Comparison of Two Level and Three Level Coding Techniques for S100 1394B UTP5 Links

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1.0 Summary

The 1394B UTP task group is studying the feasibility of S100 1394B operating over category 5 UTP cable. Given the existence of 100Base-Tx, ATM-155 and FDDI TP-PMD standards which all operate at >100Mbaud on category 5 UTP, S100 1394B is clearly feasible. However, there is a potential for a simpler, lower cost solution than these other standards if the cable length is reduced from 100m to, say, 50m. One obvious simplification would be to replace active equalizers with passive equalizers.

Assuming that a fixed passive equalizer is sufficient for a 1394B solution, one question that has been raised is whether the binary 8B10B code adopted by 1394B will perform better or worse than the 100Base-TX MLT3 code. This paper examines the relative performance of a binary signaling scheme and an MLT3 signaling scheme in an equalized UTP channel. Particular attention is given to the performance of these codes with fixed equalizers.

The two level code performs significantly better than the three level MLT3 code when fixed equalizers are used (and also with adaptive equalizers). Fixed equalizers may be used with a two level code for cable lengths up to at least 50m without incurring an intersymbol interference penalty. Ultimately the range that may be achieved on UTP5 with the two level code will depend upon the level of ingress noise and radiated emissions that the group chooses to tolerate.

This paper also discusses other well known drawbacks of the MLT3 code.

2.0 Coding options

MLT3 is a three level line code that is designed to concentrate energy towards low frequencies (by spectral shaping), where radiated emissions regulations are easier to satisfy. It was adopted by FDDI TP-PMD (FDDI over UTP cable). The FDDI standard is now referenced by 100Base-TX.

The FDDI physical layer consists of a 4B5B block code, followed by a scrambler and then an MLT3 coder. The symbol rate is 125Mbaud for a data rate of 100Mb/s. FDDI uses a 4B5B code to control the dc content of the transmitted signal, and to provide some non-data codewords for

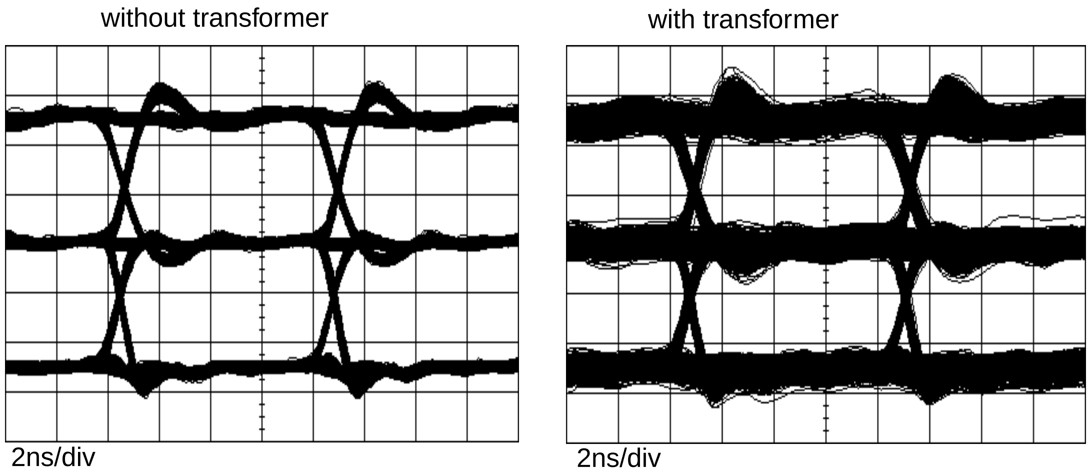


Figure 1 MLT3 eye diagrams with and without transformer coupling, showing effect of baseline wander.

control signalling. The scrambler and MLT3 coder were added to the fibre-optic form of FDDI to create the UTP physical layer. The scrambler is necessary to prevent symbol patterns with large radiated emissions characteristics. (Without the scrambler the FDDI Idle sequence of 101010... would cause discrete lines in the transmitted signal spectrum.) However, in doing so it destroys the dc control provided by the 4B5B code. This rather unfortunate situation was dictated by the existing FDDI architecture which prevented a scrambler being placed in a more suitable position before the 4B5B code.

A serious drawback of the MLT3 line code is that it has a large dc component in its spectrum which causes baseline wander distortion. Baseline wander is a term used to describe the distortion of long sequences of all +1 or all -1 symbols due to the low frequency block of transformers. The effects of the baseline wander can be seen in Figure 1. The figure shows two eye diagrams measured at the output of an experimental MLT3 transmitter with and without transformer coupling. Severe distortion occurs when the transformer is present. This distortion can in fact be much more severe than shown here if there is a persistent imbalance between the number of +1 and -1 symbols. 100Base-TX transceivers generally incorporate an equalizer to limit the effects of this distortion. This equalizer is in addition to any cable equalization.

Three level line codes also introduce additional complexity in receiver circuitry since the receiver is required to adapt its two decision thresholds as the amplitude of the received signal changes (i.e. as cable length changes). In contrast the threshold voltage in a two level receiver remains fixed at 0. This will be illustrated by the results contained in section 3. These results will also show that fixed equalization can result in much greater penalties with three level codes than two level codes.

P1394B has adopted an 8B10B block code to achieve a d.c. balanced signal. The code has been designed to have the following features:

- No d.c. content and limited length sequences of 1’s or 0’s. i.e. very little baseline wander distortion.
- Suitable for use with a scrambler.
- Non-data codewords available for signalling arbitration line states.
- A number of useful error detection features.

An alternative to MLT3 coding for UTP links is to use binary signaling i.e. to transmit unmodified 8B10B codewords. The modifications that HP has proposed for the 8B10B code were made with this in mind. Binary signaling is much simpler to implement than any 3 level code, and the results presented in section 3 will show that the binary signaling performs better than MLT3 for both adaptive and fixed equalizers. In particular, when fixed equalizers are used, the binary signaling system has significantly better performance than the 3 level system.

3.0 Performance with simple equalizers

The performance of a binary and an MLT3 system have been simulated. Both systems have the same symbol rate (125Mbaud). A linear feed forward digital filter with taps spanning five symbol periods is used to equalize a category 5 UTP channel that contains two transformers with 5kHz high pass cutoff and two 4th order Butterworth low pass filters which have 3dB loss at the symbol rate. Performance results are presented for an adaptive and a fixed equalizer. It is anticipated that a cost effective solution for long distance 1394 would not use adaptive digital filtering, but rather a fixed equalizer.

3.1 Adaptive equalizer

For each system the performance with an adaptive filter is analyzed. Performance is measured as Signal to Noise Ratio (SNR) against length of cable. For each cable length the filter is adapted to give minimum mean square error about the nominal received symbol levels. The SNR is plotted against cable length in Figure 2. For a bit error rate (BER) of 10^-10, a SNR of 16.1dB is required for the two level system and a SNR of 19.1 dB is required for the 3 level system. The SNR margin, that is the difference between the SNR achieved and that required for a BER of 10^-10, is also plotted in Figure 2.

3.2 Fixed Equalizer

For the adaptive equalizer the performance was measured in terms of the SNR. This is a useful measure when the probability distribution of the noise closely approximates a Gaussian function. For a reasonably well equalized system this is the case, and the BER can then be related to the SNR. Figure 3 shows the eye diagram at the output of an equalizer adapted to compensate a 100m cable. The distribution of the signal samples at the output of the equalizer is also shown, and it can be seen that the assumption of Gaussian noise distribution is reasonable.

However, when a channel is badly misequalized (for example a fixed equalizer designed to compensate a long cable is used with a short cable), the probability distribution of the noise becomes distinctly non-Gaussian. This is true for both two and three level systems. Figure 4

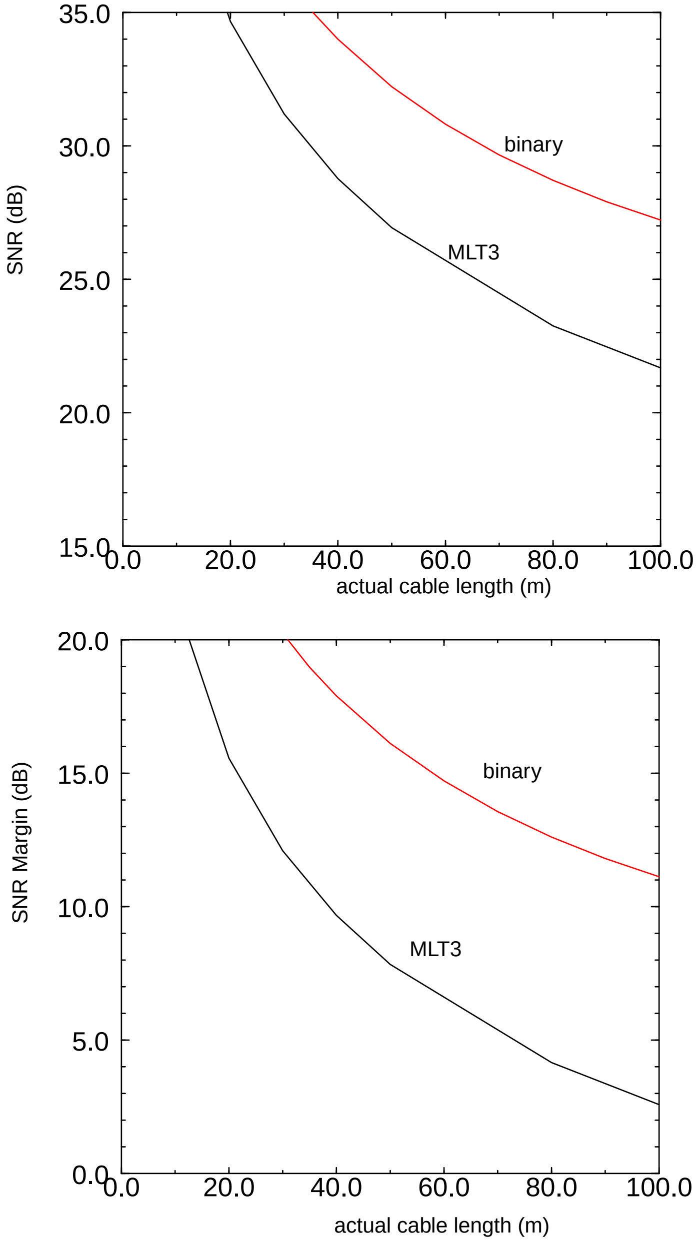


Figure 2 Signal to Noise Ratio (SNR) and SNR margin for 10^{-10} BER

shows the eye diagram and distribution of samples at the output of an equalizer compensating for 100m of cable when only 50m of cable is present.

Since the noise at the output of a mismatched equalizer is non-Gaussian, any analysis based on SNRs will be erroneous. For example, consider a two level system with a fixed equalizer compensating for 50m of cable. From Figure 2, the SNR margin when a 50m cable is present is 16dB. If the cable length is reduced to 10m with the equalizer fixed at 50m, the apparent SNR margin would be reduced to 0dB. However, from the eye diagrams at the equalizer output,

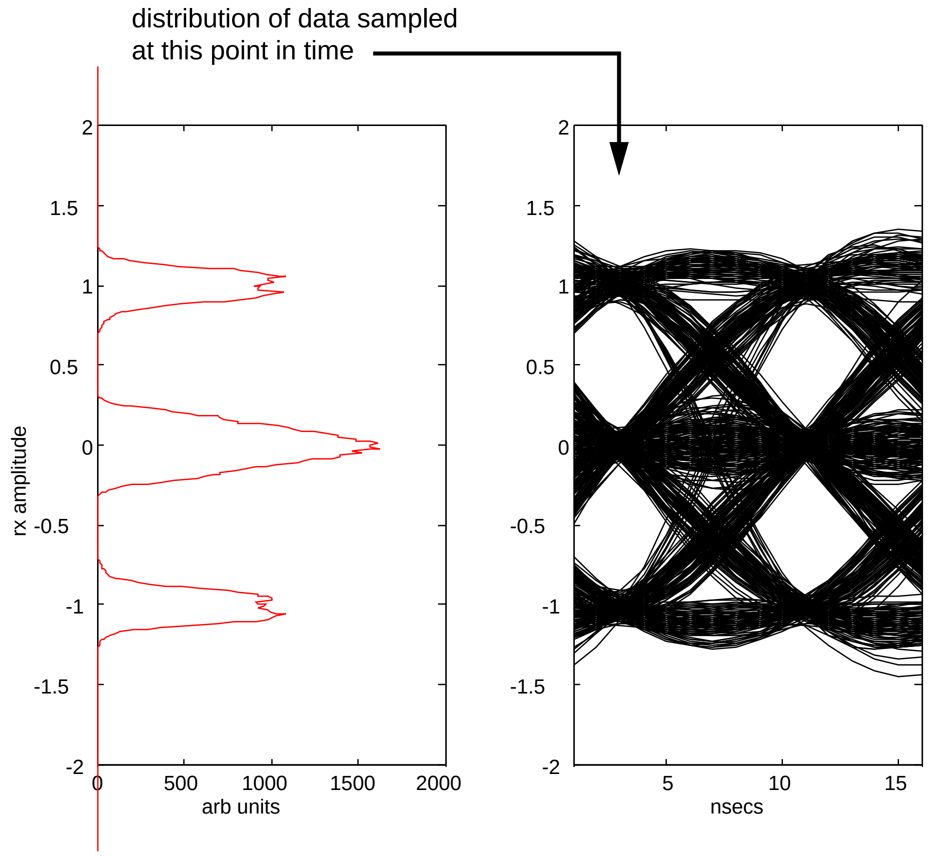


Figure 3 Distribution of sample amplitudes at output of adaptive equalizer compensating a 100m cable with MLT3 coded data, and associated eye diagram.

which are shown in Figure 5, it is clear that in the case of a 10m cable, the SNR margin is misleading as the noise is not Gaussian. The low SNR reflects the fact that there is a large amount of overshoot, which does not cause the eye opening to be reduced. The eye opening is in fact larger for the 10m cable than the 50m cable.

Performance measures based on the SNR margin are clearly flawed when an equalizer is fixed and mismatched to cable length. A better alternative is to measure the vertical decision distance at the optimum sampling time. The decision distance is the amplitude separation between samples associated with any symbol level and the nearest decision threshold. It represents the margin between the actual signal samples and the threshold at which an erroneous decision might be made. This is illustrated in Figure 5. The larger the decision distance the greater the immunity to noise causing detection errors.

3.2.1 Two level system

Simulations have been used to find the decision distance at the output of fixed equalizers for a range of cable lengths. In each case the equalizer has been adapted to give optimum performance with a given cable length, and then fixed while the cable length is varied. The results with the two level system are shown in Figure 6.

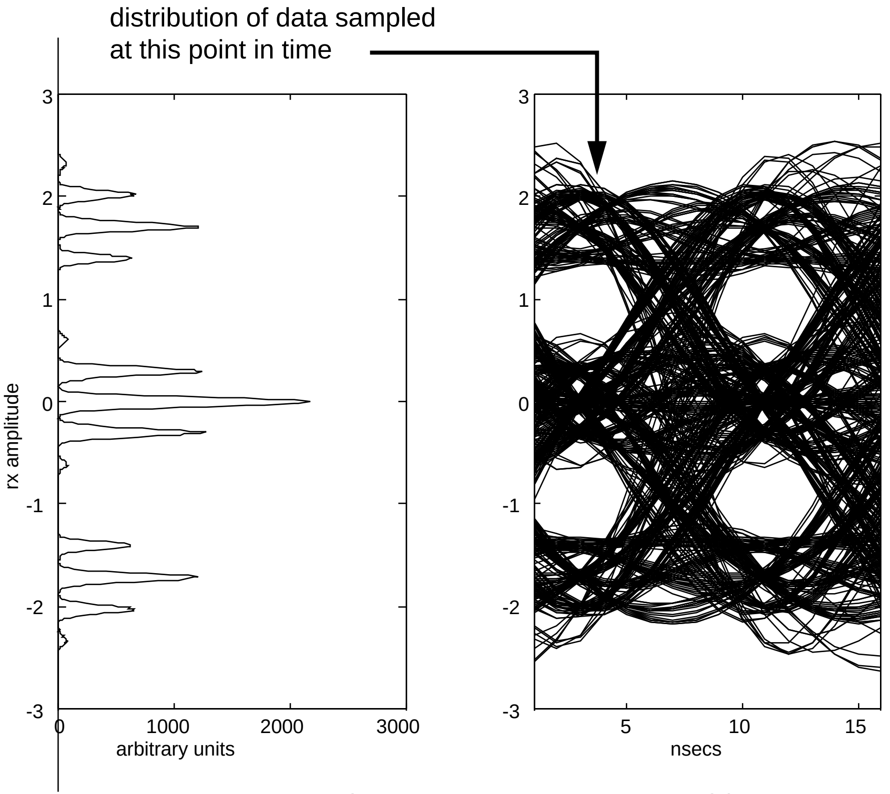


Figure 4 Distribution of sample amplitudes at output of fixed equalizer compensating a 100m cable, with actual cable length of 50m and MLT3 coded data, and associated eye diagram.

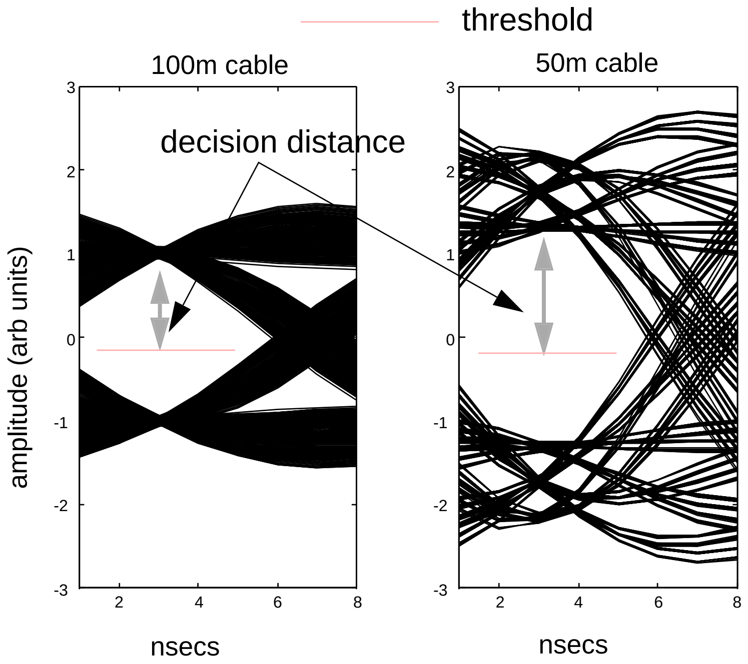


Figure 5 Eye diagrams at the output of a fixed equalizer compensating a 100m cable, for actual cable lengths of 100m and 50, with two level signaling.

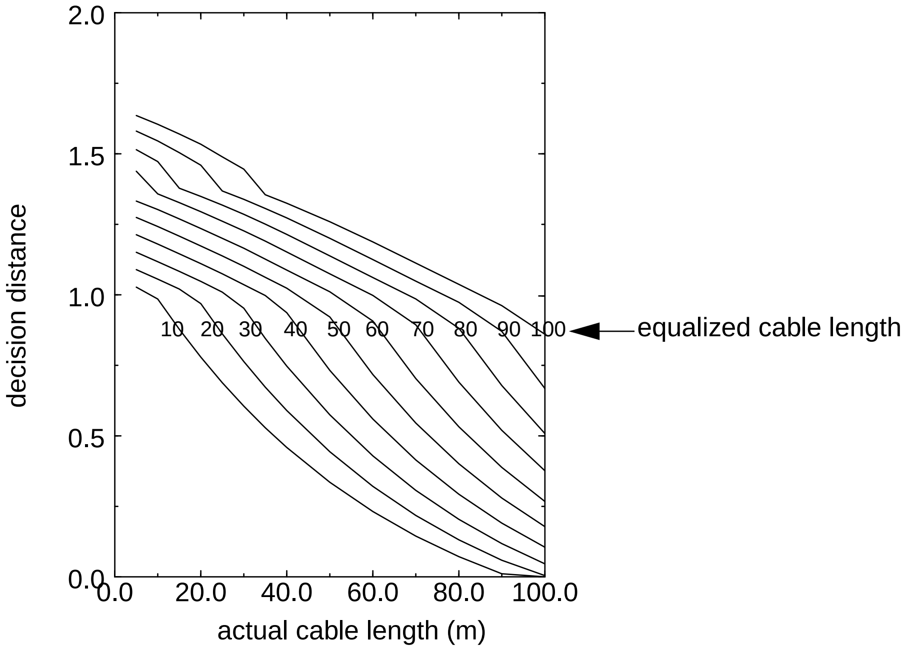


Figure 6 Decision distance at output of fixed equalizers compensating for a range of cable lengths, with two level signaling.

The performance of the two level scheme with fixed equalizers is very good. The decision distance always increases as cable length decreases. For example, if a fixed equalizer is used that compensates for 50m of cable, then for any cable length shorter than 50m the decision distance will actually be better than that at 50m.

3.2.2 Three level MLT3 code

We have already seen that with adaptive equalization the three level MLT3 coded scheme suffers a penalty with respect to the two level system. MLT3 also has inferior performance with fixed equalizers. The decision distance, shown in Figure 7, reduces when cable lengths are shorter than that compensated by the fixed equalizer. In fact, if a 20m cable is used with an fixed equalizer compensating for a 100m cable, then the decision distance is reduced to zero.

The difference between the two level code and three level code may be understood by examining the eye diagrams at the output of the fixed equalizer. Figure 8 shows these for cable lengths of 30m, 50m and 100m with a fixed equalizer compensating for a 100m cable. When shorter cable lengths are used the overshoot caused by the excessive equalizer gain at high frequencies encroaches into the amplitude separation of the middle and outer symbol levels, and reduces the decision distance. Although overshoot also occurs with the two level code, it does not encroach into the decision distance (see Figure 5).

A further disadvantage of the three level scheme is that as the cable length changes, the optimum threshold levels change. The optimum threshold levels (the threshold used to determine one symbol level from another) are close to the midpoint of the vertical eye openings. The optimum threshold levels for each cable length are marked on the eye diagrams

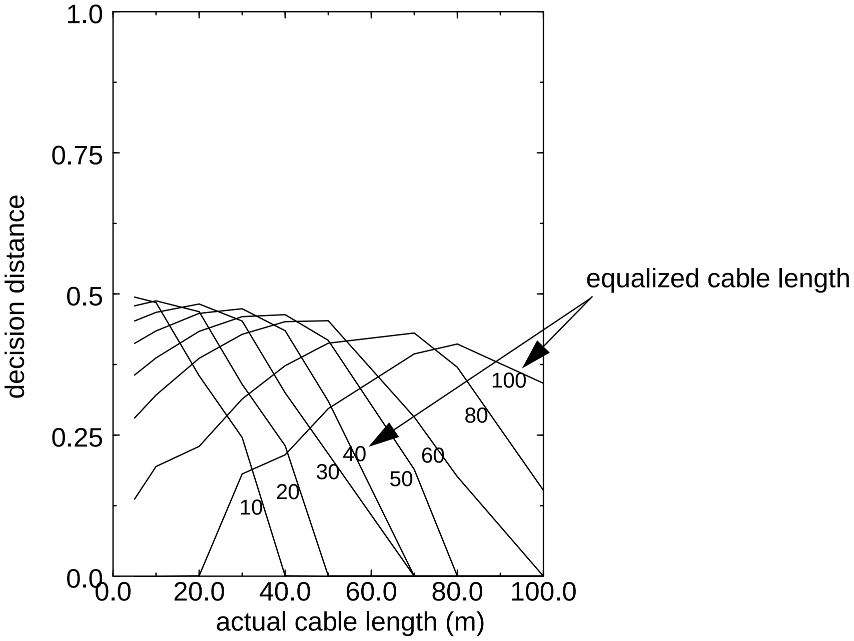


Figure 7 Decision distance at output of fixed equalizers compensating for a range of cable lengths, with MLT3 coded data.

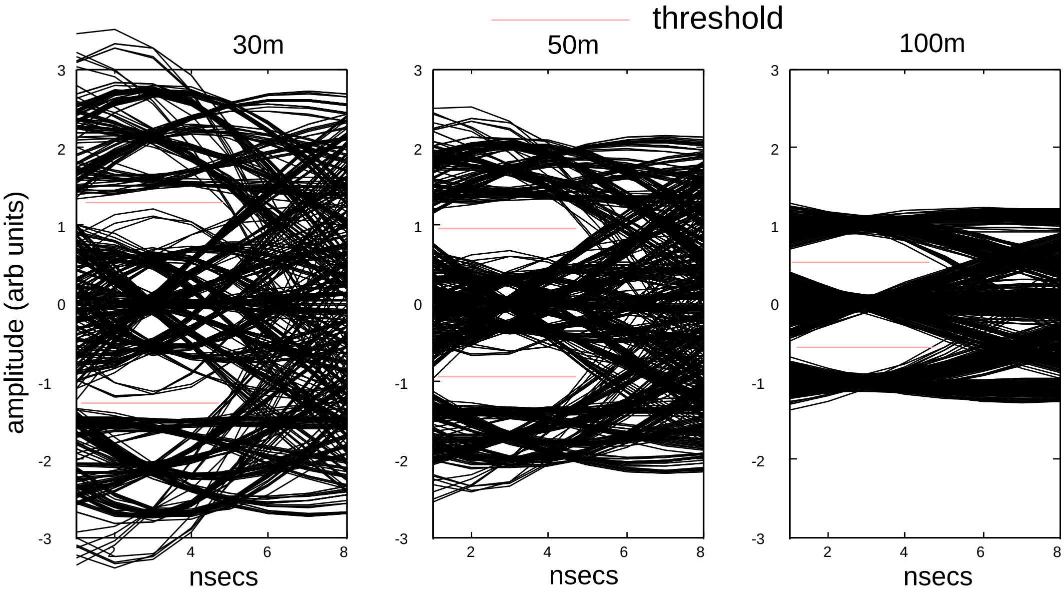
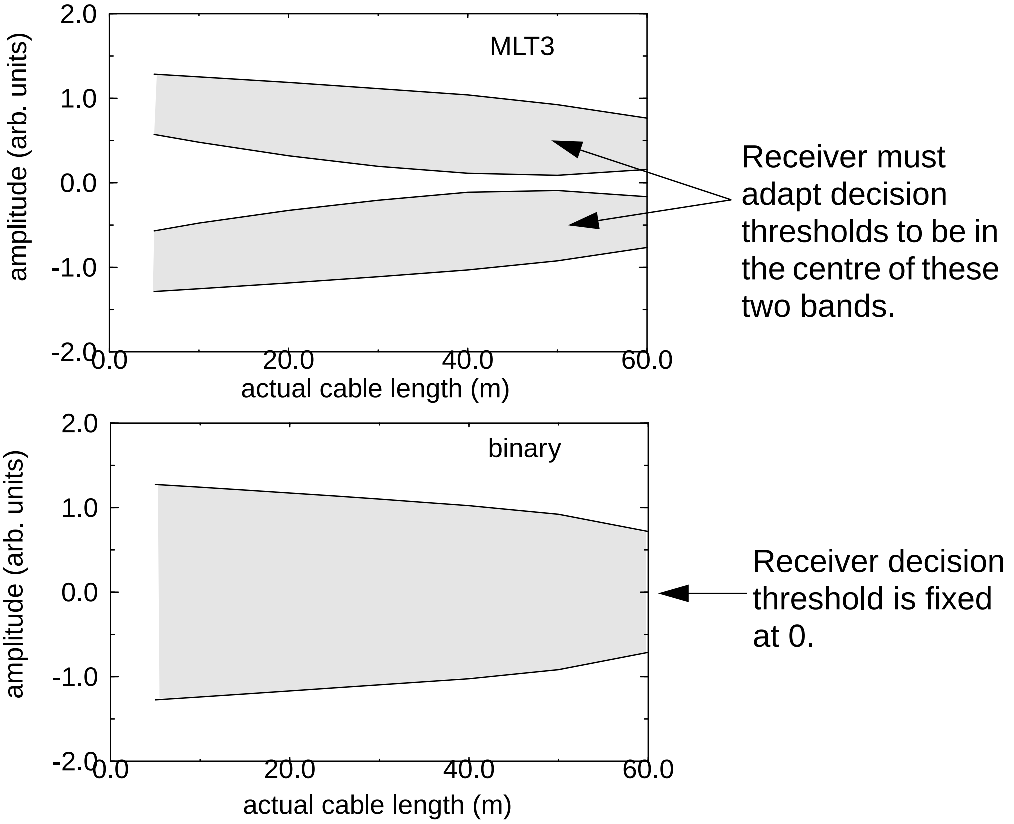


Figure 8 Eye diagram at output of fixed equalizer compensating a 100m cable, for actual cable lengths of 30m, 50m, and 100m, with MLT3 coded data.



Receiver must adapt decision thresholds to be in the centre of these two bands.

Receiver decision threshold is fixed at 0.

Figure 9 Range of amplitudes covered by eye openings (shaded) for a fixed equalizer compensating a 50m cable.

in Figure 8, where the eye openings can be seen to shift vertically as the cable length changes. A receiver in a three level system is therefore required to adapt its threshold values according to the length of cable attached. This is a complexity that is not required with the two level code.

In Figure 9 the ranges of the two eye openings are plotted against cable length for an MLT3 system with a fixed equalizer compensating a 50m cable. This figure further illustrates the shifting threshold levels and smaller decision distances compared with the two level code.

The two level scheme clearly outperforms the MLT3 scheme at all cable lengths.

4.0 Conclusions

The suitability of two and three level codes for equalized UTP5 channels has been studied. Particular attention has been given to simple fixed equalizers. With fixed equalizers, the two level code maintains a larger decision distance and therefore greater immunity to noise than the three level MLT3 code. It therefore has the potential for transmission over longer cables than MLT3.

It is possible to mistakenly infer apparently poor performance with fixed equalizers if it is assumed that the noise due to intersymbol interference in links with mismatched fixed equalizers has a Gaussian distribution. We have shown that the approximation to a Gaussian distribution is inappropriate and indeed exaggerates the intersymbol interference penalty seen with fixed equalizers. We have presented a more realistic performance measure, which reveals that with a two level code fixed equalizers are suitable for cable lengths of at least 50m.

In summary:

- Fixed equalizers perform better with two level codes than three level codes.
- Simulations predict that cable lengths of 50m are possible with fixed equalizers and a two level code.