# COUNTERACTING THE QUANTISATION NOISE FROM PCM CODECS

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## ABSTRACT

Since a large majority of telecommunication connections now involve digital PCM, the quantisation noise from PCM codecs is of concern to those transmitting data. This paper presents the effect on performance of passing a modem signal through PCM systems. It also assesses the effectiveness of some simple coding schemes in counteracting the quantisation noise produced by PCM codecs.

## INTRODUCTION

In 1984, Maijers (1) studied the effect of PCM codecs on existing modems and found that they did not cause any problems. In that year the CCITT defined the V.32 modem (2) which incorporated coded modulation. The coding scheme was chosen on the performance advantage it gave in Additive White Gaussian Noise (AWGN).

Presently the CCITT are working towards a new modem recommendation. Under this recommendation, new modems are likely to utilise a greater proportion of the available bandwidth than any previous modems. They will also aim to achieve data rates ≥ 24 kbit/s. It is therefore timely to re-address the effect that PCM codecs may have on the performance of such modems.

This paper presents results obtained at BT laboratories on the performance of a modem transmitting its signal through a PCM codec. These results show that for the more ambitious aims of the current CCITT study group, the effect on performance of PCM codecs is significant. The paper continues by considering a pair of simple coding schemes that have been designed to counteract the quantisation noise caused by the PCM codecs.

## WHEN DO PROBLEMS OCCUR?

A PSTN modem that is compatible with the V.32bis CCITT standard has been designed at BT laboratories (3). In order to test the effect of PCM codecs on such a modem, modifications were made to the symbol rate and the data rate that the modem is capable of using. All the filters were originally implemented in digital signal processors so their responses are automatically scaled as the symbol rate changes. The transmitted signal from the modem was fed directly into a Texas Instruments combined single-chip PCM codec and filter (the TCM2913). This chip was used to digitise the analogue signal and then recreate a copy of the analogue signal from the 8 kHz digital samples. The analogue output signal had AWGN added to it before being fed to the modem's receiver. The data stream leaving the modem was checked for bit errors and 1000-bit block errors.

The bit error performance of this system was measured for various combinations of symbol rate and constellation size. This performance was compared to the performance observed when AWGN was the only impairment. The results of these comparisons are presented in table 1 below.

TABLE 1 - Degradation with 1 PCM codec.

No entry indicates 0 - 0.2 dB, * indicates 0.2 - 0.5 dB and ** indicates greater than 0.5 dB.

| | 64 pts | 128 pts | 256 pts | 512 pts |
|---|---|---|---|---|
| 2400 sym/s | | | | |
| 2800 sym/s | | | | * |
| 3000 sym/s | | | * | ** |
| 3200 sym/s | | | ** | ** |

The effect of a PCM codec is negligible for most combinations of symbol rate and constellation size. When using combinations that provide data rates under 21.6 kbit/s, the effect of quantisation noise from PCM codecs need not be considered. However for combinations providing data rates of 24 kbit/s and above, this type of noise can become a serious problem.

The measured amplitude response of a PCM filter pair is shown in figure 1. This response shows a clear pass band between 200 Hz and 3400 Hz. Outside this range the filters roll off fairly steeply. The carrier frequency for all the symbol rates in table 1 was therefore set at 1800 Hz.

## WHAT EFFECT DO WE SEE?

PCM codecs are designed to try to keep the signal to quantisation noise ratio constant for a range of signal amplitudes. This means that the absolute quantisation noise will be larger for the larger signals. However the signals in question are the 8 kHz samples of the analogue signal entering the PCM codec. It is not clear how to relate the extra noise on these large signals to the noise on the QAM symbols sent by the modem. A simple model would be to alter the variance of a noise source with the power of the transmitted QAM symbol. This of course takes no account of the changes in sampling rate through the transmission path and gives a pessimistic view of the actual noise encountered. More elaborate characterisations of the quantisation noise from PCM codecs have been proposed by Pahlavan and Holsinger (4) and Saltzberg and Wang (5). In all of these models the noise around the outer points of the QAM constellation is worse than the noise around the inner points.

Pahlavan (6) has shown that, under his model of PCM quantisation noise, it is possible to achieve a performance gain by altering the signal constellation that is used to give a greater distance between the outer points than between the inner points. Betts (7) has applied this idea by projecting the signal constellation onto a non-linear mathematical surface before transmission.

Another effect has been observed when using multidimensional coded modulation over channels including a PCM codec. There are more short (< 10 bits) error events caused by a channel including a PCM codec than by an AWGN channel with a comparable bit error rate. That is, the type of errors produced by a channel including a PCM codec seem to differ from those produced by an AWGN channel.

In order to reduce constellation expansion and so improve performance, multidimensional trellis–coded modulation has been widely accepted as beneficial. Wei (8) describes the principles of such schemes as well as giving several examples. Unfortunately, to control complexity, the number of 2D subsets used to construct the code is kept low. This can result in codes with a minimum distance determined by the intra-subset distance of the 2D subsets. When such codes are passed through PCM codecs, they seem to suffer from more errors caused by decoding to the wrong point in the right 2D subset than they do over an AWGN channel. If the constellation is to remain unchanged, a change is needed in the coding to counteract these errors. Either a code with larger intra-subset distance is needed (normally leading to greater complexity) or a method of mopping up single symbol errors must be used (leading to greater redundancy). The use of extra coding to reduce the number of single symbol errors is considered below.

## MOPPING UP SINGLE SYMBOL ERRORS

To transmit 24 kbit/s at 3200 sym/s, 7.5 information bits per symbol are needed. If these are encoded using the 4D Wei code in Section IV-A of (8) then each symbol may be transmitted from a 256 point signal constellation. This 4D Wei code used has a minimum distance equal to its intra-subset distance. Also, table 1 shows that the performance of a 256 point signal constellation degrades appreciably when it is transmitted at 3200 sym/s through a PCM codec. This scheme was therefore used to test the effectiveness of adding extra coding to counteract single symbol errors.

When using the 4D Wei code there are two types of single symbol errors. These are single 2D QAM symbol errors and single 4D code symbol errors. Both can be detected (and hopefully corrected) by using single parity check codes. Each parity check code carries a penalty of one bit per code block. To keep this overhead to a reasonable level, without degrading the effect of the parity check codes, a block length of 16 QAM symbols was chosen for the symbol rate of 3200 sym/s.

### Correcting single 2D symbol errors

In order to correct a single 2D error each 2D subset is divided into odd and even points. The minimum distance between points in either half of the subset is $\sqrt{2}$ times the minimum distance between points in the whole subset. For each QAM symbol, 1 bit determines which half of the subset a point is in. 15 of these bits are coded with a single parity check code to determine the value of this bit for every 16th QAM symbol. If, in the receiver, this code is found to fail, the received point furthest from its decoded point is decoded instead as the nearest point in the other half of the decoded subset. The decoded points now satisfy the parity check code and a single 2D error should have been corrected.

### Correcting single 4D symbol errors

A single 4D error of minimum distance will occur when the wrong pair of 2D subsets has been chosen to represent the decoded 4D subset. This type of error can again be corrected by applying a single parity check code. The choice between which pair of 2D subsets represents each 4D subset is made by 1 bit in the transmitter for each pair of QAM symbols. If this bit is coded with a parity check code a single 4D error can be detected. If such an error is found then the pair of received points that are furthest from their decoded points are decoded instead as points from the alternative pair of 2D subsets. This corrects the parity check code and should clear up single 4D errors. The parity check code in this case has the additional problem that it must be consistent with the differential encoding. Luckily this is easily ensured.

### Potential gain from the parity check codes

Since each single parity check code adds an extra 1 bit of redundancy this will affect the performance. An extra bit is transmitted using a pair of QAM symbols from a

384 point signal constellation (see Section IV,C in Forney et al (9)). If this is done once in a block of 16 QAM symbols there is a degradation of about 0.2 dB. If it is done twice (once for each parity check code) then there is a degradation of about 0.4 dB.

The parity check code that corrects single 2D symbol errors reduces the number of nearest neighbours of the overall coding scheme. This helps the performance of the decoder to an extent that compensates for the 0.2 dB degradation. In AWGN this scheme would be expected to perform similarly to the 4D code alone. However, if single 2D symbol errors are more prevalent in a channel containing PCM codecs, the parity check code should help the coding scheme to show a nett performance gain over this channel.

Given that the 2D parity check code is implemented, the inclusion of the 4D parity check code will raise the minimum distance of the whole coding scheme. Unfortunately it will also increase the number of nearest neighbours at the new minimum distance. This increase in nearest neighbours along with the 0.4 dB degradation from the use of 2 extra bits will negate (over an AWGN channel) the extra distance advantage of the code. A channel containing PCM codecs should produce the type of errors that this coding scheme is designed to correct and so on such a channel this scheme should also improve performance.

## TESTING THE THEORY

To test the above theory the BT laboratories modem (3) was modified to use the schemes described above. Three coding schemes were used to transmit 24 kbit/s at 3200 sym/s. These were,

(1) the 4D Wei code only;

(2) the 4D Wei code + the 2D parity check code and;

(3) the 4D Wei code + the 2D and the 4D parity check codes.

The three schemes were tested over an AWGN channel, a channel with 1 PCM codec in it and a channel with 2 PCM codecs in it. The results are shown in figures 2 to 4 respectively.

As can be seen from these graphs, in the first two cases, the coding schemes behave very much as predicted. Statistical significance could only be attached to bit error rate measurements above $10^{-5}$. Under normal operating conditions this would be close to the acceptable ceiling for the bit error rate of a PSTN modem. At working error rates it would be expected that the schemes would conform with theory.

It is also clear from figures 2 and 3 that the slope of the error curve increases as the parity check codes are added. This suggests that the relative performance of these schemes will continue to improve as the bit error rate falls. It also means that small variations in channel conditions could have a large effect on the error rate.

An effect of adding the second parity check code was that the number of bit errors per error event increased. For the AWGN channel the average length of an error event went from around 37 bits with one parity check code (similar to the average length with no parity check codes) to just over 45 bits with two parity check codes. For the channel with 1 PCM codec the average error event length increased from 32 bits to 45 bits with the addition of the second parity check code. This means that if this code combination's block error rate had been used for comparison, its performance would look slightly better. On the other hand if an application requires error extension to be minimised, this approach to improving the modem's performance through a PCM codec could be undesirable.

Over a channel containing 2 PCM codecs the modem's performance is poor. Figure 4 suggests that, when transmitting at high data rates through cascaded PCM codecs, the extra constellation expansion due to the added redundancy outweighs the benefit gained from the inclusion of the extra coding. It was generally noted during this work that if the modem's performance was not significantly degraded by 1 PCM codec it also coped well with cascaded PCM codecs. However if 1 PCM codec caused a noticeable decline in performance then the modem suffered severe degradation from cascaded PCM codecs.

## CONCLUSION

A V32.bis modem has been modified to transmit at higher symbol rates and higher data rates. The modem's performance was then tested over a channel that included a PCM codec. Mostly there was little degradation in performance over that found on an AWGN channel. However, combinations of symbol rate and constellation size that are capable of transmitting $\geq$ 24 kbit/s did suffer from the presence of a PCM codec.

An effect of the PCM codec at these data rates was to increase the occurrence of short (< 10 bits) error events. Since a 4D Wei code was being used these error events are indicative of single 2D symbol errors. A simple parity check code was incorporated with the 4D Wei code to reduce the number of such errors. In AWGN the new scheme had similar performance to the original scheme. Over a channel including a PCM codec the new scheme improved the modem's performance. Unfortunately this improvement was not large enough to entirely mitigate the effect of the PCM codec.

A further parity check code, that was designed to clear single 4D symbol errors, was added to the coding. This combination of coding schemes performed similarly to the scheme with one parity check code. There was some evidence that this scheme's performance may be more flattering in terms of block error rate.

When the inclusion of one PCM codec significantly degraded the modem's performance, the inclusion of more PCM codecs had a severe effect on it. In these cases, the inclusion of extra codes to improve the performance did not help. The burden of extra redundancy needed to implement the codes seemed to outweigh the benefit gained from them.

The main conclusion to be drawn is that, when designing a modem to transmit at high symbol rates (≤ 3200 sym/s) or at high data rates (≤ 24 kbit/s), it is prudent to consider the effects of PCM codecs on all aspects of the modem's design.

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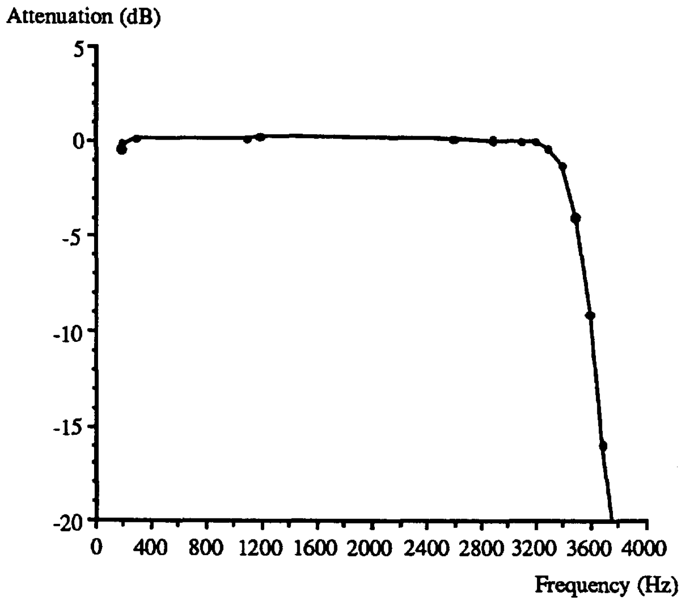


Figure 1. Amplitude response of 1 PCM codec pair.

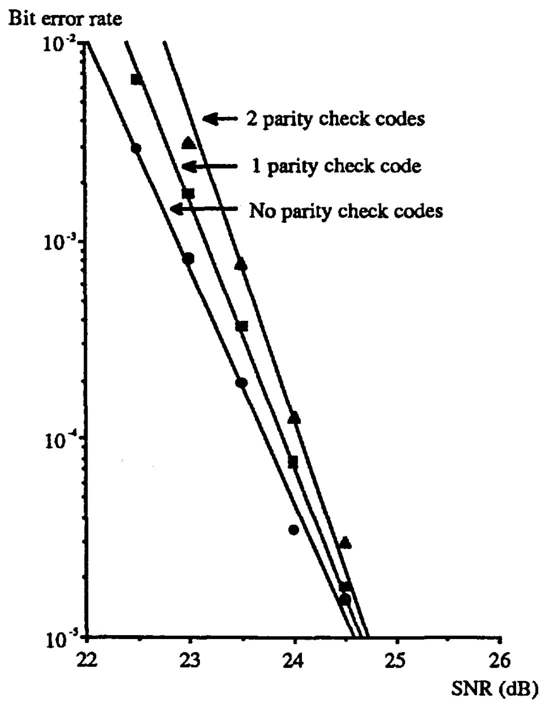


Figure 2. Error performance of coding schemes in AWGN.

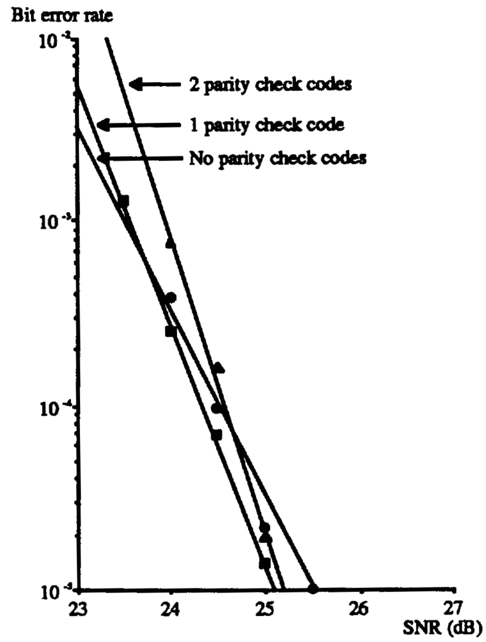


Figure 3. Performance of coding schemes over 1 PCM codec pair.

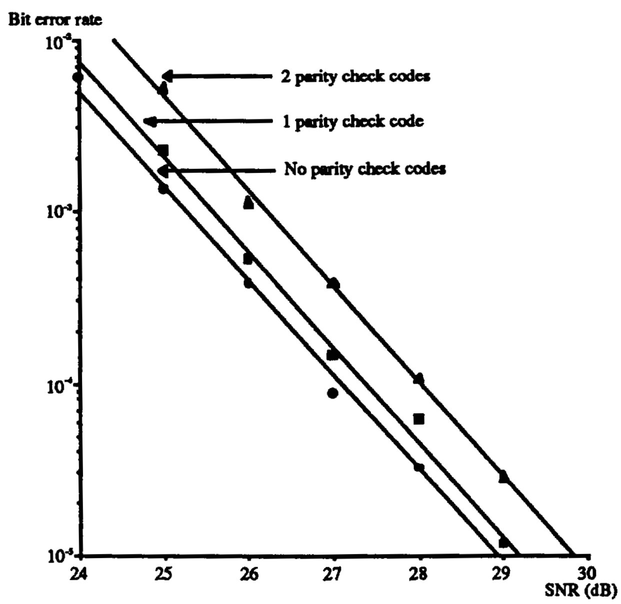


Figure 4. Performance of coding schemes over 2 PCM codec pairs.