Chapter 2

The Twisted Copper Pair

Twisted pair channels are noisy, lossy and prone to crosstalk. Both ADSL and VDSL modulation schemes are designed to overcome or reduce the effects of these impairments. Before any simulator design can be considered, a thorough understanding of the transmission environment in which ADSL and VDSL modems operate is essential. Due to the extended PSD of both modulation schemes into the MHz region, both physical line characteristics and crosstalk susceptibility are considerably different to that experienced for voice band communication on the same channel. This chapter will briefly look at physical line characteristics of twisted copper pairs into the MHz region and the nature of crosstalk specific to ADSL and VDSL systems.

2.1 Physical Line Characteristics

It is important to realise that access loops between a LEX and a customer's premises generally do not consist of a single long uniform conductive pair, but rather of a series of spliced lengths of pairs increasing in diameter towards the subscriber[1]. Due to this, the insertion loss of the access loop is generally not monotonically increasing with reach towards the subscriber and is also subject to abrupt splicing losses in addition to the cumulative losses upto that point. The nature of the access loop must be considered for future work in developing models for software to drive a hardware simulator.

Any transmission line can be described in terms of its physical characteristics of resistance, inductance, capacitance and admittance, known as the primary RLCG parameters. For the lowpass voice spectrum of 4 kHz, RLCG parameters are constant for normal gauge access pairs such as 24 and 26 gauge wire. At higher frequencies above a hundred kHz or so, the pair's resistance, inductance, capacitance and admittance vary significantly with frequency

2.1.1 RLCG Characteristics at Extended Bandwidths

Figure 2.1 shows the typical RLCG characteristics of a 1000 thousand foot (1 kft) twisted copper pair of plastic insulation coated (PIC) 24 and 26 gauge wire, generated by Matlab using cubic spline interpolation to published data[2]. The variation in resistance, inductance and admittance is clearly seen at frequencies above 100 kHz. Although primary RLCG parameters give an insight into the basic behaviour of a twisted copper pair at higher frequencies, two more useful transmission line parameters are defined. The propagation constant and characteristic impedance of the line enable the voltage and current at any point along the line and hence the insertion loss and phase shift due to any length of twisted copper pair to be determined.

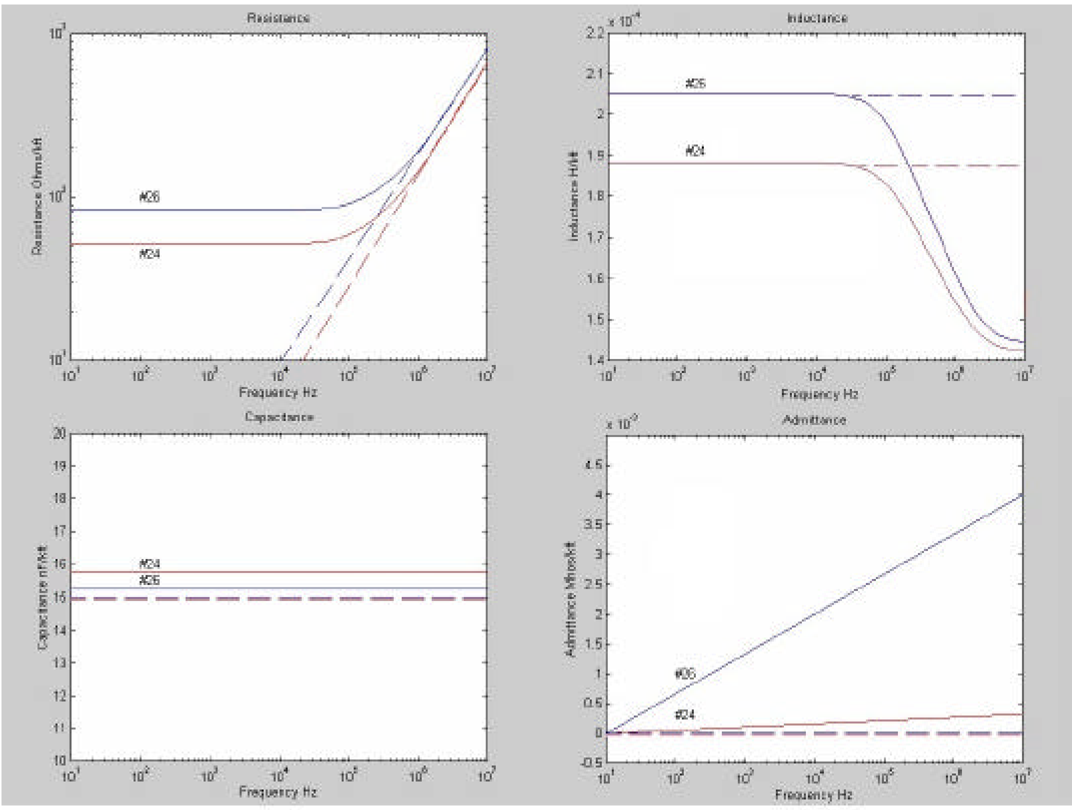

Figure 2.1 Primary PIC twisted pair parameters

2.1.2 Propagation Constant and Characteristic Impedance

Any termination design will attempt to match the terminating impedance with the line impedance for maximum possible power transfer to the receiver. For a matched line and termination impedance, the voltage at any point 'x' from the source is given by

$$V(f,x) = V_0(f)e^{-x\gamma f}$$

In terms of a transfer function from source to termination,

$$H(f) = \frac{V(f,x)}{V_0(f)} = e^{-x\gamma f}$$

The γ term is the propagation constant and is related to the primary line characteristics by

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$$

From the primary line parameters, below 100 Mhz $j\omega C >> G$, therefore the propagation constant can be approximated to

$$\gamma = j\omega\sqrt{LC}\sqrt{\left(\frac{R}{j\omega L} + 1\right)}$$

Since $j\omega L > R$ in the spectrum of interest,

$$\sqrt{\left(\frac{R}{j\omega L} + 1\right)} \approx \left(\frac{R}{j\omega L} + 1\right)$$

Thus

$$\gamma = R\sqrt{\frac{C}{L}} + j\omega\sqrt{LC}$$

The resistance increases proportionally to the root of frequency due to the skin effect and the line capacitance is constant. Although the pair's inductance varies approximately 30% between 100 kHz and 10 MHz, if as a first approximation it is assumed to be constant, the frequency dependence of the propagation constant is given by:

$$\gamma = \alpha_0 f^{1/2} + \beta_0 f$$

Where the constants α_0 and β_0 are related to the primary line parameters. C, L and R.

2.1.3 Insertion Loss

The main reason for deriving a theoretical expression for the characteristic impedance in terms of the propagation constant is to determine what behaviour a DSL line simulator must simulate due to the physical line effects. The line's transfer function can be considered in terms of magnitude and phase, allowing the insertion loss in decibels and the associated phase shift for sinusoids throughout the relevant DSL spectrum to de determined. Over a typical range of access spans, figures 2.2 and 2.3

show the analytic insertion loss and associated phase shift derived above, for 26 gauge twisted copper pairs up 10 MHz. All graphs were generated by Matlab using the primary RLCG parameters shown in figure 2.1 (see appendix1 for further details).

As will be discussed later, the simulator's required DFT resolution is critically dependent on the range of the variation of insertion loss and phase over the DSL bandwidth.

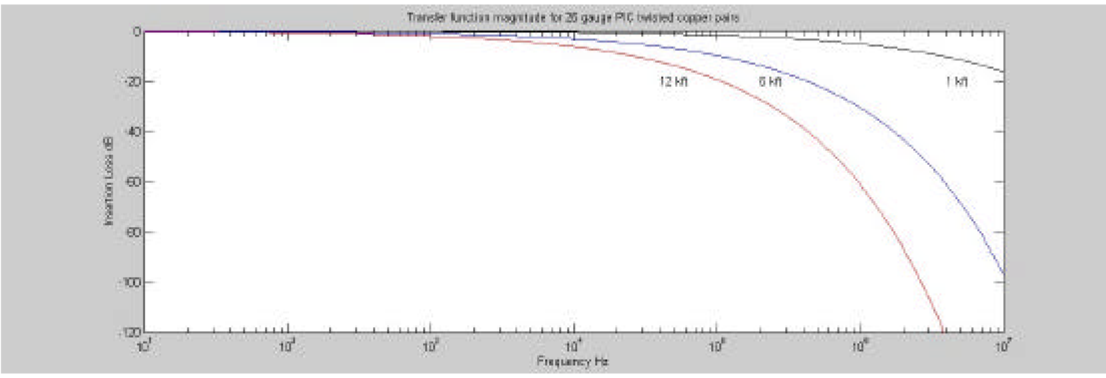

Figure 2.2 Insertion loss for 26 gauge PIC twisted copper pair

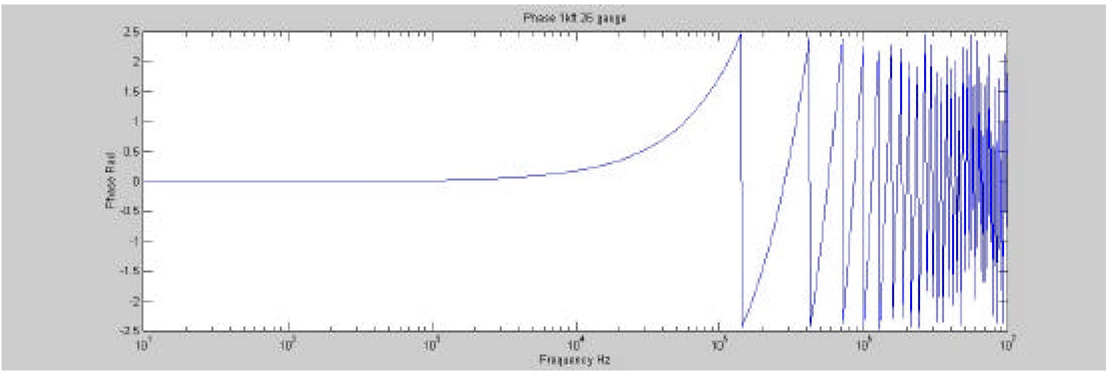

Figure 2.3 Phase shift for 26 gauge PIC twisted copper pair

As can be seen from the bode plot of phase, there is zero phase shift over the voice band, but above 100 kHz the phase response changes rapidly. Figure 2.4 shows linear plots of phase response over the ADSL bandwidth of 1 MHz for the proposed extremes of ADSL system reach.

Although these graphs are derived from approximations, experimental work[3] indicates the analytic results adequately model the access line's insertion loss and phase response over the ADSL bandwidth.

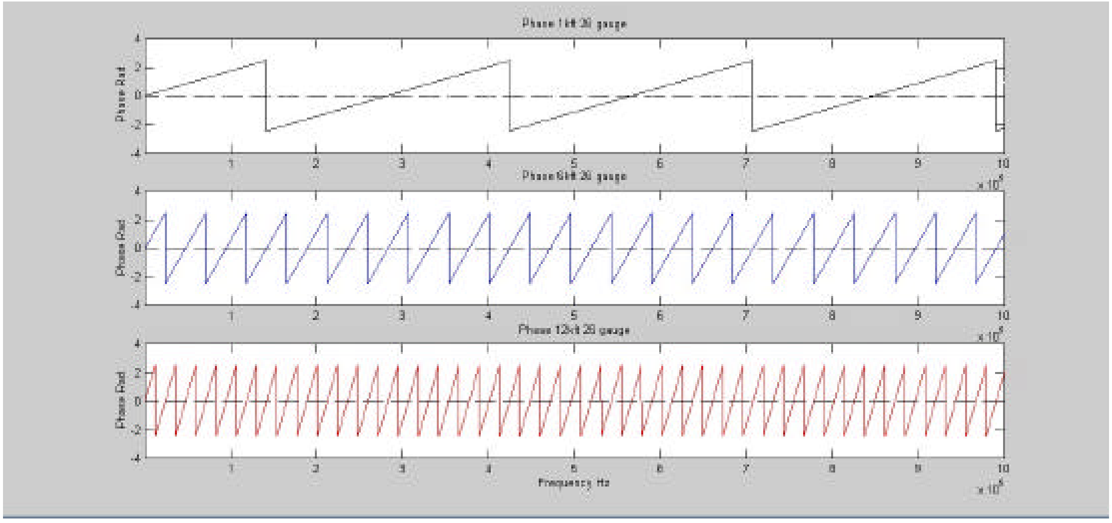

Figure 2.4 Phase shift for 26 gauge PIC twisted copper pair over ADSL bandwidth

2.2 Crosstalk in ADSL and VDSL Systems

Alexander Graham Bell patented the first use of twisted copper pairs in 1881 to alleviate the effect of crosstalk between neighbouring wires within an access bundle. Until this time, multiple conductors with a single shared ground line were common. Unacceptable levels of crosstalk in access bundles of only a few hundred metres in length were often encountered. Later, this type of scheme was termed common mode signal transmission where the driving signal is applied between the common ground and conductor. As such, any nearby signal carrying conductor, called a disturbing source, electro-magnetically induces voltages in other signal carrying wires differently to that induced in the physically different and spatially separated common ground. Clearly at the access termination, the earpiece, a potential difference will exist between the ground and conductor due to the disturbing signal – crosstalk. The twisted copper pair operates in differential mode where only a difference in potential between the two conductors causes a current to flow. There is essentially no difference in the em field from the disturber, but the two conductors are now subject to the same disturbance so they will experience an identical common change in their potential relative to some absolute ground but not to each other. At the earpiece termination there is no difference in potential across the pair, so no power is dissipated in the earpiece due to the disturber. The disturbing crosstalk has been rejected by the differential operation of the pair of wires. In other words, twisted copper pairs give rise to common mode rejection of disturbing signals. Figures 2.5 and 2.6 show common mode and differential operation of transmission lines.

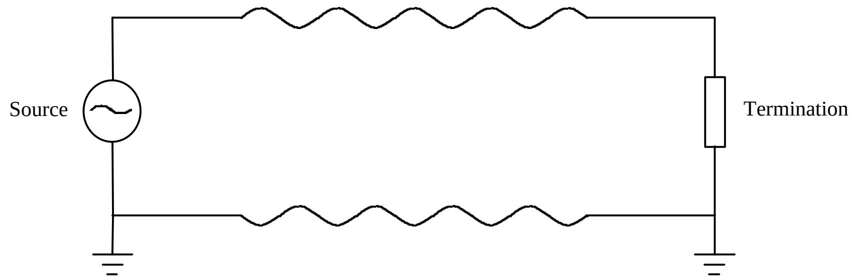

Figure 2.5 Common mode operation

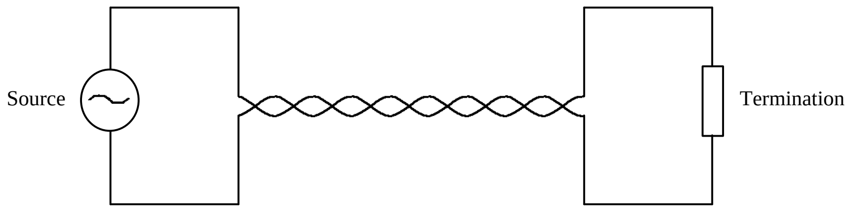

Figure 2.6 Differential mode operation

If twisted pairs reject common mode signals doesn't that imply crosstalk is eliminated at any frequency? Unfortunately due to the phenomena of capacitive and inductive inbalance[4] between different pairs along the length of the access bundle, differential crosstalk still occurs in twisted copper pairs.

Although the actual method through which crosstalk is induced is more important when considering how to generate model crosstalk for use in a simulator rather than directly in the design of the simulator hardware itself, some basic understanding is required inorder to adequately provision a simulator to copy crosstalk induction on twisted copper pairs. In any discussion on crosstalk, several definitions of different types of crosstalk are made which include:

- Self crosstalk from similar access signals (e.g. ADSL crosstalk to ADSL lines)
- Foreign crosstalk from different access signal (e.g. ISDN crosstalk to VDSL lines)

Both self and foreign crosstalk can be caused by sources located at

- the same end of an access bundle, termed Near End CrossTalk (NEXT)
- the opposite end of an access bundle, termed Far End CrossTalk (FEXT)

Figures 2.7 and 2.8 show NEXT and FEXT.

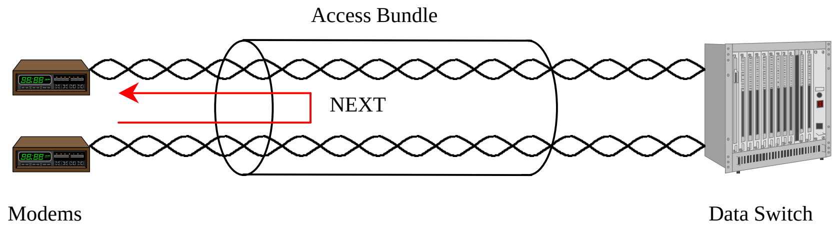

Figure 2.7 Near End CrossTalk

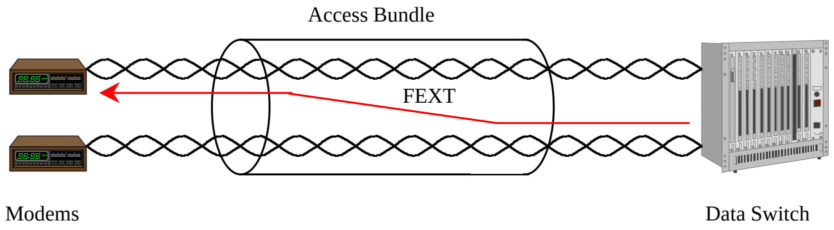

Figure 2.8 Far End CrossTalk

The effect of crosstalk on different modulation schemes is dependent mainly on the PSD relationship between the disturbed and disturbing signals[5], discussed further in subsequent chapters. To clarify this, consider the case of mythical ZDSL and YDSL disturbers inducing crosstalk in a QDSL signal which have the PSDs shown in figure 2.9.

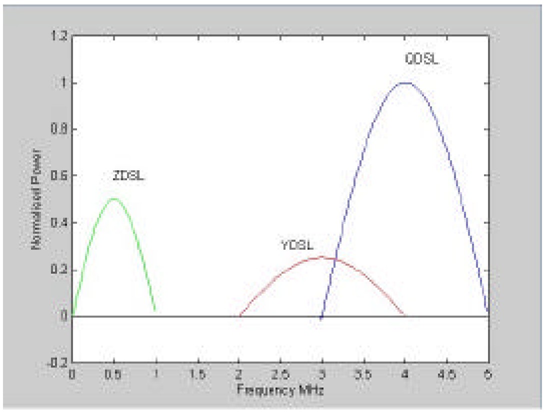

Figure 2.9 Mythical DSL power spectra

The PSDs of the QDSL and ZDSL signals don't overlap, therefore in the absence of non-linear intermodulation distortion and perfect out of band noise rejection, crosstalk from the ZDSL disturber will have no affect on the Bit Error Rate (BER) of the QDSL signal after demodulation. This is in contrast to the PSDs of the QDSL and YDSL signals, which show significant overlap. Crosstalk from a YDSL signal will have a significant impact on the BER of the QDSL signal.

2.2.1 Additive Nature of Crosstalk

Regardless of the type of crosstalk that a signal is subject to (e.g. Self NEXT, Foreign FEXT etc), the induced crosstalk power in a signal carrying pair is, like noise, fundamentally additive. In the absence of non-linear effects, a monotone disturber at frequency f_1 will induce crosstalk noise in other pairs at the same frequency f_1. This is an important property of crosstalk, which will be invoked to allow its simulation in the hardware design.

Although more relevant to further work on the development of software models to drive the hardware simulator, when modelling the effect of crosstalk from multiple disturbers, one must take a statistical approach. Crosstalk models exist which predict both NEXT and FEXT for a single disturber. These can be extended statistically to model multiple disturbers, but not by simply summing of the effect from each individual disturber[6]. For example, to model the effect of two similar disturbers one cannot just double the results from a model of one disturber

2.3 Guassian, Coloured and Impulsive Noise

As with all telecommunication systems, Additive Guassian White Noise (AGWN) and impulsive noise from sources such as switching equipment is present in DSL systems. In the extended spectra of DSL signals other important noise sources are present due to high frequency em radiation. Noise from bandlimited radio communication systems often falls within DSL spectra. A common example is Amateur Radio transmission, which has a PSD within the Discrete Multi-Tone (DMT) ADSL PSD. Such noise of often termed coloured noise and as with crosstalk, AGWN and impulsive noise are additive.

References

[1] American National Standards Institute, Asymmetric Digital Subscriber Line Metallic Interface Standard, T1.413, August 1995.

[2] Walter Y. Chen, “DSL”, Macmillan, 1998, p54-58.

[3] Harold Hughes, “Telecommunications Cables”, Wiley, 1997, p114-120.

[4] Denis J. Rauschmayer, “ADSL / VDSL Principles”, Macmillan, 1999, p44-53.

[5] Denis J. Rauschmayer, “ADSL / VDSL Principles”, Macmillan, 1999, p89-130.

[6] Walter Y. Chen, “DSL”, Macmillan, 1998, p64-67.