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LOOK-AHEAD FOR CODED SIGNAL PROCESSING CHANNELS

This invention relates to a method and means for processing, in a coded signal processing channel, sample values representative of coded binary data using a look-ahead algorithm.

The present invention is related to the channel signal processing method and means described in European Patent Application EP - 369962-A (priority date November 14 1988, Docket SA9-88-030) and European Patent Application 90850410.3 (priority date January 25 1990, Docket SA9-89-086).

The first cited application describes a five-sample look-ahead algorithm for processing sample values in a (1,7) coded partial response channel, when the pulse shapes are ideal; i.e., when the read response to the positive and negative magnetic transitions are the pulses with the sample values ...,0,2,4,2,0,... and ...,0,-2,-4,-2,0,..., respectively. It also shows how to adjust the test thresholds of the algorithm in order to accommodate variations in the pulse shape. The thresholds may be optimized empirically in response to the boundary crossings in actual test data. Alternatively, the thresholds can be expressed as a function of the sample values $...,0,\alpha_1,\beta_1,-_1,0,...$ and $...,0,-\alpha_2,-\beta_2,-_2,0,...$ in the positive and negative readback pulses.

A five-sample look-ahead algorithm was used for processing channel sample values y_0,y_1,y_2,y_3,y_4 to decode the current sample value y_0. This algorithm works well when all error modes are caused by similar noise circumstances. However, in specific applications, such as magnetic tape and optical recording, when the readback pulse is substantially reduced in amplitude during a media defect or distorted towards being too wide, the available distance is reduced for specific pairs of sequences of sample values. This increases the risk of peak shift errors, and the reliability performance of the decoder, in such

case, is predominantly determined by the lower margin of error associated with these sequences.

The second cited application describes an enhancement to the processing method just described. It involves precomputing a peak-position check including expressions using up to six-sample values y_0-y_5 ahead of the then current sample value y_0. Use of this six- (instead of five) sample look-ahead algorithm provides increased signal detection reliability and increased tolerance to readback pulse distortion by substantially reducing the exposure due to peak shift patterns. However, when these peak shift errors are removed, the primary concern shifts to patterns which are more sensitive to missing or extra bit errors, particularly in the presence of defects and nonlinearities.

A phase check is required in both of the above-cited signal processing methods in order to limit the propagation of detection errors.

There is a need for a signal processing method wherein this sensitivity to missing or extra bit errors can be minimized and wherein full advantage of a (1,7) run-length-limited code constraint can be achieved and the phase check can be eliminated.

Accordingly the present invention provides a method of processing, in a signal processing channel, digital sample values corresponding to an incoming analog signal representative of coded binary data, comprising the steps of:

. developing an eight-sample look-ahead algorithm including the following functional expressions for a baseline check:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$

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$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a then current sample value, and y_1-y_7 are sample values in successive clock cycles following y_0; and

using said algorithm during each of a series of successive clock cycles to decode one successive bit of coded binary data corresponding to said current sample value and to advance to the next clock cycle with the computed next state as the new current state.

The present invention further provides a method of processing, in a signal processing channel, digital sample values corresponding to an incoming analog signal representative of coded binary data, comprising the steps of:

precomputing from an eight-sample look-ahead algorithm the values of the following functional expressions for a baseline check:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a then current sample value, and y_1-y_7 are sample values in successive clock cycles following y_0;

from said algorithm precomputing the values of the following functional expressions for a peak-position check:

$$H_6 = y_0 + y_1 - y_2 - y_3$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4$$
$$H_8 = y_0 + y_1 - y_2 + y_4 - y_5;$$

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following completion of said precomputing steps, comparing said precomputed values against appropriate thresholds to provide respective binary decision outputs;

from said outputs in conjunction with state values corresponding to the current state, determining state values for the next state, which become the current state values for the next iteration of the clock cycle; and

during each of a series of successive clock cycles,

(a) decoding one successive bit of coded binary data corresponding to said sample value, and

(b) advancing to the next clock cycle with the computed next state as the new current state.

The invention further provides signal processing apparatus comprising means for performing the above methods.

According to the invention, an improved method and means employing an eight-sample look-ahead algorithm is disclosed for processing, in a signal processing channel, digital values corresponding to an incoming analog signal representative of coded binary data. An eight-sample look-ahead algorithm includes the following expressions for a baseline check:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

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where y_0 is a then current sample value, and y_1-y_7 are sample values in successive later clock cycles following y_0. The algorithm is used during successive clock cycles to advance from a current state to a next state and to decode one successive bit of coded binary data corresponding to said sample value at each clock cycle.

The algorithm is used (1) to precompute the values of said expressions for the baseline check and also (2) to precompute the values of the following functional expressions for a peak-position check:

$$H_6 = y_0 + y_1 - y_2 - y_3$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4$$
$$H_8 = y_0 + y_1 - y_2 + y_4 - y_5;$$

Said values are then compared against appropriate thresholds to provide respective binary decision outputs.

From these outputs in conjunction with state values corresponding to the current state, state values are determined for the next state, which become the current state values for the next iteration of the clock cycle. The algorithm is then used to decode one successive bit of coded binary data corresponding to said current sample value at each clock cycle.

In order that the invention may be fully understood a preferred embodiment thereof will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 1 is a schematic diagram of a coded digital signal processing channel;

Fig. 2A depicts written transitions of magnitude 2 between +1 and -1 levels of magnetic saturation, and Fig. 2B depicts a read response normalized by a scaling factor to correspond to said written transitions;

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Fig. 3 shows write and read waveforms for (1,7) coded data and read sample values;

Fig. 4 is a block diagram of a decoder embodying an eight-sample look-ahead feature and decision boundaries according to the invention;

Fig. 5 is a schematic diagram showing specific details of the pipelined data flow through adders and registers of a precomputation device for precomputation of the values of functional expressions of sample values for decoding y_0;

Fig. 6 is a schematic diagram of a comparator circuit with constant positive and negative threshold values;

Fig. 7 is a schematic diagram of a comparator circuit with programmable positive and negative threshold values to provide a programmable decoder that adjusts to variations in analog input signal shape; and

Fig. 8 is a schematic diagram of a comparator having thresholds at zero such that the output is determined by the sign of the input.

As illustrated in Fig. 1, a signal processing channel includes a line 10 via which an analog read signal is fed from a transducer, such as a magnetic or optical read head in a digital storage device. This read signal corresponds to a recorded (1,7) data sequence, which is a binary data sequence coded with the (1,7) RLL code during the write operation. The read signal passes through a preamplifier 11 with automatic gain control (AGC) and a low bandpass filter 12. The output of filter 12 is supplied to a phase-locked clock 13 comprising a phase-locked loop timing recovery circuit including a variable frequency oscillator (VFO). This apparatus may be identical with that used in the conventional peak-detection channel with (1,7) code.

The channel is preferably of the type referred to as extended partial response maximum likelihood (EPRML) channel which is characterized by the polynomial $(1-D)(1+D)^2$. In EPRML signaling, the signal spectrum resembles a typical magnetic recording channel transfer function, desirably obviating the need for the notch filter required in the normal PRML channel characterized by the polynomial (1-D)(1+D).

More specifically, the filter 12 and equalizer 22 operate to filter the read signal so that the response to a single magnetic transition is a pulse given by the sample values ..., 0, 2, 4, 2, 0, ... Fig. 2A depicts written transitions of magnitude 2 between +1 and -1 levels of magnetic saturation; and Fig. 2B depicts the read response that is normalized by a scaling factor to correspond thereto.

In the environment herein described, use of the (1,7) RLL code reduces crowding of write transitions on the media to 2/3 that experienced with the PRML or EPRML channel. The (1,7) code acts as a trellis code providing a built-in redundancy with its 2/3 rate. It is very tolerant to nonlinearities in a high-density, high-data-rate magnetic recording channel.

Briefly, the coded analog read signal output from filter 12 is supplied to a delay means 20. Delay means 20 may be a digital chip of the type which permits selectively adjustable delays in increments as low as a tenth of a nanosecond, depending upon the rate of the clock. Delay means 20 provides delay alignment between the analog signal and clock signal inputs to an analog-to-digital converter (ADC) 21. ADC 21 converts the analog input signal into digital sample values at successive clock times. These digital sample values, in some cases depending on the characteristic of filter 12, may be equalized by an equalizer 22. The digital sample values are then passed to a decoder 23. Positive and negative threshold constants are applied via lines 24,25, respectively, to decoder 23. Decoder 23 applies a decoding algorithm to the equalized digitized sample values to provide a coded binary data

output in line 26 and, where appropriate, a pointer flag in line 27, at successive clock times under control of clock 13.

Fig. 3 depicts the write and read waveforms and associated sequences of data and sample values in a noise-free environment as they are clocked by clock 13. With the pulse shape as shown in Figs. 2A,2B, the sample values, in accord with the decoder implementation, will range through the discrete set {-4, -2, 0, +2, +4}. Actual samples, however, will include signal anomalies and additive noise, and thus will range through various noninteger values around the integers in the discrete set.

The read clock is derived from read signal 10 using a conventional peak-detection circuit driving a variable frequency oscillator (VFO) with a phase-locked loop in the clock 13. As earlier noted, the ADC 21 under control of clock 13 converts the analog signal to digitized sample values at successive clock times; and the digitized sample values are equalized at 22.

Referring to Figure 4, decoder 40 comprises precomputation device 41 which is depicted as a block in Fig. 4 but shown in greater detail in Fig. 5.

Assume that y_i denotes the digitized sample value corresponding to the i^{th} clock cycle. Then, as illustrated in Fig. 5 hereof, the current value of y_i is illustrated as y_0, corresponding to the current clock cycle $i=0$. Decoder 40 processes these digitized equalized sample values iteratively, through the precomputation circuits in Fig. 5, receiving one new sample per clock time with a look-ahead of eight-sample values. Thus, decoder 40 receives y_{i+8} as it processes the previously received eight samples and decodes y_i into the i^{th} digit of the recorded sequences.

It should be noted that the decoding process is state dependent. The state of decoder 40 at the i^{th} clock cycle is represented by a three

digit binary number $a_i b_i c_i$, where a_i, b_i and c_i represent the binary logic levels of the write current (as illustrated in Fig. 3) for the last three bit values at the ith clock cycle. This identifies one of the six possible states, namely, 000, 100, 110, 111, 011, and 001. (The states 101 and 010 do not occur with (1,7) coded data employed in an EPRML channel). During each cycle of clock 13, decoder 40 determines one digit of the recorded (1,7) sequence and also identifies the next decoder state for processing of the next cycle.

Decoder 40 executes a novel eight-sample look-ahead algorithm using the test definitions and equations in the accompanying Table A for decoding. In this algorithm, the sample value that is currently being decoded is denoted by y_0, corresponding to the clock cycle i=0. The process is iterative and is driven by read clock 13.

Tables B and C tabulate the decoding rules for state transitions in positive phase and negative phase, respectively. As noted above, decoder 40 is state dependent; i.e., given the current state $a_0 b_0 c_0$ and sample values y_0, y_1, y_2, y_3, y_4, y_5, y_6 and y_7, the decoder determines the next state $a_1 b_1 c_1$. It also decodes this state into a data bit d_0 as a 1 or 0 (presence or absence of a magnetic transition) in the originally recorded (1,7) data sequence. The actual decision results from the outcome of the tests on the sample values as given by the equations in Tables A, B and C.

Tables B and C show how decoder 40 moves from one state to another in accordance with the combined outcome of the tests at each state. Note that the movement from one state to another is highly structured and that the form of the equations is very simple and similar at various states. The states 110, 100 and 000 (Table B) corresponding to the positive phase of the signal have mirror image symmetry with states 001, 011, and 111 respectively (Table C) corresponding to the negative phase of the signal. The mirror image symmetry is characterized by the same structure with a change in the sign for all expressions of the sample

values in the corresponding states of the two phases as seen in Tables A, B and C.

The decisions of decoder 40 are driven by the outcome of two basic checks: namely, (i) a baseline check; and (ii) a peak-position check. The outcomes of these checks are represented in the form of Boolean variables denoted by G_1 and G_2 for the baseline check; and by Q_1 and Q_2 for the peak-position check.

Variables G_1 and G_2 are logical functions of more specific checks represented by newly added Boolean variables A_1, B_1, C_1, D_1, E_1, F_1, M_1, N_1 and A_2, B_2, C_2, D_2, E_2, F_2, M_2, N_2 which use up to eight look-ahead sample values; namely, y_0, y_1, y_2, y_3, y_4, y_5, y_6 and y_7, in their functional expressions. These functional expressions represent precomputed functions of sample values for the baseline check. These functional expressions are denoted as H_1, H_2, H_3, H_4 and H_5 and are identified in the first column of Table A which sets forth the test definitions and equations for decoding.

The functional expressions H_1, H_2, H_3, H_4, H_5 for the baseline check are given by

$$H_1 = y_0 + 2y_1 - 2y_3 \quad (1)$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4 \quad (2)$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5 \quad (3)$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6 \quad (4)$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7 \quad (5)$$

Q_1 and Q_2 are logic functions of more specific checks represented by X_1, X_2, Y_1, Y_2, and also by a modified Z_1, Z_2 and by a newly added W_1 and W_2 which use up to six look-ahead sample values (namely, y_0, y_1, y_2, y_3, y_4 and y_5) in their functional expressions. These functional expressions are denoted as H_6, H_7 and H_8 and are identified in the first column of Table A as precomputed functions of sample values for the peak-position check.

The functional expressions H_6, H_7, H_8 for the peak-position check are given by

$$H_6 = y_0 + y_1 - y_2 - y_3 \quad (6)$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4 \quad (7)$$
$$H_8 = y_0 + y_1 - y_2 + y_4 - y_5 \quad (8)$$

A phase check can be used in order to limit the propagation of detection errors, but it is preferred that the phase check is eliminated and error propagation is controlled by the new baseline check with eight-sample look-ahead and the run-length constraint of the (1,7) code.

Each check is a comparison of a specific function (from the set H_1 through H_8) of the sample values against a fixed threshold. Each threshold is represented by a corresponding constant that is strongly related to the shape of the readback signal and defined by the right-hand side of the corresponding test equation. In the following test equations, the threshold constants correspond to the nominal pulse shape with sample values .., 0, 2, 4, 2, 0, .. and .., 0, -2, -4, -2, 0, .. as illustrated in Fig. 2B.

(i) Baseline Check (G_1 and G_2)

$$G_1 = A_1M_1 (B_1 + C_1 + D_1 + E_1 + N_1F_1) \quad (9)$$
$$G_2 = A_2M_2 (B_2 + C_2 + D_2 + E_2 + N_2F_2) \quad (10)$$

where

$$A_1 = 1 \quad \text{implies} \quad H_1 \leq 7 \quad (11)$$
$$M_1 = 1 \quad \text{implies} \quad H_2 \leq 9 \quad (12)$$
$$N_1 = 1 \quad \text{implies} \quad H_3 \leq 9 \quad (13)$$
$$B_1 = 1 \quad \text{implies} \quad H_1 \leq -1 \quad (14)$$
$$C_1 = 1 \quad \text{implies} \quad H_2 \leq -1 \quad (15)$$
$$D_1 = 1 \quad \text{implies} \quad H_3 \leq -1 \quad (16)$$
$$E_1 = 1 \quad \text{implies} \quad H_4 \leq -1 \quad (17)$$
$$F_1 = 1 \quad \text{implies} \quad H_5 \leq -1 \quad (18)$$

and

$$A_2 = 1 \quad \text{implies} \quad H_1 \leq 9 \tag{19}$$
$$M_2 = 1 \quad \text{implies} \quad H_2 \leq 11 \tag{20}$$
$$N_2 = 1 \quad \text{implies} \quad H_3 \leq 11 \tag{21}$$
$$B_2 = 1 \quad \text{implies} \quad H_1 \leq 1 \tag{22}$$
$$C_2 = 1 \quad \text{implies} \quad H_2 \leq 1 \tag{23}$$
$$D_2 = 1 \quad \text{implies} \quad H_3 \leq 1 \tag{24}$$
$$E_2 = 1 \quad \text{implies} \quad H_4 \leq 1 \tag{25}$$
$$F_2 = 1 \quad \text{implies} \quad H_5 \leq 1 \tag{26}$$

(ii) Peak-Position Check (Q_1 and Q_2)

$$Q_1 = X_1 + Y_1 Z_1 W_1 \tag{27}$$
$$Q_2 = X_2 + Y_2 Z_2 W_2 \tag{28}$$

where

$$X_1 = 1 \quad \text{implies} \quad H_6 \leq -2 \tag{29}$$
$$Y_1 = 1 \quad \text{implies} \quad H_6 \leq 0 \tag{30}$$
$$Z_1 = 1 \quad \text{implies} \quad H_7 \leq -5 \tag{31}$$
$$W_1 = 1 \quad \text{implies} \quad H_8 \leq -1 \tag{32}$$

and

$$X_2 = 1 \quad \text{implies} \quad H_6 \leq 0 \tag{33}$$
$$Y_2 = 1 \quad \text{implies} \quad H_6 \leq 2 \tag{34}$$
$$Z_2 = 1 \quad \text{implies} \quad H_7 \leq -3 \tag{35}$$
$$W_2 = 1 \quad \text{implies} \quad H_8 \leq 1 \tag{36}$$

Note that the baseline check is very different from those described in either of the above cited applications. In the improved baseline check, all expressions [(1) to (5)] and checks [(9) to (26)] are new, making use of additional information from an eight-sample look-ahead. In the peak-position check, however, formulae (27) and (28) for Q_1 and

Q_2, formulae (31) and (35) for Z_1 and Z_2, and formulae (32) and (36) for W_1 and W_2 are essentially similar to those in the second cited application, making use of six-sample look-ahead.

The five functions, $H_1,\ldots,H_5$ that now replace the two baseline check equations in both the above cited applications increase the available square distance by 50% as seen by the extra-bit and missing-bit errors through the baseline check. With these more powerful equations, extra bit and missing-bit errors become extremely unlikely. Furthermore, if an extra-bit or missing-bit error occurs, then the baseline check includes specific functions that return the decoder to correct phase well within the seven-digit run-length constraint of the (1,7) code. Thus, a phase check is not required and is eliminated from decoder 40.

The above tests [Equations (9) through (36)] correspond to the states 100 and 000 in the positive phase of the signal. The same tests with a sign change to all expressions [(1) through (8)] of the sample values are used for the states 011 and 111 in the negative phase of the signal. This is shown in further detail in Table A.

As earlier noted and as illustrated in Fig. 4, decoder 40 comprises the precomputation device 41 (shown in Fig. 5) for precomputing the two groups of functional expressions H_1-H_5 and H_6-H_8, for the baseline check and the peak-position check, respectively, listed in Table A using up to eight look-ahead sample values. Device 41 operates during each decoder cycle to move data one bit at a time from one register to the next with a pipelined network of registers and adders to provide the precomputed functional expressions H_1-H_8 for the baseline check and peak-position check. Each of these expressions H_1-H_8 is compared against positive and negative thresholds 42a,42b of a respective comparator logic circuit 42 (shown in greater detail in Fig. 6). The outputs from each circuit 42 are passed to intermediate logic 43 which uses the logic in section 2 of Table D to compute R_1,R_2,R_1',R_2'. These intermediate variables together

with the state values a_0, b_0, c_0 from register 45 are used by output logic block 44, applying the logic in sections 1 and 3 of Table D.

Refer now to Fig. 5 for a more detailed explanation of precomputing device 41. Device 41 comprises twenty-one registers 50-70 which hold the respective interim functions of the sample values y_0 through y_7. During each cycle, the content of each register 50-70 is moved in the direction of the arrow to the next register as appropriate functions are created through thirteen adder circuits 80-92. The outputs $H_1, H_2, \ldots, H_8$ from each of the respective eight registers 63-70 are fed to a corresponding comparator circuit 42 having constant positive and negative threshold values. As illustrated in Fig. 6, for example, the value of H_1 is compared against two fixed thresholds in the comparator circuit 42 and the two outputs correspond to those for the variables A_1, and A_1', in expression (11) and its counterpart for the negative phase. The sign change for the negative phase of H_1 is not required because $(-H_1 \leq 7)$ can be also implemented as $(H_1 \geq -7)$. There is one such comparator circuit for each of the variables A_1, M_1, N_1, B_1, C_1, D_1, E_1, F_1, A_2, M_2, N_2, B_2, C_2, D_2, E_2, and F_2 of equations (11)-(26), and for the variables X_1, X_2, Y_1, Y_2, Z_1, Z_2, W_1 and W_2, of equations (29)-(36). The outputs from the respective comparator circuits 42 are values "1" or "0" which are combined in accordance with the intermediate logic 43 (given in Section 2 of Table D) to generate the intermediate variables R_1, R_2, R_1' and R_2'. These variables, together with the state values a_0, b_0, c_0 from register 45, are used by the output logic block 44.

The output logic block 44 provides the decoded data d_0 corresponding to state $a_0b_0c_0$ in accordance with the logic of section 1 of Table D. Block 44 also creates the state value $a_1b_1c_1$ for the next state in accordance with the logic of section 3 in Table D. This state value is supplied to state register 45 to become the current state value $a_0b_0c_0$ for the next clock cycle.

Table E provides programmed values for thresholds for all the equations corresponding to the variables A, B, C, D, E, F, M, N, X, Y, Z and W.

In Table E and in the following description, a plus sign and minus sign are used to denote constants for the positive phase and the negative phase, respectively; whereas primed and nonprimed variable names are used to indicate variables for positive and negative phase, respectively. For example, the test corresponding to Boolean variable A_1 will use the constant KA_1^+ for the state 100 in the positive phase and the test corresponding to Boolean variable A_1' will use the constant KA_1^- for the state 011 in the negative phase.

To implement programmability, each comparator circuit 42 of Fig. 6 is replaced by a corresponding comparator circuit 46 illustrated in Fig. 7 as corresponding to the Boolean variable A_1. This circuit 46 is supplied with two separate values for the constant operand, namely KA_1^+ and KA_1^-, and the output will be Boolean variables A_1 and A_1' corresponding to state 100 and state 011, respectively, as shown in Fig. 7. The sign change for negative phase is not required because $(-H_1 \leq KA_1^-)$ can be also implemented as $(H_1 \geq -KA_1^-)$. The comparator circuit 46 for each of the other twenty-five Boolean variables will be similarly modified to receive two separate values for the constant operand, and the output will be two Boolean variables (the original and the primed) which, in each case, correspond to the states in the positive phase $(c_0=0)$ and negative phase $(c_0=1)$, respectively.

When anomalies in the signal shape cannot be compensated for by a filter and an equalizer, such as 12 and 22, programmable decoder 40 provides an easy means to compensate for misequalization by adjusting the thresholds in the two phases of the decoder. This flexibility permits operating decoder 40 at near-optimum performance even in the absence of ideal shape of the readback signal. In disk recording systems, this is especially important because the programmability of the

decoder can be used to change threshold constants at different tracks or bands of tracks and obtain near-optimum performance at all tracks.

In tape recording systems, media defects on the magnetic recording tape cause signal dropouts. The severity and size of such dropouts depend on the age and usage of the tape and also on the position of the recording track relative to the edge of the tape. The programmability of the decoder, especially the thresholds for the new baseline checks, is very useful in accommodating these large variations in media quality.

The programmability of decoder 40 also enables it to continuously adaptively adjust digital parameters in the decoder. More specifically, the estimated sample values at the output of decoder 40 can be monitored in comparison with the received sample values. When averaged over a preselected number of like sample values, the signal shape can be characterized in terms of the parameters α_1, β_1, $-_1$, $-\alpha_2$, $-\beta_2$, $-_{-2}$. This information can be used to obtain the corresponding threshold constants (Table E) and adaptively adjust the decoder for variations in the signal shape.

If desired, threshold values for decoder 40 can be easily verified through an extensive amount of testing, and then be adjusted in accordance with the empirical results to accommodate specific anomalies in the signal.

In particular, the first set of preselected thresholds corresponding to the baseline checks A_1, M_1, N_1, B_1, C_1, D_1, E_1, F_1, A_2, M_2, N_2, B_2, C_2, D_2, E_2, F_2, and their counterpart checks in the negative phase, is used for controlling the missing bit and extra bit errors caused by media defects-related anomalies in the incoming analog signal; and the second set of preselected thresholds corresponding to the peak-position checks X_1, X_2, Y_1, Y_2, Z_1, Z_2, W_1, W_2 and their counterparts in the negative phase, is used for controlling peak shift errors caused by nonlinearities-related anomalies in said signal.

The baseline check herein disclosed is very powerful in terms of the available distance at various checks. In fact, the available distance for the baseline check is at least 2.25 times the minimum distance for the overall detection process. Among these, the variables A_1, A_2, B_1, B_2 (and their counterparts in negative phase, as defined in Table A) have the smallest distance which may be called the minimum distance for a baseline check, affecting the missing-bit and extra-bit errors.

Since the remaining variables in the baseline check have larger distance, the complexity and amount of hardware can desirably be reduced without reducing the minimum distance of the baseline check. The thresholds corresponding to variables C_1, D_1, E_1, F_1, C_2, D_2, E_2, F_2 (and their counterparts in the negative phase) are near zero, as shown in Table A. In order to achieve the simplification, these thresholds are fixed and intentionally made not programmable so that they can be implemented without requiring a respective comparator circuit 42. With the thresholds fixed around zero, the output is determined by sensing the sign bit of the input with a sensing circuit 95 as shown in Fig. 8. This desirably will eliminate eight pairs of comparator circuits 42 or 46 and eight pairs of storage units for the threshold constants, and substitute only the four pairs 95a,95b of sign-bit sensing circuits 95 of Fig. 8 - one such pair corresponding to each variable C, D, E and F.

In addition, the thresholds corresponding to the variables M_1, N_1, M_2, N_2 are made same as the programmable threshold for the variable A_2, and the thresholds corresponding to the variables M_1', N_1', M_2', N_2' are made the same as the programmable threshold for the variable A_2'. This eliminates the need for eight storage units for storing threshold constants and also eliminates the need for four comparators because the variables M_1, N_1, M_1' and N_1' will now be identical with the variables M_2, N_2, M_2' and N_2', respectively. These changes are summarized in Table F.

While the invention has been shown and described with respect to preferred embodiments thereof, it will be understood by those skilled in

the art that changes in form and detail may be made in these embodiments without departing from the scope and teaching of the invention. Accordingly, the method and means herein disclosed are to be considered merely as illustrative, and the invention is to be limited only as specified in the claims.

Table A. Test Definitions and Equations for Decoding

Precomputed Functions of Sample Values	Positive Phase		Negative Phase	
	Decision Boundary at State 1 0 0	Decision Boundary at State 0 0 0	Decision Boundary at State 0 1 1	Decision Boundary at State 1 1 1
Baseline Check	$G_1 = A_1M_1(B_1 + C_1 + D_1 + E_1 + N_1F_1)$	$G_2 = A_2M_2(B_2 + C_2 + D_2 + E_2 + N_2F_2)$	$G_1' = A_1'M_1'(B_1' + C_1' + D_1' + E_1' + N_1'F_1')$	$G_2' = A_2'M_2'(B_2' + C_2' + D_2' + E_2' + N_2'F_2')$
$H_1 = y_0 + 2y_1 - 2y_3$	$A_1 = (H_1 \leq 7)$	$A_2 = (H_1 \leq 9)$	$A_1' = (-H_1 \leq 7)$	$A_2' = (-H_1 \leq 9)$
	$B_1 = (H_1 \leq -1)$	$B_2 = (H_1 \leq 1)$	$B_1' = (-H_1 \leq -1)$	$B_2' = (-H_1 \leq 1)$
$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$	$M_1 = (H_2 \leq 9)$	$M_2 = (H_2 \leq 11)$	$M_1' = (-H_2 \leq 9)$	$M_2' = (-H_2 \leq 11)$
	$C_1 = (H_2 \leq -1)$	$C_2 = (H_2 \leq 1)$	$C_1' = (-H_2 \leq -1)$	$C_2' = (-H_2 \leq 1)$
$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$	$N_1 = (H_3 \leq 9)$	$N_2 = (H_3 \leq 11)$	$N_1' = (-H_3 \leq 9)$	$N_2' = (-H_3 \leq 11)$
	$D_1 = (H_3 \leq -1)$	$D_2 = (H_3 \leq 1)$	$D_1' = (-H_3 \leq -1)$	$D_2' = (-H_3 \leq 1)$
$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$	$E_1 = (H_4 \leq -1)$	$E_2 = (H_4 \leq 1)$	$E_1' = (-H_4 \leq -1)$	$E_2' = (-H_4 \leq 1)$
$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$	$F_1 = (H_5 \leq -1)$	$F_2 = (H_5 \leq 1)$	$F_1' = (-H_5 \leq -1)$	$F_2' = (-H_5 \leq 1)$
Peak Position Check	$Q_1 = X_1 + Y_1Z_1W_1$	$Q_2 = X_2 + Y_2Z_2W_2$	$Q_1' = X_1' + Y_1'Z_1'W_1'$	$Q_2' = X_2' + Y_2'Z_2'W_2'$
$H_6 = y_0 + y_1 - y_2 - y_3$	$X_1 = (H_6 \leq -2)$	$X_2 = (H_6 \leq 0)$	$X_1' = (-H_6 \leq -2)$	$X_2' = (-H_6 \leq 0)$
	$Y_1 = (H_6 \leq 0)$	$Y_2 = (H_6 \leq 2)$	$Y_1' = (-H_6 \leq 0)$	$Y_2' = (-H_6 \leq 2)$
$H_7 = y_0 + y_1 - y_2 + 2y_4$	$Z_1 = (H_7 \leq -5)$	$Z_2 = (H_7 \leq -3)$	$Z_1' = (-H_7 \leq -5)$	$Z_2' = (-H_7 \leq -3)$
$H_8 = y_0 + y_1 - y_2 + y_4 - y_5$	$W_1 = (H_8 \leq -1)$	$W_2 = (H_8 \leq 1)$	$W_1' = (-H_8 \leq -1)$	$W_2' = (-H_8 \leq 1)$

TABLE A

Table B. Decoding Rules for State Transitions in Positive Phase

Current State $a_0\ b_0\ c_0$	$\tilde{y}_{-1}$	Results of Tests on Sample Values $y_0, y_1, y_2, y_3, y_4, y_5, y_6, y_7$	Decoded Data	Next State $a_1\ b_1\ c_1$	$\tilde{y}_0$
1 1 0	-2 or 0	None	1	1 0 0	-4
1 0 0	-4	$(G_1 + Q_1) = 1$	0	0 0 0	-2
		Otherwise	0	0 0 1	0
0 0 0	0 or -2	$(G_2 + Q_2) = 1$	0	0 0 0	0
		Otherwise	0	0 0 1	2

TABLE B

Table C. Decoding Rules for State Transitions in Negative Phase

Current State $a_0\ b_0\ c_0$	$\tilde{y}_{-1}$	Results of Tests on Sample Values $y_0, y_1, y_2, y_3, y_4, y_5, y_6, y_7$	Decoded Data	Next State $a_1\ b_1\ c_1$	$\tilde{y}_0$
0 0 1	2 or 0	None	1	0 1 1	4
0 1 1	4	$(G_1' + Q_1') = 1$	0	1 1 1	2
		Otherwise	0	1 1 0	0
1 1 1	0 or 2	$(G'_2 + Q'_2) = 1$	0	1 1 1	0
		Otherwise	0	1 1 0	-2

TABLE C

Table D. Intermediate Logic and Output Logic
1. Decoded Data. $d_0 = b_0\bar{c}_0 + \bar{b}_0 c_0$
2. Intermediate Logic. $R_1 = G_1 + Q_1 = A_1M_1(B_1 + C_1 + D_1 + E_1 + N_1F_1) + X_1 + Y_1Z_1W_1$ $R_2 = G_2 + Q_2 = A_2M_2(B_2 + C_2 + D_2 + E_2 + N_2F_2) + X_2 + Y_2Z_2W_2$ $R_1' = G_1' + Q_1' = A_1'M_1'(B_1' + C_1' + D_1' + E_1' + N_1'F_1') + X_1' + Y_1'Z_1'W_1'$ $R_2' = G_2' + Q_2' = A_2'M_2'(B_2' + C_2' + D_2' + E_2' + N_2'F_2') + X_2' + Y_2'Z_2'W_2'$
3. Next State. $a_1 = b_0$ $b_1 = c_0$ $c_1 = \bar{b}_0 c_0 + \overline{R_1} a_0\bar{b}_0 + \overline{R_2}\bar{a}_0\bar{c}_0 + R_1'\bar{a}_0 b_0 + R_2' a_0 c_0$

TABLE D

Table E. Programmed Values for Test Thresholds [Nominal Values]				
Test	Positive Phase		Negative Phase	
	State 1 0 0	State 0 0 0	State 0 1 1	State 1 1 1
Baseline Check				
A	$KA_1^+ = KA_2^+ - \gamma_2$ [7]	$KA_2^+ = \beta_1 + \beta_2 + \alpha_1/2$ [9]	$KA_1^- = KA_2^- - \gamma_1$ [7]	$KA_2^- = \beta_2 + \beta_1 + \alpha_2/2$ [9]
B	$KB_1^+ = KB_2^+ - \gamma_2$ [−1]	$KB_2^+ = \alpha_1/2$ [1]	$KB_1^- = KB_2^- - \gamma_1$ [−1]	$KB_2^- = \alpha_2/2$ [1]
M	$KM_1^+ = KM_2^+ - \gamma_2$ [9]	$KM_2^+ = KA_2^+ + (\gamma_1 + \alpha_2)/2$ [11]	$KM_1^- = KM_2^- - \gamma_1$ [9]	$KM_2^- = KA_2^- + (\gamma_2 + \alpha_1)/2$ [11]
C	$KC_1^+ = KC_2^+ - \gamma_2$ [−1]	$KC_2^+ = \gamma_1/2$ [1]	$KC_1^- = KC_2^- - \gamma_1$ [−1]	$KC_2^- = \gamma_2/2$ [1]
N	$KN_1^+ = KM_1^+$ [9]	$KN_2^+ = KM_2^+$ [11]	$KN_1^- = KM_1^-$ [9]	$KN_2^- = KM_2^-$ [11]
D	$KD_1^+ = KC_1^+$ [−1]	$KD_2^+ = KC_2^+$ [1]	$KD_1^- = KC_1^-$ [−1]	$KD_2^- = KC_2^-$ [1]
E	$KE_1^+ = KC_1^+$ [−1]	$KE_2^+ = KC_2^+$ [1]	$KE_1^- = KC_1^-$ [−1]	$KE_2^- = KC_2^-$ [1]
F	$KF_1^+ = KC_1^+$ [−1]	$KF_2^+ = KC_2^+$ [1]	$KF_1^- = KC_1^-$ [−1]	$KF_2^- = KC_2^-$ [1]
Peak Position Check				
X	$KX_1^+ = KX_2^+ - \gamma_2$ [−2]	$KX_2^+ = \alpha_1 - \gamma_1$ [0]	$KX_1^- = KX_2^- - \gamma_1$ [−2]	$KX_2^- = \alpha_2 - \gamma_2$ [0]
Y	$KY_1^+ = KY_2^+ - \gamma_2$ [0]	$KY_2^+ = \alpha_2 + \alpha_1 - \gamma_1$ [2]	$KY_1^- = KY_2^- - \gamma_1$ [0]	$KY_2^- = \alpha_1 + \alpha_2 - \gamma_2$ [2]
Z	$KZ_1^+ = KZ_2^+ - \gamma_2$ [−5]	$KZ_2^+ = \alpha_1 - \beta_2 - \gamma_1/2$ [−3]	$KZ_1^- = KZ_2^- - \gamma_1$ [−5]	$KZ_2^- = \alpha_2 - \beta_1 - \gamma_2/2$ [−3]
W	$KW_1^+ = KW_2^+ - \gamma_2$ [−1]	$KW_2^+ = \alpha_1 + (\gamma_2 - \gamma_1 - \alpha_2)/2$ [1]	$KW_1^- = KW_2^- - \gamma_1$ [−1]	$KW_2^- = \alpha_2 + (\gamma_1 - \gamma_2 - \alpha_1)/2$ [1]

Note: The positive and negative readback pulses are (... , 0, α_1, β_1, γ_1, 0 ...) and (... , 0, $-\alpha_2$, $-\beta_2$, $-\gamma_2$, 0, ...) respectively. The nominal values are $\alpha_1 = \alpha_2 = 2$, $\beta_1 = \beta_2 = 4$, $\gamma_1 = \gamma_2 = 2$.

TABLE E

Table F. Modified Equations for Decoding

Precomputed Functions of Sample Values	Positive Phase		Negative Phase	
	Decision Boundary at State 1 0 0	Decision Boundary at State 0 0 0	Decision Boundary at State 0 1 1	Decision Boundary at State 1 1 1
Baseline Check				
$H_1 = y_0 + 2y_1 - 2y_3$	$A_1 = (H_1 \leq KA_1^+)$	$A_2 = (H_1 \leq KA_2^+)$	$A_1' = (-H_1 \leq KA_1^-)$	$A_2' = (-H_1 \leq KA_2^-)$
	$B_1 = (H_1 \leq KB_1^+)$	$B_2 = (H_1 \leq KB_2^+)$	$B_1' = (-H_1 \leq KB_1^-)$	$B_2' = (-H_1 \leq KB_2^-)$
$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$	$M_1 = M_2$	$M_2 = (H_2 \leq KA_2^+)$	$M_1' = M_2'$	$M_2' = (-H_2 \leq KA_2^-)$
	$C_1 = C_2$	$C_2 = (H_2 < 0)$	$C_1' = C_2'$	$C_2' = (-H_2 \leq 0)$
$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$	$N_1 = N_2$	$N_2 = (H_3 \leq KA_2^+)$	$N_1' = N_2'$	$N_2' = (-H_3 \leq KA_2^-)$
	$D_1 = D_2$	$D_2 = (H_3 < 0)$	$D_1' = D_2'$	$D_2' = (-H_3 \leq 0)$
$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$	$E_1 = E_2$	$E_2 = (H_4 < 0)$	$E_1' = E_2'$	$E_2' = (-H_4 \leq 0)$
$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$	$F_1 = F_2$	$F_2 = (H_5 < 0)$	$F_1' = F_2'$	$F_2' = (-H_5 \leq 0)$
Peak Position Check				
$H_6 = y_0 + y_1 - y_2 - y_3$	$X_1 = (H_6 \leq KX_1^+)$	$X_2 = (H_6 \leq KX_2^+)$	$X_1' = (-H_6 \leq KX_1^-)$	$X_2' = (-H_6 \leq KX_2^-)$
	$Y_1 = (H_6 \leq KY_1^+)$	$Y_2 = (H_6 \leq KY_2^+)$	$Y_1' = (-H_6 \leq KY_1^-)$	$Y_2' = (-H_6 \leq KY_2^-)$
$H_7 = y_0 + y_1 - y_2 + 2y_4$	$Z_1 = (H_7 \leq KZ_1^+)$	$Z_2 = (H_7 \leq KZ_2^+)$	$Z_1' = (-H_7 \leq KZ_1^-)$	$Z_2' = (-H_7 \leq KZ_2^-)$
$H_8 = y_0 + y_1 - y_2 + y_4 - y_5$	$W_1 = (H_8 \leq KW_1^+)$	$W_2 = (H_8 \leq KW_2^+)$	$W_1' = (-H_8 \leq KW_1^-)$	$W_2' = (-H_8 \leq KW_2^-)$

TABLE F

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Claims

1. A method of processing, in a signal processing channel, digital sample values corresponding to an incoming analog signal representative of coded binary data, comprising the steps of:

developing an eight-sample look-ahead algorithm including the following functional expressions for a baseline check:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a then current sample value, and y_1-y_7 are sample values in successive clock cycles following y_0; and

using said algorithm during each of a series of successive clock cycles to decode one successive bit of coded binary data corresponding to said current sample value and to advance to the next clock cycle with the computed next state as the new current state.

2. A method as claimed in claim 1, including, during said using step, the step of precomputing the values of said functional expressions for the baseline check.

3. A method as claimed in claim 1, including, during said using step, the step of precomputing the values of the following functional expressions for a peak-position check:

$$H_6 = y_0 + y_1 - y_2 - y_3$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4$$
$$H_8 = y_0 + y_1 - y_2 + y_4 - y_5.$$

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4. A method of processing, in a signal processing channel, digital sample values corresponding to an incoming analog signal representative of coded binary data, comprising the steps of:

precomputing from an eight-sample look-ahead algorithm the values of the following functional expressions for a baseline check:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a then current sample value, and y_1-y_7 are sample values in successive clock cycles following y_0;

from said algorithm precomputing the values of the following functional expressions for a peak-position check:

$$H_6 = y_0 + y_1 - y_2 - y_3$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4$$
$$H_8 = y_0 + y_1 - y_2 + y_4 - y_5;$$

following completion of said precomputing steps, comparing said precomputed values against appropriate thresholds to provide respective binary decision outputs;

from said outputs in conjunction with state values corresponding to the current state, determining state values for the next state, which become the current state values for the next iteration of the clock cycle; and

during each of a series of successive clock cycles,

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(a) decoding one successive bit of coded binary data corresponding to said sample value, and

(b) advancing to the next clock cycle with the computed next state as the new current state.

5. A method as claimed in claim 4, wherein the state values for the next state are determined without requiring a phase check.

6. A method as claimed in claim 4 or claim 5, including the steps of:

defining each clock cycle by an electronic clock signal that is phase locked to said analog signal; and

converting the incoming analog signal to said digital sample values at a rate of one sample value per clock cycle.

7. A method as claimed in any of claims 4 to 6 including the step of:

generating a programmed value for each threshold.

8. A method as claimed in any of claims 4 to 7, including the step of:

computing each threshold from digitized parameters corresponding to the analog signal shape.

9. A method as claimed in any of claims 4 to 6, including the steps of:

fixing the values of at least some of the thresholds; and

generating programmed values for the remaining thresholds.

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10. A method as claimed in any of claims 4 to 9 wherein, during the comparing step, at least some of the values are compared against thresholds which are fixed near zero by examining the algebraic signs of such values.

11. A method as claimed in any of claims 4 to 10, including the step of

employing different thresholds for positive and negative phases of the analog signal shape as necessary to accommodate asymmetry of the signal shape.

12. A method as claimed in claim 4, including the steps of:

generating a programmed value for each threshold; and

programmably modifying values for the respective thresholds for different tracks on a disk of a disk file to optimize performance for all tracks.

13. A method as claimed in claim 4, including the steps of:

generating a programmed value for each threshold; and

programmably modifying values for the respective thresholds for accommodating signal dropouts caused by media defects on a magnetic recording tape in a tape recording system to optimize performance for all tracks.

14. A method as claimed in any preceding claim, wherein the binary data is in the form of a run-length-limited (1,7) code.

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15. Signal processing apparatus comprising:

means for generating successive clock cycles defined by an electronic clock signal that is phase locked to an incoming analog signal representative of coded binary data;

an analog-to-digital converter for converting said incoming analog signal into digital sample values; and

decoder means for processing said digital sample values to decode one successive bit of coded binary data at each successive clock cycle using an eight-sample look-ahead decoding algorithm that includes

(a) for a baseline check, the following functional expressions:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a then current sample value, and y_1-y_7 are sample values in successive clock cycles following y_0; and

(b) for a peak-position check, the following functional expressions:

$$H_6 = y_0 + y_1 - y_2 - y_3$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4$$
$$H_8 = y_0 + y_1 - y_2 + y_4 - y_5.$$

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16. Signal processing apparatus for processing digital sample values corresponding to an incoming analog signal representative of coded binary data, said channel comprising:

means for precomputing, from an eight-sample look-ahead algorithm, the values of the following functional expressions for a baseline check:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a then current sample value, and y_1-y_7 are sample values in successive clock cycles following y_0;

means for precomputing from said algorithm the values of the following functional expressions for a peak-position check:

$$H_6 = y_0 + y_1 - y_2 - y_3$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4$$
$$H_8 = y_0 + y_1 - y_2 + y_4 - y_5;$$

means for comparing said precomputed values against appropriate thresholds to provide respective binary decision outputs;

means responsive to said outputs and to state values corresponding to the current state for determining state values for the next state, which become the current state values for the next iteration of the clock cycle; and

means operative during each of a series of successive clock cycles to decode one successive bit of coded binary data corresponding

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to said current sample value and advance to the next clock cycle with the computed next state as the new current state.

17. Apparatus as claimed in claim 16, wherein said comparing means compares at least some of the values against thresholds which are fixed near zero and the comparison is made by examining the algebraic signs of such values.



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ABSTRACT

LOOK-AHEAD FOR CODED SIGNAL PROCESSING CHANNELS

A signal processing channel and method are described for processing digital sample values corresponding to an incoming analog signal representative of coded binary data. An eight-sample look-ahead algorithm is used to precompute the values of functional expressions for a baseline check and for a peak-position check. These precomputed values are compared against appropriate thresholds to provide respective binary decision outputs which, with state values corresponding to the current state, are used to determine state values for the next state, which become the current state values for the next iteration of the clock cycle. During each of a series of successive clock cycles, one successive bit of coded binary data corresponding to said current sample value is decoded, and at the next clock cycle, the computed next state becomes the new current state.

Sensitivity to missing or extra-bit errors is minimized and full advantage of a (1,7) run-length-limited code constraint is achieved. A phase check is not necessary.

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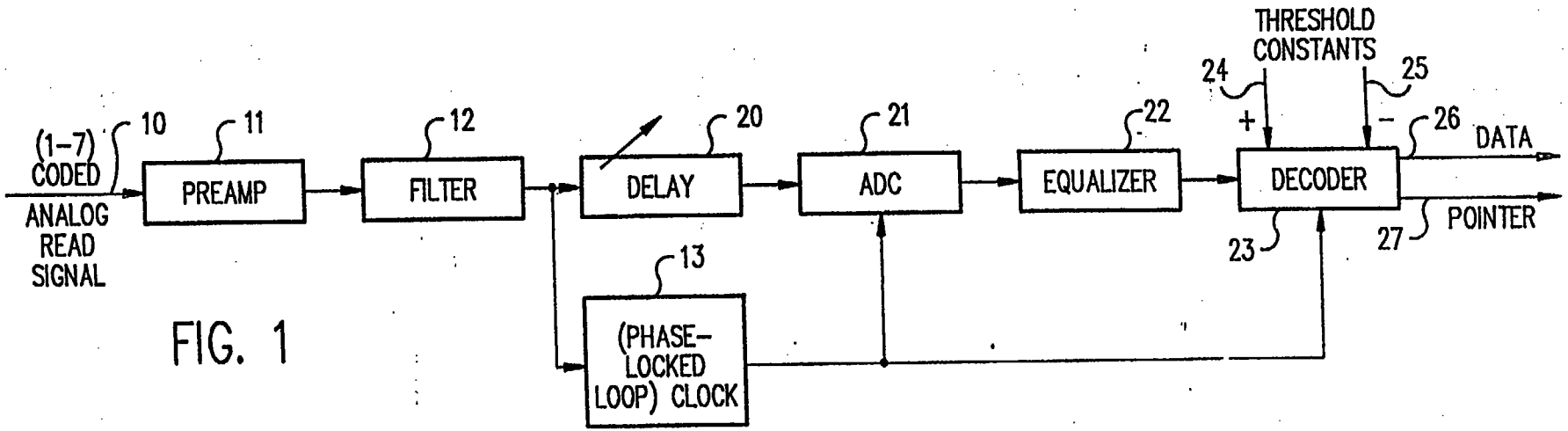


FIG. 1

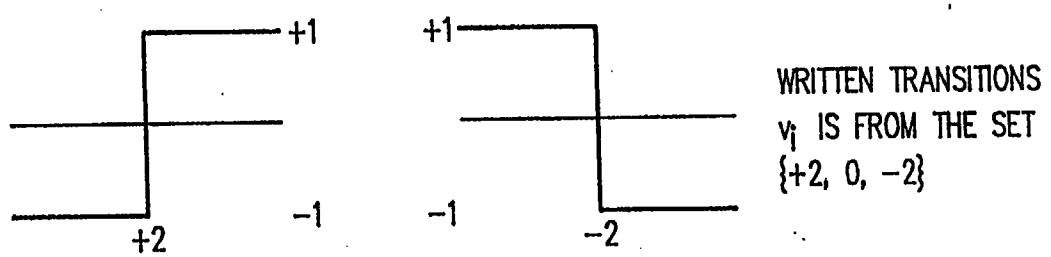


FIG. 2A

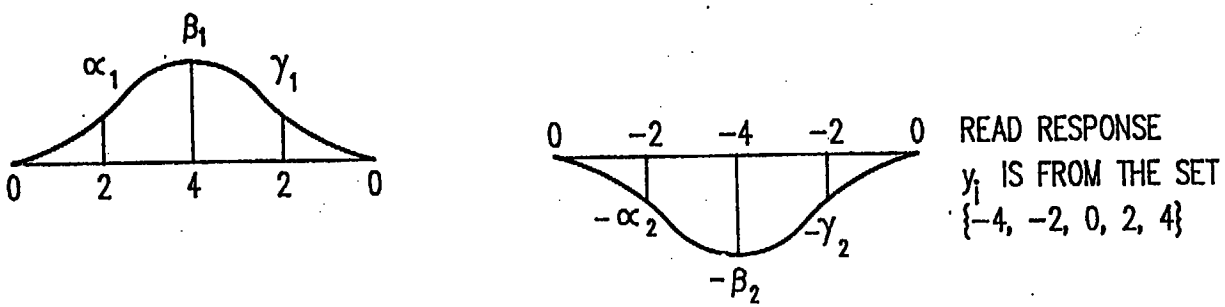


FIG. 2B

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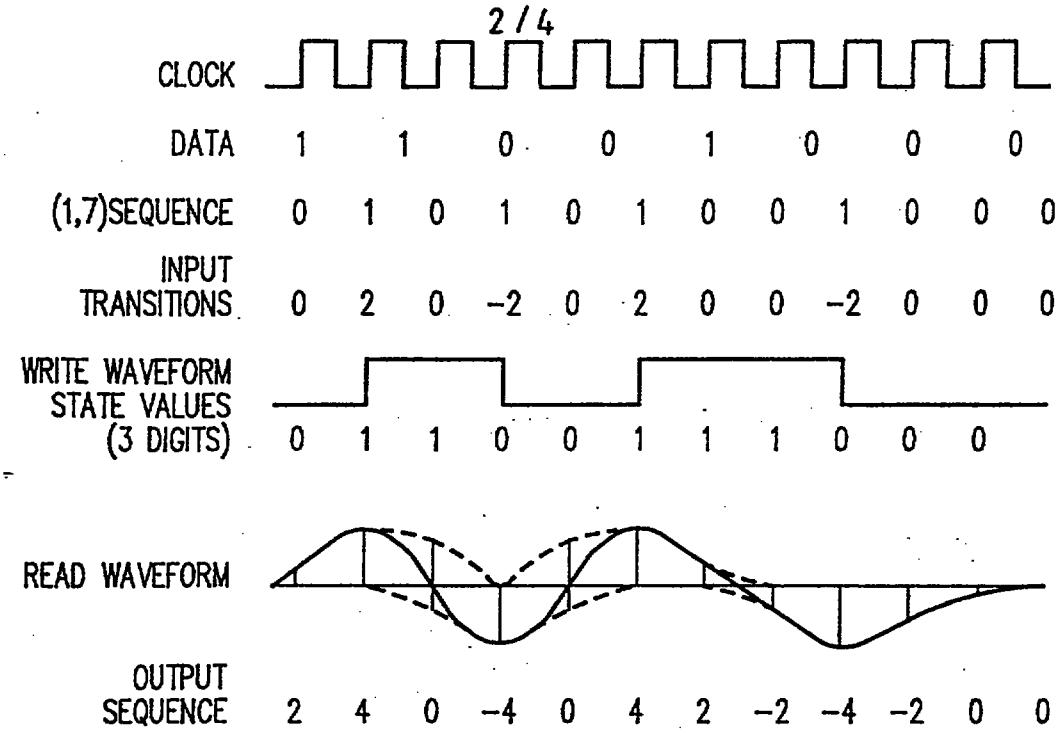


FIG. 3

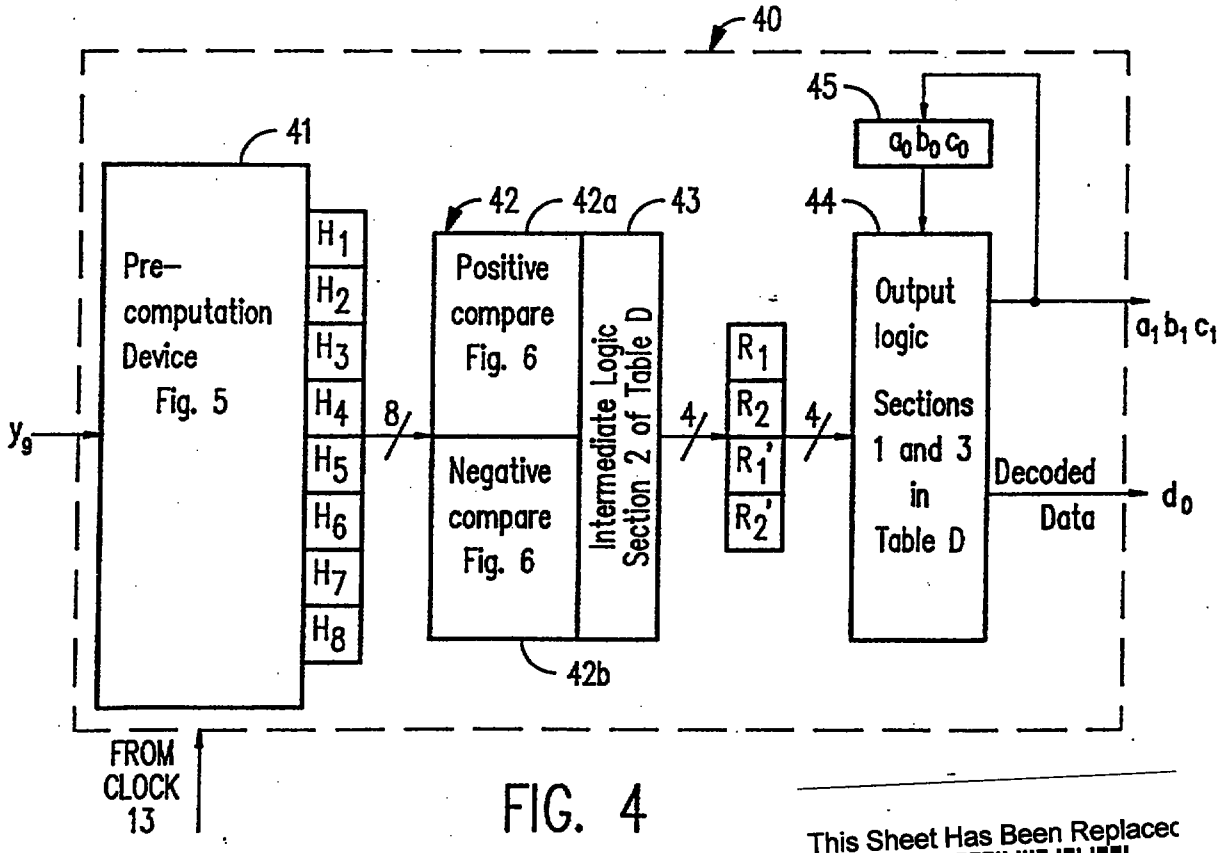


FIG. 4

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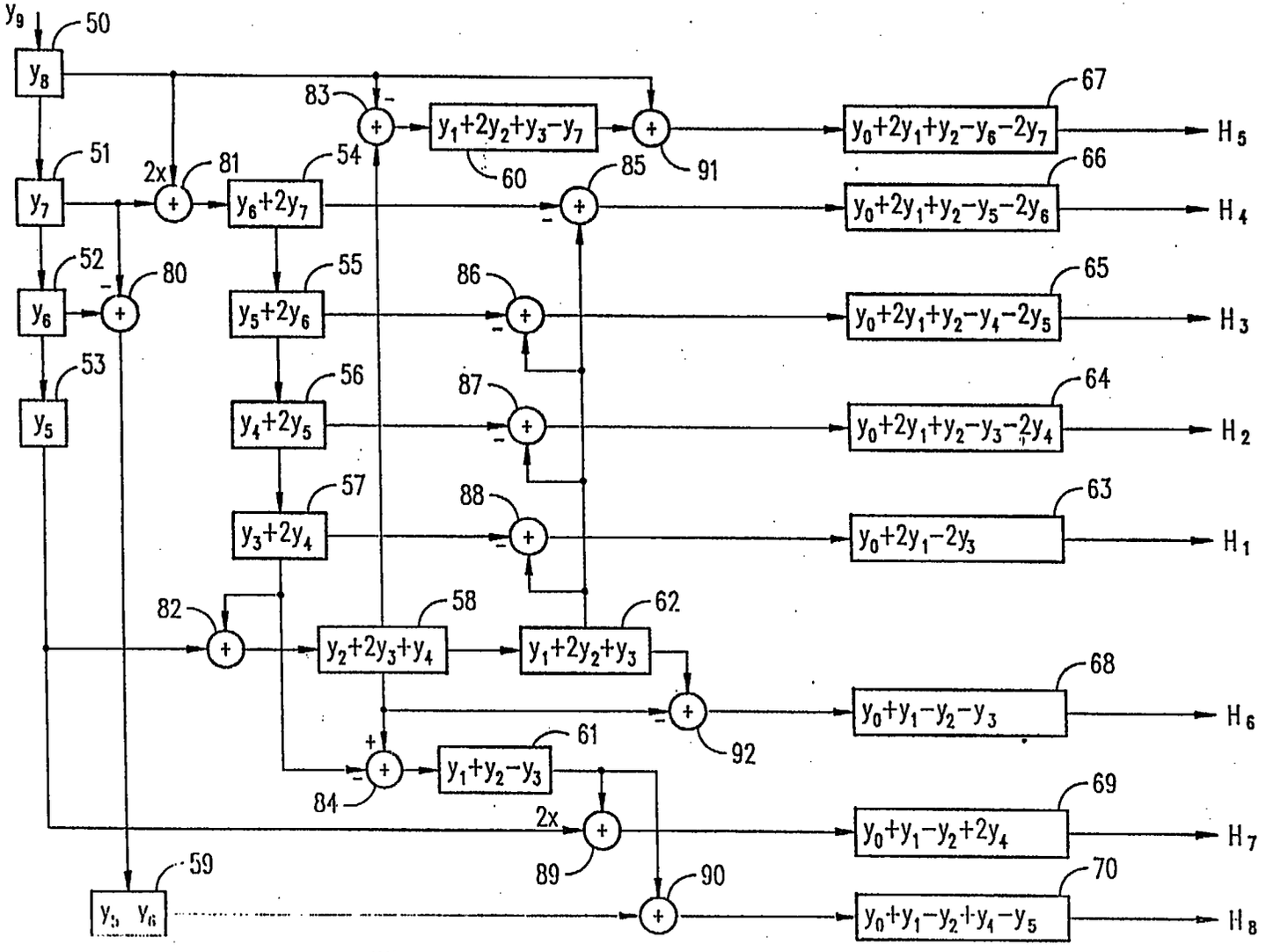


FIG. 5

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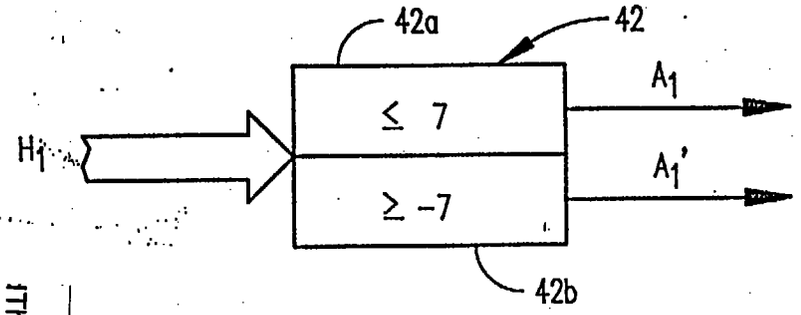


FIG. 6

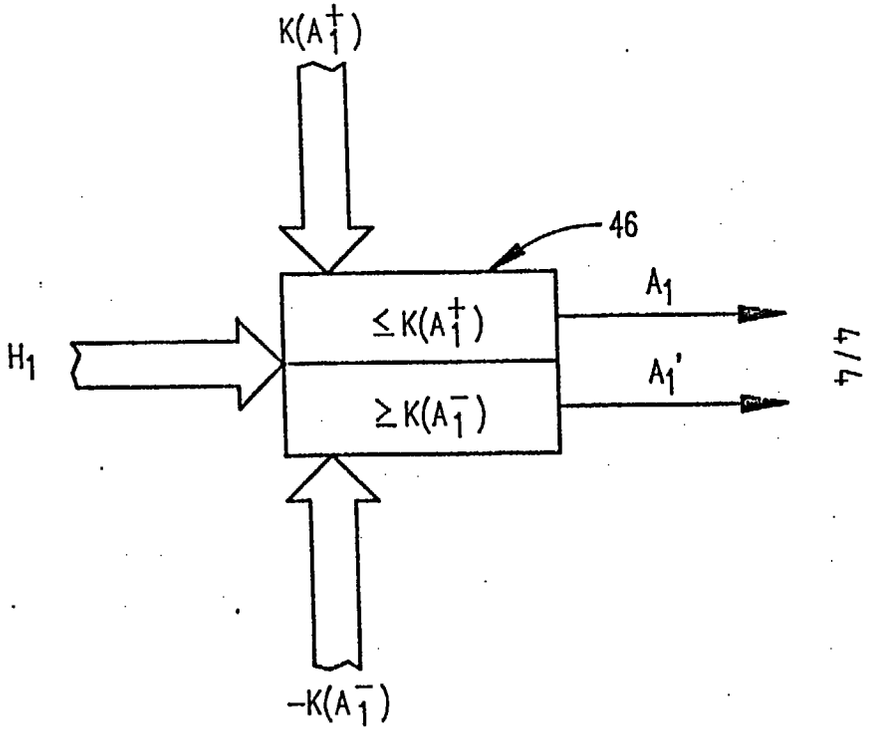


FIG. 7

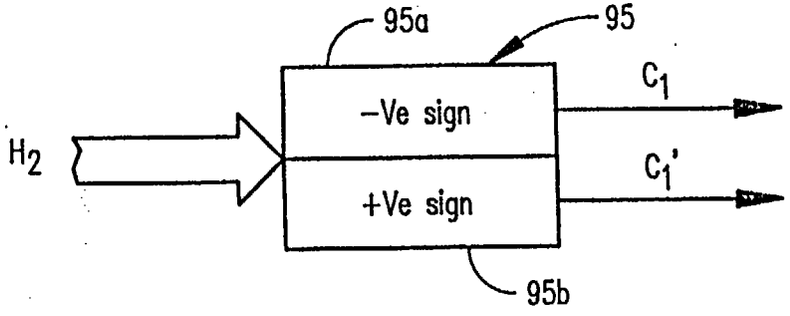


FIG. 8

T800254-P #05

LOOK-AHEAD FOR CODED SIGNAL PROCESSING CHANNELS

ABSTRACT

A signal processing channel and method are described for processing digital sample values corresponding to an incoming analog signal representative of coded binary data. An eight-sample look-ahead algorithm is used to precompute the values of functional expressions for a baseline check and for a peak-position check. These precomputed values are compared against appropriate thresholds to provide respective binary decision outputs which, with state values corresponding to the current state, are used to determine state values for the next state, which become the current state values for the next iteration of the clock (13) cycle. During each of a series of successive clock (13) cycles, one successive bit of coded binary data corresponding to said current sample value is decoded (23), and at the next clock (13) cycle, the computed next state becomes the new current state.

Sensitivity to missing or extra-bit errors is minimized and full advantage of a (1,7) run-length-limited code constraint is achieved. A phase check is not necessary.

FIG. 1

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☐ Claim(s) : paged ..... to paged .....
☑ Drawing(s) : paged 1/4 to paged 4/4
☑ Abstract : paged 32 to paged 32

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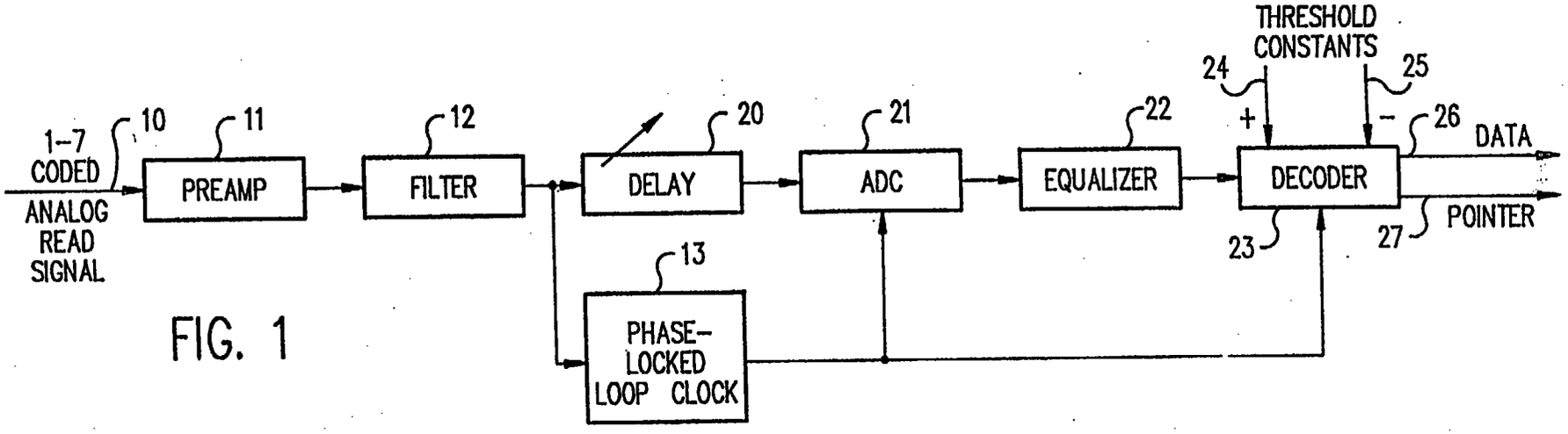


FIG. 1

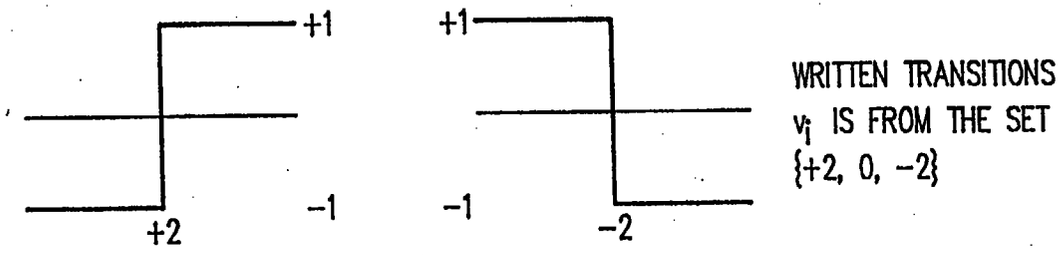


FIG. 2A

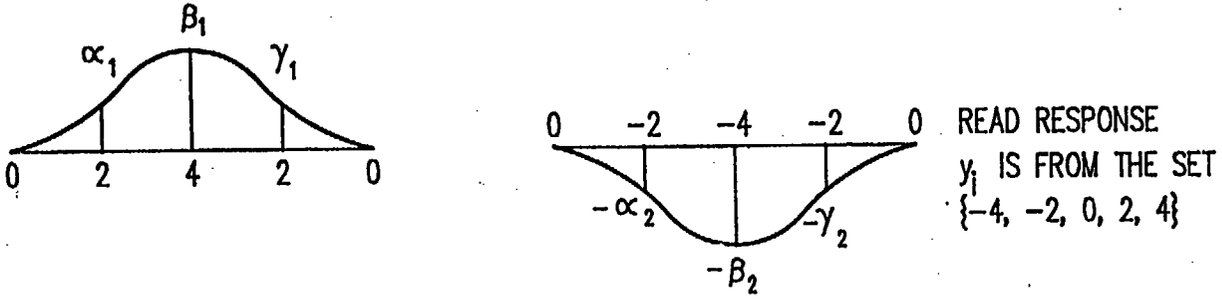


FIG. 2B

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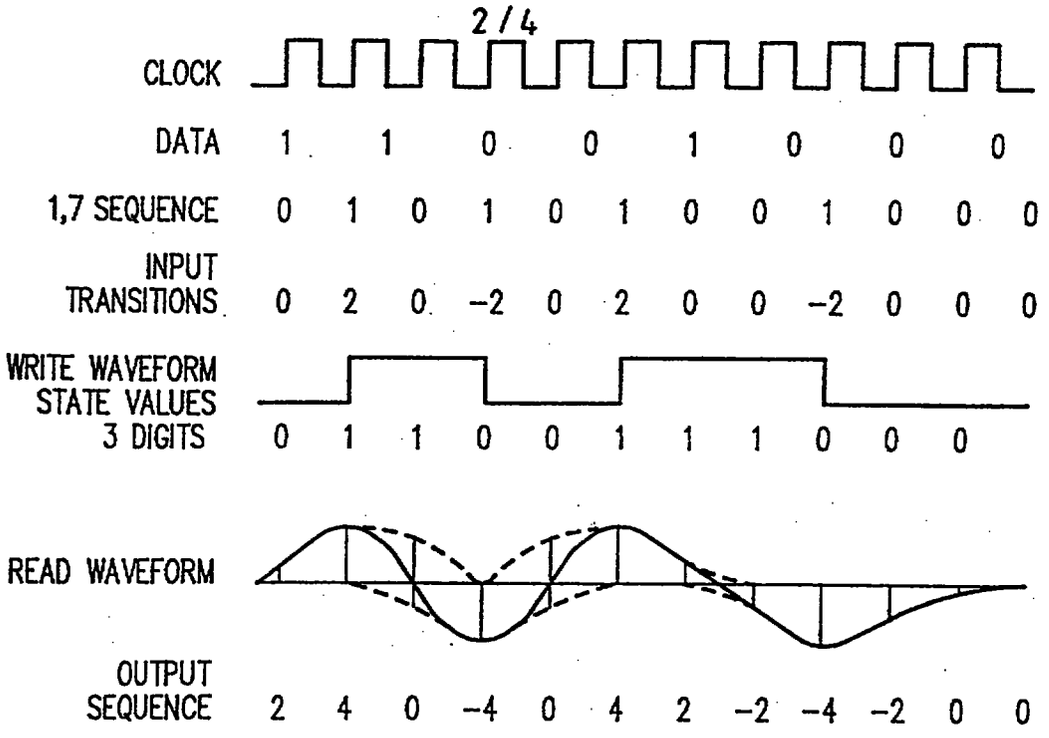


FIG. 3

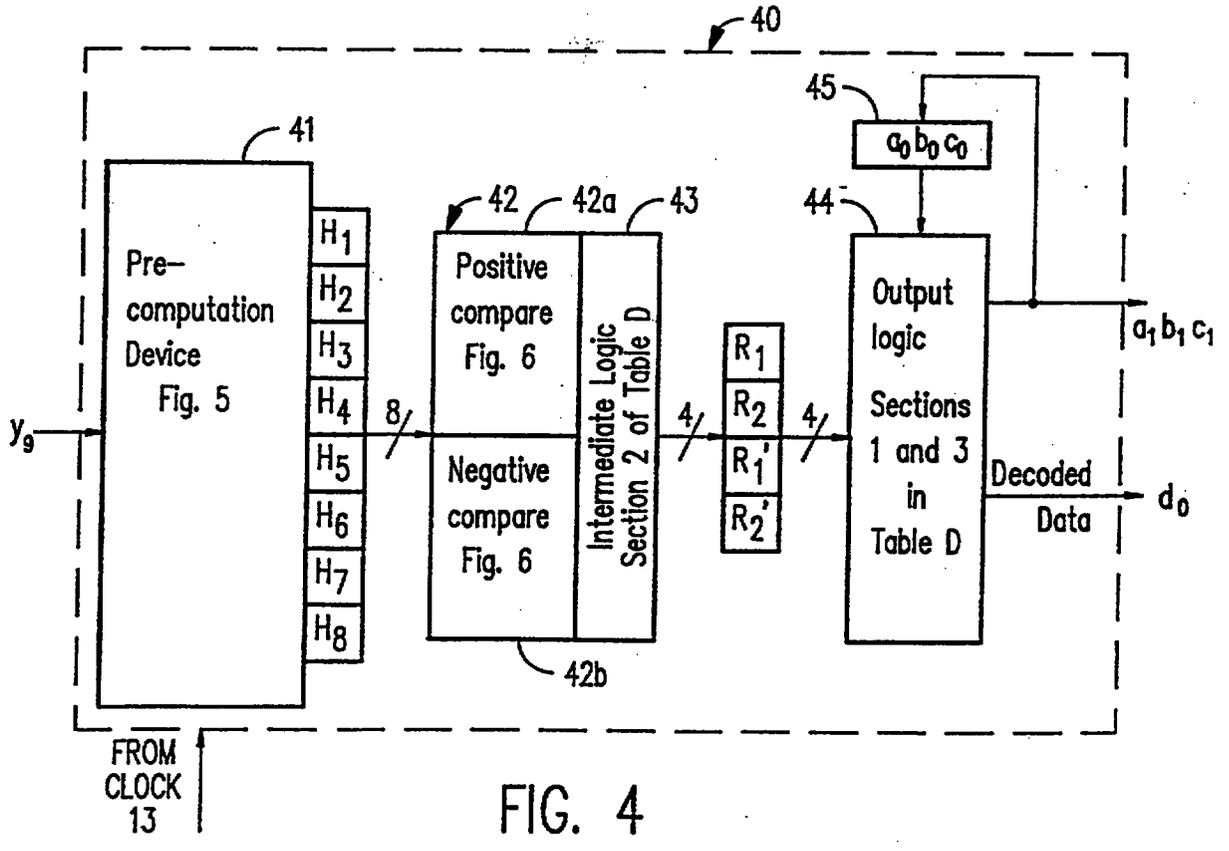


FIG. 4

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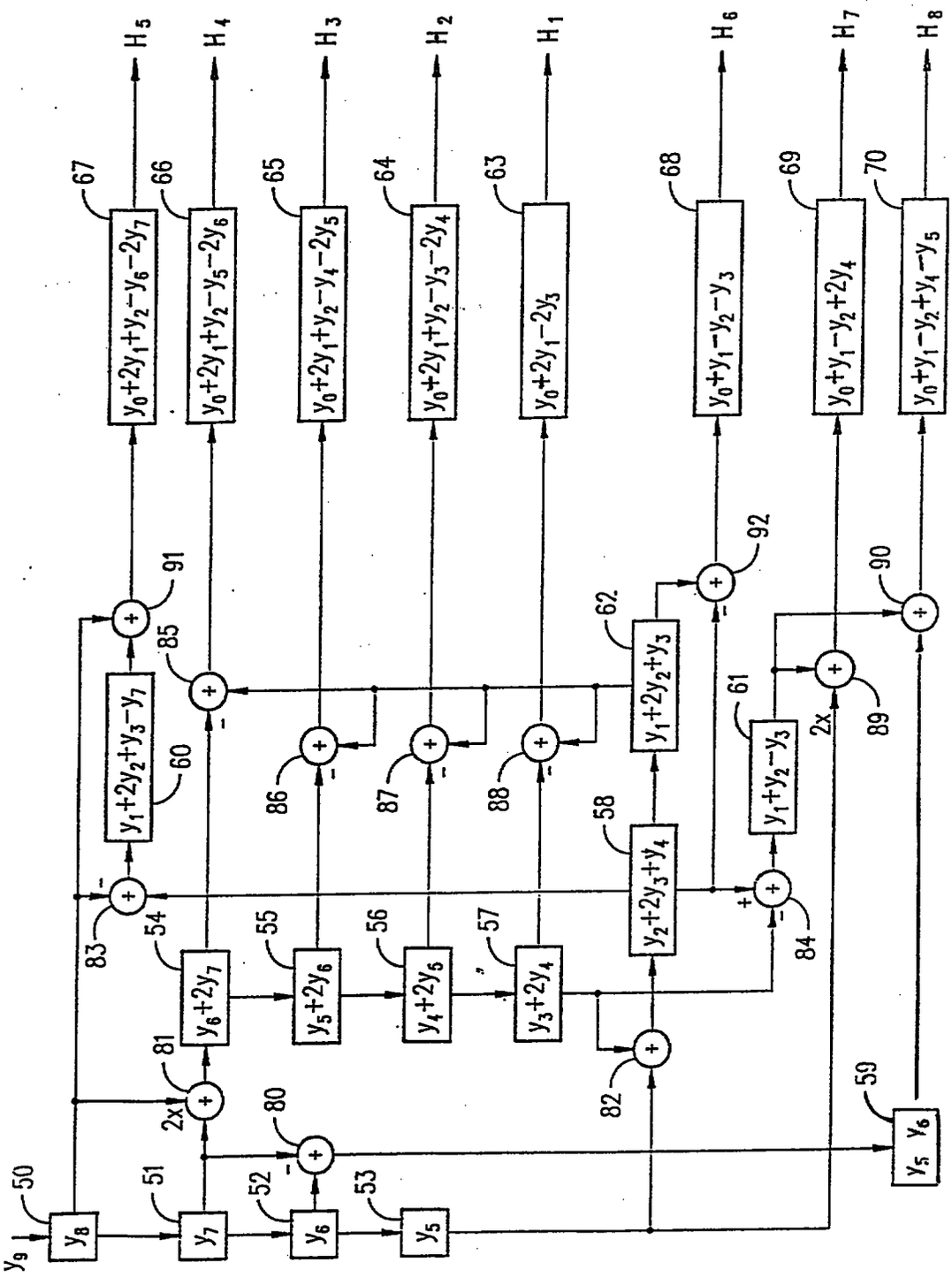


FIG. 5

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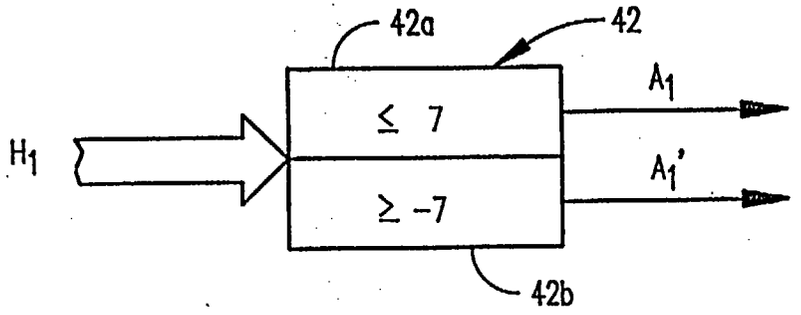


FIG. 6

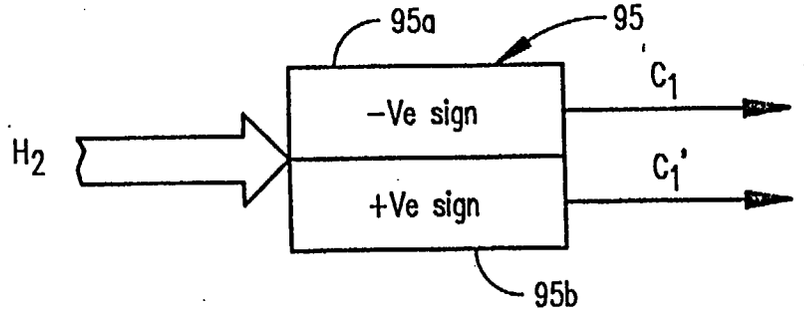


FIG. 8

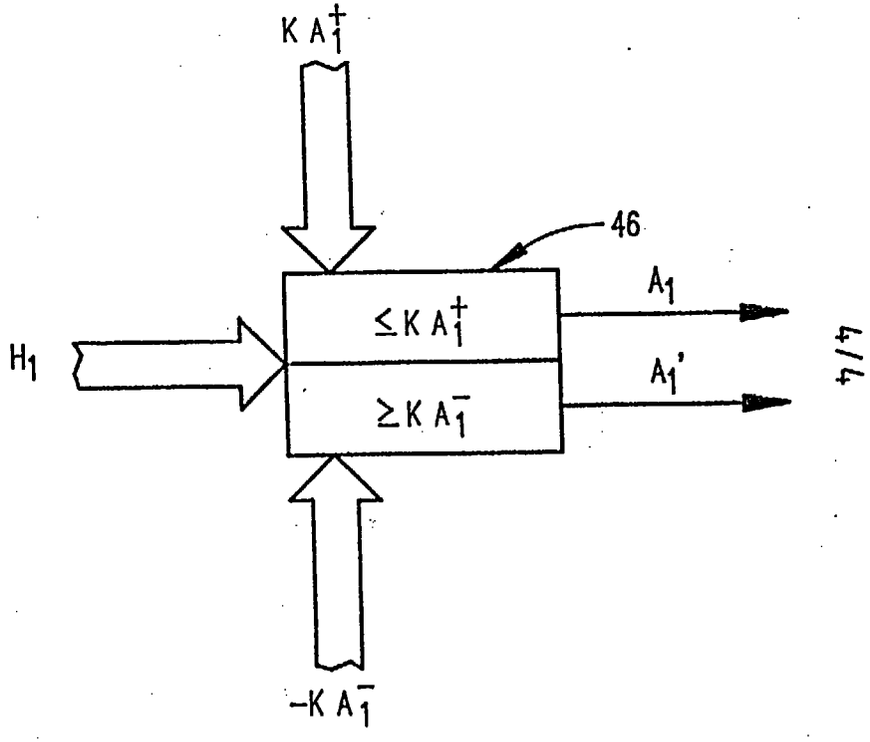


FIG. 7

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case, is predominantly determined by the lower margin of error associated with these sequences.

The second cited application describes an enhancement to the processing method just described. It involves precomputing a peak-position check including expressions using up to six-sample values y_0 - y_5 ahead of the then current sample value y_0. Use of this six- (instead of five) sample look-ahead algorithm provides increased signal detection reliability and increased tolerance to readback pulse distortion by substantially reducing the exposure due to peak shift patterns. However, when these peak shift errors are removed, the primary concern shifts to patterns which are more sensitive to missing or extra bit errors, particularly to the presence of defects and nonlinearities.

A phase check is required in both of the above-cited signal processing methods in order to limit the propagation of detection errors.

SUMMARY OF THE INVENTION

It is an object of the present invention to ameliorate one or more disadvantages of the prior art.

According to one aspect of the present invention there is provided a method of processing, in a signal processing channel, digital sample values corresponding to an incoming analog signal representative of coded binary data, characterized in that the method comprises the steps of: precomputing, from an eight-sample look-ahead algorithm, the values of the following functional expressions for a baseline check: $H_1 = Y_0 + 2y_1 - 2Y_3$, $H_2 = y_0 + 2y_1 + y_2 - y_3 = 2y_4$, $H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$, $H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$, $H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$, where y_0 is a current sample value, and y_1 - y_7 are sample values in successive clock cycles following y_0; from said algorithm, precomputing the values of the following functional expressions for a peak-position check: $H_6 = y_0 + y_1 - y_2 - y_3$, $H_7 = y_0 + y_1 - y_2 + 2y_4$, $H_8 = y_0 = y_1 - y_2 + y_4 - Y_5$; comparing said precomputed values against corresponding threshold values to provide respective binary decision outputs, the threshold values for the next cycle being selected in dependence on the next computed state; from said outputs in

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conjunction with state values corresponding to a current state, determining state values for the next state, which become the current state values for the next iteration of the clock cycle; and during each of a series of successive clock cycles, (a) decoding one successive bit (d_0) of coded binary data corresponding to said sample value, and (b) advancing to the next clock cycle with the computed next state (a, b, c) as the new current state (a_0, b_0, c_0).

According to another aspect of the present invention there is provided signal processing apparatus comprising: means for generating successive clock cycles defined by an electronic clock signal that is phase locked to an incoming analog signal representative of coded binary data; and an analog-to-digital converter for converting said incoming analog signal into digital sample values (y); characterised in that the apparatus comprises decoder means having: means for precomputing, from an eight-sample look-ahead algorithm, the values of the following functional expressions for a baseline check: $H_1 = y_0 + 2y_1 - 2y_3$, $H_2 = y_0 + 2y_1 + y_2 - y_3 = 2y_4$, $H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$, $H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$, $H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$, where y_0 is a current sample value, and $y_1 - y_7$ are sample values in successive clock cycles following y_0; means for precomputing, from said algorithm, the values of the following functional expressions for a peak-position check: $H_6 -= y_0 + y_1 - y_2 - y_3$, $H_7 = y_0 + y_1 - y_2 + 2y_4$, $H_8 = y_0 = y_1 - y_2 + y_4 - y_5$; means for comparing said precomputed values against corresponding threshold values to provide respective binary decision outputs, the threshold values for the next cycle being selected in dependence on the next computed state: means for determining, from said outputs in conjunction with state values corresponding to a current state, state values for the next state, which become the current state values for the next iteration of the clock cycle; and means for, during each of a series of successive clock cycles, (a) decoding one successive bit (d_0) of coded binary data corresponding to said sample value, and (b) advancing to the next clock cycle with the computed state (a, b, c) as the new current state (a_0, b_0, c_0).

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According to still another aspect of the present invention there is provided a method of processing, in a signal processing channel, transducer-generated analog electrical signals representative of coded binary data into digital sample values, comprising the steps of: with a clock, generating successive clock cycles; with a decoder, precomputing values for the following functional expressions for a baseline check in accordance with an eight sample look ahead algorithm: $H_1 = y_0 + 2y_1 - 2y_3$, $H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$, $H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$, $H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$, $H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$, where y_0 is a then current sample value, and $y_1 - y_7$ are sample values in successive clock cycles following y_0; and with the decoder, also precomputing the values of the following functional expressions for a peak-position check: $H_6 = y_0 + y_1 - y_2 - y_3$, $H_7 = y_0 + y_1 - y_2 + 2y_4$, $H_8 = y_0 + y_1 - y_2 + y_4 - y_5$; using the decoder, executing said algorithm during each of a series of successive clock cycles to decode one successive bit of coded binary data corresponding to said current sample value and to advance to the next clock cycle with the computed next state as the new current state; defining each clock cycle by a clock signal that is phase locked to said analog signal; and with an analog-to-digital converter, converting the incoming analog signal to said digital sample values at a rate of one sample value per clock cycle.

According to yet another aspect of the present invention there is provided a signal processing channel comprising: a phase-locked clock for generating successive clock cycles from an electronic clock signal that is phase locked to an incoming analog electrical signal representative of coded binary data; an analog-to-digital converter for converting said incoming analog signal into digital electrical signals representing digital sample values; and a decoder for processing said digital sample values to decode one successive bit of coded binary data at each successive clock cycle using an eight-sample look-ahead decoding algorithm that includes (a) for a baseline check, the following functional expressions: $H_1 = y_0 + 2y_1 - 2y_3$, $H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$, $H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$, $H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$, $H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$, where y_0 is a then current sample value, and $y_1 - y_7$ are sample values in successive

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clock cycles following y_0; and (b) for a peak-position check, the following functional expressions: $H_6 = y_0 + y_1 - y_2 - y_3$, $H_7 = y_0 + y_1 - y_2 + 2y_4$, $H_8 = y_0 + y_1 - y_2 + y_4 - y_5$.

DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

In order that the invention may be fully understood a preferred embodiment thereof will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 1 is a schematic diagram of a code digital signal processing channel;

Fig. 2A depicts written transitions of magnitude 2 between +1 and -1 levels of magnetic saturation, and Fig. 2B depicts a read response normalized by a scaling factor to correspond to said written transitions;

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CLAIMS

1. A method of processing, in a signal processing channel, digital sample values corresponding to an incoming analog signal representative of coded binary data, characterized in that the method comprises the steps of:

precomputing, from an eight-sample look-ahead algorithm, the values of the following functional expressions for a baseline check:

$$H_1 = Y_0 + 2y_1 - 2Y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 = 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a current sample value, and y_1 - y_7 are sample values in successive clock cycles following y_0;

from said algorithm, precomputing the values of the following functional expressions for a peak-position check:

$$H_6 = y_0 + y_1 - y_2 - y_3$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4$$
$$H_8 = y_0 = y_1 - y_2 + y_4 - Y_5;$$

comparing said precomputed values against corresponding threshold values to provide respective binary decision outputs, the threshold values for the next cycle being selected in dependence on the next computed state;

from said outputs in conjunction with state values corresponding to a current state, determining state values for the next state, which become the current state values for the next iteration of the clock cycle; and

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during each of a series of successive clock cycles,

(a) decoding one successive bit (d_o) of coded binary data corresponding to said sample value, and

(b) advancing to the next clock cycle with the computed next state (a, b, c) as the new current state (a_o, b_o, c_o).

2. A method as claimed in claim 1, wherein the state values for the next state are determined without requiring a phase check.

3. A method as claimed in claim 1 or claim 2, including the steps of:

defining each clock cycle by an electronic clock signal that is phase locked to said analog signal; and

converting the incoming analog signal to said digital sample values at a rate of one sample value per clock cycle.

4. A method as claimed in any of claims 1 to 3, including the step of:

generating a programmed value for each threshold.

5. A method as claimed in any of claims 1 to 4, including the step of:

computing each threshold from digitized parameters corresponding to the analog signal shape.

6. A method as claimed in any of claims 1 to 3, including the steps of:

fixing the values of at least some of the thresholds; and

generating programmed values for the remaining thresholds.

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7. A method as claimed in any of claims 1 to 6 wherein, during the comparing step, at least some of the values are compared against thresholds which are fixed near zero by examining the algebraic signs of such values.

8. A method as claimed in any of claims 1 to 8, including the step of:

employing different thresholds for positive and negative phases of the analog signal shape as necessary to accommodate asymmetry of the signal shape.

9. A method as claimed in claim 1, including the steps of:

generating a programmed value for each threshold; and

programmably modifying values for the respective thresholds for different racks on a disk of a disk file to optimize performance for all tracks.

10. A method as claimed in claim 1, including the steps of:

generating a programmed value for each threshold; and

programmably modifying values for the respective thresholds for accommodating signal dropouts caused by media defects on a magnetic recording tape in a tape recording system to optimize performance for all tracks.

11. A method as claimed in any preceding claim, wherein the binary data is in the form of a run-length-limited code.

12. Signal processing apparatus comprising:

means for generating successive clock cycles defined by an electronic clock signal that is phase locked to an incoming analog signal representative of coded binary data; and

an analog-to-digital converter for converting said incoming analog signal into digital sample values (y);

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characterised in that the apparatus comprises decoder means having:

means for precomputing, from an eight-sample look-ahead algorithm, the values of the following functional expressions for a baseline check:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 = 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a current sample value, and y_1 - y_7 are sample values in successive clock cycles following y_0;

means for precomputing, from said algorithm, the values of the following functional expressions for a peak-position check:

$$H_6 -= y_0 + y_1 - y_2 - y_3$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4$$
$$H_8 = y_0 = y_1 - y_2 + y_4 - y_5;$$

means for comparing said precomputed values against corresponding threshold values to provide respective binary decision outputs, the threshold values for the next cycle being selected in dependence on the next computed state:

means for determining, from said outputs in conjunction with state values corresponding to a current state, state values for the next state, which become the current state values for the next iteration of the clock cycle; and

means for, during each of a series of successive clock cycles,

(a) decoding one successive bit (d_0) of coded binary data corresponding to said sample value, and

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(b) advancing to the next clock cycle with the computed state (a, b, c) as the new current state (a_o, b_o, c_o).

13. A method of processing, in a signal processing channel, transducer-generated analog electrical signals representative of coded binary data into digital sample values, comprising the steps of:

with a clock, generating successive clock cycles;

with a decoder, precomputing values for the following functional expressions for a baseline check in accordance with an eight sample look ahead algorithm:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a then current sample value, and y_1 - y_7 are sample values in successive clock cycles following y_0; and

with the decoder, also precomputing the values of the following functional expressions for a peak-position check:

$$H_6 = y_0 + y_1 - y_2 - y_3$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4$$
$$H_8 = y_0 + y_1 - y_2 + y_4 - y_5;$$

using the decoder, executing said algorithm during each of a series of successive clock cycles to decode one successive bit of coded binary data corresponding to said

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current sample value and to advance to the next clock cycle with the computed next state as the new current state;

defining each clock cycle by a clock signal that is phase locked to said analog signal; and

with an analog-to-digital converter, converting the incoming analog signal to said digital sample values at a rate of one sample value per clock cycle.

14. A signal processing channel comprising:

a phase-locked clock for generating successive clock cycles from an electronic clock signal that is phase locked to an incoming analog electrical signal representative of coded binary data;

an analog-to-digital converter for converting said incoming analog signal into digital electrical signals representing digital sample values; and

a decoder for processing said digital sample values to decode one successive bit of coded binary data at each successive clock cycle using an eight-sample look-ahead decoding algorithm that includes

(a) for a baseline check, the following functional expressions:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a then current sample value, and y_1 - y_7 are sample values in successive clock cycles following y_0; and

(b) for a peak-position check, the following functional expressions:

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$$H_6 = y_0 + y_1 - y_2 - y_3$$

$$H_7 = y_0 + y_1 - y_2 + 2y_4$$

$$H_8 = y_0 + y_1 - y_2 + y_4 - y_5.$$

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case, is predominantly determined by the lower margin of error associated with these sequences.

The second cited application describes an enhancement to the processing method just described. It involves precomputing a peak-position check including expressions using up to six-sample values y_0 - y_5 ahead of the then current sample value y_0. Use of this six- (instead of five) sample look-ahead algorithm provides increased signal detection reliability and increased tolerance to readback pulse distortion by substantially reducing the exposure due to peak shift patterns. However, when these peak shift errors are removed, the primary concern shifts to patterns which are more sensitive to missing or extra bit errors, particularly to the presence of defects and nonlinearities.

A phase check is required in both of the above-cited signal processing methods in order to limit the propagation of detection errors.

SUMMARY OF THE INVENTION

It is an object of the present invention to ameliorate one or more disadvantages of the prior art.

According to one aspect of the present invention there is provided a method of processing, in a signal processing channel, digital sample values corresponding to an incoming analog signal representative of coded binary data, characterized in that the method comprises the steps of: precomputing, from an eight-sample look-ahead algorithm, the values of the following functional expressions for a baseline check: $H_1 = y_0 + 2y_1 - 2y_3$, $H_2 = y_0 + 2y_1 + y_2 - y_3 = 2y_4$, $H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$, $H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$, $H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$, where y_0 is a current sample value, and y_1 - y_7 are sample values in successive clock cycles following y_0; from said algorithm, precomputing the values of the following functional expressions for a peak-position check: $H_6 = y_0 + y_1 - y_2 - y_3$, $H_7 = y_0 + y_1 - y_2 + 2y_4$, $H_8 = y_0 = y_1 - y_2 + y_4 - y_5$; comparing said precomputed values against corresponding threshold values to provide respective binary decision outputs, the threshold values for the next cycle being selected in dependence on the next computed state; from said outputs in

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CLAIMS

1. A method of processing, in a signal processing channel, digital sample values corresponding to an incoming analog signal representative of coded binary data, characterized in that the method comprises the steps of:

precomputing, from an eight-sample look-ahead algorithm, the values of the following functional expressions for a baseline check:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 = 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a current sample value, and y_1 - y_7 are sample values in successive clock cycles following y_0;

from said algorithm, precomputing the values of the following functional expressions for a peak-position check:

$$H_6 = y_0 + y_1 - y_2 - y_3$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4$$
$$H_8 = y_0 = y_1 - y_2 + y_4 - y_5;$$

comparing said precomputed values against corresponding threshold values to provide respective binary decision outputs, the threshold values for the next cycle being selected in dependence on the next computed state;

from said outputs in conjunction with state values corresponding to a current state, determining state values for the next state, which become the current state values for the next iteration of the clock cycle; and

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(b) advancing to the next clock cycle with the next computed state (a, b, c) as the new current state (a_o, b_o, c_o).

13. A method of processing, in a signal processing channel, transducer-generated analog electrical signals representative of coded binary data into digital sample values, comprising the steps of:

with a clock, generating successive clock cycles;

with a decoder, precomputing values for the following functional expressions for a baseline check in accordance with an eight sample look ahead algorithm:

$$H_1 = y_0 + 2y_1 - 2y_3$$
$$H_2 = y_0 + 2y_1 + y_2 - y_3 - 2y_4$$
$$H_3 = y_0 + 2y_1 + y_2 - y_4 - 2y_5$$
$$H_4 = y_0 + 2y_1 + y_2 - y_5 - 2y_6$$
$$H_5 = y_0 + 2y_1 + y_2 - y_6 - 2y_7$$

where y_0 is a then current sample value, and y_1 - y_7 are sample values in successive clock cycles following y_0; and

with the decoder, also precomputing the values of the following functional expressions for a peak-position check:

$$H_6 = y_0 + y_1 - y_2 - y_3$$
$$H_7 = y_0 + y_1 - y_2 + 2y_4$$
$$H_8 = y_0 + y_1 - y_2 + y_4 - y_5;$$

using the decoder, executing said algorithm during each of a series of successive clock cycles to decode one successive bit of coded binary data corresponding to said

* C L M S *

This is the replacement sheet

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