with Institute of Mathematics at EPFL Lausanne, Switzerland.
a) E-mail: marc.albrecht@lme.uni-saarland.de
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4. The TFT value of each pixel can be set individually to absorb the surplus luminance such that it matches to the corresponding RGB value r_{ij} after the filter.

We may combine these four conditions to an inequality for each pixel *ij* that must be satisfied to obtain a clipping-free result:

$$\sum_{\ell=1}^{L} a_{ij}(\ell) \cdot x(\ell) \geq r_{ij} \tag{2}$$

or in short-hand notation $A \cdot x \geq r$ where A is a $P \times L$ matrix containing the LSF, x is the vector of the L duty cycles, and r is a vector of size P with the RGB values. Observe that the power consumption is proportional to the sum of duty cycles. Hence, our objective is to find an optimum solution for the linear program

$$\min \left\{ \sum_{\ell=1}^{L} x(\ell) : A \cdot x \geq r, 0 \leq x \leq 1 \right\}. \tag{3}$$

In the following we show how to find an almost optimum solution by means which are suited for being implemented in hardware.

3. Sorted Sector Covering Algorithm

In order to achieve an optimal solution, the interactions between the LEDs are to be considered. This means that we need few iteration steps. As it can be seen in Fig. 1 the algorithm core consists of two (optional three) phases. These phases will be described in the following subsections.

3.1 Lower Bounds (LB)

This initial step results in the image dependent mathematical lower limit of the LED duty cycles. Therefore the pixels that are assigned to an LED k are scanned once. The Lower Bounds values of the k-th LED is determined by the maximum of

$$x(k) \geq \frac{r_{ij} - \sum_{\ell \neq k} a_{ij}(\ell) \cdot x_{pre}(\ell)}{a_{ij}(k)}. \tag{4}$$

That is, we get lower bounds on the duty cycle $x(k)$ by considering each pixel *ij* which is dominated by this LED k. We subtract the maximum contributions by the other LEDs $x_{pre}(\ell)$, that corresponds to their duty-cycles for undimmed backlight, from the RGB value of this pixel. The remainder has to be covered by LED k, and hence divided by the respective light spread coefficient yields a lower bound on the duty cycle $x(k)$.

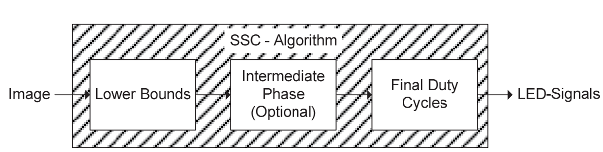

Fig. 1 The three phases of SSC algorithm.

It is easy to see that the LB for each LED can be calculated independently to the other LEDs. The processing order of the dominated pixels is irrelevant in this first phase of the algorithm.

Though most of the pixels already receive enough light by these lower bounds, we have to perform at least a second scan over all pixels to compute the final duty cycles to assert a clipping-free result.

3.2 Intermediate Phase (IP)

As already mentioned the insertion of intermediate phase between LB and FDC is optional. We recommend the IP, if each LED influences a large number of pixels (e.g. for edge-lit displays). Adding the IP leads to a higher demand on HW but allows nearly optimal results.

The basic idea of the IP is to select in every iteration the pixel (i', j') with the greatest deficit, i.e. with the largest difference between required and actually observed luminance. Then we choose the LED with the highest effect on this pixel, i.e. the one with the greatest coefficient $a_{i'j'}(k)$. Let this LED be k'. Hence, if we increase $x(k')$ by

$$\Delta := \frac{r_{i'j'} - \sum_{\ell=1}^{L} a_{i'j'}(\ell) \cdot x(\ell)}{a_{i'j'}(k')}, \tag{5}$$

the pixel (i', j') would receive enough light and would be covered. If the dominating LED is already at their maximum, the LED with the second highest influence will be increased etc. To make this algorithm a bit more sensitive, we actually do not increase by the entire amount but only by a fraction $\lambda \cdot \Delta$ for a fixed $\lambda \in (0, 1)$. The algorithm terminates if no unsatisfied pixel remains and hence yields a clipping-free solution by design. Termination is guaranteed since we discretize all quantities and thereby increase in each iteration the duty cycle of one LED by at least one least significant bit.

Processing steps needed for insertion are logarithmic in the number of pixels, and querying the most unsatisfied pixel is possible in constant time. This method yields nearly optimal results in practice.

For implementation in HW we determine a constant number of most unsatisfied pixels during this phase.

3.3 Final Duty Cycles (FDC)

For the last step of our local dimming algorithm, called FDC, we separate the display in sectors. All pixels in one sector are assigned to their dominating LED. Figure 2 shows an example for an edge-lit display with six LEDs.

The pixels in each of the six sectors are sorted by the influence of the dominating LED. We scan once over all pixels, starting at the first pixel in sector 1, first pixel of sector 2 and so on to the last Pixel of the sixth sector. Each pixel is covered by

$$x(k) \geq \frac{r_{i'j'} - \sum_{\ell \neq k} a_{ij}(\ell) \cdot x(\ell)}{a_{ij}(k)}. \tag{6}$$

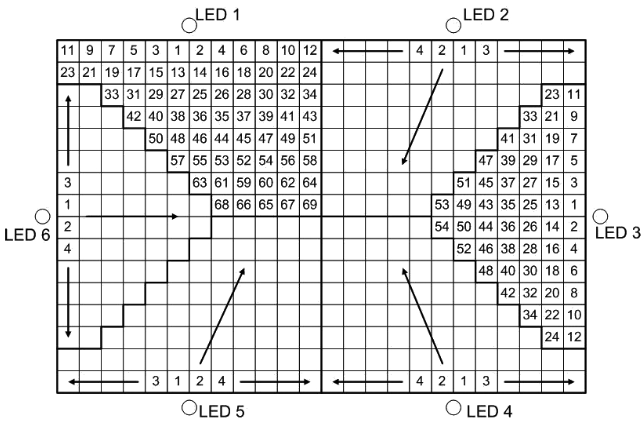

Fig. 2 Separation of an edge-lit display in six sectors.

While screening of the sectors a luminance deficit may be left in a pixel, since the upper limit of $x(k)$ is one. In this case the LED with the next highest influence will be increased according to Eq. (6), etc.

In case that several LEDs have a similar influence on the pixel, these LEDs values can be changed conjointly. In this FDC phase every pixel is required to be scanned.

The described procedure in FDC is similar to IP. However we only scan once over all pixels to cover one after another.

The final duty cycles end with clipping-free results close to the optimal solution.

For further description of the SSC Algorithm we refer to [2].

4. Image Condensation

4.1 Motivation

As we can see in the previous section, SSC's complexity mostly depends on the number of pixels to be processed. So it is worth to reduce the number of pixels in order to reduce the HW-cost. Further on it is well-known that clipping effects are often not perceivable for the human eye. However the power consumption can be lower than that without clipping.

So a pre-processor is added named as condenser [1] which extracts from a high resolution image to an image of concentrated pixels whose number is much lower. The representing value of each concentrated pixel depends on image properties and on the desired power saving. This image condensation method is different to the well-known image compression method which reduces the amount of data.

4.2 Image Condensation

The condenser is placed prior to the SSC processor (see Fig. 3).

Condensation means, that we condense a predefined number of $(s \cdot t)$ image pixels to one concentrated pixel (see Fig. 4). The total number of condensed pixels depends on

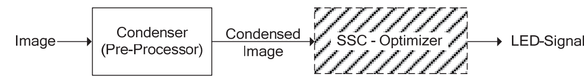

Fig. 3 Condenser with SSC algorithm core.

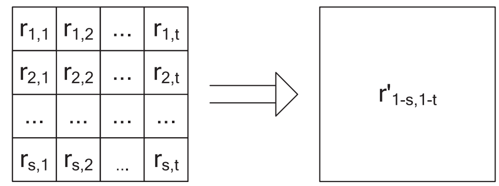

Fig. 4 Condensation of $s \cdot t$ pixels to one concentrated pixel.

the properties of the LSFs.

In comparison with state-of-the-art lowpass filters the resolution achieved with our condenser is still by magnitudes higher than the backlight resolution. The major characteristics of the source image are conserved in the resulting condensed image.

Several condensation functions can be used. For example that clipping effects are often not perceivable for the human eye, so that a filter function integrated in the condenser can further reduce the power consumption while the visual quality remains high. The output of the preprocessing unit can be controlled by different modes (condenser modes). Beside the clipping-free mode, of which the condenser output $r'_{i',j'}$ is

$$r'_{i',j'} = \max \begin{pmatrix} r_{i,j} & r_{i,j+1} & \cdots & r_{i,j+t-1} \\ r_{i+1,j} & r_{i+1,j+1} & \cdots & r_{i+1,j+t-1} \\ \cdots & \cdots & \cdots & \cdots \\ r_{i+s-1,j} & r_{i+s-1,j1} & \cdots & r_{i+s-1,j+t-1} \end{pmatrix}, \quad (7)$$

we introduce the soft-clipping mode, which can be scaled in several degrees. Therefore the condenser output is not the mandatory maximum value of the $s \cdot t$ cell anymore but lower in most instances. E.g. one possible solution for soft-clipping mode would be to assign the arithmetic mean to the concentrated pixel.

So there are two factors that influence the clipping ratio. The first factor is the size of the pixel matrix that will be condensed to one pixel and the second factor is the condensation function itself.

The clipping-free mode assures lossless image quality. The original image data is implemented one by one. Because we condense small cells of the image, we can filter/clip the image content of this small cell in such a way, that a so reproduced image has no visual defects compared to the original image.

The resolution of the image concentrated depends on the properties of the influence matrix. The sparser this matrix is, the smaller is the number of pixels that can be combined to one concentrated pixel. Thus for an edge-lit display the resolution of the condensed image can usually lower than that for a direct-lit display.

4.3 Condenser Modes

The HW complexity for SSC processor core is reduced by condensation of the image data to a lower resolution image. The soft-clipping allows further power reduction. Depending on the application and the type of the display, we developed a range of condenser modes which can be selected by the user. The wide range is justified through the fact that the LSF can vary from one display to another. The visual results of the different modes presented are discussed in Sect. 6.

4.3.1 Clipping-Free Mode

As already mentioned above the clipping-free mode leads to results which are equivalent to the original image. Therefore the condenser output is set to the maximum pixel value according to Eq. (7). It is obvious that this mode has of course a lower power saving potential compared to clipping affected modes.

4.3.2 Maximum Power Saving Mode

For mobile application sometimes it is more important to save battery power at the expense of lower image quality. In that case the maximum power saving mode can be chosen. The function to be used depends on the display system. For most displays the arithmetic mean may be a good condensation function for this mode.

4.3.3 Automatic Mode

Since the characteristics of an image can vary from one zone to another, e.g. one zone with strong high spatial frequency, while another zone is rather smooth, the cells of one image can be condensed by different functions depending on the content of the cell. Thus we added an automatic mode. The preprocessing unit analyses the data of the $s \cdot t$ cell and finds out the best trade-off between power saving and good visual quality. For finding the appropriate condensation function a Clipping Allowance Factor (*CAF*) has been introduced for each cell. One possibility for *CAF* would be a function of the arithmetic mean (*AM*) and the maximum value (*Max*) of this cell.

$$CAF = f(Max, AM) \tag{8}$$

Which condensation function for a cell is chosen, depends on the *CAF* and a set of threshold values which are predetermined. So we have the automatic mode which sorts the cells to an individual condensation function.

Fig. 5 Original Image (left) and the respective condensation functions in automatic mode (right).

The example in Fig. 5 shows an image with its respective condensation functions in automatic mode.

We choose a set of four threshold values. The cell-size is (20·15) Pixels, the condensation functions are shown from white (low power-saving) to black (high power-saving).

As it can be seen most cells of the image allow medium power saving, many cells allow high power saving and only few cells need clipping-free mode.

In general, we propose two sets of threshold values for each implementation. One for still images (higher image-quality, lower power-saving) and one for moving images (lower image-quality, higher power-saving).

The different cells condensed by different functions do not lead to any artifacts. Cells with similar contents would require the same condensation function, while for varying contents the human perception is tolerant.

The threshold values do not only depend on whether the image is moved or not — it also depends on the backlight type and properties of the display system. Each LED of an edge-lit backlight significantly influences more pixels than an LED of a direct-lit backlight. This fact also influences the way, how the image is condensed.

Another possibility to influence the condenser is the number of threshold values per set. E.g. a higher number of threshold values sometimes lead to a better adaptation of the original image. For most applications we recommend four threshold values (corresponds to five condensation functions) per set.

5. HW-System with Preprocessing, SSC Optimizer and Post-Processing

Figure 6 shows the complete local dimming HW-System. Firstly the stream that rewrites the GDRAM with new image data is processed on the fly by the condenser. The resulting condensed image pixels are written in the Condenser RAM which can be an embedded SRAM on the local dimming

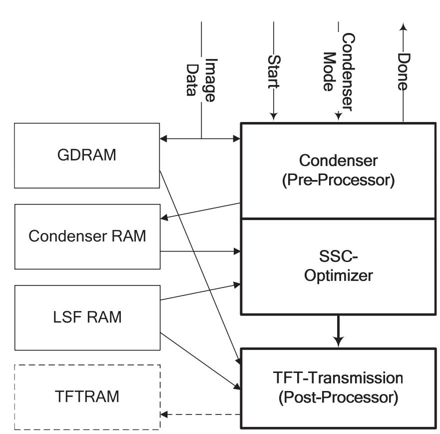

Fig. 6 HW-architecture.

processor due to its small size.

SSC Optimizer then calculates the LED duty-cycles according to the condensed image. The LSF data of the LEDs are also stored in an SRAM.

In the following frame, the determined LED values from the last frame are used to calculate the TFT values. The principle of the calculation is very simple:

$$t_{ij} = \frac{r_{ij}}{b_{ij}} \tag{9}$$

while b_{ij} is calculated according to Eq. (1). Once again, the number of the many pixels is a challenge especially for calculating the b_{ij}. The solution is similar as the preprocessing. Only sample points of b_{ij} are calculated. Therefore the LSF values are needed. The luminance for the pixels between the sampled points is interpolated so that the computation effort is drastically reduced. Thus we achieve the proper representation of the physical luminance for every pixel so that there are no artifacts such as artificial boundaries, etc.

For calculating the TFT-values a pipeline processor is used, since the number of the pixels is the full display resolution. The procedure described above is illustrated in Fig. 7.

For time-critical applications such as video, the resulting images are based on the LED values of the previous frame and the TFT values of the actual frame, as shown in Fig. 8.

If there is need for higher performance SSC also can work in parallel. For LB there is no influence on the results. For IP and FDC a parallelization may slightly downgrade the results. However, in any case a frame rate of 1000 Hz can

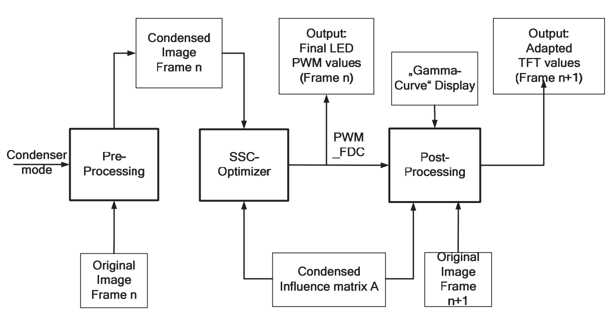

Fig. 7 Diagram of pre-processing, SSC and post-processing.

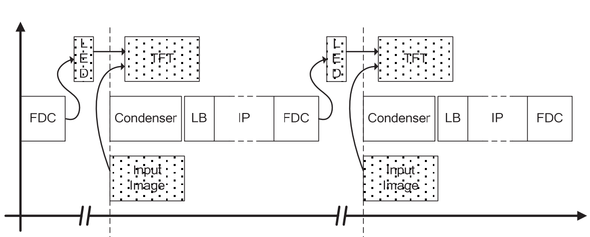

Fig. 8 Timing diagram for video application.

be achieved. For a detailed description of the parallelization we refer to [3].

6. Prototypes, Visual and Statistical Results

As already mentioned SSC uses the physical LSF model which is valid for every backlight arrangement and works for both, direct-lit as well as edge-lit. For this purpose we implemented it on two display models for both types of backlight.

6.1 Prototypes for Edge-Lit and Direct-Lit Backlight

The edge-lit prototype display is the commercial TV Samsung UE32B6000. The LSFs of the six LED strings were determined by measurements. For our purposes it was only necessary to demount the housing for reconnecting the LED strings to our own driver unit to independently drive the LEDs and control the backlight unit.

Figure 9 shows an image of our prototype (left) and the six measured LSFs (right).

The data for the direct-lit approach is based on measurement of an 8-inch SVGA display. A 42-inch HDTV is constructed combining this measurement data. To conclude the description of our local dimming prototypes, Table 1 shows the significant characteristics of the two display types.

6.2 Discussion of Visual Results

For the investigation of the visual quality we analyzed the resulted images of our test set [4]. The quality of the re-encoded stream out of the consecutive frames as described in Sect. 5 was flawless and without visual artifacts or color deviations. The two images in Fig. 10 have been processed in the different condenser modes to analyze the visual quality of the Edge-Lit TV as well as for the Direct-Lit TV.

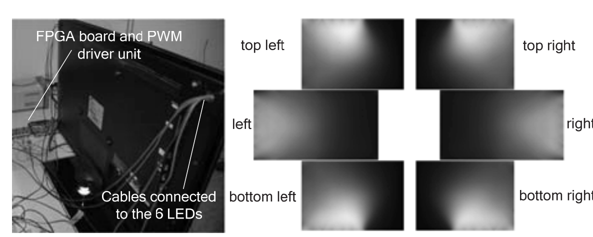

Fig. 9 Prototype (left) with measured LSFs (right).

Table 1 Display data.

Parameters	Edge-lit	Direct-lit
LEDs (groups x diodes)	6 x 38	180 x 12
Display size	32”	42”
Resolution	full HD	full HD
Condensed Cell Size (pixel)	60 x 60	20 x 15

Fig. 10 Two test images, region of interest is marked - left: landscape, right: black dog.

Fig. 11 Zoom landscape edge-lit TV (from the left): automatic mode, clipping-free mode, maximum power saving mode.

Fig. 12 Zoom landscape direct-lit TV (from the left): automatic mode, clipping-free mode, maximum power saving mode.

6.2.1 Edge-Lit TV

Figure 11 compares the results of the different condensing functions for the first image (Landscape). The section of the first example shows a typical clipping effect. The clouds of the clipping-free image include some details and structured areas such as the shadow line (see arrow). The automatic mode conserves most of these details including the shadow line while the white area looks a bit unstructured. In contrast the shadow line is not visible anymore in right-most image (maximum power saving mode). Further details are lost. The power saving for this image is 1% in clipping-free mode, 24% in automatic mode and 35% in maximum power saving mode.

The second image (see Fig. 13) is a high contrast image with dark areas and bright spots. The zoomed image area exemplifies two facts: Firstly small bright objects (the bright hairs in the dog's coat) remain visible and bright, even in maximum power saving mode. However the bright hairs appear a bit smeared. Secondly the dog's eye appears a little bit darker in maximum power saving mode than in the original image. This is due to the fact that the effective filter frequency is very low and many dark pixels around the bright regions are also condensed with the white area (condenser size = 3600 pixels). Nevertheless, the visual impression is still very good as the contrast is high and there are no strong clipping artifacts.

The power saving for this image is 24% in clipping-free mode, 80% in automatic mode and 86% in maximum power saving mode. The power saving of clipping-free mode for an edge-lit display is very low due to the fact that the LSFs are wide-spread so that the luminance of the most pixels are contributed by nearly every LED.

6.2.2 Direct-Lit TV

For direct-lit prototype, the same two images as before have been used. The results for the different condenser modes are shown in Fig. 12 and Fig. 14. All in all the results are simi-

Fig. 13 Zoom black dog edge-lit TV (from the left): automatic mode, clipping-free mode, maximum power saving mode.

Fig. 14 Zoom black dog direct-lit TV (from the left): automatic mode, clipping-free mode, maximum power saving mode.

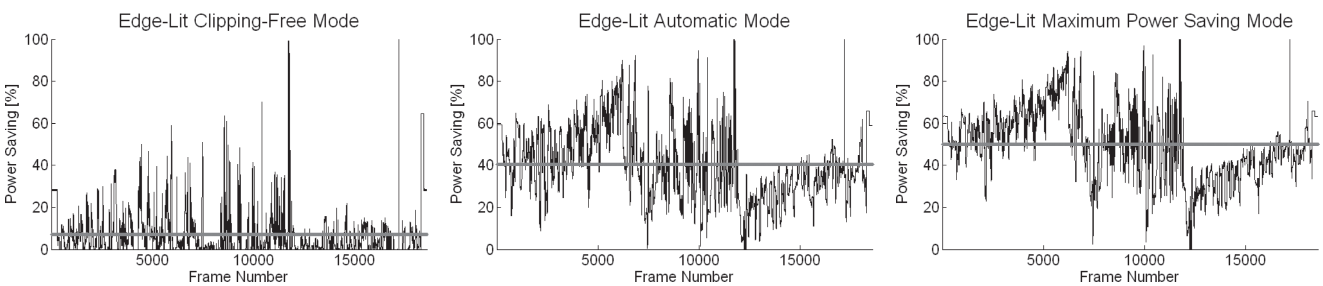

Fig. 15 Power saving of edge-lit display (from the left): Clipping-free mode, automatic mode, maximum power saving mode).

lar to those of edge-lit backlight. The automatic mode's results are flawless, too, visible clipping artifacts only appear in maximum power saving mode. Because of the higher granularity of the direct-lit type, the clipping-affected areas are smaller. Thus in automatic mode as well as in maximum power saving mode the luminance of the dog's eye in the second example is higher than that of the edge-lit prototype.

The achieved power saving is, as to be expected in most cases a little bit higher than that with edge-lit backlight: 22%, 31% and 37% for the first example and 88%, 92% and 94% for the second one respectively. This is due to the fact that the LSFs are much more local and much more LEDs (180 vs. 6) are individually controlled.

6.3 Statistical Results

To analyze the power saving of SSC with image condensation we evaluated the IEC standard video consisting of 18578 full-HD images [3]. This set is processed with our SSC processor for different condenser modes.

Figure 15 shows the power saving of the edge-lit type display for three different condenser modes. In the first mode, which delivers clipping-free results, the average power saving is 7%. In automatic mode the visual quality is still flawless, while slight clipping exists mathematically. For this TV model the power saving at the automatic mode is 40% and at the maximum saving mode it is 51% (see Table 2).

Table 2 Power saving for edge-lit LCD with 6LEDs.

Condenser Mode	Power Saving
Clipping-Free Mode	7%
Automatic Mode	40%
Maximum Power Saving Mode	51%

We expect ever more power saving for an edge-lit TV with a higher number of LEDs (e.g. 12).

For all of the results shown above the deviation to the theoretical optimum solution for each image is less than 1% in average.

For automatic mode the total image luminance is kept within a range of 3% deviation compared to the undimmed mode. In maximum power saving mode the luminance is lower in most cases, but still close to undimmed mode (5%

deviation in average). So we achieve substantial power saving with this new local dimming method.

7. Conclusion

The examples for edge-lit and direct-lit LCDs prove that the SSC optimization algorithm is a universal method for calculating the proper backlight for saving power. Considering the fact that there is currently no edge-lit TV with local dimming available, this method allows an average saving of 40%. In combination with the image condensation, the local dimming processor can be realized by at low cost, while the processing speed can be higher than any realistic frame rate.

As the method is grounded on a generic physical backlight model, it can also be adapted to further display types like 3d-dimming for RGB backlight and/or sequential color.

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Marc Albrecht received his Dipl.-Ing. degree in Data Processing from Technical University of Kaiserslautern (Germany) in 2005, and his DEA degree in Mechanical Engineering from Ecole Normale Superieure of Cachan (France) in 2005. Since that time he works as a research assistant towards his Ph.D. in the field of Local Dimming Backlight Algorithms at the Institute of Microelectronics of Saarland University, Germany.

Andreas Karrenbauer received his Dipl.-Inf. and Dr.-Ing. degrees in computer science from Saarland University in Germany in 2004 and 2007, respectively. From 2004 to 2008, he worked as a research assistant at the Max Planck Institute for Informatics in Saarbruecken. In 2008, he joined the Discrete Optimization group at EPFL in Lausanne as a Postdoc. His main research interests are in the field of Combinatorial Optimization and Algorithm Engineering.

Tobias Jung received his Dipl.-Ing. degree in Computer- and Communication Technologies at Saarland University in Saarbruecken 2008. Since that time he is working on the field of display data processing. His main topic is the development of local dimming algorithms for edge-lit displays. Tobias Jung is a Ph.D. student at the Institute of Microelectronics at Saarland University.

Chihao Xu received his Dipl.-Ing. and Dr.-Ing. degrees in electrical and electronic engineering from Technical University of Munich, Germany, in 1986 and 1990, respectively. From 1986 to 1990, he worked as a research assistant at Technical University of Munich on the modeling of power semiconductor devices. From 1991 to 2003, he worked as a R&D engineer and R&D manager at Robert Bosch, Siemens/Infineon Technologies, and Dialog Semiconductor, Germany. During this period, he was active in the research and design of power/high-voltage integrated circuits for automotive and communication applications. Since October 2003, he has been chair professor for microelectronics at Saarland University, Germany. His research focus is on display drivers with specific field addressing and driving schemes for OLED displays and local LED dimming for LCDs.