

Generation of a runlength limited digital information signal.

The invention relates to an apparatus for generating a runlength limited (RLL) digital information signal, the digital information signal having a minimum runlength of d' and a maximum runlength of k' , d' and k' being integers larger than zero and where k' is larger than d' and to a method for generating such runlength limited digital information signal. The invention further relates to an apparatus for and a method of generating a (d,k) sequence. An apparatus as defined in the opening paragraph is eg. known from USP 5,477,222, document D1 in the list of related documents that can be found at the end of this description.

Runlength limited digital information signals obtained from channel coding an information signal are described in the book 'Coding techniques for digital recorders' by K.A. Schouhamer Immink, Prentice Hall, 1991, chapter 5, document D2. Such runlength limited digital information signals are generally derived from so-called (d,k) constrained sequences. In such sequences, expressed in NRZ-I (non-return-to-zero-inverse) notation, two logical 'ones' in the sequence are separated by a run of consecutive 'zeros' of length at least d , and any run of consecutive 'zeros' is at most k . A (d,k) sequence is normally converted in a precoding step so as to obtain the runlength limited information signal. In such runlength limited information signal obtained from the above (d,k) sequence, minimum runlengths of $d+1$ of consecutive like symbols occur and maximum runlengths of $k+1$ consecutive like symbols occur in sequences expressed in NRZ notation. This precoding of a (d,k) sequence, for $d=1$ and $k=7$ as an example, results in a runlength limited information signal having a minimum runlength of 2 and a maximum runlength of 8.

A choice of a specific channel code, properly adopted to the physical channel characteristics, is limited by the fact that the d -constraint is restricted to the natural numbers ($d=0, d=1, d=2, \dots$). It has been proposed in the past to remove this limitation, by using rational d -constraints. Reference is made in this respect to the publication by P. Funk, document D3 in the list of related documents at the end of this description.

The invention has for its object to provide a different alternative for an apparatus which is capable of generating channel codes which fill up the gap between d and $d+1$ for the traditional (d,k) -based codes.

In accordance with a first aspect of the invention, the apparatus is characterized in that
5 the apparatus is adapted to generate the runlength limited digital information signal, such that a minimum runlength in the digital information signal occurs isolated from other minimum runlengths in the digital information signal.

In accordance with a second aspect of the invention, the apparatus for generating a runlength limited digital information signal, the digital information signal having a minimum
10 runlength of d' and a maximum runlength of k' , d' and k' being integers larger than zero and where k' is larger than d' , characterized in that the apparatus is adapted to generate the runlength limited digital information signal, such that a minimum runlength occurring in the digital information signal follows only a directly preceding runlength larger than d' .

In accordance with a third aspect of the invention, the apparatus for generating a
15 runlength limited digital information signal, the digital information signal having a specific minimum runlength and a maximum runlength of k' , the apparatus comprising means for generating runlengths in the digital information signal of length $d'+1$ at minimum, where d' and k' are integers larger than zero and where k' is larger than $d'+1$, characterized in that the apparatus further comprises means for generating runlengths of d' in the runlength limited
20 digital information signal, such that such runlengths of d' occur isolated from other such runlengths of d' in the digital information signal.

In accordance with a fourth aspect of the invention, the apparatus for generating a runlength limited digital information signal, the digital information signal having a specific minimum runlength and a maximum runlength of k' , the apparatus comprising means for
25 generating runlengths in the digital information signal of length $d'+1$, where d' and k' are integers larger than zero and where k' is larger than $d'+1$, characterized in that the apparatus further comprises means for generating runlengths of d' in the runlength limited digital information signal, such that such runlengths of d' occur only following a directly preceding runlength larger than d' .

30 The invention is based on the objective to generate (d,k) -based RLL channel codes, with the additional allowance of isolated I_d runlengths (that is: isolated runlengths of length d), which are normally forbidden in a pure (d,k) code. An isolated I_d runlength has to be surrounded by two other runlengths I_n with $n > d$. In contrast, for a pure $(d-1,k)$ RLL channel code, the appearance of I_d 's is unconditional. Therefore, the capacity of the new (d,k) code

with isolated I_d 's (called for short an iso- $I_d(d,k)$ code), is between the capacity of the traditional (d,k) and $(d-1,k)$ channel codes. The increase in capacity of the iso- $I_d(d,k)$ code compared to the pure (d,k) -code, goes together with an increase in the highest frequency in the bit-sequence, which equals $1/(2d+1)$ for the iso- (d,k) code, which is between $1/(2d+2)$ and $1/2d$ (for the pure (d,k) and $(d-1,k)$ codes, respectively).

It is to be understood that, where the claims define a RLL digital information signal with a minimum runlength of d' , d' should be taken equal to the parameter d introduced above, in order to bring the claims in conformity with the above argumentation.

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These and other objects of the invention will be elucidated below in the following figure description, in which

figure 1 shows a state-transition diagram for an iso- $I_1(d=1,k=4)$ code,
figure 2 shows the state-transition diagram for an iso- $I_1(d=1,k=7)$ code,
figure 3 shows the state-transition diagram for an iso- $I_2(d=2,k)$ code, and
figure 4 shows an embodiment of the apparatus in accordance with the invention,

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In the following figure description, practical examples are worked out for a number of channel codes.

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Iso- $I_d(d,k)$ code implementations with mapping of n user bits to m channel bits, have been constructed with the parity preserving property, so that DC-control can be applied. Reference is made in this respect to USP 5,477,222, document D1 in the list of related documents. Parity preserving implies that user words of n bits long, and channel words of m bits long, have the same parity (which is the number of 1's in a word, modulo 2). This property must also hold for the substitution encoding tables of the code (with $2n$ -to- $2m$ mapping), which are used when runlength violations appear upon concatenation of channel words by use of the standard encoding tables (with n -to- m mapping).

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Next a Rate $R=4/5$, iso- $I_1(d=1,k=4)$ Code will be described. The Finite-State Runlength Diagram of the code is shown in Fig.1. The states numbered 1 to 5 in the state diagram of figure 1 describe the normal $(d=1,k=4)$ code. By going from the state 1 to the state 2 and back to the state 1, a sequence ...01010... is obtained, which is a representation of the $d(=1)$ constraint. That is: at minimum one 'zero' occurs between two subsequent 'ones' in the sequence, expressed in NRZ-I notation. Further, by going through the states numbered 1, 2, 3,

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4, 5 and back to the state 1, a sequence ...01000010 ... is generated, which represents the k constraint: four 'zeroes' at most occur between two consecutive 'ones' in the sequence. It can be seen that, upon 1T precoding this NRZ-I sequence, a runlength limited sequence is obtained having runlengths of at minimum 2 and at maximum 5 runs of consecutive like symbols (in NRZ notation), or ...+--++.... and ...+-----+...., respectively.

It can further be seen that, apart from the traditional runlength constraints on the number of successive zeroes, there is now also a constraint on the number of successive ones, which should not exceed 2. This is realized by adding the state numbered 1'. By going through one of the states numbered 2, 3, 4 or 5, via the state 1 and the state 1', and going back to the state 2, a sequence ...0110.... has been obtained. Upon 1T precoding, this results in the occurrence of a run of 1, or ...++-++....

The capacity of the iso-I1(d=1,k=4) code equals $C=0.8376$. The code implementation has a rate $R=0.8$, thus yielding a code efficiency of 95.5 %. An iso-I1(d=1,k=3) code, which has a more severe constraint on k, leads to a capacity of $C=0.7947$. Such code can thus not be realised with a 4-to-5 mapping.

The standard conversion rules for the iso-I1(d=1,k=4) code are shown in table I A and table I B. The table I A is the conversion table for the conversion of the even parity words and the table I B is the conversion table for the odd parity words.

TABLE I A: Standard encoding table for even-parity channel words of iso-I1 (d=1, k=4) code.

	4-bit input word	5-bit channel word
1.	0000	00011
2.	0011	00101
3.	0110	00110
4.	1100	01001
5.	0101	01010
6.	1010	01100
7.	1001	10010
8.	1111	10100

TABLE I B: Standard encoding table for odd-parity channel words of iso-I1 (d=1, k=4) code.

	4-bit input word	5-bit channel word
1.	0001	00010
2.	0010	00100
3.	0100	01000
4.	1000	01011
5.	1110	01101
6.	1101	10011
7.	1011	10101
8.	0111	10110

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Further, substitution tables are needed to maintain the various constraints across the boundaries of consecutive converted words. The table II A corrects for the runlength violation otherwise occurring when concatenating some of the even parity input words, more specifically when concatenating the input words numbered 1 and 7, or when concatenating the input words 1 and 8, or when concatenating the input words 6 and 1 or when concatenating the input words 8 and 1, of the table I A. The middle column in the table II A shows that the runlength violations are in the form of three directly successive 'ones' or in the form of five directly successive 'zeroes', assuming the conversion in accordance with the rules of the table I A would have been carried out. The right column gives the substitution sequence. It should be noted that the second 5-bit word in the substitution table is not included in the converted words of the tables I A and I B. Therefore, those words can be used as an identification, upon decoding, that the two 5-bit converted words should be reconverted in accordance with the table II A.

Table II B corrects for the runlength violation otherwise occurring when concatenating some of the even parity input words from the table I A with some of the odd parity input words from the table I B. Table II C corrects for the runlength violation otherwise occurring when concatenating some of the odd parity input words from the table I B with some of the even parity input words from the table I A. Table II D corrects for the runlength violation

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otherwise occurring when concatenating some of the odd parity input words from the table I

B.

TABLE II A: Substitution encoding table: EE-concatenation of iso-I1 (d=1,k=4) code.

	EE-indices	original concatenation	substitution
1.	1 // 7	00011 10010	00101 10001
2.	1 // 8	00011 10100	00100 11001
3.	6 // 1	01100 00011	01001 10001
4.	8 // 1	10100 00011	10100 10001

TABLE II B: Substitution encoding table: EO-concatenation of iso-I1 (d=1,k=4) code.

	EO-indices	original concatenation	substitution
1.	1 // 6	0001110011	0010100001
2.	1 // 7	0001110101	0011011001
3.	1 // 8	0001110110	0011011010
4.	6 // 1	0110000010	0110011010
5.	8 // 1	1010000010	1010011010

TABLE II C: Substitution encoding table: OE-concatenation of iso-I1 (d=1,k=4) code.

	OE-indices	original concatenation	substitution
1.	2//1	00100 00011	00100 10001
2.	3//1	01000 00011	01000 10001
3.	3//2	01000 00101	01010 11001
4.	3//3	01000 00110	01010 11010
5.	4//7	01011 10010	01100 11001
6.	4//8	01011 10100	01101 10001
7.	6//7	10011 10010	10010 11010
8.	6//8	10011 10100	10110 10001

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TABLE II D: Substitution encoding table: OO-concatenation of iso-I1 (d=1,k=4) code.

	OO-indices	original concatenation	substitution
1.	2//1	00100 00010	00100 11010
2.	3//1	01000 00010	01000 11001
3.	3//2	01000 00100	01000 11010
4.	4//6	01011 10011	01101 00001
5.	4//7	01011 10101	01010 10001
6.	4//8	01011 10110	01100 10001
7.	6//6	10011 10011	10110 11001
8.	6//7	10011 10101	10110 11010
9.	6//8	10011 10110	10010 10001

Summarizing, the advantages of the R=4/5 iso-I1(d=1,k=4) code are:

- standard mapping (4-to-5) and substitutional mapping (8-to-10) compatible with byte-oriented error correction, and error-propagation only occurs when the substitution tables during decoding involve two successive bytes
- low k-value, thus limited intersymbol-interference (ISI), and proper clocking.
- 5 - DC-control via parity preserve principle.
- relatively simple encoding tables.

Next, a Rate $R=6/7$ iso-II($d=1, k=7$) code will be described. The finite-state runlength diagram of the code is shown in Fig.2. The states numbered 1 to 8 in the state diagram of figure 2 describe the normal ($d=1, k=7$) code. By going from the state 1 to the state 2 and back to the state 1, a sequence ...01010... is obtained, which is a representation of the $d(=1)$ constraint. That is: at minimum one 'zero' occurs between two subsequent 'ones' in the sequence, expressed in NRZ-I notation. Further, by going through the states numbered 1, 2, 3,, 7, 8 and back to the state 1, a sequence ...0100000010 ... is generated, which represents the k constraint: seven 'zeroes' at most occur between two consecutive 'ones' in the sequence. It can be seen that, upon 1T precoding this NRZ-I sequence, a runlength limited sequence is obtained having runlengths of at minimum 2 and at maximum 8 runs of consecutive like symbols (in NRZ notation), or ... + - - + ... and ... + - - - - - + ..., respectively.

It can further be seen that, apart from the traditional runlength constraints on the number of successive zeroes, there is now also a constraint on the number of successive ones, which should not exceed 2. This is realized by adding the state numbered 1'. By going through one of the states numbered 2, 3, 4 or 5, via the state 1 and the state 1', and going back to the state 2, a sequence0110.... has been obtained. Upon 1T precoding, this results in the occurrence of a run of 1.

25 The capacity of the RLL code equals $C=0.8732$. The code implementation has a rate $R=0.8571$, thus yielding a code efficiency of 98.2 %.

The standard encoding rules for the code is shown in the tables III A and III B. The table III A discloses the conversion of even parity input words into converted words and the table III B discloses the conversion of the odd parity input words.

TABLE III A: Standard encoding table for even-parity words for iso-I2 (d=1,k=7) code.

	6-bit input word	7-bit channel word
1.	000000	0000101
2.	000011	0000110
3.	000101	0001001
4.	001001	0001010
5.	010001	0001100
6.	100001	0010001
7.	000110	0010010
8.	001010	0010100
9.	010010	0011000
10.	100010	0011011
11.	001100	0100001
12.	010100	0100010
13.	100100	0100100
14.	011000	0101000
15.	101000	0101011
16.	110000	0101101
17.	001111	0110000
18.	010111	0110011
19.	011011	0110101
20.	011101	0110110
21.	011110	1000001
22.	100111	1000010
23.	101011	1000100
24.	101101	1001000
25.	101110	1001011
26.	110011	1001101
27.	110101	1010000
28.	110110	1010011
29.	111001	1010101
30.	111010	1010110
31.	111100	1011001
32.	111111	1011010

TABLE III B: Standard encoding table for odd-parity words for iso-I2 (d=1,k=7) code.

	6-bit input word	7-bit channel word
1.	000001	0000010
2.	000010	0000100
3.	000100	0001000
4.	001000	0001011
5.	010000	0001101
6.	100000	0010000
7.	000111	0010011
8.	001011	0010101
9.	010011	0010110
10.	100011	0011001
11.	001101	0011010
12.	010101	0100000
13.	100101	0100011
14.	011001	0100101
15.	101001	0100110
16.	110001	0101001
17.	001110	0101010
18.	010110	0101100
19.	100110	0110001
20.	011010	0110010
21.	101010	0110100
22.	110010	1000011
23.	011100	1000101
24.	101100	1000110
25.	110100	1001001
26.	111000	1001010
27.	011111	1001100
28.	101111	1010001
29.	110111	1010010
30.	111011	1010100
31.	111101	1011000
32.	111110	1011011

Further, the runlength violation problems which would arise upon free concatenation by the standard table, are removed by the substitution tables, shown in the table IV A to IV D, where the table IV A solves the problem when concatenating even parity input words from the table III A, the table IV B solves the problem when concatenating even parity words from the table III A with odd parity input words from the table III B, the table IV C solves the problem when concatenating odd parity input words from the table III B with even parity input words from the table III A and the table IV D solves the problem when concatenating odd parity words from the table III B.

TABLE IV A: Substitution encoding table: EE-concatenation for iso-I1 (d=1,k=7) code.

	EE indices	original concatenation	substitution
1.	10 // 21	0011011 1000001	0010010 1100101
2.	10 // 22	0011011 1000010	0010010 1100110
3.	10 // 23	0011011 1000100	0010010 1101001
4.	10 // 24	0011011 1001000	0010010 1101010
5.	10 // 25	0011011 1001011	0010010 1101100
6.	10 // 26	0011011 1001101	0010100 1100101
7.	10 // 27	0011011 1010000	0010100 1100110
8.	10 // 28	0011011 1010011	0010100 1101001
9.	10 // 29	0011011 1010101	0010100 1101010
10.	10 // 30	0011011 1010110	0010100 1101100
11.	10 // 31	0011011 1011001	0011000 1100101
12.	10 // 32	0011011 1011010	0011000 1100110
13.	15 // 21	0101011 1000001	0100010 1100101
14.	15 // 22	0101011 1000010	0100010 1100110
15.	15 // 23	0101011 1000100	0100010 1101001
16.	15 // 24	0101011 1001000	0100010 1101010
17.	15 // 25	0101011 1001011	0100010 1101100
18.	15 // 26	0101011 1001101	0100100 1100101
19.	15 // 27	0101011 1010000	0100100 1100110
20.	15 // 28	0101011 1010011	0100100 1101001
21.	15 // 29	0101011 1010101	0100100 1101010
22.	15 // 30	0101011 1010110	0100100 1101100
23.	15 // 31	0101011 1011001	0101000 1100101
24.	15 // 32	0101011 1011010	0101000 1100110
25.	17 // 1	0110000 0000101	0101000 1101001
26.	17 // 2	0110000 0000110	0101000 1101010
27.	18 // 21	0110011 1000001	0101000 1101100
28.	18 // 22	0110011 1000010	0110000 1100101
29.	18 // 23	0110011 1000100	0110000 1100110
30.	18 // 24	0110011 1001000	0110000 1101001
31.	18 // 25	0110011 1001011	0110000 1101010
32.	18 // 26	0110011 1001101	0110000 1101100
33.	18 // 27	0110011 1010000	0110110 1100101
34.	18 // 28	0110011 1010011	0110110 1100110
35.	18 // 29	0110011 1010101	0110110 1101001
36.	18 // 30	0110011 1010110	0110110 1101010
37.	18 // 31	0110011 1011001	0110110 1101100
38.	18 // 32	0110011 1011010	0100110 1100001
39.	25 // 21	1001011 1000001	1000100 1100101
40.	25 // 22	1001011 1000010	1000100 1100110
41.	25 // 23	1001011 1000100	1000100 1101001
42.	25 // 24	1001011 1001000	1000100 1101010
43.	25 // 25	1001011 1001011	1000100 1101100

44.	25 // 26	1001011 1001101	1001000 1100101
45.	25 // 27	1001011 1010000	1001000 1100110
46.	25 // 28	1001011 1010011	1001000 1101001
47.	25 // 29	1001011 1010101	1001000 1101010
48.	25 // 30	1001011 1010110	1001000 1101100
49.	25 // 31	1001011 1011001	1010000 1100101
50.	25 // 32	1001011 1011010	1010000 1100110
52.	27 // 2	1010000 0000110	1010000 1101010
53.	28 // 21	1010011 1000001	1010000 1101100
54.	28 // 22	1010011 1000010	1010110 1100101
55.	28 // 23	1010011 1000100	1010110 1100110
56.	28 // 24	1010011 1001000	1010110 1101001
57.	28 // 25	1010011 1001011	1010110 1101010
58.	28 // 26	1010011 1001101	1010110 1101100
59.	28 // 27	1010011 1010000	1011010 1100101
60.	28 // 28	1010011 1010011	1011010 1100110
61.	28 // 29	1010011 1010101	1011010 1101001
62.	28 // 30	1010011 1010110	1011010 1101010
63.	28 // 31	1010011 1011001	1011010 1101100
64.	28 // 32	1010011 1011010	1000110 1100001

TABLE IV B: Substitution encoding table: EO-concatenation for iso-I1 (d=1,k=7) code.

	EO indices	original concatenation	substitution
1.	9 // 1	0011000 0000010	0010010 1100001
2.	10 // 22	0011011 1000011	0010010 1100010
3.	10 // 23	0011011 1000101	0010010 1100100
4.	10 // 24	0011011 1000110	0010010 1101101
5.	10 // 25	0011011 1001001	0010100 1100001
6.	10 // 26	0011011 1001010	0010100 1100010
7.	10 // 27	0011011 1001100	0010100 1100100
8.	10 // 28	0011011 1010001	0010100 1101101
9.	10 // 29	0011011 1010010	0011000 1100001
10.	10 // 30	0011011 1010100	0011000 1100010
11.	10 // 31	0011011 1011000	0011000 1100100
12.	10 // 32	0011011 1011011	0011000 1101101
13.	14 // 1	0101000 0000010	0100010 1100001
14.	15 // 22	0101011 1000011	0100010 1100010
15.	15 // 23	0101011 1000101	0100010 1100100
16.	15 // 24	0101011 1000110	0100010 1101101
17.	15 // 25	0101011 1001001	0100100 1100001
18.	15 // 26	0101011 1001010	0100100 1100010
19.	15 // 27	0101011 1001100	0100100 1100100
20.	15 // 28	0101011 1010001	0100100 1101101
21.	15 // 29	0101011 1010010	0101000 1100001
22.	15 // 30	0101011 1010100	0101000 1100010
23.	15 // 31	0101011 1011000	0101000 1100100
24.	15 // 32	0101011 1011011	0101000 1101101
25.	17 // 1	0110000 0000010	0110000 1100001
26.	17 // 2	0110000 0000100	0110000 1100010
27.	18 // 22	0110011 1000011	0110000 1100100
28.	18 // 23	0110011 1000101	0110000 1101101
29.	18 // 24	0110011 1000110	0110110 1100001
30.	18 // 25	0110011 1001001	0110110 1100010
31.	18 // 26	0110011 1001010	0110110 1100100
32.	18 // 27	0110011 1001100	0110110 1101101
33.	18 // 28	0110011 1010001	0100110 1100101
34.	18 // 29	0110011 1010010	0100110 1100110
35.	18 // 30	0110011 1010100	0100110 1101001
36.	18 // 31	0110011 1011000	0100110 1101010
37.	18 // 32	0110011 1011011	0100110 1101100
38.	24 // 1	1001000 0000010	1000100 1100001
39.	25 // 22	1001011 1000011	1000100 1100010
40.	25 // 23	1001011 1000101	1000100 1100100
41.	25 // 24	1001011 1000110	1000100 1101101
42.	25 // 25	1001011 1001001	1001000 1100001

43.	25 // 26	1001011 1001010	1001000 1100010
44.	25 // 27	1001011 1001100	1001000 1100100
45.	25 // 28	1001011 1010001	1001000 1101101
46.	25 // 29	1001011 1010010	1010000 1100001
47.	25 // 30	1001011 1010100	1010000 1100010
48.	25 // 31	1001011 1011000	1010000 1100100
49.	25 // 32	1001011 1011011	1010000 1101101
50.	27 // 1	1010000 0000010	1010110 1100001
51.	27 // 2	1010000 0000100	1010110 1100010
52.	28 // 22	1010011 1000011	1010110 1100100
53.	28 // 23	1010011 1000101	1010110 1101101
54.	28 // 24	1010011 1000110	1011010 1100001
55.	28 // 25	1010011 1001001	1011010 1100010
56.	28 // 26	1010011 1001010	1011010 1100100
57.	28 // 27	1010011 1001100	1011010 1101101
58.	28 // 28	1010011 1010001	1000110 1100101
59.	28 // 29	1010011 1010010	1000110 1100110
60.	28 // 30	1010011 1010100	1000110 1101001
61.	28 // 31	1010011 1011000	1000110 1101010
62.	28 // 32	1010011 1011011	1000110 1101100

TABLE IV C: Substitution encoding table: OE-concatenation for iso-I1 (d=1,k=7) code.

	OE indices	original concatenation	substitution
1.	4 // 21	0001011 1000001	0001010 1100001
2.	4 // 22	0001011 1000010	0001010 1100010
3.	4 // 23	0001011 1000100	0001010 1100100
4.	4 // 24	0001011 1001000	0001010 1101101
5.	4 // 25	0001011 1001011	0001100 1100001
6.	4 // 26	0001011 1001101	0001100 1100010
7.	4 // 27	0001011 1010000	0001100 1100100
8.	4 // 28	0001011 1010011	0001100 1101101
9.	4 // 29	0001011 1010101	0001000 1100101
10.	4 // 30	0001011 1010110	0001000 1100110
11.	4 // 31	0001011 1011001	0001000 1101001
12.	4 // 32	0001011 1011010	0001000 1101010
13.	6 // 1	0010000 0000101	0010000 1100101
14.	6 // 2	0010000 0000110	0010000 1100110
15.	7 // 21	0010011 1000001	0010000 1101001
16.	7 // 22	0010011 1000010	0010000 1101010
17.	7 // 23	0010011 1000100	0010000 1101100
18.	7 // 24	0010011 1001000	0010110 1100101
19.	7 // 25	0010011 1001011	0010110 1100110
20.	7 // 26	0010011 1001101	0010110 1101001
21.	7 // 27	0010011 1010000	0010110 1101010
22.	7 // 28	0010011 1010011	0010110 1101100
23.	7 // 29	0010011 1010101	0011010 1100101
24.	7 // 30	0010011 1010110	0011010 1100110
25.	7 // 31	0010011 1011001	0011010 1101001
26.	7 // 32	0010011 1011010	0011010 1101010
27.	12 // 1	0100000 0000101	0101010 1100101
28.	12 // 2	0100000 0000110	0101010 1100110
29.	12 // 3	0100000 0001001	0101010 1101001
30.	12 // 4	0100000 0001010	0101010 1101010
31.	12 // 5	0100000 0001100	0101010 1101100
32.	13 // 21	0100011 1000001	0101100 1100101
33.	13 // 22	0100011 1000010	0101100 1100110
34.	13 // 23	0100011 1000100	0101100 1101001
35.	13 // 24	0100011 1001000	0101100 1101010
36.	13 // 25	0100011 1001011	0101100 1101100
37.	13 // 26	0100011 1001101	0110010 1100101
38.	13 // 27	0100011 1010000	0110010 1100110
39.	13 // 28	0100011 1010011	0110010 1101001
40.	13 // 29	0100011 1010101	0110010 1101010
41.	13 // 30	0100011 1010110	0110010 1101100
42.	13 // 31	0100011 1011001	0110100 1100101
43.	13 // 32	0100011 1011010	0110100 1100110

44.	22 // 21	1000011 1000001	1001010 1100101
45.	22 // 22	1000011 1000010	1001010 1100110
46.	22 // 23	1000011 1000100	1001010 1101001
47.	22 // 24	1000011 1001000	1001010 1101010
48.	22 // 25	1000011 1001011	1001010 1101100
49.	22 // 26	1000011 1001101	1001100 1100101
50.	22 // 27	1000011 1010000	1001100 1100110
51.	22 // 28	1000011 1010011	1001100 1101001
52.	22 // 29	1000011 1010101	1001100 1101010
53.	22 // 30	1000011 1010110	1001100 1101100
54.	22 // 31	1000011 1011001	1010010 1100101
55.	22 // 32	1000011 1011010	1010010 1100110
56.	32 // 21	1011011 1000001	1010010 1101001
57.	32 // 22	1011011 1000010	1010010 1101010
58.	32 // 23	1011011 1000100	1010010 1101100
59.	32 // 24	1011011 1001000	1010100 1100101
60.	32 // 25	1011011 1001011	1010100 1100110
61.	32 // 26	1011011 1001101	1010100 1101001
62.	32 // 27	1011011 1010000	1010100 1101010
63.	32 // 28	1011011 1010011	1010100 1101100
64.	32 // 29	1011011 1010101	1011000 1100101
65.	32 // 30	1011011 1010110	1011000 1100110
66.	32 // 31	1011011 1011001	1011000 1101001
67.	32 // 32	1011011 1011010	1011000 1101010

TABLE IV D: Substitution encoding table: OO-concatenation for iso-I1 (d=1,k=7) code.

	OO indices	original concatenation	substitution
1.	3 // 1	0001000 0000010	0001010 1100101
2.	4 // 22	0001011 1000011	0001010 1100110
3.	4 // 23	0001011 1000101	0001010 1101001
4.	4 // 24	0001011 1000110	0001010 1101010
5.	4 // 25	0001011 1001001	0001010 1101100
6.	4 // 26	0001011 1001010	0001100 1100101
7.	4 // 27	0001011 1001100	0001100 1100110
8.	4 // 28	0001011 1010001	0001100 1101001
9.	4 // 29	0001011 1010010	0001100 1101010
10.	4 // 30	0001011 1010100	0001100 1101100
11.	4 // 31	0001011 1011000	0001000 1100001
12.	4 // 32	0001011 1011011	0001000 1100010
13.	6 // 1	0010000 0000010	0011000 1101001
14.	6 // 2	0010000 0000100	0011000 1101010
15.	7 // 22	0010011 1000011	0011000 1101100
16.	7 // 23	0010011 1000101	0010000 1100001
17.	7 // 24	0010011 1000110	0010000 1100010
18.	7 // 25	0010011 1001001	0010000 1100100
19.	7 // 26	0010011 1001010	0010000 1101101
20.	7 // 27	0010011 1001100	0010110 1100001
21.	7 // 28	0010011 1010001	0010110 1100010
22.	7 // 29	0010011 1010010	0010110 1100100
23.	7 // 30	0010011 1010100	0010110 1101101
24.	7 // 31	0010011 1011000	0011010 1100001
25.	7 // 32	0010011 1011011	0011010 1100010
26.	12 // 1	0100000 0000010	0100110 1100010
27.	12 // 2	0100000 0000100	0100110 1100100
28.	12 // 3	0100000 0001000	0100110 1101101
29.	12 // 4	0100000 0001011	0101010 1100001
30.	12 // 5	0100000 0001101	0101010 1100010
31.	13 // 22	0100011 1000011	0101010 1100100
32.	13 // 23	0100011 1000101	0101010 1101101
33.	13 // 24	0100011 1000110	0101100 1100001
34.	13 // 25	0100011 1001001	0101100 1100010
35.	13 // 26	0100011 1001010	0101100 1100100
36.	13 // 27	0100011 1001100	0101100 1101101
37.	13 // 28	0100011 1010001	0110010 1100001
38.	13 // 29	0100011 1010010	0110010 1100010
39.	13 // 30	0100011 1010100	0110010 1100100
40.	13 // 31	0100011 1011000	0110010 1101101
41.	13 // 32	0100011 1011011	0110100 1100001
42.	22 // 22	1000011 1000011	1000110 1100010
43.	22 // 23	1000011 1000101	1000110 1100100

44.	22 // 24	1000011 1000110	1000110 1101101
45.	22 // 25	1000011 1001001	1001010 1100001
46.	22 // 26	1000011 1001010	1001010 1100010
47.	22 // 27	1000011 1001100	1001010 1100100
48.	22 // 28	1000011 1010001	1001010 1101101
49.	22 // 29	1000011 1010010	1001100 1100001
50.	22 // 30	1000011 1010100	1001100 1100010
51.	22 // 31	1000011 1011000	1001100 1100100
52.	22 // 32	1000011 1011011	1001100 1101101
53.	31 // 1	1011000 0000010	1010010 1100001
54.	32 // 22	1011011 1000011	1010010 1100010
55.	32 // 23	1011011 1000101	1010010 1100100
56.	32 // 24	1011011 1000110	1010010 1101101
57.	32 // 25	1011011 1001001	1010100 1100001
58.	32 // 26	1011011 1001010	1010100 1100010
59.	32 // 27	1011011 1001100	1010100 1100100
60.	32 // 28	1011011 1010001	1010100 1101101
61.	32 // 29	1011011 1010010	1011000 1100001
62.	32 // 30	1011011 1010100	1011000 1100010
63.	32 // 31	1011011 1011000	1011000 1100100
64.	32 // 32	1011011 1011011	1011000 1101101

Next, a rate $R=3/5$, iso- $I_2(d=2, k=10)$ Code is described. This code has a rate between $R=1/2$ of EFMPlus ($d=2, k=10$), see document D4 in the list of documents at the end of the description, and $R=2/3$ of the code disclosed in document D1.

- 5 The Finite-State Runlength Diagram of the code is shown in Fig.3. It can be seen that apart from the traditional runlengths $I_3, I_4, \dots, I_{(k+1)}$, now also runlengths I_2 are allowed, on condition that they are not preceded nor succeeded by another I_2 . This is outlined in the finite state runlength diagram by going from state 2 to state $k+2$, emitting a 1, after which two zeroes are emitted on passing along state $k+3$ on the way to state 3. Continuing from state 3 on, the
- 10 minimum runlength is an I_3 . The capacity of the RLL code (for $k=10$) equals $C=0.646057$. The code implementation has a rate $R=0.6$, thus yielding a code efficiency of 92.9 %.

The standard encoding rules are shown in the table V.

TABLE V: Standard encoding rules for iso-I2 (d=2, k=10) code.

	input word	channel word
1.	000	00101
2.	011	01001
3.	101	01010
4.	110	10001
5.	001	00001
6.	010	00010
7.	100	00100
8.	111	01000

- 5 Runlength violation problems could arise upon free concatenation of some of the 3-bit input words upon conversion by use of the standard table. Those combinations of 3-bit input words are given in the table VI and the runlength violations are removed by the combinations of 5-bit channel words given in this table VI.

10 TABLE VI: Substitution encoding table iso-I2 (d=2, k=10) code.

	input word	channel word
1.	000 011	00101 00000
2.	000 101	00010 10000
3.	000 110	00100 10000
4.	011 101	01001 00000
5.	011 110	01000 10000
6.	101 110	01010 00000
7.	110 101	10010 10010
8.	110 110	10001 00000
9.	000 111	00001 00000
10.	001 101	00010 00000
11.	001 110	00100 10100

It can be summarized that the advantages of the R=3/5 iso-I2(d=2,k=10) code are:

- rate between that of EFMPlus (d=2) and (d=1) codes.
- 15 - DC-control via parity preserve principle.

- relatively simple encoding tables.

A point of attention is that

- standard mapping (3-to-5) and substitutional mapping (6-to-10) are not compatible with byte-oriented error correction. In order to avoid extra error propagation, an error correction
5 code may be devised on formats using 9 bit or 12 bit symbols.

Figure 4 shows schematically an apparatus for generating one of the (d,k) sequences described above. The apparatus is identified by the encoding unit 40, which has an input 42 for receiving the sequence of input words. The encoding unit 40 converts the sequence of input words into the (d,k) sequence with the properties described above, and supplies the (d,k)
10 sequence to its output 46. The output 46 is coupled to an input 48 of an aT precoder 50, more preferably a 1T precoder, well known in the art. The 1T precoding carried out on the (d,k) sequence, results in a RLL signal of the type (d,k), which is supplied to an output 52. The output 52 is coupled to an input 54 of a writing unit 56 for writing the RLL signal on a record carrier 60, such as a magnetic record carrier eg. in the form of a tape. The writing unit 56
15 comprises at least one write head 58 for realizing this. Instead of a magnetic record carrier, the RLL signal could have been recorded on an optical record carrier, such as an optical disk 60a.

Whilst the invention has been described with reference to preferred embodiments thereof, it is to be understood that these are not limitative examples. Thus, various modifications may become apparent to those skilled in the art, without departing from the scope of the invention, as defined by the claims. As an example. The invention has been
20 explained above with reference to embodiments where binary signals have been encoded and decoded. It will be clear that the invention is equally well applicable on m-ary valued signals, where m is larger than 2.

Further, the invention lies in each and every novel feature and combination of features.

LIST OF RELATED DOCUMENTS

- (D1) USP 5,477,222 (PHN 14.448)
- 5 (D2) K.A. Schouhamer Immink, Coding Techniques for Digital Recorders, Prentice Hall, 1991.
- (D3) P. Funk, Run-Length-Limited Codes with Multiple Spacing, IEEE Transactions on Magnetics, Vol. MAG-18, 1982, pp. 772-775.
- (D4) USP 5,696,505 (PHN 14.746)

CLAIMS:

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1. Apparatus for generating a runlength limited (RLL) digital information signal, the digital information signal having a minimum runlength of d' and a maximum runlength of k' , d' and k' being integers larger than zero and where k' is larger than d' , characterized in that the apparatus is adapted to generate the runlength limited digital information signal, such that
5 a minimum runlength in the digital information signal occurs isolated from other minimum runlengths in the digital information signal.
2. Apparatus for generating a runlength limited digital information signal, the digital information signal having a minimum runlength of d' and a maximum runlength of k' , d' and
10 k' being integers larger than zero and where k' is larger than d' , characterized in that the apparatus is adapted to generate the runlength limited digital information signal, such that a minimum runlength occurring in the digital information signal follows only a directly preceding runlength larger than d' .
- 15 3. Apparatus for generating a runlength limited digital information signal, the digital information signal having a specific minimum runlength and a maximum runlength of k' , the apparatus comprising means for generating runlengths in the digital information signal of length $d'+1$ at minimum, where d' and k' are integers larger than zero and where k' is larger than $d'+1$, characterized in that the apparatus further comprises means for generating
20 runlengths of d' in the runlength limited digital information signal, such that such runlengths of d' occur isolated from other such runlengths of d' in the digital information signal.
4. Apparatus for generating a runlength limited digital information signal, the digital information signal having a specific minimum runlength and a maximum runlength of k' , the
25 apparatus comprising means for generating runlengths in the digital information signal of length $d'+1$, where d' and k' are integers larger than zero and where k' is larger than $d'+1$, characterized in that the apparatus further comprises means for generating runlengths of d' in the runlength limited digital information signal, such that such runlengths of d' occur only following a directly preceding runlength larger than d' .



5. Apparatus as claimed in anyone of the preceding claims, characterized in that it further comprises means for recording the runlength limited digital information signal on a record carrier.

5

6. Apparatus as claimed in claim 5, characterized in that the recording means are adapted to record the information signal on a magnetic record carrier.

10

7. Apparatus as claimed in claim 5, characterized in that the recording means are adapted to record the information signal on an optical record carrier.

15

8. Method of generating a runlength limited digital information signal, the digital information signal having a minimum runlength of d' and a maximum runlength of k' , d' and k' being integers larger than zero and where k' is larger than d' , characterized in that the method comprises the step of generating the runlength limited digital information signal, such that a minimum runlength in the digital information signal occurs isolated from other minimum runlengths in the digital information signal.

20

9. Method of generating a runlength limited digital information signal, the digital information signal having a minimum runlength of d' and a maximum runlength of k' , d' and k' being integers larger than zero and where k' is larger than d' , characterized in that the method comprises the step of generating the runlength limited digital information signal, such that a minimum runlength occurring in the digital information signal follows only a directly preceding runlength larger than d' .

25

10. Method of generating a runlength limited digital information signal, the digital information signal having a specific minimum runlength and a maximum runlength of k' , the method comprising the step of generating runlengths in the digital information signal of length $d'+1$ at minimum, d' and k' being integers larger than zero and where k' is larger than $d'+1$, characterized in that the method further comprises the step of generating runlengths of d' in the runlength limited digital information signal, such that such runlengths of d' occur isolated from other such runlengths of d' in the digital information signal.

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11. Method of generating a runlength limited digital information signal, the digital information signal having a specific minimum runlength and a maximum runlength of k' , the method comprising the step of generating runlengths in the digital information signal of length $d'+1$, d' and k' being integers larger than zero and where k' is larger than $d'+1$, characterized in that the method further comprises the step of generating runlengths of d' in the runlength limited digital information signal, such that such runlengths of d' occur only following a directly preceding runlength larger than d' .
12. Method as claimed in any of the claims 9, 10, 11 or 12, further comprising the step of recording the runlength limited digital information signal on a record carrier.
13. Apparatus for generating a (d,k) sequence, two logical 'ones' in said sequence being separated by a run of consecutive 'zeros' of at least d , characterized in that said runs of d consecutive 'zeros' occur isolated from each other in said sequence.
14. Method of generating a (d,k) sequence, two logical 'ones' in said sequence being separated by a run of consecutive 'zeros' of at least d , characterized in that said runs of d consecutive 'zeros' occur isolated from each other in said sequence.
15. Apparatus for generating a modified (d,k) sequence, characterized in that minimum runs of $d-1$ consecutive 'zeros' between two subsequent 'ones' are allowed and occur isolated from each other in said modified sequence.
16. Method of generating a modified (d,k) sequence, characterized in that minimum runs of $d-1$ consecutive 'zeros' between two subsequent 'ones' are allowed and occur isolated from each other in said modified sequence.



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