BBC RD 1974/24

1969 THE QUEEN'S AWARD TO INDUSTRY
1974 THE QUEEN'S AWARD TO INDUSTRY

RESEARCH DEPARTMENT REPORT

DIGITAL SOUND SIGNALS: the effect of transmission errors in a near-instantaneous digitally companded system

D.F. Reid, B.Sc.
M.G. Croll, B.Sc., A.R.C.S.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

BBC RD 1974/24
UDC 534.86:
621.376.56

DIGITAL SOUND SIGNALS: THE EFFECT OF TRANSMISSION ERRORS IN A NEAR-INSTANTANEOUS DIGITALLY COMPANDED SYSTEM

D.F. Reid, B.Sc.
M.G. Croll, B.Sc., A.R.C.S.

Summary

Experiments are described which determined the audible effect of digit errors on 'near-instantaneous' digitally companded sound signals of the type described in a previous report (1973/41). A method of error protection is proposed.

Initial listening tests showed the digitally companded signals to be more immune to bit errors than linearly coded signals. To take advantage of this greater immunity a new error-protection scheme was devised. This scheme uses a little over half the number of error-protection bits per channel, as compared with the requirements of a system where the sound signals are linearly coded. Listening tests confirmed that, with the proposed error-protection scheme, the effect of errors is similar to that in the linearly coded 13-channel p.c.m. multiplex system in service with the BBC.

Issued under the authority of

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

June 1974

(EL-93)

DIGITAL SOUND SIGNALS: THE EFFECT OF TRANSMISSION ERRORS IN A NEAR-INSTANTANEOUS DIGITALLY COMPANDED SYSTEM

Section	Title	Page
	Summary	Title Page
1.	Introduction	1
2.	Transmission codes	1
3.	Apparatus used for tests	2
4.	The effects of transmission errors with various coding laws	2
	4.1. General	2
	4.2. Linear coding	2
	4.3. Near-instantaneous companding	3
	4.3.1. Errors in the complete bit-stream	3
	4.3.2. Errors in the sign digit	3
	4.3.3. Errors in the remainder of the sample word	3
	4.3.4. Errors in the scale-factor word	3
5.	Error protection	3
	5.1. General	3
	5.2. Programme amplitude distribution	4
	5.3. Error concealment	4
	5.3.1. Concealment of sample-word errors	4
	5.3.2. Concealment of scale-factor word errors	4
	5.4. An error protection system for four-segment near-instantaneous companding	5
	5.4.1. General	5
	5.4.2. Considerations affecting the choice of a suitable error protection system	5
	5.4.3. The proposed system	5
6.	Simulation of the proposed error protection system for the four-segment near-instantaneous law	5
	6.1. General	5
	6.2. The error protection simulator	5
	6.3. Listening tests	6
7.	Conclusions	7
8.	Recommendations	7
9.	References	7

© BBC 2004. All rights reserved. Except as provided below, no part of this document may be reproduced in any material form (including photocopying or storing it in any medium by electronic means) without the prior written permission of BBC Research & Development except in accordance with the provisions of the (UK) Copyright, Designs and Patents Act 1988.

The BBC grants permission to individuals and organisations to make copies of the entire document (including this copyright notice) for their own internal use. No copies of this document may be published, distributed or made available to third parties whether by paper, electronic or other means without the BBC's prior written permission. Where necessary, third parties should be directed to the relevant page on BBC's website at http://www.bbc.co.uk/rd/pubs/ for a copy of this document.

DIGITAL SOUND SIGNALS: THE EFFECT OF TRANSMISSION ERRORS IN A NEAR-INSTANTANEOUS DIGITALLY COMPANDED SYSTEM

D.F. Reid, B.Sc.
M.G. Croll, B.Sc., A.R.C.S.

1. Introduction

In a digital transmission system a digit error occurs when a binary '1' is received where a binary '0' is transmitted (or vice-versa). These digit errors are introduced into a binary p.c.m. transmission system if noise voltages or other interferences add to the signal in such a way as to cause the receiving terminal apparatus to interpret a binary digit incorrectly.

The rate at which errors occur and their distribution depend upon the characteristics of the transmission path. For a cable system the bit-error rate probability density function is approximately Gaussian because steady random noise is present with the signal when it is amplified at repeaters. With microwave transmission links, fading causes the noise added to the signal to be, in effect, modulated in level resulting in bursts of errors in the digit stream. In the latter case a burst of errors can be considered as a comparatively high error rate present for a short time. Hence, the performance of systems in the presence of errors can be characterised, for most applications, by the effect of random errors at various mean error-rates.

For linearly-coded p.c.m. sound signals the effect of transmission errors at different mean rates has been evaluated[1] by subjective tests. Also, methods of reducing these effects by simple error protection[2] and digit error correction[3] have been investigated and evaluated. As a result, a form of error protection was recommended in which the five most significant bits (m.s.b.'s) of each 13-bit linearly-coded sample word were protected by using a single-bit parity check and replacing erroneous sample words with the previous correct sample word. This form of error protection is used to reduce the effect of digit errors in the 13-channel p.c.m. sound system now in service with the BBC, giving a just perceptible impairment at a bit-error probability of about 10^{-5}.

In a p.c.m. system employing digital companding[4] the digital code is changed to reduce the transmitted bit-rate and, in general, the effect of transmission errors can be expected to be different from that in a linearly-coded p.c.m. system.

In this report the effects of transmission errors are described for 'near-instantaneous' digitally companded sound signals. Briefly, a digitally companded signal is one in which a reduced number of digits of each linearly-coded sample word is transmitted, together with additional information describing the significance of the transmitted digits. The additional signal is a scale-factor word which, for near-instantaneous companding, is transmitted only at intervals corresponding to a group of some 20 to 30 samples. It is associated with the group of sample words and is determined by the greatest peak signal value occurring in each group. A more detailed description appears in Reference 4. The present report also describes an investigation of error protection schemes for such signals. In particular, an error protection scheme is proposed for the near-instantaneous companding system recommended in Reference 5.

2. Transmission codes

Since errors may be caused by interference or noise in the transmission path of a digital system it is relevant to consider the transmission codes likely to be used. A transmission code is one which is suitable for transmitting data over appreciable distances. Such a code could be two-level (binary) or three-level (ternary), etc. The suitability of any one code would depend on the characteristics of both the transmission path and the data to be transmitted.

A binary code is used, for instance, in the BBC 13-channel p.c.m. sound system, which is transmitted over bearer circuits similar to those required for 625-line monochrome television signals. Alternate digits of the original binary-coded sample words are inverted to convey sufficient timing information to achieve stable bit-rate clock regeneration at the demultiplexer.

Ternary codes which are being produced for use by the British Post Office (BPO) for future digital networks include HDB3 (high density, bipolar, three-level) and 4B3T (4 binary digits represented by 3 ternary digits). Present plans are for a digital hierarchy with bit rates which are approximate multiples of a CCITT first-order rate of 2·048 Mb/s, using ternary transmission codes.[6] However, these have not been finally decided although HDB3 is expected to be the customer interface code for all orders of multiplexing. This code has some error-detection properties since inadmissible sequences of symbols can arise from a transmission error. Also, a single transmission error may, after transcoding to a binary sequence, give rise to one or more errors, an effect referred to as error extension.[6] However, by suitable disposition of sample word bits and parity check bits it would be possible to mitigate the effects of such error extension.

Ideally, an investigation into the effects of errors on the digitally companded sound signal would be made using the transmission code which would be used in practice. However, as the transmission code and any error protection or correction system provided by the bearer has not been decided, such an investigation is not yet possible. Furthermore, it is not known whether the interface between two transmission codes (say, from HDB3 to 4B3T) will include error protection. The work described in this report therefore used only binary signals, from the compandor, and the results are compared with the effects of errors on 13-bit linearly-coded binary signals.

3. Apparatus used for tests

The investigations were carried out using the experimental digital companding equipment described in Reference 4. This equipment included CCITT pre- and de-emphasis networks.[7] The gain of the pre-emphasis was set to +4 dB at 15 kHz as recommended for use in the 2·048 Mb/s, 6-channel multiplex digitally companded system proposed by the BBC.[5] Throughout the investigation the effects of errors on a linearly-coded p.c.m. system are used for comparison. Earlier work[2,3] on the effects of errors in linear p.c.m. systems employed 50μsec pre- and de-emphasis characteristics. However, to remove an additional variable and to simplify comparative tests in the current investigation, the CCITT pre- and de-emphasis networks were also used when assessing the impairments caused by errors with linear coding. Differences in the audibility of the effects of errors on a linearly coded system when using the different emphasis characteristics are considered to be negligible.

A special error generator had to be constructed for the work described in this report because the connection between the compressor and expander comprising the experimental single-channel compandor was not representative of an actual single-wire transmission system. In a practical system the spectrum of the signal, obtained as a series of pulses, from the sending equipment would be specially shaped before the signal was sent along a transmission path to the receiver. The receiver would contain circuits for detecting the pulses and generating timing information from them. As discussed in the Introduction, noise added to the transmitted signal could cause the detection circuits to misinterpret the incoming data and hence introduce digit errors.

In the error generator, shown in Fig. 1, a noisy transmission path is simulated. Gaussian white noise is applied to a detection circuit which generates error pulses. A pulse is produced if the instantaneous voltage of the noise waveform exceeds a voltage threshold at a positive-going clock transition. The resulting waveform is applied to one input of an 'exclusive or' gate, the sound signal serial bit-stream being applied to the other input. Random errors are consequently generated by inverting digits in the sound signal bit-stream. The average rate at which errors are produced can be varied by adjusting the reference voltage applied to the comparator.

This arrangement was particularly convenient for the investigations as, by including gating arrangements, a detalied study of the effects of errors in particular digits could be made. Error protection schemes could be roughly assessed by excluding errors from those bits which would be protected.

4. The effects of transmission errors with various coding laws

4.1. General

To determine the effects of transmission errors when various coding laws are used, pre-recorded orchestral music and solo piano items were transmitted through the experimental digital compandor. Listening tests were carried out using a BBC type LS5/5 high-quality monitoring loudspeaker in a room with a volume of 85 cubic metres having a mid-band reverberation time of 0·3s. Errors were introduced at random into the digits of the serial bit-stream with the error generator set to give initially a bit-error probability of 10^{-3} which was selected as sufficiently high to enable resultant audible effects to be easily assessed.

In the following Sections general observations are presented concerning the effects of errors when different coding laws are used, together with some overall comparison of the relative susceptibilities of linearly-coded and near-instantaneously companded systems.

4.2. Linear coding

The effects of errors in linearly-coded p.c.m. signals were studied for two different codes. One, referred to as 'straight' binary, is such that the most negative excursion of

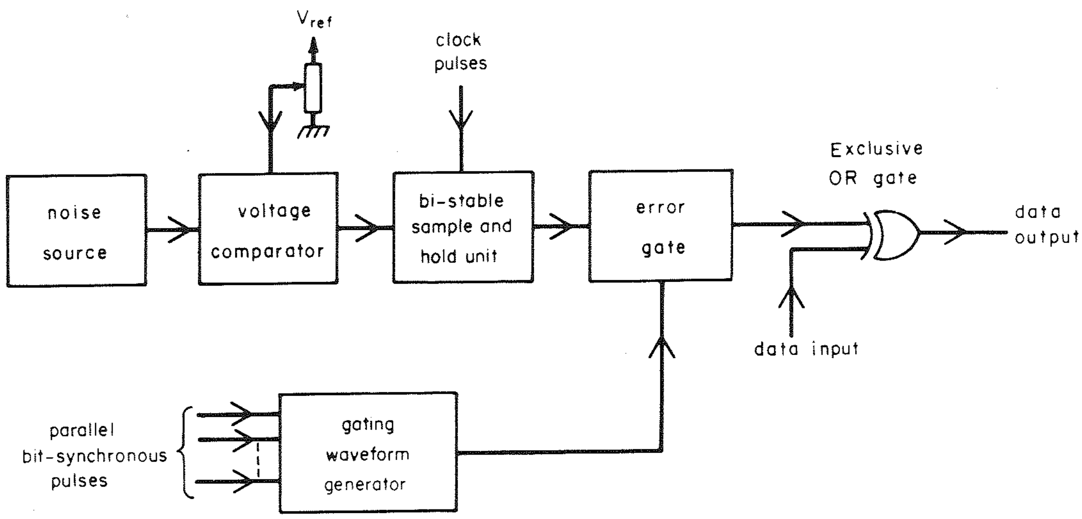

Fig. 1 - The error generator

the analogue signal is represented as an all '0's code and the most positive excursion is represented as an all '1's code. This code, with inversion of alternate bits as described in Section 2, is used in the BBC 13 bits per sample linearly-coded multiplex p.c.m. system. Another code in common use is the symmetrical binary code in which one digit denotes the sign of the analogue signal and the remaining digits denote the magnitude of the signal. This code is of interest in this investigation because of its similarities with codes used in digital companding, where the sign digit is unaltered and the digital code describing the signal magnitude is companded.

With both linear codes, errors produced a fairly steady background crackle, the magnitude of each constituent click being dependent on the significance of the bit in error. With the symmetrical binary code, however, there were slightly fewer very loud clicks and some of these depended on the programme signal level. This slight difference arises since the effects of errors in the sign digit of the symmetrical code are only comparable to those in the most significant digit of the straight binary code for high level signals. At other times the effects of errors in the sign digit are much less and were found – as expected – to be inaudible when no programme was present.

Therefore, for linear coding, a symmetrical binary code is somewhat superior to a straight binary code in that transmission errors produce slightly less impairment.

4.3. Near-instantaneous companding

4.3.1. Errors in the complete bit-stream

In general the effects of digit errors in near-instantaneous companded signal (comprising sign digits, sample words and scale-factor words) were far less severe than with linearly-coded signals. There were fewer loud clicks and the level of the background crackle was far lower but depended, to some extent, on the programme amplitude. The level of the background crackle also depended on the number of segments or coding ranges in the particular companding law being tested,* and was lower when more ranges were employed. The effects of errors with a four-segment near-instantaneous digital companding law were similar to the effects of errors in the ten least significant bits of a 13-bit linearly-coded signal.

To identify the effects of errors in each part of the bit-stream from the digital compressor, errors were introduced selectively into the different parts of the signal.

4.3.2. Errors in the sign digit

The effect of errors in the sign digit of the companded signal is identical to the effect of errors in the sign digit of symmetrical binary, linearly-coded signals. This has been described in Section 4.2.

* In digital companding, compression and expansion involves switching between straight-line characteristics whose slopes are related by factors of two. The degree of compression and the number of bits saved depends on the number of such segments employed.[4]

4.3.3. Errors in the remainder of the sample word

The remainder of the sample word is that part of the bit-stream which is digitally compressed, and does not include the sign digit or scale-factor word. Errors in the remainder of the sample word caused the background crackle which was described in Section 4.3.1. When programme of very high level with substantial high-frequency content was present, thus causing the compandor to operate on the segment intended for highest signal levels, the effect of the errors was indistinguishable from that in a linearly-coded signal in which errors had been excluded from the most significant digit. At all other times, the level of this background crackle was much lower. For very low level programme the level of the background crackle depended on the number of segments in the companding law being tested; the level of this crackle was very low for a seven-segment law and tended to increase as the number of segments was reduced.

Because of programme-modulation, the effect of the errors in the remainder of the sample word was masked to some extent by the programme. Overall, the effect of these errors with a four-segment law was similar to the effect of errors in the nine least significant bits of a 13 bits per sample linearly-coded signal.

4.3.4. Errors in the scale-factor word

Errors in the scale-factor word caused clicks, the rate of occurrence of which was low because of the low bit rate used for transmitting the scale-factor words.

The subjective effect of each of these clicks is comparable to the effect of an error in the most significant digit of a straight binary linearly-coded signal. However, the rate at which the scale-factor errors occur is more than an order of magnitude lower than that of errors in the sample word and the overall impairment is consequently less severe.

5. Error protection

5.1. General

Error protection is achieved in the BBC linearly-coded digital sound system using 13 bits per sample by assigning a parity check digit to the five most significant bits of each word and repeating the previous correct sample when an error is detected within the parity group. This technique has been found to be both effective and simple to instrument.

The work outlined in Section 4 showed that the effects of errors on digitally companded signals were different from the effects on linearly-coded signals, and indicated where error protection of companded signals might be most advantageously applied. The parts of the digitally companded signal which require protection against digit errors are the scale-factor word, the sign digit and some of the most significant bits of the remainder of the sample word. The number of bits from the sample word

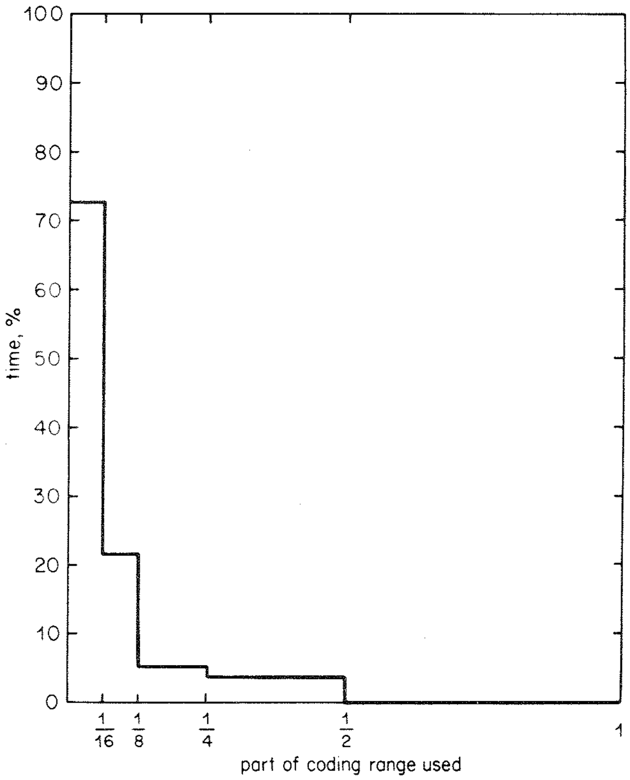

Fig. 2 - Time-amplitude distribution of piano solo programme item

which must be protected will depend on the average weight of the most significant bits* and will be related to the time the compandor spends in each range. To determine how the programme time is distributed among the different companding ranges an investigation was carried out into the amplitude distribution of various programme items.

5.2. Programme amplitude distribution

The investigation was carried out using a digital counter to count how often each particular scale-factor word was transmitted. Hence the percentages of the time that the signal occupied each range could be determined.

The programme material used initially in this test was an excerpt of solo piano music. The level was set to peak to +8 dBm before pre-emphasis, this being ½ dB less than would be required to occupy the full coding range of the analogue-to-digital converter (a.d.c.). The results are shown in Fig. 2 for a five-slope system. These results show that the signal occupied the lowest segment of the five-segment law for 72·6% of the time. The equivalent figure for a four-segment law is obtained by adding the percentages for the two lowest segments of the five-segment law and is 94·3%. This programme item did not cause the compandor to operate in the coarsest segment, because the higher-frequency content was not particularly great.

Various other programme items were tested to find for what percentage of the time the signal would occupy the lowest slope of a four-segment law and it was found that even with popular music (non-compressed) the lowest figure was 79%.

These results show that the bits corresponding to the most significant bits of the original linearly-coded signal are not often transmitted when a four-slope near-instantaneous companding system is used. This accounts for the greater immunity to transmission errors of a companded p.c.m. signal compared with a linearly-coded p.c.m. signal, as found from the tests described in Section 4 of this report. It follows that, for a given degree of impairment arising from a given error probability, fewer bits of the sample word required protection for a companded signal than for a linearly-coded signal.

5.3. Error concealment

5.3.1. Concealment of sample-word errors

For error concealment with the 13 bits per sample linearly-coded system, erroneous samples are replaced by the previous correct sample. This technique can also be applied to digitally companded systems. Errors in the sample words can be concealed either by repeating the previous correct sample word in digital form or by repeating the previous sample in the digital-to-analogue converter (d.a.c.). If sample words are repeated in digital form, it is necessary to take into account any change which has occurred in the scale-factor word between the two samples. It is instrumentally simpler therefore to repeat the decoded analogue samples.

5.3.2. Concealment of scale-factor word errors

It was found from the tests described in Section 5.2 that the scale-factor word did not change very often. This suggested that repetition of the previous scale-factor word would be a valid method of concealing scale-factor word errors.

Tests were conducted in which scale-factor words were repeated at random, thus simulating the error-concealment technique proposed above. The number of audible clicks produced, when various programme items were played through the compandor, was counted. Also the total number of scale-factor word repetitions was counted. It was found that for a particular excerpt of solo piano this method gave the correct scale-factor word for 98% of the errors. With other programme items the method of concealment was less effective and the worst case investigated (solo trumpet) showed that method to be effective for 67% of the errors. On average this simple method of error concealment corrected errors occurring in the scale-factor word for about 90% of the time.

* In the near-instantaneous digital companding technique, described in Reference 4, the most significant bits transmitted are of maximum weight only with high-level, high-frequency signals, as a consequence of the depression of the level of lower frequency signals by the pre-emphasis characteristic used.

5.4. An error protection system for four-segment near-instantaneous companding

5.4.1. General

The investigation into error protection concentrated on the four-slope, near-instantaneous companding system, considered to be the most suitable for high-quality sound transmissions.[4,5]

5.4.2. Considerations affecting the choice of a suitable error protection system

Reference 1 indicates that, for a linearly-coded straight binary signal, the optimum number of the more significant bits in each word to which a single parity bit should be assigned is five. If more bits (of lower significance) are protected, then the subjective effect of repeating the previous correct sample is likely to be worse than that of the error which was detected. Similarly, if fewer bits are protected the optimum balance between concealments and undetected errors is not obtained. Moreover, this number of bits satisfies the requirement that a signal failure may be detected.*

For digitally companded signals it has been shown in Section 5.2 above, that with a four-segment law the compandor spends about 90% of total programme time in its lowest range. During this time the most significant bit transmitted, excluding the sign digit, is the fifth most significant bit of the original linearly-coded signal. It therefore appears that protection of the sign bit and one or two of the most significant bits of the same word would make the effect of sample repetition similar to the effect of undetected errors. Furthermore, if one parity bit were used to check the chosen bits of two digitally companded words, the ratio of error concealments to undetected errors would be similar to that in the linearly-coded system.

To make the parity group, comprising the protected bits plus the check bit, capable of detecting signal failure for the companded system, the group must again contain an even number of bits. An arrangement which satisfies this condition, as well as that discussed above, would be for one parity bit to check two bits taken from one word and three bits taken from another. It is, of course, important that the two words grouped for this purpose should not be successive words from the same channel, as this would cause the same sample to be repeated twice. With the proposed arrangement the number of bits in each parity group would be the same as in the linearly-coded system so that the number of concealments would be exactly the same per channel for any given bit-error probability.

* In a practical multiplex system it must be possible to detect whether the signal has failed, so that all channels can be muted for the duration of the failure and action necessary to restore the service can be initiated. A signal failure could result in a continuous stream of either '1's or '0's at the receiving terminal. A stream of '0's is even whereas a stream of '1's is only even if the number of '1's is even. Therefore it follows that, if both cases of signal failure are to violate parity, the total number of digits within a parity group, including the check digit, should be even and that the check bit should be such that the number of '1's is always odd.

5.4.3. The proposed system

It is proposed that, for six digitally companded high-quality sound channels in a 2·048 Mb/s bit stream, error protection should be provided by assigning the parity check bits as follows:

(a) 1 parity bit for each scale factor word, an erroneous scale factor word being replaced by the previous correct one.

(b) 1 parity bit for the sign and two most significant bits of one channel together with the sign and most significant bit of another channel, the previous correct samples in both channels being repeated when an error is detected.

6. Simulation of the proposed error protection system for the four-segment near-instantaneous law

6.1. General

The error protection system outlined in 5.4.3. was simulated so that its effectiveness could be assessed and compared with the system currently in service for protecting 13 bits per sample linearly-coded signals. For the simulation an additional unit was constructed in which errors in the sample word were concealed by repeating decoded analogue samples (as described in Section 5.3.1) and errors in the scale-factor word were concealed by repeating the previous scale-factor word. Signals to produce these concealments were generated by a circuit which detected when an odd number of errors had been introduced into the associated parity groups. This circuit simulated exactly the operation of a parity decoder without actually generating, inserting or decoding parity bits.

6.2. The error protection simulator

A block diagram of the error protection simulator is shown in Fig. 3. The experimental digital compandor uses a serial bit-stream with 16 bits available for each word (as shown in Fig. 4), whereas the companding law under study requires only about 10 bits per sample. This leaves some spare bits which were used in forming three 6-bit parity groups which corresponded to the three error protection conditions,

(a) linear coding: one parity bit protecting the first five m.s.b.'s.

(b) four-segment near-instantaneous companding:

 (i) one parity bit protecting the sign bit + the m.s.b. + three spare bits which would correspond to the sign bit and the two m.s.b.'s in another channel,

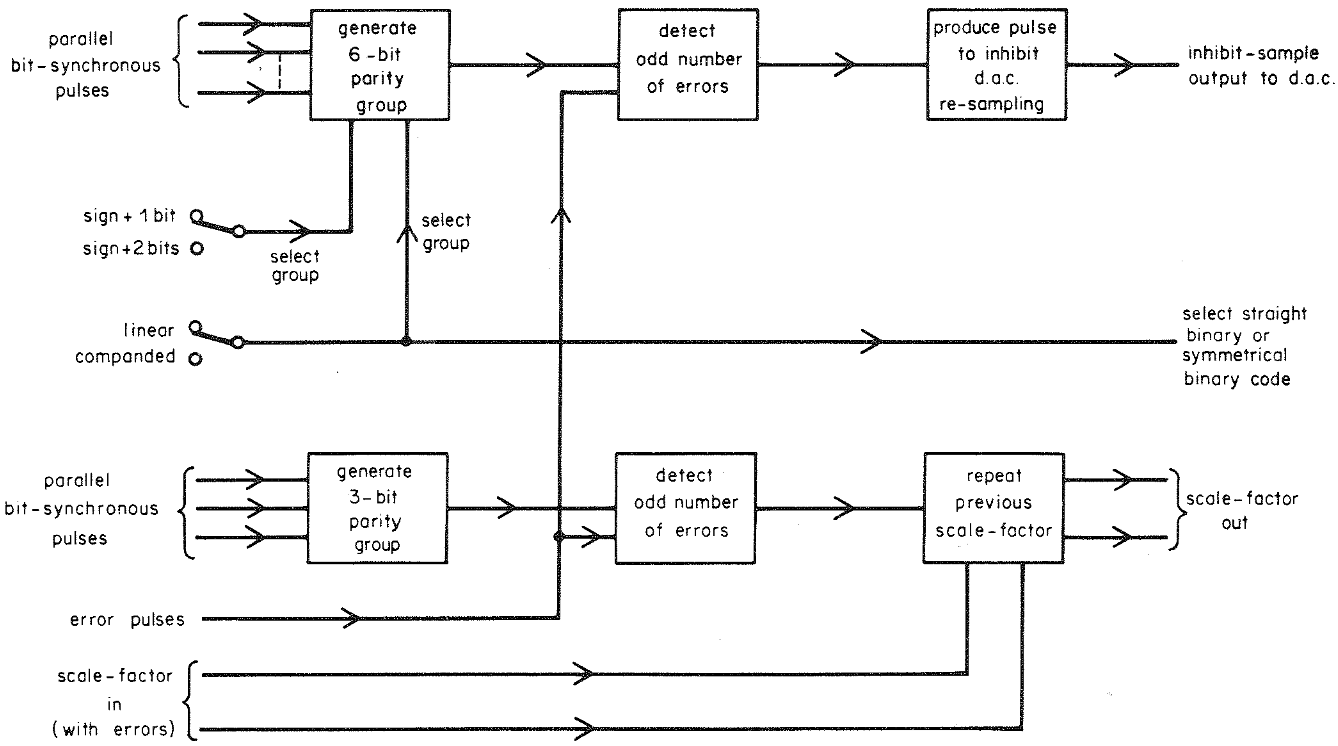

Fig. 3 - The error-protection simulator

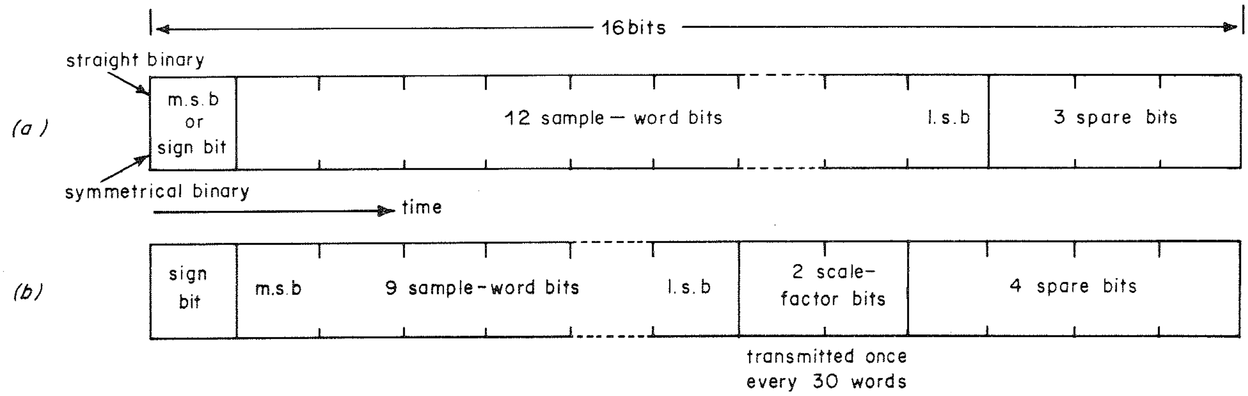

Fig. 4 - Sequence of bits in the sound signal serial bit stream for
(*a*) linear coding (*b*) 4-segment near-instantaneous companding
Note: m.s.b. = most significant bit
l.s.b. = least signigicant bit

(ii) one parity bit protecting the sign bit + the first two m.s.b.'s + two spare bits which would correspond to the sign bit and m.s.b. in another channel.

To generate sample-word concealments those error pulses falling within the appropriate 6-bit parity group were counted. An odd number of errors caused a pulse to be produced which inhibited the d.a.c. from forming a new sample. Switches enabled the correct parity group to be selected for each condition.

In addition, one 3-bit parity group was formed from the two-bit scale factor and one spare bit. To generate scale-factor word concealments the number of error pulses falling within the 3-bit parity group was counted and the digit stream containing the scale-factor words (with errors) was altered so as to repeat scale-factor words if the number of errors was odd. Circuits were provided to inhibit this operation when the linear code was selected.

6.3. Listening tests

Listening tests were conducted with the conditions as described in Section 4.1. Programme material included solo trumpet, solo piano and speech. Three listeners, experienced in assessing high-quality sound signals, compared the subjective impairment heard when errors were introduced into digitally companded signals, error-protected as proposed in Section 5.4.3, and into linearly-coded signals, error-protected as described in Section 6.2(a). The impairment heard in the digitally companded channel with the sign and two most significant bits protected was slightly less than that in the channel with the sign and the most significant bit protected. The impairment heard in the latter channel was closely similar to that heard in the error-protected linearly-coded channel.

7. Conclusions

The effect of transmission errors in digital sound p.c.m. systems using both linear coding and near-instantaneous companding has been investigated. In general, the companded system is found to be more immune to the effects of errors than a linearly-coded system and consequently the proportion of parity bits required for error protection can be reduced. Firm recommendations, based on the results of an accurate simulation, are made for an error protection scheme for a p.c.m. system which uses a four-slope, near-instantaneous compandor. When such a companded signal is protected as recommended, a just perceptible impairment would be produced for an error probability of 10^{-5}. In the system the rate of transmission of parity bits per channel is approximately 17 kb/s whereas in the linearly-coded system now in BBC service the corresponding rate is 32 kb/s. Since it is not yet known what transmission codes will be used in practice, the investigation was made with binary codes only. Ternary codes such as HDB3 or 4B3T are likely transmission codes. Further work may be required when the exact form of code has been decided.

8. Recommendations

It is recommended, as a result of the work described in this report, that the 2·048 Mb/s multiplexing system for six high-quality sound channels be protected from digital transmission errors by parity checking, the parity check bits being employed as follows:

(a) One parity bit for the sign and two most significant bits of one sample word together with the sign and most significant bit of another sample word taken from a different channel.

(b) One parity bit for each scale-factor word.

It is further recommended that, when an error is detected, the procedure for the concealment of that error be as follows. When an error is detected in a parity group corresponding to (a) above, the erroneous sample-words should be replaced by the previous correct sample-word in each of the two channels, and when an error is detected in a parity group corresponding to (b), the erroneous scale-factor word should be replaced by the previous correct one.

9. References

1. MITCHELL, G.R. *and* MOFFAT, M.E.B. 1972. Pulse-code modulation for high-quality sound-signal distribution: subjective effect of digit errors. BBC Research Department Report No. 1972/40. Also available in BBC Engineering, 1973, No. 96, pp. 27 – 33.

2. CHEW, J.R. *and* MOFFAT, M.E.B. 1972. Pulse code modulation for high-quality sound signal distribution: protection against digit errors. BBC Research Department Report No. 1972/18.

3. CROLL, M.G. 1971. Pulse code modulation for high-quality sound signal distribution: simulation of an advanced form of error protection. BBC Research Department Report No. 1971/37.

4. OSBORNE, D.W. *and* CROLL, M.G. 1973. Digital sound signals: bit-rate reduction using an experimental digital compandor. BBC Research Department Report No. 1973/41.

5. CROLL, M.G., OSBORNE, D.W. *and* REID, D.F. Digital sound signals: multiplexing six high-quality sound channels for transmission at a bit-rate of 2·048 Mb/s. BBC Research Department Report No. 1973/42.

6. MOORE, T.A. 1973. Digital transmission codes: preliminary investigation of HDB3 and related ternary codes for broadcast signal distribution. BBC Research Department Report No. 1973/21.

7. CCITT, 1957, Red Book, Vol. III, p. 273.

SMW/AMM