Kees and his channel coding for CD

Seminar in Honor of Kees Schouhamer Immink
June 16, 2017, Rotterdam

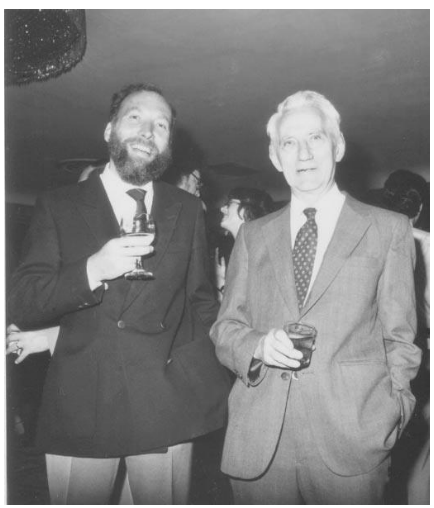
Ronald M. Aarts

18 Dec 1946

1977

1995

16 June 2017



1985

Properties and Constructions of Binary Channel Codes

Proefschrift

ter verkrijging van de graad van doctor in de technische wetenschappen aan de Technische Hogeschool Eindhoven, op gezag van de rector magnificus, prof. dr. S. T. M. Ackermans, voor een commissie aangewezen door het college van dekanen in het openbaar te verdedigen op vrijdag 3 mei 1985 te 16.00 uur

door

Kornelis Antonie Schouhamer Immink

geboren te Rotterdam

2006

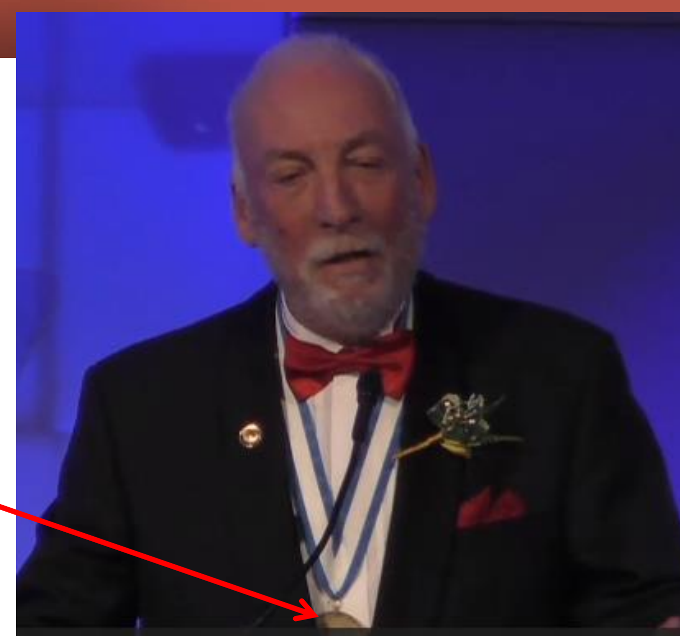
2014

RMA, Kees, Clasien, Delft 11 Sept. 1995

IEEE SPECTRUM

The Shiny Bits

Kees Immink's peculiar genius helped create the CD, and now he's applying it to DNA storage P. 32



Joost Kahlman, Eindhoven, 1985 by Ed van der Elsken

THE COMPACT DISC DIGITAL AUDIO SYSTEM:
MODULATION AND ERROR-CORRECTION

1674 (H-8)

Lodewijk B. Vries, Kees A. Immink,
Jaap G. Nijboer, Henk Hoeve
N. V. Philips
Eindhoven, The Netherlands

and

Toshi T. Doi, Kentaroh Odaka,
Hiroshi Ogawa
Sony Corporation
Tokyo, Japan

Presented at the 67th Convention 1980 Oct. 31/Nov. 3 New York

AUDIO ES

AES

AN AUDIO ENGINEERING SOCIETY PREPRINT

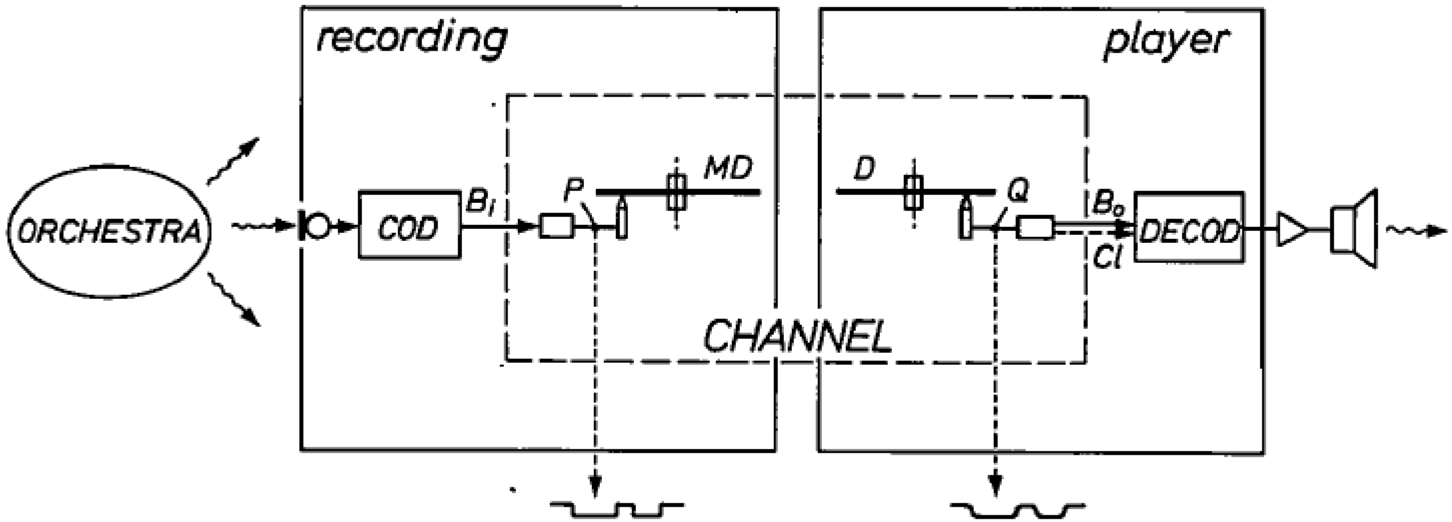


Fig. 1. The Compact Disc system, considered as a transmission system that brings sound from the studio into the living room. The transmission channel between the encoding system (*COD*) at the recording end and the decoding system (*DECOD*) in the player, 'transmits' the bit stream B_i to *DECOD* via the write laser, the master disc (*MD*), the disc manufacture, the disc (*D*) in the player and the optical pick-up; in the ideal case B_o is the same as B_i. The bits of B_o, as well as the clock signal (*Cl*) for further digital operations, have to be detected from the output signal of the pick-up unit at *Q*.

Philips tech. Rev. 40, 157-164, 1982, No. 6

Compact Disc: system aspects and modulation

J. P. J. Heemskerk and K. A. Schouhamer Immink

Why channel code for CD?

- Make bitstream suitable for the optical transmission channel
- Allowing reception with simple receivers (e.g. clock recovery)
- Reduce interference with system, e.g. servo for track following

Run Length Codes

INFORMATION AND CONTROL 17, 436–461 (1970)

Block Codes for a Class of Constrained Noiseless Channels*

D. T. TANG AND L. R. BAHL

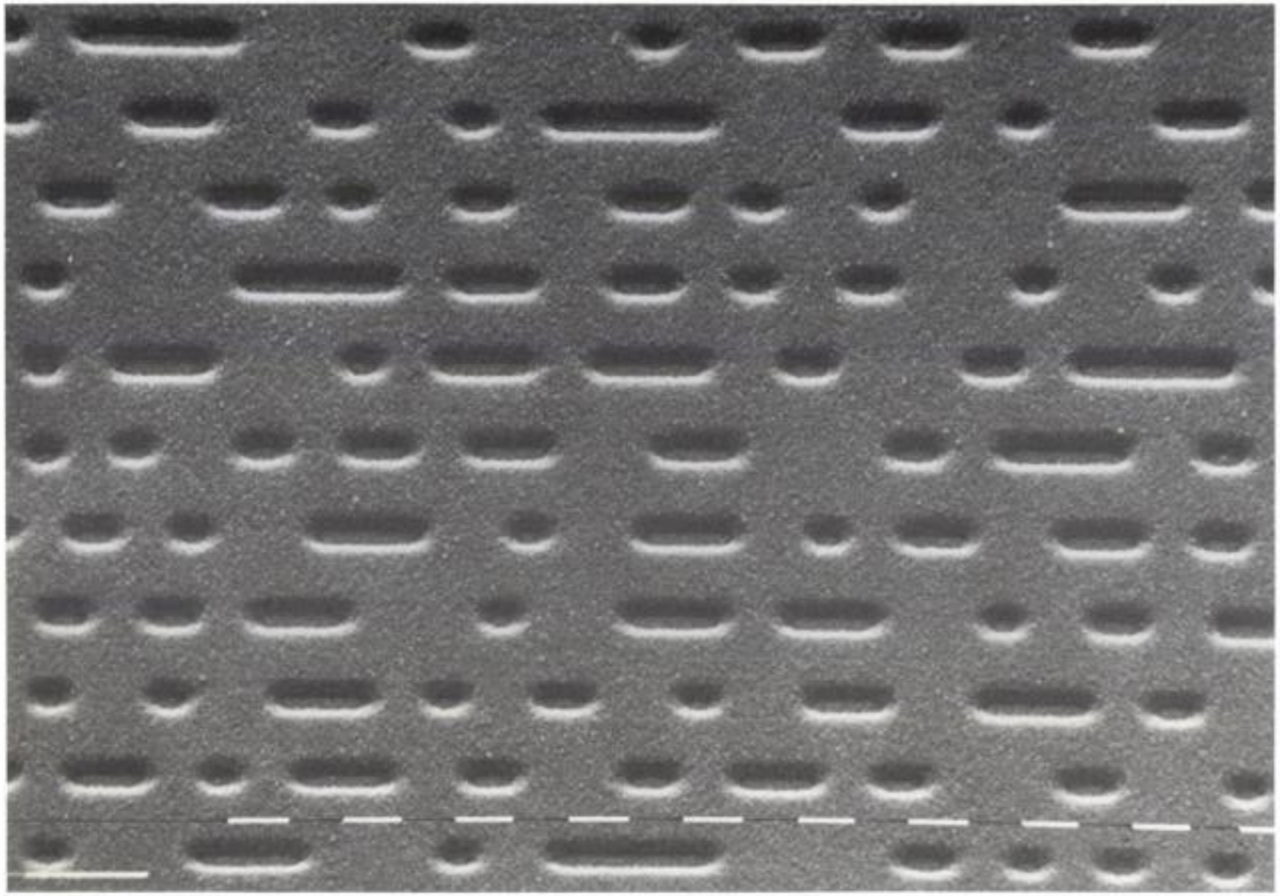
IBM Thomas J. Watson Research Center, Yorktown Heights, New York

A class of discrete noiseless channels having upper and lower bounds on the separation between adjacent nonzero input symbols is considered. Recursion relations are derived for determining the number of input sequences which satisfy the constraints for all block lengths, and the asymptotic information rate is calculated. Applications to compaction and synchronization are discussed. An optimal algebraic block coding scheme for such channels is developed.

DEFINITION 1. A *dk*-limited *q*-nary sequence satisfies simultaneously the following conditions:

1. *d*-constraint—two nonzero symbols are separated by a run of consecutive zeros of length at least *d*.
2. *k*-constraint—any run of consecutive zeros is of length at most *k*.

Tang and Bahl 1970



The information on the Compact Disc is recorded in digital form as a spiral track consisting of a succession of pits. The pitch of the track is 1.6 μm, the width 0.6 μm and the depth of the pits 0.12 μm. The length of a pit or the land between two pits has a minimum value of 0.9 and a maximum value of 3.3 μm. The scale at the bottom indicates intervals of 1 μm.

d-Limited Sequences

Let $N_d(n)$ denote the number of distinct d-sequences of length n. (For convenience, d-limited sequences will be abbreviated to d-sequences). Define

$$N_d(n) \triangleq 0 \qquad \text{for} \quad n < 0, \tag{1}$$

$$N_d(0) \triangleq 1. \tag{2}$$

For $n > 0$, the number of d-sequences, $N_d(n)$, is given in Theorem 1.

THEOREM 1. *The number of d-sequences of length n is given by*

$$N_d(n) = n(q-1) + 1 \qquad \textit{for} \quad 1 \leqslant n \leqslant d+1, \tag{3}$$

$$N_d(n) = N_d(n-1) + (q-1)\,N_d(n-d-1) \qquad \textit{for} \quad n > d+1. \tag{4}$$

In the binary case Eqs. (3) *and* (4) *reduce to*

$$N_d(n) = n + 1 \qquad \textit{for} \quad 1 \leqslant n \leqslant d+1, \tag{5}$$

$$N_d(n) = N_d(n-1) + N_d(n-d-1) \qquad \textit{for} \quad n > d+1. \tag{6}$$

Tang and Bahl 1970

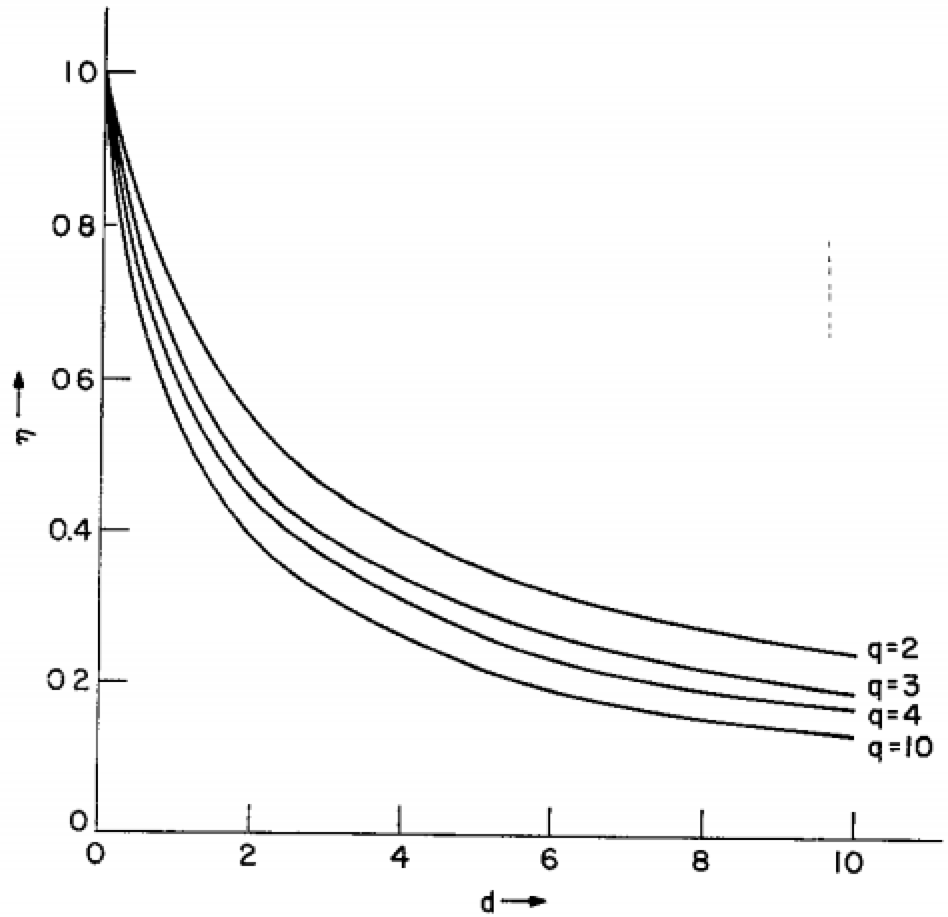


FIG. 1. Asymptotic information rate of *d*-sequences.

Tang and Bahl 1970

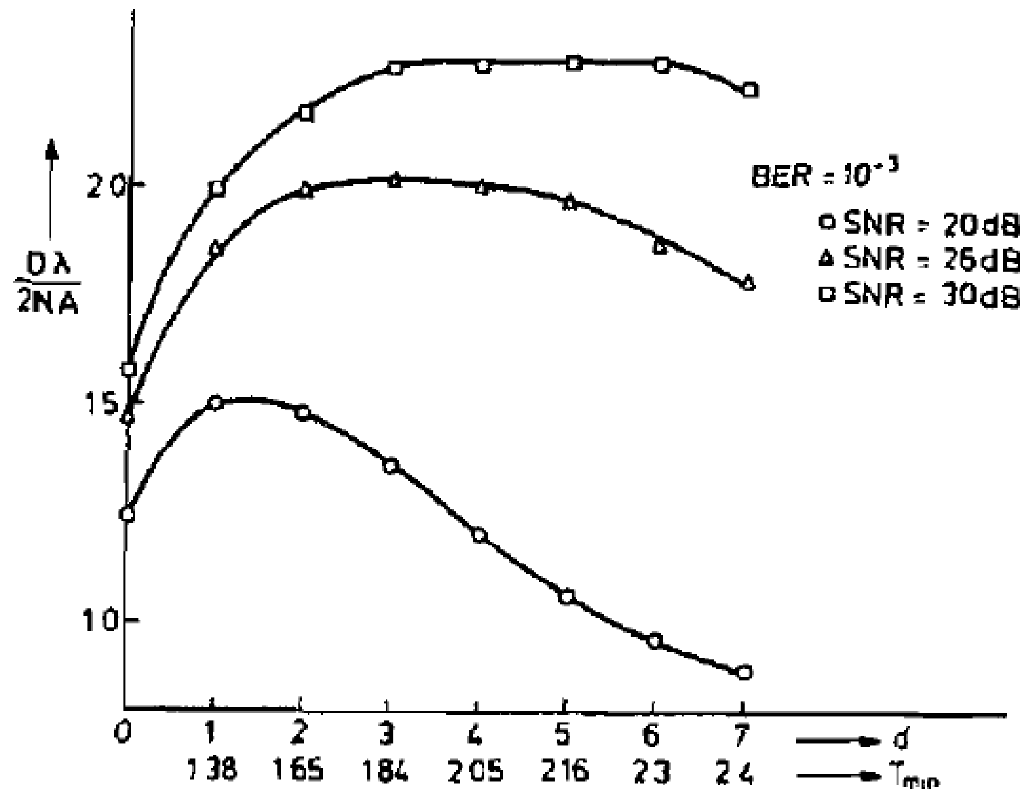


figure 1. Maximum achievable information density versus minimum pitsize (T_{min}) for a Gaussian channel. Substituting some practical values: SNR = 26 dB, NA = 0.4, λ = 780 nm yields a maximum density of 2.25 bits per micron.

K.A.S. Immink, 'Modulation systems for digital audio discs with optical read-out', Proceedings IEEE Int. Conf. on Acoustics, speech and signal processing, Atlanta, pp. 587-589, June 1981.

NAT.LAB. TECHNICAL NOTE NR. 152/80

Ir. K.A. Immink

COMPACT DISC NOTES OF THE PERIOD MARCH-JULY 1980

Remark

The system described in this chapter with three merging bits was first called BES and later officially EFM. During the July meeting it was adopted by Philips and Sony as the CD--standard. It will be exhaustively described in T.N. 153/80.

5. High density recording by selected block codes.

K.A. Immink, M.P.M. Bierhoff*

I. Conclusions

1. At the Philips' Research Labs a new modulation system is developed for Compact Disc, which is superior with respect of ASAP2 and M3. It is called SEM (seven to eight modulation).
2. The information density, that can be obtained equals the ASAP2 density, however the DC-content is much smaller.

5. The modulation system

The NRZ-signals from the A/D-convertor and the error correction parity generator may have a high dc-content and are not self-clocking (the run-length* is not limited). Therefore they cannot be used on the disc.
The signals have to be converted into another code which should meet some special requirements.

5.1 Requirements for the modulation system

a. Clock-content

The bit-clock must be regenerated from the signal after read-out. Therefore, the signal must have a sufficient number of transients and the maximum run-length (Tmax) must be as small as possible.

b. Correct read-out at high information densities.

The light-spot with which the disc is to be read out has finite dimensions. These dimensions give rise to intersymbolinterference. This effect can be minimized by making the minimum run-length (Tmin) as large as possible. So a good technical compromise between Tmin and clock content has been made on experiments.

c. Servo

The modulation code must be dc-free, because the low-frequencies of the spectrum give rise to noise in the servo-systems.

d. Error-propagation

The error-propagation of the modulation system should be limited to the eight consecutive data bits forming a symbol.

L.B. Vries, K.A.S. Immink, J.B. Nyboer, H. Hoeve, T.T. Doi, K. Odaka and H. Ogawa,
'The Compact Disc Digital Audio System: Modulation and Error correction', 67th AES Convention, no 1674, New York, Oct. 1980.

5.2 The Eight-to-Fourteen modulation (EFM) code.

- Each block of 8 data bits is mapped into 14 channel bits. To each block of 14 channel bits 3 extra bits are added, for merging and for low freq. suppression.

- The information is contained in the positions of the transients. For mapping 8 data bits 256 combinations of channel bits are needed.

- The code is constructed in such a way that the minimum distance between 2 transients is 3 channel bits (≈1.5 data bits) and the sampling window or eye-pattern is 1 channel bit (≈ 0.5 data bit).
  This yields a good compromise between intersymbol-interference and clock accuracy (phase-jitter). The maximum runlength within the blocks is 11 channel bit (5.5 data bits) (see fig. 2)

- Since the extra 3 bits do not contain any information, an extra transient may be inserted in these bits. In this way the maximum-run-length (*max) between two blocks and the dc-content of the frequency spectrum can be controlled.

- The modulator and demodulator can be realised with a look-up table in a ROM.

- Because of the block structure this modulation code is extremely suitable for use in conjunction with the error-correction system, which operation is also based on 8-bit blocks.

* Run-length = distance between transients in the signal.

L.B. Vries, K.A.S. Immink, J.B. Nyboer, H. Hoeve, T.T. Doi, K. Odaka and H. Ogawa, 'The Compact Disc Digital Audio System: Modulation and Error correction', 67th AES Convention, no 1674, New York, Oct. 1980.

Table 11 Part of the EFM Coding Table

Data	*Code*	*Data*	*Code*
100	01000100100010	114	10010010000010
101	00000000100010	115	00100000100010
102	01000000100010	116	01000010000010
103	00100100100010	117	00000010000010
104	01001001000010	118	00010001000010
105	10000001000010	119	00100001000010
106	10010001000010	120	01001000000010
107	10001001000010	121	00001001001000
108	01000001000010	122	10010000000010
109	00000001000010	123	10001000000010
110	00010001000010	124	01000000000010
111	00100001000010	125	00001000000010
112	10000000100010	126	00010000100010
113	10000010000010	127	00100000000010

which shows the decimal representation of the 8-bit source word (left column) and its 14-bit channel representation (right column). Space limitations prohibit the presentation of the complete table, for full details the reader is advised to consult the patent literature [26].

K.A.S. Immink, 'Runlength-Limited Sequences', *Proceedings IEEE,* vol. 78, no. 11, pp. 1745-1759, Nov. 1990

details [21]). Hence it sufficies to study good, efficient basic codes.

5. Conclusions

We calculated the maximum tangential information density that can be attained with modulation systems based on runlength-limited codes on a two-level channel.
The resulting maximum information density is dependent of the applied channel model. Especially the exact "tail" of the read-out impulse response, normally considered as second order, is rather important.
Hence the comparison of modulation systems with computer simulation only should be considered as quite delicate.
If on practical grounds the minimum tolerable eye should be larger than -15 dB then we conclude that it is not worthwhile to consider modulation systems with $d > 2$ ($T_{min} > 1.6$).

For modulation systems with $d < 3$ and minimum eye height > -15 dB the difference in maximum attainable information density is small.

mk

Eindhoven, februari 1982

Natuurkundig Laboratorium der
N.V. Philips' Gloeilampenfabrieken

Eight-to-fourteen modulation

From Wikipedia, the free encyclopedia

Eight-to-fourteen modulation (**EFM**) is a data encoding technique – formally, a *channel code* – used by compact discs (CD), laserdiscs (LD) and pre-Hi-MD MiniDiscs. EFMPlus is a related code, used in DVDs and SACDs. EFM and EFMPlus were both invented by Kees A. Schouhamer Immink. European Patent Office President Benoît Battistelli: "Immink's invention of EFM made a decisive contribution to the digital revolution."[1]

Contents [hide]

Technological classification [edit]

EFM[2] belongs to the class of DC-free run length limited (RLL) codes; these have the following two properties:

- the spectrum (power density function) of the encoded sequence vanishes at the low-frequency end **and**
- both the minimum and maximum number of consecutive bits of the same kind are within specified bounds.[3][4]

In optical recording systems, servo mechanisms accurately follow the track in three dimensions: radial, focus, and rotational speed. Everyday handling damage, such as dust, fingerprints, and tiny scratches, not only affects retrieved data, but also disrupts the servo functions. In some cases, the servos may skip tracks or get stuck. Specific sequences of pits and lands are particularly susceptible to disc defects, and disc playability can be improved if such sequences are barred from recording. The use of EFM produces a disc that is highly resilient to handling and solves the engineering challenge in a very efficient manner.

How it works [edit]

Under EFM rules, the data to be stored is first broken into eight-bit blocks (bytes). Each eight-bit block is translated into a corresponding fourteen-bit codeword using a lookup table.

United States Patent [19]

Immink et al.

[11] **Patent Number: 4,501,000**

[45] **Date of Patent: Feb. 19, 1985**

[54] **METHOD OF CODING BINARY DATA**

[75] Inventors: **Kornelis A. Immink; Jakob G. Nijboer,** both of Eindhoven, Netherlands; **Hiroshi Ogawa; Kentaro Odaka,** both of Tokyo, Japan

[73] Assignee: **Sony Corporation,** Tokyo, Japan

[21] Appl. No.: **286,982**

[22] Filed: **Jul. 27, 1981**

[51] **Int. Cl.**[3] **H03K 13/02**

[52] **U.S. Cl.** .... **375/25;** 375/106; 340/347 DD

[58] **Field of Search** .... 375/18, 19, 25, 106, 375/112; 340/347 DD; 360/40, 48; 371/55, 57; 358/13

[56] **References Cited**

U.S. PATENT DOCUMENTS

3,631,471	12/1971	Griffiths	340/347 DD
3,810,111	5/1974	Patel	360/40
3,995,264	11/1976	Ouchi	371/55
4,003,041	1/1977	Van Duuren	340/347 DD
4,020,282	4/1977	Halpern	375/34
4,092,595	5/1978	Weir et al.	375/17
4,229,808	10/1980	Hui	360/48
4,309,694	1/1982	Henry	340/347 DD

Primary Examiner—Robert L. Griffin
Assistant Examiner—Stephen Chin
Attorney, Agent, or Firm—Lewis H. Eslinger; Alvin Sinderbrand

[57] **ABSTRACT**

A system for block encoding words of a digital signal achieves a maximum of error compaction and ensures reliability of a self-clocking decoder, while minimizing any DC in the encoded signal. Data words of m bits are translated into information blocks of n_1 bits ($n_1 > m$) that satisfy a (d,k)-constraint in which at least d "0" bits, but no more than k "0" bits occur between successive "1" bits. The information blocks are catenated by inserting separation blocks of n_2 bits therebetween, selected so that the (d,k)-constraint is satisfied over the boundary between any two information words. For each information word, the separation block that will yield the lowest net digital sum value is selected. Then, the encoded signal is modulated as an NRZ-M signal in which a "1" becomes a transition and a "0" becomes an absence of a transition. A unique synchronizing block is inserted periodically. A decoder circuit, using the synchronizing blocks to control its timing, disregards the separation blocks, but detects the information blocks and translates them back into reconstituted data words of m bits. The foregoing technique can be used to advantage in recording digitized music on an optical disc.

13 Claims, 10 Drawing Figures

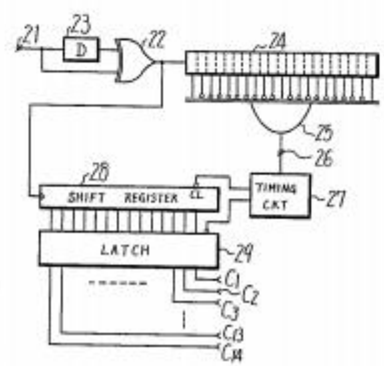


Figure 5 illustrates, finally, how the merging bits are determined. Our measure of the low-frequency content is

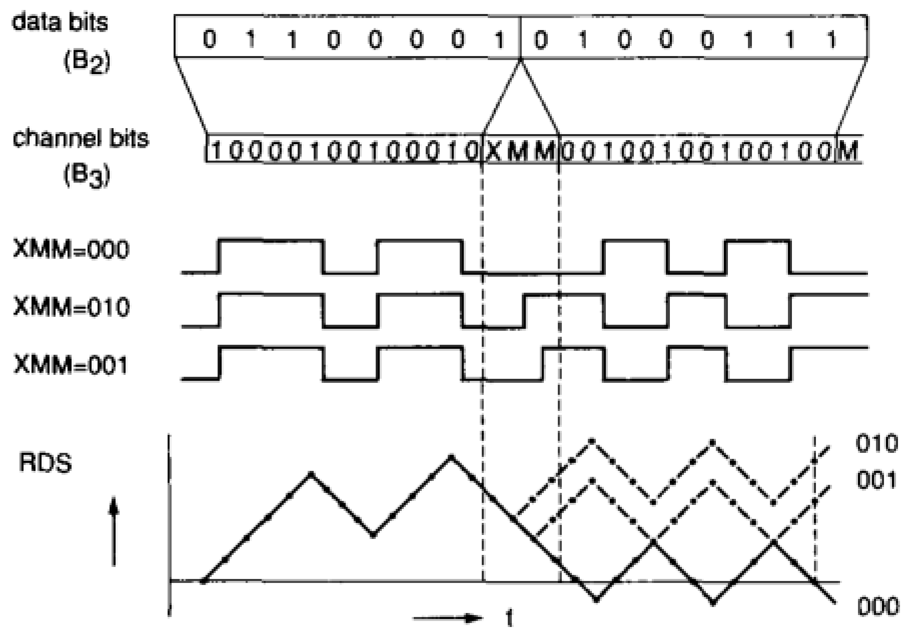


Fig. 5. Strategy for minimizing the running digital sum (RDS). Eight user bits B_2 are translated into fourteen channel bits B_3, the fourteen bits are merged by means of three merging bits in such a way that the runlength conditions continue to be satisfied. The condition that there should be at least two "zeros" between "ones" requires a "zero" at the first merging bit position. In this case there are thus three alternatives for the merging bits: "000," "010," and "001." The encoder chooses the alternative that gives the lowest absolute value of the RDS at the end of a new codeword, i.e., "000" in this case.

K.A.S. Immink, 'Runlength-Limited Sequences', *Proceedings IEEE,* vol. 78, no. 11, pp. 1745-1759, Nov. 1990

Writing your own CD (1983)

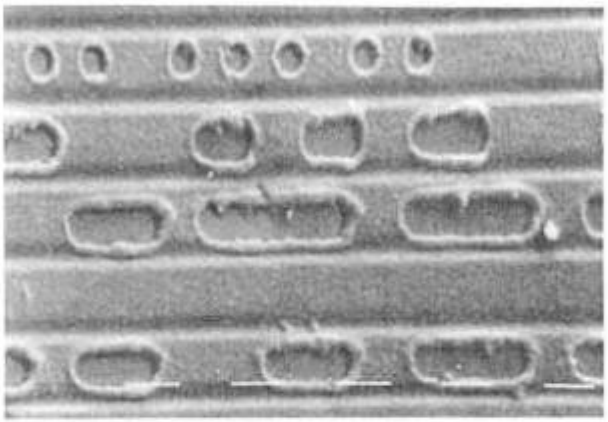


Figure 7. A scanning electron microscope photograph of a 10000 times enlarged disc sample with a Te compound layer. The upper track contains monohole information, the other tracks runlength sequences. The observation angle is 45°, with one white bar corresponding to 1 μm.

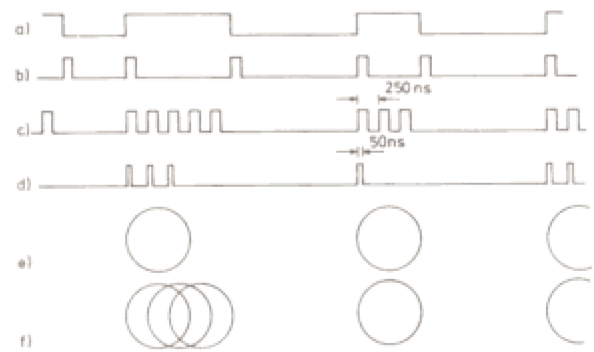


Figure 8.
a) A runlength limited sequence.
b) A dk-sequence.
c) A pulse derived from an RLL sequence used for writing overlapping monoholes.
d) Write pulses for overlapping monoholes fed to the laser (2 pulses deleted).
e) Schematic pits on the disc when monoholes are used.
f) Schematic pits on the disc when pitlength modulation (overlapping monoholes) is used.

K.A. Schouhamer Immink and R.M. Aarts.
Maximization of recording density obtainable in Te-alloys.
Proceedings of SPIE- The Int. Soc. for Optical Eng., April 19-20, Geneva, Switzerland., pages 181-188, 1983.

United States Patent [19]
[11] **Patent Number: 4,473,829**
[45] **Date of Patent: Sep. 25, 1984**

Schouhamer Immink et al.

[54] **METHOD OF RECORDING A DIGITAL INFORMATION SIGNAL ON A RECORD CARRIER HAVING A RADIATION-SENSITIVE INFORMATION LAYER, APPARATUS FOR CARRYING OUT THE METHOD, AND OPTICAL RECORD CARRIER PROVIDED WITH SUCH A DIGITAL INFORMATION SIGNAL**

[75] Inventors: **Kornelis A. Schouhamer Immink; Ronaldus M. Aarts; Willem G. Opheij,** all of Eindhoven, Netherlands

[73] Assignee: **U.S. Philips Corporation,** New York, N.Y.

[21] Appl. No.: **378,567**

[22] Filed: **May 17, 1982**

[30] **Foreign Application Priority Data**

Apr. 2, 1982 [NL] Netherlands 8201411

[51] **Int. Cl.**[3] **G01D 15/10**
[52] **U.S. Cl.** .... **346/1.1;** 346/76 L
[58] **Field of Search** .... 346/1.1, 76 L, 108; 369/59; 360/40, 44; 375/110

[56] **References Cited**

U.S. PATENT DOCUMENTS

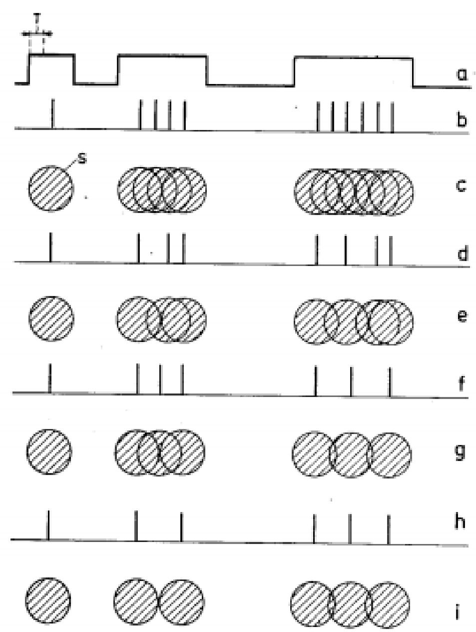
3,474,457 10/1969 Becker .... 346/76 L
4,027,335 5/1977 Miller 360/40
4,353,130 10/1982 Carasso et al. 369/59

Primary Examiner—Joseph W. Hartary
Assistant Examiner—Todd E. DeBoer
Attorney, Agent, or Firm—Robert T. Mayer; Algy Tamoshunas

[57] **ABSTRACT**

A method of recording a binary information signal on a record carrier having a radiation-sensitive information layer. The information signal is encoded in such a way that at least n ($n \geqq 2$) consecutive bit cells are of the same type. This information is recorded as pattern of unitary recording marks on the record carrier. Each unitary recording mark then corresponds to a number of m bit cells of the same first type in the information signal, where $1 < m \leqq n$. A greater number of consecutive bit cells of said first type is represented by a plurality of unitary recording marks which are at least contiguous but which preferably overlap each other.

10 Claims, 12 Drawing Figures



United States Patent [19]

Schouhamer Immink et al.

[11] **Patent Number: 4,660,097**

[45] **Date of Patent: Apr. 21, 1987**

[54] **COLOR VIDEO SYSTEM WITH DIGITAL AUDIO PULSE WIDTH MODULATION**

[75] Inventors: **Kornelis A. Schouhamer Immink; Ronaldus M. Aarts; Josephus A. H. M. Kahlman**, all of Eindhoven, Netherlands

[73] Assignee: **U.S. Philips Corporation**, New York, N.Y.

[21] Appl. No.: **804,241**

[22] Filed: **Dec. 2, 1985**

Related U.S. Application Data

[63] Continuation of Ser. No. 488,573, Apr. 25, 1983, abandoned.

[30] **Foreign Application Priority Data**

Feb. 14, 1983 [NL] Netherlands 8300541

[51] **Int. Cl.**[4] **A04N 5/92**; A04N 9/80

[52] **U.S. Cl.** **358/310**; 358/330; 358/328; 358/343; 360/19.1; 360/32

[58] **Field of Search** 358/310, 330, 342, 343, 358/12, 13, 335, 142, 143, 328; 360/19.1, 32, 33.1; 375/22

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,022,986	5/1977	Teer	360/32
4,068,259	1/1978	Tinet	358/310
4,223,282	9/1980	Boer	455/44
4,447,834	5/1984	Sugiyama	358/310
4,480,270	10/1984	Wilkinson	358/343

OTHER PUBLICATIONS

"Philips Technical Review", vol. 40, 1982, No. 6, pp. 149–180 publ. 9/10/82.

"System Coding Parameters, Mechanics and Electro-Mechanics of the Reflective Video Disc Player" by Bogels, IEEE Trans. on Cons. Elec., vol. CE-22, No. 4, pp. 309–317, Nov. 1976.

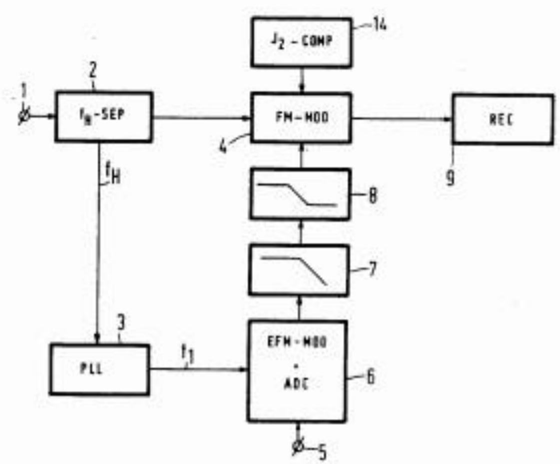
Primary Examiner—Alan Faber

Attorney, Agent, or Firm—Thomas A. Briody; Jack Oisher; William J. Streeter

[57] **ABSTRACT**

A method of encoding a recording signal which includes a composite color video signal and a digital audio signal, for recording the same on and reading it from an optical video disc is disclosed. The color video signal is frequency-modulated on a carrier wave in the customary manner, while the audio signal pulse-width modulates the carrier wave.

33 Claims, 8 Drawing Figures



EFMPlus: THE CODING FORMAT OF THE MULTIMEDIA COMPACT DISC

Kees A. Schouhamer Immink
Philips Research Laboratories,
5656 AA Eindhoven, The Netherlands

***Abstract*–We report on an alternative to Eight-to-Fourteen Modulation (EFM), called EFMPlus, which has been adopted as coding format of the MultiMedia Compact Disc proposal. The rate of the new code is 8/16, which means that a 6-7 % higher information density can be obtained. EFMPlus is the spitting image of EFM (same minimum and maximum runlength, clock content etc). Computer simulations have shown that the low-frequency content of the new code is only slightly larger than its conventional EFM counterpart.**

I Introduction

Table 1: Main parameters of MultiMedia CD.

read-out wavelength	635 nm
reference NA	0.52
disc diameter	12 cm / 8cm
disc thickness	1.2 mm
layers	single or dual layer
reference scanning speed	4 m/s
reference channel bit rate	26.6 Mbit/s
min. pit (or land) length	0.451 μm
track pitch	0.84 μm
recording code	EFMPlus
sector size	2048 bytes
error correction	CIRCPlus
max. user bit rate @ ref speed	11.2 Mbit/s

US005696505A

United States Patent [19]

Schouhamer Immink

[11] **Patent Number:** **5,696,505**

[45] **Date of Patent:** **Dec. 9, 1997**

[54] **METHOD OF CONVERTING A SERIES OF M-BIT INFORMATION WORDS TO A MODULATED SIGNAL, METHOD OF PRODUCING A RECORD CARRIER, CODING DEVICE, DECODING DEVICE, RECORDING DEVICE, READING DEVICE, SIGNAL, AS WELL AS RECORD CARRIER**

[75] Inventor: **Kornelis A. Schouhamer Immink**, Eindhoven, Netherlands

[73] Assignee: **U.S. Phillips Corporation**, Tarrytown, N.Y.

[21] Appl. No.: **385,533**

[22] Filed: **Feb. 8, 1995**

[30] **Foreign Application Priority Data**

Feb. 15, 1994 [EP] European Pat. Off. 94200387

[51] **Int. Cl.**^{6} **H03M 7/00**

[52] **U.S. Cl.** **341/59**; 341/95

[58] **Field of Search** 341/95, 58, 59, 341/106

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,517,552	5/1985	Shirota et al.	340/347
4,520,346	5/1985	Shimada	340/347
4,683,572	7/1987	Baggen et al.	371/37
4,833,470	5/1989	Iketani	341/59
4,855,742	8/1989	Verboom	341/102
5,048,003	9/1991	Baggen et al.	

FOREIGN PATENT DOCUMENTS

0319101	6/1989	European Pat. Off.	G11B 20/14
0392506A2	10/1991	European Pat. Off.	G11B 20/14

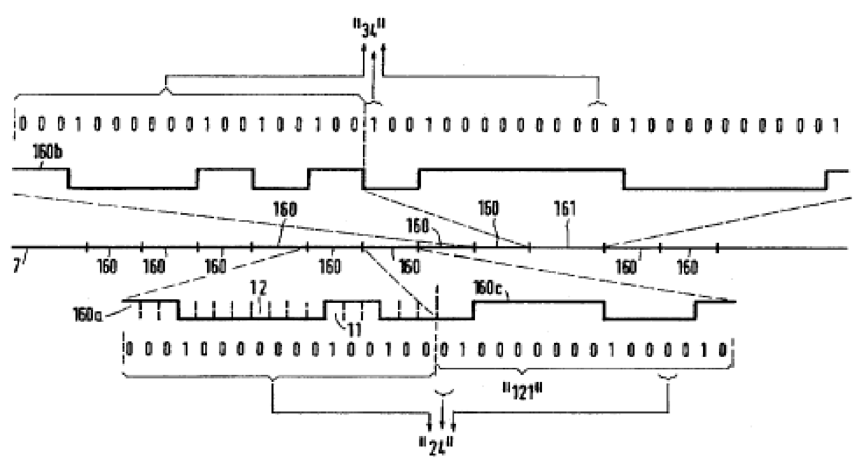
Primary Examiner—Brian K. Young
Assistant Examiner—Peguy JeanPierre
Attorney, Agent, or Firm—Richard A. Weiss

[57] **ABSTRACT**

A a series of m-bit information words is converted to a modulated signal. For each information word from the series, an n-bit code word is delivered. The delivered code words are converted to the modulated signal. The code words are distributed over at least one group of a first type and at least one group of a second type. When a code word belonging to a group of the first type is delivered, its group establishes a coding state of a first type. When a code word belonging to an group of the second type is delivered, a coding state of a second type is established which is determined by the information word which is to be converted to the delivered code word. When one of the code words is assigned to the received information word, this code word is selected from a set of code words which depends on the coding state established. The sets of code words belonging to the coding states of the second type are disjunct. In this coding method, the number of unique bit combinations that may be established by the code words in the series are enlarged.

The modulated signal obtained may be reconverted to information words by first converting the modulated signal to a series of code words and then assigning an information word to each of the code words from the series in dependence on the code word to be converted and also in dependence on the logical values of the bit string bits which are situated at predetermined positions relative to the code word.

38 Claims, 20 Drawing Sheets



Kees het ga je goed!

We verwachten nog veel van je