Final report

1.1 Project details

Project title	Energieffektiv kontrol af LED bagbelyst TV skærm og omgivende lys
Project identification (program abbrev. and file)	EUDP-13-I, Journalnr.: 64013-0150
Name of the programme which has funded the project	EUDP-13-I
Project managing company/institution (name and address)	DTU Fotonik
Project partners	Bang & Olufsen A/S
CVR (central business register)	30060946
Date for submission	

1.2 Short description of project objective and results

The goal of the project was to develop and demonstrate energy efficient control of LED backlight for TV displays. The novel approach is based on energy aware optimization. The project worked with and demonstrated LED backlight control for two different backlight architectures and for HDTV and UHD. The technique also included as an important input measurement of ambient light for optimal energy efficiency. For high quality TV material relative image dependent energy saving of 30% for the display was achieved. Taking the ambient light into account energy saving of up to seven times was demonstrated. It was shown that including the ambient light plays a crucially important role in energy efficient backlight control with high visual quality.

Projektets mål er at udvikle og demonstrere energieffektiv kontrol af LED bagbelysing til TV skærme. Den nye tilgang er baseret på optimering under hensyn til energiforbruget. Projektet udviklede og demonstrerede control af LED bagbelysning på to forskellige bagbelysings-arkitekturer og for HDTV og UHD. Teknikken inkluderede også som et væsentligt element måling af det omgivende lys for optimal energieffektivitet. For høj kvalitets TV materiale blev en relativ energi besparelse på 30% for displayet opnået. Ved også at benytte måling af niveauet af det omgivende lys blev energibesparelse op til syv gange demonstreret. Det blev påvist at tage højde for niveauet i det omgivende lys spiller en afgørende rolle i energieffektiv kontrol af bagbelysning ved høj visual kvalitet.

1.3 Executive summary

Bang & Olufsen and DTU Fotonik developed and demonstrated energy efficient advanced control of TV displays with LED backlights. This includes the utilization of measurements of the ambient light at the time of viewing the TV, in the control.
The goal of simultaneous reduction of energy consumption and image quality improvement in typical TV viewing in a living room was achieved. The high image quality shall contribute to the success of the energy efficient display. The energy goal of implementing and demon-

strating 20% energy reduction on the display energy consumption compared with other high quality algorithms was also achieved.
The project developed and demonstrated energy efficient TV platforms with local dimming of LED backlight. The main platform for the project was an experimental programmable platform established jointly at both DTU Fotonik and Bang & Olufsen. This was utilized extensively for development, testing and demonstration at both DTU Fotonik and Bang & Olufsen. This activity included measurements of the ambient light. Demonstration and testing were performed in an environment with controlled ambient light to demonstrate the light aware control and energy efficient solution.
The results of the project included demonstration of energy efficient control of LED backlight LCD displays for two different architectures including measurements of ambient light.
The LED backlight TV is dominating the market and the backlight accounts for most of the energy consumption. Thus efficient solutions to control the LEDs provide significant potentials for saving energy in households worldwide. Bang & Olufsen has used ideas on the backlight dimming from the collaboration in their newest TV set, BeoVision Avant.
The energy goals of the project were achieved including providing energy optimal, high quality LED backlight display control.

1.4 Project objectives

The goal of the project was simultaneous reduction of energy consumption and truly improved experienced image quality for typical TV viewing. The approach to achieve the goal was adaptive control of LED backlight the use of ambient light measurements. The adaptive algorithms for backlight control are based on analysis of images and use of information of the ambient light measurement.

A large part of the project was based on identical programmable TV platforms established at Bang & Olufsen and DTU Fotonik. For both partners adjustable settings of lights were established and used during development and testing. Based on ideas and input from the joint project Bang & Olufsen implanted the novel techniques in their newest TV model, the BeoVision Avant.

The project generally evolved as planned organized in the work packages, Energy control (WP2), Prototype platforms (WP3), and Test and measurements (WP4). Besides these technical WPs, the Project management (WP1) also included dissemination of the project and energy saving issues of LED backlight control in TVs and ambient light.

The project generally proceeded according to overall plans and the three project milestones were achieved. The three project Milestones and results within these are:

- Ambient light measurements (M1)

  - A model of the influence of ambient light for the visual quality of a displayed image was established. The interaction of ambient light and backlight was studied, implemented and tested in TVs at Bang & Olufsen

- Power control algorithms (M2)

  - Integration of ambient light measurements in optimal LED backlight control
  - Power control algorithm for sustained optimal performance

- Demonstration of energy efficient HD and Ultra HD (M3)

  - Demo of energy efficient, ambient light aware LED backlight control
  - Demo of joint energy efficient adjustment of backlight and ambient light

The results and milestones are presented and discussed in more detail in the next Section.

The project plan has on a quarterly basis been reviewed by the partners. A shift of focus towards edge-lit rather than direct-lit backlight architecture was decided compared with our original plans and ideas were made. A major reason was Bang & Olufsen's focus on the edge-lit backlight architecture for the novel adaptive backlight dimming. A related issue is that edge-lit dominates over direct-lit on the market today. Another aspect of increased focus in the project was the temporal aspects of the video. A few high contrast video sequences were chosen. These sequences lead to more work with flicker control than originally anticipated. They both provided an opportunity for large reductions in power and improved contrast in the displayed video and when doing so, they pose a challenge visually in the temporal dimension. Large efforts were put into evaluating these sequences and achieving high power savings at the same time as achieving a good quality. These aspects are also discussed in more detail in the next section.

1.5 Project results and dissemination of results

The *main activities* are reflected by the work packages (WPs) and Milestones (M), which are briefly listed in Sec. 1.4. Here we will describe and discuss these in more detail.
The topic is as mentioned LED backlight dimming in TV displays. The energy consumption of the display is directly proportional to the LED values, thus dimming the LED backlight directly translates into energy savings. The display constitutes the major part of the energy consumption besides this there is a (approximately constant) contribution from the electronics of the TV, which is not considered in this project. For a more comprehensive basic introduction to backlight dimming, please refer to [1] and for a more in depth technical overview please refer to e.g. [3] or [4]. An overview is given in Figure 1, illustrating how the LED backlight is dimmed in dark part of the image and thereafter the LC (liquid crystal) pixels are adjusted.

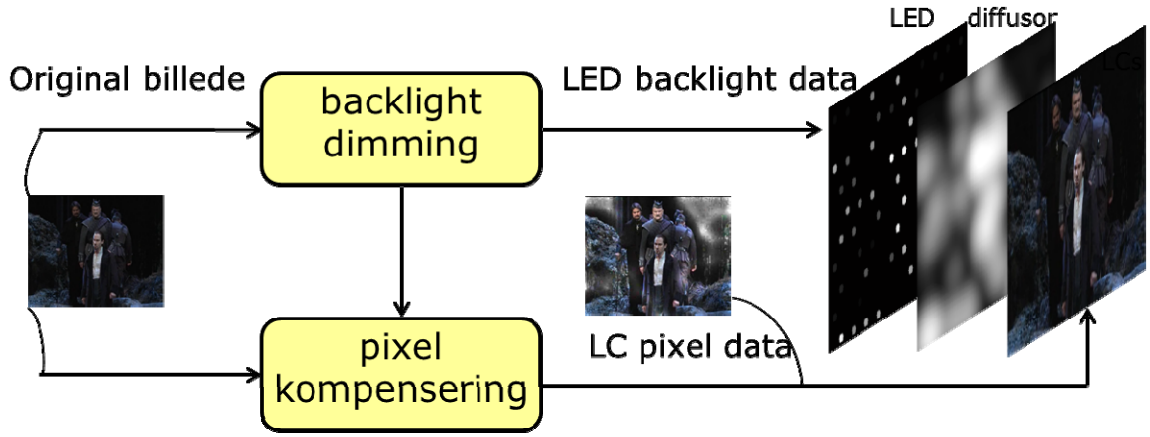

Figure 1. Based on image data the LED backlight values are dimmed and thereafter the LC pixel values are adjusted [1].

Controlling the LED backlight has been the main activity of the project. The power control (WP2, M2) is constituted by controlling the LED backlights. Based on an initial experimental platform, this has been updated for the project incl. the temporal issues which are crucial for TV display. The hardware for the platform was provided by Bang & Olufsen in a previous project, but prepared such that it may be programmed, a feature heavily used at DTU Fotonik. The platform included an FPGA, which is a flexible programmable hardware very suited for experiments and specialized solutions. Identical platforms were available at both DTU Fotonik and Bang & Olufsen. This allowed exchange of software and video results electronically. (An ftp site was set-up for this.) Along the project Bang & Olufsen has introduced these ideas in the new BeoVision Avant.
Ambient light measurements were defined and established (M1) and introduced in the backlight control (M2) for lab experiments and in the BeoVision Avant. Thorough testing and measurements (WP4) were performed. This was centered on a demo (M3) and test set-up based on the experimental platform and with variable ambient light. It was first established in a preliminary version in the video-lab at DTU Fotonik and later in a carefully designed and

controlled set-up at Bang & Olufsen, which could be used for subjective testing of the video quality. Testing was done over a wide range of values for the display brightness (a global setting as expressed by peak white of the display) in the range of 75-480 cd/m^2 for display. This is directly proportional to the display power consumption. This value is set based on the ambient light. For the image depending local dimming, the target 20% compared to other LED local dimming techniques for HDTV was achieved. The two savings factor together.

The *technical results* of the project include:
The final technical result of the project was demonstration and test of energy efficient control of LED backlight display for HDTV and UHD including measurements of ambient light. The primary set-up spanned the combination of a range of the display (peak white) brightness values of 75, 200, 490 cd/m^2 (the latter being the max. value for the given TV) and a range of ambient light level: 0 (lights off), 5 lux and 60 lux [2] and it was based on the experimental platform of a Full HD edge-lit display. This was used for visual testing Bang & Olufsen and also as the primary demonstration of the project. This test and demo was based on intial pilot testing [5] only changing the levels of ambient light, modeling of the contrast and LCD leakage [4], and the visual impact of backlight dimming [8]. The results showed significant visual improvement of quality of a local backlight dimming providing a 30% reduction of display power consumption at high quality. It showed that there is a significant interaction of display peak with and ambient light and a balance of ambient light and peak white was preferred. This leads to the suggestion for a low power or home cinema mode in low ambient light, reducing display power consumption by as much as a factor of 10 overall, i.e. to 10%. Reducing artificial ambient light, e.g. living room light in the evenings as part of this set-up will also reduce household energy consumption.
To illustrate the effects, Figure 2 depicts the effects of dimming vs. no dimming. (The image is composed of two photos of a Bang & Olufsen screen displaying the same image but with and without dimming. The left part is from the set-up with no dimming and the right part from the set-up with dimming.) The dimming directly gives energy savings.

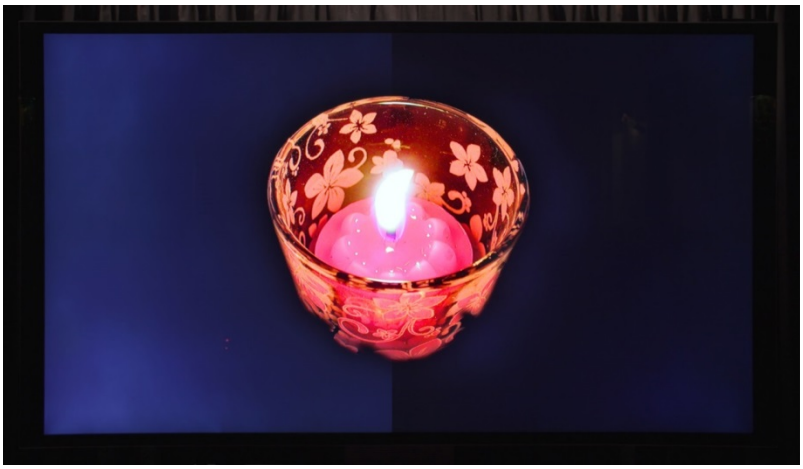

Figure 2. Illustration of dimming vs. no dimming. In the right part local dimming (direct dimming) is applied, whereas in the left part full backlight is used and the leakages of light through the LC pixels are clearly visible.

For dark, high contrast test sequences, we demonstrated as much as an overall reduction of display power consumption by a factor of 100, but also the achieving high quality at this high level of reduction of LED power consumption is very challenging. A first approach is to give such sequences special treatment.

A technical result supporting the main overall result reported above is a model of the influence of ambient light on the visual quality of the display. The influence of perceived quality is reported in [2] and [4] and how to integrate it in the backlight control is reported in [9]. The light levels of ambient light reported is as measured onto the screen as this is the most important and potentially having direct influence on energy consumption. Other measures as color temperature was not pursued as while it has direct influence on color perception and quality, the influence on LED backlight and thereby energy was evaluated to be marginal.

The backlight control frame work, developed at DTU Fotonik, includes an option to further dim the LED backlight and thereby increase energy savings, in an optimal trade-off with quality. In this case the highlight parts of the displayed image will be effected. To provide gracefull degradation so-called soft clipping may be applied. The effects and preferences for this was studied in [6]. The proposed method for this was the preferred approach in the study. The use of direct backlight was also studied at DTU Fotonik and part of quality study reported in [7].

As part of the project, Bang & Olufsen developed and implemented real-time power control for sustained energy efficiency for both Full HD and Ultra HD resolutions.
The solutions for different display sizes encompass both direct lit and edge-lit UHD.
For the backlight algorithm a fast (histogram based) backlight algorithm developed for Full HD is extended to UHD. The influence of ambient light is the same for UHD is the same as for FHD. The way the two resolutions are handled currently is based on downsampling/upsampling. The dimming algorithm developed for FHD has shown robustness with respect to downsampling/upsampling of UHD by a factor 2 in both horizontal and vertical direction, and this holds for both the measurements part and the compensation path. B&O has developed a solution for the current BeoVision Avant TV set, where the measure is downsampled by factor 2 in both directions. In the compensation part the FHD version of the point spread functions characterizing each LED segment is upsampled to UHD, and afterwards the LC elements are compensated at full UHD resolution.

Commercial results
Bang & Olufsen has developed and implemented real-time backlight dimming for both Full HD and Ultra HD resolutions in their newest TV, the BeoVision Avant. The current UHD TV architecture is in an intermediate step, where there as in most current TV sets is a partly parallel solution for UHD. This UHD TV architecture is in an intermediate step, but soon newer architectures will be ready with complete support for UHD. In the further process a shift FPGA programmable solutions towards IC (integrated circuit) solutions could provide additional savings in the electronic part.

It is as such not possible to prove a significant increase in revenue or employment of this project. For Bang & Olufsen the project has been an element in a continuing and comprehensive development process on image enhancement and energy optimization. Activities as these are extremely important to maintain Bang & Olufsen's position as a High-end TV brand. Thus the project contributes to maintaining employment in Denmark/Europe and secures a future for Bang & Olufsen as an important player in the Danish society.

Thus the expected results for applying the techniques commercially has been achieved.

As described above the *expected* energy goals of the project are also achieved:
- energy optimal, high quality LED backlight display control: Both image adaptive taking image data into account frame by frame in the video sequence and reacting to the ambient light dimming the overall light level at lower ambient light levels.
- demonstrate energy savings of 20% compared to other LED local dimming techniques for HDTV: This was evaluated on the ISO/IEC database used in current TV energy regulations [9] providing high quality at a relative power consumption of 70-75%, which provides 20% higher energy savings than other high quality solutions [9].
- demonstrate additional savings using ambient light level: As argued above the display energy savings achieved by local dimming and reducing overall (peak white) brightness factors together [2], [9].

As an example of quality and energy performance, Figure 3 depicts distortion measured by MSE (mean square error, low values correspond to high quality) vs. relative average power consumption of the display. The two optimization based techniques ('Power' and 'EnergyEff') developed at DTU Fotonik is compared in a high quality set-up with state-of-the art 'Albrecht' algorithm.

All in all, the objectives of the project have been achieved. As mentioned, the most savings may be achieved by adjusting the screen brightness according to the ambient light. This may be as much as a factor of 5, or as the experiments even up to a factor of almost 7. For combined reduction down to 10%. No goals as such were set for the savings by this reduction of overall brightness. There were two reasons for this: First it depends on the ambient light level when watching TV and we have no statistics for this. The other is it is also difficult to compare with other solutions. For the local dimming, it is much more well-defined what the savings are and therefore we set a goal for this part of the project.

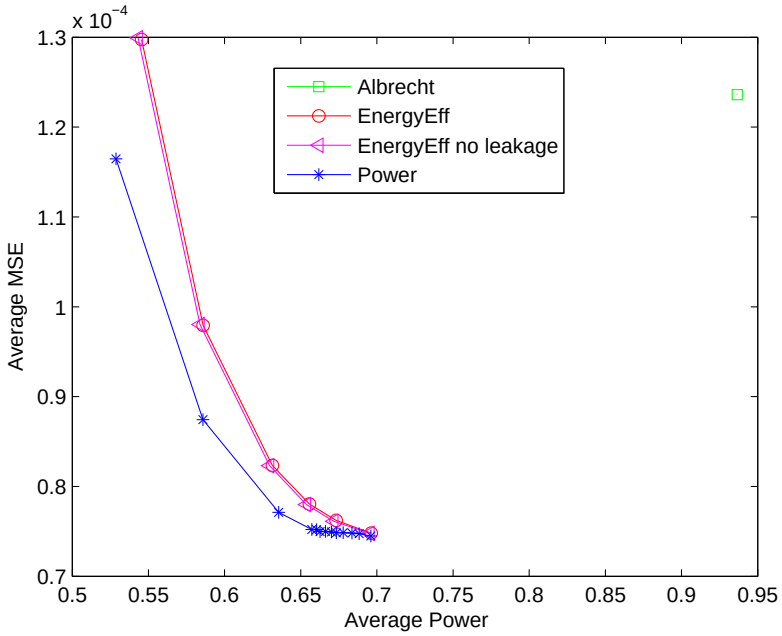

Figure 3. Quality and power consumption for local backlight dimming. High quality test with the DTU Fotonik algorithms ('Power', 'EnergyEff) compared with the 'Albrecht' method.

Dissemination

The project results have disseminated as follows, in publications [1-9], (see publication list) as well as demos, presentation and student activities.

An overview of the dissemination activities are:

- A web-pages for the project: http://www.energyefficientledtv.fotonik.dtu.dk/
- Research publication in international journal [4]
- Book chapter [3]
- Contributions to international conferences [2, 5-8]
- Article in the Danish press [1]
- Project report [9]
- Visual testing and demos at B&O.
- Demos at DTU for Louis Poulsen A/S, open house activities at DTU Fotonik, spring and fall, 2014, and demo for the LED Systems group at DTU Fotonik, Roskilde.
- 'Grøn Dyst' student project at DTU 2014 and other course related activities at DTU.

More publications e.g. a follow-up journal paper reporting results of the technical report, not yet published, are anticipated.

1.6 Utilization of project results

The project results are already in use commercially and they are expected to be further used both commercially and in new research activities.

The new technology is already being *commercially* marketed now. Bang & Olufsen launched a new TV, BeoVision Avant, with Ultra High-Definition LCD using edge-type LED back-light. In this product, Bang & Olufsen has developed a new local backlight dimming algorithm. The

algorithm gives an improved contrast of the images and reduces the energy consumption of the TV. The energy saving is further optimized as a function of the ambient light in the room, where the TV is used. Several partial results of the research lead by DTU Fotonik has been used in this new algorithm.

The BeoVision Avant is being sold in many countries world-wide (in Europe, North and South America, Middle East, Africa and Australasia.)
The product has received many positive reivews on e.g. image quality and the demand and sales have exceeded expectations considerably.

Bang & Olufsen has co-authored a number of publications about the project results. This will also be used in the marketing of Bang & Olufsen's products.
Projects as this EUDP project contribute to maintaining and strengthening Bang & Olufsen's competencies in image processing and display technology. This is essential towards attracting the right technology and research partners.

The technology developed and studied within the project enables to satisfy the tightened legislation for TVs, which is expected to by be put into force in Europe in 2016.

The project has led to novel ideas connected to new and coming technologies being investigated in the TV industry for increasing the quality (e.g. HDR - High Dynamic Range). It is an obvious opportunity to investigate these new technologies departing from the results achieved in this EUDP project and thus also carry over the new techniques for energy efficiency in image dependent control of TV displays. In this connection, HDR technology has a clear potential and thereby also commercial relevance for Bang & Olufsen. Also continuing the work on ambient light has potentials.

The project partners do not expect to take out patents.

The project results contribute to realize energy policy in form of energy efficient TV products, and in this connection achieve energy efficiency in TV display and at the same time high image quality.

No Ph.D.s have been directly involved in the project, one reason being that the project was set-up as a focussed shorter term project not spanning the three years of a Ph.D.

1.7 Project conclusion and perspective

The goal of addressing energy savings and high visual quality at the same time has been achieved. Image dependent local dimming of LED TV has been implemented, evaluated, tested and demonstrating. In the lab set-up, high quality settings have been demonstrated for an energy savings of 30% for the ISO reference TV material and 20% compared to other high quality LED local dimming techniques for HDTV has been calculated. For movie material the corresponding energy savings would be about 50% for high quality. The energy saving numbers are given for the display, which generally consumes most of the energy in the TV set. From this starting point a further trade-off between energy and quality may be invoked, e.g. to meet a specified level of energy consumption.

The use of measurements of ambient light was also studied. This was directly used to dim the brightness of the screen e.g. the peak white (PW), thus directly saving energy. Reductions by up to a factor of seven were demonstrated under dark viewing conditions enabled by the backlight dimming. Further methods to integrate this in the local backlight dimming were performed and finally the interaction of peak white and ambient light level was studied. A visual test of backlight dimming under differing ambient light conditions was conducted. This clearly showed dimming and brightness (PW) do interact in relation to visual perception and the importance of combining the two techniques, for high quality energy efficient settings in low ambient light settings. The testing confirmed the changing of preferences of PW at different ambient light levels. Adjustment of displayed signal to ambient light provides a nice

set-up for both improving video quality and providing energy savings, and the local backlight dimming and reduction of PW factors together energy-wise. Viewing movies in a low light home cinema like setting will combine for a factor of 7-14. To express the average combined savings would require statistics of ambient light, information which is not available to our knowledge.

The better the control and understanding of the crucial elements as ambient light, peak white, backlight dimming, the better quality and energy saving strategies may be devised. In a bit more technical terms on the local dimming side, the adaptivity in the algorithm shall ideally also incorporate the brightness of the image sequences. For dark sequences our local dimming will reduce backlight and energy significantly and the processing shall ensure good temporal performance and avoid fluctuations in dark parts. For brighter sequences this is less critical and we harvest an initial but less pronounced energy saving and the control can focus on selecting the refined second order effects in terms of a trade-off of quality and energy. One approach to the adaptivity is to extend the basic quality – energy frame work, by treating dark sequences as special cases, but preferably in a continuous manner.

The project has worked with both full HD (FHD) and Ultra High Definition (UHD) in 4K resolution. In terms of backlight architecture both edge-lit and direct lit has been used. The focus has been on edge-lit FHD. A fast backlight algorithm for FHD has been extended to UHD with success. The same ambient light solution has been applied to FHD and UHD. The dimming algorithm developed for FHD has shown robustness with respect to UHD as detailed in the report.

The *perspectives* of the project includes both direct applications at B&O, potential effects in TVs and on legislation and longer terms perspectives.

The project has advanced local backlight dimming for TVs. This has been implemented in B&O TVs and will continue to be relevant to their TV production for the coming years. The research publications may also inspire other manufacturers to improve upon energy savings by local backlight dimming and measurement of ambient light.

The project has provided better understanding of local backlight dimming and energy savings. This may influence legislation on energy legislation and grades. Besides providing efficient techniques, the project also shed light on the importance of brightness.

As mentioned, considering the interaction of TV brightness (e.g. PW) and ambient light in the is crucial for optimal energy savings. An instantiation of this could be special modes as *home cinema* or *energy savings*, which both could address energy savings and high quality at the same time, but emphasizing one or the other in implementation and/or towards the consumer.

A further perpsective study would be to integrate control of light in the room in question e.g. a living room and the TV, e.g. in connection with the *home cinema* and *energy savings* modes. The extension to include room lights would provide a combination of overall energy consumption and quality of experience (QoE) under the given viewing condition.

As higher quality TV/video material and displays become available, the details of the interaction should be revisited or further developed.

Annex

Project Publications:

[1] S. Forchhammer, B. Verbraak, J. Meldgaard Pedersen, S. Bech, "Grøn Skærmteknologi giver en god sort," (in Danish) to appear in *DTU Fotonik Højdepunkter i Lysets År 2015*, also sent to videnskab.dk.

[2] C. Mantel, S. Bech, J. Korhonen, S. Forchhammer, J. Melgaard Pedersen, "Subjective quality of videos displayed with local backlight dimming at different peak white and ambient light levels," Submitted to QoMex, Greece, 2015.

[3] S. Forchhammer, J. Korhonen, C. Mantel, X.Shu, X. Wu, "High Dynamic Range Video – From Acquisition to Display and Applications," Chapter 13 in *HDR display characterization and modeling*, Editors: F. Dufaux, P. Le Callet, R. Mantiuk and M. Mrak, Elsevier 2015.

[4] C. Mantel, S. Bech, J. Korhonen, S. Forchhammer, J. Melgaard Pedersen, "Modeling the Subjective Quality of Highly Contrasted Videos Displayed on LCD With Local Backlight Dimming," *IEEE Trans. Image Processing*, Vol. 24, No. 2, 2015, p. 573-582.

[5] C. Mantel, J. Korhonen, J. Meldgaard Pedersen, S. Bech, J.D. Andersen, S. Forchhammer, "Subjective quality of video sequences rendered on LCD with local backlight dimming at different lighting conditions," in *Proc. SPIE*. Vol. 9396 SPIE - International Society for Optical Engineering, 2015. 93960S.

[6] J. Korhonen, C. Mantel, S. Forchhammer, "Subjective comparison of brightness preservation methods for local backlight dimming displays," in *Color Imaging XX: Displaying, Processing, Hardcopy, and Applications, Proceedings of SPIE* Vol. 9395 (SPIE, Bellingham, WA 2015), 939504.

[7] C. Mantel, S.C. Ferchiu, S. Forchhammer, "Comparing subjective and objective quality assessment of HDR images compressed with JPEG-XT," in *Proc. IEEE 16th International Workshop on Multimedia Signal Processing*. IEEE, 2014.

[8] C. Mantel, S. Bech, S. Forchhammer, J. Korhonen, J. Melgaard Pedersen, "Investigating subjective attributes of quality for videos displayed with local backlight dimming," *Proc. QoMEX,* 2014.

[9] Technical report. *Energy Efficient Control of LED Backlight TV Displays and Ambient Light*. Eds. J. D. Andersen, C. Mantel, Søren Forchhammer. DTU Fotonik. 2015.

Relevant links:

Project home page: http://www.energyefficientledtv.fotonik.dtu.dk/

Energy reports and regulations:

[10] International Standard IEC 62087-BD ed3.0: Methods of measurement for the power consumption of audio, video and related equipment, INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2011.

[11] "Implementing directive 2005/32/ec of the European parliament and of the council with regard to ecodesign requirements for televisions," *Official Journal of the European Union*, 2009.

[12]"Minimum allowable Values of Energy Efficiency and Energy Efficiency Grades for flat Panel Television", National Standard of the People's Republic of China GB24850-2010. Update

[13] B. Harrison, M. Scholand, CLASP European Programme, Review of Ecodesign and Energy Labelling Regulations for Televisions and Draft Regulation for Electronic Displays: Discussion Paper, Nov. 10, 2014
http://www.clasponline.org/en/Resources/Resources/PublicationLibrary/2014/EU-Ecodesign-and-Energy-Labeling-of-Electronic-Displays.aspx