Analysis of
Physical Layer Requirements
For 155 Mb/s
Twisted Pair ATM

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Introduction

This paper analyzes the physical layer operation of 155 Mb/s twisted pair ATM equipment, presenting a detailed examination of channel bandwidth utilization and the performance trade-offs inherent in various bandwidth limiting techniques.

The data and analysis developed here support the conclusion that in order to meet the required Bit Error Rate of 10^{-10}, the 155 Mb/s ATM application relies on the channel frequency response beyond the 100 MHz band specified by category 5.

ATM Forum Specification

The ATM Forum standard, *ATM Physical Medium Dependent Interface Specification for 155 Mb/s over Twisted Pair Cable (AF-0015.000),* defines the data signaling method, transceiver characteristics and minimum channel requirements for ATM applications operating over twisted pair media.

The ATM Twisted Pair Channel

The ATM twisted pair communications channel consists of a transmit and a receive pair with a transceiver connected at either end of the link. Since ATM equipment transmits and receives simultaneously, noise power at the receiver is dominated by NEXT and signal power is determined by the attenuation of the channel.

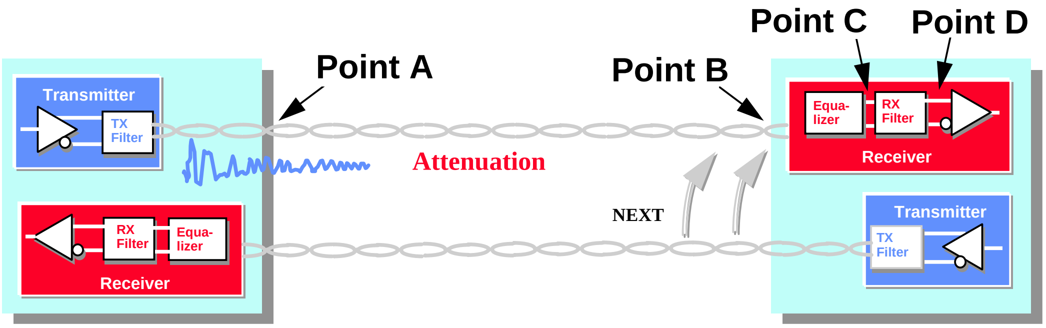

Figure 1: **Twisted pair channel with the network equipment attached**

The robustness of an ATM link depends on the quality of the data signal at the point in the receiver where the data is recovered or converted from analog to digital form. The condition of the signal at the recovery circuit (Point D in Figure 1) is a function of the transmit signal, the NEXT and attenuation properties of the twisted pair channel and the receiver front end circuitry.

155.52 Mb/s NRZ Modulation

Sections 2.1 and 2.2 of AF-PHY-0015.000 define the data rate and line coding technique as 155.52 Mb/s binary Non-Return to Zero (NRZ).

As a starting point in determining the required bandwidth for this application, we can look at the spectrum of an ideal *unfiltered* 155.52 Mb/s NRZ signal. The transmit spectrum of such a signal is depicted below.

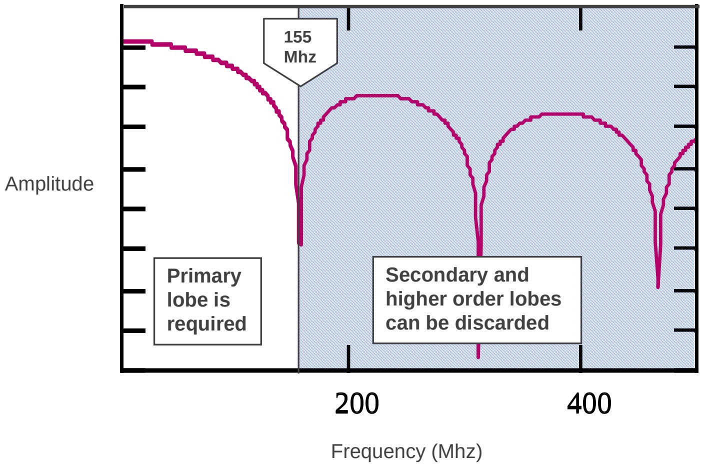

Figure 2: **0-500 MHz frequency spectrum of unfiltered 155.52 Mb/s NRZ**

The spectrum consists of multiple *lobes*, each of which spans 155.52 MHz. The first lobe extends from 0 to 155.52 MHz, the second from 155.52 MHz to 311.04 MHz, etc. In the case of a completely unfiltered transmitter, the spectral pattern of successive lobes every 155.52 MHz extends out to infinite frequency.

Only the first lobe of the NRZ spectrum (i.e. up to 155 MHz) is required[1] for proper data recovery. Figure 2 shows the portion of the unfiltered NRZ spectrum which can be ignored without further analysis.

Depending on the design of the transmitter filter, it is theoretically possible to limit the transmit spectrum to some value under 155 MHz. Doing so, however, introduces performance compromises which may be unacceptable. The following sections examine these effects in detail.

Effect of Filtering on the Data Signal

Filtering a data signal, if done improperly, can cause distortion and impair data recovery. Specially constructed, low distortion filters should be employed when attempting to band limit a data signal.

Relationship of Signal Bandwidth to Eye Pattern Opening

The following figures demonstrate how the opening of the eye pattern shrinks with a progressively increased amount of filtering.

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[1] Feher, *Wireless Digital Communications*, Prentice Hall, 1995

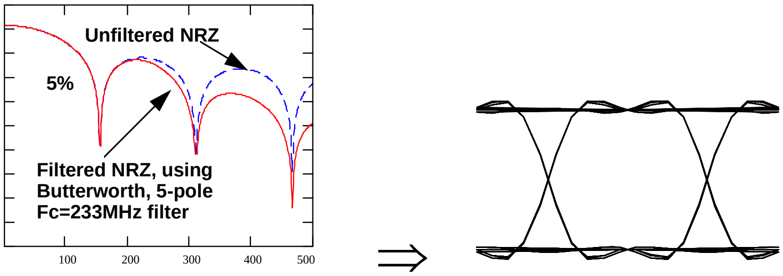


Figure 3: Filter A. **155 Mb/s NRZ spectrum, band limited using a 5-pole Butterworth filter with Fc=233 MHz. The resulting waveform exhibits the fastest rise time allowable by the ATM Forum standard, $T_{r/f}$ = 1.5 ns. The first lobe of the spectrum is entirely unfiltered, so 5% of total signal power in the first lobe resides between 100 and 155 MHz.**

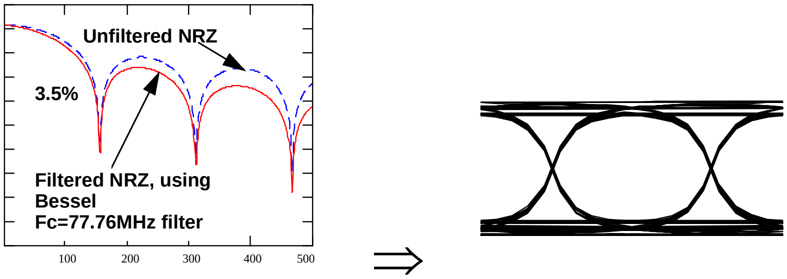


Figure 4: Filter B. **155 Mb/s NRZ signal filtered with a Bessel filter, Fc=77.76 MHz. This filter leaves 3.5% of total power in the first lobe between 100 and 155 MHz. Compared to the eye pattern in Figure 3, this eye pattern is slightly more rounded and more closed in the vertical direction.**

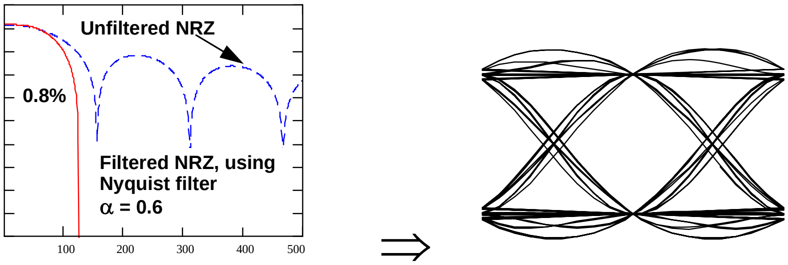
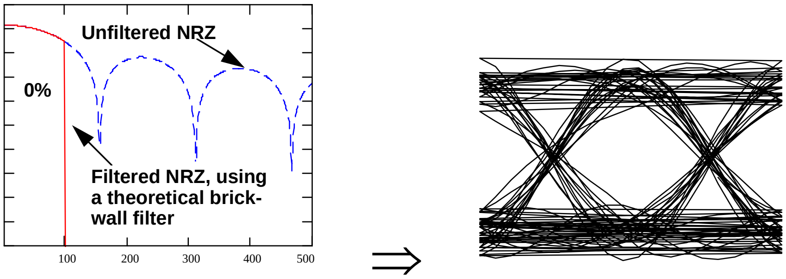


Figure 5: Filter C. **Applying a Nyquist[2] filter with α=0.6, limits the spectral power between 100 and 155 MHz to 0.8% of the power in the first lobe of the spectrum. However, this bandwidth reduction comes at a price of slow rise times and a significantly contracted open portion of the eye pattern.**



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[2] Kamilo Feher, Wireless Digital Communications, Prentice Hall, 1995

Figure 6: **An infinitely sharp (theoretical brick wall) filter at 100 MHz eliminates the spectral power above 100 MHz, but results in a significantly distorted data waveform.**

Summary: As can be observed in Figures 3-6, band limiting the 155 Mb/s NRZ spectrum to less than 155 MHz results in closure of the eye pattern. It is easy to see that the degree of eye pattern opening is directly related to the bandwidth of the filtered signal.

Since filtering can cause distortion and hinder data recovery, it is important that the amount and type of filtering be carefully controlled. In order to guarantee inter-operability among different vendors' equipment, a consistent transmit spectrum must be maintained among all the ATM products.

Transmit Signal

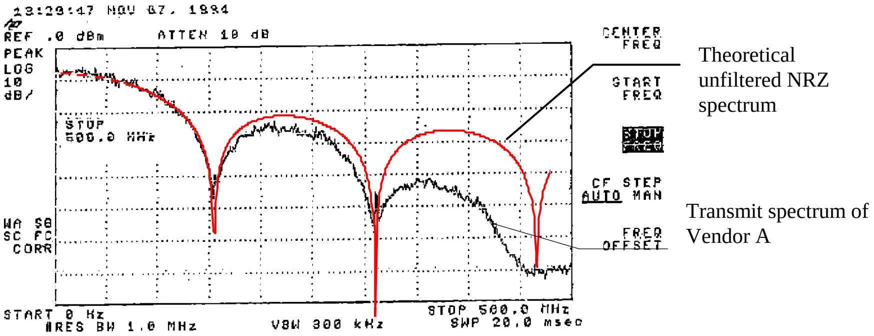
What should the minimum bandwidth of the transmit signal be?

The ATM signal can be band limited in order to reduce the effect of NEXT. Such filtering could be done at either the transmitter or the receiver, but the location of the filter should be consistent from product to product. If transceiver A band limits the first spectral lobe in its transmitter while transceiver B band limits the first spectral lobe in its receiver, the data signal originated by A and received by B would be subject to twice the normal amount of filtering.

Since excessive filtering could distort the data signal and render it unrecoverable, double-filtering should be avoided through a consistent choice of whether the filtering is done by the transmitter or by the receiver.

All the ATM products that we have examined maintain the entire first lobe of the transmit spectrum intact and unfiltered, so as to optimize system performance and inter-operability. The amount of filtering applied to the higher frequency lobes of the spectrum varies from product to product. The spectral energy above the first lobe, or 155 MHz, does not improve the quality of the data signal and can be eliminated.

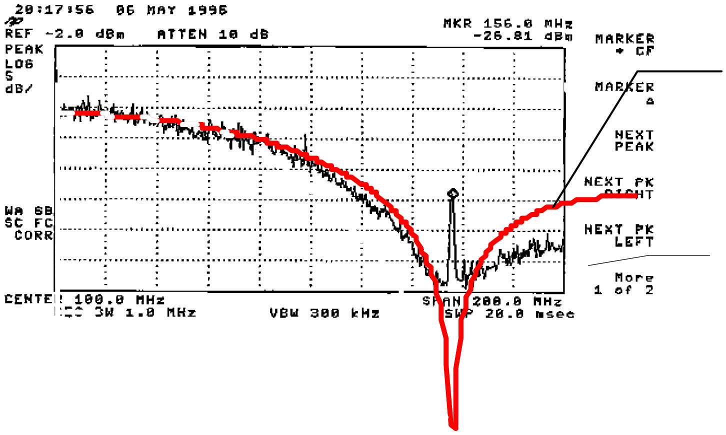
Following are some examples of ATM transmitter implementations.



Theoretical unfiltered NRZ spectrum

Transmit spectrum of Vendor A

Figure 7: **Spectrum of vendor A. The plot shows the measured spectrum by itself, overlaid with the theoretical spectrum of an unfiltered NRZ signal and a filtered NRZ signal. It is clear that the fundamental lobe of the vendor A spectrum, extending to 155 MHz is completely unfiltered. The signal transmitted by vendor A contains 5% of energy between 100 and 155 MHz.**

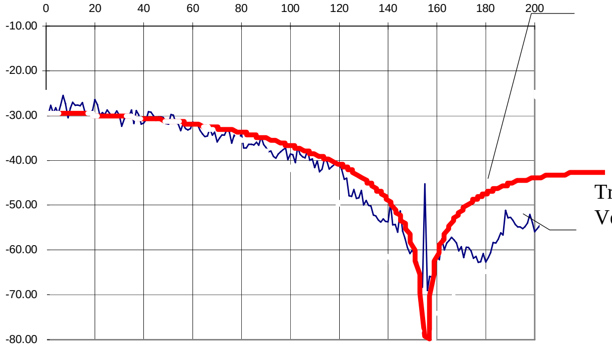


Theoretical unfiltered NRZ spectrum

Transmit spectrum of Vendor B

Figure 8: **Spectrum of vendor B. The fundamental lobe is unfiltered, resulting in 5% of signal energy between 100 and 155 MHz.**

Theoretical unfiltered NRZ spectrum



Transmit spectrum of Vendor C

Figure 9: **Spectrum of vendor C. Again, practically no filtering on the fundamental lobe resulting in almost 5% of spectral energy between 100 and 155 MHz.**

Summary: To maintain inter-operability among the products from different vendors, it is important that the choice of whether the signal is band-limited in the transmitter or in the receiver be consistent in all implementations.

It appears that band limiting the first spectral lobe, if done at all, may be performed in the receiver. All of the products that we have tested maintain the NRZ transmit spectrum up to 155 MHz entirely intact and at full power.

Effects of the Channel Properties on Signal Quality

As the data signal traverses the cable, it is subject to the effects of Near End Crosstalk (NEXT) and attenuation. NEXT acts as the main source of noise. Attenuation reduces the signal power and introduces distortion.

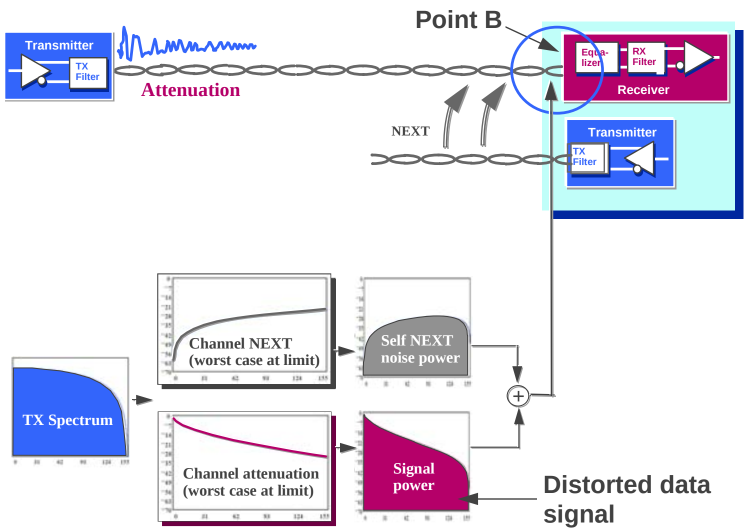


Figure 10: **ATM signal and noise spectra at the entry to the receiver; NEXT and attenuation responses shown here represent the worst case TSB-67 channel**

At the input to the receiver, the spectral shape of the data signal is a function of the transmit spectrum[3] and channel attenuation. The spectral shape of the noise is determined by the transmit spectrum and channel NEXT.

The receive signal spectrum has the sloping shape of the channel attenuation response and significantly deviates from the shape of the transmit spectrum. This data signal is severely distorted.

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[3] The transmit spectrum is assumed to have the first lobe entirely preserved. The higher frequency lobes can be safely eliminated and, for this reason, could be ignored.

Effects of Attenuation

The distortion caused by the worst case attenuation response allowed for a 100 meter category 5 channel renders the eye pattern completely closed and the data unrecoverable without an equalizer. The following figure demonstrates what happens to an NRZ data signal subject to the worst case attenuation response defined in TSB-67 for the channel. The TSB-67 attenuation limit was extended to 155 MHz for this simulation.

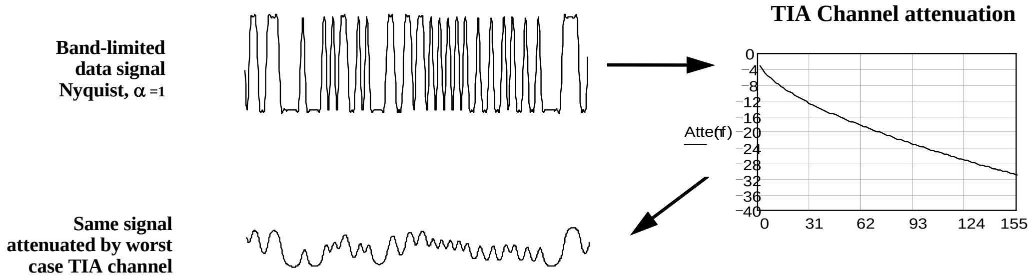

Figure 11: **Signal distortion due to channel attenuation.**

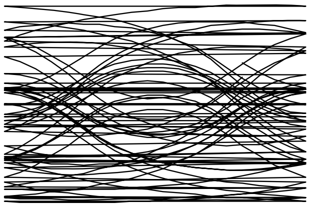

Figure 12: **Eye pattern of the data signal subject to worst case channel attenuation (Point B, Figures 10,1).**

The eye pattern of the distorted signal (Figure 12) is completely closed and the data is unrecoverable without an equalizer.

Signal Equalization

An ideal equalizer will exactly cancel out the effects of channel attenuation and restore the data signal to its original shape as it appears at Point A in Figure 1. In reality, with a non-ideal equalizer, some distortion will remain at the output of the equalizer (Point C, Figure 1), manifesting itself as time domain jitter.

Quoting from the ATM Forum standard, Section 4.4:

> “The amount of distortion differs with the length of cabling between the transmitter and receiver. Measuring jitter before the signal is equalized is meaningless.”

The ATM Forum standard allows the transmit signal to have up to 2 ns of jitter (Section 3.7) and budgets 1.5 ns of jitter to the effects of the channel. This means that jitter at Point C, Figure 1 could be as high as 3.5 ns (Section 4.4).

Summary: The received data signal can exhibit up to 3.5 ns of jitter. This is a significant amount of jitter that contracts the eye pattern by 55% in the horizontal direction. We will come back to this point later and analyze the effect of receive jitter on the eye pattern.

Receive Signal Spectrum

ATM products employ adaptive equalizers, which cancel out the effects of channel attenuation, so that the combined response of the channel and the equalizer is the attenuation uniform over frequency.

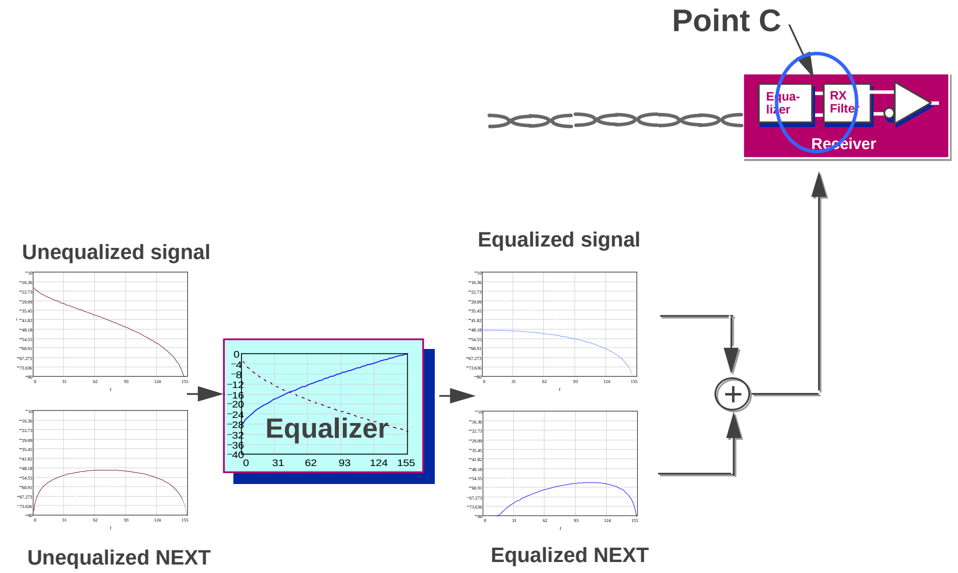

Figure 13: **Channel attenuation made uniform over frequency by receiver equalizer**

The loss, resulting from the channel attenuation followed by a receiver equalizer, determines the power of the equalized signal.

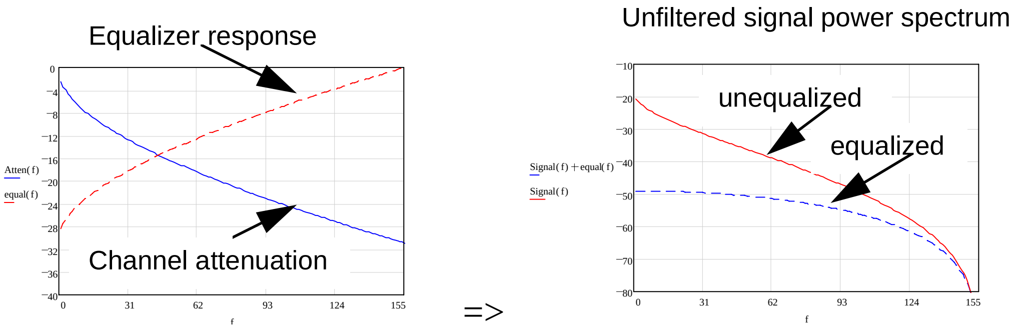

Figure 14: **Shape of the NRZ signal after traversing a worst case TSB-67 channel. The unequalized signal has the tilting shape of the channel attenuation. The equalized signal has the original shape of the NRZ signal but exhibits a flat loss of power.**

Receive Noise Spectrum

The ATM Forum standard specifies that Self NEXT, a noise parameter composed of NEXT and other ambient noise sources, be within 20 mV ptp (Section 5.3.1). Since NEXT is the dominant source of noise on a twisted pair channel, the spectral shape of the noise power is typically dominated by the channel NEXT response. The noise spectrum is also shaped by the receiver equalizer, attenuating the low frequency contents of the noise spectrum, as shown in the following figure.

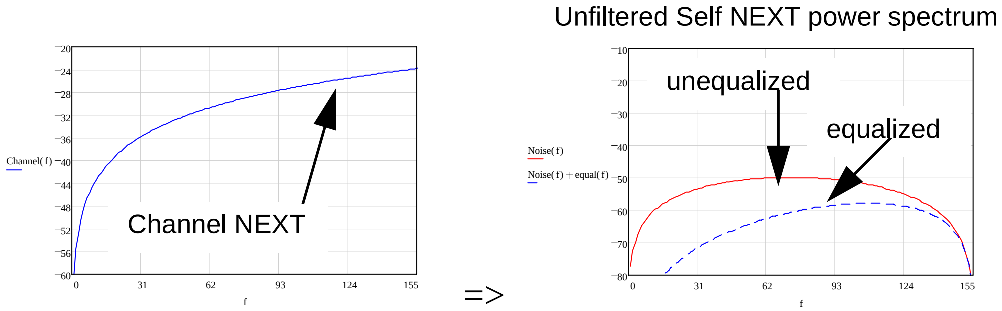

Figure 15: **Noise spectrum, shaped by the transmit signal, the NEXT response of the channel and the receiver equalizer (Point C of Figures 13, 1)**

Effect of Receiver Filtering on Signal and Noise Power

Low pass filtering can be employed in the receiver in order to reduce noise power. A low pass filter could safely cut out the spectrum above 155 MHz without distorting the data signal. The key question is, can we filter the first lobe of the spectrum so as to limit the bandwidth of the receive signal to 100 MHz?

The receive signal and noise spectra, band limited by a Nyquist filter (Filter C, Figure 5) to 100 MHz, would look as shown in the following figure.

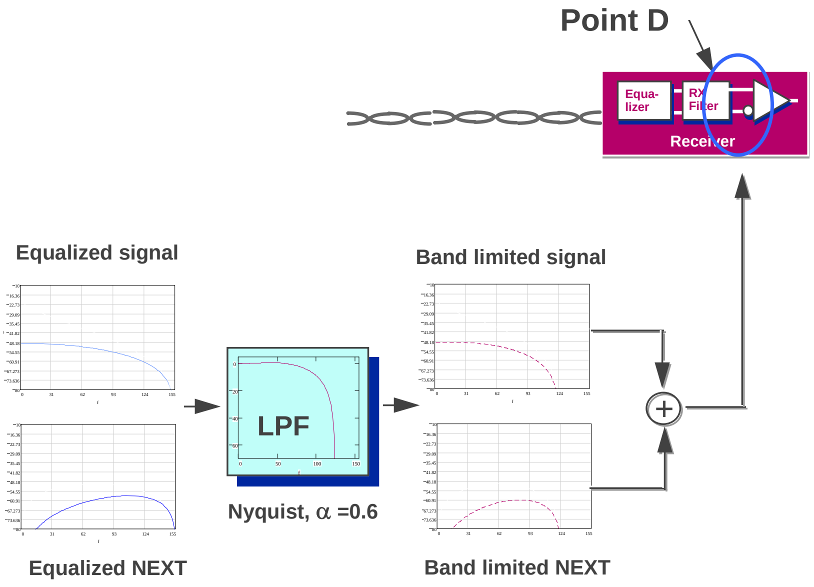

Figure 16: **NRZ signal and noise, filtered at the receiver using a Nyquist filter with α=0.6**

Because the equalized[4] noise spectrum slopes upward with frequency while the signal spectrum slopes downward, a low pass filter that cuts into the first lobe of the spectrum eliminates more noise power than signal power. This would seem to improve the SNR in the receiver, but let us take a closer look.

SNR at the data recovery circuitry can be calculated by integrating the equalized signal and noise spectra (Point D of Figures 16,1) to obtain the total signal and noise power. The resulting SNR figures are as follows:

	Filter A (5% of power in 100-155 MHz band)	**Filter B (3.5% of power in 100-155 MHz band)**	**Filter C (0.8% of power in 100-155 MHz band)**
SNR computed by integrating signal and noise power spectra	9.3 dB	10.4 dB	13.0 dB
Apparent improvement in SNR due to filtering the first lobe of the spectrum	0 dB	1.1 dB	3.7 dB

Table 1: **SNR with different receiver low pass filters**

Table 1 shows that the Nyquist filter, band limiting the first lobe of the spectrum to 100 MHz, at first glance appears to improve the SNR by 3.7 dB (from 9.3 to 13 dB). But this is not the complete story. We also need to consider the degradation in the SNR due to the distortion effects of filtering combined with receive jitter.

Effect of Jitter and Filtering on Signal Quality in the Receiver

Let us take a look at the eye patterns after the equalizer and filter inside the receiver (Point D, Figures 16, 1) and the effect of band limiting on these eye patterns.

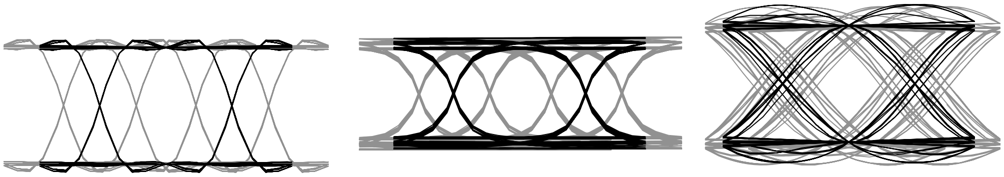

Figure 17: **Eye patterns of a data signal band limited by filters A, B and C respectively (Figures 3, 4 and 5) with 3.5 ns of allowable receive jitter.**

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[4] All ATM products employ adaptive equalizers. Therefore, for further analysis we will use the equalized signal and noise power spectra.

The highest quality receive data signal is the least filtered signal (Figure 18, left). The eye pattern of this signal is open to the maximum extent both vertically and horizontally. The lowest quality signal is the most heavily filtered signal (Figure 18, right).

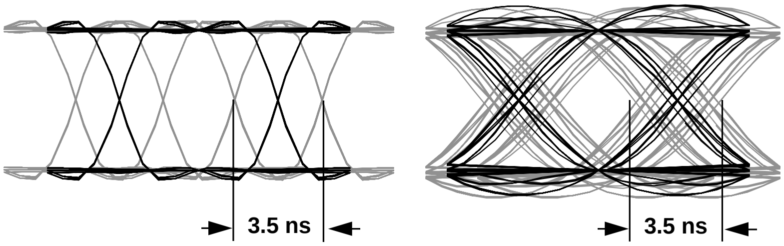

Figure 18: **Left -- best quality receive eye pattern (Filter A); right -- worst quality receive eye pattern (Filter C)**

In the presence of noise, the degree of eye opening determines the robustness of the physical layer[5]. Since the open area of the lightly filtered eye pattern (figure 18, left) is considerably greater than the open area of the heavily filtered eye pattern (figure 18, right), the lightly filtered signal will be easier to recover than the heavily filtered signal.

Let us take a look at the place inside the receiver where the data patterns, shown in figure 17, would be sampled We will focus on the open portion of the eye pattern where the recovered data clock actually samples the bits.

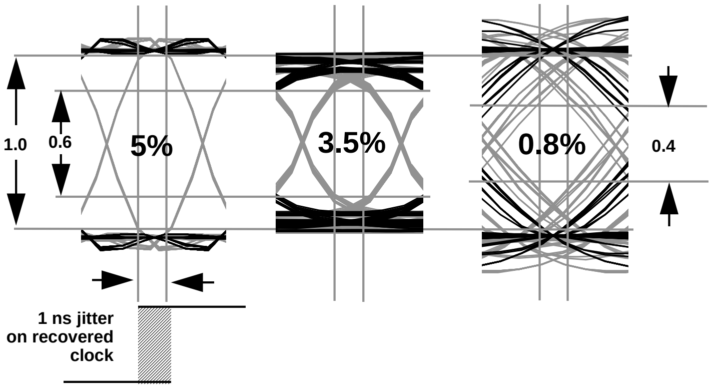

Figure 19: **Portion of the receive eye patterns (from Figure 17) where data sampling is performed. The eye patterns exhibit the effects of filtering and receive jitter of 3.5 ns. The jitter on the recovered clock is assumed to be 1 ns. At sampling time, the vertical opening in the heavily filtered eye pattern(right) is about 40% of the opening in the lightly filtered eye pattern (left). The % figures in the middle of the eye patterns represent the percentage of signal power located between 100 and 155 MHz.**

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[5] The ATM Forum calls for a maximum bit error rate (BER) of 10^{-10} (Section 2.3). BER is a function of Signal to Noise Ratio (SNR). Therefore, we can analyze the degree of network robustness based on the data signal's immunity to noise.

Looking at Figure 19, it is evident that the effect of 3.5 ns of jitter combined with the slow rise time[6], is very significant. Jitter alone causes an almost 55% reduction in the horizontal opening of the eye pattern. Jitter, in combination with the slow rise time, causes about a 60% reduction in the vertical opening of the eye pattern. This contraction of the eye pattern results in a loss of noise immunity, or a degradation in the SNR performance.

Because the vertical opening of the heavily filtered eye pattern is only 40% that of the lightly filtered eye pattern, the degradation in noise immunity due to filtering is almost 8 dB[7].

Summary: Although, at first glance, low pass filtering *appears to* improve the Signal to Noise Ratio (SNR), this improvement is offset by the degradation of signal quality due to distortion. Low pass filtering results in the vertical closure of the eye pattern, thereby adversely affecting the SNR performance.

So, what is the net effect of filtering the first spectral lobe of the ATM data signal?

Low Pass Filtering in the Receiver

Recalling the SNR figures presented in Table 1 and completing the SNR analysis based on signal distortion, we can summarize the net effect of low pass filtering as follows:

	Filter A (5% of power in 100-155 MHz band)	**Filter B (3.5% of power in 100-155 MHz band)**	**Filter C (0.8% of power in 100-155 MHz band)**
SNR computed by integrating signal and noise power spectra	9.3 dB	10.4 dB	13.0 dB
Apparent improvement in SNR due to filtering the first lobe of the spectrum	0 dB	1.1 dB	3.7 dB
Degradation in the SNR due to distortion caused by filtering	0 dB	-4.4 dB	-8.0 dB
Net effect of filtering on SNR	**0 dB**	**-3.3 dB (degradation)**	**-4.3 dB (degradation)**

Table 2: **Effects of band limiting on SNR**

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[6] The rise and fall times of a data signal are a function of the degree to which the signal is band-limited The wider the bandwidth of the signal, the shorter the rise time and, hence, the wider the eye opening. The spectral shape of the NRZ signal with a specified rise/fall time, $T_{r/f}$, can be approximated by filtering a broadband NRZ signal with a low pass filter having a 3 dB cut-off frequency, Fc, defined by:

$$F_c = \frac{3.5}{T_{r/f}}$$

The 3 dB cut-off frequency of a transmit filter that yields $T_{r/f}$ of 1.5 ns is 233 MHz. The 3 dB point of a filter that yields $T_{r/f}$ of 3.5 ns is 100 MHz.

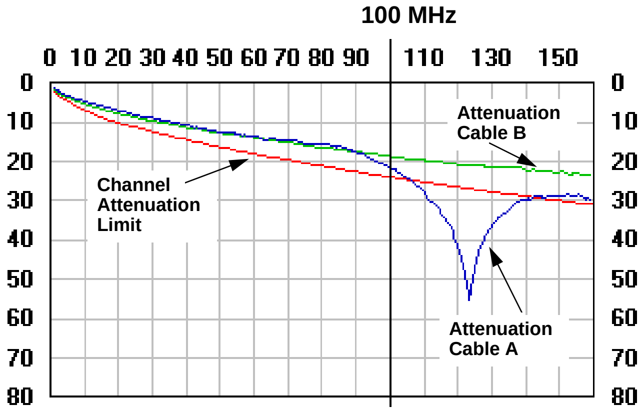
[7] 20* LOG(0.4) = 7.96 dB

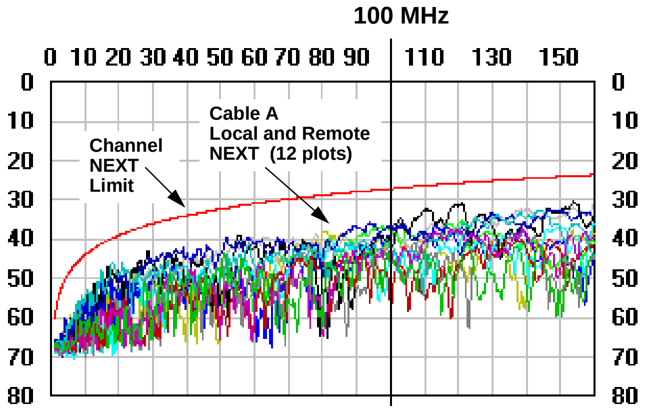
Summary: The net effect of employing a Nyquist filter and reducing the bandwidth of the receive signal from 155 to 100 MHz is a degradation in the SNR by 4.3 dB.

But what does the degradation of SNR mean in terms of network operation and how does it effect the end user? Most likely, a degradation in the SNR will result in the degradation of the BER performance of ATM networking equipment in the presence of noise.

Bit Error Rate Test

In order to demonstrate the channel effects on the BER performance of ATM equipment, we have conducted an experiment using two category 5 cables. Although both cables passed the category 5 certification and their attenuation properties up to 100 were almost identical, one of the cables had a defect in its attenuation response above 100 MHz.





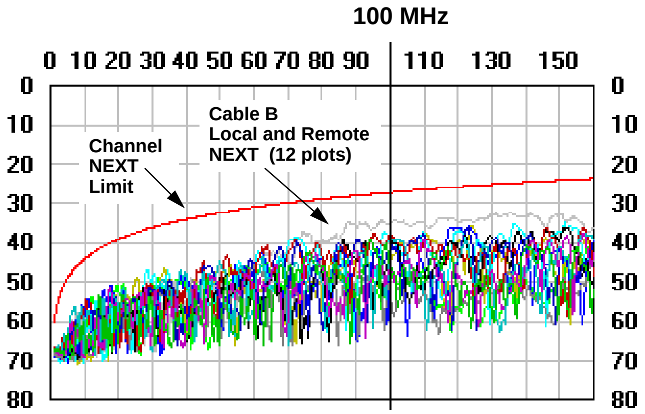


Figure 20: **Attenuation and NEXT properties of cables A and B used in the BER test. Cables A and B have very similar attenuation up to 100 MHz but cable A has a defect above 100 MHz while cable B exhibits a normal attenuation response. The Near End Crosstalk response of both cables appears normal and complies with category 5 limits.**

Test Set-up

The BER test was performed using two 155 Mb/s ATM physical layer evaluation boards connected to the Microwave Logic BER measurement system. The evaluation boards were supplied by the manufacturer of the physical layer device, a device that is incorporated into a number of existing 155 Mb/s products. The boards included standard magnetics and clock recovery. One board was connected to the pattern generator -- gigaBERT-660 Tx. The other board was connected to the BER analyzer -- gigaBERT-660 DRx.

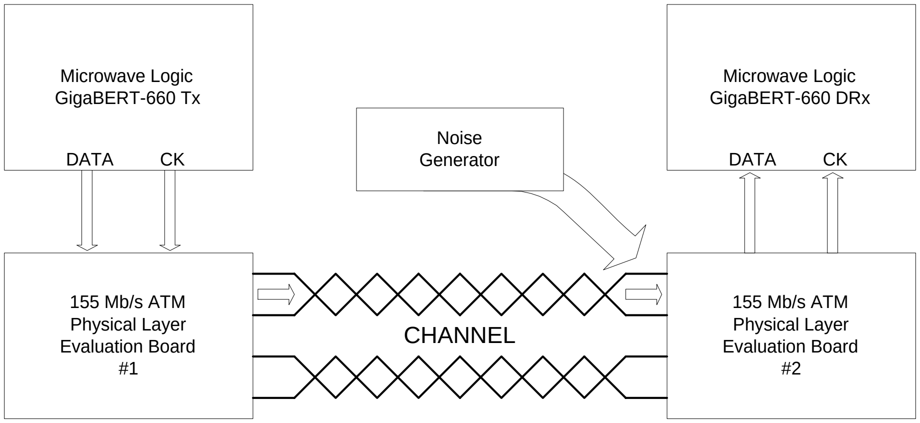


Figure 21: **Test setup**

The data was transmitted in one direction only and noise was added to the received signal. The noise source was a swept sine wave. The following 8 byte data pattern was constantly repeated:

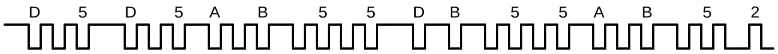


Figure 22: **Data pattern used in the BER test**

As Figure 22 shows, the data pattern had very frequent transitions. The transmit jitter was less than 0.5 ns peak to peak. GigaBERT-660 DRx analyzed the received data pattern, counted the errors and computed the Bit Error Rate.

Test Procedure

The BER tests were conducted over cables A and B with the noise in the form of a swept sine wave injected at the receiver through two 330 ohm resistors. The injected noise remained just under 20 mV peak to peak. The noise and the data pattern were fixed for all the tests. The only variable was the cable. The BER test with each cable exhibited very repeatable and easily reproducible results.

Test Results

The BER performance figures shown below were obtained after a 12 hour test with each cable.

CABLE	NOISE LEVEL	TEST TIME	Bit Error Rate (BER)	Passes TSB-67 ?	Meets ATM Forum 10^{-10} BER Requirement ?
A	19 mV	12 hours	9.6×10^{-8}	Yes	**No**
B	19 mV	12 hours	1.1×10^{-11}	Yes	Yes

Analysis of Results

The BER test described above is a very simple but powerful demonstration of the fact that ATM signal energy above 100 MHz is significant. This test demonstrates that a twisted pair channel can have flaws above 100 MHz, which may not be detectable by a category 5 certification, but which can nevertheless have devastating effects on the ATM network's BER performance.

The two cables used in the test appear to be very similar up to 100 MHz (Figure 20) and would not raise any concerns about the operation of the 155 Mb/s ATM network if extended frequency data was not available. However, our test demonstrates that these two cables would yield vastly different quality of service to the 155 Mb/s ATM users. Cable B, which behaves as expected over the extended frequency range, would maintain superior BER performance. Cable A, which has a defect above 100 MHz, would violate the BER requirements of the ATM Forum standard by up to 2 orders of magnitude and would result in a significantly slower data throughput than cable B.

The test also demonstrates that it is possible for an installation to be certified as category 5 but still have defects that could render the BER performance of a 155 Mb/s ATM network non-compliant with the ATM Forum AF-PHY-0015.000 standard.

Conclusions

We have demonstrated that the useful portion of the ATM spectrum extends beyond 100 MHz with approximately 5% of the signal energy located between 100 and 155 MHz.

Transmit Spectrum Needed to Assure Vendor Inter-Operability

All the ATM products we have examined maintain the first lobe of the transmit spectrum unfiltered because filtering this portion of the signal spectrum could, by virtue of signal distortion, impair inter-operability.

ATM Channel Requirements

Since the ATM data signal cannot be band limited to 100 MHz without adverse effects, the channel response above 100 MHz should be verified. Any excess NEXT above 100 MHz adds to the noise at the receiver. Any excess attenuation above 100 MHz affects equalization and closes off the already marginal eye pattern, degrading the SNR performance and increasing the BER.

Importance of the ATM Spectrum above 100 MHz

Although only 5% of the ATM spectrum exceeds 100 MHz, this portion of the spectrum contributes to the integrity of the ATM physical layer by shaping the received signal eye pattern for optimal recoverability.

The BER test performed on the cables with and without defects above 100 MHz demonstrates that characterizing category 5 installations up to 100 MHz may not be sufficient to guarantee proper operation of twisted pair 155 Mb/s ATM networks.

Category 5 twisted pair constitutes a robust and reliable physical layer for the 155 Mb/s ATM because it behaves predictably and consistently above 100 MHz. However, when field testing category 5 installations expected to carry ATM traffic, it is a good idea to verify the consistent behavior of these installations above 100 MHz, preferably up to 155 MHz.

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