Tape Formats and Multitrack Formats

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The tape format of a digital audio recorder is directly related to its capabilities for error correction, editing, and punch-in and punch-out. A digital recorder can be classified as a stationary-head or rotary-head machine. Various tape formats, limited by the physical constraints of the recording mechanism, are described.

0 INTRODUCTION

Tape format is an important aspect of the digital audio recorder as it limits function and performance, and is closely related to tape interchangeability. To play back on recorder B a tape recorded by recorder A, both A and B must use the same tape format. In designing the format, one must consider error correction, editing, and punch-in and punch-out. The modulation code must also be selected carefully for efficient recording. This paper discusses tape format mainly from the point of view of error correction. The error-correcting code itself is covered elsewhere [13–15].

1 ERRORS IN THE RECORDING CHANNEL

Fig. 1 shows a type of error occurring in the recording channel. The horizontal axis denotes the number of tracks in which errors occur simultaneously. The vertical axis shows the number of errors during 440 min, a measure of the error probability. The recorder used for measurement has the following parameters: track width 305 μm, track pitch 620 μm, minimum wavelength 2.5 μm, tape speed 38.1 cm/s, and tape H_c 670 Oe. From the figure it is seen that the two-track error is about 1/10 000 of the one-track error, and errors involving three or more tracks are very rare. Fig. 2 shows error run length versus error probability. The horizontal axis denotes the error run length in a frame; a two-frame error means that one erroneous frame is succeeded by another erroneous frame. The dashed line is a mathematical model simulating the data. Fig. 3 shows the variation of the error rate from track to track. The best track from the standpoint of error rate is track 3, while the worst is track 4. The error rate of the best track is about 1/100 that of the worst track. Fig. 4 is an example

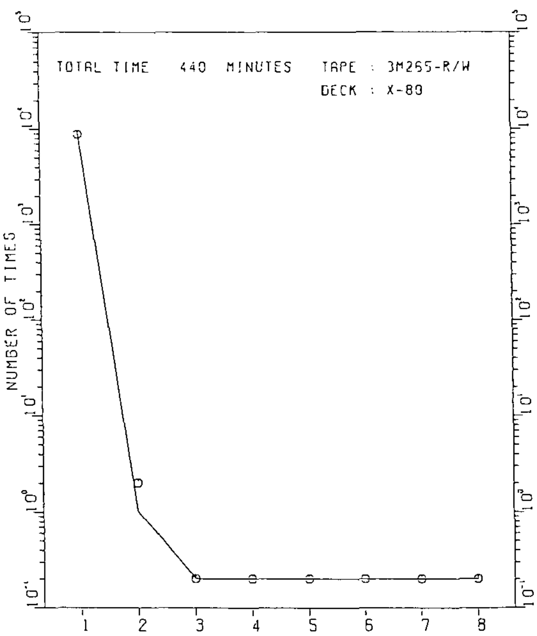

Fig. 1. Probability versus number of erroneous tracks.

of variations in error rate from track to track when the machine is misadjusted. The horizontal axis shows the measuring time, while the vertical axis denotes track position.

2 OTHER FUNDAMENTAL MATTERS

2.1 Analog Track [1]

For cueing the tape, an analog track is provided. In Fig. 5 the vertical axis shows the playback level, the horizontal axis the track position. Because the playback level decreases at the edge of the tape, tracks for long-wavelength signals are allocated at the edge of the tape, as shown in Fig. 6. The control track is placed at the center of the tape in some formats [2]. Because of its importance, the best position is assigned to it.

2.2 Punch-in and Punch-out of Digital Recorder

Punch-in and punch-out in digital recording is somewhat different from that in analog practice. The code is interleaved when recorded, and therefore the tape has to run for the length of the interleave before error-corrected playback data are available. In analog recording the record head plays back in sync recording,

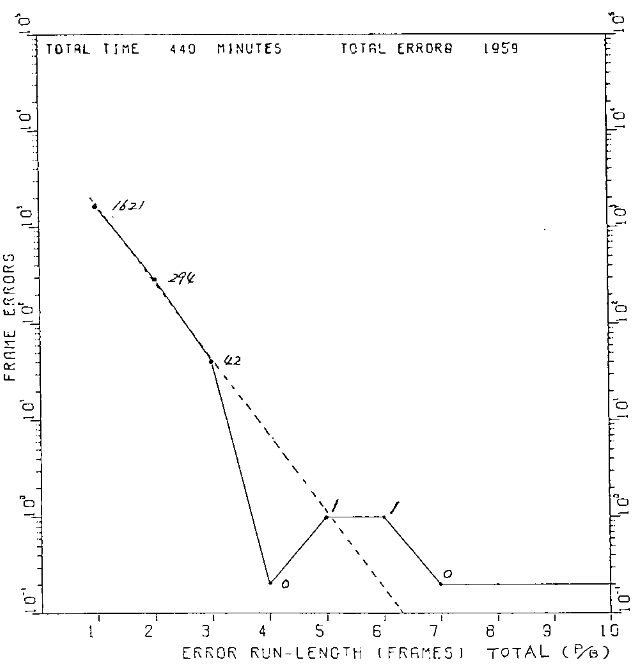

Fig. 2. Error run length versus error probability.

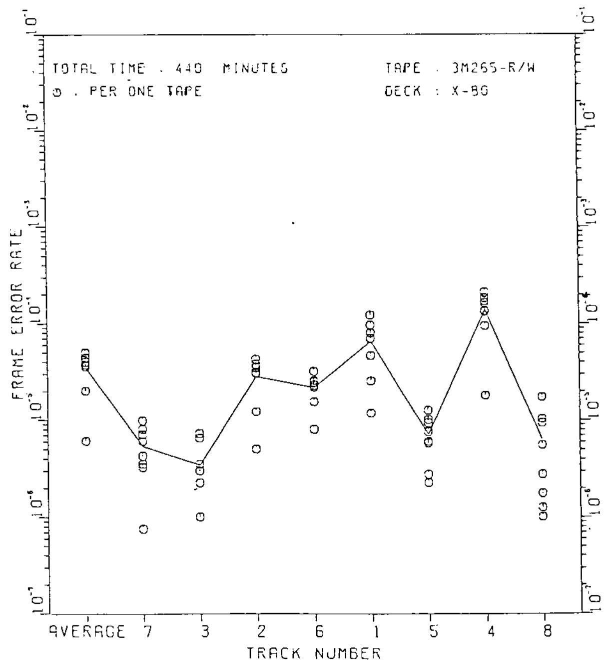

Fig. 3. Error probability versus track position.

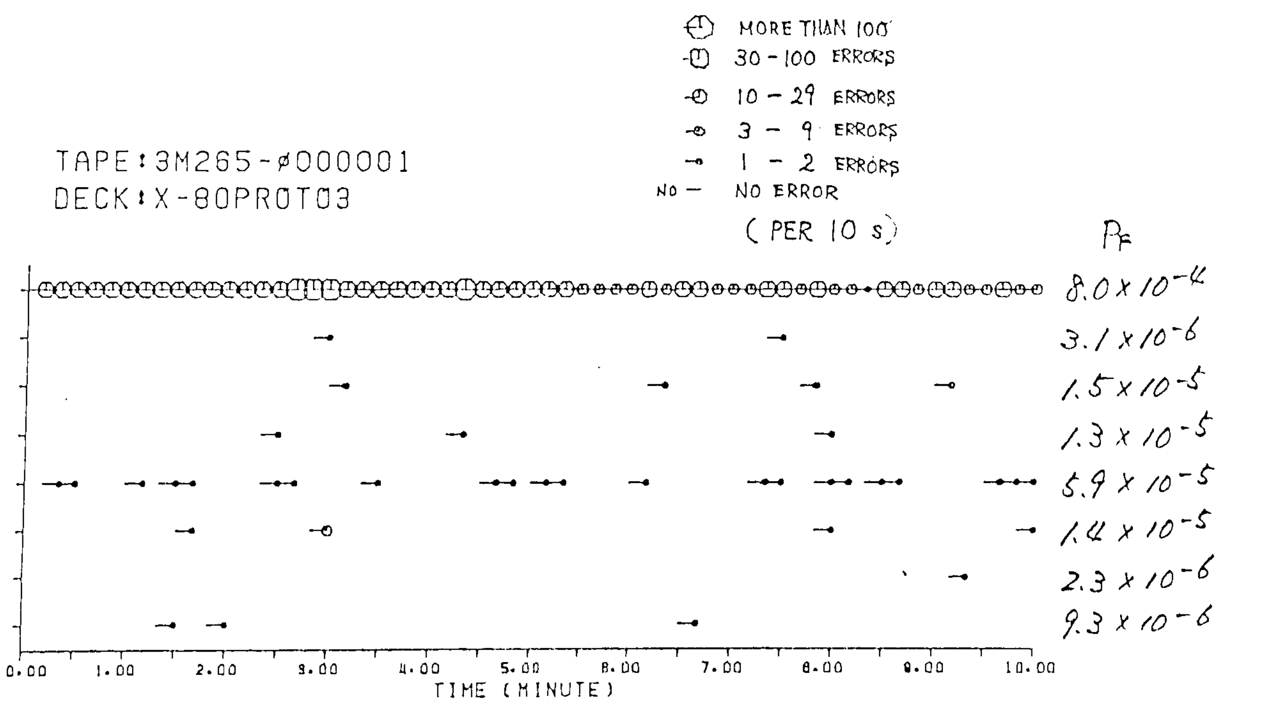

Fig. 4. Error probability versus track position when machine is misadjusted.

but a sync playback head is necessary for a digital recorder. Fig. 7 shows the head alignment of a multichannel digital recorder. R stands for read head, W for write head. The R–W and W–R combinations are used for sync recording and read after write, respectively. Fig. 8 is the block diagram of a multichannel digital recorder [3].

The input signal is digitalized by the analog-to-digital (A/D) converter and passes through the fader to the encoder. The check bits of the error-correcting code are generated at the encoder, which also acts as the formatter. The encoder output is modulated so that it

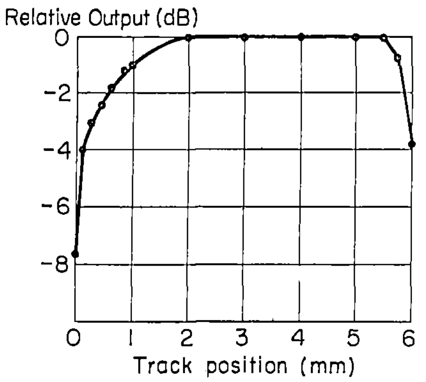

Fig. 5. Playback level versus track position.

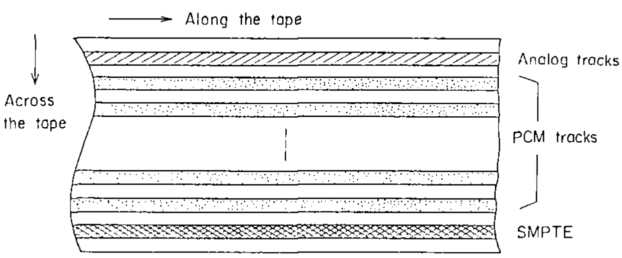

Fig. 6. Analog track.

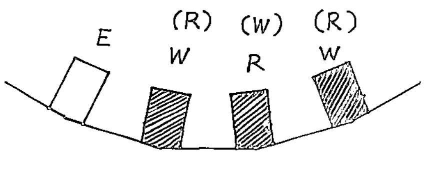

Fig. 7. Head alignment of multichannel digital audio recorder.

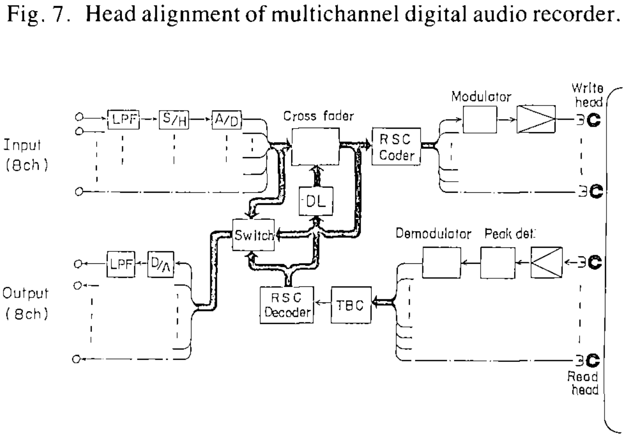

Fig. 8. Block diagram of multichannel digital audio recorder.

can be recorded efficiently and passes to the record head. The playback head is placed before the record head, as described above. The playback signal is demodulated and its time-base error is removed with the time-base corrector (TBC). Code errors are corrected at the decoder whose output passes through a delay circuit. The delay time plus the time needed for signal processing equals the time the tape runs from playback to record head. The delay-circuit output is mixed with the input signal in the punch-in and punch-out mode with a cross fader.

2.3 Frame Length [4]

The length of the frame (code) must be decided by error characteristics. Fig. 9 shows mean times between the occurrence of error correction and misdetection versus frame length. *B* stands for average burst length. When the average burst length is 200, the code shows the highest error correctability at a frame length of somewhat less than 200; when the average burst length is 1000, the code shows maximum correctability at a frame length of somewhat less than 1000. The frame length should approximately equal the average burst length.

3 TAPE FORMAT OF MULTICHANNEL RECORDER [4]

Fig. 10 shows an example of the tape format. There are ten tracks for eight audio channels, and each hor-

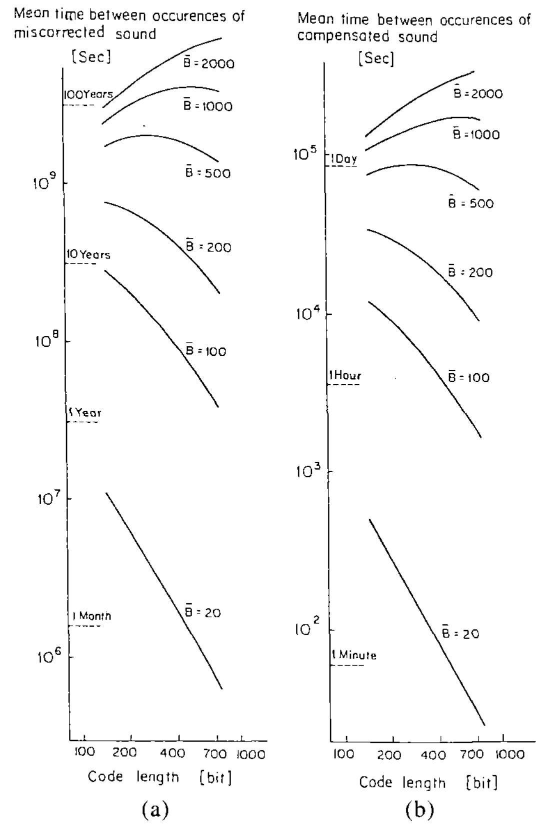

Fig. 9. Frame length versus error-correcting capability. (a) Mean time between occurrences of miscorrected sound [seconds]. (b) Mean time between occurrences of compensated sound [seconds].

izontal line corresponds to a recording track. Channel 1 is recorded on track 1, channel 2 on track 2, and so on. Two extra tracks are provided to record check bits of the error-correcting code. The sync pattern which indicates the beginning of the block is recorded at the beginning of each frame, where frame means one track portion of one block. A cyclic-redundancy check code is provided at the end of the frame to indicate an error. Check bits in the vertical direction are generated by an algorithm of the Reed–Solomon code, 4 bits of each track being assembled to make a code word of the Reed–Solomon code, as shown in Fig. 11. When channels 2, 3, and 4 are punched in and out, the corresponding check bits are renewed, as shown in Fig. 12. Inaccuracies in head mounting and tape speed make reconstruction of the code block difficult. Fig. 13 shows an enlarged drawing of the punch-in portions of tracks 1 and 2. 1/1 represents the first frame of channel 1, 2/1 the second frame of channel 1; 1/2 represents the first frame of channel 2. Although 1/1 and 1/2 should be coupled for decoding, 2/1 and 1/2 might be coupled. To solve this difficulty, a main-block and subblock system is employed. Fig. 10(b) shows one main block in which 16 subblocks are assembled. The main block is first reconstructed without failure, as shown in Fig. 14, and then subblocks can be coupled correctly for decoding in the punch-in and punch-out mode.

The code is interleaved in recording in order to protect it from large-size errors. Fig. 15 shows one example of interleave; odd samples and even samples are widely separated. The hatched portion shows frames which belong to the same code block. Fig. 16 shows the largest error that can be corrected and the error that can be detected but not corrected. A 2.9-mm-width vertical erroneous bar can be corrected if there is no error at the guard space. A 4.8-mm-width horizontal erroneous band can be corrected if there is no extra error on the tape. An 11.6-mm-width vertical erroneous bar can be compensated by linear interpolation. Fig. 17 shows error correctability for a mixture of random and burst errors. The horizontal axes show the error bit rate, while the vertical axis corresponds to the mean time between occurrences of error compensation and noise caused by misdetection. When the average burst error length is 200 bits and the error bit rate is 10^{-4}, a rather bad case, the mean time between occurrences of error compensation is about one day, a very practical value.

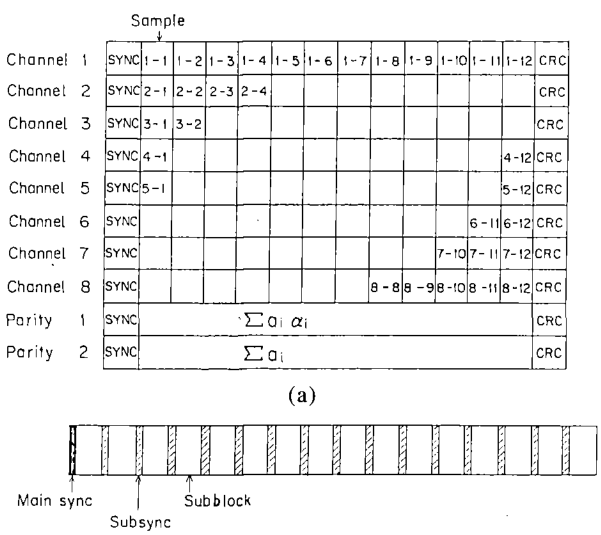

Fig. 10. Code format. (a) Construction of a subblock. (b) Construction of a main block.

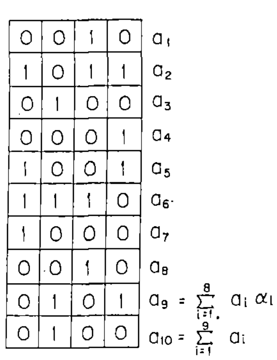

Fig. 11. Code word of Reed–Solomon code.

4 VARIOUS TYPES OF MULTICHANNEL TAPE FORMAT

Fig. 18 is a perspective view of a thin-film head [5], and Fig. 19 shows the corresponding tape format [6]. The thin-film head has the following characteristics.

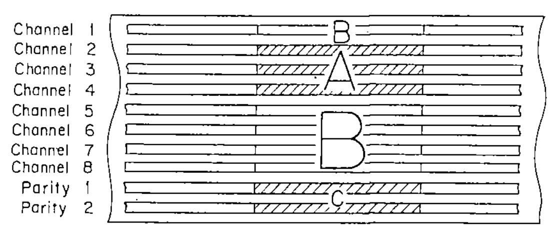

Fig. 12. Punch-in and punch-out. Hatched area–punched-in portion; B–non-punched-in portion.

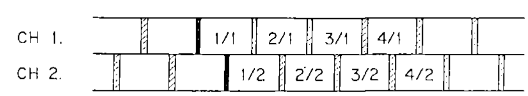

Fig. 13. Reconstruction of code block.

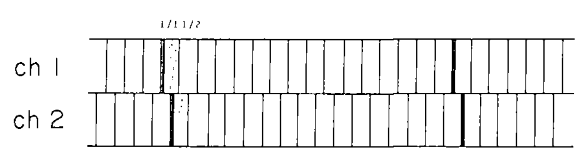

Fig. 14. Reconstruction of code block (main frame).

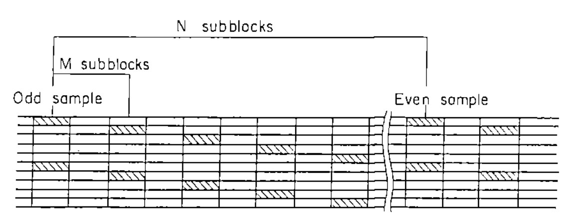

Fig. 15. Interleave of code.

1) A large number of tracks does not increase the difficulty in manufacturing the head.

2) The track position and width can be made very accurate.

Four tracks are used for recording one audio channel. A parity track records only check bits of the error-correcting code. D_1 and D_2 represent one subframe which has 20 samples. Each subframe has a sync pattern at the beginning and a cyclic-redundancy check code at the end, as shown in Fig. 20. P_1 is generated from D_1, D_2, and D_3 in the vertical direction with a simple parity algorithm. All P parities are generated in the same way. A Q parity is made as follows: when Q_2 and Q_5 are considered, they are generated from D_1, D_4; D_8, D_{11}; D_{15}, D_{18}; D_{19}, D_{22}; . . . ; D_{37}, D_{40} in the helical direction. Audio data are distributed as D_1, D_2, D_3, D_1, D_2, D_3, ... When one track dies, it can be corrected from the P parity in this format. When one track dies and there is another error whose length is shorter than two subframes, this can be corrected with P and Q parities. Table 1 shows another type of tape format. There are three tape speeds [2]. The error-correcting code used in this format has been called cross interleave code. Fig. 21 shows a simplified example of a cross interleave encoder [7]. P parity is generated from two samples S_{2n} and S_{2n+1} by a simple parity algorithm. Then sample S_{2n+1} and P are delayed d frames and $2d$ frames, respectively. Q parity is generated from S_{2n} and delayed S_{2n+1}, P by a simple parity algorithm. S_{2n+1}, P, and Q are delayed again for interleaving before

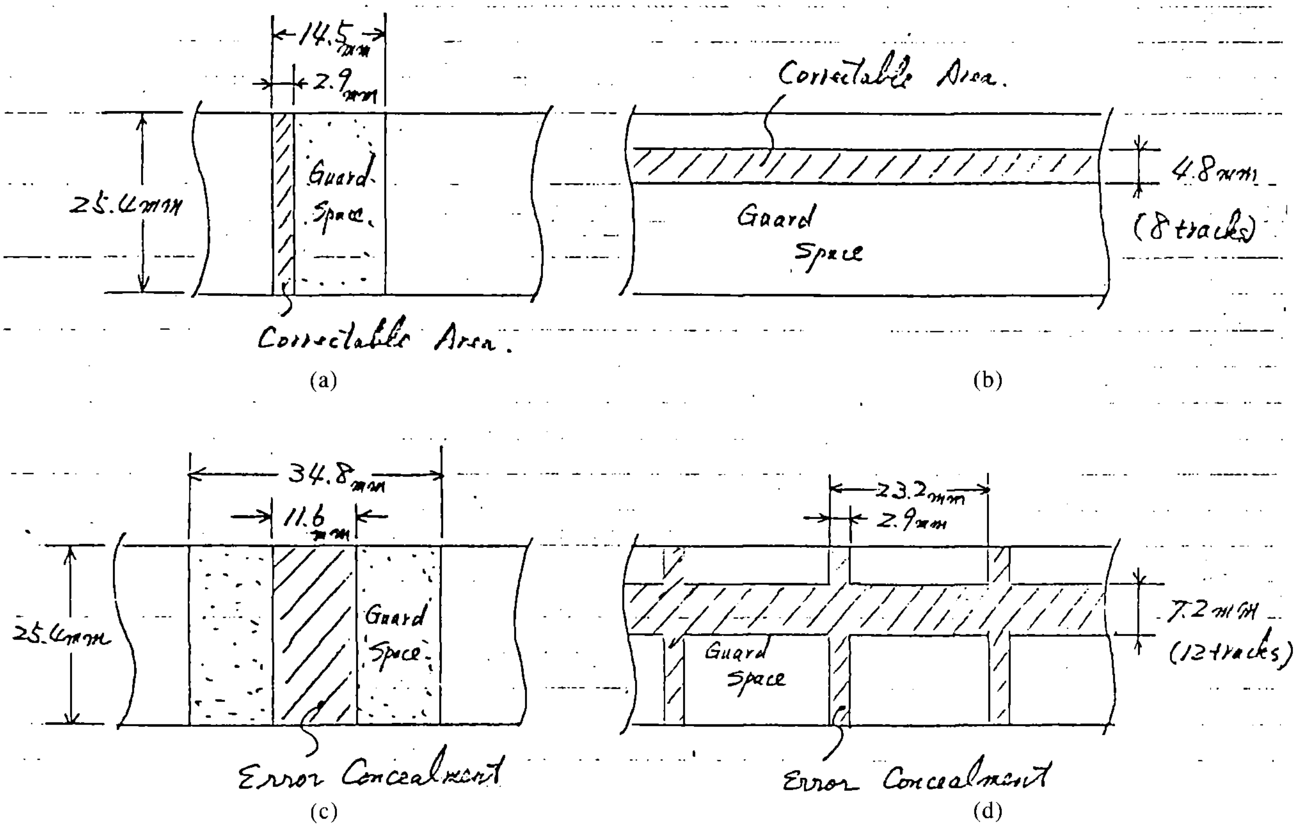

Fig. 16. Correctable large-size errors.

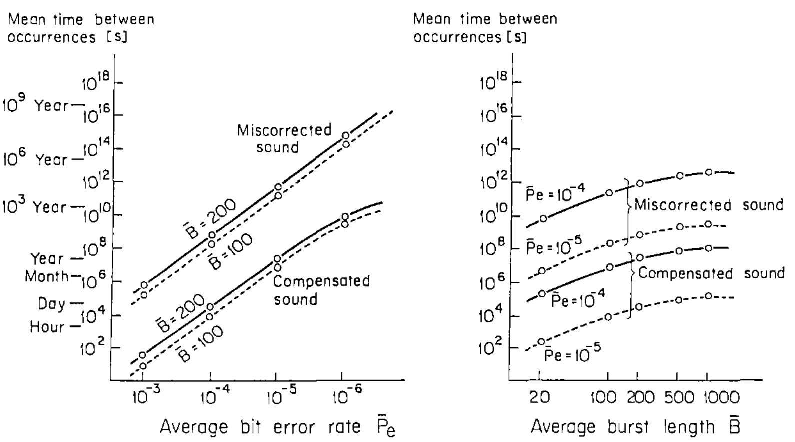

Fig. 17. Error correctability when error is random.

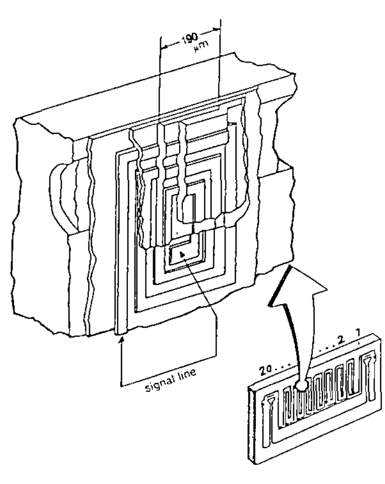

Fig. 18. Thin-film head.

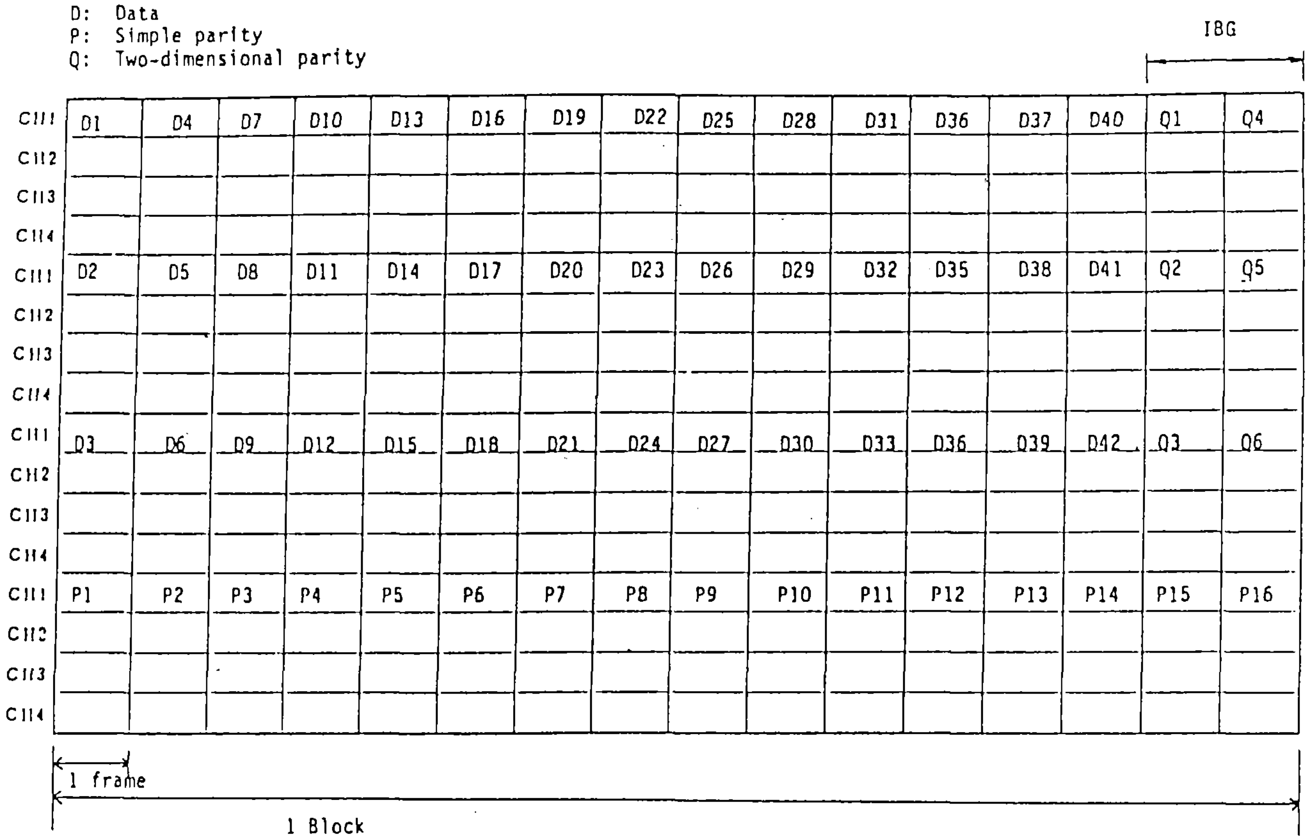

Fig. 19. Tape format for recorder using thin-film head.

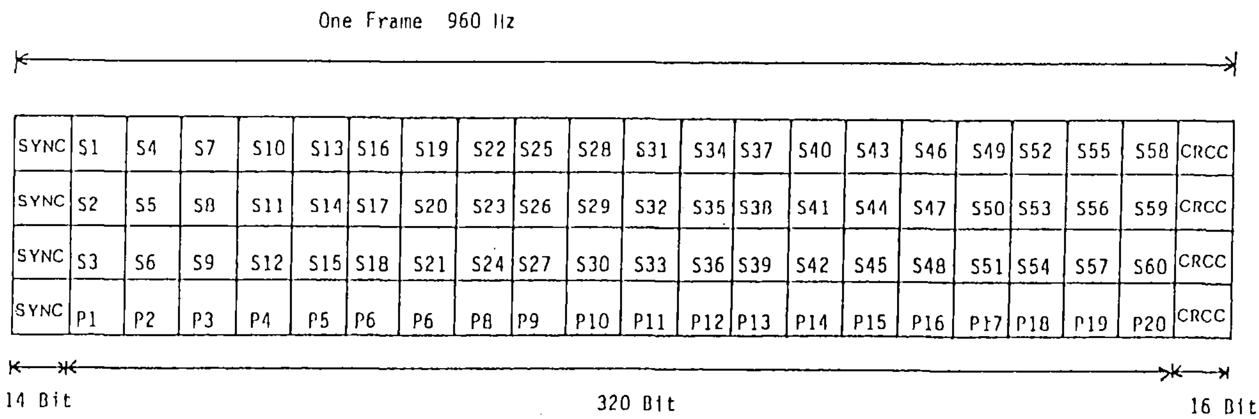

Fig. 20. Tape format of one subblock.

Table 1. Specifications of recorder.

Item	High Speed			Medium Speed			Low Speed
Tape width (in)	¼	½	1	¼	½	1	¼
Number of digital channels	8	24	48	4	12	24	2
Number of tracks used per digital channel		1			2		4
Number of auxiliary tracks provided on one tape							
Analog		2			2		2
External		1			1		1
Sampling rate f_s(kHz)	50.4 or 44.1 or 32.0						
Tape speed (cm/s) at							
f_s = 50.4 kHz		76.00			38.00		19.00
f_s = 44.1 kHz		66.50			33.25		16.63
f_s = 32.0 kHz		48.25			24.13		12.06
Quantization	16-bit linear per word						
Channel coding	HDM-1						
Error correction	CRCC, cross interleave						
Redundancy	33% (including parities and synchronization)						

they complete the frame structure. Therefore all samples and parities err at random, even though the error occurring in the recording channel is a burst error. The frame structure is similar to the previously explained format. There are sync pattern, data, and cyclic-redundancy check codes. Fig. 22 shows the error correction of the code. A circle corresponds to one sample. P_0 is generated from samples 0 and 1, while Q_0 is generated from samples 6 and 5 and P_2. When sample 5 and P_4 are not correct, they can be corrected using Q_0 and Q_2. When samples 6 and 5 and P_4 are erroneous, sample 6 can be corrected with P_6. Then sample 5 and P_4 are corrected as mentioned above. When a combination of samples 5, 6, and 7 and P_4 dies, they cannot be corrected. However, they can be compensated because their error is detected. Fig. 23 shows the actual tape format of the code [2]. Even and odd samples are separated by the greatest distance. P and Q of odd samples are generated from samples 1, 5, 9, 3, 7, and 11, and P and Q of even samples are generated from samples 2, 6, 10, 4, 8, and 12.

5 BRIEF EXPLANATION OF VIDEO TAPE RECORDER

The bandwidth of the video signal is 4 MHz, while that of a two-channel digital audio signal is about 2 MHz. A video tape recorder is therefore a suitable machine for recording a digital audio signal. An advantage of using video tape recorders is that they are less expensive because they are mass-produced. The digital signal must first be converted to video form. When this pseudo-video signal is fed to a television monitor, the code pattern can be observed on the screen. (Unfortunately it is impossible to enjoy the music in this way.) A video tape recorder thinks it is a real video signal and records it as if it were. Fig. 24 illustrates scanning of the television screen. Because an interlace method is employed, the scanning spot moves from 1 to (1), from 3 to (3), and so on in odd fields. It then scans the space between previously scanned lines in even fields. Two fields make one frame. The time needed for scanning from left to right (and return) is one horizontal period. The time for scanning from top to bottom (and retrace) is one vertical period. The video signal, therefore, can be thought of as discontinuous at horizontal and vertical retrace points. In order to slow the tape speed while maintaining high relative speed between head and tape, a scanning head method is used. Fig. 25 shows the tape transport mechanism of a helical-scanning video cassette recorder (VCR). Two video heads are mounted on the circumference of the head cylinder. Tape runs slowly while the head cylinder rotates at 1800 r/min. A fixed head is provided for recording analog audio and control signals. The control

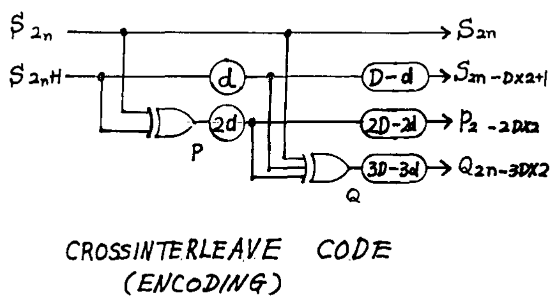

Fig. 21. Simplified cross interleave encoder.

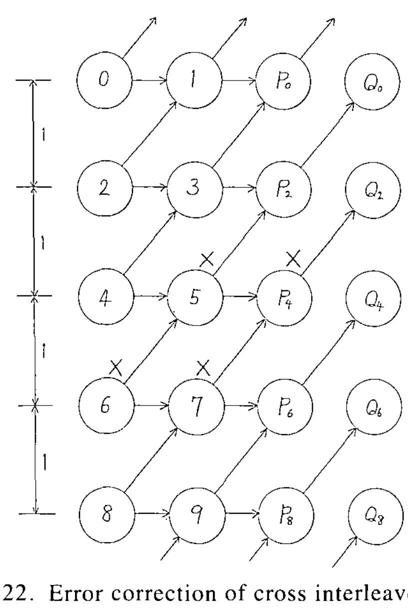

Fig. 22. Error correction of cross interleave code.

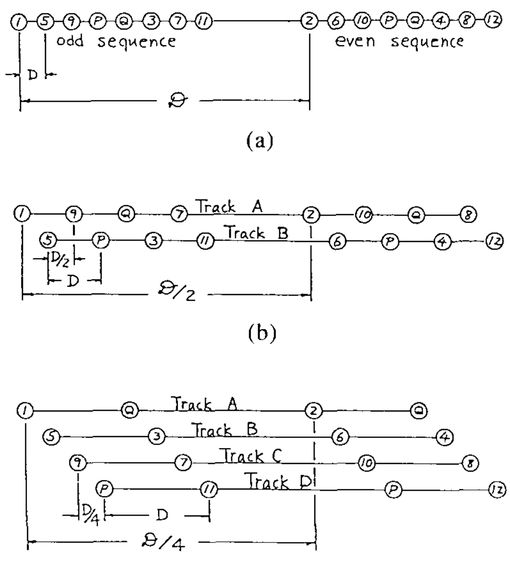

Fig. 23. Tape format for fixed-head-type recorder. (a) High speed. (b) Medium Speed. (c) Low speed.

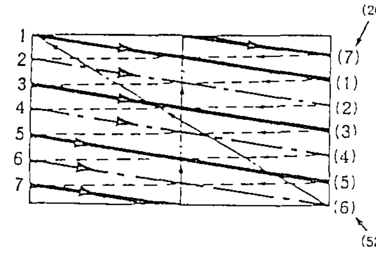

Fig. 24. Scanning of television screen.

signal is used to phase lock the rotation of the head cylinder and the capstan servo. A recorded tape pattern is illustrated in Fig. 26. The video signal for one vertical period is recorded on each video track. Although there is a guard space between video tracks in the case of U-type VCRs there is none on the home-use VCR shown in Fig. 26. Because only one VCR track is recorded at a time, a simple large burst can destroy a large number of successive samples. Therefore interleave is necessary when the code is recorded, and for a long interleave, a large memory is needed. A short interleave is not effective, and the length of interleave must be a compromise based on the probability distribution function of the burst error.

6 TAPE FORMAT OF ROTARY-HEAD DIGITAL RECORDER

The fundamental research for digital voice recording using a large main-frame computer started in the 1950s. The first digital audio recorder was demonstrated by NHK, the Japan Broadcast Corporation, in 1969. Fig. 27 illustrates the recorded waveform [8]. Two samples are allocated in one horizontal line. The code error is detected by monitoring check bits and the amplitude of the playback FM signal. When an error occurs, the erroneous sample is replaced by the average value of the valid preceding sample and the valid following sample. Fig. 28 shows the waveform of one horizontal period of the first professional digital recorder [9]. A four-head broadcast video recorder is used, which can record eight audio channels. For punch-in and punch-out, two video recorders are synchronously locked, one for recording and the other for playback. Because of the large bandwidth, three samples of eight channels are recorded in one horizontal line. When the machine is used for four-channel recording, the samples are recorded twice and compared for error detection. An erroneous sample is replaced by linear interpolation. Fig. 29 shows the waveform for one vertical period of the EIAJ pulse-code-modulated adapter [10]. The control-signal block is provided at the beginning of the signal period. Fig. 30 shows the waveform for one horizontal period, where the data sync pattern is placed

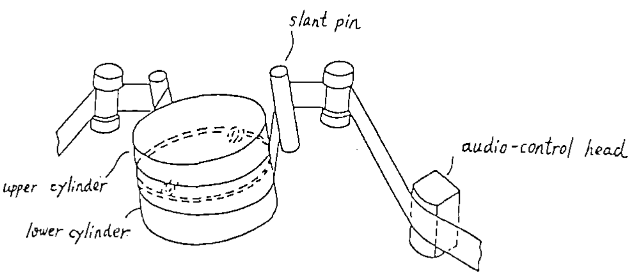

Fig. 25. Tape transport mechanism of helical-scanning video cassette recorder.

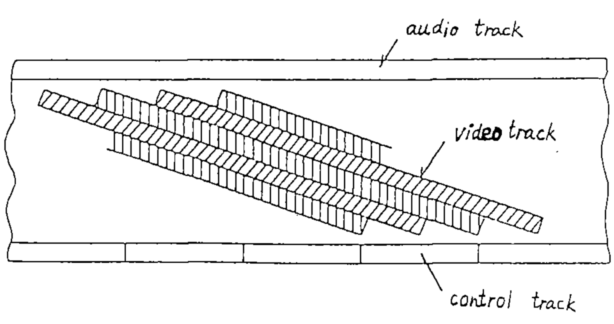

Fig. 26. Recorded pattern of video cassette recorder.

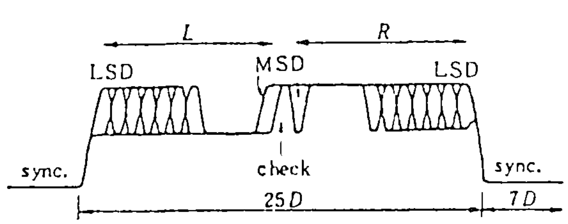

Fig. 27. Tape format of the first digital audio recorder.

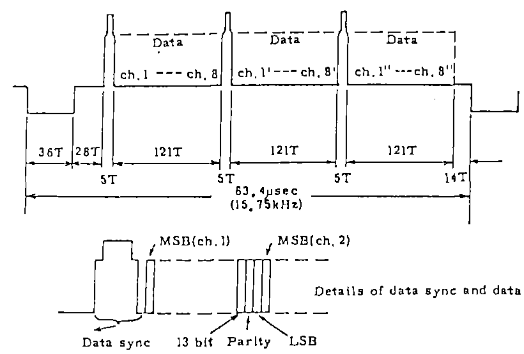

Fig. 28. Tape format of the first digital audio recorder for professional use.

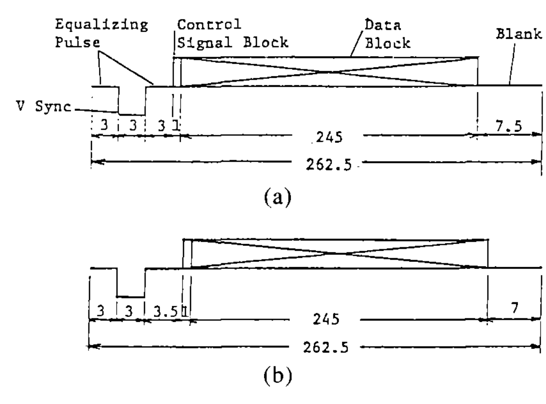

Fig. 29. Waveform of EIAJ-type digital audio adapter. One vertical period. (a) Field 1. (b) Field 2.

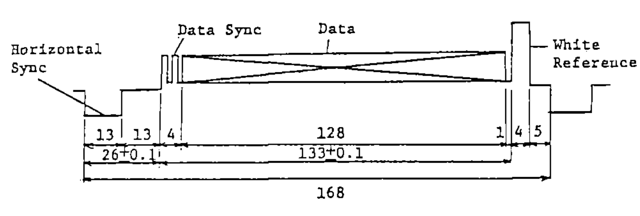

Fig. 30. Waveform of EIAJ-type digital audio adapter. One horizontal period.

just after the horizontal blanking pulse and the white reference just before it. The white reference is provided to keep the signal level at the automatic gain control appropriate for proper frequency modulation. Fig. 31 shows interleave of the data. A horizontal bar corresponds to one horizontal line. There are six 14-bit samples, two 14-bit check bits, and a 16-bit cyclic-redundancy check in one horizontal period. The diagonal combination shown by the dashed lines illustrates one code word. P_n and Q_n are generated from L_{3n}, R_{3n}, L_{3n+1}, R_{3n+1}, L_{3n+2}, and R_{3n+2} by an algorithm of b-adjacent code. This error-correcting code can correct a two-word error, so that a burst error of 31 horizontal line lengths can be corrected. Fig. 32 shows a code format for professional use with a U-type VCR [11]. L_1, L_2 and R_1, R_2 stand for the first and second samples of the left channel and the first and second samples of the right channel, respectively. C_1 is generated from L_1 and R_1 according to a simple parity algorithm. C_2 is generated from R_2 and L_2. C_3 is generated from L_1, R_2, and L_3 and by a simple parity algorithm in the horizontal direction. The signal is recorded in the order of first row, second row, third row, and so on, as illustrated in Fig. 32(c). Fig. 33 illustrates another tape format using the U-type VCR [12]. The waveform of one vertical period is shown in Fig. 33(a) and (b). A white reference is provided for automatic gain control, as described above. Fig. 33(c) and (d) illustrates the waveform of one horizontal period, with Fig. 33(c) showing the flag bit and Fig. 33(d) the audio data. P_1 and P_2 stand for check bits of the error-correcting code generated by an algorithm which is approximately similar to the cross interleave code. A cyclic-redundancy check code, denoted by C, is 22 bits long to reduce the probability of misdetection.

7 CONCLUSION

Tape formats of both fixed-head and rotary-head digital audio recorders were described. The independence of error in each track of fixed-head recorders makes it easy to design the tape format. Because only one track at a time is recorded in rotary-head recorders, interleave of the code is essential. For multichannel recording, the fixed-head recorder is more desirable than the VCR because punch-in and punch-out is possible with only one machine. Several currently used tape formats are presented for reference.

8 REFERENCES

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[2] T. T. Doi, Y. Tsuchiya, M. Tanaka, and N. Watanabe, "A Format for a Stationary-Head Digital Audio Recorder Which Covers a Wide Range of Applications,"

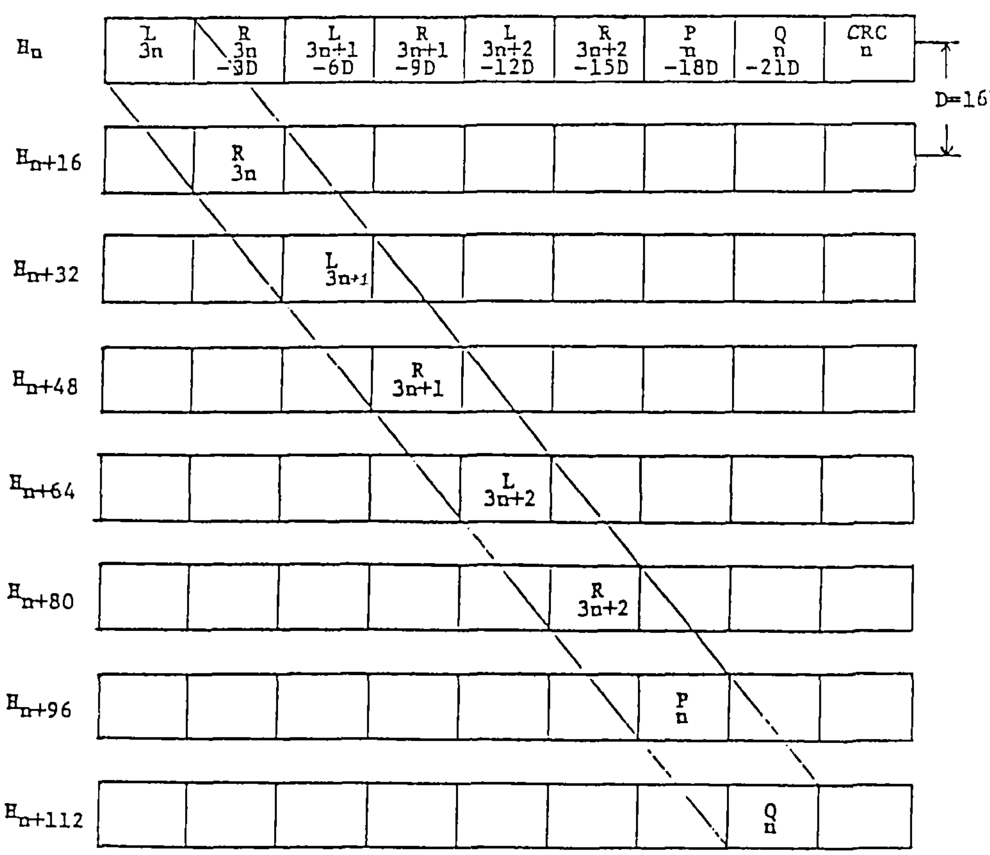

Fig. 31. Code block of EIAJ-type digital audio recorder.

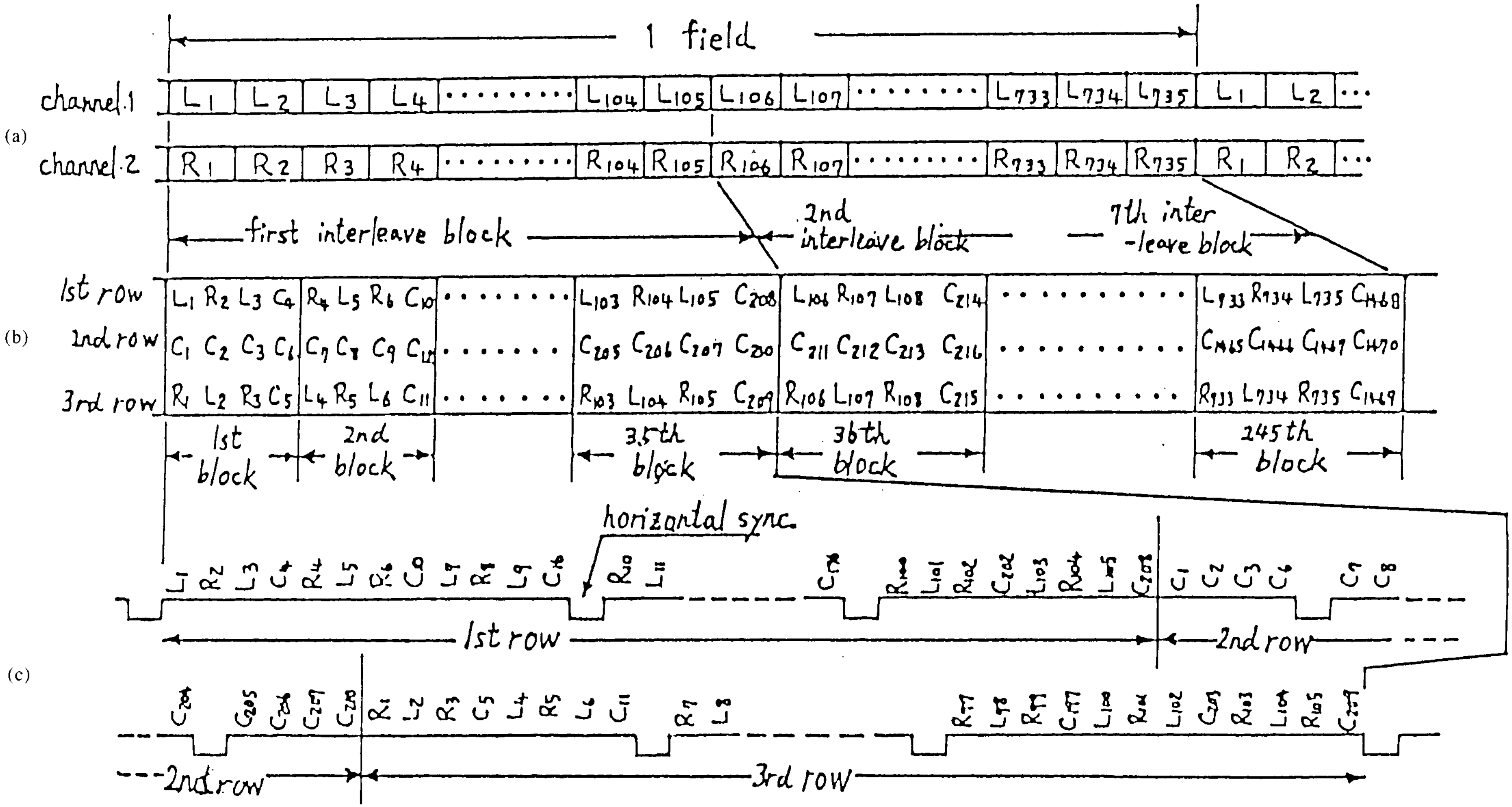

Fig. 32. Code format of rotary-head-type digital audio recorder for professional use.

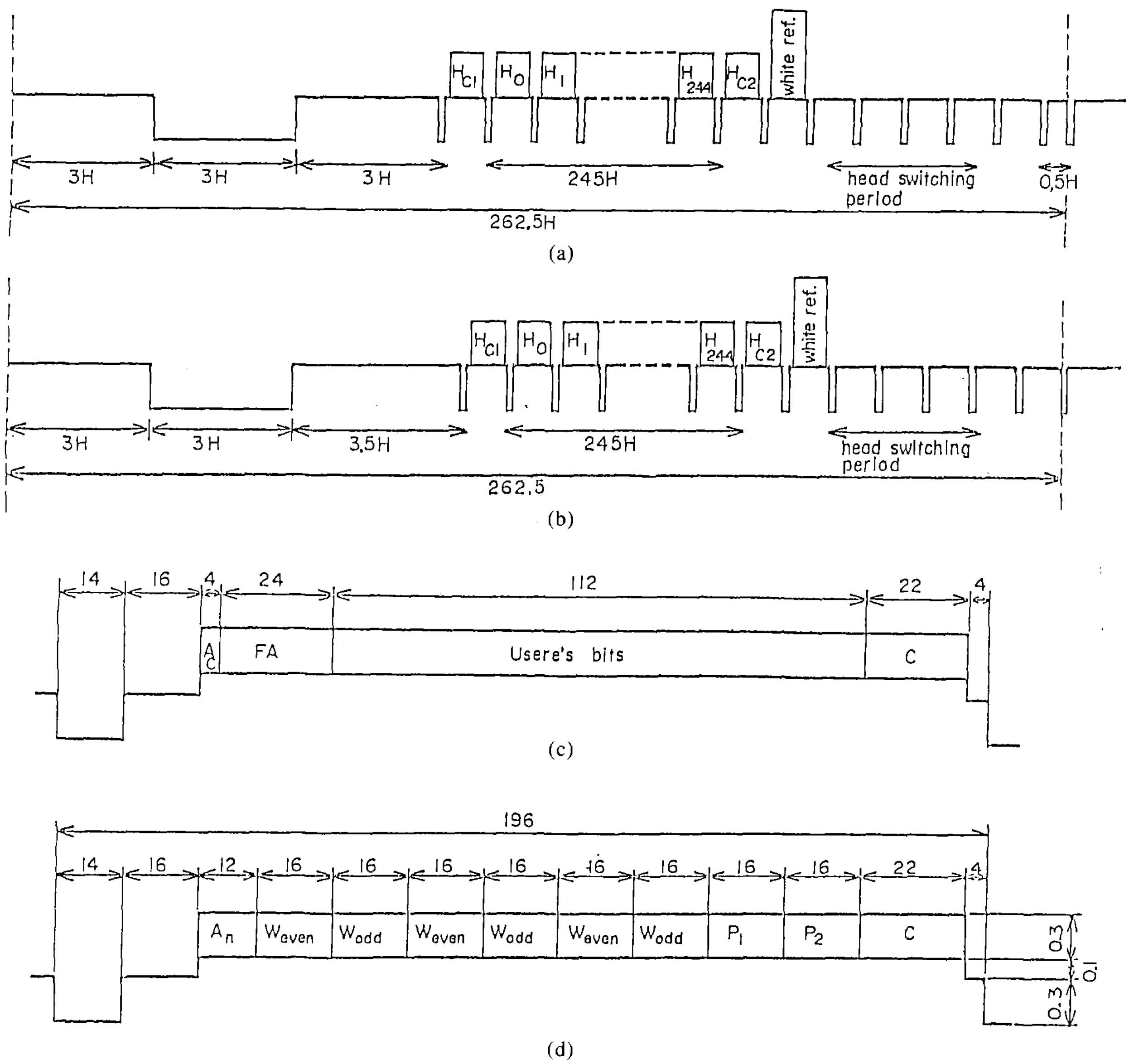

Fig. 33. Another code format of rotary-head-type digital audio recorder for professional use. (a), (b) one vertical period. (c), (d) one horizontal period.

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