Rec. 601

— the origins of the 4:2:2 DTV standard

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The year 2005 marks the 25th anniversary of the development of the 4:2:2 Component Digital Television Standard. This standard – as documented in SMPTE 125, several EBU Recommendations and ITU-R Recommendation 601 – was the first international standard adopted for interfacing equipment directly in the digital domain avoiding the need to first restore the signal to an analogue format.

This article [1] – one of three published in this edition to celebrate the 25th anniversary of "Rec. 601" – presents an overview of this historic achievement. It provides a history of the standard's origins, explaining how it came into being, why various parameter values were chosen, the process that led the world community to an agreement, and how the 4:2:2 standard led to today's digital high-definition production standards.

The 4:2:2 digital interface standard was designed so that the basic parameter values provided would work equally well in both the 525-line/60 Hz and 625-line/50 Hz television production environments.

The standard was developed in a remarkably short time, considering its pioneering scope, as the worldwide television community recognized the urgent need for a solid basis for the development of an all-digital television production system. A system based on a luminance sampling frequency of ***13.5 MHz*** was first proposed in February 1980; the world television community essentially agreed to proceed on a ***component-based*** system in September 1980 at the IBC. A group of manufacturers supplied devices incorporating the proposed interface at an SMPTE-sponsored test demonstration in San Francisco in February 1981; most parameter values were essentially agreed by March 1981 and the ITU-R (then called the CCIR) Plenary Assembly adopted the standard in February 1982.

Development of an NTSC composite standard

By 1977, a number of digital television products had become available for use in professional television production. These included graphics generators, noise reducers, timebase correctors and synchronizers and standards converters, amongst others. However, each manufacturer had adopted its own concept of a digital interface, and this meant that these digital devices, when formed into a workable production system, had to be interfaced at the analogue level, thereby forfeiting many of the advantages of their internal digital processing.

In March 1977, the Society of Motion Picture and Television Engineers (SMPTE) began development of a digital television interface standard. The work was assigned by the SMPTE's Committee

1. Also published simultaneously in the SMPTE Journal

on New Technology, chaired by Fred Remley, to the Working Group on Digital Video Standards, chaired by Dr Robert Hopkins.

By 1979, the Working Group on Digital Video Standards was completing development of a digital interface standard for NTSC television production. Given the state-of-the-art at the time and the desire to develop a standard based on the most efficient mechanism, the Working Group created a standard that allowed the NTSC television video signal to be sampled as a single ***composite-colour*** television signal. It was agreed after a long debate on the merits of three-times sub-carrier ($3f_{sc}$) versus four-times sub-carrier ($4f_{sc}$) sampling that the *Composite Digital Television Standard* would require the composite television signal, with its luminance channel and colour sub-carrier, to be sampled at four-times the colour sub-carrier frequency ($4f_{sc}$) or 14.31818 MHz.

During the last quarter of 1979, agreement was reached on a set of parameter values, and the drafting of the Composite Digital Television Standard was considered completed. It defined a signal sampled at 4fsc with 8-bit samples. This standard seemed to resolve the problem of providing a direct digital interface for production facilities utilizing the NTSC standard. As will be pointed out later in this article, however, this work was placed on hold while discussions on the possibility of a worldwide ***component*** standard were being considered.

Developments within the European community

At the same time, the European community was seeking a common digital interface standard for use in Europe. However, the European community was faced with an additional set of problems. Some European nations had adopted various forms of the PAL 625-line/50 Hz composite colour television standard as their ***broadcast standard*** and other European nations had adopted various forms of the SECAM 625-line/50 Hz composite colour television standard.

It is understood that digital processing of any signal requires that the sample locations be clearly defined in time and space and, for television, sampling is simplified if the samples are aligned so that they are line-, field-, and frame-position repetitive, yielding an orthogonal (rectangular-grid) sampling pattern.

While the NTSC system colour sub-carrier frequency (f_{sc}) was an integer sub-multiple of the horizontal line frequency (f_H) [f_{sc} = (m/n) x f_H] lending itself to orthogonal sampling, the PAL system colour sub-carrier employed a field-frequency off-set and the SECAM colour system employed frequency modulation, which made sampling the colour information contained within those systems a more difficult challenge.

In September 1972, the European Broadcasting Union (EBU) formed Working Party C, chaired by Peter Rainger to investigate the subject of coding television systems. In 1977, based on the work of Working Party C, the EBU issued a document recommending that the European community consider a component television production standard, since a component signal could be encoded as either a PAL or SECAM composite signal just prior to transmission.

At a meeting in Montreux, Switzerland in the spring of 1979, the EBU reached agreement with production equipment manufacturers that the future of digital programme production in Europe lay in component coding rather than composite coding, and the EBU established a research and development programme among its Members to determine appropriate parameter values.

This launched an extensive programme of work within the EBU on digital video coding for programme production. The work was conducted within a handful of research laboratories across Europe and within a reorganized EBU committee structure including Working Party V on New Systems and Services, chaired by Peter Rainger, a subgroup V1, chaired by Yves Guinet, which assumed the tasks originally assigned to Working Party C, and a specialist supporting committee V1-VID (Video) chaired by Howard Jones. David Wood, representing the EBU Technical Centre, served as the secretariat of all of the EBU committees concerned with digital video coding.

A turning point for the EBU – the 1980 Technical Committee meeting in London

Most of the individuals involved in the SMPTE and EBU efforts came to realize that the world community would be best served if there could be an agreement on a single production or studio digital interface standard regardless of which colour-standard (525-line NTSC, 625-line PAL, or 625-line SECAM) was being employed for transmission.

The EBU Technical Committee endorsed this conclusion at a meeting in April 1980, and instructed its technical groups: V, V1, and V1-VID to support this effort [1].

Responding to this dialogue and so as not to prejudice the efforts being made to reach agreement on a worldwide component standard, Dr Hopkins in January 1980 put the finished work on the NTSC Composite Digital Television Standard temporarily aside – so that any minor modifications to the document that would serve to meet possible *worldwide* applications could be incorporated before final approval. Since copies of the document were bound in red binders, the standard was referred to as the "Red Book".

SMPTE organized for the task at hand

Three SMPTE committees were charged with addressing various aspects of worldwide digital standards. The first group, organized in late 1974, was the Digital Study Group chaired by Charles Ginsburg. The Study Group was charged with investigating all issues concerning the application of digital technology to television.

By 1980, the Committee on New Technology was being chaired by Robert Hopkins. The Committee on New Technology established a Task Force on Component Digital Coding, with Frank Davidoff as chairman. This Task Force, which began work in February 1980, was charged with developing a recommendation for a single worldwide digital interface standard [2]. While membership in SMPTE committees is open to any interested and affected party, the membership of the Task Force had been limited to recognized experts in the field.

The third group involved in the project was the already-established Working Group on Digital Video Standards, where Ken Davies had replaced Robert Hopkins as chairman. This Working Group would process recommendations developed by the Study Group or the Task Force and document appropriate standards, recommended practices and engineering guidelines.

First considerations

In 1979, EBU VI-VID proposed a single three-channel (Y, R-Y, B-Y) component standard. The system stipulated a 12.0 MHz luminance (Y channel) sampling frequency and provided for each of the colour-difference signals (R-Y and B-Y) to be sampled at 4.0 MHz. The relationship between the luminance and colour-difference signals was noted sometimes as (12:4:4) and sometimes as

(3:1:1). The proposal, based on the results of subjective quality evaluations, suggested these values were adequate to deliver 625/50i picture quality, transparently [3].

The agenda of the January 1980 meeting of SMPTE's Digital Study Group included a discussion on a worldwide digital television interface standard. At that meeting, the Study Group considered the report of the European community.

It was recognized that while a three-color representation of the television signal using Red, Blue and Green (R,G,B) was the simplest three-component representation, a more efficient component representation, but one that is more complex, is to provide a luminance or grey scale channel (Y) and two colour-difference signals (R-Y and B-Y). The R-Y and B-Y components take advantage of the characteristics of the human visual system which is less sensitive to high-resolution information for colour than for luminance. This allows for the use of a lower number of samples to represent the colour-difference signals without observable losses in the restored images. Colour-difference components (I,Q or U,V or D_r, D_b) were already in use in the NTSC, PAL and SECAM systems to reduce the bandwidth required to support colour information.

Members of the NTSC community present at the January 1980 Study Group meeting believed that the EBU V1-VID proposed 12.0 MHz, (3:1:1) set of parameters would not meet the needs for television post-production, particularly with respect to ***chroma-keying*** which was then becoming an important tool. In addition, it was argued that: (1) the sampling frequency was too low (too close to the Nyquist point) for use in a production environment where multiple generations of edits were required to accommodate special effects, chroma-keying, etc. and (2) a 12.0 MHz sampling system would not produce an orthogonal array of samples in NTSC (at 12.0 MHz, there would be 762.666 pixels per line).

The NTSC community offered for consideration a single three-channel component standard based on (Y, R-Y, B-Y). This system stipulated a $4f_{sc}$ (14.318 MHz) luminance-sampling frequency equal to 910 x f_{H525}, where f_{H525} is the NTSC horizontal line frequency. The proposal further provided for each of the colour-difference components to be sampled at $2f_{sc}$ or 7.159 MHz. This relationship between the luminance and colour-difference signals was noted as ***4:2:2***.

Representatives of the European television community present at the January 1980 Study Group meeting pointed to some potential difficulties with this proposal. The objections included: (1) that the sampling frequency was too high for use in practical digital recording at the time and (2) a 14.318 MHz sampling system would not produce an orthogonal array of samples in a 625-line system (at 14.318 MHz, there would be 916.36 pixels per line).

The NTSC community suggested that the European community adopt a luminance-sampling frequency that was a multiple of the 625-line frequency nearest to 14.318 MHz.

Seeking a Common Reference

During the January 1980 Study Group meeting, Stan Baron asked why the parties involved had not considered a sampling frequency that was a multiple of the 4.5 MHz sound carrier, since the horizontal line frequencies of both the 525-line and 625-line systems had an integer relationship to 4.5 MHz.

The original definition of the ***NTSC colour system*** established a relationship between the sound-carrier frequency (f_S) and the horizontal line frequency (f_{H525}):

$$f_{H525} = f_S/286 = 15734.265 \text{ Hz}$$

It had further defined the vertical field rate (f_{V525}):

$$f_{V525} = (f_{H525} \times 2)/525 = 59.94006 \text{ Hz}$$

... and also defined the colour sub-carrier (f_{SC}):

$$f_{SC} = (f_{H525} \text{ x } 455)/2 = 3.579545 \text{ MHz.}$$

Therefore, all the frequency components of the NTSC system could be derived as integer sub-multiples of the sound carrier [4].

The ***625-line system*** defined the horizontal line frequency (f_{H625}) as:

$$f_{H625} = 15625 \text{ Hz}$$

... and the vertical field rate (f_{V625}) as:

$$f_{V625} = (f_{H625} \text{ x } 2)/625 = 50 \text{ Hz.}$$

It was noted from the beginning that the relationship between f_S and the horizontal line frequency (f_{H625}) could be expressed as:

$$f_{H625} = f_S/288$$

Therefore, any sampling frequency that was an integer multiple of 4.5 MHz would produce samples in either the 525-line or 625-line systems that were orthogonal.

Stan Baron was asked to submit papers to the Study Group and the Task Force describing the relationship. The assignment was to cover two topics. The first topic was how the 625-line community might arrive at a sampling frequency close to 14.318 MHz. The second topic was to explain the relationship between the horizontal frequencies of the 525-line and 625-line systems and 4.5 MHz.

This resulted in Stan authoring a series of papers written between February and April 1980, addressed to the SMPTE Task Force explaining why 13.5 MHz should be considered the choice for a common luminance-sampling frequency. The series of papers was intended to serve as a tutorial with each of the papers expanding on the points previously raised.

At a subsequent meeting in January 1981, the EBU had considered an additional set of parameters based on a 13.0 MHz, (4:2:2) system. Additional research conducted by EBU members had shown that a (4:2:2) arrangement was needed in order to cope with picture processing requirements, such as chroma-key, and the EBU members believed a 13.0 MHz system appeared to be the most economic system that provided adequate picture processing.

Crunching the numbers

The first note addressed to the Task Force was dated 11 February 1980 [5]. This paper pointed to the fact that since the horizontal line frequency of the 525-line system (f_{H525}) had been defined as 4.5 MHz/286 (2.25 MHz/143), and the horizontal line frequency of the 625-line system (f_{H625}) was equal to 4.5 MHz/288 (2.25 MHz/144), any sampling frequency that was a multiple of 4.5 MHz/2 could be synchronized to both systems. Since it would be desirable to sample colour-difference signals at less than the sampling rate of the luminance signal, then a sampling frequency that was a multiple of 2.25 MHz would be appropriate for use with the colour-difference components while a sampling frequency that was a multiple of 4.5 MHz would be appropriate for use with the luminance component.

Since the European community had argued that the sampling frequency must be lower than 14.318 MHz and the NTSC countries had argued that the sampling frequency must be higher than 12.00 MHz, the paper and cover letter dated 11 February 1980 suggested consideration of 3 x 4.5 MHz or 13.5 MHz as the common luminance (Y) channel-sampling frequency (858 times the 525-line horizontal line-frequency rate and 864 times the 625-line rate both equal 13.5 MHz).

The series of notes offered a tristimulous component colour system based on (Y, R-Y, B-Y) and a luminance/colour sampling relationship of (4:2:2), with the colour signals sampled at 6.75 MHz. In order for the system to facilitate standards conversion, both the luminance and colour-difference samples should be orthogonal. This implies a number of samples per active line that is divisible by four.

The February 1980 note further suggested that the number of samples per active line period should be greater than 715.5 to accommodate all of the European standards active line periods. While the number of pixels per active line equal to ***720 samples per line*** was not suggested until the next note, (720 is the number found in Rec. 601 and SMPTE 125), 720 is the first value that "works". 716 is the first number greater than 715.5 that is divisible by 4 (716 = 4 x 179), but does not lend itself to standards conversion between 525-line component and composite colour systems or provide sufficiently small pixel groupings to facilitate special effects. Arguments in support of 720 were provided in additional notes prior to IBC in September 1980.

Note that 720 equals 6! [i.e. 6-factorial, or 6x5x4x3x2x1] which is also equal to 2^4 x 3^2 x 5. This allows for many small factors, important for finding an economical solution to conversion between the 525-line component and composite colour standards and for image manipulation in special effects. The composite 525-line digital standard provided for 768 samples per active line. 768 = 2^8 x 3. The relationship between 768 and 720 can be described as 768/720 = (2^8 x 3)/(2^4 x 3^2 x 5) = (2^4)/(3 x 5) = 16/15. A set of 16 samples in the composite standard could be used to calculate a set of 15 samples in the component standard.

Proof of performance

At the 1980 IBC conference, international consensus became focused on the 13.5 MHz, (4:2:2) system. However, both the 12.0 MHz and 14.318 MHz systems retained some support for a variety of practical considerations.

Discussions within the Working Group on Digital Video Standards indicated that consensus could not be achieved without the introduction of convincing evidence.

The SMPTE proposed to hold a *"Component-Coded Digital Video Demonstration"* in San Francisco in February 1981, organized by and under the direction of the Working Group on Digital Video Standards, to evaluate component-coded systems. A series of practical tests/demonstrations were organized to examine the merits of various proposals with respect to picture quality, production effects, recording capability and practical interfacing, and to establish an informed basis for decision-making.

The test room in San Francisco awaits the first subjects

The EBU had scheduled a series of demonstrations at the IBA in January 1981, for the same purpose. The SMPTE invited the EBU to hold its February meeting of the *Bureau* of the Technical Committee in San Francisco to be followed by a joint meeting to discuss the results. It was agreed that demonstrations would be conducted at three different sampling frequencies (near 12.0 MHz, 13. 5 MHz, and 14.318 MHz) and at various levels of performance.

Approximately one year from the date of the original 13.5 MHz proposal, from 2 - 6 February 1981, the SMPTE conducted demonstrations at KPIX Television, Studio N facilities in San Francisco in which a number of companies participated. Each participating sponsor developed equipment with the digital interface built to the specifications provided. The demonstration was intended to provide proof of performance and to allow the international community to come to an agreement [6].

The demonstration organizing committee had to improvise many special interfaces and interconnections, as well as create a range of test objects, test signals, critical observation criteria, and a scoring and analysis system and methodology.

The demonstrations were supported with equipment and personnel by many of the companies that were pioneers in the development of digital television and included: ABC Television, Ampex Corporation, Barco, Canadian Broadcasting Corporation, CBS Technology Centre, Digital Video Systems, Dynair, Inc., KPIX-Westinghouse Broadcasting, Leitch Video Ltd., Marconi Electronics, RCA Corporation and RCA Laboratories, Sony Corporation, Tektronix Inc., Thomson-CSF, VG Electronics Ltd. and VGR Corporation.

Developing an agreement

The San Francisco demonstrations proved the viability of the ***13.5 MHz (4:2:2)*** proposal. Members of the EBU and SMPTE committees met at a joint meeting chaired by Peter Rainger in March 1981 and agreed to propose the 13.5 MHz (4:2:2) standard as the worldwide standard. By autumn 1981, NHK in Japan led by Mr Tadokoro, had performed its own independent evaluations and concurred that the 13.5 MHz (4:2:2) standard offered the optimum solution.

A number of points were generally agreed upon and formed the basis of a new worldwide standard. They included:

1) The existing colorimetry of the EBU (for PAL and SECAM) and NTSC colour models would be retained for 625-line and 525-line signals respectively, as colour matrixing to a common colorimetry was considered over-burdensome;
2) An 8-bit-per-sample representation would be defined initially, being within the state-of-the-art, but a 10-bit-per-sample representation would be required for many production uses;
3) The range of the signal to be included should include head-room (above white level) and foot-room (below black level) to allow for production overshoots;
4) The line length to be sampled should be somewhat wider than those of the analogue systems (NTSC, PAL, SECAM) under consideration to faithfully preserve picture edges and to avoid picture cropping;
5) A bit-parallel, sample multiplexed interface (e.g. transmitting R-Y, Y, B-Y, Y, R-Y, ...) was practical but, in the long-term, a fully bit- and word-serial system would be desirable;
6) The gross data rate should be recordable within the capacity of digital tape recorders then in the development stages by Ampex, Bosch, RCA and Sony.

Abbreviations

CCIR	(ITU) International Radio Consultative Committee
IBC	International Broadcasting Convention
IRE	A relative unit of measure (named after the Institute of Radio Engineers). One IRE equals 1/140th of the composite video signal's peak-to-peak voltage.
ITU-R	ITU - Radiocommunication Sector
NTSC	National Television System Committee (USA)
OTI	*Organización de la Televisión Iberoamericana*
PAL	Phase Alternation Line
RGB	Red-Green-Blue (colour model)
SECAM	*Séquentiel couleur à mémoire*
SMPTE	Society of Motion Picture and Television Engineers (USA)
YUV	The luminance (Y) and colour difference (U and V) signals of the PAL colour television system

The standard, as documented, provided for each digital sample to consist of at least 8 bits, with 10 allowed. The values for the black and white levels were defined, as was the range of the colour signal. (R-Y) and (B-Y) became C_R [=0.713 x (R-Y)] and C_B [=0.564 x (B-Y)]. While the original note dated February 1980 addressed to the Task Force proposed a code of 252_{10} (1111 1100) for “white” at 100 IRE and a code of 72_{10} (0100 1000) for “black” at 0 IRE, to allow capture of the sync levels, agreement was reached to utilize better the range of codes to capture the grey scale values with more precision and provide more overhead. “White” was to be represented by an eight-bit code of 240_{10} (1111 0000) and “black” was to be represented by an eight-bit code 16_{10} (0001 0000). Codes for defining the beginning and the end of picture lines and picture area were agreed upon, as well as synchronizing coding for line, field and frame, each coding sequence being unique and not occurring in the video signal.

The SMPTE and EBU organized an effort over the next few months to familiarize the remainder of the worldwide television community with the advantages offered by the 13.5 MHz (4:2:2) system and the reasoning behind its set of parameters. The members of the SMPTE Task Force travelled to Europe and to the Far East. The members of the EBU committees travelled to the, then, Eastern European block nations and to the members of the OTI, the organization of the South American broadcasters. The objective of these “world tours” was to build a consensus prior to the upcoming discussion at the ITU in the autumn of 1981. The success of this effort could serve as a model to be followed in developing future agreements.

SMPTE 125

A draft SMPTE standard document was offered for consideration by the Working Group that listed the parameter values for a 13.5 MHz system. Since copies of the document were bound in a green binder prior to final acceptance by the SMPTE, the standard was referred to as the “Green Book”.

In April 1981, the draft of the standard titled *“Coding Parameters for a Digital Video Interface between Studio Equipment for 525-line, 60-field Operation”* was distributed to a wider audience for comment. This updated draft reflected the status of the standard after the tests in San Francisco, and agreements reached at the joint EBU/SMPTE meeting in March 1981. At a meeting of EBU group V1/VID in June 1981, members – prompted by John Rossi from CBS – agreed that slightly more headroom was needed, and the EBU community consequently requested a subtle change to the value of white in the luminance channel, and it assumed the value of 23510. This change was approved in August 1981.

After review and some modification (as noted above), the “Green Book” was adopted as ***SMPTE Standard 125***.

Recommendation 601

The European Broadcasting Union generated an EBU Standard containing a companion set of parameter values. The SMPTE 125 and EBU documents were then submitted to the International Telecommunications Union (ITU).

The ITU, a treaty organization within the United Nations, is responsible for international agreements on communications. The ITU Radio Communications Bureau (ITU-R/CCIR) is concerned with wireless communications, including allocation and use of the radio frequency spectrum. The ITU also provides technical standards, which are called “Recommendations”.

David Wood explains the proposed standard to delegates at an ITU meeting

A document describing the digital parameters contained in the 13.5 MHz (4:2:2) system was approved for adoption as document 11/1027 at ITU-R/CCIR meetings in Geneva in September and October 1981. A revised version, document 11/1027 Rev. 1, dated 17 February 1982, and titled *"Draft Rec. AA/11 (Mod F): Encoding parameters of digital television for studios"* was adopted by the ITU-R/CCIR Plenary Assembly in February 1982. It described the digital interface standard for transfer of video information between equipment designed for use in either 525-line or 625-line conventional colour television facilities. Upon approval, document 11/1027 Rev. 1 became ***ITU Recommendation 601*** [7].

The foundation for the all-digital television service

It is understood that volume drives the cost to the user of any technology. The greater the volume, the lower the per-unit cost. By providing a standard that enabled the design and manufacture of equipment that could operate in both 525-line/60 Hz and 625-line/50 Hz production environments, the 4:2:2 Component Digital Television Standard allowed for a scale of economy and reliability that was unprecedented.

The 4:2:2 Component Digital Television Standard permitted equipment supplied by different manufacturers to exchange video and embedded audio and data streams and/or to record and play back those streams directly in the digital domain without having to be restored to an analogue signal. This meant that the number of different processes and/or generations of recordings could be increased without the noticeable degradation of the information experienced with equipment based on analogue technology.

A few years after the adoption of the 4:2:2 Component Digital Television Standard, all-digital production facilities were shown to be practical [8].

Stanley Baron obtained BSEE and MSEE degrees from New York University and was involved in the design and development of digital television systems over four decades, beginning in 1962. He was the inventor of the first commercially-available digital graphics generator for television applications. In 1980, he described a digital sampling structure and equipment interface for television that was compatible with existing 50 Hz and 60 Hz television broadcast standards. His proposal became the basis of the international standards for component 4:2:2 digital television.

Mr Baron retired at the end of 1998 as Managing Director, Television Technology for the National Broadcasting Company (NBC) in New York where he was responsible for the investigation, evaluation and implementation of new television technology. He served as Chairman of the Advanced Television Systems Committee, Technology Committee, (ATSC-T3), charged by the FCC with responsibility for documenting the digital Advanced Television System standard, and was elected by the member nations as Chairman of the ITU's Task Group, ITU/R-TG11/3, charged with responsibility for developing international agreements on digital terrestrial television broadcasting.

Stan Baron is a past-president of the Society of Motion Picture and Television Engineers (SMPTE). He also served two terms as SMPTE Engineering Vice President with responsibility for supervising approximately 100 projects and approximately 600 professionals involved in developing US and international technical standards. He has been elected a Fellow of the Royal Television Society (UK), a Fellow of the SMPTE, a Fellow of the IEEE, and a Fellow of the BKSTS (UK).

David Wood is Head of New Technology at the EBU Headquarters in Geneva. He is a graduate of the Electronics Department at Southampton University in the UK and the UNIIRT in Ukraine. He worked for the BBC and the former IBA in the UK, before joining the EBU.

Within the EBU, David Wood is currently Secretary of the Digital Strategy group, the On-line Services group and the Television Quality Evolution group.

As noted above, Rec. 601 provided 720 samples per active line for the luminance channel and 360 samples for each of the colour-difference signals.

When the ITU defined HDTV, they stipulated: *"the horizontal resolution for HDTV as being twice that of conventional television systems"* described in Rec. 601 and a picture aspect ratio of 16:9. A 16:9 picture ratio requires one-third more pixels than a 4:3 picture ratio. Starting with 720, doubling the resolution to 1440 and adjusting the count for a 16:9 aspect ratio leads to the 1920 sample per active line defined as the basis for HDTV [9]. Accommodating the Hollywood and computer communities' request for "square-pixels", meant that the number of lines should be 1920 x (9/16) = ***1080***.

Progressive scan systems at 1280 pixels per line and 720 lines per frame are also a member of the "720-pixel" family. 720 pixels x 4/3 (resolution improvement) x 4/3 (16:9 aspect ratio adjustment) = 1280. Accommodating the Hollywood and computer communities' request for "square-pixels", meant that the number of lines should be 1280 x (9/16) = ***720***.

Therefore, most digital television systems, including digital video tape systems and DVD recordings are derived from the 4:2:2 basic standard format. The 720 pixel-per-active-line structure became the basis of a family of structures (the 720-pixel family) that was adopted for MPEG-based systems including both conventional television and HDTV systems.

The appearance of high-quality, fully-digital production facilities that provide digital video, audio and metadata streams, and the successful development of digital compression and modulation schemes, allowed for the introduction of digital television ***broadcast*** services.

These digital television broadcast services, in turn, provided more efficient use of the spectrum, higher-quality images accompanied by multi-channel Surround Sound, the ability to include supporting digital data streams in the broadcast channel, and the possibility of transmitting a theatre experience to the home ... and all of this was built on the foundation provided by the 4:2:2 Component Digital Television Standard, first described in February 1980 and adopted as an international agreement in February 1982.

Acknowledgments

This article is intended to acknowledge the early work on digital component-coded television carried out over several years by many individuals, organizations and administrations throughout the world. It is not possible in a limited space to list all of the individuals or organizations involved, but by casting a spotlight on the results of their work and its significance over the past 25 years, we honour them all.

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