

# Video Coding: Part II of Fundamentals of Source and Video Coding

---

**Heiko Schwarz**

Fraunhofer Institute for Telecommunications —  
Heinrich Hertz Institute  
Germany  
heiko.schwarz@hhi.fraunhofer.de

**Thomas Wiegand**

Berlin Institute of Technology and Fraunhofer Institute  
for Telecommunications — Heinrich Hertz Institute  
Germany  
thomas.wiegand@tu-berlin.de

**now**

the essence of knowledge

Boston — Delft

## Foundations and Trends<sup>®</sup> in Signal Processing

*Published, sold and distributed by:*

now Publishers Inc.  
PO Box 1024  
Hanover, MA 02339  
United States  
Tel. +1-781-985-4510  
www.nowpublishers.com  
sales@nowpublishers.com

*Outside North America:*

now Publishers Inc.  
PO Box 179  
2600 AD Delft  
The Netherlands  
Tel. +31-6-51115274

The preferred citation for this publication is

H. Schwarz and T. Wiegand. *Video Coding: Part II of Fundamentals of Source and Video Coding*. Foundations and Trends<sup>®</sup> in Signal Processing, vol. 10, no. 1–3, pp. 1–346, 2016.

*This Foundations and Trends<sup>®</sup> issue was typeset in L<sup>A</sup>T<sub>E</sub>X using a class file designed by Neal Parikh. Printed on acid-free paper.*

ISBN: 978-1-68083-178-8  
© 2016 H. Schwarz and T. Wiegand

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, mechanical, photocopying, recording or otherwise, without prior written permission of the publishers.

Photocopying. In the USA: This journal is registered at the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923. Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by now Publishers Inc for users registered with the Copyright Clearance Center (CCC). The ‘services’ for users can be found on the internet at: [www.copyright.com](http://www.copyright.com)

For those organizations that have been granted a photocopy license, a separate system of payment has been arranged. Authorization does not extend to other kinds of copying, such as that for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale. In the rest of the world: Permission to photocopy must be obtained from the copyright owner. Please apply to now Publishers Inc., PO Box 1024, Hanover, MA 02339, USA; Tel. +1 781 871 0245; [www.nowpublishers.com](http://www.nowpublishers.com); [sales@nowpublishers.com](mailto:sales@nowpublishers.com)

now Publishers Inc. has an exclusive license to publish this material worldwide. Permission to use this content must be obtained from the copyright license holder. Please apply to now Publishers, PO Box 179, 2600 AD Delft, The Netherlands, [www.nowpublishers.com](http://www.nowpublishers.com); e-mail: [sales@nowpublishers.com](mailto:sales@nowpublishers.com)

**Foundations and Trends<sup>®</sup> in Signal Processing**  
Volume 10, Issue 1–3, 2016  
**Editorial Board**

**Editor-in-Chief**

**Yonina Eldar**

Technion - Israel Institute of Technology  
Israel

**Editors**

Robert M. Gray  
Founding Editor-in-Chief  
*Stanford University*

Pao-Chi Chang  
*NCU, Taiwan*

Pamela Cosman  
*UC San Diego*

Michelle Effros  
*Caltech*

Yariv Ephraim  
*GMU*

Alfonso Farina  
*Selex ES*

Sadaoki Furui  
*Tokyo Tech*

Georgios Giannakis  
*University of Minnesota*

Vivek Goyal  
*Boston University*

Sinan Gunturk  
*Courant Institute*

Christine Guillemot  
*INRIA*

Robert W. Heath, Jr.  
*UT Austin*

Sheila Hemami  
*Northeastern University*

Lina Karam  
*Arizona State U*

Nick Kingsbury  
*University of Cambridge*

Alex Kot  
*NTU, Singapore*

Jelena Kovacevic  
*CMU*

Geert Leus  
*TU Delft*

Jia Li  
*Penn State*

Henrique Malvar  
*Microsoft Research*

B.S. Manjunath  
*UC Santa Barbara*

Urbashi Mitra  
*USC*

Björn Ottersten  
*KTH Stockholm*

Vincent Poor  
*Princeton University*

Anna Scaglione  
*UC Davis*

Mihaela van der Shaar  
*UCLA*

Nicholas D. Sidiropoulos  
*TU Crete*

Michael Unser  
*EPFL*

P. P. Vaidyanathan  
*Caltech*

Ami Wiesel  
*Hebrew U*

Min Wu  
*University of Maryland*

Josiane Zerubia  
*INRIA*

# Editorial Scope

## Topics

Foundations and Trends<sup>®</sup> in Signal Processing publishes survey and tutorial articles in the following topics:

- Adaptive signal processing
- Audio signal processing
- Biological and biomedical signal processing
- Complexity in signal processing
- Digital signal processing
- Distributed and network signal processing
- Image and video processing
- Linear and nonlinear filtering
- Multidimensional signal processing
- Multimodal signal processing
- Multirate signal processing
- Multiresolution signal processing
- Nonlinear signal processing
- Randomized algorithms in signal processing
- Sensor and multiple source signal processing, source separation
- Signal decompositions, subband and transform methods, sparse representations
- Signal processing for communications
- Signal processing for security and forensic analysis, biometric signal processing
- Signal quantization, sampling, analog-to-digital conversion, coding and compression
- Signal reconstruction, digital-to-analog conversion, enhancement, decoding and inverse problems
- Speech/audio/image/video compression
- Speech and spoken language processing
- Statistical/machine learning
- Statistical signal processing

## Information for Librarians

Foundations and Trends<sup>®</sup> in Signal Processing, 2016, Volume 10, 4 issues. ISSN paper version 1932-8346. ISSN online version 1932-8354. Also available as a combined paper and online subscription.

Foundations and Trends<sup>®</sup> in Signal Processing  
Vol. 10, No. 1–3 (2016) 1–346  
© 2016 H. Schwarz and T. Wiegand  
DOI: 10.1561/20000000078



## **Video Coding: Part II of Fundamentals of Source and Video Coding**

Heiko Schwarz  
Fraunhofer Institute for Telecommunications —  
Heinrich Hertz Institute  
Germany  
heiko.schwarz@hhi.fraunhofer.de

Thomas Wiegand  
Berlin Institute of Technology and Fraunhofer Institute  
for Telecommunications — Heinrich Hertz Institute  
Germany  
thomas.wiegand@tu-berlin.de

# Contents

---

<b>1</b>	<b>Introduction</b>	<b>2</b>
1.1	The Video Communication Problem . . . . .	3
1.2	Scope and Overview of the Text . . . . .	6
<b>2</b>	<b>Acquisition, Representation, Display, and Perception</b>	<b>8</b>
2.1	Fundamentals of Image Formation . . . . .	9
2.2	Visual Perception . . . . .	16
2.3	Representation of Digital Images and Video . . . . .	47
2.4	Image Acquisition . . . . .	59
2.5	Display of Images and Video . . . . .	67
2.6	Chapter Summary . . . . .	70
<b>3</b>	<b>Video Coding Overview</b>	<b>73</b>
3.1	Properties of Digital Video Signals . . . . .	75
3.2	Intra-Picture Coding . . . . .	77
3.3	Hybrid Video Coding . . . . .	79
3.4	Coding Efficiency . . . . .	95
3.5	Chapter Summary . . . . .	99
<b>4</b>	<b>Video Encoder Control</b>	<b>101</b>
4.1	Encoder Control using Lagrange Multipliers . . . . .	102
4.2	Lagrangian Optimization in Hybrid Video Encoders . . . . .	108

4.3	Additional Aspects of Video Encoders . . . . .	132
4.4	Chapter Summary . . . . .	140
<b>5</b>	<b>Intra-Picture Coding</b>	<b>142</b>
5.1	Transform Coding of Sample Blocks . . . . .	144
5.2	Intra-Picture Prediction between Transform Blocks . . . . .	183
5.3	Block Sizes for Prediction and Transform Coding . . . . .	192
5.4	Chapter Summary . . . . .	202
<b>6</b>	<b>Inter-Picture Coding</b>	<b>204</b>
6.1	Accuracy of Motion-Compensated Prediction . . . . .	207
6.2	Block Sizes for Motion-Compensated Prediction . . . . .	228
6.3	Advanced Motion-Compensated Prediction . . . . .	236
6.4	Coding of Motion Parameters . . . . .	250
6.5	Coding Structures . . . . .	256
6.6	In-Loop Filters . . . . .	265
6.7	Chapter Summary . . . . .	281
<b>7</b>	<b>Video Coding Standards</b>	<b>284</b>
7.1	Syntax Features and Coding Tools . . . . .	287
7.2	Comparison of Coding Efficiency . . . . .	298
7.3	Chapter Summary . . . . .	305
<b>8</b>	<b>Summary</b>	<b>307</b>
	<b>Acknowledgements</b>	<b>312</b>
	<b>Appendices</b>	<b>314</b>
<b>A</b>	<b>Test Sequences</b>	<b>315</b>
<b>B</b>	<b>Software for Coding Experiments</b>	<b>317</b>
	<b>References</b>	<b>319</b>

## Abstract

Digital video coding technologies have become an integral part of the way we create, communicate, and consume visual information. In the first part of this two-part text, we introduced the fundamental source coding techniques entropy coding, quantization, prediction, and transform coding. The present second part describes the application of these techniques to video coding. We introduce the basic design of hybrid video encoders and decoders, explain the basic concepts of intra-picture coding, motion-compensated prediction, and prediction error coding, and discuss encoder optimization techniques. Special emphasis is put on a fair analysis of various design aspects and coding tools in terms of coding efficiency. We highlight the application of the discussed concepts in modern video coding standards and compare important standards with respect to the achievable coding efficiency.

---

H. Schwarz and T. Wiegand. *Video Coding: Part II of Fundamentals of Source and Video Coding*. Foundations and Trends<sup>®</sup> in Signal Processing, vol. 10, no. 1–3, pp. 1–346, 2016.

DOI: 10.1561/20000000078.



# 1

---

## Introduction

---

The application areas of digital video today range from multimedia messaging, video telephony, and video conferencing over mobile television, wireless and wired Internet video streaming, standard- and high-definition television broadcasting, subscription and pay-per-view services to personal video recorders, digital camcorders, and optical storage media such as the digital versatile disc (DVD) or the Blu-ray disc. Ultra-high definition (UHD) television sets, with a resolution of  $3840 \times 2160$  image points, four times as many as high-definition screens, have recently become available for end consumers. Due to its horizontal resolution, this UHD format is often also called 4K format. Internet streaming providers have started to produce and deliver content in 4K. At the time of writing this text, the first satellite broadcasters are testing a new UHD infrastructure; the first UHD demo channels are already on air [230] and the first sport events and concerts have been successfully broadcasted live in 4K [231].

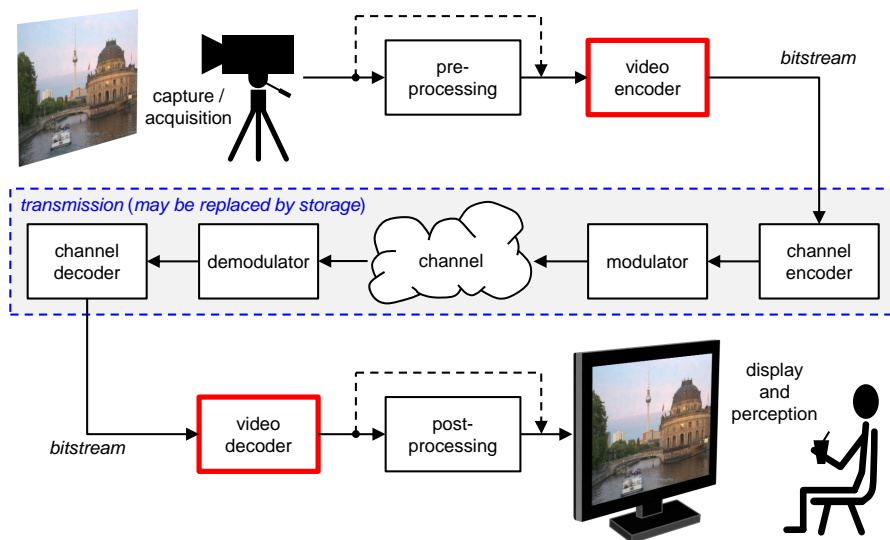
One of the key techniques that enabled the variety of digital video applications is *video coding*, also called *video compression*. Even though the main task of video coding is to compress visual information so that it requires as little bit rate as possible, the availability of advanced

video coding techniques also enables a number of new applications. For example, the availability of the improved video coding standard H.264 | MPEG-4 AVC [121] was a driving factor for the broad introduction of high-definition television (HDTV) and several video streaming services. Future video services and applications will benefit from the even more efficient standard H.265 | MPEG-H HEVC [123]. In fact, the percentage of the Internet traffic that is caused by the transmission of compressed video data increases continuously. According to a study by Cisco [48], 66% of the bits transmitted in the consumer Internet in 2013 were video data. For 2018, an increase to 79% is predicted.

Even though the various applications of digital video differ in the spatial resolution, the required compression ratio, and the acceptable video quality, the same basic video compression principles are employed. In the following, we give an overview of the main elements of a video communication chain, from the capturing of pictures to display and human perception. The main focus of the present text lies however on the description of the fundamental principles of video compression. In that context, we will also discuss the improvements in video coding technology that led to a continuous increase of coding efficiency from one generation of video coding standards to the next.

## 1.1 The Video Communication Problem

The most important processing steps of a typical video transmission system are illustrated in the block diagram of [Figure 1.1](#). At the beginning of the signal processing chain, a digital video signal is *captured* by a camera. The lens of the camera projects an image of a 3D scene onto the surface of an image sensor, which samples the optical signal. The resulting raw data samples are further processed inside the camera and transformed into a representation format. The video signal eventually delivered by the camera consists of arrays of discrete-amplitude samples. An optional *preprocessing* step may be applied, for example, for improving the contrast and color representation or for reducing the noise; the latter has typically a beneficial effect on the following coding step. The *video encoder* maps the sample arrays of the representation



**Figure 1.1:** Structure of a typical video communication scenario. The pre- and postprocessing steps are optional; the transmission may be replaced by storage.

format into a so-called *bitstream*, which usually has a much lower bit rate than the raw data samples.

In the simplest case, the video bitstream generated by the encoder is *stored*, typically inside a container format such as the Audio Video Interleave (AVI), Quicktime, or Matroska format. In most applications, however, the compressed video is transmitted. The transmission chain usually consists of a channel encoder, a modulator, the actual physical transmission channel, a demodulator, and a channel decoder. The *channel encoder* extends the bitstream by adding structured redundancy suitable for detecting or correcting potential transmission errors at the receiver side. The *modulator* maps the resulting data stream into an analog signal, which is transmitted over the physical *channel*. At the receiver side, the *demodulator* extracts a digital data stream from the received analog signal. The *channel decoder* produces the received bitstream by detecting and correcting transmission errors and extracting the video data packets from the data stream. Note that if not all transmission errors can be corrected, the received bitstream is not identical to the bitstream generated by the video encoder.

The *video decoder* reconstructs the sample arrays from the received bitstream or, alternatively, the bitstream read from a storage device. Optionally, the decoded signal may be *postprocessed* in order to reduce the impact of transmission errors and coding artifacts on the subjective video quality. At the end of the communication chain, the video signal is typically *displayed* and *perceived* by human beings.

This monograph focuses on the video encoder and video decoder, which are often summarized under the term *video codec*. The encoder maps the samples of the original video pictures to a set of so-called coding parameters and writes these coding parameters to a bitstream. The bitstream represents the input video in compressed form and is transmitted to the video decoder. The format in which the coding parameters are written to the bitstream is referred to as *bitstream syntax*. It has to be known to both the encoder and the decoder. The video decoder parses the received bitstream according to the given bitstream syntax and thereby decodes the transmitted coding parameters. Finally, the video pictures are reconstructed by following a defined decoding process, which is controlled by the transmitted coding parameters.

For achieving the required transmission bit rates, video codecs apply lossy coding algorithms. Hence, even in error-free transmission scenarios, the digital video signal reconstructed by the decoder is different from the encoder's input signal. Since, in most applications, the coded video is perceived by human beings, the degradation of the perceived video quality should be as small as possible. The basic video coding problem can be stated as representing a video signal with the highest possible subjective quality without exceeding an available bit rate or, alternatively, as conveying the video signal with the lowest possible bit rate while maintaining a specified subjective quality. In practice, the subjective quality of a video signal is very hard to specify and therefore objective distortion measures calculated based on the differences between the original and decoded sample values are often used instead. The ability of a codec to choose a suitable trade-off between signal distortion and bit rate is referred to as its *coding efficiency*. Besides the coding efficiency, the applicability of a video codec for a certain communication scenario is also influenced by the implementation com-

plexity of the algorithms used as well as the structural and processing delay of the codec, which determine, among other factors, the crucial end-to-end delay between capturing and displaying a video picture.

In the most common setup of video codecs, the video decoder merely extracts the coding parameters from the received bitstream and follows a defined decoding process for reconstructing the video pictures. Given a particular bitstream syntax and decoding process, all decoder implementations generate the same (or, sometimes, nearly the same) video pictures. The achievable coding efficiency is limited by the set of syntax features and coding tools that are supported in the bitstream syntax and the decoding process. However, the actual coding efficiency of a bitstream is highly dependent on the encoder implementation. For a given bitstream syntax and decoding process, both the bit rate and the reconstruction quality are determined by the encoding algorithm that maps the original pictures into a sequence of coding parameters.

## **1.2 Scope and Overview of the Text**

The present text provides a description of the fundamental concepts of video coding. It is aimed at aiding students and engineers to investigate the subject. Since the topic of video coding and video communication is too broad and too deep to exhaustively describe all its aspects in the chosen presentation format, we concentrate on the signal processing in video encoders and decoders. This also means that we will leave out a number of areas, including software and hardware implementation aspects, the topics of pre- and postprocessing, and the whole field of video transmission and error-robust coding.

The intention of this text is to provide an in-depth treatment of the basic principles and coding tools found in modern video codecs. Subjects that we consider particularly important will be covered in greater detail. For giving examples and analyzing certain coding tools, we will often refer to video coding standards. These standards do not only represent the dominant technology for real-world applications, but also reflect the state-of-the-art in the field of video coding. In fact, many advanced coding tools have been developed in international standard-

ization projects. Video coding approaches that are less relevant for practical applications, such as 3D subband coding or distributed video coding, will not be explained in this text. Moreover, we will neither discuss scalable nor 3D video coding. These coding schemes typically represent extensions of conventional video coding designs. Even though they include some additional coding tools, the same fundamental concepts as in conventional video coding are employed.

The monograph is divided into two parts. In the first part [301], we introduced the fundamental source coding techniques entropy coding, quantization, prediction, and transform coding and analyzed their coding efficiency based on simple models for 1D random signals. The present second part describes the application of these techniques to video coding. We describe the basic structure of video codecs, discuss the fundamental concepts of video coding, and highlight their application in modern video coding standards. The effectiveness of various coding tools will be demonstrated based on experimental results.

[Section 2](#) gives an overview of the acquisition, representation, and display of video signals. It describes the raw data formats used in video coding applications and highlights the relationship between the acquisition, representation, and display of video signals and the way we perceive visual information. [Section 3](#) introduces the basic principles of hybrid video coding and describes the structure of typical video encoders and decoders. It further introduces the measures that we will use for comparing the coding efficiency of different codecs. [Section 4](#) describes the concept of a Lagrangian encoder control, which we will use in all coding experiments. The usage of a unified and highly effective encoder control allows us to fairly compare different coding tools in terms of coding efficiency. [Section 5](#) discusses the application of transform coding in video codecs and introduces techniques for intra-picture coding. [Section 6](#) describes coding tools for inter-picture coding. It introduces the concept of motion-compensated prediction and analyzes several design aspects in terms of coding efficiency. [Section 7](#) compares important video coding standards with respect to their coding efficiency. A summary of important results is given in [Section 8](#).

## References

---

- [1] L. Acqualagna, S. Bosse, A. K. Porbadnigk, G. Curio, K.-R. Müller, T. Wiegand, and B. Blankertz. EEG-based classification of video quality perception using steady state visual evoked potentials (SSVEPs). *Journal of Neural Engineering*, 12(2):026012, March 2015.
- [2] N. Ahmed, T. Natarajan, and K. R. Rao. Discrete Cosine Transform. *IEEE Transactions on Computers*, C-23(1):90–93, January 1974.
- [3] E. Akyol and K. Rose. A necessary and sufficient condition for transform optimality in source coding. In *Proc. of International Symposium on Information Theory (ISIT)*, pages 2597–2601, 2011.
- [4] H. C. Andrews and W. K. Pratt. Fourier transform coding of images. In *Proc. Hawaii Int. Conf. System Sciences*, pages 677–679, 1968.
- [5] C. Archer and T. K. Leen. A generalized Lloyd-type algorithm for adaptive transform coder design. *IEEE Transactions on Signal Processing*, 52(1):255–264, January 2004.
- [6] S. E. J. Arnold, S. Faruq, V. Savolainen, P. W. McOwan, and L. Chittka. FReD: The Floral Reflectance Database – A Web Portal for Analyses of Flower Colour. *PLoS ONE*, 5(12):e14287, December 2010. <http://reflectance.co.uk>.
- [7] P. G. J. Barten. Spatiotemporal model for the contrast sensitivity of the human eye and its temporal aspects. In J. P. Allebach and B. E. Rogowitz, editors, *Proc. of SPIE, Human Vision, Visual Processing, and Digital Display IV*, volume 1913, pages 2–14, September 1993.

- [8] P. G. J. Barten. *Contrast Sensitivity of the Human Eye and Its Effects on Image Quality*. SPIE Optical Engineering Press, Bellingham, Washington, 1999.
- [9] P. G. J. Barten. Formula for the contrast sensitivity of the human eye. In Y. Miyake and D. R. Rasmussen, editors, *Proc. of SPIE, Image Quality and System Performance*, volume 5294, pages 231–238, December 2003.
- [10] D. A. Baylor, B. J. Nunn, and J. L. Schnapf. Spectral sensitivity of cones of the monkey macaca fascicularis. *The Journal of Physiology*, 390(1):145–160, 1987.
- [11] G. Bjøntegaard. Calculation of average PSNR differences between RD curves. ITU-T SG 16 / Q6, doc. VCEG-M33, April 2001.
- [12] G. Bjøntegaard and K. Lillevold. Context-adaptive VLC (CVLC) coding of coefficients. Joint Video Team, doc. JVT-C028, May 2002.
- [13] T. Blu, P. Thevenaz, and M. Unser. MOMS: Maximal-order interpolation of minimal support. *IEEE Transactions on Image Processing*, 10(7):1069–1080, July 2001.
- [14] M. Born and E. Wolf. *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*. Cambridge University Press, Cambridge, UK, 7th (expanded) edition, 1999.
- [15] F. Bossen. ABT cleanup and complexity reduction. Joint Video Team, doc. JVT-E087, October 2002.
- [16] F. Bossen. Common test conditions and software reference configurations. Joint Collaborative Team on Video Coding, doc. JCTVC-H1100, February 2012.
- [17] J. M. Boyce. Weighted prediction in the H.264/MPEG AVC video coding standard. In *Proc. of International Symposium on Circuits and Systems (ISCAS)*, volume 3, pages 789–792, 2004.
- [18] J. M. Boyce, Y. Ye, J. Chen, and A. K. Ramasubramonian. Overview of SHVC: Scalable extensions of the high efficiency video coding (HEVC) standard. *IEEE Transactions on Circuits and Systems for Video Technology*, 26(1):20–34, January 2016.
- [19] D. H. Brainard and A. Stockman. Colorimetry. In M. Bass, C. DeCusatis, J. Enoch, V. Lakshminarayanan, G. Li, C. Macdonald, V. Mahajan, and E. van Stryland, editors, *Vision and Vision Optics*, volume III of *The Optical Society of America Handbook of Optics*, pages 10.1–10.56. McGraw Hill, 3rd edition, 2009.



- [20] S. Brofferio, C. Cafforio, P. Del Re, G. Quaglia, A. Racciu, and F. Rocca. Redundancy reduction of video signals using movement compensation. *Alta Frequenza*, 43:836–843, October 1974.
- [21] P. K. Brown and G. Wald. Visual pigments in single rods and cones of the human retina. *Science*, 144(3614):45–52, April 1964.
- [22] G. Buchsbaum and A. Gottschalk. Trichromacy, opponent colours coding and optimum colour information transmission in the retina. *Proceedings of the Royal Society B: Biological Sciences*, 220(1218):89–113, November 1983.
- [23] M. Budagavi, A. Fuldseth, G. Bjøntegaard, V. Sze, and M. Sadafale. Core transform design in the high efficiency video coding (HEVC) standard. *IEEE Journal of Selected Topics in Signal Processing*, 7(6):1029–1041, December 2013.
- [24] C. Cafforio and F. Rocca. Methods for measuring small displacements of television images. *IEEE Transactions on Information Theory*, 22(5):573–579, September 1976.
- [25] F. W. Campbell and R. W. Gubisch. Optical quality of the human eye. *The Journal of Physiology*, 186(3):558–578, 1966.
- [26] F. W. Campbell and J. G. Robson. Application of Fourier analysis to the visibility of gratings. *The Journal of Physiology*, 197(3):551–566, 1968.
- [27] M. H. Chan, Y. B. Yu, and A. G. Constantinides. Variable size block matching motion compensation with applications to video coding. *IEE Proceedings I, Communications, Speech and Vision*, 137(4):205–212, August 1990.
- [28] J. Chen, Y. Chen, M. Karczewicz, X. Li, H. Liu, L. Zhang, and X. Zhao. Coding tools investigation for next generation video coding. ITU-T SG 16, doc. COM-16-C806, January 2015.
- [29] M. C. Chen and A. N. Willson, Jr. Rate-distortion optimal motion estimation algorithm for video coding. In *Proc. of International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, volume 4, pages 2096–2099, 1996.
- [30] M. C. Chen and A. N. Willson, Jr. Rate-distortion optimal motion estimation algorithms for motion-compensated transform video coding. *IEEE Transactions on Circuits and Systems for Video Technology*, 8(2):147–158, April 1998.

- [31] M. C. Chen and A. N. Willson, Jr. Motion-vector optimization of control grid interpolation and overlapped block motion compensation using iterated dynamic programming. *IEEE Transactions on Image Processing*, 9(7):1145–1157, July 2000.
- [32] W.-H. Chen, C. Smith, and S. Fralick. A fast computational algorithm for the Discrete Cosine Transform. *IEEE Transactions on Communications*, 25(9):1004–1009, September 1977.
- [33] Z. Chen and C. Guillemot. Perceptually-friendly H.264/AVC video coding based on foveated just-noticeable-distortion model. *IEEE Transactions on Circuits and Systems for Video Technology*, 20(6):806–819, June 2010.
- [34] T. Chiang and Y.-Q. Zhang. A new rate control scheme using quadratic rate distortion model. *IEEE Transactions on Circuits and Systems for Video Technology*, 7(1):246–250, February 1997.
- [35] S.-J. Choi and J. W. Woods. Motion-compensated 3-D subband coding of video. *IEEE Transactions on Image Processing*, 8(2):155–167, 1999.
- [36] P. A. Chou, T. Lookabaugh, and R. M. Gray. Optimal pruning with applications to tree-structured source coding and modeling. *IEEE Transactions on Information Theory*, 35(2):299–315, March 1989.
- [37] T. Chujoh and R. Noda. Internal bit depth increase for coding efficiency. ITU-T SG 16 / Q6, doc. VCEG-AE13, January 2007.
- [38] T. Chujoh, A. Tanizawa, and T. Yamakage. Adaptive loop filter for improving coding efficiency. ITU-T SG 16, doc. COM-16-C402, April 2008.
- [39] T. Chujoh, N. Wada, T. Watanabe, and T. Yamakage. Block-based adaptive loop filter. ITU-T SG 16 / Q6, doc. VCEG-AI18, July 2008.
- [40] T. Chujoh, N. Wada, and G. Yasuda. Quadtree-based adaptive loop filter. ITU-T SG 16, doc. COM-16-C181, January 2009.
- [41] W. C. Chung, F. Kossentini, and M. J. T. Smith. An efficient motion estimation technique based on a rate-distortion criterion. In *Proc. of International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, volume 4, pages 1926–1929, 1996.
- [42] CIE. *CIE Proceedings 1924*. Cambridge University Press, Cambridge, 1926.
- [43] CIE. *CIE Proceedings 1931*. Cambridge University Press, Cambridge, 1932.
- [44] CIE. *CIE Proceedings 1951*. Bureau Central de la CIE, Paris, 1951.

- [45] CIE. *CIE Proceedings 1963*. Bureau Central de la CIE, Paris, 1964.
- [46] CIE. *A Colour Appearance Model for Colour Management Systems: CIECAM02, Publication 159:2004*. Bureau Central de la CIE, Vienna, 2004.
- [47] CIE. *Fundamental Chromaticity Diagram with Physiological Axes – Part 1, Publication 170-1*. Bureau Central de la CIE, Vienna, 2006.
- [48] Cisco Systems, Inc. Cisco visual networking index: Forecast and methodology, 2013-2018. White paper, June 2014. Retrieved January 8, 2015, from <http://www.cisco.com>.
- [49] G. Cote, S. Shirani, and F. Kossentini. Optimal mode selection and synchronization for robust video communications over error-prone networks. *IEEE Journal on Selected Areas in Communications*, 18(6):952–965, June 2000.
- [50] C. A. Curcio, K. R. Sloan, R. E. Kalina, and A. E. Hendrickson. Human photoreceptor topography. *The Journal of Comparative Neurology*, 292(4):497–523, February 1990. Data available at <http://www.cis.uab.edu/curcio/PRtopo>.
- [51] I. Daubechies, M. Defrise, and C. De Mol. An iterative thresholding algorithm for linear inverse problems with a sparsity constraint. *Communications on Pure and Applied Mathematics*, 57(11):1413–1457, 2004.
- [52] R. De Forni and D. S. Taubman. On the benefits of leaf merging in quad-tree motion models. In *Proc. of International Conference on Image Processing (ICIP)*, volume 2, pages 858–861, 2005.
- [53] R. L. De Valois, I. Abramov, and G. H. Jacobs. Analysis of response patterns of LGN cells. *Journal of the Optical Society of America*, 56(7):966–977, July 1966.
- [54] R. Dosselmann and X. D. Yang. A comprehensive assessment of the structural similarity index. *Signal, Image and Video Processing*, 5(1):81–91, November 2011.
- [55] R. Dosselmann and X. D. Yang. A rank-order comparison of image quality metrics. In *Proc. of Canadian Conference on Electrical and Computer Engineering*, pages 1–4, 2013.
- [56] F. Dufaux, W. Gao, S. Tubaro, and A. Vetro. Distributed video coding: Trends and perspectives. *EURASIP Journal on Image and Video Processing*, 2009:1–13, 2009.
- [57] M. Effros, H. Feng, and K. Zeger. Suboptimality of the Karhunen-Loeve transform for transform coding. *IEEE Transactions on Information Theory*, 50(8):1605–1619, August 2004.

- [58] J. D. Eggerton and M. D. Srinath. Statistical distributions of image DCT coefficients. *Computers & Electrical Engineering*, 12(3–4):137–145, January 1986.
- [59] H. Enomoto and K. Shibata. Features of Hadamard transformed television signal. In *National Conference IECE Japan*, 1965. Paper 881.
- [60] T. Eude, R. Grisel, H. Cherifi, and R. Debrie. On the distribution of the DCT coefficients. In *Proc. of International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, volume 5, pages 365–368, 1994.
- [61] European Broadcasting Union. EBU standard for chromaticity tolerances for studio monitors. EBU Tech. 3213, August 1975.
- [62] H. Everett III. Generalized Lagrange multiplier method for solving problems of optimum allocation of resources. *Operations Research*, 11(3):399–417, June 1963.
- [63] M. D. Fairchild. *Color Appearance Models*. John Wiley & Sons, 3rd edition, 2013.
- [64] H. S. Fairman, M. H. Brill, and H. Hemmendinger. How the CIE 1931 color-matching functions were derived from Wright-Guild data. *Color Research & Application*, 22(1):11–23, February 1997.
- [65] M. Flierl and B. Girod. Generalized B pictures and the draft H.264/AVC video-compression standard. *IEEE Transactions on Circuits and Systems for Video Technology*, 13(7):587–597, July 2003.
- [66] M. Flierl, T. Wiegand, and B. Girod. A locally optimal design algorithm for block-based multi-hypothesis motion-compensated prediction. In *Proc. of Data Compression Conference (DCC)*, pages 239–248, 1998.
- [67] M. Flierl, T. Wiegand, and B. Girod. Rate-constrained multihypothesis prediction for motion-compensated video compression. *IEEE Transactions on Circuits and Systems for Video Technology*, 12(11):957–969, November 2002.
- [68] D. Flynn, D. Marpe, M. Naccari, T. Nguyen, C. Rosewarne, K. Sharman, J. Sole, and J. Xu. Overview of the range extensions for the HEVC standard: Tools, profiles and performance. *IEEE Transactions on Circuits and Systems for Video Technology*, 26(1):4–19, January 2016.
- [69] E. François, C. Fogg, Y. He, X. Li, A. Luthra, and A. Segall. High dynamic range and wide color gamut video coding in HEVC: Status and potential future enhancements. *IEEE Transactions on Circuits and Systems for Video Technology*, 26(1):63–75, January 2016.

- [70] C.-M. Fu, E. Alshina, A. Alshin, Y.-W. Huang, C.-Y. Chen, C.-Y. Tsai, C.-W. Hsu, S. Lei, J.-H. Park, and W.-J. Han. Sample adaptive offset in the HEVC standard. *IEEE Transactions on Circuits and Systems for Video Technology*, 22(12):1755–1764, December 2012.
- [71] A. Fuldseth, G. Bjøntegaard, M. Budagavi, and V. Sze. CE10: Core transform design for HEVC. Joint Collaborative Team on Video Coding, doc. JCTVC-G495, November 2011.
- [72] K. S. Gibson and E. P. T. Tyndall. Visibility of radiant energy. *Scientific Papers of the Bureau of Standards*, 19(475):131–191, 1923.
- [73] F. Giorda and A. Racciu. Bandwidth reduction of video signals via shift vector transmission. *IEEE Transactions on Communications*, 23(9):1002–1004, September 1975.
- [74] B. Girod. The efficiency of motion-compensating prediction for hybrid coding of video sequences. *IEEE Journal on Selected Areas in Communications*, 5(7):1140–1154, August 1987.
- [75] B. Girod. Motion-compensating prediction with fractional-pel accuracy. *IEEE Transactions on Communications*, 41(4):604–612, April 1993.
- [76] B. Girod. Why B-pictures work: A theory of multi-hypothesis motion-compensated prediction. In *Proc. of International Conference on Image Processing (ICIP)*, volume 2, pages 213–217, 1998.
- [77] B. Girod. Efficiency analysis of multihypothesis motion-compensated prediction for video coding. *IEEE Transactions on Image Processing*, 9(2):173–183, February 2000.
- [78] B. Girod, A. M. Aaron, S. Rane, and D. Rebollo-Monedero. Distributed video coding. *Proceedings of the IEEE*, 93(1):71–83, January 2005.
- [79] H. Gish and J. N. Pierce. Asymptotically efficient quantizing. *IEEE Transactions on Information Theory*, 14(5):676–683, September 1968.
- [80] G. H. Golub and C. F. Van Loan. *Matrix Computations*. The Johns Hopkins University Press, Baltimore, USA, 4th edition, 2013.
- [81] J. W. Goodman. *Introduction to Fourier Optics*. The MacGraw-Hill Companies, Inc., 1996.
- [82] S. Gordon, D. Marpe, and T. Wiegand. Simplified use of  $8 \times 8$  transforms. Joint Video Team, doc. JVT-J029, December 2003.
- [83] A. Goshtasby, F. Cheng, and B. A. Barsky. B-spline curves and surfaces viewed as digital filters. *Computer Vision, Graphics, and Image Processing*, 52(2):264–275, November 1990.

- [84] V. K. Goyal. High-rate transform coding: How high is high, and does it matter? In *Proc. of International Symposium on Information Theory*, page 207, 2000.
- [85] I. S. Gradshteyn and I. M. Ryzhik. *Table of Integrals, Series, and Products*. Academic Press, New York, 4th edition, 1980.
- [86] H. Grassmann. Zur Theorie der Farbenmischung. *Annalen der Physik*, 165(5):69–84, 1853.
- [87] H. Gross, F. Blechinger, and B. Achtner. *Survey of Optical Instruments*, volume 4 of *Handbook of Optical Instruments*. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2008.
- [88] J. Guild. A trichromatic colorimeter suitable for standardisation work. *Transactions of the Optical Society*, 27(2):106–129, December 1925.
- [89] J. Guild. The colorimetric properties of the spectrum. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 230(681-693):149–187, January 1932.
- [90] A. Habibi. Hybrid coding of pictorial data. *IEEE Transactions on Communications*, 22(5):614–624, May 1974.
- [91] A. Habibi and P. A. Wintz. Image coding by linear transformation and block quantization. *IEEE Transactions on Communication Technology*, 19(1):50–62, February 1971.
- [92] J. Han, A. Saxena, V. Melkote, and K. Rose. Jointly optimized spatial prediction and block transform for video and image coding. *IEEE Transactions on Image Processing*, 21(4):1874–1884, April 2012.
- [93] B. G. Haskell and A. Puri. Conditional motion compensated interpolation of digital motion video. United States Patent No. 4,958,226, September 1990.
- [94] B. G. Haskell, A. Puri, and A. N. Netravali. *Digital Video: An Introduction to MPEG-2*. Chapman & Hall, New York, NY, USA, 1997.
- [95] E. Hecht. *Optics*. Addison-Wesley, 4th edition, 2001.
- [96] P. Helle, S. Oudin, B. Bross, D. Marpe, M. O. Bici, K. Ugur, J. Jung, G. Clare, and T. Wiegand. Block merging for quadtree-based partitioning in HEVC. *IEEE Transactions on Circuits and Systems for Video Technology*, 22(12):1720–1731, December 2012.
- [97] H. Helmholtz. *Handbuch der Physiologischen Optik*, volume IX of *Allgemeine Encyclopädie der Physik*. Leopold Voss, Leipzig, 1867.
- [98] E. Hering. *Grundzüge der Lehre vom Lichtsinn*. Verlag von Julius Springer, Berlin, 1920.

- [99] S.-H. Hong and B. K. Yi. Polygon texture unit visual encoding. Joint Collaborative Team on Video Coding, doc. JCTVC-I0546, May 2012.
- [100] H. S. Hou. A fast recursive algorithm for computing the discrete cosine transform. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, 35(10):1455–1461, October 1987.
- [101] T.-Y. Huang, C.-K. Kao, and H. H. Chen. Acceleration of rate-distortion optimized quantization for H.264/AVC. In *Proc. of International Symposium on Circuits and Systems (ISCAS)*, pages 473–476, 2013.
- [102] T.-Y. Huang, P.-Y. Su, C.-K. Kao, T.-S. Ou, and H. H. Chen. Quality improvement of video codec by rate-distortion optimized quantization. In *Proc. of International Symposium on Multimedia (ISM)*, pages 482–487, 2011.
- [103] E. M. Hung, R. L. de Queiroz, and D. Mukherjee. On macroblock partition for motion compensation. In *Proc. of International Conference on Image Processing (ICIP)*, pages 1697–1700, 2006.
- [104] L. M. Hurvich and D. Jameson. Some quantitative aspects of an opponent-colors theory. II. Brightness, saturation, and hue in normal and dichromatic vision. *Journal of the Optical Society of America*, 45(8):602–616, August 1955.
- [105] IEC. Multimedia systems and equipment – Colour measurement and management – Part 2-1: Colour management – Default RGB colour space – sRGB. International Standard 61966-2-1, October 1999.
- [106] IEC. Extended-gamut YCC colour space for video applications – xvYCC. IEC 61966-2-4, January 2006.
- [107] P. Ishwar and P. Moulin. Switched control grid interpolation for motion compensated video coding. In *Proc. of International Conference on Image Processing (ICIP)*, volume 3, pages 650–653, 1997.
- [108] ISO and CIE. Colorimetry – Part 2: CIE standard illuminants. ISO/IEC 11664-2 | CIE S 014-2, 2007.
- [109] ISO and CIE. Colorimetry – Part 4: CIE 1976 L\*a\*b\* colour space. ISO/IEC 11664-4 | CIE S 014-4, 2008.
- [110] ISO and CIE. Colorimetry – Part 5: CIE 1976 L\*u\*v\* colour space and u', v' uniform chromaticity scale diagram. ISO/IEC 11664-5 | CIE S 014-5, 2009.
- [111] ISO/IEC. Coding of audio-visual objects – Part 2: Visual. ISO/IEC 14496-2, edition 1, 2001; edition 2, 2004.

- [112] ISO/IEC. Coding of moving pictures and associated audio for digital storage media at up to 1.5 Mbit/s – Part 2: Video. ISO/IEC 11172-2, 1993.
- [113] ISO/IEC. Test Model 5. ISO/IEC JTC 1/SC 29/WG 11, doc. MPEG-N0400, 1993.
- [114] ITU-R. Studio encoding parameters of digital television for standard 4:3 and wide-screen 16:9 aspect ratios. Recommendation ITU-R BT.601-7, March 2011.
- [115] ITU-R. Methodology for the subjective assessment of the quality of television pictures. Recommendation ITU-R BT.500-13, January 2012.
- [116] ITU-R. Parameter values for ultra-high definition television systems for production and international programme exchange. Recommendation ITU-R BT.2020-1, June 2014.
- [117] ITU-R. The present state of ultra-high definition television. Report ITU-R BT.2246-3, March 2014.
- [118] ITU-T. Codecs for videoconferencing using primary digital group transmission. ITU-T Recommendation H.120, edition 1, 1984; edition 2, 1988; edition 3, 1993.
- [119] ITU-T. Video codec for audiovisual services at  $p \times 64$  kbits. ITU-T Recommendation H.261, edition 1, 1988; edition 2, 1990; edition 3, 1993.
- [120] ITU-T. Video coding for low bit rate communication. ITU-T Recommendation H.263, edition 1, 1996; edition 2, 1998; edition 3, 2005.
- [121] ITU-T and ISO/IEC. Advanced video coding for generic audiovisual services. ITU-T Recommendation H.264 | ISO/IEC 14496-10, edition 1, 2003; edition 2, 2005; edition 3, 2007; edition 4, 2009; edition 5, 2010; edition 6, 2011; edition 7, 2012; edition 8, 2013; edition 9, 2014.
- [122] ITU-T and ISO/IEC. Generic coding of moving pictures and associated audio information: Video. ITU-T Recommendation H.262 | ISO/IEC 13818-2, edition 1, 1995; edition 2, 2000; edition 3, 2012.
- [123] ITU-T and ISO/IEC. High efficiency video coding. ITU-T Recommendation H.265 | ISO/IEC 23008-10, edition 1, 2013; edition 2, 2014.
- [124] ITU-T and ISO/IEC. JPEG XR image coding system – Image coding specification. ITU-T Recommendation T.832 | ISO/IEC 29199-2 (JPEG XR), edition 1, 2009; edition 2, 2012.



- [125] ITU-T and ISO/IEC. Reference software for advanced video coding. ITU-T Recommendation H.264.2 | ISO/IEC 14496-5, edition 1, 2005, edition 2, 2008, edition 3, 2010, edition 4, 2012. Available at <http://iphome.hhi.de/suehring/tml/>.
- [126] ITU-T and ISO/IEC. Reference software for high efficiency video coding. ITU-T Recommendation H.265 | ISO/IEC 23008-10, 2014. Software repository at [https://hevc.hhi.fraunhofer.de/svn/svn\\_HEVCSoftware/](https://hevc.hhi.fraunhofer.de/svn/svn_HEVCSoftware/).
- [127] ITU-T and ISO/IEC. Digital compression and coding of continuous-tone still images – requirements and guidelines. ITU-T Recommendation T.81 | ISO/IEC 10918-1 (JPEG), September 1992.
- [128] ITU-T and ISO/IEC. JPEG 2000 image coding system: Core coding system. ITU-T Recommendation T.800 | ISO/IEC 15444-1 (JPEG 2000), August 2002.
- [129] J. R. Jain and A. K. Jain. Displacement measurement and its application in interframe image coding. *IEEE Transactions on Communications*, 29(12):1799–1808, December 1981.
- [130] D. Jameson and L. M. Hurvich. Some quantitative aspects of an opponent-colors theory. I. Chromatic responses and spectral saturation. *Journal of the Optical Society of America*, 45(7):546–552, July 1955.
- [131] N. S. Jayant and P. Noll. *Digital Coding of Waveforms, Principles and Applications to Speech and Video*. Prentice-Hall, Inc., Englewood Cliffs, NJ, USA, 1994.
- [132] J. Jung and G. Laroche. Competition-based scheme for motion vector selection and coding. ITU-T SG 16 / Q6, doc. VCEG-AC06, July 2006.
- [133] S. Kamp, B. Bross, and M. Wien. Fast decoder side motion vector derivation for inter frame video coding. In *Proc. of Picture Coding Symposium (PCS)*, pages 1–4, 2009.
- [134] S. Kamp, M. Evertz, and M. Wien. Decoder side motion vector derivation for inter frame video coding. In *Proc. of International Conference on Image Processing (ICIP)*, pages 1120–1123, 2008.
- [135] S. Kamp and M. Wien. Decoder-side motion vector derivation for block-based video coding. *IEEE Transactions on Circuits and Systems for Video Technology*, 22(12):1732–1745, December 2012.
- [136] S. Kanumuri, T. K. Tan, and F. Bossen. Enhancements to Intra coding. Joint Collaborative Team on Video Coding, doc. JCTVC-D235, January 2011.

- [137] M. Karczewicz, P. Chen, R. Joshi, X. Wang, W.-J. Chien, and R. Panchal. Video coding technology proposal by Qualcomm Inc. Joint Collaborative Team on Video Coding, doc. JCTVC-A121, April 2010.
- [138] M. Karczewicz, P. Chen, R. L. Joshi, X. Wang, W.-J. Chien, R. Panchal, Y. Reznik, M. Coban, and S. Chong. A hybrid video coder based on extended macroblock sizes, improved interpolation, and flexible motion representation. *IEEE Transactions on Circuits and Systems for Video Technology*, 20(12):1698–1708, December 2010.
- [139] M. Karczewicz, P. Chen, Y. Ye, and R. Joshi. R-D based quantization in H.264. In Andrew G. Tescher, editor, *Proc. of SPIE, Applications of Digital Image Processing*, volume 7443, pages 744314–1, August 2009.
- [140] M. Karczewicz, J. Nieweglowski, and P. Haavisto. Video coding using motion compensation with polynomial motion vector fields. *Signal Processing: Image Communication*, 10(1–3):63–91, July 1997.
- [141] M. Karczewicz, J. Nieweglowski, J. Lainema, and O. Kalevo. Video coding using motion compensation with polynomial motion vector fields. In *Proc. of International Workshop on Wireless Image/Video Communications*, pages 26–31, 1996.
- [142] M. Karczewicz, Y. Ye, and P. Chen. Switched interpolation filter with offset. ITU-T SG 16, doc. COM-16-C463, April 2008.
- [143] M. Karczewicz, Y. Ye, P. Chen, and G. Motta. Single pass encoding using switched interpolation filters with offset. ITU-T SG 16 / Q6, doc. VCEG-AJ29, October 2008.
- [144] M. Karczewicz, Y. Ye, and I. Chong. Rate distortion optimized quantization. ITU-T SG 16 / Q6, doc. VCEG-AH21, April 2008.
- [145] G. Karlsson and M. Vetterli. Three dimensional sub-band coding of video. In *Proc. of International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, pages 1100–1103, 1988.
- [146] R. D. Kell. Improvements relating to electric picture transmission systems. British Patent No. 341,811, 1929.
- [147] D. H. Kelly. Frequency doubling in visual responses. *Journal of the Optical Society of America*, 56(11):1628–1632, 1966.
- [148] D. H. Kelly. Spatiotemporal variation of chromatic and achromatic contrast thresholds. *Journal of the Optical Society of America*, 73(6):742–749, 1983.
- [149] C. W. Kim, D. W. Wang, and I. S. Kwang. High-complexity mode decision for error prone environments. Joint Video Team, doc. JVT-C101, May 2002.

- [150] S. Klomp, M. Munderloh, Y. Vatis, and J. Ostermann. Decoder-side block motion estimation for H.264 / MPEG-4 AVC based video coding. In *Proc. of International Symposium on Circuits and Systems (ISCAS)*, pages 1641–1644, 2009.
- [151] J. J. Koenderink. *Color for the Sciences*. MIT Press, Cambridge, MA, 2010.
- [152] T. Koga, K. Iinuma, A. Hirano, Y. Iijima, and T. Ishiguro. Motion-compensated interframe coding for video conferencing. In *Proc. of Nat. Telecommun. Conf.*, pages C9.6.1–C9.6.5, November/December 1981.
- [153] C. W. Kok. Fast algorithm for computing discrete cosine transform. *IEEE Transactions on Signal Processing*, 45(3):757–760, March 1997.
- [154] F. Kossentini, Y.-W. Lee, M. J. T. Smith, and R. K. Ward. Predictive RD optimized motion estimation for very low bit-rate video coding. *IEEE Journal on Selected Areas in Communications*, 15(9):1752–1763, December 1997.
- [155] T.-Y. Kuo, J. Chalidabhongse, and C.-C. J. Kuo. Fast motion vector search for overlapped block motion compensation (OBMC). In *Proc. of Asilomar Conference on Signals, Systems and Computers*, pages 948–952, 1996.
- [156] J. Lainema, F. Bossen, W.-J. Han, J. Min, and K. Ugur. Intra coding of the HEVC standard. *IEEE Transactions on Circuits and Systems for Video Technology*, 22(12):1792–1801, December 2012.
- [157] H. Lakshman, B. Bross, H. Schwarz, and T. Wiegand. Fractional-sample motion compensation using generalized interpolation. In *Proc. of Picture Coding Symposium (PCS)*, pages 530–533, 2010.
- [158] H. Lakshman, H. Schwarz, T. Blu, and T. Wiegand. Generalized interpolation for motion compensated prediction. In *Proc. of International Conference on Image Processing (ICIP)*, pages 1213–1216, 2011.
- [159] H. Lakshman, H. Schwarz, and T. Wiegand. Adaptive motion model selection using a cubic spline based estimation framework. In *Proc. of International Conference on Image Processing (ICIP)*, pages 805–808, 2010.
- [160] H. Lakshman, H. Schwarz, and T. Wiegand. Video coding with cubic spline interpolation and adaptive motion model selection. In *Proc. of International Conference on Signal Processing and Communications (SPCOM)*, pages 1–5, 2010.

- [161] H. Lakshman, H. Schwarz, and T. Wiegand. Generalized interpolation-based fractional sample motion compensation. *IEEE Transactions on Circuits and Systems for Video Technology*, 23(3):455–466, March 2013.
- [162] E. Y. Lam and J. W. Goodman. A mathematical analysis of the DCT coefficient distributions for images. *IEEE Transactions on Image Processing*, 9(10):1661–1666, October 2000.
- [163] G. Laroche, J. Jung, and B. Pesquet-Popescu. RD optimized coding for motion vector predictor selection. *IEEE Transactions on Circuits and Systems for Video Technology*, 18(9):1247–1257, September 2008.
- [164] J. Lee and B. W. Dickinson. Joint optimization of frame type selection and bit allocation for MPEG video encoders. In *Proc. of International Conference on Image Processing (ICIP)*, volume 2, pages 962–966, 1994.
- [165] J. Lee and B. W. Dickinson. Rate-distortion optimized frame type selection for MPEG encoding. *IEEE Transactions on Circuits and Systems for Video Technology*, 7(3):501–510, June 1997.
- [166] R. Li, B. Zeng, and M. L. Liou. A new three-step search algorithm for block motion estimation. *IEEE Transactions on Circuits and Systems for Video Technology*, 4(4):438–442, August 1994.
- [167] J. Liang and D. R. Williams. Aberrations and retinal image quality of the normal human eye. *Journal of the Optical Society of America A*, 14(11):2873–2883, November 1997.
- [168] K.-P. Lim, G. J. Sullivan, and T. Wiegand. Text description of Joint Model reference encoding methods and decoding concealment methods. Joint Video Team, doc. JVT-O079, April 2005.
- [169] J. O. Limb and J. Murphy. Measuring the speed of moving objects from television signals. *IEEE Transactions on Communications*, 23(4):474–478, April 1975.
- [170] P. List, A. Joch, J. Lainema, G. Bjøntegaard, and M. Karczewicz. Adaptive deblocking filter. *IEEE Transactions on Circuits and Systems for Video Technology*, 13(7):614–619, July 2003.
- [171] C. Loeffler, A. Ligtenberg, and G. S. Moschytz. Practical fast 1-D DCT algorithms with 11 multiplications. In *Proc. of International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, pages 988–991, 1989.
- [172] M. R. Luo and C. Li. CIECAM02 and its recent developments. In Christine Fernandez-Maloigne, editor, *Advanced Color Image Processing and Analysis*, pages 19–58. Springer New York, May 2012.

- [173] S. Ma, W. Gao, and Y. Lu. Rate-distortion analysis for H.264/AVC video coding and its application to rate control. *IEEE Transactions on Circuits and Systems for Video Technology*, 15(12):1533–1544, December 2005.
- [174] D. L. MacAdam. Visual sensitivities to color differences in daylight. *Journal of the Optical Society of America*, 32(5):247–273, 1942.
- [175] H. S. Malvar, A. Hallapuro, M. Karczewicz, and L. Kerofsky. Low-complexity transform and quantization in H.264/AVC. *IEEE Transactions on Circuits and Systems for Video Technology*, 13(7):598–603, July 2003.
- [176] S. Marcos. Image quality of the human eye. *International Ophthalmology Clinics*, 43(2):43–62, 2003.
- [177] D. Marpe, H. Schwarz, and T. Wiegand. Context-based adaptive binary arithmetic coding in the H.264/AVC video compression standard. *IEEE Transactions on Circuits and Systems for Video Technology*, 13(7):620–636, July 2003.
- [178] D. Marpe, T. Wiegand, and G. J. Sullivan. The H.264/MPEG4 advanced video coding standard and its applications. *IEEE Communications Magazine*, 44(8):134–143, August 2006.
- [179] J. C. Maxwell. Experiments on colour, as perceived by the eye, with remarks on colour-blindness. *Transactions of the Royal Society of Edinburgh*, 21(02):275–298, January 1857.
- [180] K. McCann, C. Rosewarne, B. Bross, M. Naccari, K. Sharman, and G. J. Sullivan. High Efficiency Video Coding (HEVC) Test Model 16 (HM16) encoder description. Joint Collaborative Team on Video Coding, doc. JCTVC-R1002, June 2014.
- [181] F. W. Mounts. A video encoding system with conditional picture-element replenishment. *Bell System Technical Journal*, 48(7):2545–2554, September 1969.
- [182] K. T. Mullen. The contrast sensitivity of human colour vision to red-green and blue-yellow chromatic gratings. *The Journal of Physiology*, 359:381–400, February 1985.
- [183] F. Muller. Distribution shape of two-dimensional DCT coefficients of natural images. *Electronics Letters*, 29(22):1935–1936, October 1993.
- [184] A. N. Netravali and J. D. Robbins. Motion-compensated television coding: Part I. *Bell System Technical Journal*, 58(3):631–670, March 1979.

- [185] A. N. Netravali and J. D. Robbins. Video signal interpolation using motion estimation. United States Patent No. 4,383,272, May 1983.
- [186] T. Nguyen, P. Helle, M. Winken, B. Bross, D. Marpe, H. Schwarz, and T. Wiegand. Transform coding techniques in HEVC. *IEEE Journal of Selected Topics in Signal Processing*, 7(6):978–989, December 2013.
- [187] T. Nguyen and D. Marpe. Objective performance evaluation of the HEVC Main Still Picture profile. *IEEE Transactions on Circuits and Systems for Video Technology*, 25(5):790–797, May 2015.
- [188] S. Nogaki and M. Ohta. An overlapped block motion compensation for high quality motion picture coding. In *Proc. of International Symposium on Circuits and Systems (ISCAS)*, volume 1, pages 184–187, 1992.
- [189] A. Norkin, G. Bjøntegaard, A. Fuldseth, M. Narroschke, M. Ikeda, K. Andersson, M. Zhou, and G. Van der Auwera. HEVC deblocking filter. *IEEE Transactions on Circuits and Systems for Video Technology*, 22(12):1746–1754, December 2012.
- [190] A. Nosratinia and M. T. Orchard. Optimal warping prediction for video coding. In *Proc. of International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, volume 4, pages 1986–1989, 1996.
- [191] J.-R. Ohm. Three-dimensional subband coding with motion compensation. *IEEE Transactions on Image Processing*, 3(5):559–571, 1994.
- [192] J.-R. Ohm, G. J. Sullivan, H. Schwarz, T. K. Tan, and T. Wiegand. Comparison of the coding efficiency of video coding standards—including High Efficiency Video Coding (HEVC). *IEEE Transactions on Circuits and Systems for Video Technology*, 22(12):1669–1684, December 2012.
- [193] M. T. Orchard and G. J. Sullivan. Overlapped block motion compensation: An estimation-theoretic approach. *IEEE Transactions on Image Processing*, 3(5):693–699, September 1994.
- [194] A. Ortega and K. Ramchandran. Rate-distortion methods for image and video compression. *IEEE Signal Processing Magazine*, 15(6):23–50, November 1998.
- [195] G. A. Østerberg. Topography of the layer of rods and cones in the human retina. *Acta Ophthalmologica*, 13(Supplement 6):1–97, 1935.
- [196] S. E. Palmer. *Vision Science: Photons to Phenomenology*. A Bradford Book. MIT Press, Cambridge, MA, 1999.

- [197] F. Pan, X. Lin, S. Rahardja, K. P. Lim, Z. G. Li, D. Wu, and S. Wu. Fast mode decision algorithm for intraprediction in H.264/AVC video coding. *IEEE Transactions on Circuits and Systems for Video Technology*, 15(7):813–822, 2005.
- [198] F. Pereira, L. Torres, C. Guillemot, T. Ebrahimi, R. Leonardi, and S. Klomp. Distributed video coding: Selecting the most promising application scenarios. *Signal Processing: Image Communication*, 23(5):339–352, June 2008.
- [199] F. C. Pereira and T. Ebrahimi. *The MPEG-4 Book*. Prentice Hall, Upper Saddle River, NJ, USA, 2002.
- [200] M. H. Pinson and S. Wolf. A new standardized method for objectively measuring video quality. *IEEE Transactions on Broadcasting*, 50(3):312–322, September 2004.
- [201] C. Poynton. *Digital Video and HDTV Algorithms and Interfaces*. The Morgan Kaufmann Series in Computer Graphics and Geometric Modeling. Morgan Kaufmann Publishers, San Francisco, CA, 2003.
- [202] W. K. Pratt, J. Kane, and H. C. Andrews. Hadamard transform image coding. *Proceedings of the IEEE*, 57(1):58–68, January 1969.
- [203] A. Puri and R. Aravind. Comparing motion-interpolation structures for video coding. In *Proc. of SPIE, Visual Communications and Image Processing*, volume 1360, pages 1560–1571, September 1990.
- [204] A. Puri and R. Aravind. Motion-compensated video coding with adaptive perceptual quantization. *IEEE Transactions on Circuits and Systems for Video Technology*, 1(4):351–361, December 1991.
- [205] K. Ramchandran, A. Ortega, and M. Vetterli. Bit allocation for dependent quantization with applications to MPEG video coders. In *Proc. of International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, volume 5, pages 381–384, 1993.
- [206] K. Ramchandran, A. Ortega, and M. Vetterli. Bit allocation for dependent quantization with applications to multiresolution and MPEG video coders. *IEEE Transactions on Image Processing*, 3(5):533–545, September 1994.
- [207] K. Ramchandran and M. Vetterli. Rate-distortion optimal fast thresholding with complete JPEG/MPEG decoder compatibility. *IEEE Transactions on Image Processing*, 3(5):700–704, September 1994.
- [208] E. Reinhard, E. A. Khan, A. O. Akyüz, and G. M. Johnson. *Color Imaging: Fundamentals and Applications*. A K Peters, Ltd., Wellesley, MA, 2008.

- [209] R. Reininger and J. D. Gibson. Distributions of the two-dimensional DCT coefficients for images. *IEEE Transactions on Communications*, 31(6):835–839, June 1983.
- [210] J. Ribas-Corbera, P. A. Chou, and S. L. Regunathan. A generalized hypothetical reference decoder for H.264/AVC. *IEEE Transactions on Circuits and Systems for Video Technology*, 13(7):674–687, July 2003.
- [211] J. Ribas-Corbera and S. Lei. Rate control in DCT video coding for low-delay communications. *IEEE Transactions on Circuits and Systems for Video Technology*, 9(1):172–185, February 1999.
- [212] J. Ribas-Corbera and S. Lei. A frame-layer bit allocation for H.263+. *IEEE Transactions on Circuits and Systems for Video Technology*, 10(7):1154–1158, October 2000.
- [213] J. G. Robson. Spatial and temporal contrast-sensitivity functions of the visual system. *Journal of the Optical Society of America*, 56(8):1141–1142, August 1966.
- [214] F. Rocca. Television bandwidth compression utilizing frame-to-frame correlation and movement compensation. In T. S. Huang and O. J. Tretiak, editors, *Picture Bandwidth Compression*, pages 673–680, Gordon & Breach, New York, 1972.
- [215] F. Rocca and S. Zanoletti. Bandwidth reduction via movement compensation on a model of the random video process. *IEEE Transactions on Communications*, 20(5):960–965, October 1972.
- [216] P. Salama, N. B. Shroff, and E. J. Delp. Error concealment in MPEG video streams over ATM networks. *IEEE Journal on Selected Areas in Communications*, 18(6):1129–1144, June 2000.
- [217] A. Saxena and F. C. Fernandes. DCT/DST-based transform coding for intra prediction in image/video coding. *IEEE Transactions on Image Processing*, 22(10):3974–3981, October 2013.
- [218] J. L. Schnapf, T. W. Kraft, and D. A. Baylor. Spectral sensitivity of human cone photoreceptors. *Nature*, 325(6103):439–441, January 1987.
- [219] S. Scholler, S. Bosse, M. S. Treder, B. Blankertz, G. Curio, K.-R. Müller, and T. Wiegand. Toward a direct measure of video quality perception using EEG. *IEEE Transactions on Image Processing*, 21(5):2619–2629, May 2012.
- [220] M. R. Schroeder. Transform coding of image difference signals. United States Patent No. 3,679,821, July 1972.



- [221] B. Schumitsch, H. Schwarz, and T. Wiegand. Inter-frame optimization of transform coefficient selection in hybrid video coding. In *Proc. of Picture Coding Symposium (PCS)*, volume 3, pages 59–64, 2004.
- [222] G. M. Schuster and A. K. Katsaggelos. Fast and efficient mode and quantizer selection in the rate distortion sense for H.263. In R. Ansari and M. J. T. Smith, editors, *Proc. of SPIE, Visual Communications and Image Processing*, volume 2727, pages 784–795, February 1996.
- [223] G. M. Schuster and A. K. Katsaggelos. A video compression scheme with optimal bit allocation among segmentation, motion, and residual error. *IEEE Transactions on Image Processing*, 6(11):1487–1502, November 1997.
- [224] H. Schwarz, D. Marpe, and T. Wiegand. Hierarchical B pictures. Joint Video Team, doc. JVT-P014, July 2005.
- [225] H. Schwarz, D. Marpe, and T. Wiegand. Analysis of hierarchical B pictures and MCTF. In *Proc. of International Conference on Multimedia and Expo (ICME)*, pages 1929–1932, 2006.
- [226] H. Schwarz, D. Marpe, and T. Wiegand. Overview of the scalable video coding extension of the H.264/AVC standard. *IEEE Transactions on Circuits and Systems for Video Technology*, 17(9):1103–1120, September 2007.
- [227] H. Schwarz, J. Vieron, T. Wiegand, M. Wien, A. Eleftheriadis, and V. Bottreau. JSVM software, text, and conformance status. Joint Video Team, doc. JVT-AF013, November 2009.
- [228] A. Secker and D. Taubman. Lifting-based invertible motion adaptive transform (LIMAT) framework for highly scalable video compression. *IEEE Transactions on Image Processing*, 12(12):1530–1542, 2003.
- [229] N. Sekiguchi, D. R. Williams, and D. H. Brainard. Aberration-free measurements of the visibility of isoluminant gratings. *Journal of the Optical Society of America A*, 10(10):2105–2117, 1993.
- [230] SES S.A. Ultra HD, 2014. Retrieved January 8, 2015, from <http://www.ses.com/ultra-hd>.
- [231] SES S.A. Ultra HD rocks: SES marks first TV milestone broadcasting a live concert in UHD, December 2014. Retrieved January 8, 2015, from <http://www.ses.com/20451210>.
- [232] Y. Shoham and A. Gersho. Efficient bit allocation for an arbitrary set of quantizers. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, 36(9):1445–1453, September 1988.

- [233] T. Sikora. The MPEG-4 video standard verification model. *IEEE Transactions on Circuits and Systems for Video Technology*, 7(1):19–31, February 1997.
- [234] T. Smith and J. Guild. The C.I.E. colorimetric standards and their use. *Transactions of the Optical Society*, 33(3):73–134, January 1932.
- [235] SMPTE. Composite analog video signal — NTSC for studio applications. SMPTE Standard 170M-2004, November 2004.
- [236] J. Sole, R. Joshi, T. Nguyen, T. Ji, M. Karczewicz, G. Clare, F. Henry, and A. Duenas. Transform coefficient coding in HEVC. *IEEE Transactions on Circuits and Systems for Video Technology*, 22(12):1765–1777, December 2012.
- [237] M. Soryani and R. J. Clarke. Image segmentation and motion-adaptive frame interpolation for coding moving sequences. In *Proc. of International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, pages 1882–1885, 1989.
- [238] R. Srinivasan and K. R. Rao. Predictive coding based on efficient motion estimation. *IEEE Transactions on Communications*, 33(8):888–896, August 1985.
- [239] E. Steinbach, T. Wiegand, and B. Girod. Using multiple global motion models for improved block-based video coding. In *Proc. of International Conference on Image Processing (ICIP)*, volume 2, pages 56–60, 1999.
- [240] W. S. Stiles and J. M. Burch. N.P.L. colour-matching investigation: Final report (1958). *Optica Acta: International Journal of Optics*, 6(1):1–26, January 1959.
- [241] T. Stockhammer, M. M. Hannuksela, and T. Wiegand. H.264/AVC in wireless environments. *IEEE Transactions on Circuits and Systems for Video Technology*, 13(7):657–673, July 2003.
- [242] T. Stockhammer, D. Kontopodis, and T. Wiegand. Rate-distortion optimization for H.26L video coding in packet loss environment. In *Proc. of Packet Video Workshop*, 2002.
- [243] A. Stockman and D. H. Brainard. Color vision mechanism. In M. Bass, C. DeCusatis, J. Enoch, V. Lakshminarayanan, G. Li, C. Macdonald, V. Mahajan, and E. van Stryland, editors, *Vision and Vision Optics*, volume III of *The Optical Society of America Handbook of Optics*, pages 11.1–11.86. McGraw Hill, 3rd edition, 2009.

- [244] A. Stockman and L. T. Sharpe. The spectral sensitivities of the middle- and long-wavelength-sensitive cones derived from measurements in observers of known genotype. *Vision Research*, 40(13):1711–1737, June 2000.
- [245] A. Stockman, L. T. Sharpe, and C. Fach. The spectral sensitivity of the human short-wavelength sensitive cones derived from thresholds and color matches. *Vision Research*, 39(17):2901–2927, August 1999.
- [246] P. Strobach. Tree-structured scene adaptive coder. *IEEE Transactions on Communications*, 38(4):477–486, April 1990.
- [247] G. J. Sullivan. Efficient scalar quantization of exponential and Laplacian random variables. *IEEE Transactions on Information Theory*, 42(5):1365–1374, September 1996.
- [248] G. J. Sullivan and R. L. Baker. Efficient quadtree coding of images and video. In *Proc. of International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, pages 2661–2664, 1991.
- [249] G. J. Sullivan and R. L. Baker. Motion compensation for video compression using control grid interpolation. In *Proc. of International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, pages 2713–2716, 1991.
- [250] G. J. Sullivan and R. L. Baker. Rate-distortion optimized motion compensation for video compression using fixed or variable size blocks. In *Proc. of Global Telecommunications Conference*, pages 85–90, 1991.
- [251] G. J. Sullivan and R. L. Baker. Efficient quadtree coding of images and video. *IEEE Transactions on Image Processing*, 3(3):327–331, May 1994.
- [252] G. J. Sullivan, J.-R. Ohm, W.-J. Han, and T. Wiegand. Overview of the high efficiency video coding (HEVC) standard. *IEEE Transactions on Circuits and Systems for Video Technology*, 22(12):1649–1668, 2012.
- [253] G. J. Sullivan and M. T. Orchard. Methods of reduced-complexity overlapped block motion compensation. In *Proc. of International Conference on Image Processing (ICIP)*, volume 2, pages 957–961, 1994.
- [254] G. J. Sullivan and T. Wiegand. Rate-distortion optimization for video compression. *IEEE Signal Processing Magazine*, 15(6):74–90, 1998.
- [255] Y. Suzuki, C. S. Boon, and S. Kato. Block-based reduced resolution inter frame coding with template matching prediction. In *Proc. of International Conference on Image Processing (ICIP)*, pages 1701–1704, 2006.

- [256] Y. Suzuki, C. S. Boon, and T. K. Tan. Inter frame coding with template matching averaging. In *Proc. of International Conference on Image Processing (ICIP)*, volume 3, pages 409–412, 2007.
- [257] G. Svaetichin. Spectral response curves from single cones. *Acta Physiologica Scandinavica*, 39(Supplement 134):17–46, 1956.
- [258] G. Svaetichin and E. F. MacNichol. Retinal mechanisms for chromatic and achromatic vision. *Annals of the New York Academy of Sciences*, 74(2):385–404, November 1958.
- [259] V. Sze and M. Budagavi. CE11: Parallelization of HHI transform coding (fixed diagonal scan from C227). Joint Collaborative Team on Video Coding, doc. JCTVC-F129, July 2011.
- [260] V. Sze and M. Budagavi. High throughput CABAC entropy coding in HEVC. *IEEE Transactions on Circuits and Systems for Video Technology*, 22(12):1778–1791, December 2012.
- [261] M. Tagliasacchi, M. Sarchi, and S. Tubaro. Motion estimation by quadtree pruning and merging. In *Proc. of International Conference on Multimedia and Expo (IMCE)*, pages 1861–1864, 2006.
- [262] Y. Taki, M. Hatori, and S. Tanaka. Interframe coding that follows the motion. In *Proc. of 1974 IECEJ (Institute of Electronics and Communication Engineers of Japan) Annual Convention*, page 1263, July 1974.
- [263] T. K. Tan, R. Weerakkody, M. Mrak, N. Ramzan, V. Baroncini, J.-R. Ohm, and G. J. Sullivan. Video quality evaluation methodology and verification testing of HEVC compression performance. *IEEE Transactions on Circuits and Systems for Video Technology*, 26(1):76–90, January 2016.
- [264] C.-W. Tang, C.-H. Chen, Y.-H. Yu, and C.-J. Tsai. Visual sensitivity guided bit allocation for video coding. *IEEE Transactions on Multimedia*, 8(1):11–18, February 2006.
- [265] B. Tao and M. T. Orchard. Window design for overlapped block motion compensation through statistical motion modeling. In *Proc. of Asilomar Conference on Signals, Systems & Computers*, volume 1, pages 372–376, 1997.
- [266] D. Taubman and A. Zakhor. Multirate 3-D subband coding of video. *IEEE Transactions on Image Processing*, 3(5):572–588, 1994.

- [267] G. Tech, Y. Chen, K. Müller, J.-R. Ohm, A. Vetro, and Y.-K. Wang. Overview of the multiview and 3D extensions of high efficiency video coding. *IEEE Transactions on Circuits and Systems for Video Technology*, 26(1):35–49, January 2016.
- [268] R. Thoma and M. Bierling. Motion compensating interpolation considering covered and uncovered background. *Signal Processing: Image Communication*, 1(2):191–212, October 1989.
- [269] A. M. Tourapis. Enhanced predictive zonal search for single and multiple frame motion estimation. In C.-C. Jay Kuo, editor, *Proc. of SPIE, Visual Communications and Image Processing*, volume 4671, pages 1069–1079, January 2002.
- [270] K. Ugur, A. Alshin, E. Alshina, F. Bossen, W.-J. Han, J.-H. Park, and J. Lainema. Interpolation filter design in HEVC and its coding efficiency — Complexity analysis. In *Proc. of International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pages 1704–1708, 2013.
- [271] K. Ugur, A. Alshin, E. Alshina, F. Bossen, W.-J. Han, J.-H. Park, and J. Lainema. Motion compensated prediction and interpolation filter design in H.265/HEVC. *IEEE Journal of Selected Topics in Signal Processing*, 7(6):946–956, December 2013.
- [272] United States National Television System Committee. Recommendation for transmission standards for color television, December 1953.
- [273] M. Unser. Splines: A perfect fit for signal and image processing. *IEEE Signal Processing Magazine*, 16(6):22–38, November 1999.
- [274] M. Unser, A. Aldroubi, and M. Eden. B-spline signal processing: Part I — Theory. *IEEE Transactions on Signal Processing*, 41(2):821–833, February 1993.
- [275] M. Unser, A. Aldroubi, and M. Eden. B-spline signal processing: Part II — Efficiency design and applications. *IEEE Transactions on Signal Processing*, 41(2):834–848, February 1993.
- [276] J. Vaisey and A. Gersho. Variable block-size image coding. In *Proc. of International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, volume 12, pages 1051–1054, 1987.
- [277] J. Vaisey and A. Gersho. Image compression with variable block size segmentation. *IEEE Transactions on Signal Processing*, 40(8):2040–2060, August 1992.
- [278] A. van Meeteren and J. J. Vos. Resolution and contrast sensitivity at low luminances. *Vision Research*, 12(5):825–833, May 1972.

- [279] F. L. van Nes and M. A. Bouman. Spatial modulation transfer in the human eye. *Journal of the Optical Society of America*, 57(3):401–406, March 1967.
- [280] Y. Vatis, B. Edler, D. T. Nguyen, and J. Ostermann. Motion- and aliasing-compensated prediction using a two-dimensional non-separable adaptive Wiener interpolation filter. In *Proc. of International Conference on Image Processing (ICIP)*, volume 2, pages II–894–7, 2005.
- [281] Y. Vatis and J. Ostermann. Locally adaptive non-separable interpolation filter for H.264/AVC. In *Proc. of International Conference on Image Processing (ICIP)*, pages 33–36, 2006.
- [282] Y. Vatis and J. Ostermann. Adaptive interpolation filter for H.264/AVC. *IEEE Transactions on Circuits and Systems for Video Technology*, 19(2):179–192, February 2009.
- [283] A. Vetro, T. Wiegand, and G. J. Sullivan. Overview of the stereo and multiview video coding extensions of the H.264/MPEG-4 AVC standard. *Proceedings of the IEEE*, 99(4):626–642, April 2011.
- [284] J. von Kries. Theoretische Studien über die Umstimmung des Sehorgans. In *Festschrift der Albrecht-Ludwigs-Universität in Freiburg*, pages 143–158. C. A. Wagner’s Universitäts-Buchdruckerei, Freiburg, Germany, 1920.
- [285] B. A. Wandell. *Foundations of Vision*. Sinauer Associates, Inc., Sunderland, Massachusetts, 1995.
- [286] Y. Wang and Q.-F. Zhu. Error control and concealment for video communication: a review. *Proceedings of the IEEE*, 86(5):974–997, May 1998.
- [287] Y.-K. Wang, M. M. Hannuksela, V. Varsa, A. Hourunranta, and M. Gabbouj. The error concealment feature in the H.26L test model. In *Proc. of International Conference on Image Processing (ICIP)*, volume 2, pages 729–732, 2002.
- [288] Z. Wang, A. C. Bovik, H. R. Sheikh, and E. P. Simoncelli. Image quality assessment: From error visibility to structural similarity. *IEEE Transactions on Image Processing*, 13(4):600–612, April 2004.
- [289] A. Watanabe, T. Mori, S. Nagata, and K. Hiwatashi. Spatial sine-wave responses of the human visual system. *Vision Research*, 8(9):1245–1263, September 1968.
- [290] T. Wedi. Adaptive interpolation filter for motion compensated prediction. In *Proc. of International Conference on Image Processing (ICIP)*, volume 2, pages 509–512, 2002.

- [291] T. Wedi. Adaptive interpolation filters and high-resolution displacements for video coding. *IEEE Transactions on Circuits and Systems for Video Technology*, 16(4):484–491, April 2006.
- [292] T. Wedi and H. G. Musmann. Motion- and aliasing-compensated prediction for hybrid video coding. *IEEE Transactions on Circuits and Systems for Video Technology*, 13(7):577–586, July 2003.
- [293] J. Wen, M. Luttrell, and J. Villasenor. Trellis-based R-D optimal quantization in H.263+. *IEEE Transactions on Image Processing*, 9(8):1431–1434, August 2000.
- [294] J. Wen, M. Luttrell, J. Villasenor, and J. H. Park. Simulation results on trellis-based adaptive quantization. ITU-T SG 16 / Q15, doc. Q15-D-40, April 1998.
- [295] T. Wiegand and B. Andrews. An improved H.263 coder using rate-distortion optimization. ITU-T SG 16 / Q15, doc. Q15-D-13, April 1998.
- [296] T. Wiegand, N. Färber, K. Stuhlmüller, and B. Girod. Error-resilient video transmission using long-term memory motion-compensated prediction. *IEEE Journal on Selected Areas in Communications*, 18(6):1050–1062, June 2000.
- [297] T. Wiegand and B. Girod. Lagrange multiplier selection in hybrid video coder control. In *Proc. of International Conference on Image Processing (ICIP)*, volume 3, pages 542–545, 2001.
- [298] T. Wiegand, W.-J. Han, B. Bross, J.-R. Ohm, and G. J. Sullivan. Working draft 1 of High-Efficiency Video Coding. Joint Collaborative Team on Video Coding, doc. JCTVC-C403, October 2010.
- [299] T. Wiegand, M. Lightstone, T. G. Campbell, and S. K. Mitra. Efficient mode selection for block-based motion compensated video coding. In *Proc. of International Conference on Image Processing (ICIP)*, volume 2, pages 559–562, 1995.
- [300] T. Wiegand, M. Lightstone, D. Mukherjee, T. G. Campbell, and S. K. Mitra. Rate-distortion optimized mode selection for very low bit rate video coding and the emerging H.263 standard. *IEEE Transactions on Circuits and Systems for Video Technology*, 6(2):182–190, April 1996.
- [301] T. Wiegand and H. Schwarz. Source coding: Part I of fundamentals of source and video coding. *Foundations and Trends in Signal Processing*, 4(1–2):1–222, January 2011.

- [302] T. Wiegand, H. Schwarz, A. Joch, F. Kossentini, and G. J. Sullivan. Rate-constrained coder control and comparison of video coding standards. *IEEE Transactions on Circuits and Systems for Video Technology*, 13(7):688–703, July 2003.
- [303] T. Wiegand, E. G. Steinbach, A. Stensrud, and B. Girod. Multiple-reference-picture video coding using polynomial motion models. In *Proc. of SPIE, Visual Communications and Image Processing*, volume 3309, pages 134–145, January 1998.
- [304] T. Wiegand, G. J. Sullivan, G. Bjøntegaard, and A. Luthra. Overview of the H.264/AVC video coding standard. *IEEE Transactions on Circuits and Systems for Video Technology*, 13(7):560–576, 2003.
- [305] T. Wiegand, X. Zhang, and B. Girod. Motion-compensating long-term memory prediction. In *Proc. of International Conference on Image Processing (ICIP)*, volume 2, pages 53–56, 1997.
- [306] T. Wiegand, X. Zhang, and B. Girod. Long-term memory motion-compensated prediction. *IEEE Transactions on Circuits and Systems for Video Technology*, 9(1):70–84, February 1999.
- [307] M. Wien. Variable block-size transforms for H.264/AVC. *IEEE Transactions on Circuits and Systems for Video Technology*, 13(7):604–613, July 2003.
- [308] D. R. Williams. Topography of the foveal cone mosaic in the living human eye. *Vision Research*, 28(3):433–454, 1988.
- [309] M. Winken. *Multi-Frame Optimized Quantization for High Efficiency Video Coding*. Phd thesis, Technical University Berlin, October 2014.
- [310] M. Winken, H. Schwarz, D. Marpe, and T. Wiegand. Joint optimization of transform coefficients for hierarchical B picture coding in H.264/AVC. In *Proc. of International Conference on Image Processing (ICIP)*, volume 4, pages 89–92, 2007.
- [311] P. A. Wintz. Transform picture coding. *Proceedings of the IEEE*, 60(7):809–820, July 1972.
- [312] S. Wittmann and T. Wedi. Post-filter SEI message for 4:4:4 coding. Joint Video Team, doc. JVT-S030, April 2006.
- [313] S. Wittmann and T. Wedi. SEI message on post-filter hints. Joint Video Team, doc. JVT-U035, October 2006.
- [314] S. Wittmann and T. Wedi. SEI message on post-filter hints for high fidelity. Joint Video Team, doc. JVT-T039, July 2006.



- [315] S. Wittmann and T. Wedi. Separable adaptive interpolation filter for video coding. In *Proc. of International Conference on Image Processing (ICIP)*, pages 2500–2503, 2008.
- [316] J. W. Woods and T. S. Huang. Picture bandwidth compression by linear transformation and block quantization. In T. S. Huang and O. J. Tretiak, editors, *Picture Bandwidth Compression*, pages 555–573, Gordon & Breach, New York, 1972.
- [317] S. J. Wright, R. D. Nowak, and M. A. T. Figueiredo. Sparse reconstruction by separable approximation. *IEEE Transactions on Signal Processing*, 57(7):2479–2493, 2009.
- [318] W. D. Wright. A trichromatic colorimeter with spectral primaries. *Transactions of the Optical Society*, 29(5):225–242, May 1928.
- [319] W. D. Wright. A re-determination of the trichromatic coefficients of the spectral colours. *Transactions of the Optical Society*, 30(4):141–164, March 1929.
- [320] D. Wu, F. Pan, K. P. Lim, S. Wu, Z. G. Li, X. Lin, S. Rahardja, and C. C. Ko. Fast intermode decision in H.264/AVC video coding. *IEEE Transactions on Circuits and Systems for Video Technology*, 15(7):953–958, July 2005.
- [321] H. R. Wu, A. R. Reibman, W. Lin, F. Pereira, and S. S. Hemami. Perceptual visual signal compression and transmission. *Proceedings of the IEEE*, 101(9):2025–2043, 2013.
- [322] S.-W. Wu and A. Gersho. Rate-constrained optimal block-adaptive coding for digital tape recording of HDTV. *IEEE Transactions on Circuits and Systems for Video Technology*, 1(1):100–112, March 1991.
- [323] S.-W. Wu and A. Gersho. Joint estimation of forward and backward motion vectors for interpolative prediction of video. *IEEE Transactions on Image Processing*, 3(5):684–687, September 1994.
- [324] G. Wyszecki and W. S. Stiles. *Color Science: Concepts and Methods, Quantitative Data and Formulae*. John Wiley & Sons, Inc., New York, 2nd edition, 1982.
- [325] J. Xu, R. Joshi, and R. A. Cohen. Overview of the emerging HEVC screen content coding extension. *IEEE Transactions on Circuits and Systems for Video Technology*, 26(1):50–62, January 2016.
- [326] E.-H. Yang and X. Yu. Rate distortion optimization for H.264 inter-frame coding: A general framework and algorithms. *IEEE Transactions on Image Processing*, 16(7):1774–1784, July 2007.

- [327] E.-H. Yang and X. Yu. Soft decision quantization for H.264 with Main profile compatibility. *IEEE Transactions on Circuits and Systems for Video Technology*, 19(1):122–127, January 2009.
- [328] P. Yin, H.-Y. C. Tourapis, A. M. Tourapis, and J. Boyce. Fast mode decision and motion estimation for JVT/H.264. In *Proc. of International Conference on Image Processing (ICIP)*, volume 3, pages 853–856, 2003.
- [329] Y. Yokoyama and S. Nogaki. A rate control method with preanalysis for real-time MPEG-2 video coding. In *Proc. of International Conference on Image Processing (ICIP)*, volume 3, pages 514–517, 2001.
- [330] J. Yonemitsu and B. D. Andrews. Video signal coding method. United States Patent No. 5,155,593, October 1992.
- [331] T. Young. The Bakerian Lecture: On the theory of light and colours. *Philosophical Transactions of the Royal Society of London*, 92:12–48, January 1802.
- [332] Y. Yuan, X. Zheng, X. Peng, L. Liu, Y. Wang, X. Cao, J. Xu, C. Lai, J. Zheng, Y. He, and H. Yu. Asymmetric motion partition with OBMC and non-square TU. Joint Collaborative Team on Video Coding, doc. JCTVC-E376, July 2011.
- [333] J. Zhang, M. O. Ahmad, and M. N. S. Swamy. Quadtree structured region-wise motion compensation for video compression. *IEEE Transactions on Circuits and Systems for Video Technology*, 9(5):808–822, August 1999.
- [334] R. Zhang, S. L. Regunathan, and K. Rose. Video coding with optimal inter/intra-mode switching for packet loss resilience. *IEEE Journal on Selected Areas in Communications*, 18(6):966–976, June 2000.
- [335] M. Zibulevsky and M. Elad. L1-L2 optimization in signal and image processing. *IEEE Signal Processing Magazine*, 27(3):76–88, May 2010.