Studies on the Bit Rate Requirements for a HDTV Format With 1920 × 1080 pixel Resolution, Progressive Scanning at 50 Hz Frame Rate Targeting Large Flat Panel Displays

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***Abstract*—This paper considers the potential for an HDTV delivery format with 1920 × 1080 pixels progressive scanning and 50 frames per second in broadcast applications. The paper discusses the difficulties in characterizing the display to be assumed for reception. It elaborates on the required bit rate of the 1080p/50 format when critical content is coded in MPEG-4 H.264 AVC Part 10 and subjectively viewed on a large, flat panel display with 1920 × 1080 pixel resolution. The paper describes the initial subjective quality evaluations that have been made in these conditions. The results of these initial tests suggest that the required bit-rate for a 1080p/50 HDTV signal in emission could be kept equal or lower than that of 2nd generation HDTV formats, to achieve equal or better image quality.**

***Index Terms*—Compression in broadcasting, flat panel displays, high-definition television, progressive scanning.**

I. Introduction

HIGH-DEFINITION Television acceptance in home environments is directly coupled to two key factors: first, the availability of adequate HDTV broadcasts to the consumer's home and second, that HDTV display devices are available at mass market costs. Although the United States, Japan and Australia have been broadcasting HDTV for some years, real interest by the general public has only recently appeared with the availability of inexpensive HDTV displays. Even Europe, which temporarily discontinued HDTV activity with the end of the Eureka 95 project [1] has recently seen a rebirth of HDTV and has defined specifications for HDTV displays and receiver [2]. At the time of writing this paper a number of broadcasters in Europe have started to offer HDTV broadcasts either as part of Pay-TV *bouquets* or free-to-air service, and all other major public broadcasters in Europe have put HDTV on their mid- and long term agendas. Also the announcements for HD-DVD, Blu-Ray and Game consoles with HDTV resolutions have been increasing consumer demand for HDTV broadcasting. An overview of the situation of HDTV services in Europe is given in [3]–[5] and an introduction and discussion of the relevant HDTV base-band formats is available in [3], [6]. A debate in Europe led to the recommendation of the European Broadcasting Union to favor a progressive scanning emission format [7] with 1280 × 720 pixel progressive scanning and 50 Hz frame rate (720p/50). Objections were raised by those who had decided in the past to adopt the HDTV format with 1920 × 1080 interlaced scanning at 25 Hz frame rate or 50 fields (1080i/25). The decision to adopt a progressive emission format followed a number of scientific tests [8]–[14]. The most important factors can be summarized as:

- Virtually all future HDTV displays sold in Europe will be matrix displays that require de-interlacing of an interlaced video signal such as 1080i/25. The video quality achieved after the de-interlacing process would depend in part on the sophistication of the de-interlacing algorithm that would affect the price of the consumer display.
- Progressive scan at 50 frames per second provides better motion portrayal than interlaced scan systems with 25 frames or 50 fields per second. This is particularly important for critical HDTV genres such as sport.
- Modern compressions systems such as MPEG-4 AVC Part 10 [15] or VC1 [16] compress progressive images more efficiently than interlaced images, thus providing a better image quality at a given bit-rate than with interlaced images. Even if the production format is interlaced, there could be some image quality and bit rate advantages if high quality de-interlacing is done at the play-out point before the emission encoder.
- There is increasing use of computerized image processing and personal computer-based receivers that can manage progressive images better than interlaced (i.e. rendering of artificial scenes in native progressive formats instead of converting to interlaced [17]).

Considerations were given by Gauntlet [18] on the optimum HDTV emission format for use with advanced compression schemes and by Haglund [19] on the required bit-rate when using MPEG-2 compression and wide XGA displays.

For the purpose of this paper we define the HDTV formats according to the following nomenclature (Table I):

II. Motivation

The problem statements which formed the basis for the research are as follows:

- Will an HDTV format with 1920 horizontal pixels and 1080 vertical pixels (lines) with progressive scanning at 50

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Color versions of Figs. 1–6, 9–12, and 14–17 available at http://ieeexplore.ieee.org.

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TABLE I
HDTV NOMENCLATURES FOR THIS PAPER

720p/50	An HDTV format with 1280 horizontal pixels and 720 vertical pixels (lines) resolution, progressively scanned at 50 frames per second as specified in SMPTE 296M-2001
720p/25	An HDTV format with 1280 horizontal and 720 vertical pixels resolution, progressively scanned at 25 frames per second as specified in SMPTE 296M-2001
1080i/25	An HDTV format with 1920 horizontal and 1080 vertical pixels resolution, scanned with interlace at 50 fields per second as specified in SMPTE 274 or ITU-R BT.709-5
1080p/50	An HDTV format with 1920 horizontal and 1080 vertical pixels resolution, progressively scanned at 50 frames per second as specified in SMPTE 274 or ITU-R BT.709-5
1080p/25	An HDTV format with 1920 horizontal and 1080 vertical pixels resolution, progressively scanned at 25 frames per second as specified in SMPTE 274 or ITU-R BT.709-5

Hz frame rates (1080p/50) provide a significant perceived viewing improvement over today's 720p/50 and 1080i/25 HDTV formats when advanced compression is performed in the emission path, and what would be the required bit rate for critical images?

- In television production, HDTV cameras have been introduced with 1920 × 1080 pixel CCD or CMOS sensors. Dual link HD-SDI [20] interfaces are available and a single link HD-SDI interface type for 1080p/50 [21], [22] has been recently standardized providing studio infrastructure possibilities for uncompressed 1080p/50. In addition, standardization in the SMPTE is under way to specify a mezzanine compression system for 1080p/50–60 for transport over 1.485 Gbit/s HD-SDI links [23]
- More flat panel displays with 1920 × 1080 pixel resolution are entering the consumer market with HDMI or DVI interfaces that also support 1080p/50 and 1080p/60, and in addition Blu-Ray Players and several game stations will also provide 1080p/50–60 HDMI outputs. Consequently the question of also using 1080p/50–60 as a broadcast format arises.

III. HDTV BASICS

The International Telecommunication Union [24] defined HDTV about 20 years ago as:

> "A High definition system is a system designed to allow viewing at about three times the picture height, such that the system is virtually, or nearly, transparent to the quality of portrayal that would have been perceived in the original scene or performance by a discerning viewer with normal vision acuity. Such factors include improved motion portrayal and improved perception of depth".

This definition does not include any detailed technical specification such as required video or display resolution, only the preferred viewing distance from the screen. However, taking into account the resolution of the human eye under normal vision conditions with one arc-minute resolution threshold, and the preferred viewing distance of three times picture height (3h), a theoretical calculation of the required display resolution can be made. Mitsuhashi [25] published in 1982 experimental results showing that about 900 effective scanning lines are required at a viewing distance of two to three picture heights (h) and Sugawara *et al.* [26] have recently calculated that 1920 horizontal and 1080 vertical pixels would be the optimum theoretically required resolution for a display with 50 inch diagonal at a viewing distance of two meters. This would only be available with a 1080 progressively scanned picture, and not with a 1080 interlaced scanned picture.

Salmon and Drewery [8] found in experiments that with an image scanned at 1920 × 1080 p, a display of 55 inch diagonal or larger would be needed to saturate the eye with detail.

Fig. 1. Room configuration (in bright light for the photo).

IV. TEST CONFIGURATION AND TEST EQUIPMENT

Subjective tests according to the following set up were established.

A. Viewing Room

A viewing room was set up according to the guidelines of ITU-R BT.500-11 [27] with D6500 ambient light conditions. Before each session on successive days, the room ambient light conditions were rechecked with a Minolta CS100 photospot meter to be 10% of the peak brightness of the display. D6500 fluorescent lights were used for backlight illumination and care was taken that no light or reflections appeared on the display front surface (Fig. 1).

B. Display Selection and Characterization

A most critical part for performing subjective image quality assessment for HDTV is the selection of an appropriate display and its characterization. The professional broadcasting community is aware that consumers will no longer view television (or HDTV) on cathode ray tube (CRT) based displays, but instead, flat panel displays (FPD) such as liquid crystal displays (LCD) or plasma display panels (PDP), projection devices (e.g. micro-mirror based) and so on will be used. These types of displays mask picture impairments to a lesser extent than CRTs, and thus, compared to CRT displays, can be apparent magnifiers of impairments. In addition, and a significant difficulty for subjective tests, none of the available FPDs can yet be considered as equivalent to a grade 1 reference monitor [28], [29]. There are ongoing initiatives by ITU-R, SMPTE and EBU to

TABLE II
DISPLAY SETTINGS

DVI interconnection to video server signal source.
Display standard settings were activated by resetting the display.
Pure Cinema: Off
Frame repetition: 100Hz
DVI RGB range: 0-255 for test images and 16-235 for subjective tests.
Color temperature setting: Mid ("natural tone")
Gamma characteristic: 2
Color transient improvement: off
Digital noise reduction: activated
MPEG Noise Reduction: off
Dynamic contrast: off
Black level enhancement: activated
Automatic contrast level: off
Interlacer: 2 (standard setting)

define criteria for using an FPD as a grade 1 equivalent; however this work is not yet complete. Among other factors, there are clear difficulties in specifying the typical FPD processing parameters for video signal processing such as de-interlacing or image scaling. Thus, the selected display for our tests has been characterized by a set of measurements. The purpose of these measurements was to allow repeatability of the assessment sessions and to put them into context for future work. As guidance and literature before selecting the measurements, we studied and followed the CRT grade 1 specifications [30] and ITU-R documents [31] and in particular the VESA FPD measurement standard [32]. The VESA FPD standard was also used as a guideline for reporting the measurement results. The chosen display characterization represents a compromise considering the non-availability of clear guidance for using FPDs in image assessment (subjective tests), the efforts required for the characterization and the aforementioned specifications.

For the purpose of the subjective tests a prototype PDP with 50 inches diagonal and a resolution of 1920 × 1080 pixels was used.

For the display characterization a darkened room was used and for all measurements and the display was set to the following state (Table II):

Brightness and Contrast: Brightness adjustment was performed with a PLUGE signal that covered 1829 cm^2 of the screen with RGB white.

First, brightness was adjusted until the PLUGE signal was just visible, then contrast was adjusted until peak brightness was at 100 $\mathrm{cd/m}^2$ (measured with Minolta CS100 in slow response mode at 1 m distance and perpendicular to the screen). This procedure was repeated until a good compromise was found between the threshold of disappearance/visibility of the PLUGE black level steps and brightness and luminance of 100 $\mathrm{cd/m}^2$ was obtained.

Five consecutive luminance (L_i) measurements, at approximately 10-second intervals, were conducted to determine peak luminance (Table III) with the PLUGE signal.

The arithmetic mean of the luminance measurements was calculated with

$$\mu_L = \frac{1}{n}\sum_{i=1}^{n} L_i \tag{IV-1}$$

TABLE III
LUMINANCE MEASUREMENT OF PEAK BRIGHTNESS USING PLUGE SIGNAL

PLUGE signal measurement				
Measurement		L[cd/m²]	CIE x	CIE y
1..5	μ_L	100	0.288	0.294
	σ_L	0	0	0

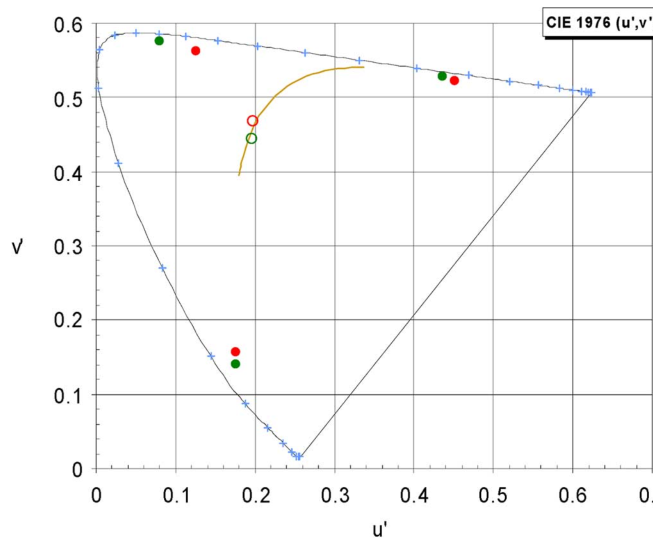

Fig. 2. Color space and white point of the test display (green dots) compared to the color primaries and white point of [30] (red dots).

where n = number of measurements and L_i = the luminance in $\mathrm{cd/m}^2$, and the standard deviation with

$$\sigma_L = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(L_i - \mu_L)^2} \tag{IV-2}$$

Full Screen Luminance and Color Measurements: White, black and RGB primary signals were generated with full range excursions (0–255) and presented to the display. Luminance L was determined with five measurements every 10 seconds with a Minolta CS 100 in slow response mode, perpendicular to the screen center at 1m distance. Table IV shows the arithmetic mean of the five measurements and the standard deviation. The CIE x, y coordinates were read from the measurement device and the CIE 1976 u′, v′ coordinates were calculated according to

$$u' = \frac{4x}{3 + 2y - 2x} \tag{IV-3}$$

$$v' = \frac{9y}{3 + 12y - 2x} \tag{IV-4}$$

Typically with PDPs, peak luminance in a full screen measurement is significantly different than in small area measurements. This factor makes it always obligatory to state which signal was used for the contrast measurement (a procedure that is not followed in the industry's display data sheets).

The color points in Fig. 2 show the arithmetic mean values (Table IV) of the measured display compared to the normal values of a grade 1 CRT monitor [30]. As we can see, the green

TABLE IV
FULL SCREEN LUMINANCE MEASUREMENTS

Full screen luminance measurements					
Video Signal and digital level (R,G,B)	**L [cd/m²]**	**CIE x**	**CIE y**	**CIE u'**	**CIE v'**
$\mu_{white1..5}$ (255,255,255)	48.100	0.290	0.292	0.196	0.446
$\mu_{black1..5}$ (0, 0, 0)	0.019	-	-	-	-
$\mu_{red1..5}$ (255, 0, 0)	14.740	0.638	0.344	0.436	0.310
$\mu_{gree1..5}$ (0, 255, 0)	43.620	0.221	0.709	0.080	1.506
$\mu_{blue1..5}$ (0, 0, 255)	6.230	0.146	0.052	0.175	0.101
σ_{white}	0.158	0.000	0.000	0.000	0.000
σ_{black}	0.000	-	-	-	-
σ_{red}	0.680	0.001	0.001	0.001	0.002
σ_{green}	0.823	0.000	0.000	0.001	0.001
σ_{blue}	0.140	0.000	0.000	0.001	0.000

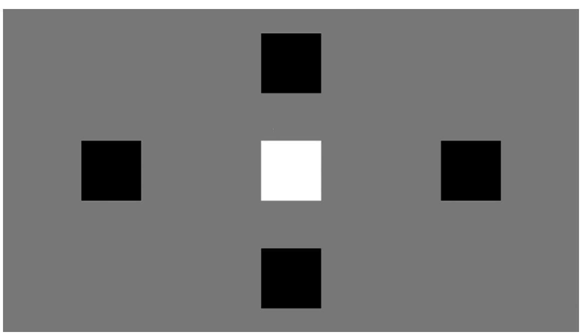

Fig. 3. Test signal for contrast ratio measurement (enumeration of black box indices: $\text{left} = 1, \text{upper} = 2, \text{right} = 3, \text{lower} = 4$).

value extends slightly beyond the color space and tolerance values given for CRTs, whereas the values for red and blue are within tolerance.

Darkroom Contrast Ratio Measurement: As we have seen in peak luminance measurement, contrast measurement depends very much on the relative areas of black and white shown on the display, and consequently on internal current regulation (white requires full current). This also affects the measured ratio of luminance white to luminance black. It is therefore important that contrast measurement must always include details of the measurement signal used when determining the contrast ratio:

$$C = \frac{L_w}{L_b} \tag{IV-5}$$

We determined the contrast ratio for the full screen with the values of Table IV.

$$C = \frac{\mu_w}{\mu_b} = 2531 \tag{IV-6}$$

and with a test signal (Fig. 3) that approximated the guidelines of ITU-R BT.815 [33].

The size of the test image was 1920 × 1080 pixels. Each box had a size of 200 × 200 pixels. Black level was (0, 0, 0), white level (255, 255, 255) and grey level 127.

TABLE V
CONTRAST WITH TEST SIGNAL

Contrast Measurement with CS100	L_w [cd/m²]	L_{b1} [cd/m²]	L_{b2} [cd/m²]	L_{b3} [cd/m²]	L_{b4} [cd/m²]
$\mu_{1..5}$	95.580	0.286	0.284	0.288	0.294
σ	0.110	0.005	0.005	0.004	0.005

TABLE VI
CONTRAST MEASUREMENT WITH THOMA TMF6

Contrast Measurement TMF6					
	L_w [cd/m²]	L_{b1} [cd/m²]	L_{b2} [cd/m²]	L_{b3} [cd/m²]	L_{b4} [cd/m²]
$\mu_{1..5}$	70.800	0.124	0.120	0.113	0.142
σ	0.000	0.000	0.000	0.000	0.000

White and black luminance were measured five times perpendicular to the test image boxes at 1m distance with the CS100 (Table V).

The measured average for all values $\mathrm{L_{b1-4}}$ was $0.288\ \mathrm{cd/m^2}$. The contrast ratio was then calculated as $\mathrm{C} = 332$.

The difference between full screen contrast and contrast with the test signal was remarkable. For that reason a second measurement with a Thoma TMF6 (Table VI) was conducted. The measurement head of the Thoma TMF6 was placed directly on the screen.

C was calculated as 567, which was again significantly different from the full screen value and the measurement with the CS100. This result has shown the difficulty with light measurements and the huge errors that can be caused by several factors such as: veiling glare, stray light influences, limits of the measurement device, and so forth. Whereas the contrast ratio difference between the full screen and test signal can be explained by the internal processing of the PDP, the difference of more than 100% in measurement results between using a CS100 and a TMF6 was more difficult to account for and led to questioning the procedure overall. We therefore acquired a more accurate

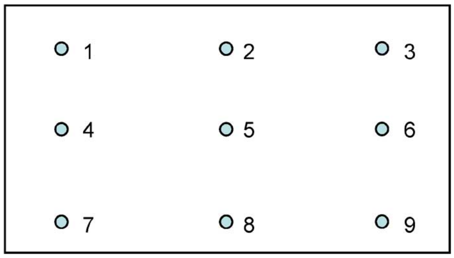

Fig. 4. Measurement points on the screen for uniformity.

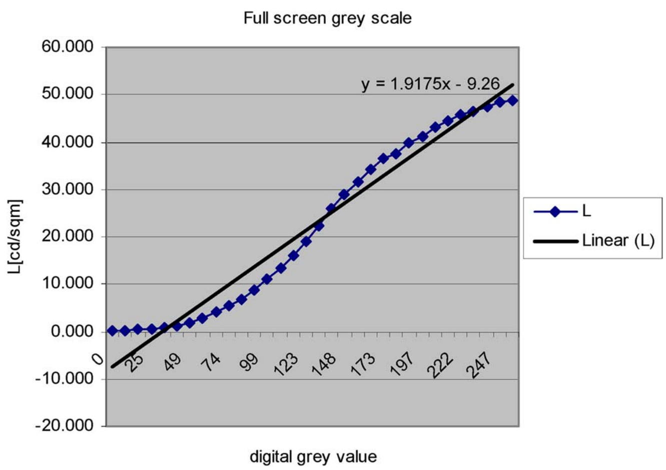

Fig. 5. Grey scale or Gamma curve for full screen presentation (blue: measured curve, black: linear regression).

photospot meter (type Minolta CS200) and repeated the measurements, with similar results to the CS100.

Uniformity of White, Black and RGB: We measured the uniformity of the display at nine positions on the screen (Fig. 4).

We used the Thoma TMF6 measurement device and placed it directly on the screen surface. When comparing the measurement values for position 5 with the results of Table IV as shown in the Appendix we see a measurement difference of about 3–4% due to the measurement device used, the configuration (distance to screen), stray light, reflections, and so on.

The non-uniformity is given by

$$Nonuniformity = 100\% \frac{L_{\max} - L_{\min}}{L_{\max}} \quad \text{(IV-7)}$$

The results of the uniformity measurements are given in Table IX in the Appendix.

Full Screen Grey Scale Measurement: Grey scale was measured five times every 10 seconds with a stimulus of one of 32 digital grey values. A Minolta CS 100 was used at a distance of 1m perpendicular to the center of the screen. Table X in the Appendix shows the individual measurements and **Error! Reference not found.** the measurements in a graph.

Gamma is defined by

$$L = aV_i^{\gamma} + L_K \quad \text{(IV-8)}$$

$$a = \frac{L_w - L_K}{255^{\gamma}} \quad \text{(IV-9)}$$

where V_i is the input command level (0…255), a a constant.

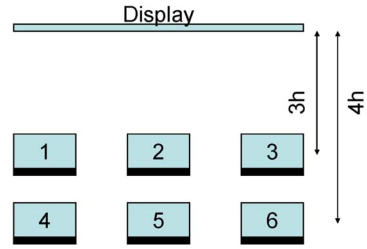

Fig. 6. Seating positions at 3h and 4h.

Using linear regression with

$$y = \gamma x + b \quad \text{(IV-10)}$$

we can calculate for **Error! Reference not found.** a gamma $\gamma = 1.91$. This is very close to the display setting gamma of 2.

C. Data Range for Subjective Tests

The video data range setting on the DVI input of the display was limited to 16–235 according to the encoding rules of HDTV signals in ITU-R BT.709 [34] and SMPTE 274M [35] for 1080i/25 and 1080p/50 and SMPTE 296M [36] for the 720p/50 signal.

D. Display Scaling

For these tests we permitted display scaling, which means that the 720p/50 HDTV signal was up-scaled to the native resolution of the display. It could be argued that direct pixel mapping should have been used, but this would have resulted in a smaller image on the display thus requiring a different viewing distance for all observers and increasing the test complexity. A further argument for our decision to permit up-scaling was the fact that up-scaling is employed in practical home viewing conditions.

E. Seating Position

The advantage of the PDP having less critical viewing angle conditions than the LCD allowed the placement of three observers per row in front of the screen. The distance for the first row was three picture heights and for the second row four picture heights (Fig. 6).

F. Server and Infrastructure

The set up for the equipment and infrastructure is shown in Fig. 7.

Interfacing between the signal source and the display was DVI with 4 m length. The 1080p/50, 720p/50 and 1080i/25 source material was played out from a video server in uncompressed form via DVI.

G. Observers, Test Procedure and Showing of Sequences

Selection of observers: 21 non-expert viewers, male and female of average age, were selected as observers after screening for normal vision. Training sequences and an explanation were given before the viewings, and short relaxation breaks between the test series were offered to the observers.

The Double Stimulus Impairment Scale (DSIS) method according to ITU-R BT.500-11 [27] was used in preparation and presentation of the test sequences.

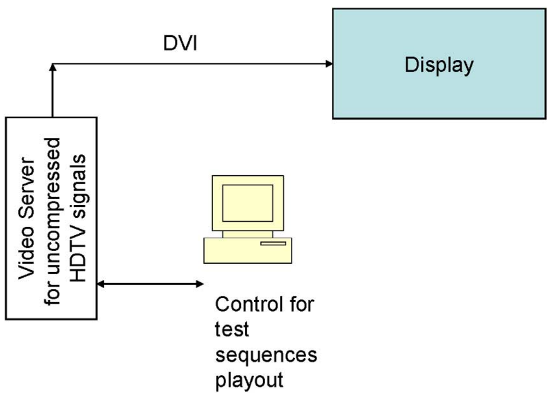

Fig. 7. Infrastructure.

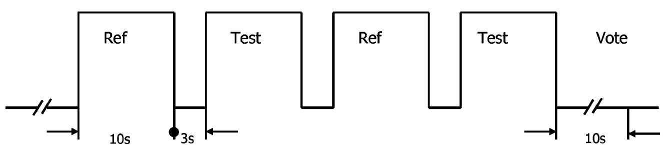

Fig. 8. Test sequence.

As shown in Fig. 8 each sequence was shown twice according to ITU-R BT.500-11 DSIS Variant II, thus repetition $r = 2$.

The uncompressed reference image with a length of 10 seconds was followed by mid gray of 3 seconds, followed by the impaired test image. After that the observers had time to vote.

During the voting period the observers were asked whether they could observe a difference between the reference and the test signal and to mark their result in the corresponding category according to the five in ITU-R BT.500-11 defined terms:

— 5 imperceptible
— 4 perceptible, but not annoying
— 3 slightly annoying
— 2 annoying
— 1 very annoying

In order to increase the reliability of the tests it was decided to add some sequences with identical reference and test sequences in the test series. These sequences were also used to identify the reliability of the votes.

The test series comprised the following HDTV formats:

Series A:
Reference: 1080p/50 uncompressed, 4:2:2, 8 bit resolution
Test: 1080p/50 at 20 Mbit/s, 18 Mbit/s, 16 Mbit/s, 13 Mbit/s, 10 Mbit/s and 8 Mbit/s and uncompressed.

Series B
Reference: 1080i/25 uncompressed, 4:2:2, 8 bit resolution
Test: 1080i/25, 4:2:2, 8 bit resolution at 20 Mbit/s, 18 Mbit/s, 16 Mbit/s, 13 Mbit/s, 10 Mbit/s and 8 Mbit/s and uncompressed.

Series C
Reference: 720p/50 uncompressed, 4:2:2, 8 bit resolution
Test: 1080i/25, 4:2:2, 8 bit resolution at 20 Mbit/s, 18 Mbit/s, 16 Mbit/s, 13 Mbit/s, 10 Mbit/s and 8 Mbit/s and uncompressed.

In total, four consecutive subjective tests over two days conducted, three with six observers and one with three observers.

Fig. 9. Crowd Run sequence (uncompressed 720p/50 converted to JPEG in this figure).

The observers were not informed about which HDTV format they were evaluating and in addition the presentation of the Series A, B, C was changed between the tests:

Session 1: A, B, C
Session 2: C, B, A
Session 3: A, C, B
Session 4: B, C, A

Voting was conducted on paper. Data from each observer comprised name, age, gender, vision (from screening tests), and seating position. Each page of the voting sheets corresponded to one reference-test sequence and a supervisor made sure that the observer did not vote on the wrong pages.

H. MPEG-4 AVC Coding of Test Sequences

Due to the fact that up to now no hardware encoder and decoder for 1080p/50 coding with MPEG-4 AVC has been available, the Heinrich Herz Institute (FhG-HHI) in Berlin performed the encoding and decoding of the sequences in software according to the parameters shown in Table XI in the Appendix.

I. Test Content

A crucial question was the selection of appropriate test content. For this initial subjective tests it was decided to use only critical content (critical but not unduly so), with complex detail and movement as usually contained in sport sequences. In addition, the prerequisite was that identical content should be available in all three HDTV formats under test. Thus it was necessary to use either artificially generated sequences, sequences which were shot with three cameras at the same time, or to use a single camera with sufficiently high resolution to allow down-converting to the three HDTV formats under test. The latter possibility seemed feasible and was chosen. Swedish Television (SVT) had generated 65 mm film-content at 50 frames per second, thus avoiding typical cinema motion artifacts. The material is known under the name "SVT High Definition Multi Format Test Set" and available via [16]. The selected scene is called "Crowd Run" (Fig. 9) which can be categorized as difficult and demanding but not unduly so, in the sense that it could be part of an actual sport television program.

The material was digitized and processed, and down-converted to the three required HDTV formats for the subjective tests according to the details described in [16].

V. Evaluation Procedure According to ITU-R BT.500-11

Observers voted on paper and all data were transferred to Excel for processing in Visual Basic. The first four votes were ignored in the evaluation process, to ensure that observers had time to become familiar with the content and the method.

First, the mean score for each presented series and bit-rate was calculated:

$$\overline{u}_{jkr} = \frac{1}{N}\sum_{i=1}^{N} u_{ijkr} \qquad \text{(V-1)}$$

where:

N number of observers

u_{ijkr} voting results of observer i for test j, sequence k, repetition r.

The standard deviation is given by:

$$S_{jkr} = \sqrt{\sum_{i=1}^{N} \frac{(\overline{u}_{jkr} - u_{ijkr})^2}{(N-1)}} \qquad \text{(V-2)}$$

ITU-T BT.500-11 suggests a 95% confidence interval given by

$$[\overline{u}_{jkr} - \delta_{jkr}, \overline{u}_{jkr} + \delta_{jkr}] \qquad \text{(V-3)}$$

with

$$\delta_{jkr} = 1.96\frac{S_{jkr}}{\sqrt{N}} \qquad \text{(V-4)}$$

For screening of the observers it is suggested to test whether the distribution of scores follows a normal distribution or not. The β_2 test calculates the kurtosis coefficient by:

$$\beta_{2jkr} = \frac{m_4}{m_2} \qquad \text{(V-5)}$$

with:

$$m_x = \frac{\sum_{i=1}^{N}(u_{ijkr} - \overline{u}_{jkr})^x}{N} \qquad \text{(V-6)}$$

Each observer was then tested through all of his votes by the procedure outlined in ITU-R BT.500-11 Section 2.3.1. None of the observers was excluded.

VI. Test Results

For the three HDTV formats 1080p/50, 720p/50 and 1080i/25, we show in Fig. 10, Fig. 11 and Fig. 12 the mean score $\bar{u}_{jkr} +/- \lambda_{jkr}$ for the viewing distance of 3h and of 4h.

VII. Interpretation and Discussion of Subjective Test Results

The tests have reinforced the conclusions of an earlier investigation of Haglund [19] in which the 720p/50 and the 1080i/25 formats with various sequences were tested by using MPEG-2 compression and FPD for viewing. In these tests it was found that the 720p/50 failure characteristic was better than 1080i/25 and expert viewings have concluded with a preference to 720p/50.

Our tests have extended this initial research by using MPEG-4 AVC compression, a defined display characterization, a defined evaluation method and have also included the 1080p/50 format.

The presented tests should not be interpreted as direct comparison tests between the 720p/50, 1080i/25 and 1080p/50 format, because we have investigated each format individually with the Double-Stimulus-Impairment-Scale method. However, when comparing the failure characteristics in Fig. 10, Fig. 11 and Fig. 12 we find that the 1080i/25 format degrades more rapidly than the 720p/50 and 1080p/50 format. In addition, we see that the 720p/50 and 1080p/50 format has shown very

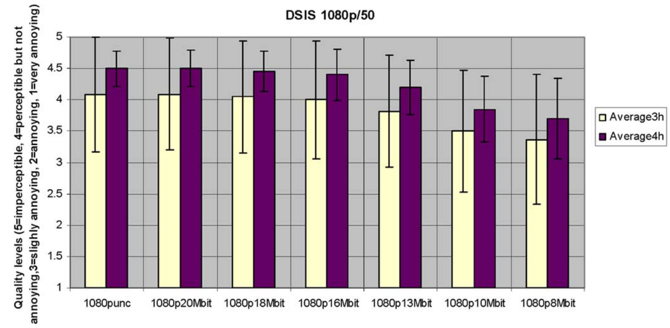

Fig. 10. Mean score of 1080p/50 for various bit rates at 4h and 3h viewing distance with corresponding error bars.

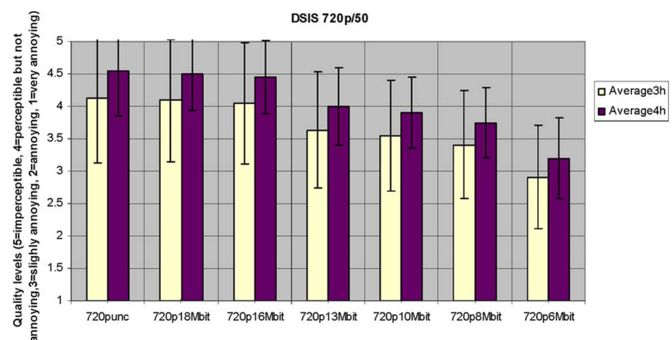

Fig. 11. Mean score of 720p/50 for various bit rates at 4h and 3h viewing distance with corresponding error bars.

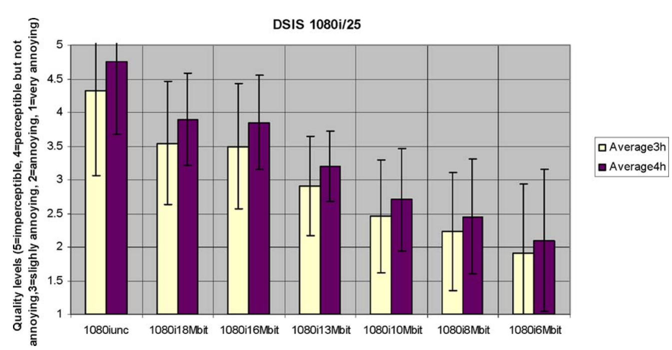

Fig. 12. Mean score of 1080i/25 for various bit rates at 4h and 3h viewing distance with corresponding error bars.

similar curves although the 720p/50 format was presented on a 1920 × 1080 pixel display. Surprising result of these tests was that in practice the 1080p/50 HDTV format performed remarkably well. Even at 8 Mbit/s the format was still rated above "slightly annoying" compared to the 1080p/50 uncompressed reference. The 1080p/50 signal has double the pixel rate and base-band bandwidth of the 1080i/25 signal, so if these were the only factors influencing compression efficiency, the result would be remarkable. If this was the case, one would have expected 1080p/50 to require a higher bit rate than the 1080i/25 format to achieve acceptable quality in its failure curve.

The reason for the impressive performance of the 1080p/50 can probably be found in the following areas:

- The 1080p/50 image starts with a higher quality than the 1080i/25 image, and the 1080p display is able to reap the benefits of this.
- An MPEG-4 AVC encoder compresses progressive signals more efficiently than interlaced, and this is probably due to improvements in the possible accuracy of motion estimation. In fact, the first stages of the compression system are substituting for the interlacing; they are doing the same job—bandwidth reduction—more efficiently than interlacing.
- With a progressive 1080p/50 signal, signal processing in the 1920 × 1080 display is minimized, because no de-interlacing or scaling to the native resolution of the display needs to be performed
- The entropy respectively criticality of the chosen test sequence (sport genre) was particular suited for progressive video signal processing in the encoder and representation on the matrix display.

VIII. Simulation of Test Sequences

For the simulation the full available sequences of the "SVT High Definition Multi Format Test Set" were used. 13 different clips were contained in this sequence, among them the sport sequence used for the subjective tests.

To carry out the comparison between the different HDTV formats, all 13 test sequences of 10 seconds each were downsampled from the original resolution of 3840 × 2160 pixels to 3rd and 2nd generation HDTV broadcast formats of 1080p/50, 1080i/25 and 720p/50 at full resolution of 1920 and 1280 pixels/line respectively. 1080p/25 and 720p/25 formats were also included for comparison. In order to investigate the effect of compression efficiency, all test sequences were then encoded in all scanning formats at three different levels of picture quality, corresponding roughly to ITU-R picture grades of excellent, good and fair. Each quality grade corresponds to a particular average quantization value, which in turn produces different bit rates for each sequence at each scanning format. The quantization values corresponding to the three quality grades were selected with subjective viewing tests. It was found that a quantization factor of 20 was sufficient to produced 'excellent' picture quality on all test sequences. Similarly quantization factors of 27 and 35 were chosen for 'good' and 'fair' picture grades. Once chosen, the same quantization values were used for each sequence at each scanning format. The resulting bit rates were then normalized to the corresponding bit rates in 1080p/50 format. To avoid a bias due to encoder implementation preferences the H.264 software reference encoder JVT9.0 was used for the compression.

TABLE VII
List of Test Sequences in Order of H.264 Coding Criticality

Sequence	Criticality
Park Joy	98.1%
Princess Run	97.2%
Crowd Run	95.3%
Ducks Takeoff	89.7%
Seeking	85.0%
Passing By	73.8%
Tree Tilt	70.1%
Umbrella	57.9%
Old Town Pan	56.1%
Old Town Cross	44.9%
Into Castle	30.8%
Into Tree	28.0%
Dance Kiss	24.3%

Table VII gives a summary of the test sequences which cover the entire range from highly critical to relatively easy material.

A. Criticality Estimate

The criticality of the 13 test sequences was compared to a large set (>200) of reference sequences with a wide variety of content, including sports (skiing, soccer), news, movies, etc. For the purpose of this paper, H.264 coding criticality is defined as the bit rate demand for 'good' picture quality in the 1080i/25 format as compared to the reference sequences. The 1080i/25 format was chosen because it was the format in which the largest set of reference sequences was available. Although there is no guarantee that the set of reference sequences was representative of broadcast material, comparison against a large number of reference sequences gives a rough indication of how the criticality of the test sequences compared to other sequences. To measure the criticality of the 13 test sequences, the bit rate demand of these test sequences was compared with the bit rate demand of the reference sequences with the same encoder configuration. A criticality of 90%, therefore, means that 90% of all reference sequences needed fewer bits to encode with the same quality as this sequence.

Simulation Set-Up: Fig. 13 shows a block diagram of the test set-up. The reference encoders were configured for constant quality, variable bit rate. Although Fig. 13 does not show a decoder, the proper operation of the encoders was verified with software decoding. Constant quality encoding is achieved by configuring the encoder for variable bit rate. It should be noted that picture quality in this sense represents only objective compression quality. It does not include subjective preferences of the different scanning formats.

Encoder Configuration: Table VIII shows the main encoding parameters used for the simulations.

Simulation Results: Fig. 14 to Fig. 17 show the bit rate savings of 1080i/25, 720p/50, 1080p/25 and 720p/25 as compared to 1080p/50 respectively. Each test sequence was coded in these scanning formats at three different levels of quantization, corresponding to excellent, good and fair picture qualities. The required bit rates, normalized to the bit rate of 1080p/50, were

TABLE VIII
MAIN ENCODING PARAMETERS

Parameter	1080p/50	1080p/25	1080i/ 25	720p/50	720p/25
Hor. Resolution	1920	1920	1920	1280	1280
Vert. Resolution	1080	1080	1080	720	720
No of ref frames	2	2	2	2	2
I frame distance	50	25	25	50	25
No of B frames	2	2	2	2	2
Prediction mode	4x4.. 16x16	4x4.. 16x16	4x4.. 16x16	4x4.. 16x16	4x4.. 16x16
Symbol mode	CABAC	CABAC	CABAC	CABAC	CABAC
Pic. Interlace	frame	frame	field/frame ad.	frame	frame
MB interlace	frame	frame	field/frame ad.	frame	frame
Full pel search range	64	64	64	64	64
Sub-pel search	1/4	1/4	1/4	1/4	1/4
Direct mode	spatial	spatial	spatial	spatial	spatial
Loop filter offset	0, 0	0, 0	0, 0	0, 0	0, 0
RD optimisation	on	on	on	on	on
8x8 transforms	adaptive	adaptive	Adaptive	adaptive	adaptive
Scaling matrix	not present	not present	not present	not present	not present
YUV bit depth	8	8	8	8	8

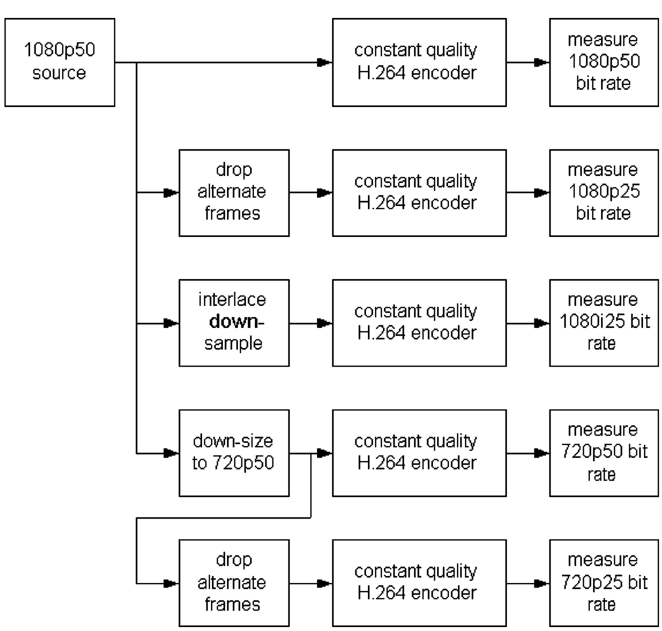

Fig. 13. Block diagram of the simulation set-up.

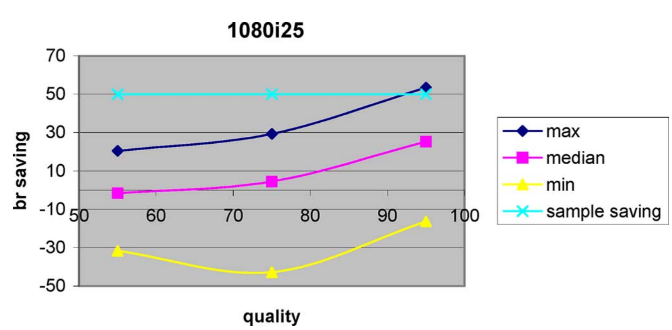

Fig. 14. Bit rate saving of 1080i/25 compression compared to 1080p/50.

sorted to find the minimum, maximum and median bit rate savings. The results for excellent, good and fair picture qualities are plotted at quality points of 95, 75 and 55 respectively. It can be seen that the highest bit rate savings are consistently achieved at high picture qualities, whereas for 'good' and 'fair' picture grades the bit rate savings are substantially lower. In other words, the bit rate demand ratios converge towards the sample rate ratios at high picture quality, whereas at lower picture qualities 1080p/50 compression requires less bit rate than would be expected from the sample rate. k

In 1080i/25 at high picture quality, only one of the test sequences (Old Town Pan) achieved the theoretical bit rate saving of 50% that could be expected from the lower sample rate of the 1080i/25 format. More importantly, the median bit rate 'saving'

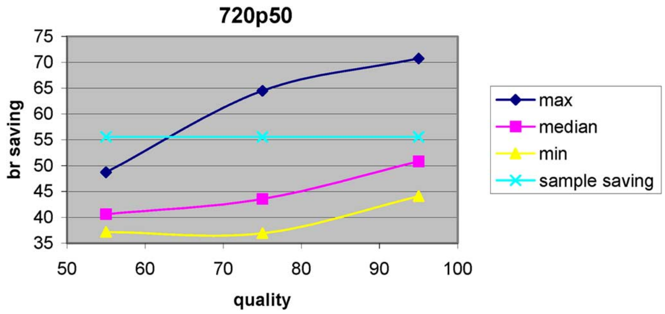

Fig. 15. Bit rate saving of 720p/50 compression compared to 1080p/50.

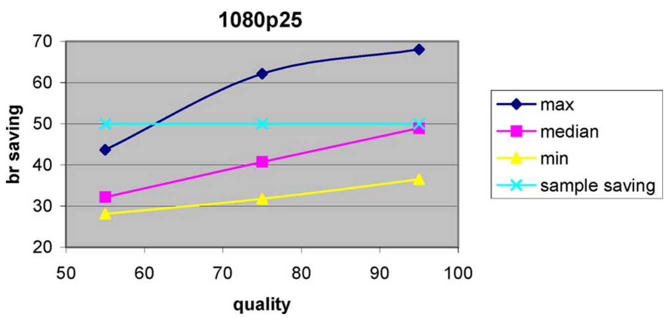

Fig. 16. Bit rate saving of 1080p/25 compression compared to 1080p/50.

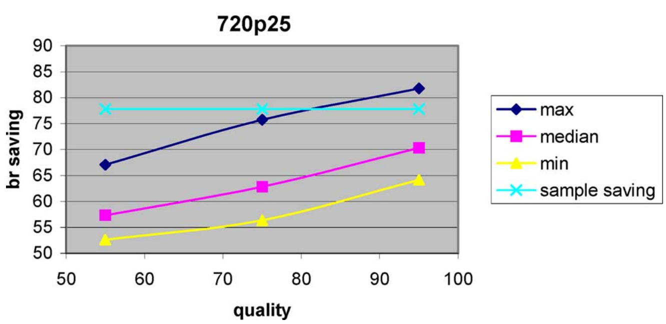

Fig. 17. Bit rate saving of 720p/25 compression compared to 1080p/50.

of 1080i/25 compared to 1080p/50 is negative for medium picture qualities, i.e. a typical 1080i/25 sequence requires 5% more bit rate than the same sequence coded at the same quality in 1080p/50 format. Note that picture quality in this context relates to H.264 compression quality and does not take quality differences between progressive and interlaced scanning into account.

Similarly, in 720p/50 format fewer than half of the test sequences achieve the theoretical bit rate saving of 55% at high picture quality. At medium picture qualities the bit rate saving in 720p/50 drops to about 40% on average.

Interestingly, 1080p/25 compression of a typical test sequence at high picture quality achieves the theoretical bit rate saving of 50% exactly. For lower picture qualities the bit rate saving drops linearly down to 32%.

In 720p/25 format, on the other hand, only one third of the test sequences achieve the theoretical bit rate saving of 78% at high picture quality. Again the relationship with picture quality is almost linear down to a bit rate saving of 57% for 'fair' picture quality. The lower efficiency of 720p/25 compared to 1080p/25 is probably due to the relatively higher spectral density of spatial detail in the 720p image.

TABLE IX
UNIFORMITY MEASUREMENT

Uniformity measurement: white			
	L[cd/m²]	CIE x	CIE y
1	50.5	0.282	0.296
2	48.7	0.282	0.296
3	46.7	0.285	0.296
4	45.1	0.281	0.296
5	47.7	0.28	0.296
6	46.7	0.28	0.296
7	52.5	0.281	0.296
8	51.8	0.281	0.297
9	51.1	0.281	0.297
μ	48.978	0.281	0.296
L_{min}	46.7	0.28	0.296
L_{max}	52.5	0.281	0.297
Nonunif.	11.05%	0.36%	0.34%
Uniformity measurement: red			
1	21.6	0.66	0.323
2	20.6	0.661	0.324
3	21	0.662	0.324
4	21.8	0.661	0.324
5	19.3	0.661	0.324
6	20.4	0.661	0.324
7	22.8	0.661	0.324
8	21.9	0.662	0.323
9	22.1	0.662	0.324
μ	21.278	0.661	0.324
L_{min}	19.3	0.66	0.323
L_{max}	22.8	0.662	0.324
Nonunif.	15.35%	0.30%	0.31%
Uniformity measurement: green			
1	64.4	0.22	0.729
2	60.1	0.221	0.728
3	60.1	0.221	0.728
4	64.5	0.222	0.728
5	57	0.222	0.728
6	59.1	0.222	0.729
7	66.5	0.22	0.731
8	63.3	0.22	0.731
9	64.6	0.22	0.731
μ	62.178	0.221	0.729
L_{min}	59.1	0.22	0.728
L_{max}	66.5	0.221	0.731
Nonunif.	11.13%	0.45%	0.41%
Uniformity measurement: blue			
1	8.8	0.143	0.62
2	8.4	0.143	0.62
3	8.6	0.143	0.62
4	8.8	0.143	0.62
5	8.1	0.142	0.63
6	8.8	0.143	0.63
7	9.9	0.143	0.61
8	9.6	0.143	0.62
9	9.9	0.143	0.62
μ	8.989	0.143	0.621
L_{min}	8.1	0.142	0.62
L_{max}	9.9	0.143	0.63
Nonunif.	18.18%	0.70%	1.59%

TABLE X
GRAY SCALE MEASUREMENT

Grey scale measurement							
digital level	L_1 [cd/m^2]	L_2 [cd/m^2]	L_3 [cd/m^2]	L_4 [cd/m^2]	L_5 [cd/m^2]	μ [cd/m^2]	σ [cd/m^2]
0	0.19	0.19	0.19	0.19	0.18	0.188	0.004
8	0.21	0.21	0.21	0.21	0.21	0.210	0.000
16	0.33	0.33	0.34	0.33	0.33	0.332	0.004
25	0.62	0.61	0.61	0.61	0.61	0.612	0.004
33	0.84	0.84	0.85	0.85	0.85	0.846	0.005
41	1.24	1.25	1.25	1.25	1.25	1.248	0.004
49	1.91	1.91	1.91	1.91	1.91	1.910	0.000
58	2.92	2.92	2.92	2.92	2.93	2.922	0.004
66	4.15	4.21	4.2	4.19	4.2	4.190	0.023
74	5.43	5.42	5.41	5.42	5.44	5.424	0.011
82	6.89	6.89	6.89	6.87	6.88	6.884	0.009
90	8.81	8.83	8.81	8.83	8.82	8.820	0.010
99	11.2	11.2	11.2	11.2	11.2	11.200	0.000
107	13.5	13.5	13.5	13.5	13.5	13.500	0.000
115	15.9	16	15.9	15.9	15.9	15.920	0.045
123	18.9	18.9	18.9	18.9	18.9	18.900	0.000
132	22.4	22.5	22.4	22.4	22.4	22.420	0.045
140	26.1	26.1	26.1	26.1	26.1	26.100	0.000
148	29	29.1	29	29	29	29.020	0.045
156	31.7	31.7	31.7	31.7	31.7	31.700	0.000
165	34.2	34.1	34.2	34.2	34.2	34.180	0.045
173	36.5	36.5	36.5	36.5	36.5	36.500	0.000
181	37.6	37.7	37.7	37.7	37.7	37.680	0.045
189	39.6	39.7	39.7	39.7	39.7	39.680	0.045
197	41.1	41.2	41.2	41.2	41.2	41.180	0.045
206	43.1	43.1	43.1	43.2	43.1	43.120	0.045
214	44.3	44.3	44.3	44.4	44.3	44.320	0.045
222	45.7	45.8	45.6	45.6	45.8	45.700	0.100
230	46.4	46.6	46.6	46.6	46.6	46.560	0.089
239	47.5	47.5	47.5	47.6	47.5	47.520	0.045
247	48.4	48.4	48.5	48.4	48.4	48.420	0.045
255	48.9	48.9	48.9	48.9	49	48.920	0.045

IX. CONCLUSION AND RECOMMENDATION FOR FURTHER WORK

The potential 3rd generation HDTV format, 1080p/50, has been used as a basis for the comparison of bit rate demands of 2nd generation HDTV formats in subjective tests and with simulations. It has been shown that the coding efficiency of 1080p/50 is very similar (simulations) or even better (subjective tests) than 1080i/25 despite the fact that twice

TABLE XI
ENCODER SETTINGS

Encoder configuration	720p /50	1080i/2 5	1080p/ 50	
InputFrequencyRate	50	25	50	# Input Frequency Rate
InputFrequencyScale	1	1	1	# Input Frequency Scale
InputPicSizeX	1280	1920	1920	# Input Frame Size X
InputPicSizeY	720	1080	1080	# Input Frame Size Y
InputFormat	0	1	0	# Input Format (0:progressiv e, 1:frame with top field first, 2:frame with bottom field first)
OutputFrequencyRate	50	25	50	# Output Frequency Rate
OutputFrequencyScale	1	1	1	# Output Frequency Scale
ProfileIdc	100	100	100	# Profile (66:Baseline, 77:Main, 88:Extended, 100: High)
LevelIdc	40	40	50	# Level (e.g. 41 -> Level 4.1, 16=Level 1b)
SPSId	0	0	0	# SPS ID (0..31)
PPSId	0	0	0	# PPS ID (0..255)
GapsInFrameNum	0	0	0	# Gaps In Frame Num Allowed Flag
RespectLevelConstraints	1	1	1	# Respect Level constraints (0:off, >0:on)
NumberReferenceFrame s	4	3	3	# Number of Reference Frames
IntraAlwaysRandomAcc ess	1	1	1	# Intra can always be used as random access point (1:on, 0:off)
Log2MaxFrameNum	4	4	4	# specify max frame_num value (4..16)
IFrameDistance	24	24	24	# I Frame Distance (-1=only first frame)
IFrameIdrDistance	-1	-1	-1	# I Frame IDR Distance (e.g. 2:every third I frame is IDR, -1: only first)
BFrameNumber	2	2	2	# Number of B Frames

TABLE XI (Continued.)
ENCODER SETTINGS

StoreBFrames	0	0	0	**# Store B Frames (0:do not store, 1:store)**
ContIntraRepetition	**1**	1	1	**# Force Continous Intra Frame Repetition**
PPSQuant	**36**	**36**	**36**	**# Qp transmitted in PPS / rate control init**
SymbolType	1	1	1	# Symbol Type (0=VLC, 1=CABAC)
CabacInit	3	3	3	# CABAC initialization (0-2: fixed table number; 3: adaptive)
CabacRateCalculation	0	0	0	# use Cabac for Rate Approximatio n for CABAC (0:use VLC approximatio n; 1: use CABAC approximatio n)
TargetBitRate	6000	6000	6000	# Target Bit Rate in kbit/sec (0=no rate control)
MinRateControlQp	20	20	20	
IntraRateControl	0	0	0	# intra rate control (0:off, >0:on)
PreProcess	1	1	1	
Delay	10	10	10	
InterlacedMode	0	3	0	# Interlaced Mode (0:frame only, 1:fields only, 2:frame/field(intra), 3:RD, 4:random)
MbaffMode	0	3	0	# MbAFF for frames (0: off, 1: frame MBs, 2: field MBs, 3: RD, 4: random, 5: chessboard a, 6: chessboard b)
SliceMode	0	0	0	# Slice Mode (0: single slice, 1: fixed number of MBs, 2: random, 3: random multiple types)

the number of pixels have to be coded. This is due to the higher compression efficiency and better motion tracking of progressively scanned video signals compared to interlaced scanning.

TABLE XI (*Continued.*)
ENCODER SETTINGS

OneSliceTypeIndication	0	0	0	# Indicate same slice type per picture via slice_type (only for SliceMode<3, default = 1)
SliceNumMbs	0	0	0	# Number of Macroblocks (only for SliceMode=1)
MaxNumSlices	0	0	0	# Max. Number of Random Slices (only for SliceMode=2)
FastCodingMode	0	0	0	# Fast Coding Mode (0: normal, 1: fast)
FastInterlacedMode	= 0	= 0	= 0	# Fast Frame/Field Decisions (in R-D cases only; 0: normal, 1: fast)
CoeffThr	0	0	0	# Coeff Threshold
ConstrainedIntraPred	0	0	0	# Constrained Intra Prediction Flag
PocMode	0	0	0	# POC Mode
SearchMode	6	6	6	# Search Mode (0:BlockSearch, 1:SpiralSearch, 2:LogSearch, 3:FastSearch)
AdvancedSearchQuality	2	2	2	# 1(fast) - 6(good) ---- (only for SearchMode = 6)
FullPelDFunc	0	0	0	# Search Function Full Pel (0:SAD, 1:SSE, 2:HADAMARD)
SubPelDFunc	0	0	0	# Search Function Sub Pel (0:SAD, 1:SSE, 2:HADAMARD)
SearchRange	96	128	128	# Search Range (Full Pel)
MaxIterations	0	0	0	# Max Number of Iterations for B-Search (0: non-iterative search (old version))

TABLE XI (*Continued.*)
ENCODER SETTINGS

IterSearchRange	8	8	8	# Search Range for iterative search (0: use normal search; >0: search with given search range)
BackwardSearch	1	1	1	# Backward Search (0: as forward, 1:iterative, 2:use foreward MV)
DirectMode	0	0	0	# Direct Spatial Flag (0=Temporal, 1=Spatial)
DiscardSubPelSearch	0	0	0	# Discard Sub Pel Search (0-evaluated sub pel positions .. 31)
MaxRefIdxL0ActivePSliceNonRef	32	32	32	# maximum numer of reference frames used with non ref frames of P slices
MaxRefIdxL0ActivePSliceRef	32	32	32	# maximum numer of reference frames used with ref frames of P slices
MaxRefIdxL0ActiveBSliceNonRef	1	1	1	# maximum numer of reference frames used with non ref frames of list 0 of B slices
MaxRefIdxL1ActiveBSliceNonRef	1	1	1	# maximum numer of reference frames used with non ref frames of list 1 of B slices
MaxRefIdxL0ActiveBSliceRef	1	1	1	# maximum numer of reference frames used with ref frames of list 0 of B slices
MaxRefIdxL1ActiveBSliceRef	1	1	1	# maximum numer of reference frames used with ref frames of list 1 of B slices
8x8TransformEnable	1	1	1	# 8x8 Transform (0=disable,1=enable)

The results of the initial subjective tests suggest that it is very worthwhile to continue research and studies on the 1080p/50–60 format for future HDTV applications and future delivery to the home. The problem of finding a transparent large FPD reference display is significant and requires urgent work. We have conducted a basic characterization of the display used for the tests to permit similar set-up and tests. The authors are aware that the subjective tests conducted in this paper represent only initial research and it is suggested that further tests are performed with a different kind of content genre, a different type of creating content (i.e. with CMOS and CCD cameras with native 1920 × 1080 pixel or higher resolution and at least 50p frame rates) and that viewing is conducted on different kinds of display technologies such as liquid crystal displays and back projection displays and if possible with a grade 1-equivalent FPD. In addition, alternative criteria may be used for encoding and decoding. The authors will perform further tests in the suggested direction and will publish them in the near future. The authors would welcome feedback on their studies.

APPENDIX

Display uniformity measurement is shown in Table IX.

Display grey scale measurement is shown in Table X.

Encoder setting for the subjective tests is shown in Table XI.

ACKNOWLEDGMENT

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