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Invited paper

The history of consumer magnetic video tape recording, from a rarity to a mass product

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Abstract

Since the first experiments on magnetic recording by Valdemar Poulsen in 1898 the use of this technology has grown tremendously and magnetic storage is used in almost every home in the world. A special challenge was the recording of video signals which need a high bandwidth. In the 1950s, television broadcasts had started which created a need for storage in the broadcast world. The first broadcast recorder was the Quadruplex from Ampex in 1956. Later solutions were found for application in the consumer market. Better mechanics, magnetic tapes and recording heads allowed the mass production of a cheap consumer recorder. The size and weight decreased tremendously and portable camcorders are very common. Recording of broadcasts, video rental and home movies are now very popular. The factors which contributed to the maturing of this technology will be reviewed in this paper. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: History; Magnetic recording; Video recording; Review

1. Introduction

The need to store video came about when television was introduced after the second world war. First Black and White was introduced and later Color became available. In US the color system was based on a 60 Hz field rate and was called NTSC (National Television System Committee, 1953). Europe followed later with the PAL (Phase Alternating Line, 1962) system based on 50 Hz field rate. In the Netherlands the first television broadcast occurred 50 years ago and was carried out by Philips Research in Eindhoven. Fig. 1 gives an impression of a broadcast session at Philips Research. At that time no recorder was available and everything had to be live!

The first video machines were based on recorders with stationary heads. A high tape speed was needed in order to realize the necessary bandwidth ($\sim$ 5 MHz) for video. The efforts to develop these systems was strongly encouraged in the USA by entertainers like Bing Crosby, who wanted to record their programs before broadcasting [1]. These systems were not very successful and suffered from several serious drawbacks.

An important breakthrough was the introduction of rotary heads to realize the necessary high relative head-tape velocity at a low tape speed. This led to professional tape recorders like the Quadruplex [2,3] of the Ampex company in 1956. This machine employed frequency modulation (FM) recording which greatly improved the picture quality. It was based on the transversal scan principle in which the directions of tape and head travel are perpendicular to each other.

A major stepping stone in the simplification process was the introduction of helical scan recording by Toshiba in 1959. In this technology, the scanning path of the rotating heads is at a relatively small angle with respect to the direction of tape travel. Video Tape Recorders (VTR) of this type were first introduced in the professional world and later for consumer use.

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Fig. 1. The first live television broadcast in the Netherlands at Philips Research Eindhoven (1948).

These recorders all used a guard band between the successive tracks to prevent crosstalk. A major innovation was the application of azimuth recording (1968 Matsushita) which reduces the crosstalk and leads to a dramatic increase in playing time. Up till 1970 all recorders were of the open reel type. With azimuth recording and improved tapes, Video Cassette Recorders (VCR) were possible with adequate playing time. The helical scan principle, azimuth recording and a cassette are the key elements which are still used in all consumer VCRs and camcorders today.

The new generation of VCRs uses the same key elements, but adds the use of digitized video information. The video signal is digitized and the digital data are stored. Digital video was first used in a professional application (D1, Sony 1986) and later as a home recorder and camcorder (Digital Video (DV) 1993).

The video recorder has changed from a rarity in the 1950s to a mass product in the 1990s. Of course, the new technologies contributed. However, a very important factor is the success of the industrialization of the manufacturing process. Today a VCR can be bought for a few hundred dollars.

In the next sections we will discuss the developments of the VCR in more detail.

2. The video signal, NTSC and PAL

A video signal consists of a sequence of pictures like in a movie. It is known from early investigations in the motion picture field that roughly 25 pictures per second are necessary to give the subjective impression of a continuous motion. In the movie studio, 24 pictures per second are stored as individual still pictures on film. In the movie theater they are projected with the same rate. A strong intensity flicker is observed by the human eye. Increasing the rate to 50–70 Hz results in a barely visible flicker. In the movie theater this is taken care of by interrupting the light 3 times per picture leading to 72 Hz rate and a flicker-free image.

The same principles are applied to the transmission of pictures to the home but with some additions and changes. First of all the two-dimensional (2D) information in the picture has to be transformed into a serial 1D signal because the transmission channel is 1D by nature. This is accomplished by scanning the brightness of the picture in horizontal lines from left to right and top to bottom as invented by Nipkow (1884). The number of lines in a picture is 525 for the USA and 625 for Europe. Identical to the movie world a picture rate of 25–30 Hz would be enough for natural motion. However, a multiple projection of the same picture on the TV screen in accordance with the practice in the movie theatre was not possible due to the absence of large picture memories at that time. For this reason another technique was adopted. The picture, called frame in the case of video, was split into two interlaced sub-pictures called fields, one containing the even lines and the other with the odd lines. Fields are then transmitted and displayed with twice the frame rate leading to a doubling of the flicker frequency to 50–60 Hz. This technique is known as interlace scan. To minimize the disturbing influence of the power supply on the displayed picture (among others due to the cathode heaters in the vacuum tubes), the field rate was chosen identical to the frequency of the power lines. As a result, a 60 Hz field rate was used in the USA and 50 Hz in Europe leading to 30 and 25 Hz frame rates, respectively.

With the number of lines as indicated above, the line frequency is around 16 kHz in both cases. For a balanced resolution in the horizontal and vertical direction of the picture, the number of picture elements (pixels) in a line should be equal to the number of lines in the picture. The highest frequency occurs when the pixels are alternatingly black and white, resulting in a necessary bandwidth of 4–5 MHz. Later the color signals had to be added to the already existing B/W video signal in a compatible way. The NTSC in the USA designed a very ingenious system for this. The color picture was built up from three pictures in the basic colors Red, Green and Blue. From each picture an intensity signal is obtained by picture scanning as described for the B/W system. Then the three signals are combined by weighted addition to a luminance signal Y that is identical to the B/W intensity signal. Moreover, the RGB signals are transformed into two bandwidth limited color signals P and Q (U,V in Europe). The two color signals are combined into 1 chroma signal C by quadrature AM modulation on a chroma subcarrier and is added to the luminance signal Y. The chroma signal is located at the higher end of the Y bandwidth. Compatibility is obtained because the Y signal generates the B/W picture on the already existing TV sets.

In the video recorder it is important to limit the bandwidth as far as possible because of size and playing time. For this reason the bandwidth of the Y signal is reduced to around 2.5 MHz which results in an acceptable horizontal resolution. This Y signal is then frequency modulated on a carrier with a frequency of around 4.5 MHz [4]. The Audio signal is recorded in a longitudinal track at the edge of the tape by a stationary head. Nowadays hi-fi Audio systems are available in which the FM Audio is recorded additionally in the helical tracks deep into the tape coating with a differing azimuth prior to the recording of the video signal which is located in the surface area of the tape. The color signal is recorded with the so-called color-under system, in which the chroma signal is first limited in bandwidth and then remixed to a line locked low frequency in a part of the bandwidth not used by the frequency-modulated Y signal. The frequency spectrum of a VCR is shown in Fig. 2. At playback the original composite signal consisting of the Y and C signal is restored and fed into the TV set.

3. The Quadruplex broadcast recorder

The first experiments and demonstrations to store video were carried out with modified audio recorders. These recorders used a fixed recording and playback head. The signal frequency f is given by $f = v/\lambda$, where v is the head-tape speed and λ is the recording wavelength. As a consequence, tape speeds up to many m/s had to be used. The important breakthrough was the introduction of rotary heads to realize the necessary high relative head-tape velocity at a low tape speed. Work on such a system started in 1951 at Ampex. After a period of experimenting with various scanning geometries the transversal scan was adopted and the first Quadruplex video recorder, the VRX-1000 became available in 1956 [1–3]. This machine employed frequency modulation (FM) recording which greatly improved the picture quality. In a transversal scan system the directions of tape and head travel are perpendicular to each other. Fig. 3 shows the geometry. The tape is guided by a circular guide which folds the tape in a kind of circular shape which fits the radius of the head drum. The rotating wheel (with a diameter of 5.08 cm) contains four heads and at least one of the heads is in contact with the tape.

In this case the track length is limited by the tape width, leading to a strong segmentation of the video field over a large number of tracks. This could clearly be seen in the resulting video; the four heads often were a little different which caused a deviation of the quality of the corresponding video parts. The carrier frequency was 4.75 MHz and the luminance bandwidth was 2.5 MHz (same as VHS recorder of today). The tape was 2 in (5.08 cm) wide, the head-to-tape speed was 39.9 m/s (PAL) which corresponds to a wavelength at the carrier frequency of 8.4 μm. The tape speed and track pitch were 0.38 m/s and 0.25 mm, respectively. These machines were the world-wide standard for professional video from 1956 to around 1980.

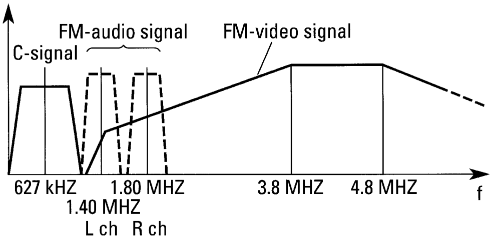

Fig. 2. The Frequency spectrum of VCR (values for VHS).

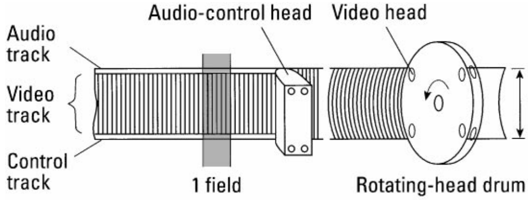

Fig. 3. The transversal scan principle of the Quadruplex recorder (Ampex 1956 [3]).

4. Helical scan recording

Helical scan recording was an important innovation which simplified a video recorder and made it less expensive. In this case the scanning path of the rotating heads is at a relatively small angle with respect to the direction of tape travel. As a consequence, the track length is no longer limited by the tape width and can be chosen such that one video field exactly fits to one track. Fig. 4 shows this geometry. Two heads are on opposite sides of the rotating drum. Because at least one is in contact with the tape a continuous video signal is available. This kind of geometry was first introduced in the professional world in 1961, the Ampex VR-660 using 2 in wide tape. The first system based on this principle and intended for home use in Europe was the LDL1000 introduced by Philips in 1969. This was a Black and White recorder with open reels and a size comparable to the open reel Audio recorders of that time. Price level was comparable to a color TV set which was a sensation at that time. The main application was recording of a broadcast to watch it at a more convenient time (time shift). Later another application became important: video rental. In the meantime the use of the Compact Cassette (introduced in 1963) for audio recording was becoming more and more popular. Sony and Matsushita showed a cassette VTR in 1969. The earliest product with a cassette in Europe was the Video Cassette Recorder (VCR) introduced by Philips as N1500 (1970) (Fig. 5). This system included some other important innovations. For the first time a complete tuner section and modulator were incorporated in such device. This not only allowed the recording of an independent program but also simplified the connection of the VCR to the infrastructure at home. Moreover a clock was incorporated that enabled the timed recording of programs while not being at home. It also included the economical recording of color signals by means of the color-under system. Later in the seventies a battle between three competing systems started. Two systems from Japanese origin: VHS (Video Home System) from JVC (1976), Beta from Sony (1975) and a third system, the V2000, from Philips (1979).

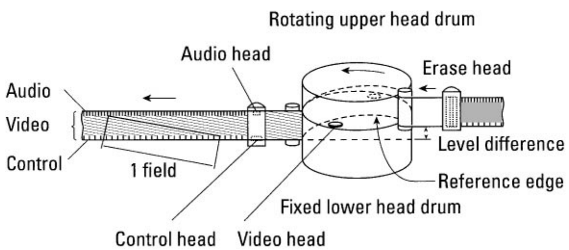

Fig. 4. The helical scan geometry.

5. Azimuth recording

These systems applied a major innovation called azimuth recording [4], first shown by Matsushita in 1968. This technique reduces the crosstalk between tracks considerably and enabled the use of much narrower track pitches leading to a dramatic increase in playing time and simultaneously to a reduction in size. An important factor in the battle for market acceptation was the availability of prerecorded software. Duplication of video

Fig. 5. N1500 VCR from Philips (1970).

recordings was developed [5]. In the mid 1980s only VHS remained. At present, after more than twenty years, VHS and its derivatives like S-VHS still are the mainstream of consumer VCRs. The installed base is more than five hundred million machines world wide. Most of the original equipment manufactures are located in Japan or Asia. Only one is left in Europe and none in the USA.

Table 1 shows the parameters of the three competing systems VHS, Betamax and V2000 (PAL versions). The parameters are very similar. The V2000 system had some distinctive features. The cassette had two sides and had to be flipped for the second part of the playing time. Moreover, the heads were mounted on piezo electric actuators and could be moved up and down. As a consequence the heads could adapt to the change in tape speed during fast forward or reverse play. Therefore, the video fields were not interrupted and high quality trickplay was possible using two heads only. This feature was up till then only applied in professional machines. Today in the VHS recorder acceptable trickplay quality is obtained by using more than two heads on the drum.

Nobody was very happy with the battle in the market. Therefore, the following generation of recorders was developed based on the standard agreed upon in the "8 mm Video Conference" in 1982–1984. The 8 mm system introduced by Sony (1984) was not really successful in the home recorder market. However, this format allowed the production of small recorders which were very suitable for making home movies. A new market was created by the advent of the 8 mm camcorder which became very popular. The VHS recorder was adapted for this market and the VHS-C was born. The 8 mm system was based on improved heads and tapes. This allowed a small cassette with adequate playing time for a home movie. The parameters of the 8mm system are given in Table 2

Table 1
Parameters of VCRs (PAL version)

	$\lambda_{carrier}$ (μm)	T pitch (μm)	Azimuth (deg)	Playing time (h)	ht speed (m/s)
VHS	1.00	49/24.5	± 6	2–6	4.8
Betamax	1.12	33	± 7	1–3	5.8
V2000	1.06	23	± 15	2*4	5.0

Table 2
Parameters for 8 mm and DV in PAL version

	$\lambda_{carrier}$ (μm)	T pitch (μm)	Azimuth (deg)	Playing time (h)	ht speed (m/s)
8 mm	0.57	34/17	± 10	1.5–3	3.1
DV	0.50	10	± 20	1 − 4.5	10.2

together with the values for the Digital Video (DV) system. DV was introduced in 1993 as a digital recorder for home movies. The very small camcorders based on the DV standard are becoming more and more popular. More on DV and digital video in the next section.

6. The digital age (DV & D-VHS)

The first investigations on digital video recording were aimed at the broadcast industry because of the need for high picture quality and no degradation during editing of the source material. A first experimental system was presented by the BBC in 1974. After a decade of experimenting this resulted in the international standard for digital broadcast recording D-1 in 1986. During the 1980s numerous investigations were published on the digital video recording for consumer use. Digital compression of the video signals was clearly the enabling technology. The outcome of these efforts is the announcement of the DV standard in 1993 [4,6] and the D-VHS standard in 1995. Meanwhile products for both systems are available in the market. The DV standard mainly focussed on a compact size for camcorder use. Picture quality, editability without degradation, robustness, power consumption and limited complexity were important and natural ingredients of such a system. For this reason the emerging MPEG technology for video compression was not adopted for this system, but a special compression with a much lower complexity and better editability was developed. A block diagram of the system is given in Fig. 6. In the recorder the video data are digitized. The high-frequency video data give rise to a bit stream of considerable size ($\sim$124 Mb/s). This is too much to store in a small cassette, even with the advanced tape used for DV. Digital compression has to be applied. Like MPEG, DV uses discrete cosine transformation (DCT) on a block of 8×8 pixels for the conversion from the pixel to the frequency domain. Compression is achieved by adaptive quantization (Q) of the coefficients and subsequent variable length coding (VLC). The coding is segment based which means that a fixed bit rate

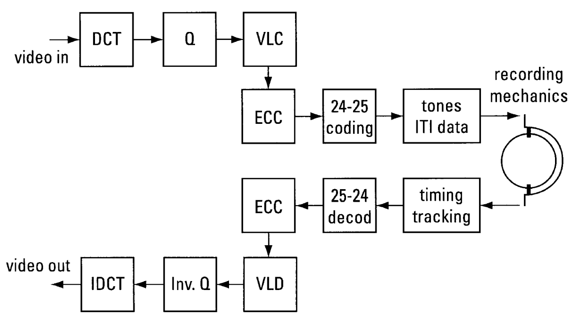

Fig. 6. Block diagram of the DV system.

after compression is realized within such independently coded segments. The resulting video bit rate after compression is 25 Mb/s. For robustness against random and burst errors a track based two-dimensional Reed-Solomon error correction system (ECC) is used. To adapt the spectral content of the data to the recording channel a 24–25 channel modulation is applied, i.e. each 24 data bits are replaced by 25 channel bits. The data rate is now 41.8 Mb/s including the audio data. A small diameter (21.7 mm) scanner with two opposite heads is used to write the data to the tape. The data in a video field are not in one track anymore. However, no quality degradation is introduced because the digital data can be combined easily. The main parameters of the DV system are given in Table 3. The standard describes two cassette sizes, standard and small. The latter one is used for the camcorders and has a size of $66 \times 48 \times 12$ mm with a playing time of 1 h. There are additional interesting features. The cassette has an option for a memory. This memory stores the position of the important scenes and contributes to the user friendliness of the camcorder. A second one is the presence of a digital interface (IEEE 1394) with miniature plugs. This can be attached to other digital products like PCs and opens a new area of editing and loss less copying.

The millions of VHS recoders and the mature technology make it an interesting option to adapt the VHS machine to the digital age. This thought resulted in the D-VHS standard (1995). The basic philosophy is analog for analog and digital for digital, which means that the D-VHS system records analog signals in the well-known way and digital signals with the new digital recording format. The backwards compatibility ensures on the one hand, that the large amount of available software titles for VHS can still be used in this new system, and on the other hand that the customer has no compatibility problem with his own personal VHS library. The compatibility has led to a system in which the same magnetic head configuration is used as for normal analog VHS. The tape grade used for D-VHS is the better quality S-VHS tape packaged in a special D-VHS cassette. Table 4 shows the main parameters of the D-VHS system.

In the D-VHS recorder we encounter a similar structure as for DV. Error correction and a channel code are applied. This time there is no data compression present because the source is a digital compressed signal from outside. D-VHS is a transparent broadcast streamer for Digital Video Broadcast (DVB) signals. In the studio the video signal is digitized and compressed before transmission to the home. At home the digital stream is received by a set-top box. The data are transferred to the recorder by the digital interface (IEEE 1394, like DV). At replay, the restored MPEG signal is sent back to the set-top box and can be viewed on the television screen. The D-VHS system ensures a new future for the VHS technology in the digital age.

Table 3
Parameters used in DV

Bit length	0.25 μm
Track pitch	10 μm
Data rate	42 Mb/s
Video rate	25 Mb/s
Audio	1.6 Mb/s
Tape width	0.25 (in)
Tape kind	Advanced ME

Table 4
Parameters of the D-VHS system

Bit length	0.30 μm
Track pitch	29 μm
Data rate	19 Mb/s
Data rate (video)	14 Mb/s
Tape width	0.5 (in)
Tape kind	D-VHS

7. Technology of heads and tapes

The improvements discussed above were only possible because of the continuous progress in recording performance. The main factors are the increased quality of the tapes and heads applied in the recorders. The tapes used in the 1950s had a relatively rough coating made of a dispersion of Fe_2O_3 particles. The next important step was the advent of Co-doped γ-Fe_2O_3 and CrO_2 (coercivity $H_c \sim 600$ Oe (50 kA/m) tapes which are still the main stream of tapes used today in the VHS recorder [7]. The improvement of quality of these tapes allowed even long play versions of the VHS recorder with acceptable picture quality and versions with higher picture quality like the S-VHS. The next step was the introduction of Metal Powder (MP) tape, first for audio and later ($\sim$1985) for the 8 mm video system. The metal powder particles are pure iron with a thin oxide coating to prevent corrosion. The higher performance was used to obtain higher densities to be able to use a small cassette with adequate playing time. Also these MP media followed a continuous process of improvement of the quality by the application of finer particles, a better dispersion, improved coating techniques and better substrate materials. This resulted in the high performance MP tape of today with a very thin coating ($\sim$150 nm), a H_c of 2400 Oe (190 kA/m) and a thin substrate ($\sim$5 μm). During the 1980s a lot of effort (especially in Japan) was put into a new superior kind of tape produced by evaporating a Co-alloy on the substrate: the Metal Evaporated (ME) tape which was first commercially available for Hi8 system. An improved version of this ME tape [8] is applied in the Digital

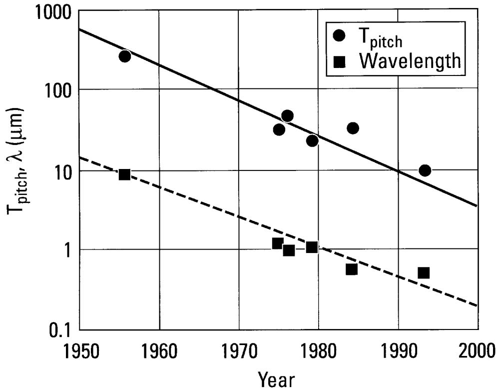

Fig. 7. Track pitch and minimum wavelength plotted versus introduction year (more in Ref. [2]).

Video (DV) recorder. This advanced ME tape sustains such a high recording density that an adequate playing time in a small cassette of a DV camcorder is possible. Fig. 7 shows the track pitch and wavelength used in the systems of Tables 1–4 plotted against the introduction year.

During the same period head technology was improved as well to match the tape performance. In the fifties mostly polycrystalline ferrite heads were applied. However, because of the narrower tracks and smaller wavelengths monocrystalline MnZn ferrite became widely used. Most of the VHS recorders have these kind of heads with a width of around 25–50 μm and a gap of ~0.4 μm. However the saturation induction of the ferrite material is limited and not enough for MP tapes with coercivities up to 2400 Oe (190 kA/m). To increase the saturation induction metals are applied. The metal is used in the gap of the recording head in some cases. Some heads have a construction were the metal is an integral part of the head core. A more in depth account concerning tapes and heads can be found in Refs. [7–10].

8. Mass production and mechanics

A third factor besides tape and heads is the tremendous progress in precision in the mechanical part of the recorder. This increased precision was realized in a mass production environment where millions of recorders a year can be produced. The success of the industrialization of the manufacturing process is largely responsible for the transition from an expensive Quadruplex product for professional use in the 1950s to a cheap consumer machine which we can buy for a few hundred dollars today.

9. Conclusions

It is clear that we have come a long way from the Quadruplex in 1956 to the DV in 1993. In 1956 all electronics had to be realized with vacuum tubes. Since then the transistor and IC technology have emerged. The possibility to design and produce complex ICs is essential for a product like DV. Also accuracy of production processes for mechanical parts has increased tremendously. These facts combined with progress in heads and tape makes a product with a track pitch of 10 μm possible.

The video recorder has certainly evolved from a high-tech rarity to a high-tech mass product. It will be interesting to see how this development will continue in the next century.

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