100 Mb/s Data Transmission on UTP and STP Cabling for Demand Priority Networks

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demand priority, unshielded twisted pair, shielded twisted pair

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Abstract- Recently there have been considerable advances towards higher speed (100Mb/s) workgroup LANs which support the existing UTP and STP structured cabling currently utilized by 10BASE-T and Token Ring LANs. This paper describes the transmission techniques used by an IEEE 802.12 Demand Priority network with UTP and STP structured cabling. The UTP transmission scheme supports category 3, 4 and 5 UTP (i.e. voice-grade and data-grade) using a 5B6B block coded binary signalling scheme on four pairs. This binary signalling scheme is shown to provide better immunity against crosstalk and external (impulse) noise than multilevel signalling schemes. The STP scheme combines the strengths of the 5B6B block code with signalling technology similar to existing SDDI links.

I Introduction

The vast majority of existing Local Area Network (LAN) connections are to either a 10Mb/s IEEE 802.3 ("Ethernet") or a 4Mb/s IEEE 802.5 ("Token Ring") network [1]. Although Ethernet originally supported only coaxial links, since the mid-1980's Ethernet (type 10BASE-T) connections using voice-grade Unshielded Twisted Pair (UTP) cables in a star wired "hub and spoke" topology have been available. These allow standard structured cabling to be exploited, providing for easy reconfiguration and management of the LAN, and have proved a popular alternative to coaxial connections. By 1990, two thirds of LAN connections were to UTP media [2].

Recently there have been considerable advances towards higher speed (100Mb/s) workgroup LANs which support the existing structured cabling currently utilized by 10BASE-T and Token Ring LANs. A draft standard for a 100Mb/s LAN has been developed within the IEEE 802.12 Demand Priority working group [3]. Demand Priority is a round-robin protocol which provides bounded latency and deterministic access to the network, and supports both 802.3 and 802.5 frame formats [4]. The round-robin protocol is implemented in a hub or repeater at the centre of a hub-and-spoke topology network (see Figure 1). The repeater controls traffic flow on the network by receiving requests to transmit from end-nodes, and granting these request in a fair and deterministic manner. Demand priority repeaters may be cascaded to form networks of greater than 2.5km diameter without the need for bridges.

This paper describes the transmission techniques used by a Demand Priority network with UTP and Shielded Twisted Pair (STP) cables. In section II we present an analysis of two approaches to 100Mb/s transmission on UTP cable: multilevel signalling and multipair signalling. The choice of a multipair signalling scheme for Demand Priority LANs using UTP is explained and an example implementation is described. The STP transmission scheme is discussed in Section III.

II UTP Transmission

The objective of the Demand Priority UTP physical layer is to provide the required 100Mb/s data rate using the same media as a 10BASE-T network. 10BASE-T allows links with up to 100m of voice-grade unshielded twisted pair cable, including 25 pair cables and binder groups. The maximum length of 100m was historically chosen to be compatible with popular structured cabling systems which permit cable lengths of up to 90m between wiring closets and wall outlets, and a further 10m of patchcord. Structured cabling has now been standardized by the EIA, in the form of EIA 568 [5] and more recently by ISO in the form of DIS 11801 [6]. These wiring standards define several categories of UTP representing varying degrees of quality. Voice-grade UTP is approximately equivalent to Category 3 cable, and the higher quality Category 4 and Category 5 cables are sometimes referred to as data-grade. The four pair transmission scheme described in this section operates on any Category 3, 4 or 5 cable.

In meeting its objective, the UTP physical layer should provide similar immunity to noise as 10BASE-T. The two most significant sources of noise in a UTP transmission system are crosstalk from other twisted pairs in the same cable and impulse noise induced by other equipment. When connections between a repeater and end nodes are made with one standard four-pair UTP cable per end node, Near End crosstalk (NEXT) noise is insignificant, since only one network link occupies each cable. However, NEXT may be significant if 25 pair cable is used to connect multiple end-nodes to a repeater. (25 pair cables are supported by the IEEE 802.12 Demand Priority standard.) If 25 pair cables are used, NEXT may occur between ports of a Demand Priority repeater whenever a packet is being received at one port and retransmitted at other ports (see Figure 1). In particular, if the packet is retransmitted at a number of ports the crosstalk would increase as the number of retransmitting ports increases. The Demand Priority protocol prevents this accumulation of crosstalk disturbers by implementing a store and forward mechanism for packets with multiple addresses. When repeater ports are connected to a 25 pair cable, packets with multiple addresses are stored by the repeater until reception is complete and then

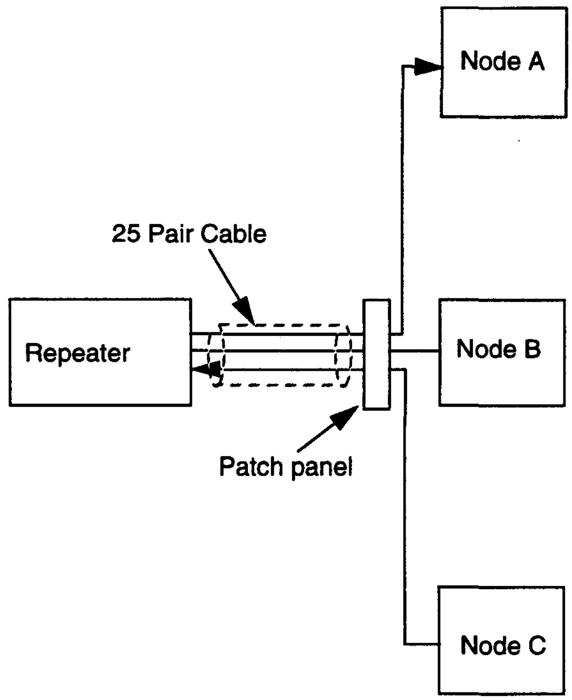

Figure 1: Crosstalk in Demand Priority LANs using 25 pair cables: Node C transmitting to Node A.

simultaneously forwarded to the addressed ports. NEXT is therefore limited to that due to a single disturbing port during simultaneous reception and retransmission of an individually addressed packet.

Impulses with magnitude up to 264mV are permitted on UTP by the 10BASE-T standard [7]. The same level of impulse noise is permitted for the Demand Priority UTP physical layer.

As well as providing immunity to external radiated noise sources, any transmission scheme must itself comply with regulations governing the permissible levels of radiated energy. These regulations apply stringent limits at frequencies greater than 30 MHz. For this reason, we have explored techniques which compress the 100 Mb/s data rate into a channel bandwidth below 30 MHz. Two techniques have been examined: multilevel, or m-ary (m>2), signalling, and multipair signalling. For each technique the performance in the presence of both crosstalk and external noise sources has been analyzed as a function of bandwidth compression.

A. Analysis of multilevel schemes.

For an m-ary transmission scheme, the signal to NEXT ratio may be calculated as follows. Consider the block diagram shown in Figure 2. We assume that the equalizer compensates

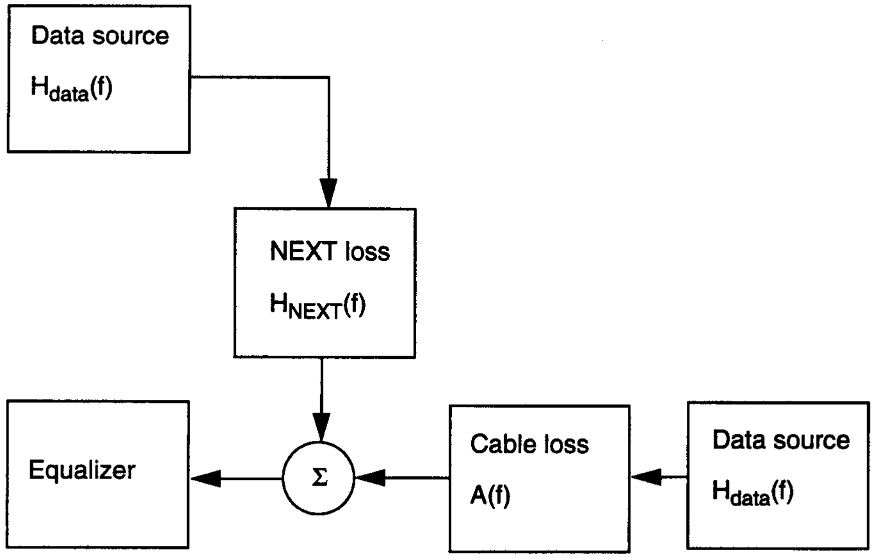

Figure 2: Block Diagram of UTP link with NEXT disturber.

for the cable loss and shapes the transmission channel response to have a raised cosine response of the form:

$$H_{chan}(f) = 1 \text{ for f } < B\frac{(1-\alpha)}{2} \quad (1)$$

$$H_{chan}(f) = 0.5 \times \left(1 - \sin\left(\frac{\pi f}{B\alpha} - \frac{\pi}{2\alpha}\right)\right) \text{ for } B\frac{(1-\alpha)}{2} < f < B\frac{(1+\alpha)}{2} \quad (2)$$

$$H_{chan}(f) = 0 \text{ for f } > B\frac{(1+\alpha)}{2} \quad (3)$$

where f is frequency in Hz, B is the baud rate (symbols per second), and α is the excess bandwidth factor ($0 \le \alpha \le 1$). Crosstalk from a transmitter to a near end receiver is subject to the NEXT loss between the transmitter and receiver, $H_{NEXT}(f)$, but is not subject to the cable loss, A(f). The NEXT noise channel is therefore given by:

$$H_{noise}(f) = \frac{H_{chan}(f) \times H_{NEXT}(f)}{A(f)} \quad (4)$$

The noise voltage due to NEXT at the output of the receiver equalizer may be described in terms of $H_{noise}(f)$ and the disturbing data source, $H_{data}(f)$:

$$N(f) = H_{noise}(f) \times H_{data}(f) \times \sqrt{W} \tag{5}$$

where W is the mean power transmitted by the data source. We next assume that the peak transmit voltage, V, is constant for all schemes i.e. a binary scheme uses symbols of +V, -V; a ternary scheme uses symbols of +V, 0, -V. This is a reasonable assumption because the power supply voltage available to any transmission scheme is generally fixed. For an m-ary scheme with a random choice of symbols the mean power transmitted by the data source is:

$$W = V^2\left(\frac{m+1}{3(m-1)}\right) \tag{6}$$

The rms noise voltage due to NEXT is therefore:

$$v_n = V\sqrt{\left(\frac{m+1}{3(m-1)}\right)B\int_{-\infty}^{\infty}\left(\frac{H_{chan}(f) \times H_{NEXT}(f) \times H_{data}(f)}{A(f)}\right)^2 df} \tag{7}$$

We define the Signal to NEXT ratio (S/NEXT) as:

$$\text{S/NEXT} = \frac{\Delta}{2v_n} \tag{8}$$

where Δ is the voltage separation between transmitted symbols. (Note that for an ideal raised cosine channel the symbol voltage levels at the output of the channel will be equal to those at the input.) In general the separation, Δ, of the transmitted signal levels is 2V/(m-1). Thus:

$$\text{S/NEXT} = \left[(m-1)\sqrt{\left(\frac{m+1}{3(m-1)}\right)B\int_{-\infty}^{\infty}\left(\frac{H_{chan}(f) \times H_{NEXT}(f) \times H_{data}(f)}{A(f)}\right)^2 df}\,\right]^{-1} \tag{9}$$

It is worth noting that the S/NEXT ratio cannot be used to predict bit error rate, and hence absolute system performance, in the usual way since crosstalk noise does not obey Gaussian statistics [8]. However, this ratio is still useful as a measure of the comparative performance of different transmission schemes. A more rigorous crosstalk analysis that may be used to predict absolute system performance is described in [9].

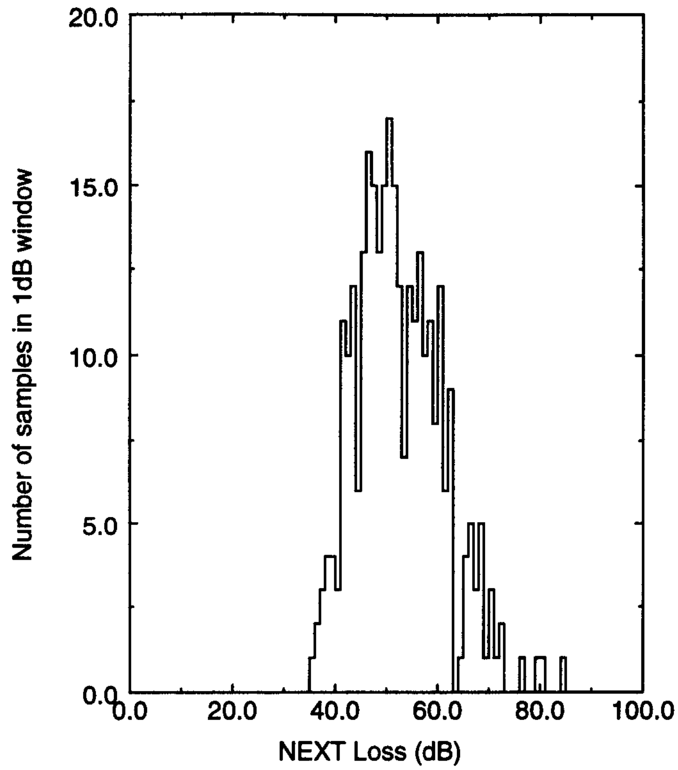

Figure 3: Distribution of NEXT Loss at 10 MHz for pairs in a 25-pair UTP bundle.

A general expression for the NEXT loss between twisted pairs is not available due to the significant variability of coupling between different pairs in a cable. Figure 3 shows the distribution of NEXT loss at 10 MHz for pair combinations in a 25 pair cable. The NEXT loss varies by more than 40 dB depending upon the choice of pairs. This is a well understood characteristic of NEXT loss and has been reported elsewhere [10]. The relationship between the *minimum* NEXT loss between two pairs in a cable and frequency is given by [11]:

$$NEXT_{min} = X - 15\log\left(\frac{f}{10^7}\right) \text{ (dB)} \tag{10}$$

where X is the minimum NEXT loss at 10MHz. This relationship is plotted in Figure 4 for X = 30 dB, along with measurements of NEXT loss between several pairs in a typical 25 pair cable. Although equation (10) defines the lower bound of the NEXT loss, the NEXT loss between any two pairs does not approach this bound across the complete frequency range. Nevertheless, the expression for $NEXT_{min}$ is often used as a general expression for NEXT loss for the purposes of a comparative analysis (e.g [12]). i.e.:

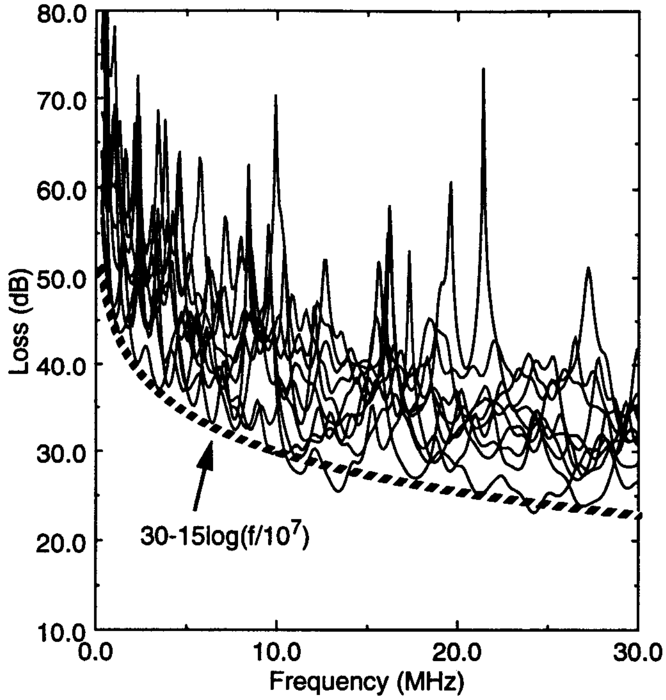

Figure 4: Minimum NEXT loss and measured NEXT loss for pair combinations in a 25-pair UTP bundle.

$$H_{NEXT}(f) = 10^{\frac{-X}{20}}\left(\frac{f}{10^7}\right)^{0.75} \tag{11}$$

The maximum loss of a 100m voice-grade twisted pair is defined by the relationship [11]:

$$ATT_{max} = 2.32\sqrt{\frac{f}{10^6}} + \frac{0.238f}{10^6} \quad \text{(dB)} \tag{12}$$

The attenuation of twisted pairs is much less variable than the NEXT loss, as confirmed by the distribution shown in Figure 5 for a typical 25 pair cable. It is therefore appropriate to use equation (12) as a general expression for the cable loss.i.e.:

$$A(f) = 10^{-\frac{1}{2}\left(\frac{2.32\sqrt{f}}{10^4} + \frac{0.238f}{10^7}\right)} \tag{13}$$

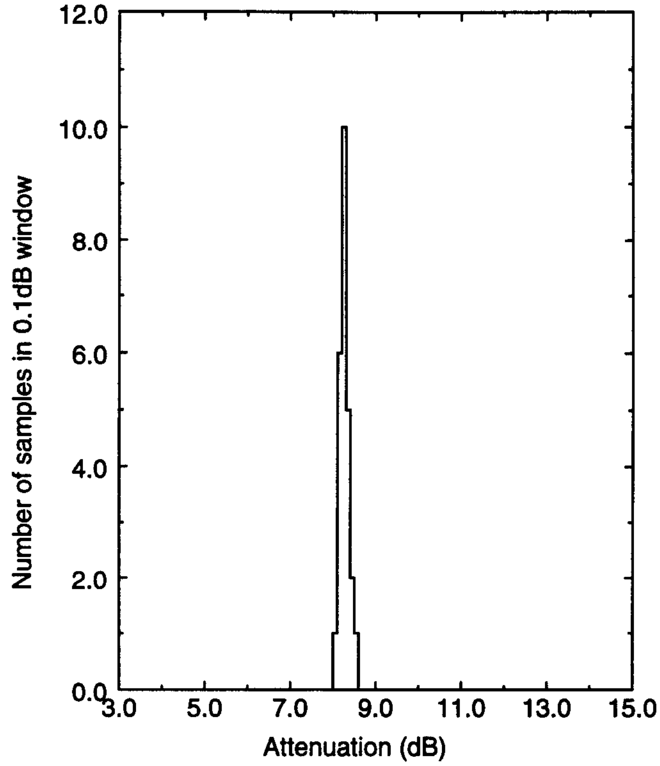

Figure 5: Distribution of Attenuation at 10 MHz for pairs in a 25-pair UTP bundle.

Using equations (11) and (13) in (9), and assuming the data source has a uniform power spectral density (i.e. $H_{data}(f) = 1/B$) we can now calculate S/NEXT for an m-ary transmission scheme. Also of interest is the baud rate of an m-ary scheme as a function of bit rate, R. These are related by the expression:

$$\frac{B}{R} = \frac{1}{log_2(m)} \qquad (14)$$

In Figure 6 we have plotted S/NEXT as a function of B/R for R=100 Mb/s. S/NEXT increases as m increases from 2, reaching a maximum (in this case for m=6) before decreasing for m>6. This behavior is somewhat counter-intuitive, and is due partly to the decrease in NEXT loss with frequency, and partly to the increasing cable loss with frequency. The reduction in NEXT loss with frequency results in larger crosstalk noise power spectral density (p.s.d) at higher frequencies. Therefore as m increases, not only is the channel bandwidth requirement reduced, but the average crosstalk noise p.s.d. in that bandwidth is also reduced. Studies of digital subscriber loops have also shown that S/NEXT may be optimized in those systems by careful choice of m [13][14]. For interest, Figure 6 also shows S/NEXT plotted for a flat NEXT loss characteristic (i.e. $H_{NEXT}(f)$ =

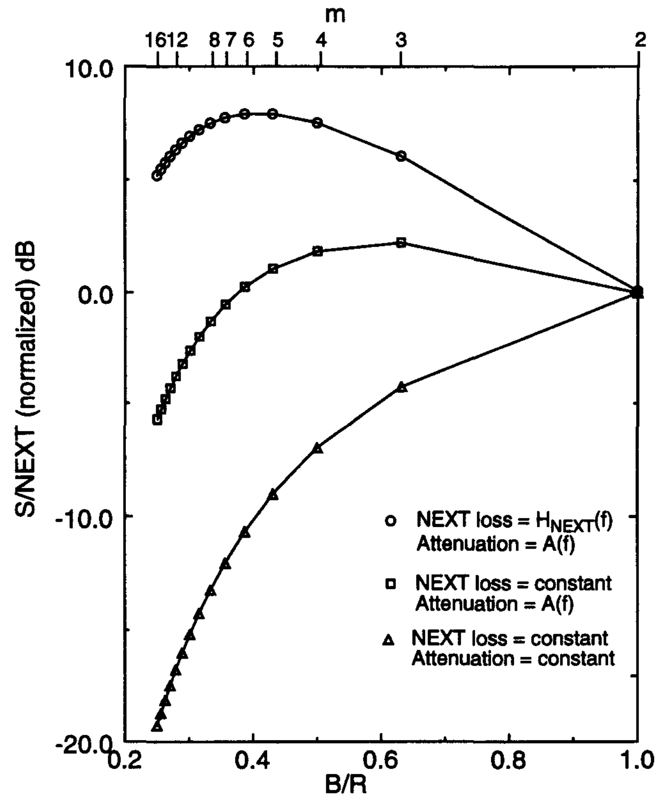

Figure 6: S/NEXT ratio versus bandwidth for m-ary signalling (α=0.5, R=100Mb/s).

constant), and S/NEXT when the cable loss is constant (i.e. A(f) = constant). For the latter, S/NEXT is steadily reduced as m increases.

To examine the immunity of m-ary schemes to external noise sources (e.g. impulse noise) we represent the external noise as a constant noise voltage, v_{ext}, at the input to the receiver. The signal to external noise ratio, S/Ext, is defined as:

$$\text{S/Ext} = \frac{\Delta}{2Gv_{ext}} = \frac{V}{G(m-1)\,v_{ext}} \qquad (15)$$

where G is the maximum gain of the receiver equalizer across its frequency response. G is dependent upon the loss of the cable to be equalized, and so G decreases as m increases. We have calculated G from the response of an equalizer providing a 50% excess bandwidth for various values of m and a bit rate of 100Mb/s, and used the results to plot S/Ext against B/R in Figure 7. There is a small improvement in S/Ext for a ternary system (m=3) over a binary system (m=2) but S/Ext then deteriorates rapidly as m increases and the baud rate decreases.

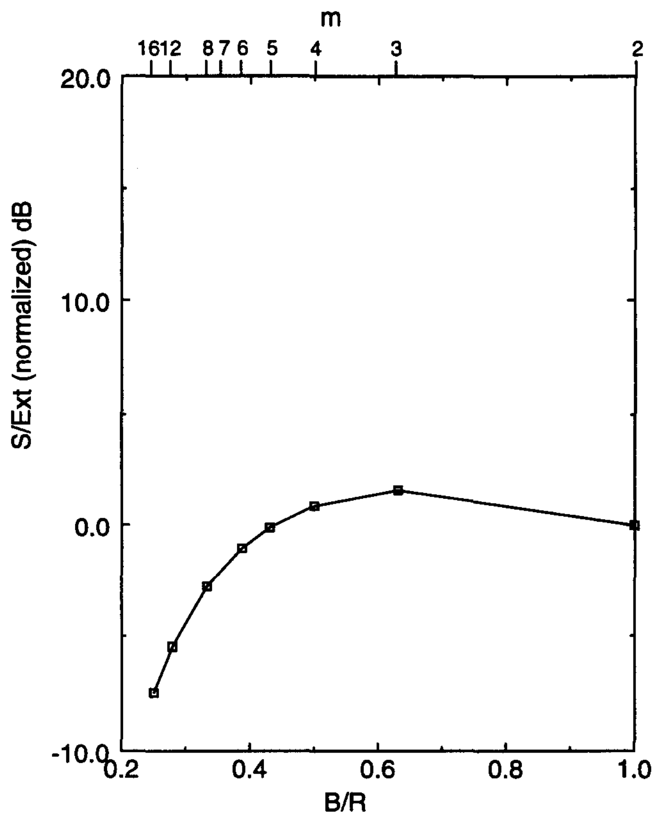

Figure 7: S/Ext ratio versus bandwidth for m-ary signalling (α=0.5, R=100Mb/s).

It should be noted that the S/Ext and S/NEXT results calculated here are only valid for true m-ary signalling, and are not valid for codes such as MLT-3 [15], a pseudo-ternary code which provides no bandwidth compression.

B. Analysis of multipair schemes.

An alternative approach to bandwidth compression is to simply transmit data using binary signalling on n ($n \geq 1$) twisted pairs, reducing the bandwidth required on each pair by a factor n. Structured cabling routinely uses 4 pair cables from wiring closets to wall outlets. Indeed, more than 85% of current installations provide four pairs to each wall outlet [16]. Furthermore, current building wiring standards (e.g. [5]) specify that four pair cable should be used between wiring closets and wall outlets in all structured cabling installations. Only two of these pairs are used by a 10BASE-T network (one for each direction of a full duplex link), but potentially up to all four pairs are available for data transmission.

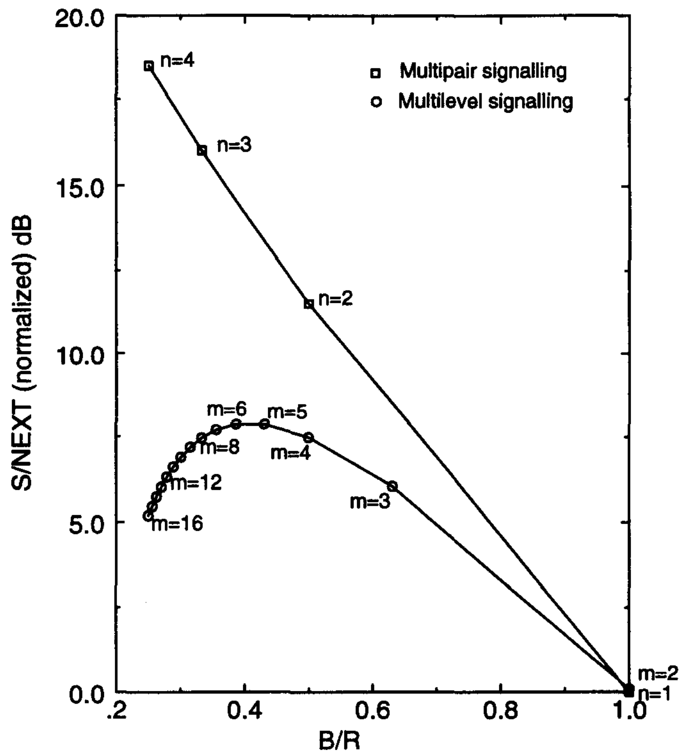

Figure 8: S/NEXT ratio versus bandwidth for multipair and multilevel signalling (α=0.5, R=100Mb/s).

Equation (9) may be used to calculate S/NEXT of an n-pair binary signalling scheme, with m=2 and B=R/n. For multipair signalling, the expression for minimum NEXT loss is modified to account for the presence of multiple disturbing pairs when n>1:

$$H_{NEXT}(f) = \sqrt{n} \times 10^{\frac{-X}{20}} \left(\frac{f}{10^7}\right)^{0.75} \tag{16}$$

We assume here that the NEXT power loss due to multiple disturbers is inversely proportional to the number of disturbers. This is a pessimistic assumption since it is unlikely that all disturbers simultaneously exhibit the minimum NEXT loss. Other, less pessimistic, multiple disturber models have been used (e.g. [13], [14]), in which the multiple disturber NEXT power loss scales by some factor less than n.

Figure 8 shows S/NEXT plotted against B/R for a 100 Mb/s multipair scheme. S/NEXT increases as the number of pairs increases since the more severe crosstalk at higher frequencies is avoided by reducing the bandwidth per pair. At the same time the symbol separation, Δ, remains at the maximum value of 2V as n increases. S/NEXT for m-ary

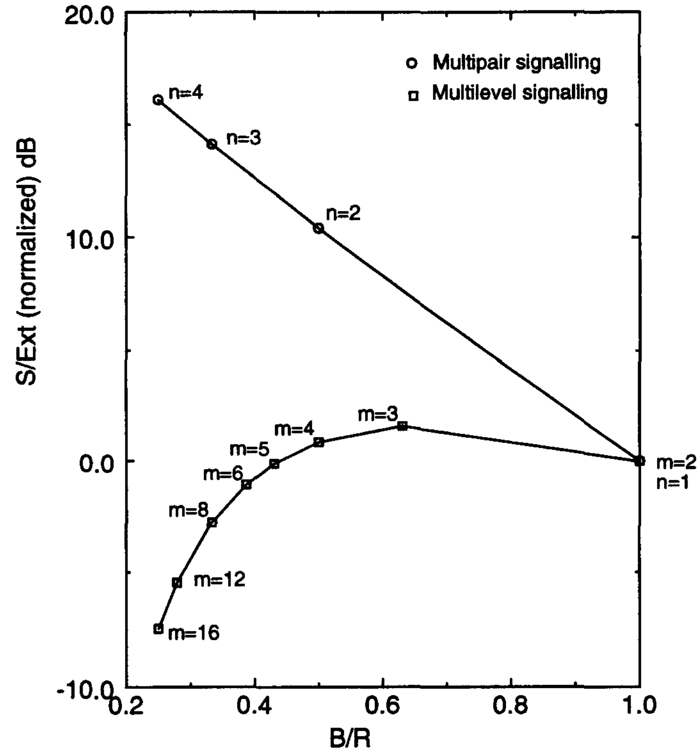

Figure 9: S/Ext ratio versus bandwidth for multipair and multilevel signalling (α=0.5, R=100Mb/s).

signalling is also shown for comparison. For B/R=0.25, the multipair scheme (n=4) has a 13.3 dB S/NEXT advantage over the 16 level scheme (m= 16).

Maintaining maximum symbol separation is key to providing immunity to external noise in any transmission system. A multipair scheme provides bandwidth compression with no compromise of the immunity to external noise. In this case, S/Ext is independent of n:

$$\text{S/Ext} = \frac{V}{Gv_{ext}} \tag{17}$$

Comparison of the performance of multilevel and multipair schemes, summarized in Figure 8 and Figure 9, shows that multipair schemes have a clear advantage over multilevel schemes. A multipair scheme provides bandwidth compression with improved immunity to external noise. This immunity deteriorates significantly when multilevel signalling is employed. Furthermore, multipair signalling has superior S/NEXT performance than multilevel signalling. For these reasons a multipair scheme was chosen in favour of a multilevel scheme for the Demand Priority UTP physical link. UTP links are half duplex, with data being transmitted on all four pairs of a cable.

C. Block coding

Connections to twisted pair links are typically made via transformers. The data spectrum must therefore be shaped in some way to account for the lack of a d.c. path through these transformers and avoid severe signal degradation due to baseline wander [17]. A 5B6B block code is used [18], which has a spectral null at d.c. and incurs relatively little bandwidth expansion (20%). Hence, for a 100 Mb/s four pair scheme, the transmission rate per pair increases from 25 Mb/s to 30 Mb/s due to 5B6B coding.

Close to perfect d.c. balance (i.e. an equal number of +V and -V symbols transmitted) is achieved as follows: Twenty of the required six bit codewords are balanced, consisting of three ones and three zeros (or, after NRZ coding, three +V and three -V symbols). The remaining twelve six bit codewords must be unbalanced, and are chosen from one of two sets. The first set consists of "weight-2" codewords, having 2 ones and four zeros. The second set consists of "weight-4" codewords having four ones and two zeros. Whenever an unbalanced codeword is needed, the "weight-2" and "weight-4" sets are used alternately, starting with the "weight-2" set. The maximum imbalance at the end of any codeword occurs when the number of zeros that have been transmitted exceeds the number of ones by two. The running digital sum (r.d.s) is bounded such that $-5 \leq \text{r.d.s} \leq 3$ [19].

The particular 5B6B code chosen for Demand Priority networks ensures good transition density, with a maximum run-length of 6 bits. Coupled with a CRC-32 frame check [20], this particular code also meets the IEEE requirement for any LAN, that no undetectable packet errors shall occur due to 3 or less single bit errors [21].

D. Implementation

A block diagram of a Demand Priority UTP physical link implementation is shown in Figure 10. At the transmitter, quintets of data are split between four channels prior to scrambling and 5B6B coding. Scrambling is not required for d.c. balance, as this is provided by the block code, but does increase the probability of a random selection of codewords. This helps to avoid possible problems with radiated emissions when discrete spectral lines are generated due to repetitive transmission of a single codeword.

Preamble, start- and end-of-sequence patterns are added to each channel before the coded data is passed to a transceiver chip. An example of a transceiver is the AT&T T7380 chip [22] which NRZ codes and transmits the data using symbol levels of +/-2.5V. One 5th order Butterworth filter (3dB point at 20MHz) per pair is used for both transmit and receive filtering, depending upon the direction of transmission. A simple, analog, adaptive equalizer is used in the receiving transceiver to compensate for varying lengths of cable and minimize intersymbol interference on each channel. The recovered data is decoded and the quintets from the four channels are assembled into the original data stream.

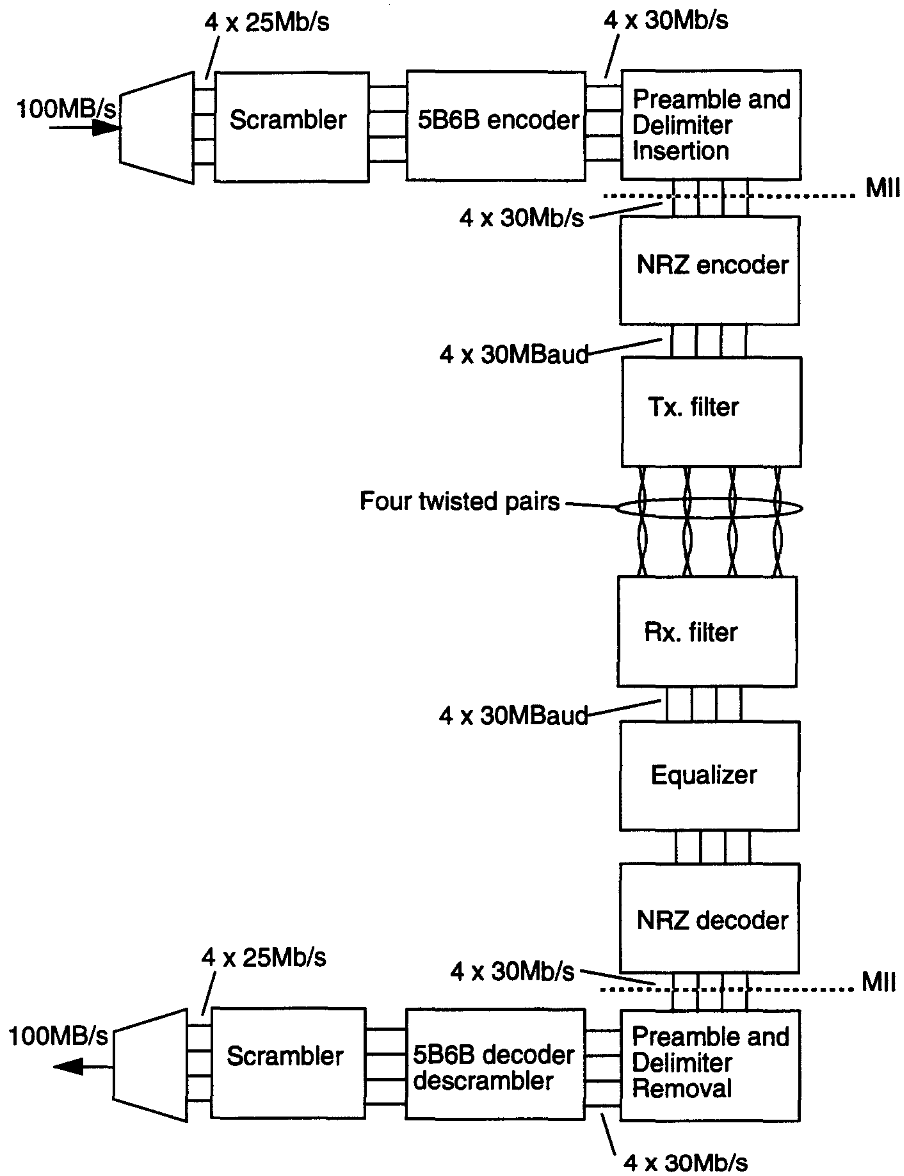

Figure 10: Block Diagram of Demand Priority UTP Physical Layer.

The eye diagram at the output of the equalizer on one channel is shown in Figure 11, for 121m of category 3 UTP. The peak-to-peak jitter is approximately 6ns, or 18% of a bit time.

III STP Transmission

The IEEE 802.12 Demand Priority standard provides a Media Independent Interface (MII) for the attachment of a variety of physical layers to a repeater or end node. In this section we describe a scheme for transmitting Demand Priority traffic over 100m of Shielded

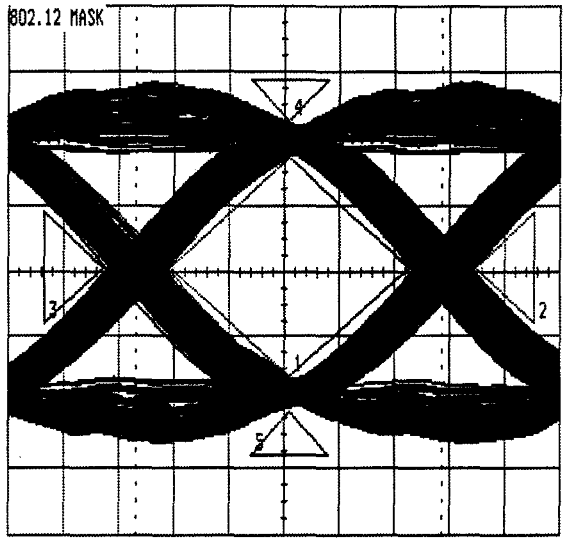

Figure 11: Measured eye diagram at output of equalizer with 121m of category 3 UTP cable.

Twisted Pair (STP) cable, consisting of two individually screened, 150 Ω twisted pairs. This cable, often referred to as "IBM Type 1", is widely used in Token Ring networks. STP has excellent transmission properties (less attenuation and greater NEXT loss than even data-grade, EIA/TIA category 5, UTP), and is already used for data transmission in excess of 100 Mb/s. For example, the SDDI specification [23] describes the use of STP for transmission of FDDI traffic at 100 Mb/s (125 MBaud after coding).

The modulation and line coding aspects of the SDDI scheme have been adopted for the Demand Priority STP physical layer; i.e. binary signalling at a rate of 100 Mb/s (before coding) per pair. Only one pair is required for transmission in each direction, and so in contrast to the UTP physical layer, one pair is dedicated to receive and one pair to transmit at each transceiver. This is made possible by the low attenuation of the cable and the reduction in radiated emissions compared with UTP, provided by the shield [24].

The 4B5B block code and NRZI coding used for SDDI and FDDI [25] have not been adopted for Demand Priority STP physical layers. An alternative scheme has been developed based on the same 5B6B block code used for the UTP physical layers. This approach has the advantage of increasing the amount of logic that is common to all Demand Priority physical layers. We will show below that the performance of this scheme is at least as good as the 4B5B+NRZI code.

Data to be transmitted is scrambled and 5B6B block coded before being passed across the MII as four parallel 30 Mb/s channels (see Figure 10). The STP transceiver multiplexes the four channels to a single serialized stream on a codeword by codeword basis, as shown in

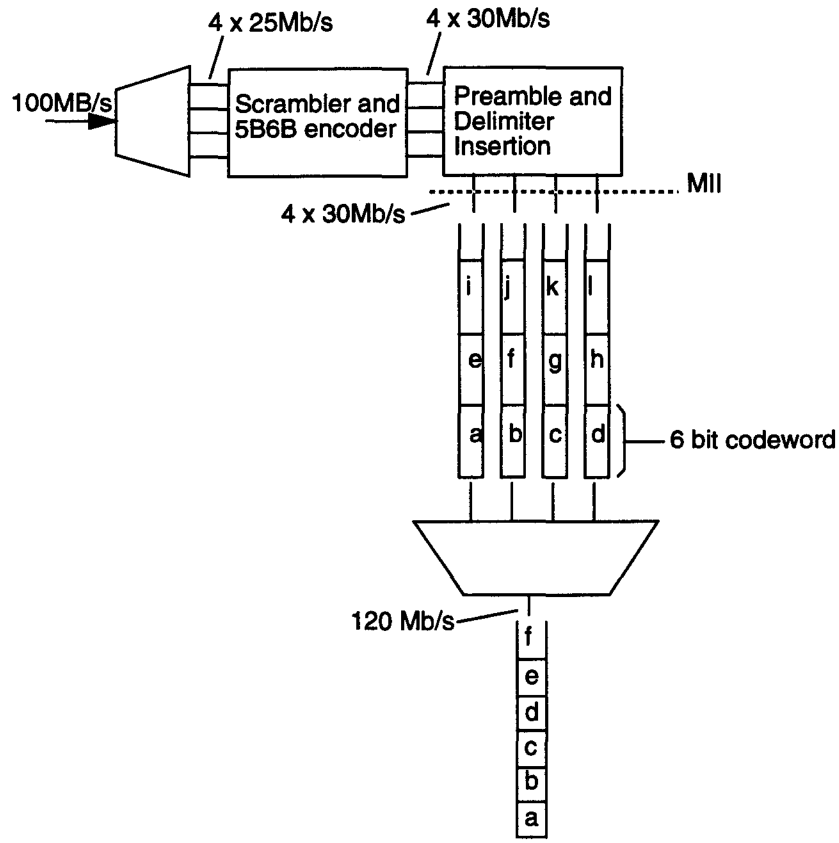

Figure 12: Multiplexing of 5B6B Codewords for STP Physical Layer.

Figure 12. The serialized data stream is then NRZ coded and transmitted on one twisted pair using symbol levels of +/- 0.25V (nominal). The transmission rate on the STP is therefore 120 MBaud. (The same scheme is also used for a multimode optical fiber physical layer.)

A feature of the 5B6B code is that its favorable properties are maintained even after codeword multiplexing, i.e.:

- Spectral null at d.c.
- Maximum run length is six bits.
- With CRC-32, no errored packets are undetected for 3 or less single bit errors.
- The running digital sum remains bounded, in this case $-11 \leq$ r.d.s. ≤ 3 [19].

The effects of baseline wander have been simulated for a stream of multiplexed, randomly chosen codewords. The intersymbol interference due to baseline wander is calculated for each bit in a sample of 10^8 bits. The distribution of ISI is shown in Figure 13 for a channel with a low frequency rolloff characteristic having 3dB loss at 100 kHz. The maximum ISI

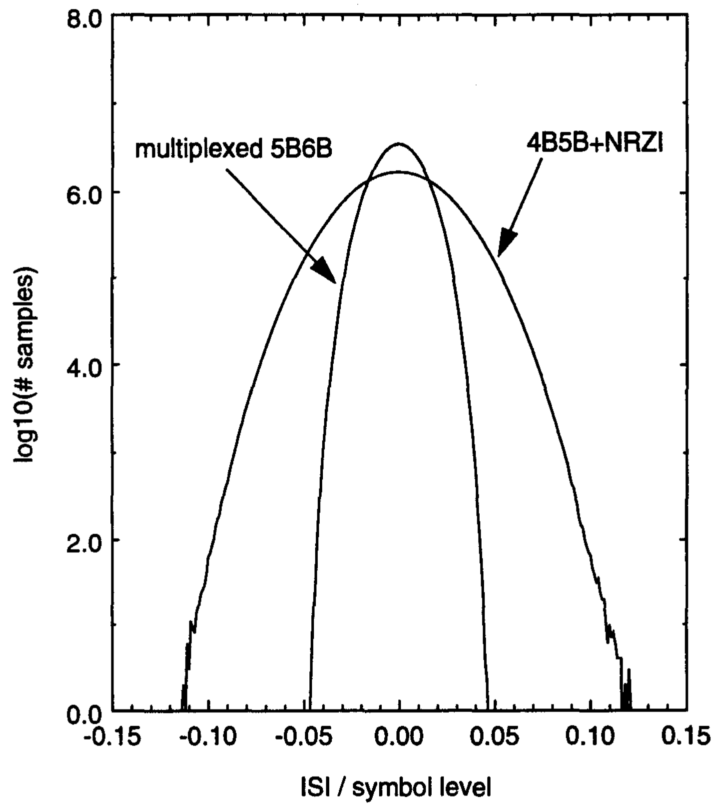

Figure 13: Distribution of ISI due to baseline wander for 5B6B and 4B5B+NRZI coded random data.

observed is less than 5% of the symbol level, and the distribution is falling rapidly at this point towards an asymptotic limit. The distribution of ISI for the FDDI 4B5B+NRZI code is also shown. In this case the maximum observed ISI is approximately 11% of the symbol level, and the distribution does not exhibit the same trend towards an asymptotic limit.

The superior performance of the 5B6B code can be explained as follows. Although the maximum run length of the 5B6B code (six) is greater than that of the FDDI 4B5B+NRZI code (four), the 5B6B running digital sum is bounded, whereas the 4B5B+NRZI running digital sum is unbounded (in fact if l is the number of bits transmitted then the expected value of the r.d.s. is proportional to $\sqrt{l}$ [26]). With the 4B5B+NRZI code, large changes in the r.d.s. may occur over relatively short periods of time, resulting in more severe ISI.

IV Summary

We have described two data transmission schemes that have been developed to carry 100 Mb/s IEEE 802.12 Demand Priority traffic over Unshielded Twisted Pair and Shielded Twisted Pair cables commonly found in current network infrastructures. The UTP scheme supports category 3, 4 and 5 UTP (i.e. voice-grade and data-grade) using a 5B6B block coded binary signalling scheme on four pairs. The Signal-to-NEXT and Signal-to-External Noise ratios for this scheme have been calculated and compared with multilevel (m-ary) signalling techniques. The binary signalling scheme provides the maximum immunity against crosstalk and external (impulse) noise, maintaining the robustness of the widely successful 10BASE-T network.

The STP scheme combines the strengths of the 5B6B block code with signalling technology similar to existing SDDI links: i.e binary NRZ signalling on a single pair per direction. The ISI due to baseline wander of the multiplexed 5B6B code has been shown to be less than that of the SDDI/FDDI 4B5B+NRZI code.

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