Chapter 1

Introduction

1.1 Research Motivation and Objective

With the recent rapid growth of high-speed Digital Subscriber Line (DSL) access subscriptions, there is a high demand in the telecommunication industry for equipment to accurately predict DSL access performance over a telephone subscriber line (also referred to as a local loop). The subscriber line is a metallic twisted-pair network link between a customer and a telephone Central Office (CO). While some of the existing DSL analysis equipment is already capable of assessing the performance rate, it requires two-point operation (sending test signals from one end of the loop and measuring the signals at the other end) involving the dispatch of a service vehicle. This leads to expensive testing processes and it is therefore an undesirable solution for DSL access providers. A more cost-effective solution would be to estimate the expected DSL performance on the basis of single-point measurements, preferably from the provider end. However, such test equipment is not currently on the market [1], [2].

In the single-point measurement procedure proposed by Wong and Aboulnasr [3] the performance, in terms of the insertion loss (IL) (see Section 1.4 for definition), of a local loop is estimated from a single-point input impedance measurement from the CO end. The measured input impedance is modeled with an RC network regardless of the complexity of the loop topology. Their method is designed to approximate the IL at one frequency point. To assess DSL connectivity, the performance over the entire DSL bandwidth needs to be considered.

This work poses the single-point subscriber line measurement as a model-based system identification problem. A local loop model consists of the network topology and the characteristics — namely type and length — of each twisted-pair segment. Simulation of the model is based on transmission line theory [4], [5] and the electrical characteristics of twisted-pairs. While the local loop is a linear time-invariant system, its behavior is complex and nonlinear in its parameters. Hence, common identification techniques (*e.g.,* least squares and instrumental variable methods) are not applicable, and we therefore investigate an iterative modeling approach to search for the best-fitting loop model. Upon successful identification of the loop, the theoretical DSL access performance rate can then be readily computed.

The remainder of this chapter will solidify the research foundation by briefly introducing DSL technology, telephony (DSL) local loop history and expected structures, and the effect of the local loop structure on DSL performance. These materials are extracted from [6] – [17]. This chapter concludes with the thesis overview .

1.2 DSL Technology

Since the mid-1990's, we have experienced a rapid data-rate-hungry evolution of the Internet, especially with the emergence of the World Wide Web (WWW), its multimedia-intensive contents, and the booming growth of WWW hosts and users. In addition, the number of small offices/home offices (SOHO), which often require fast access to a corporate local area network (LAN), has been growing steadily in recent years. Such high data-rate demands surpass the capability of now mature voiceband modems (< 56 kbps). The first higher-speed alternative, the Integrated Services Digital Network (ISDN), was introduced in the mid-1990's to accommodate high data-rate demand. However, despite superior access speed, at 128 kbps, it did not gain wide popularity due to its high cost, incompatibility with the existing telephone service (POTS — plain old telephone service), and discrepancies in the ISDN standards. To search for even faster speeds without repeating ISDN's oversights, several broadband access technologies (operating > 1.5 Mbps) — one of which is DSL technology — emerged, and these new services have been gaining popularity rapidly in data communication in recent years.

A broadband communication network, or simply a broadband network, is capable of transporting voice, data, and video in a single converged communication network. While such a unified network is not yet realized, largely due to the already existing independent infrastructure for each service, several broadband access technologies capable of broadband communication are already available today. They are classified into three basic categories: copper-loop, cable (both fiber and coaxial), and wireless access technologies. The DSL technology, equivalent to the copper-loop access technology, has been developed by the telecommunications industry to utilize its largest asset, millions of miles of installed twisted-pairs, beyond the existing POTS. At the present time, DSL technology has shown many advantages over other alternative broadband access solutions.

DSL technology gains much of its advantage over its peer technologies by utilizing, and sometimes even sharing with POTS, telephony subscriber lines to provide an affordable, ubiquitous data access solution. However, because of the narrowband nature (0–4 kHz) of POTS, the local loops are not always conditioned for broadband DSL access. In other words, "high-speed" access is not guaranteed for all local loops. To compound the issue, the local loops are generally laid out without sufficient documentation, preventing DSL providers from theoretically calculating the expected data rate for a local loop. This is the primary driving force for the development of local-loop DSL performance prediction capability.

While there are many varieties of DSL technology, collectively referred to as xDSL, their overall systems are very similar. As illustrated in Figure 1-1, the DSL system consists of the subscriber premise, central office (CO) premise, and the local loop, which connects two premises. Primary components of the CO are the DSL Access Multiplexer (DSLAM) and the CO-end modem (xTU-C). The DSLAM links the DSL traffic to a higher-speed backbone network, such as OC (Optical Carrier)-3 and OC-12, further connected to a Network Service Provider (NSP), and the xTU-C interfaces the local loop and the CO. The xTU-R is the subscriber-side counterpart of the xTU-C. For those DSL technologies capable of coexisting with POTS — *e.g.*, Asynchronous DSL (ADSL) and Very High Speed DSL (VDSL) technologies — POTS splitters, which combine POTS and DSL service over a subscriber line, exist on the local loop side of both modems. The POTS connections are made to telephone devices on the subscriber side and to the public switched telephone network (PSTN) on the CO side.

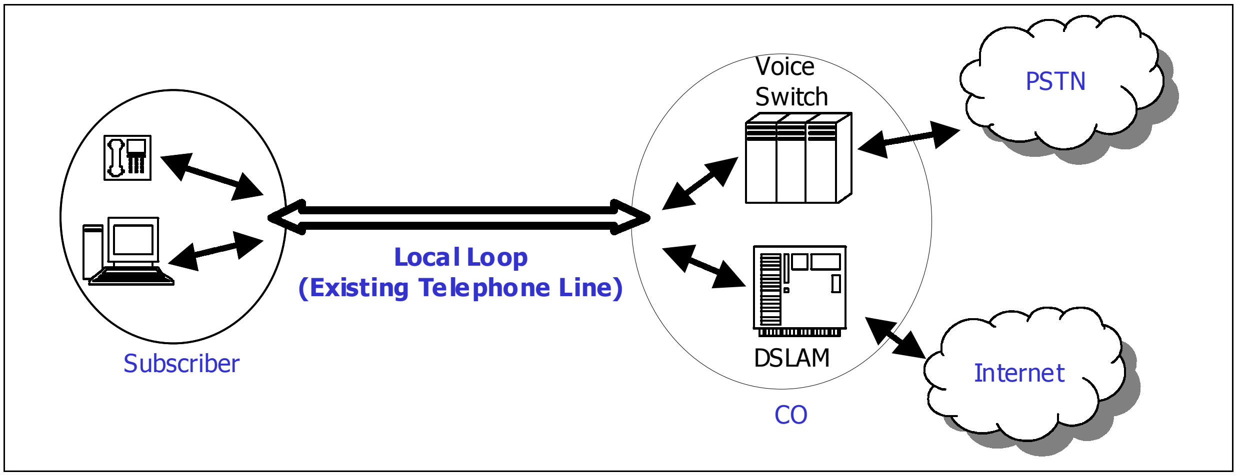

Figure 1-1: Simplified DSL Architecture.

Standardization of xDSL technologies has been underway since the late 1980's. For instance, Committee T1 of the American National Standard Institute (ANSI) initiated the ADSL effort, which is the most prominent xDSL technology to date. Also, the International Telecommunications Union (ITU) and European Technical Standard Institute (ETSI) have joined the effort, and thus their standards for ADSL are largely based on the ANSI standard.

1.3 Subscriber Loop Environment

As discussed in the previous section, the primary motivation behind the development of DSL technology is the exploitation of existing local telephone loops. The invention of the twisted-pair local loop in the late 19th century was an innovative solution to reduce crosstalk between wires in the telephone cable, which encloses many wires in its sheath. Some of the first loops are still in operation today in some parts of the country. This section introduces the expected features of the twisted pairs and local loops.

1.3.1 Twisted-Pair Types

One of the aforementioned twisted-pair characteristics is the type, which is mainly categorized by the twisted-pair's physical characteristics. The wire gauge size and cable insulation type are two characteristics that are widely documented twisted-pair classifications. Other classifications encountered are those based on bit-rate (5 classes based on maximum supported bit rate), ambient temperature, cable location (*e.g.*, aerial, buried, or buried in a conduit), and cable manufacturer.

However, the wire conductor material, which makes a large contribution to the cable electrical characteristics, is not often used for discrimination since it is almost always copper.

In the U.S., the gauges of twisted pairs are specified using American Wire Gauge (AWG) designations. The typical gauges found in U.S. loops are 19, 22, 24, and 26 AWG, with a larger AWG number corresponding to a smaller wire diameter. Thinner twisted pairs (larger AWG number) are often used underground close to the CO while thicker wires are used as an aerial drop line to the customer premise.

Figure 1-2 illustrates the variation in the twisted-pair characteristics with respect to varying gauge sizes — namely, 22, 24, and 26 AWG — based on the tabulated twisted-pair characteristics in the ANSI T1.601-1999 standard. Figure 1-2(a) and (b) are the attenuation function $\alpha(f)$ and phase function $\beta(f)$ (the real and imaginary parts of the propagation function $\gamma(f)$) respectively. Figure 1-2(c) and (d) show the characteristic impedance $Z_0(f)$ (the magnitude and phase, respectively). The insulation type of these twisted-pairs is plastic or PIC (polyolefin-insulated cable) and is measured at 21 °C ambient temperature.

Unlike the gauge size, which appears in a different part of the local loop, the variation in cable insulation material has a more historical background. The earliest twisted-pair cables were insulated with paper (often referred to as "pulp") and were installed until the 1970's. One of the disadvantages of pulp insulation is its sensitivity to the surrounding humidity. Although the paper-insulated cable possesses good electrical characteristics in dry environments, moisture severely degrades its characteristics. To overcome the moisture problem, plastic insulation was introduced in the 1970's and is still being used today. There are several different types of plastics commonly used as insulators: polyethylene, polypropylene, and PVC.

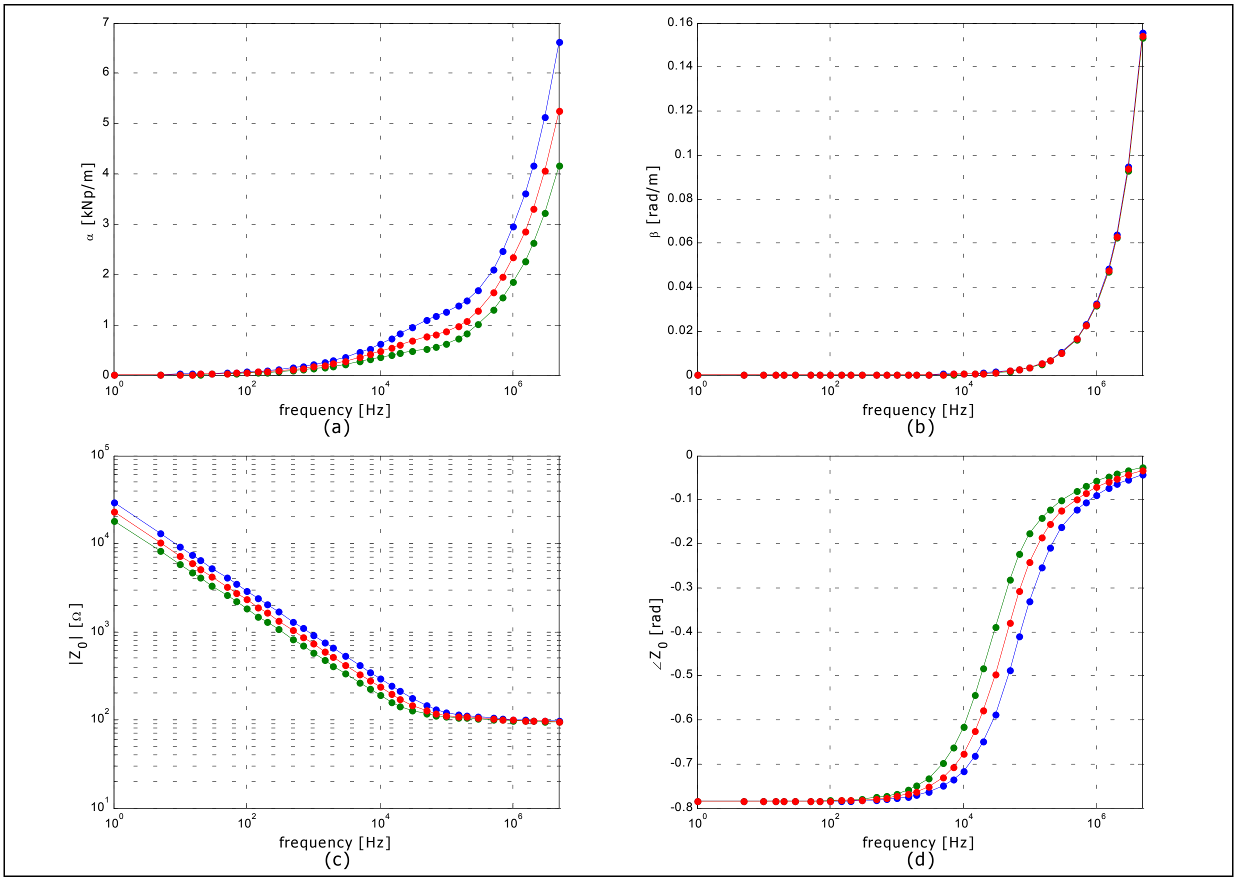

Figure 1-2: Twisted-pair electrical characteristics for 22 AWG (green), 24 AWG (red), and 26 AWG (blue) – attenuation function (a), phase function (b), magnitude (c) and phase (d) of characteristic impedance.

Figure 1-3 shows the variation in electrical characteristic between PIC and pulp insulations. Both twisted pairs are 24 AWG with an ambient temperature of 21 °C. While $\beta(f)$ (Figure 1-3(b)) and $|Z_0(f)|$ (Figure 1-3(c)) show very little deviation between the two types of insulation, the others, $\alpha(f)$ (Figure 1-3(a)) and $\angle Z_0(f)$ (Figure 1-3(c)), indicate a mismatch between the two types over a limited frequency range. The largest deviations occur in $\alpha(f)$ and $\angle Z_0(f)$ above 100 kHz and below 1 kHz, respectively.

The observed deviation in electrical characteristic for varying gauges and insulation types would likely appear for other variations of twisted-pairs' physical characteristics. To reduce the complexity of the problem, it is assumed in this thesis that only the gauge sizes are unknown and that the other categories constitute known information. Increasing the number of twisted-pair types increases the number of potential loop models and this results in increased computational effort for the eventual system identification.

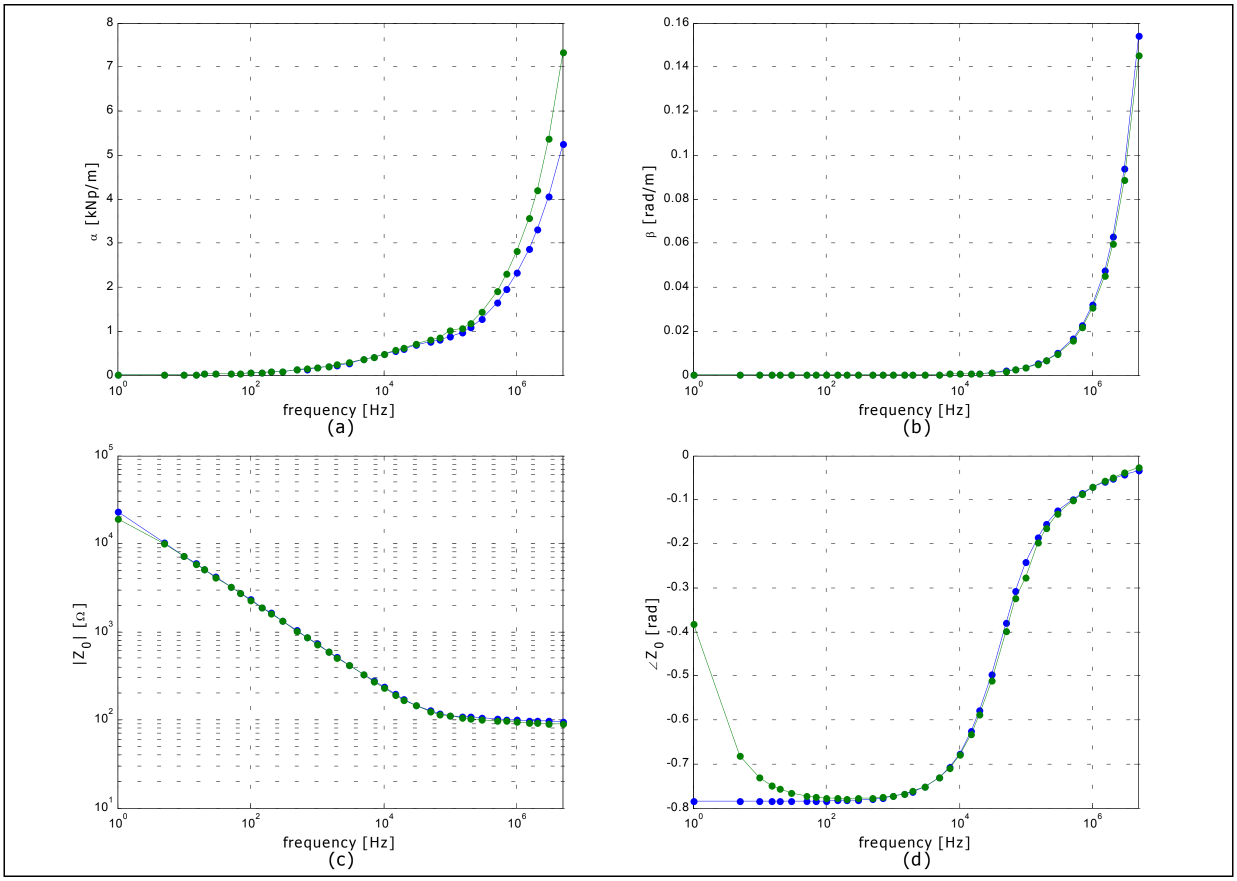

Figure 1-3: PIC (blue), and pulp (green) insulated 24-AWG twisted-pair electrical characteristics – attenuation function (a), phase function (b), magnitude (c) and phase (d) of characteristic impedance.

1.3.2 Subscriber Loop Structure

The subscriber loop can be divided into three functional sections: feeder (or main) cable, distribution cable, and drop wire. The feeder cable, a bundle of twisted-pairs, is the thickest cable and runs from the CO to distribution cabinets. Typically the main cable contains 1,000 to 2,500 twisted-pairs in its sheath and is located underground in a protective housing. The distribution cable, which links a distribution cabinet to a potential customer site, commonly uses a cable with 6 to 500 pairs. Lastly, the drop wire connects the distribution cables to subscriber premises. The connection is made with a splice case. Figure 1-4 illustrates the physical structure of wiring from the CO to a customer. Note that within one cable section, multiple cables can be spliced together.

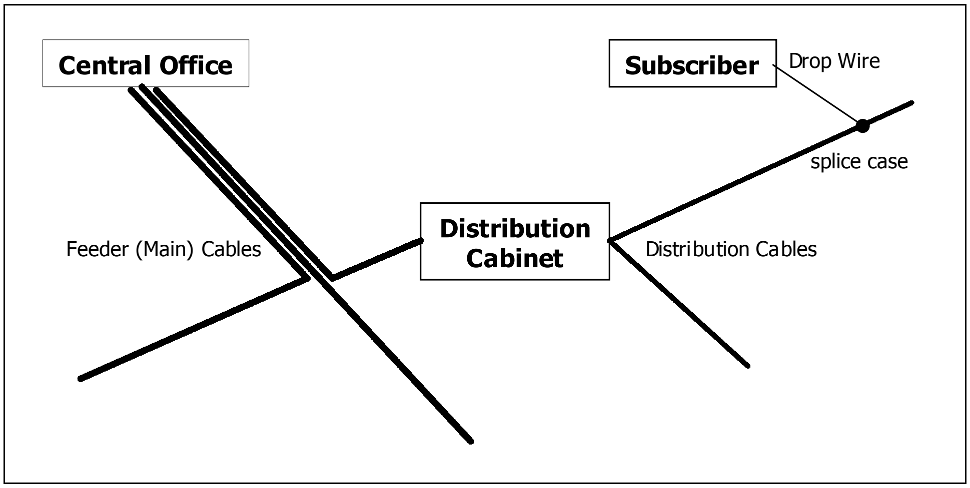

Figure 1-4: General structure of telephone subscriber loop.

According to a 1983 AT&T Bell labs' loop survey [12] an average loop length (sum of all cable lengths) is 3.3 km, and about 79% of all loops are less than 4.5 km long. Since then, along with the establishment of the Carrier Serving Area (CSA) concept in 1987, the newly installed loop lengths have been getting much shorter (the CSA guideline recommends a length of less than 2.75 km (9 kft.) to accommodate the expected emergence of high-speed data communication.

It is common practice in loop installation to connect multiple distribution cables to a feeder cable, so as to reach multiple potential customer sites. This allows the phone company to provide more flexible service. Hence, a telephone line in operation (*i.e.*, connected to a customer) can have one or more stubs of unused distribution cable that are not terminated. Such distribution cables are referred to as bridged taps (BT).

Another common practice is the use of loading coils to facilitate service over long distances (> 4.5 km). With the long loop distance, the twisted pair loses its flat voiceband frequency response, which is essential for voice communication. The loading coils, which are installed at intervals of about 1 km apart, equalize the voiceband response. These loading coils have a negative impact on DSL, which has an operating frequency band that is much higher than that of POTS, and therefore CSA guidelines require that all loops not be loaded. In this thesis, all loops are assumed to be free of loading coils.

For the purpose of testing high-speed data communication devices, ANSI and Telcordia Technologies (formally Bellcore) have instituted sets of test local loops (in ANSI T1.601-1999 ADSL Standard and Bellcore Technical Advisory TA-NWT-001210, respectively). We will use these loops throughout this thesis to measure the performance of our identification algorithm(s). The Telcordia test loops are hereafter referred as Carrier Serving Area (CSA) loops. The structures of these test loops are illustrated in Appendix A.

1.4 Local Loop Performance Measure and High-Speed Data Transmission Limitations Imposed by Loop Structure

The subscriber-line features, loop length, and bridged taps affect DSL performance in varying degrees. There are two performance measures to assess loop performance: data rate and insertion loss. Data rate is the maximum data throughput for a channel. However, accurate computation of the data rate requires additional information regarding DSL implementation. Insertion loss is the signal loss caused by inserting the loop between source and load. In other words, it is the ratio of the power delivered to the load with the loop in place and the power delivered to the load if the load is directly connected to the source.

The distance between the source (the CO) and the load (a customer) is one of the primary performance constraints. Naturally, when the loop length is longer the signal is attenuated more, and performance is reduced further. Figure 1-5 illustrates the ADSL downstream data rate as a function of loop length. The loop consists of only one segment, and the performance roll-off point (~ 3.5 km) will be shorter if the loop structure is complex (*i.e.*, the use of multiple gauges and the existence of BTs).

The bridged taps, which provide greater flexibility for POTS service, have a negative impact on the high-speed connection. The BT introduces undesirable notches in the frequency response as exemplified in Figure 1-6 by adding 250-m 24-AWG BT to the midway point of the 1-km 24-AWG single segment loop. Loop performance improvement can be obtained by removing the BT; CSA guidelines therefore institute strict limits on the number of BTs allowed in a loop.

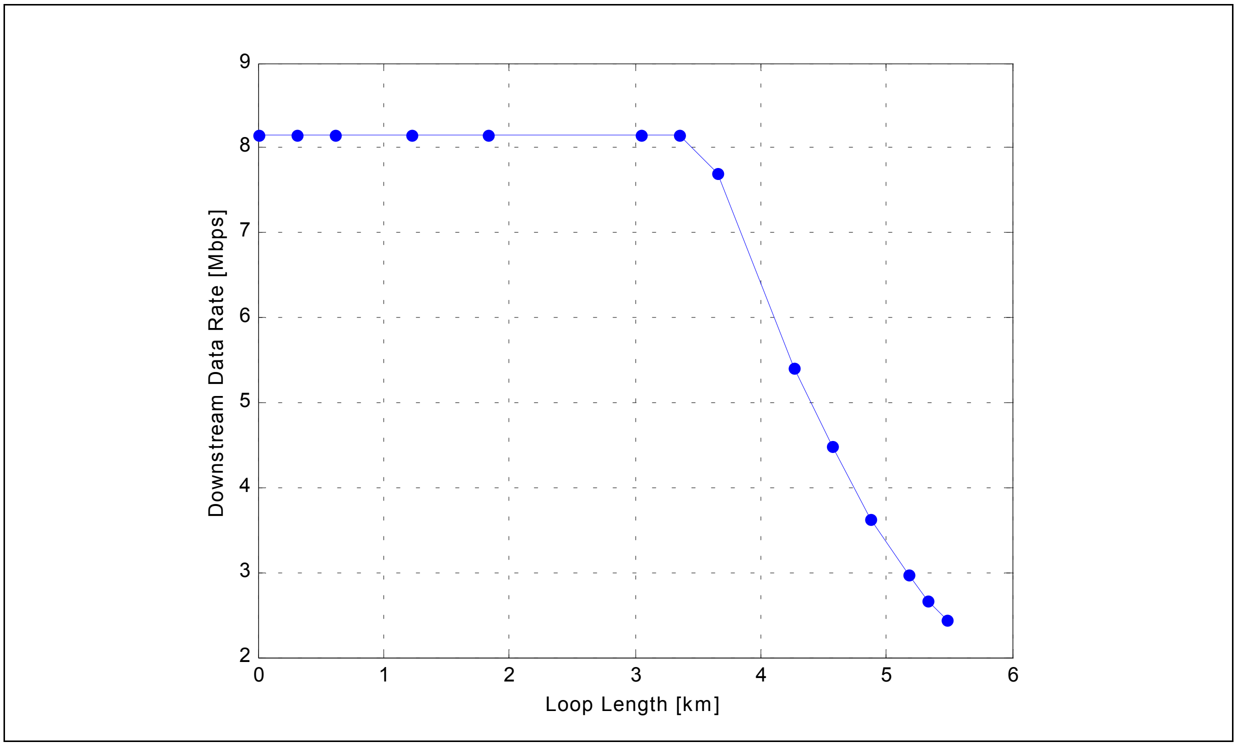

Figure 1-5: Texas Instruments Study — Simulated ADSL downstream data rate as function of length of single 24-AWG segment.

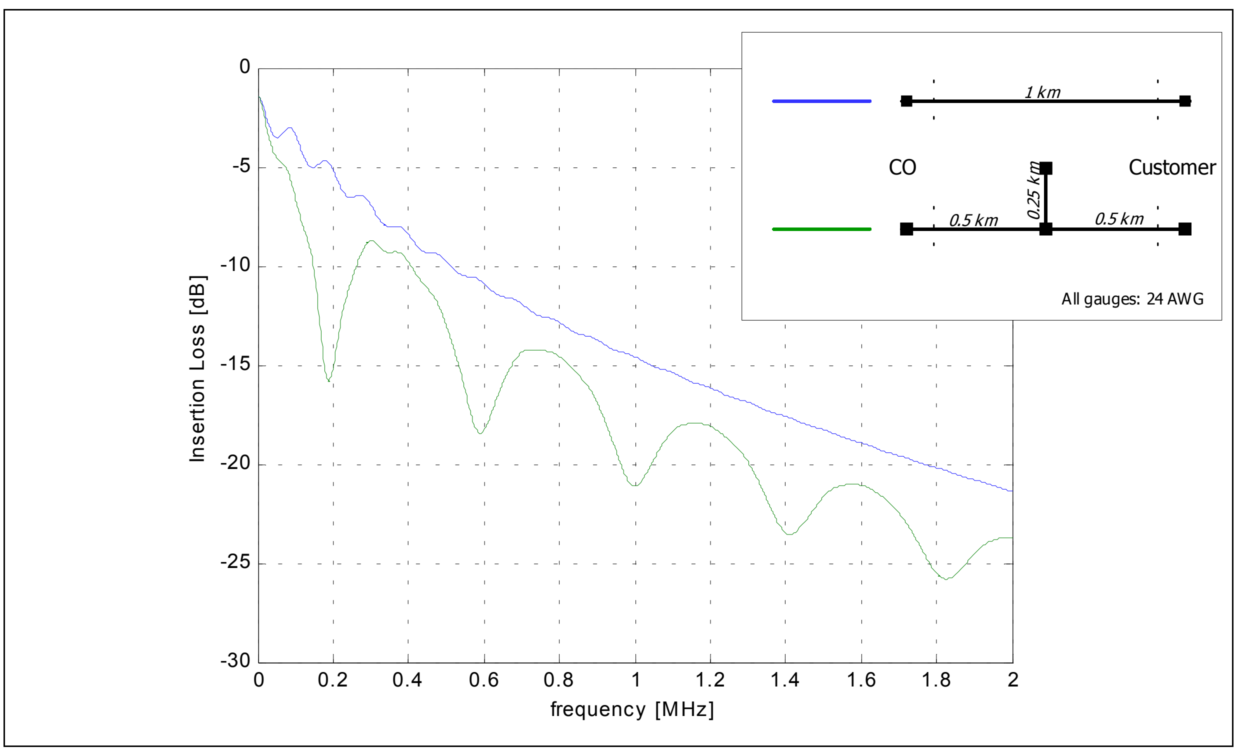

Figure 1-6: Insertion loss due to single 1-km 24-AWG segment loop (blue), and result of adding a 250-m 24-AWG BT to the loop at midway (green).

1.5 Organization and Overview

Most of this thesis follows the actual research progress. Chapter 2 covers the first phase involving the analytical modeling of the twisted-pair electrical characteristics and the simulation of a subscriber line. The types of simulations considered are time-domain reflectometry (TDR) response, input impedance, and frequency response of the loop. Thereafter, the identification procedures are developed assuming the simulation results as the measurements. This document does not deal with the actual measurement results to test identification algorithm performance. The final section of the chapter discusses the general *a priori* knowledge that we can obtain from transmission line theory.

In Chapter 3, the first identification attempt - based on the TDR response in the time domain - is described. The TDR response exposes the loop discontinuities (which occur at the cable connection and the end of cables) to the human eye, and the identification algorithm adopts how a TDR expert would dissect the measurement and builds a corresponding loop model. Through this attempt, we have built the intuition that the TDR response is a sum of reflections, which are scaled, delayed, and dispersed versions of the input signal. A couple of Method of Direction Estimation (MODE) based algorithms are considered to decompose the reflections from the TDR response and to ultimately estimate the locations of loop discontinuities from the loop frequency response. Chapter 4 describes the details of this development, which is the cornerstone of this research.

Based on the success with the MODE-type algorithm in extracting loop length from the frequency response, the entire loop identification process is transferred over to the frequency-domain, as discussed in Chapter 5. Finally, Chapter 6 covers the fine-tuning of the frequency-response based approach in order to enhance its performance and efficiency.