Brightness Preservation for LCD Backlight Dimming

LCDバックライト削減，省電力のための輝度保存

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Abstract

Global backlight dimming is a dominant method for power reduction in LDC displays. Unfortunately, this results in an overall lowering of the brightness of the displayed image, which reduces the perceived quality. This is especially a problem when the display is viewed side-by-side with a competitor display which is brighter because it does not engage in power reduction. Fortunately, image processing can be used to compensate for the loss of brightness via a simple boost and clip operation, if calibrated correctly. Such an approach can also be used for simple brightness boosting without the use of backlight dimming, an application for displays which have difficulty achieving desired brightness (such as mobile displays viewed in the daylight). We propose a low complexity approach which replaces hard clipping with smooth roll-off to reduce clipping artifacts. An additional high quality approach uses a two-channel spatial frequency decomposition to preserve highlight detail attenuated by the roll-off. Image quality is improved and power savings can be increased by more aggressive backlight dimming.

広範囲にバックライト照度を下げることは，LCDディスプレイ省電力の主要な手法である。残念ながら，これは表示画像の輝度を全体的に低下させ，知覚品質を下げる結果となる。省電力を行わないために明るい競合他社のディスプレイと並べて見る場合に，特に問題となる。幸い，正確に較正すれば，単純な強調とクリッピング処理による画像処理を利用して，輝度の喪失を補償できる。本手法は，バックライト輝度の低下を使用しない，単なる輝度向上にも利用可能で，目的とする輝度に達するのが困難なディスプレイの用途（日中に観られるモバイル・ディスプレイなど）にも利用できる。我々は，クリッピングによるノイズを削減するため，ハード・クリッピングを滑らかなロールオフで置き換える低複雑度の取り組みを提案する。加えて高品質の手法は，ロールオフによって弱められる重要な細部を保存するため，２チャネルの空間周波数分解を使用する。さらに積極的なバックライト低下により，画質を改善し，省電力を進めることができる。

Introduction

The backlight is a significant source of power consumption in an LCD. In an effort to reduce power consumption an LCD can dim its backlight. Image dimming is an immediate consequence but can be compensated for by brightening the image data sent to the LCD. Since an LCD is a multiplicative system, dimming the backlight can be compensated by scaling the LCD image by the inverse of the dimming factor. Several authors [1-4], have proposed techniques which adapt the backlight to the brightness of the image and then use image processing to compensate for the backlight dimming. For typical content, significant power savings have been reported based on this image adaptive backlight scaling technique. An important aspect of these works is selecting an appropriate backlight level.

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The problem we address differs in that a fixed backlight dimming is used and applied for all image content.

The goal is to maintain high image quality with a fixed backlight dimming. We examine the problem of preserving image quality when the desired image brightness exceeds the maximum brightness of the lower power display. This may happen either on bright content when using a fixed reduced backlight for all content or when using an aggressive backlight dimming strategy. An important goal of our problem is preserving highlight detail when simple image scaling would result in clipping image data when compensating for backlight dimming. We have developed two approaches to preserving image highlight detail while compensating for backlight dimming: smooth tonescale roll-off and spatial frequency two-channel decomposition. Our goal is preserving image quality on a range of input imagery with a fixed backlight dimming of 20%. The techniques developed can be used to improve the image quality or backlight dimming aggressiveness of backlight modulation based systems.

1. Brightness preservation

In this section, we provide a brief discussion of the ability to compensate for backlight dimming by emulating the full backlight output on a reduced backlight display. Next we present two algorithms for improved quality brightness preservation [5]. The first is low complexity consisting of a tonescale modification only. The second has higher complexity but preserves contrast through use of a two-channel decomposition of the image.

1・1 Backlight compensation

The output of an sRGB calibrated LCD with 100% and 80% backlight levels is illustrated in Fig. 1. For a moderate output, as indicated by the dashed horizontal line, the low power display is capable of producing the same output luminance as the full backlight display if it is driven with different data. Thus the backlight dimming can be compensated by image processing.

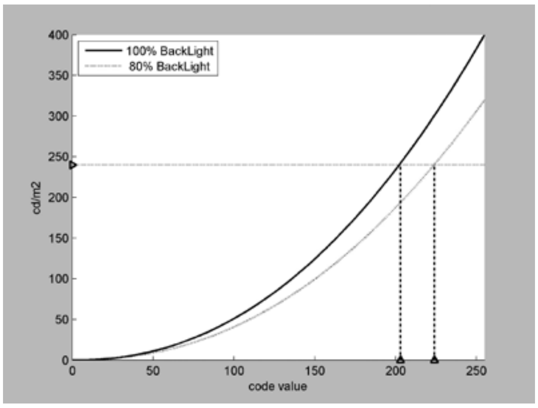


Fig. 1 Photometric matching.

Compensation consists of multiplying the original data by the reciprocal of the relative illumination in the linear light domain before sending it to the low power display. The output of an LCD at each backlight (BL) level is modeled in Eq. (1). The output L(BL,cv) depends on the digital code value, cv, raised to the power gamma and scales with backlight level BL.

$$L(BL, cv) = BL \bullet \left(\frac{cv}{255}\right)^{\gamma} \qquad (1)$$

To achieve the same output with a reduced backlight, the LCD data can be compensated by using the desired relation $L(BL_{Reduced}, y) = L(BL_{Full}, x)$. Given a reduced backlight and a code value displayed at full backlight, Eq. (2) defines the relation for the code value on the reduced backlight to give matching output. $CV_{Reduced}$ means the code value needed to make the LCD output with reduced backlight as bright as the LCD output with full backlight and code value CV_{Full}. Equation (2) describes the case we want to equalize.

$$BL_{Reduced} \bullet \left(\frac{CV_{Reduced}}{255}\right)^{\gamma} = BL_{Full} \bullet \left(\frac{CV_{Full}}{255}\right)^{\gamma} \qquad (2)$$

Solving for the needed code value for compensation yields the result of Eq. (3). A change in backlight is compensated by linear scaling in the digital code value domain by a factor dependant upon the relative backlight ratio and display gamma.

$$CV_{Reduced} = \left(\frac{BL_{Full}}{BL_{Reduced}}\right)^{1/\gamma} \bullet CV_{Full} \qquad (3)$$

Compensation for backlight dimming consists of a tonescale which is linear with a slope determined by the display gamma and the relative backlight illumination. Digital range limits on the tonescale generally impose some degree of clipping in the compensating tonescale. Clipping arises when $CV_{Reduced}$ exceeds the code value range (e.g. 255). Previous work devoted to adaptive backlight modulation has recognized this fact and selected an image dependant backlight level which either avoids or minimizes the presence of clipping. For example, the work in Raman [6] accounts for the limited display contrast range and selects a backlight controlling the severity of clipping artifacts. The formulation of our problem does not permit increasing the backlight for bright images and hence we consider other solutions to avoiding clipping artifacts.

2. Brightness preservation (BP) algorithms

2・1 Tonescale roll-off

As shown above, the photometric matching process can be represented as a tonescale change. Clipping artifacts can be traced to the zero-slope of the compensating tonescale function. As a low complexity solution for image brightening, we modify the tonescale to eliminate this discontinuity creating a roll-off BP tonescale map. This tonescale is designed to provide a photometric match for low to mid image values and avoid the pixel clipping at the high end. We require both the tonescale and its first derivative be continuous at the transition point. As a design parameter, we introduce a transition point, Maximum Fidelity Point (MFP). For code values below the MFP, both the clipped and BP tonescales are identical. They diverge at the MFP. The BP tonescale is designed to have a smooth roll-off to 255 beginning at the MFP. The smoothness of the BP tonescale avoids artifacts which can result when the tonescale has a slope discontinuity as well as lost detail due to clipping. Sample tonescale functions based on 80% power and a gamma of 2.2 are shown in Fig. 2. The clipping point and MFP (roll-off point) are indicated on this plot.

The output of the full power and low power display with different tonescale functions is shown in Fig. 3. The clipping tonescale reproduces the full power output for all digital code values below a clipping point, 233 in this case. The BP roll-off tonescale reproduces the full power output for input below the MFP. We note that for code values above the MFP the brightness is not fully restored but the hard clipping has been eliminated. Above the MFP, the contrast is gradually reduced so as to avoid clipping artifacts. The image independent design implies that some images which do not clip and can be fully compensated by the simple boost process will suffer slight dimming of highlights. This is a consequence of a design trade-off in producing an image independent algorithm. The tonescale based BP algorithm is very low complexity. The BP tonescale is designed for a reduced backlight level by selecting the MFP and smooth extension of the tonescale above the MFP. The tonescale design may be done off-line for maximal complexity reduction. The MFP provides the key design parameter. If MFP values are selected above the clipping point, the BP tonescale reduces to the boost with clipping. The designer has the ability to trade-off the steepness of the reduction in contrast and the degree of under compensation at points above the MFP.

2・2 MFP selection

An important parameter in the BP algorithm is the tonescale roll-off point referred to as the MFP. The MFP provides a balance between preserving brightness of mid-tones and preserving highlight detail. Fig. 4 illustrates two tonescale curves designed for 20% backlight dimming and gamma of 2.2 but with different MFP values. Compared to the tonescale with smaller MFP, MFP=160, the tonescale with the larger MFP, MFP=210, gives a greater boost of upper mid-tones; however the slope is lower at the highlights. This difference translates to brighter upper mid-tones but greater loss of bright detail for BP based on the higher MFP value. One solution to this is the two-channel BP algorithm discussed below which preserves bright detail while increasing the MFP to

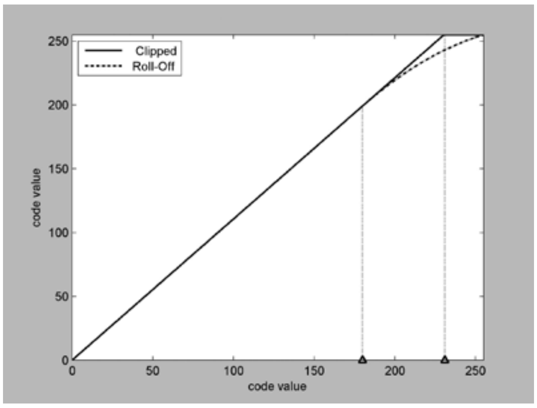


Fig. 2 Roll-off vs. clipped tonescale.

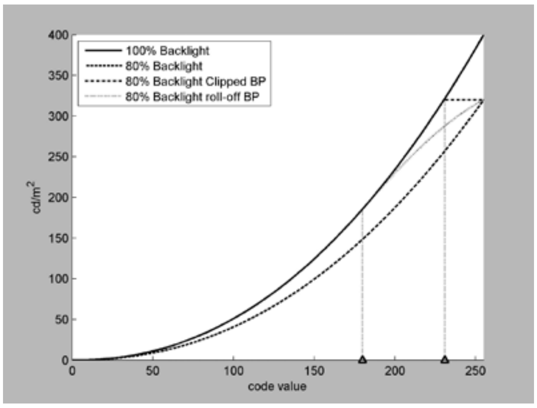


Fig. 3 Tonescale backlight compensation.

improve brightness of upper mid-tones. We note that when used with a varying backlight, a dynamic MFP selection algorithm must be specified.

2・3 Two-channel BP

More aggressive backlight dimming and/or more demanding image quality concerns led to the development of a more advanced algorithm. Spatial two-channel decomposition has been used to preserve detail in tonescale operations [7]. This prior work addressed preserving image detail under general tonescale mapping. A two-channel decomposition of an image is followed by the construction of a artifact avoidance signal. The high-pass channel is modified using the avoidance signal to create a texture signal. The original image is used with the texture signal to create a pedestal signal. The tone-scale is applied to the pedestal signal and a possible gain is applied to the texture signal. The modified pedestal and texture signals are recombined. In the current work, the goal of image processing is to compensate for backlight dimming thus the class of tone-scale operators is limited i.e. each tonescale is linear below its MFP. Complexity is reduced by using only a two-channel decomposition. Additionally, the algorithm is linked to the backlight dimming as both the tonescale and scalar gain applied to the HP channel are derived from the backlight dimming and display gamma. The two-channel BP algorithm, diagramed in Fig. 5 operates by first decomposing the image into low-pass (LP) and high-pass (HP) components. The LP component is processed with the tonescale based BP algorithm introduced above. The entire HP channel is scaled by a single compensating factor equal to the slope of the BP tonescale below the MFP. The LP and HP results are then summed. As a result the HP channel does not go through the roll-off region of the BP tonescale and is not attenuated. For LP pixels below the MFP, the tone mapping is a linear scaling and the output is fully compensated. For pixels with LP component above the MFP, the detail is passed through the HP channel and preserved while the LP data is processed by the roll-off portion of the tonescale and hence the local average brightness is reduced.

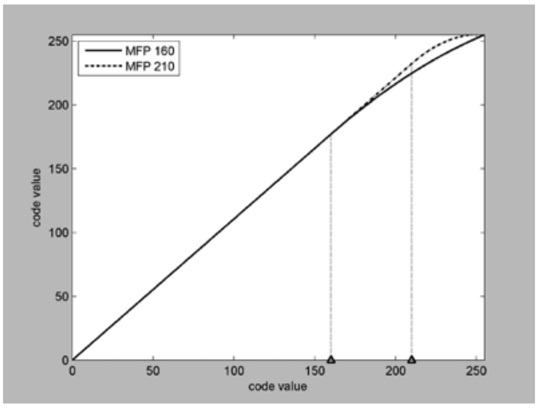


Fig. 4 Two MFP tonescales.

2・4 Illustration

A sample image is used to illustrate the effectiveness of BP. In this example we use a simple 5x5 rect filter for the channel separation. An original image is shown at full backlight Fig. 6a. The original image data is used unmodified and the output on a display with 70% backlight is simulated in Fig. 6b. Observe the dimming of the image. The image is processed with BP and the output on a display with 70% backlight is simulated in Fig 6.c. The image brightness reduction introduced by the dimming in backlight is eliminated.

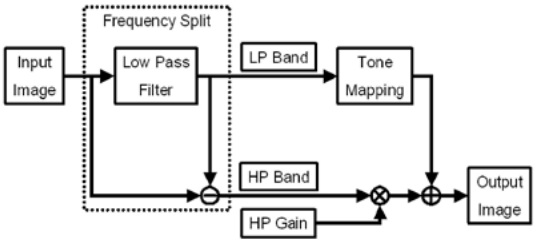


Fig. 5 Two-channel BP block diagram.

3. Evaluation

We compare the proposed BP algorithms with two known techniques for image brightening: reducing gamma and a boost with clipping. Additionally we examine potential tonescale quantization issues.

3・1 Comparison with reducing gamma

A well known technique for brightening an image is to process it to reduce gamma. Reducing gamma is a point-wise tonescale operation and can be compared with our simpler algorithm using the proposed BP tonescale. For this evaluation we show the combination of the image processing with backlight dimming using the model of Eq. (1). This display output following image processing and backlight dimming are shown in Fig. 7. The brightening effect of reducing gamma from 2.2 to 1.9 can be seen by comparing the “80% Backlight curve” (gamma 2.2)

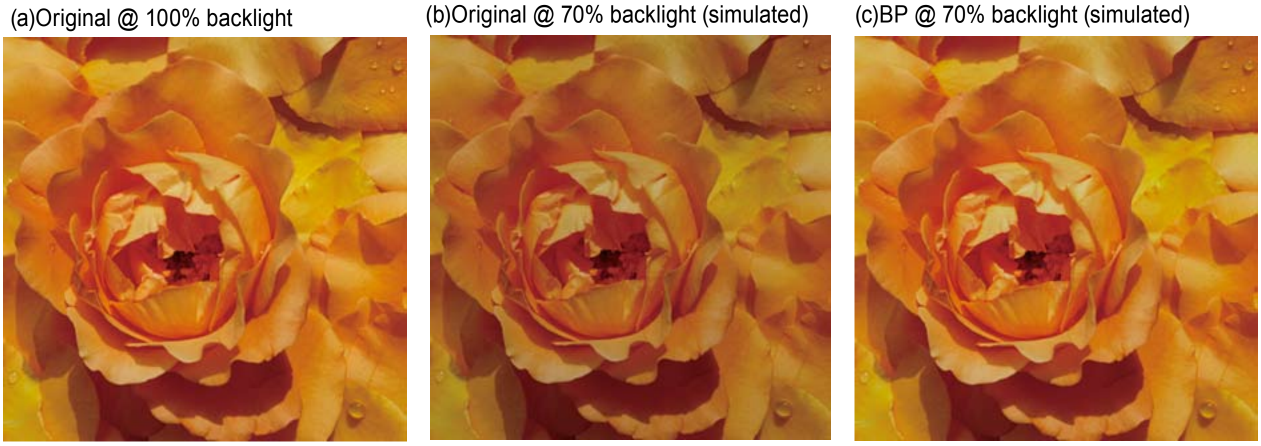

(a)Original @ 100% backlight (b)Original @ 70% backlight (simulated) (c)BP @ 70% backlight (simulated)

Fig. 6 Reduced backlight compensation.

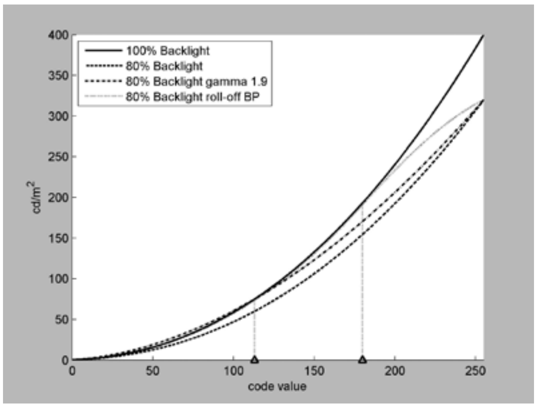


Fig. 7 Comparison with reducing gamma.

with the "80% Backlight gamma 1.9" curves. When the approach using gamma reduction is evaluated in the brightness compensation application, it is found that a reduction in gamma only gives accurate compensation at a single code value (e.g., 100), in Fig. 7. Code values above this code value are not sufficiently brightened performing worse than the proposed BP methods suggesting a value of gamma less than 1.9 would be needed to achieve greater restoration of mid-tone brightness.

Not seen in Fig. 7 is the elevated low gray values caused by simply reducing gamma. To examine this in more detail we expand our model display equation to include the effect of a nonzero LCD black level. We incorporate backlight dependence in the well known GOG [8] model to can express the output of the LCD with nonzero black level in Eq. (4).

$$
\begin{aligned}
L(BL,cv) &= BL \cdot \left(Gain \cdot \frac{cv}{cvMax} + offset \right)^{\gamma} \\
offset &= \left(\frac{black}{white} \right)^{\frac{1}{\gamma}} \\
Gain &= 1 - offset
\end{aligned}
\tag{4}
$$

A log-log plot is used in Fig. 8 to examine the low code value range. Reducing gamma over-brightens the region of non-zero low code values raising the output with reduced backlight even above the full backlight output. Further reduction in gamma to increase the brightening at high code values further increases the black level.

3・2 Image quality comparison

We compare the performance of the boost-clip, smooth tonescale roll-off BP, and two-channel BP algorithms in preserving highlight detail. These algorithms all give the similar results for image data below the MFP. They differ primarily in their handling of highlight detail. An original image with highlight detail, shown in Fig. 9, was selected to examine the difference in algorithms. The original image is processed by all three algorithms assuming a 20% dimming in backlight and gamma of 2.2.

The wave contains highlight detail which is above the range of a display with 80% backlight. With gamma of 2.2 and backlight of 80%, original image code values above 230 cannot be represented on the low power display. We

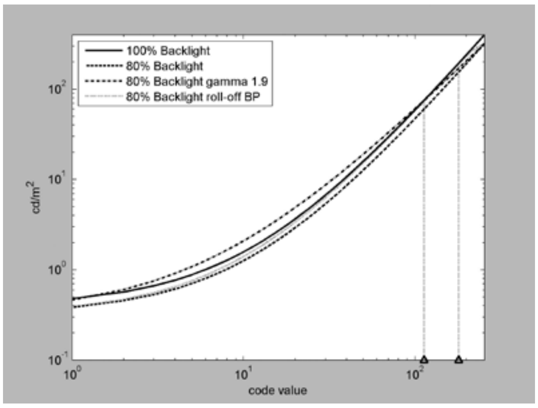


Fig. 8 Reducing gamma on dark levels.

selected an MFP of 180 as appropriate for 80% backlight. Fig. 10 uses pseudo-color to indicate those pixels modified by the algorithms. The boost and clip algorithm restores the luminance of all pixels but those greater than 230. Larger pixel values are clipped. These clipped pixels are pseudo-colored magenta in Fig. 10a. The tonescale roll-off BP algorithm restores the luminance of all pixels but those greater than the MFP. The pixels above the MFP are distorted. These distorted pixels are pseudo-colored cyan in Fig. 10b. The BP algorithms distort a larger set of pixels in exchange for avoiding hard clipping.

Focusing on a block from the clipped region, we see the difference in the algorithms in Fig. 11. The clipping tonescale, Fig. 11b, gives the greatest loss of detail compared to the original. The tonescale roll-off BP, Fig. 11c, attenuates detail rather than loosing it completely via clipping. The two-channel BP algorithm, Fig. 11d, gives the greatest detail preservation.

3・3 Tonescale quantization issues

The derivation of tonescale function given above ignored limitations on the bit-depth of the display. When implemented on a display supporting 8-bit color depth, the algorithm output must be quantized and may introduce quantization artifacts in the displayed image. In Fig. 12, the tonescale designed to correct for 80% backlight is shown on a display supporting 8-bits. The 8-bit limitation causes discontinuities in the tonescale compared to the ideal tonescale derived earlier.

Tonescale discontinuities as seen in Fig. 12 are known to cause visible contouring in nearly flat images. The visibility of this contouring is expected to be reduced due to the dimming in backlight, but remains as a potential source of artifacts. To reduce the potential for these artifacts, we utilize the bit-depth extension (BDE) method9. In this technique the bit-depth limitation of the display is overcome by adding noise based on the Visual Contrast Sensitivity Function (CSF) to the image prior to quantizing to the display bit-depth. This technique relies upon having an image with bit-depth greater than the display. Thus we represent the tonescale with 10-bits and apply BDE before quantizing to 8-bits and sending the data to the display. Any visible contour artifacts are removed. At a typical viewing distance, the BDE noise is invisible but the banding is broken up. Thus implementing BP with 10-bits followed by BDE avoids quantization artifacts.

Fig. 9 Original image for evaluation.

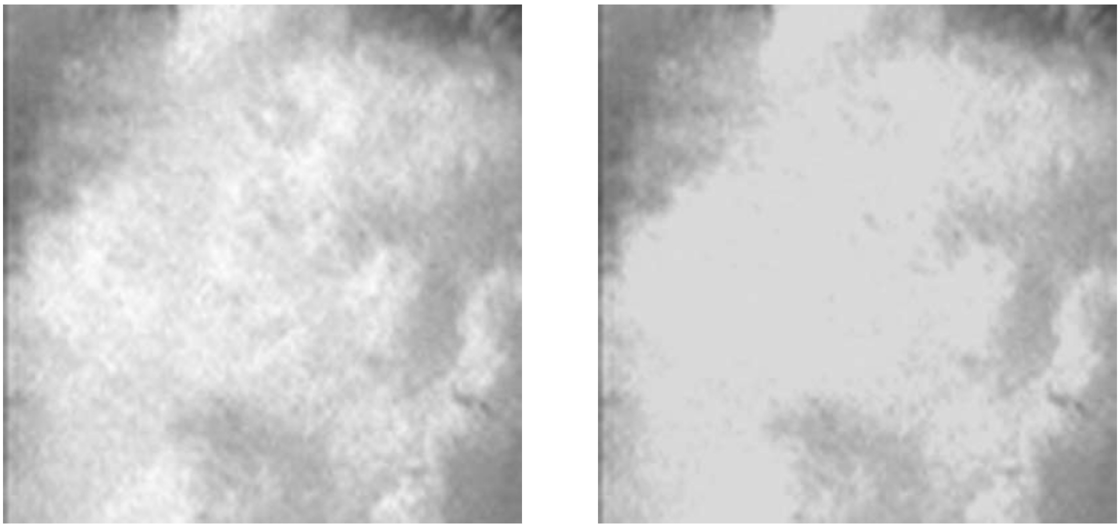
(a) Simple boost (clipped pixels magenta)

(b) Tonescale roll-off BP (distorted pixels cyan)

Fig. 10 Pseudo-color showing clipped and distorted regions.

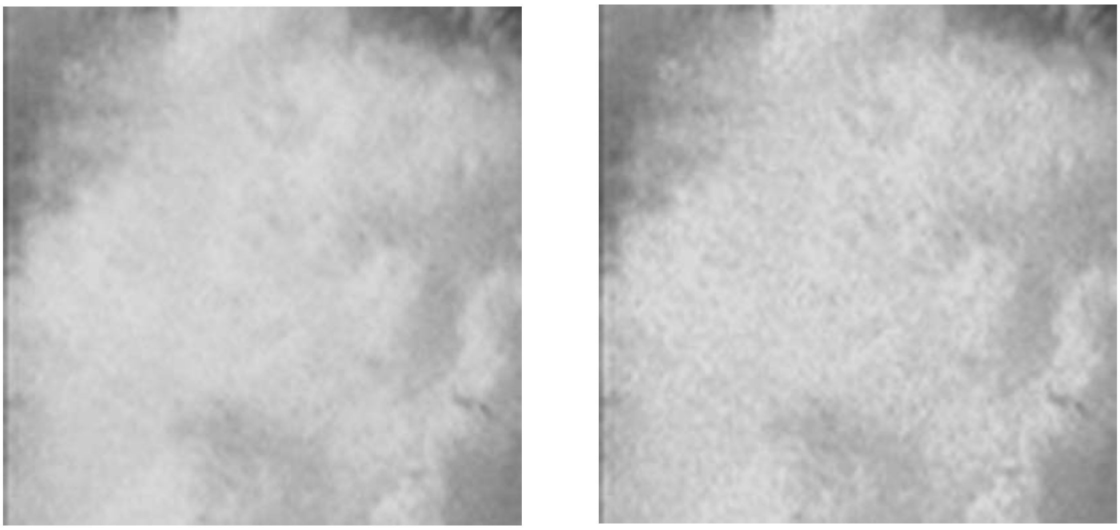
3・4 Temporal artifacts

The BP algorithm as described above for a static backlight dimming consists mainly of a static tonescale operator so no temporal artifacts are expected and none have been observed. When used with backlight modulation temporal artifacts certainly may arise due to the backlight selection. For instance the black level will follow the selected backlight regardless of BP operations. This may produce visible flicker on some content. The issue here is more related to the backlight selection process than the BP algorithm.



(a) Original (full backlight)

(b) Clipping tonescale (simulated 80% backlight)



(c) Tonescale roll-off BP (simulated 80% backlight)

(d) Two-channel BP (simulated 80% backlight)

Fig. 11 Algorithm comparison (block containing bright detail).

Conclusions

We described two methods for preserving image quality while compensating for backlight dimming. These preserve image quality lost by simple boost and clip or reducing gamma techniques when the image is processed to compensate for backlight dimming. These algorithms differ in the trade-off of complexity for highlight detail preservation. The tonescale only operation is simplest but attenuates bright detail. The two-channel BP algorithm preserves more highlight detail but requires a decomposition of the image into two spatial frequency channels. Both algorithms are non-adaptive and hence avoid temporal artifacts which can afflict image adaptive processes such as independent frame histogram equalization. We have primarily used this method for compensating for a fixed backlight dimming but it may be applied as part of an adaptive backlight system, allowing more aggressive backlight dimming.

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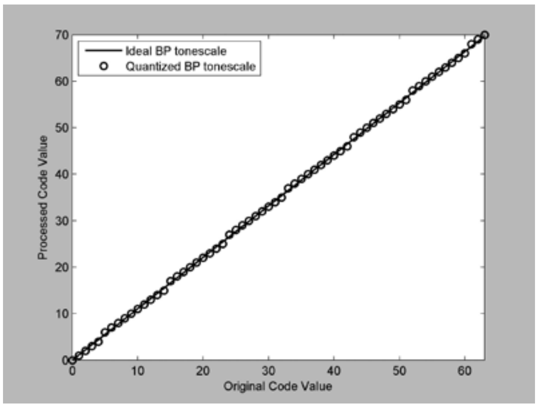

Fig. 12 Quantized compensating tonescale.

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