Special Section on the Joint Call for Proposals on High Efficiency Video Coding (HEVC) Standardization

THE FIRST commercially successful digital video compression standard emerged 20 years ago in the form of Recommendation ITU-T H.261. MPEG-1 and H.262/MPEG-2 video (the latter was jointly standardized by ITU-T and ISO/IEC) were then developed very soon thereafter, and they resulted in an explosion of products and services that created consumer video technology as we know it today.

Each international video coding standard has been built on a foundation of knowledge from the preceding generation, and has enabled an expanding array of product offerings and design improvements, as video support spread into a more diversified set of applications—particularly including Internet streaming and personal videotelephony, among others. More recently, the last major step forward in video compression capability for world-wide use across a broad variety of applications was the creation of the H.264/MPEG-4 Advanced Video Coding (AVC) standard [1]–[4]. In particular, it was the 2004 development of the Fidelity Range Extensions of that standard that included the specification of the increasingly-dominant feature set known as the High Profile of H.264/MPEG-4 AVC [4]. H.264/MPEG-4 AVC was developed jointly by ITU-T and ISO/IEC experts, and is published as both ITU-T Rec. H.264 and ISO/IEC 14496-10. It has become the primary format in use for essentially all video applications (and video applications are becoming a majority of network traffic world-wide).

As time has moved forward, video content has continued to become an increasing presence in our lives, with an ever-growing diversification of usage models and ever-increasing demands for higher quality. Yesterday's TV switched over to digital content delivery and was rapidly surpassed in quality as DVD and HDTV emerged, and now DVD itself has started to decline as Blu-ray, HD video-on-demand, and Internet delivery have surpassed it with better balances of quality and convenience. Boxy standard-definition interlaced CRT displays have disappeared and been replaced by flat panels of ever-increasing size and image resolution. Moreover, video conferencing has evolved from special-purpose communication links and expensive conference room systems to Internet-based communications using home and office-based PCs, ubiquitous wall-mounted displays, and an expanding variety of mobile devices.

I. CALL FOR PROPOSALS ON HEVC[1]

Since developing the High Profile of H.264/MPEG-4 AVC, the premier video coding standardization organizations, namely the ITU-T Video Coding Experts Group (VCEG) and the ISO/IEC Moving Picture Experts Group (MPEG), have been actively seeking emerging developments to identify when the next major step forward in compression capability would become feasible. (During this time, VCEG and MPEG have also jointly developed major functionality extensions of the H.264/MPEG-4 AVC standard that are not discussed here.)

VCEG had recently been exploring potential improvements relative to H.264/MPEG-4 AVC within the framework of an exploration activity and a coordinated software experiment platform development effort referred to as key technology area (KTA) investigation. Initial KTA investigations began around the end of 2004, and in April 2005 a decision was made to establish a new group-maintained KTA software codebase—starting from the current state of other group-maintained AVC reference software known as the Joint Model (JM). The KTA software maintained a close relationship with the JM reference software as they were both further refined in subsequent work. Various promising technologies were identified and tested in that context.

In closely related efforts involving many of the same experts, MPEG organized several workshops on the topic of future video coding standardization from 2006 to 2008, inviting presentations by developers of potential technology, and MPEG subsequently organized a Call for Evidence on High Performance Video Coding in 2009, where expert viewing tests were conducted in comparison against example H.264/MPEG-4 AVC encodings. By mid-to-late 2009, it became clear that sufficient technology advances were beginning to emerge and mature. After their respective investigations, both organizations concluded that the time had come to initiate the definition of the next generation of video coding standard, and it was decided to perform such work jointly. After reaching a consensus in both groups and establishing the necessary arrangements for joint work, an agreement was reached in January 2010 to establish a Joint Collaborative Team on Video Coding (JCT-VC) and to issue a joint Call for Proposals (CfP) [5]. The JCT-VC then held its first meeting from 15 to 23 April 2010, Dresden, Germany, to evaluate the responses to the CfP. This Special Section presents some of the proposals that were submitted in response to that call. The CfP itself and the initial steps on the project have previously been reviewed in [6].

Respondents to the CfP submitted complete documentation of their proposed algorithms, an extensive set of objective performance measures, a working decoder, and a set of encod-

Date of current version January 22, 2011.
Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.
Digital Object Identifier 10.1109/TCSVT.2010.2095692

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[1] This section of the *Special Section* introduction was written by Jens-Rainer Ohm and Gary J. Sullivan by invitation from the guest editor.

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TABLE I

CLASSES OF VIDEO RESOLUTIONS AND BIT RATE POINTS USED IN THE CFP

Class	Rate 1	Rate 2	Rate 3	Rate 4	Rate 5
A: 2560×1600p30	2.5 Mbit/s	3.5 Mbit/s	5 Mbit/s	8 Mbit/s	14 Mbit/s
B1: 1080p24	1 Mbit/s	1.6 Mbit/s	2.5 Mbit/s	4 Mbit/s	6 Mbit/s
B2: 1080p50-60	2 Mbit/s	3 Mbit/s	4.5 Mbit/s	7 Mbit/s	10 Mbit/s
C: WVGAp30-60	384 kbit/s	512 kbit/s	768 kbit/s	1.2 Mbit/s	2 Mbit/s
D: WQVGAp30-60	256 kbit/s	384 kbit/s	512 kbit/s	850 kbit/s	1.5 Mbit/s
E: 720p60	256 kbit/s	384 kbit/s	512 kbit/s	850 kbit/s	1.5 Mbit/s

ings of 18 source video sequences, which were grouped into five classes of video resolution, ranging from quarter WVGA (416 × 240) at the low end up to areas of size 2560 × 1600 cropped from 4 K × 2 K Ultra HD (UHD) material at the high end. The source video test material was progressively scanned with frame rates ranging from 24 to 60 frames/s. The source material was provided using 4:2:0 YCbCr color sampling with 8 bits per sample. The video sequences that were used in the subjective testing had durations of 10 s each. Respondents were required to submit complete results for all test cases. This included encodings for two application scenario conditions and five bit rate points per sequence.

Imposing coding constraint conditions as follows reflected the two application scenarios:

1) *random access*: a set of conditions requiring relatively frequent (approximately 1 s) random access points (representing applications such as broadcast television);
2) *low delay*: a set of conditions requiring low algorithmic delay (representing video usage for real-time communication, with no picture reordering between decoder processing and output).

The target bit rates, which were not to be exceeded by submissions, were as shown in Table 1.

For each test case, two H.264/MPEG-4 AVC "anchor" encodings were generated and their decoded results were included in the formal subjective tests in the same way as if they had been submitted for a proposal. The anchors were generated by encoding the selected source sequences using a reference H.264/MPEG-4 AVC encoder based on version 16.2 of the JM reference software developed by VCEG and MPEG. The purpose of the anchors was to facilitate the analysis of the results by providing two reference points using well understood coding technology configured for the same constraints that were imposed on the proposals. However, it should be noted that the JM 16.2 encoder is only one example of a method for coding video according to the H.264/MPEG-4 AVC standard—it does not represent the typical or best encoding quality that is achievable by using that standardized syntax (and this may be especially true for HD and UHD video material).

A total of 27 formal proposal responses were received, which resulted in a total of approximately 23 000 video clips to be tested. About 130 test sessions of approximately 20 min each were organized at three test laboratories, involving 850 test subjects who were employed for the viewing, which resulted in the collection of approximately 300 000 quality scores. A total of 4205 mean opinion score (MOS) values were derived from these raw scores and where then analyzed and represented on tables and graphs with associated confidence interval (CI) values in the test report [7], so that the performance of the proposals could be understood reasonably easily—both in relation to the other proposals and in relation to the performance of the Anchors. As far as the authors are aware, this was the largest video subjective quality testing effort ever conducted.

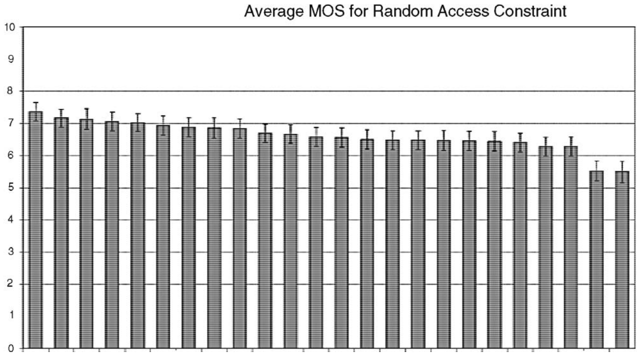

Fig. 1. Overall average MOS results over all classes for random access coding conditions.

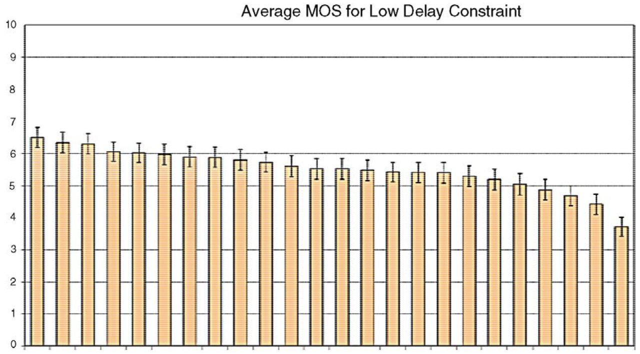

Fig. 2. Overall average MOS results over all classes for low delay coding conditions.

Figs. 1 and 2 show results averaged over all of the test sequences, where Fig. 1 shows the average results for the random access constraint conditions, and Fig. 2 shows the average results for the low delay constraint conditions. The results were based on an 11-grade scale, where 0 represented the worst and 10 represented the best individual quality measurements. Along with each MOS data point in the figures, a 95% CI is shown.

For the random access cases, the same "Alpha" anchor encoded using the H.264/MPEG-4 AVC High Profile was tested twice, and the two right-most bars indicate the two results. For low delay cases a higher quality "Beta" anchor relating to H.264/MPEG-4 AVC High Profile is shown second from the right and a lower-complexity "Gamma" anchor relating to H.264/MPEG-4 AVC Constrained Baseline Profile is the right-most case. It can be observed in these figures that a number of proposals exhibited average MOS performance that substantially exceeded that of the anchors.

A significant quality gap can be observed between the subjective MOS measures for the H.264/MPEG-4 AVC anchors and those of most proposals. From a more detailed analysis performed after the tests and provided in the test report [7] and meeting report, it could be concluded that the best-performing proposals in a significant number of cases showed similar quality as the H.264/MPEG-4 AVC anchors when encoded at roughly half of the anchor bit rate. It must, however, be noted that different individual proposals performed the best in the various tested cases, and there was no individual proposal that provided this degree of gain on all sequences.

The technical assessment of the proposed technology at the first JCT-VC meeting revealed that all of the proposed algorithms were based on the traditional hybrid coding approach, combining motion-compensated prediction between video frames, with intra-picture prediction, closed-loop operation with in-loop filtering, 2-D transformation of the spatial residual signals, and advanced adaptive entropy coding. Many specific candidate technology improvements were identified from the proposal responses, as was summarized in two technology survey documents issued at the meeting [9], [10].

After reviewing the state of the effort, the JCT-VC settled on the project name of high efficiency video coding (HEVC) for the new initiative. As an initial step toward moving forward into collaborative work, an initial test model under consideration (TMuC) document [11] was produced, combining identified key elements from a group of seven well-performing proposals. This first TMuC became the basis of a first software implementation, which after its development has begun to enable more rigorous assessment of the coding tools that it contains as well as additional tools to be investigated toward the development of the standard.

The referenced JCT-VC report documents [7]–[11], as well as the technology proposals themselves (those presented in this Special Section [12]–[17] and the others), are publicly available for further study (through http://www.itu.int/ITU-T/studygroups/com16/jct-vc/index.html).

II. ORGANIZATION OF THE SPECIAL SECTION

Although at this point of development it is still unclear which specific elements the final HEVC standard will contain, the selection of the papers in the Special Section was made such that together they would cover most of the promising tools and technologies that seem likely to be included in the standard. Some of these tools may be complementary to one another, whilst others may be overlapping in functionality.

The papers in this Special Section review the following responses to the CfP.

Proposal JCTVC-A114 [12], presented here in a paper by Bossen *et al.*, was jointly developed by France Telecom S.A., Paris, France, NTT Corporation, NTT DOCOMO, Inc., Tokyo, Japan, Panasonic Corporation, Osaka, Japan, Technicolor S.A., Paris, and their affiliated companies. It ranked among the best-performing proposals in the subjective test. It proposes a video coding scheme based on a simplified block structure that significantly outperforms the coding efficiency of the H.264/MPEG-4 AVC standard. Its conceptual design is similar to a typical block-based hybrid coder applying prediction and subsequent prediction error coding. It uses a simplified block structure of 8×8 and 16×16 luma samples. The motion representation is based on a minimum partitioning with blocks sharing motion borders. Other improved coding techniques include: block-based intensity compensation, motion vector competition, adaptive motion vector resolution, adaptive interpolation filters, edge-based intra prediction and enhanced chrominance prediction, intra template matching, larger transforms and adaptive switchable transforms selection for intra and inter blocks, non-linear and frame-adaptive de-noising loop filters. Finally, the entropy coder uses a generic flexible zero-tree representation applied to both motion and texture data. Attention has also been given to algorithm designs that facilitate parallelization. Compared to H.264/MPEG-4 AVC, the new coding scheme offers clear benefits in terms of subjective video quality at the same bit rate. Based on PSNR objective measurements, at the same quality, an average bit-rate reduction of 31% compared to H.264/MPEG-4 AVC is reported.

Proposal JCTVC-A116 [13], presented here in a paper by Marpe *et al.*, was developed at the Fraunhofer Institute for Telecommunications–Heinrich Hertz Institute, Berlin, Germany. The proposed design uses nested and pre-configurable quadtree structures. Using these structures, the spatial partitioning for inter-picture and intra-picture prediction, as well as the space-frequency resolution of the corresponding prediction residual, can be adapted to the local characteristics of the video signal in a highly flexible way. Moreover, the leaf nodes of the quadtree can be merged in order to reduce the amount of bits used for signaling the prediction signal. For fractional-sample motion-compensated prediction, a fixed-point implementation of the maximal-order-minimum-support algorithm is presented that uses an IIR/FIR filter. The entropy coding of the presented video compression design is based on the novel concept of probability interval partitioning entropy (PIPE) coding. It is asserted that PIPE achieves the coding efficiency of arithmetic coding at a complexity level similar to prefix codes. The proposal was ranked among the best-performing proposals in overall subjective quality while requiring only moderate increases in encoder and decoder complexity relative to H.264/MPEG-4 AVC.

Proposal JCTVC-A119 [14], presented here in a paper by Ugur *et al.*, contained the joint proposal submitted by Tandberg, Nokia, Tampere, Finland, and Ericsson to the CfP. The subjective quality of the proposal was evaluated within the HEVC project and the results indicate that the proposed method achieves similar visual quality measured by Mean Opinion Score to H.264/MPEG-4 AVC High Profile anchors, while using significantly fewer bits. The coding efficiency improvements were achieved with lower complexity than the H.264/MPEG-4 AVC Baseline Profile, indicating that the proposal is well-suited for use in high resolution, high quality applications in resource constrained environments. The proposal utilized a quad-tree based coding structure with a support for large macroblocks of size 64×64, 32×32, and 16×16 pixels. Entropy coding was performed using a low complexity variable length coding scheme with improved context adaptation compared to the CAVLC entropy coding mode of H.264/MPEG-4 AVC. The proposal also included improved interpolation and deblocking filter designs that provide better coding efficiency, yet have low complexity. Finally, improved intra coding methods were presented providing better subjective quality over H.264/MPEG-4 AVC.

Proposal JCTVC-A121 [15], presented here in a paper by Karczewicz *et al.*, contained a video coding technology proposal submitted by Qualcomm in response to the CfP. The proposal ranked among the best-performing proposals in terms of both subjective evaluations and objective metrics. For the random access and low delay configurations, it achieved reported average bit rate reductions of 31% and 33% for equivalent PSNR, respectively, compared to the corresponding H.264/MPEG-4 AVC anchors. The proposed design follows a traditional hybrid coding approach. Its key features are extended macroblock sizes, improved interpolation methods for motion, and flexible motion representation. It uses block sizes up to 64 × 64 to exploit the spatial correlation, especially for higher resolution sequences. Single-pass switched interpolation filters with offsets (single-pass SIFO) and luma high precision filtering are used for improved interpolation for motion estimation and compensation. The use of geometric motion partitioning and adaptive motion vector resolution (up to 1/8th pixel) provide flexibility in motion representation. Two other important features of the design are mode dependent directional transforms for intra coding and efficient 16 point transforms.

Proposals JCTVC-A124 [16] and JCTVC-A125 [17], presented here in a paper by Han *et al.*, contained responses to the CfP by Samsung Electronics, Suwon, Korea, and British Broadcasting Corporation, London, U.K., respectively. These responses demonstrated two configurations of the Samsung/BBC coding framework: a high performance operating point and a lower-complexity operating point. The high performance operating point was reported to provide an average bit-rate reduction of 39% compared to H.264/MPEG-4 AVC, based on the PSNR objective measure. The lower complexity operating point was reported to provide an average bit-rate reduction of 31%, together with a decoder run-time that was comparable to H.264/MPEG-4 AVC. In the subjective tests, these two responses were ranked among the best-performing proposals in overall subjective quality, as measured by the average MOS scores. The compression scheme is based on a flexible hierarchy of unit representation which includes three block concepts: those of a coding unit (CU), prediction unit (PU) and transform unit (TU). The use of this structure is intended to facilitate the optimization of each according to its role: the CU as a macroblock-like unit which supports region splitting in a manner similar to a conventional quadtree, the PU to support square or non-square motion partition shapes for motion compensation, and the TU to allow the transform size to be defined independently from the PU. Other coding tools are extended to arbitrary unit size to maintain consistency with the proposed design, e.g., integer transforms are extended to support up to 64 × 64 block sizes and intra prediction is designed to support an arbitrary number of angles for variable block sizes. A non-cascading interpolation filter design allowing arbitrary motion accuracy and a leaky prediction technique using both open-loop and closed-loop predictors are also employed. Finally, several techniques for improving the coding efficiency of in-loop filtering are presented.

This Special Section is the first of its kind in the history of IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY. It has been published under a new editorial policy primarily introduced to cover new emerging topics in a timely manner. As the video coding proposals that are described here were publicly submitted for the first time in April 2010, we believe that this goal has been achieved.

ACKNOWLEDGMENT

The authors wish to thank H. Gharavi, Editor-in-Chief, for his encouragement and support for the preparation of this Special Section.

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Dr. Ohm has chaired the ISO/IEC WG 11 (MPEG) Video Subgroup since May 2002. From January 2005 to November 2009, he co-chaired the Joint Video Team of MPEG and ITU-T SG 16 VCEG. Currently, he is co-chairing the Joint Collaborative Team on Video Coding of ISO and ITU-T, with the mandate to develop the next-generation High-Efficiency Video Coding standard. He has authored textbooks on multimedia signal processing, analysis and coding, communications engineering and signal transmission, as well as authoring numerous papers in the various fields mentioned above. He is a member of various professional organizations, including VDE/ITG, EURASIP, and AES.

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Dr. Sullivan has received the IEEE Consumer Electronics Engineering Excellence Award, the INCITS Technical Excellence Award, the IMTC Leadership Award, the University of Louisville J. B. Speed Professional Award in Engineering, the Microsoft Technical Achievement in Standardization Award, and the Microsoft Business Achievement in Standardization Award. The standardization projects that he led for development of the H.264/MPEG-4 AVC video coding standard have been recognized by an ATAS Primetime Emmy Engineering Award and a pair of NATAS Technology and Engineering Emmy Awards. He is a Fellow of SPIE. He was a Guest Editor for the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY for its Special Issue on the H.264/AVC Video Coding Standard in July 2003 and its Special Issue on Scalable Video Coding-Standardization and Beyond in September 2007.

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Mr. Ugur is a member of a research team that won the Nokia Quality Award in 2006.