# Chapter 4

# Line Simulator Requirements

Chapters 2 and 3 described the twisted copper pair environment at extended frequencies and listed the PSDs expected for ADSL and VDSL systems. The copper line gives rise the physical impairments of insertion loss and phase shift. Multiple xDSL lines within the same access bundle cause both self and foreign NEXT and FEXT. As with all electronics, additive impulsive and Guassian white noise is incident on the line. Due to the extended operational spectra, especially of VDSL, RF passband noise, often referred to as coloured noise, will impact on the systems overall BER. The line simulator must be able to accurately copy this behaviour throughout the relevant spectrum, but without inducing further signal impairments.

## 4.1 Physical Line Characteristics

A twisted copper line's insertion loss and phase response are functions of both frequency and reach. Chapter 2 developed theoretical expressions for both impairments and gave an indication of the predicted spread of their values using experimental data for the primary RLCG line parameters. Close examination is necessary to quantitatively describe the necessary simulator behaviour for both ADSL and VDSL CAP/QAM modulation schemes.

### 4.1.1 Insertion Loss

Figure 2.2, chapter 2, shows the predicted maximum insertion loss for lines to a maximum length of 12 kft, operating at frequencies to 10 MHz. Table 4.1 overleaf summaries the extremes of insertion loss.

| Reach | Maximum Insertion Loss (dB) | | |
|---|---|---|---|
| | **@ 1 MHz (DMT ADSL BW)** | **@ 1.5 MHz (CAP ADSL) BW** | **@ 20 MHz (VDSL BW)** |
| 1 kft | 5 | 7 | ≈ 30 |
| 6 kft | 30 | 35 | ≈ 120 |
| 12 kft | 62 | 87 | Not Applicable |

Table 4.1 Maximum insertion losses

For a uniform homogenous access line, the insertion loss is monotonically increasing. Pre-empting chapter 5, any digital simulation will in some manner quantise the frequency spectrum of the signal being modified by calculating a set of frequency values (called frequency samples) from a set of time domain samples of the signal. The discrete frequency representation will be modified according to the line's behaviour, termed frequency filtering. Whatever time-frequency transform is used, the size of the finite frequency quantisation interval will introduce new distortion when the insertion loss is simulated because the real line's insertion loss varies over the bandwidth of the frequency quantisation interval. The spacing of the calculated frequency samples is termed the transform resolution, with a single interval called a cell. Discrete transforms have a single complex data point for each transform cell. Sinusoids of different frequencies within a single cell cannot be distinguished[1], therefore a discrete transform can only model the insertion loss as a set of stepped discrete values. From this it is apparent the frequency resolution of the chosen transform must be small enough so that the line's behaviour can be approximated as flat over that region without introducing too much error. For example, consider a transform with just 16 frequency intervals to simulate the 20 MHz bandwidth of a VDSL signal over a 6 kft line. The transform's frequency resolution is 1.25 MHz (20 x $10^6$/16). Figure 4.1 reproduces the insertion loss for a 6 kft 26 gauge twisted copper pair with an overlay grid spaced at the frequency samples of the 16 cell transform (shown upto 10 MHz). The red stepped line shows the discrete frequency filter's approximation to the real line's continuous response.

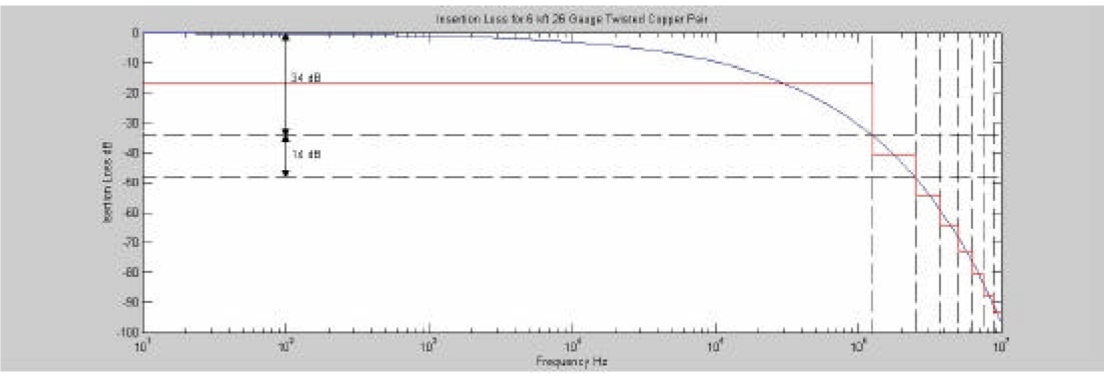


Figure 4.1 Insertion loss range

Over 20 MHz, a 6 kft line's insertion loss varies by 120 dB (extrapolated beyond 10 MHz). The average variation of insertion loss is 7.5 dB (120/16) across each transform cell. The greatest variation occurs in the cell with the lowest frequency interval between 0 to 1.25 MHz which, from figure 4.1, is approximately 34 dB (The variation in the next interval is smaller at 14 dB). Clearly a transform with such a large large resolution compared to the actual variation in insertion loss wouldn't capture the line's behaviour at the lower frequencies. However, since DSL systems work along side the existing POTs, there is a 30 kHz guard band from DC, unoccupied by DSL signals, which doesn't need simulating. For VDSL, which operates between approximately 1.1 and 20 MHz, the maximum variation of insertion loss to be simulated occurs in the transform interval from 1.25 to 2.5 MHz, not the first interval from DC to 1.25 MHz. This interval will be termed the first relevant frequency interval and is the 14 dB variation shown in figure 4.1.

Table 4.2 lists the mean and maximum variation of insertion loss across the first relevant transform interval (not from DC), for DMT ADSL and VDSL systems for various power of two [note 1] frequency transform resolutions. Maximum losses were determined using the Matlab version 5 function `[x,y]=ginput(1)` which allows the user to specify graphical points on the response curves of figure 2.2 using a mouse and crosshairs (see appendix 2). An overlay grid was first placed on the response curve of the insertion loss, thereby indicating the transform's first relevant frequency interval. As an example, the insertion loss curve for a 12 kft twisted copper pair is shown in figure 4.2. For illustration, the overlay grid marks the first relevant frequency intervals above 30 kHz (the lowest loaded carrier for DMT ADSL), for transforms with resolutions of 32, 256 and 1024 frequency points over the part of the ADSL bandwidth between 10 kHz and 1MHz.

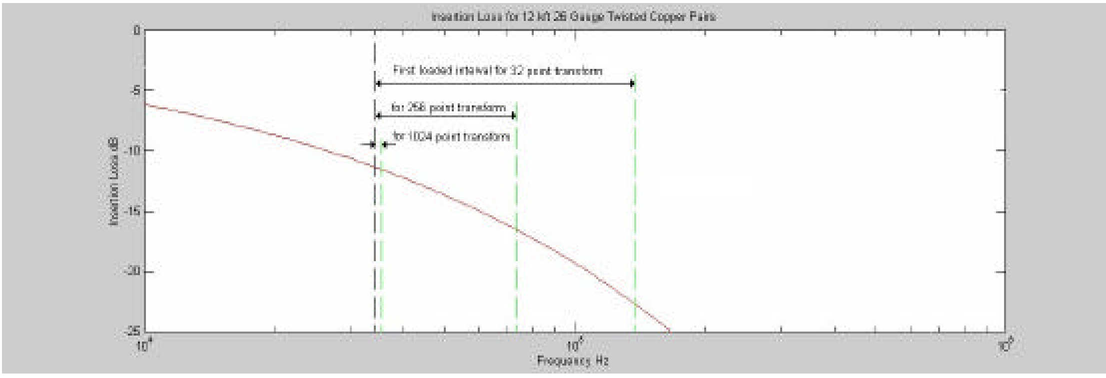


Figure 4.2. Insertion loss for 12 kft twisted copper pair with overlay grid showing the first relevant frequency transform interval

Clearly, with the small transform, the real copper pair exhibits substantial variation of insertion loss across the transform's resolution interval compared to the larger transforms.

## 4.1.2 Phase Shift

As shown from figure 2.4, chapter 2, the phase response of a twisted copper pair varies from $-\pi$ to $\pi$ radians many times across DSL spectrums for even the shortest length of twisted copper lines. The frequency over which the phase repeats is known as the full phase rotational bandwidth and is of prime

Note 1: Chapter 5 shows that any DFT capable of computation within the time sampling window must be a Fast Fourier Transform where the input vector length is formed to be a power of two (or four).

| No' of points | ADSL DMT (1.1 MHz BW) | | | | | | | VDSL CAP / QAM (20 MHz BW) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Resolution kHz** | Mean Interval Loss (Across the entire DSL spectrum) dB | | | **Max Interval Loss (Across the first relevant transform interval) dB** | | | **Resolution kHz** | Mean Interval Loss (Across the entire DSL spectrum) dB | | **Max Interval Loss (Across the first relevant transform interval) dB** | |
| | | 1 kft | 6 kft | 12 kft | **1 kft** | **6 kft** | **12 kft** | | 1 kft | 6 kft | **1 kft** | **6 kft** |
| 16 | **68.8** | 0.313 | 0.938 | 3.88 | **1.33** | **7.97** | **16.1** | **1 250** | 0.938 | 7.50 | **2.32** | **14.10** |
| 32 | **34.4** | 0.156 | 0.469 | 1.94 | **0.35** | **2.32** | **4.75** | **625** | 0.469 | 3.75 | **1.27** | **7.63** |
| 64 | **17.2** | 0.078 | 0.234 | 0.97 | **0.21** | **1.36** | **2.64** | **313** | 0.234 | 1.88 | **0.67** | **4.26** |
| 128 | **8.6** | 0.039 | 0.117 | 0.48 | **0.11** | **0.67** | **1.36** | **156** | 0.117 | 0.94 | **0.34** | **2.28** |
| 256 | **4.3** | 0.020 | 0.059 | 0.24 | **0.06** | **0.34** | **0.69** | **78** | 0.059 | 0.47 | **0.18** | **1.06** |
| 512 | **2.1** | 0.010 | 0.029 | 0.12 | **0.03** | **0.18** | **0.35** | **39** | 0.029 | 0.23 | **0.09** | **0.59** |
| 1024 | **1.1** | 0.005 | 0.015 | 0.06 | **0.01** | **0.09** | **0.18** | **20** | 0.015 | 0.12 | **0.04** | **0.26** |

Table 4.2 Insertion loss for various frequency transform resolutions

importance to the simulator design. The resolution of the discrete frequency transform used in the simulator must be small enough so that the phase change exhibited on the real line across the resolution bandwidth may be approximated as flat without introducing excessive distortion in the signal. Unlike the insertion loss, which has a maximum variation across the transform's first frequency interval, the rate of change of phase shift is constant across the spectrum resulting in an equal phase change across all of the transform cells. The full phase rotation bandwidths for 26 gauge 1, 6 and 12 kft twisted copper pairs are shown in detail in figure 4.3 and summarised in table 4.3.

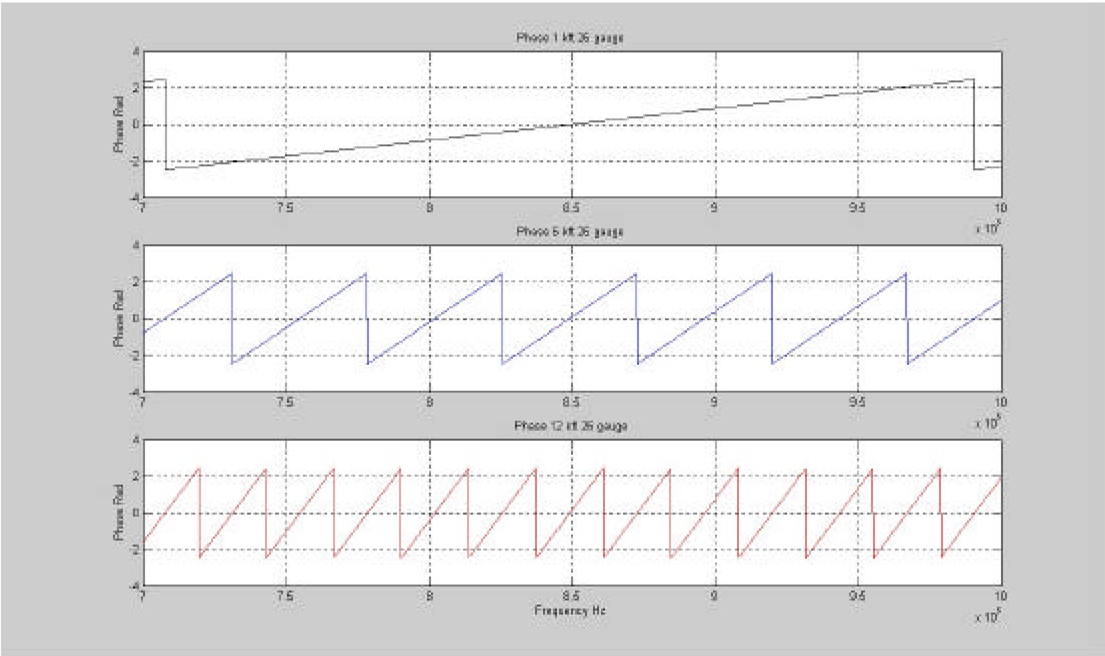


Figure 4.3. Detailed phase response for 26 gauge pairs

| Reach | Full Phase Rotation Bandwidth (-π to π) | Phase Variation per kHz (rads) |
|---|---|---|
| 1 kft | ≈ 275 kHz | 0.023 |
| 6 kft | ≈ 46 kHz | 0.136 |
| 12 kft | ≈ 23 kHz | 0.273 |

Table 4.3. Full phase rotation bandwidths for 26 gauge pairs

### 4.1.3 Acceptable Phase and Magnitude Variations

Before deciding on a minimum transform resolution the question as to what are acceptable variations in magnitude and phase across the transform cell arises? This is a very difficult question to answer.

Ideally the effect of increasing variations across the interval should be investigated with a prototype simulator with variable transform resolution simulating an access line between two xDSL modems. The minimum transform resolution would be determined according the simulator's experimental performance compared with an actual physical line for identical xDSL modem pairs. As an initial design, a maximum cell variation of 10%, allowing a maximum insertion loss variation of 0.4 dB (10log1.1) and phase variation of 0.628 radians will be used.

# 4.2 Crosstalk

The Analogue Front Ends[2] (AFEs) of DSL receivers and transmitters incorporate bandpass filtering to strictly limit the transmission bandwidth. In the absence of inter-modulation distortion, signal power falling outside the filtered bandwidth will be removed. A simulator therefore only needs to simulate crosstalk inband of its own PSD mask. The particular DSL modulation scheme defines the required simulation bandwidth, so therefore also specifies the required crosstalk simulation frequency range.

The required transform frequency resolution for crosstalk simulation is also dependent on the particular modulation scheme. For example, a simulator with a transform resolution of 10 kHz, won't have the required resolution to simulate crosstalk to individual DMT ADSL subcarriers spaced at 4.3125 kHz.

# 4.3 AWGN, Impulsive and Coloured Noise

Following the same argument as for crosstalk, the line simulator's bandwidth for modelling AWGN, impulsive and coloured noise will be fully specified by the requirements of the DSL signal's bandwidth.

# 4.4 ADSL Line Simulator Requirements

With specified PSDs and the simulation requirements of maximum insertion loss and phase shift variation over a transform cell, frequency transform parameters can be determined. Different specific simulation requirements exist for each distinct DSL access method so each will require different transform.

## 4.4.1 DMT ADSL

DMT ADSL modulates downstream data onto 256 subcarriers spaced at 4.3125 kHz intervals, the first at 4.3125 and the last at 1 104 kHz. A DMT ADSL line simulator must be capable of modifying each individual subcarrier component, therefore there must be at least one frequency transform data point for each subcarrier. The upstream is similar, but limited to 32 carriers extending to 138 kHz.

### 4.4.1.1 Transform Requirements due to Insertion Loss

From table 4.2, with an insertion variation limit of 0.4 dB and access line lengths of 1, 6 and 12 kft, the required minimum transform resolution, number of frequency points and observable bandwidth are shown in table 4.4 for the downstream channel. The upstream transform requirements are satisfied by those for the downstream because the DMT spacing is the same, but over a smaller spectrum and with the same guard band of 30 kHz.

| Reach | Minimum Transform Resolution (Downstream) | Minimum Number of Frequency Cells over Min’ Observable Bandwidth (Downstream) | Minimum Observable Bandwidth (Downstream) |
|---|---|---|---|
| 1 kft | 4.3125 kHz | 256 | 1.104 MHz |
| 6 kft | | 256 | |
| 12 kft | | 512 | |

Table 4.4 DMT ADSL simulator transform requirements considering a maximum 10 % insertion loss variation across the first relevant transform cell

### 4.4.1.2 Transform Requirements due to Phase Shift

The transform requirements due to the maximum phase shift variation limit of 0.628 radians are determined from table 4.3 and listed in table 4.5 below, again for power of two transforms. As with the insertion loss, due to the rapid phase change with frequency for the long 12 kft lines (shown in the bottom plot of figure 4.3), the ADSL spectrum must be divided into an excessive 512 cells to achieve the specified limit of 10% phase variation across the resolution interval.

| Reach | Minimum Transform Resolution (Downstream) | Minimum Number of Frequency Cells over Min’ Observable Bandwidth (Downstream) | Minimum Observable Bandwidth (Downstream) |
|---|---|---|---|
| 1 kft | 17.25 kHz | 64 | 1.104 MHz |
| 6 kft | 4.3125 kHz | 256 | |
| 12 kft | 2.16 kHz | 512 | |

Table 4.5 DMT ADSL simulator transform requirements considering phase shift variation

#### 4.4.1.3 Overall Transform Requirements

In order to satisfy the requirements for both loss and phase response and crosstalk, the higher resolution transform of the two tables and that given for crosstalk by DMT spacing must be used for each line type. Ideally the simulator should use a frequency transform with 512 samples to cover the entire range of specified reaches for DMT ADSL lines. However, as will be shown in chapter 5, a transform with 256 frequency samples within the 1.104 MHz bandwidth is more easily implemented. If a 256 cell frequency transform is used for long lines upto 12 kft long, the maximum interval insertion loss variation would be 0.69 dB (17%) over the first relevant frequency interval and the phase shift interval variation would be 1.18 radians (19%).

The frequency transform parameters in tables 4.4 and 4.5 satisfy both FDM and EC DMT ADSL.

### 4.4.2 CAP ADSL

CAP ADSL systems modulate data onto just one carrier in each direction, so the transform requirements are not dependent on a subcarrier spacing. The required transform resolution due to insertion loss and phase variation is the same as for the DMT simulator. CAP ADSL bandwidth is 50 % larger than that for DMT ADSL. Chapter 5 will show that a 1024 point DFT [note 2], with frequency sample spacing at the DMT subcarriers has a maximum observable frequency of 2.2 MHz. This indicates that the same transform hardware can be used to simulate CAP as well as DMT systems. However, a problem could occur due to the DMT simulator's AFEs which will incorporate lowpass filters with a 1.1MHz corner frequency. This would stop a very important part of the CAP spectrum from entering the simulator's frequency transform block. A solution would be to use the same transform block, but different AFEs for the two schemes.

## 4.5 VDSL Line Simulator Requirements

VDSL transmission spectrums are much larger than those for ADSL. In addition, whereas the DMT ADSL bandwidth is fixed regardless of the data rate, VDSL bandwidths are dependent on the data rate, shown previously in figure 3.10. Therefore the simulator requirements depend on the VDSL modem's designed data rate.

For a full rate service with a 20 MHz bandwidth and a short 1 kft access line, the minimum transform resolution considering the insertion loss is 39 kHz. This corresponds to 512 cells across the 20 MHz spectrum. The rate of phase variation is independent of frequency, but dependent on line length. From table 4.3, a 1 kft line requires a resolution of 27 kHz (the same for a 1 kft ADSL line, table 4.5) to limit the phase variation to 10% across the transform cells. From this requirement, the minimum number of transform cells is 741.

Note 2: When the term point is used in the context of a DFT, it refers to the combined number of positive and negative frequency points, so a 1024 point DFT divides its observable spectrum into only 512 positive frequency intervals or cells

# 4.6 Summary of Transform Requirements

Summarising, the required frequency tranforms for the three DSL modulation schemes under consideration are shown in table 4.6.

| | Minimum Obervable Bandwidth | Minimum No. of Cells over the Minimum Observable Bandwidth |
|---|---|---|
| ADSL DMT | 1.1 MHz | 256 |
| ADSL CAP | 1.5 MHz | 256 over 1.1 MHz |
| VDSL CAP / QAM | 20 MHz | 741 |

Table 4.6 Overall ADSL and VDSL simulator transform requirements

## References

[1] E. Oran Brigham, "The Fast Fourier Transform and Its Applications", Prentice Hall, 1988, p170.

[2] Denis J. Rauschmayer, "ADSL / VDSL Principles", Macmillan, 1999, p208.