

Characterization of the Line Configuration in Wired Communication Networks

Kazi Moinul Islam

A Thesis
in
The Department
of
Electrical and Computer Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science at
Concordia University
Montréal, Québec, Canada

October 2011

© Kazi Moinul Islam, 2011

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: **Kazi Moinul Islam**

Entitled: **Characterization of the Line Configuration in Wired Communication Networks**

and submitted in partial fulfilment of the requirements for the degree of

Master of Applied Science

complies with the regulations of this University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

_____ Dr. Rabin Raut, Chair

_____ Dr. Youmin Zhang (MIE), External

_____ Dr. Wei-Ping Zhu, Examiner

_____ Dr. Amir G. Aghdam, Supervisor

Approved by _____

Dr. W. E. Lynch, Chair of the ECE Department

_____ 2011 _____

Dr. Robin Drew, Dean of Engineering and Computer Science

Abstract

Characterization of the Line Configuration in Wired Communication Networks

Kazi Moinul Islam

This thesis presents an algorithm to identify the full configuration of a wired transmission line from its frequency response. It is assumed that the line can have up to two bridged taps. Each bridged tap divides the main line to two segments, and with two bridged taps there will be at most three segments in the main line. Furthermore, each segment of the main line and the bridged taps can have three different gauges. The problem of characterizing the line configuration is concerned with identifying each segment (main line segments and bridged taps) in terms of its length and gauge. The problem is solved in two phases: initialization and optimization. The algorithm can be used as single ended line testing, which means the line can be characterized by performing a simple test from the central office. Simulations demonstrate the accuracy of the proposed method.

I dedicate this work to my father, Kazi Nazrul Islam, because of his exceptional support and encouragement for my study from my childhood.

Acknowledgements

Thanks are due first to my supervisor, Dr. Amir G. Aghdam. Because he gave me the opportunity to work for this interesting project. Moreover, I am really grateful to him for his close supervision during my work to solve this complex problem. I also got lots of help from his past work that was done by him to characterize the line configuration with single bridged tap. I would also like to thank to my colleagues Farzad Salehisadaghiani and Mohammad Salehizadeh for their valuable suggestions time to time, during my work.

Table of Contents

List of Figures	viii
List of Tables	ix
List of Abbreviations	x
1 Introduction	1
1.1 Background	1
1.2 Frequency Response of a Single Transmission Line	3
1.3 Two-Port Characterization of Transmission Lines	5
1.4 Two-Port Characterization of Bridged Taps	8
1.5 Frequency Response of a Subscriber Loop with Multiple Segments	9
1.6 Frequency-Dependency of the <i>RLCG</i> Parameters	11
1.7 Objective	15
1.8 Contribution and Publication	16
2 Determination of the Lengths of the Bridged Taps and the Total Length of the Line	17
2.1 Effects of Different Transmission Line Segments	17
2.2 Determine the Lengths of the Bridged Taps	19
2.3 A Method to Determine the Total Length of the Transmission Line	22
2.3.1 Simulation Result for Initial Length Estimate of the Main Line	23
2.4 Frequency-Dependency of the <i>RLCG</i> Parameters	25
3 Identification of Line Configuration	30
3.1 Finding an Initial Estimate for Line Configuration	30

3.2	Search for the Optimum Configuration	32
3.3	Reducing Program Execution Time	35
3.4	MATLAB Programs	36
3.4.1	Steps or Pseudocode of the Initialization Phase	36
3.4.2	Steps or Pseudocode of the Optimization Phase	37
3.5	Simulation Results	39
4	Conclusions	47
4.1	Summary	47
4.2	Future Work	48
	Bibliography	50
A	Appendix	56
A.1	MATLAB Code to Determine the Length of Bridged Taps	56
A.2	MATLAB Code to Determine the Total Length of Line	58
A.3	MATLAB Code to Deal with the Variable Nature of <i>RLCG</i> Values with Frequency	60
B	Appendix	63
B.1	Modified Section of MATLAB Code for the Initialization Phase	63

List of Figures

1.1	A two-port network model of a twisted pair transmission line.	4
1.2	Incremental section of the twisted-pair transmission line.	6
1.3	An example of a subscriber loop from the central office to the customer premise equipment, with only one bridged tap connected to the main line.	9
1.4	Subscriber loop with two bridged taps.	10
1.5	Resistance vs frequency for a 26 gauge cable.	12
1.6	Resistance at low frequencies for a 26 gauge cable.	13
1.7	Inductance vs frequency for a 26 gauge cable.	14
1.8	Inductance at low frequencies for a 26 gauge cable.	14
2.1	The effect of a bridged tap in the transmission line.	18
2.2	The magnitude response of a loop with single bridged tap.	20
2.3	The magnitude response of a loop with two bridged taps.	21
2.4	The real magnitude response and the associated fitting polynomial of order 10 for Configuration 1.	24
2.5	The real magnitude response and the associated fitting polynomial of order 10 for Configuration 2.	25
3.1	The flowchart of the proposed algorithm.	34
3.2	Magnitude response for the transmission line of Example 1.	39
3.3	Magnitude response for the transmission line of Example 2.	41
3.4	Magnitude response for the transmission line of Example 3.	43
3.5	Magnitude response for the transmission line of Example 4.	45

List of Tables

1.1	Parameter values for a 26 gauge twisted pair cable	15
1.2	Parameter values for a 24 gauge twisted pair cable	15
2.1	<i>RLGC</i> values for a 26 gauge twisted pair cable	27
2.2	<i>RLGC</i> values for a 24 gauge twisted pair cable	28
2.3	<i>RLGC</i> values for a 22 gauge twisted pair cable	29

List of Abbreviations

DSL Digital Subscriber Line

VDSL Very high speed Digital Subscriber Line

POTS Plain Old Telephone Service

QoS Quality of Service

CO Central Office

CPE Customer Premise Equipment

ONU Optical Network Unit

Chapter 1

Introduction

1.1 Background

Telephone lines were originally installed for voice traffic. Since their original deployment (which goes back as far as 1881) there has been a technological revolution in the communications industry. In particular, development of digital subscriber line (DSL) technology in 1989 has opened up a new dimension in wired communication, enabling the transmission of megabits of data per second over the same twisted pair channel which is used for plain old telephone service (POTS) [1], [2], [3], [4]. The operators are now generating revenues from voice service (at low frequency) and high speed data service (at high frequency) using the same infra structure.

DSL services can be classified as symmetric and asymmetric [1]. In a symmetric DSL service, transmission of data in both downstream and upstream directions is performed in the same frequency band. In an asymmetric DSL service, on the other hand, a higher transmission rate is assigned to the downstream channel, and there is no overlap between the downstream and upstream frequency bands [1]. Each service type has its own advantages and disadvantages in terms of quality of service (QoS), robustness, etc. whose details are not in the scope of this report. However, they both suffer from a number of issues related to the physical characteristics of the channel. For example, some of the problems reported by the DSL customers are directly or indirectly related to the line configuration, and in particular to the characteristics (location and length) of any bridged tap which may exist in the line [4]. Bridged taps are open-circuited twisted pairs which are used by the telephone companies to increase the flexibility in providing service to customers [1]. However, they can potentially degrade the frequency response of the channel, specially in high frequencies (which is normally used for DSL services) [4], [5]. If the bridged tap is very long (e.g., the same length as the main line), it introduces approximately a flat attenuation of 3.5 dB in the loops frequency response [48].

Many of the DSL service problems are related to the line configuration which was implemented before DSL was invented. It is not feasible to make fundamental changes in the telephone line network configuration in order to obtain a more suitable network for DSL service. It is also not cost-efficient to hire technicians to run tests and find the source of the problem after each trouble report, if it can be identified simply performing a test from the central office (CO) [6], [7]. Characterization of the transmission line is important for network monitoring and maintenance. It can also help increase the number

of customers that can be provisioned for DSL, or increase the average bit rate of existing customers. Some of the new DSL services require higher bandwidths, bit rates, and reliability, which can only be assured by having accurate knowledge of the lines [18].

In this work, it is desired to develop a program which can be used to fully characterize a transmission line, using some information (about the frequency response of the line) which can be collected at the CO. The full characterization means determining the number of different line segments as well as the length and gauge of every one of them. Each segment can have three different gauges, and each bridged tap segment has prescribed upper and lower limits for its length. It is also assumed that each transmission line can have at most two bridged taps (this assumption is in accordance with the DSL standard loops). The proposed characterization algorithm performs in two phases: initialization and optimization.

1.2 Frequency Response of a Single Transmission Line

Twisted-pair transmission lines can be modeled as a two-port (or $ABCD$) network as shown in Figure 1.1 [1]. The voltage and current of each port depends on the source and load impedances satisfying the following matrix relation:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \Phi \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (1.1)$$

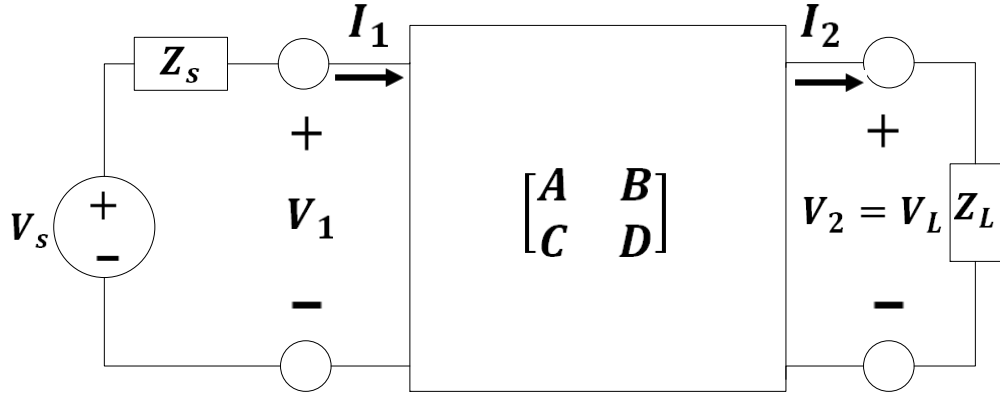


Figure 1.1: A two-port network model of a twisted pair transmission line.

where Φ is a 2×2 matrix of the four frequency-dependent parameters A, B, C and D . All of these parameters depend only on the network and not on external connections, and are given by:

$$A = \left. \frac{V_1}{V_2} \right|_{I_2=0}; \quad B = \left. \frac{V_1}{I_2} \right|_{V_2=0}; \quad C = \left. \frac{I_1}{V_2} \right|_{I_2=0}; \quad D = \left. \frac{I_1}{I_2} \right|_{V_2=0} \quad (1.2)$$

The parameters A, B, C and D are known as open-load voltage ratio, shorted-load impedance, open-load admittance and shorted-load current ratio, respectively.

Now, consider the following function which depends on the load impedance connected at the right side of Figure 1.1.

$$T(f) = \frac{V_2}{V_1} = \frac{V_2}{A \cdot V_2 + B \cdot I_2} = \frac{1}{A + B \cdot \frac{I_2}{V_2}} \quad (1.3)$$

The load impedance is defined as follow:

$$Z_L = \frac{V_2}{I_2} \quad (1.4)$$

Substituting the load impedance in equation (1.3) yields:

$$T(f) = \frac{1}{A + \frac{B}{Z_L}} = \frac{Z_L}{A \cdot Z_L + B} \quad (1.5)$$

Assume now that V_S is the input voltage supply with finite internal impedance Z_S as shown in Figure 1.1, and V_L is the output voltage across the load Z_L . So, we can relate $T(f)$ to the transfer function $H(f)$ between input and output as given below:

$$\frac{V_L(f)}{V_S(f)} = H(f) = \frac{V_L(f)}{V_1(f)} \cdot \frac{V_1(f)}{V_S(f)} = \frac{Z_1}{Z_1 + Z_S} \cdot T(f) \quad (1.6)$$

where Z_1 is the input impedance of the terminated two-port. The frequency response, $H(f)$ generally depends on the load and source impedances. The input impedance of the two-port is calculated by using the following equation:

$$Z_1 = \frac{V_1}{I_1} = \frac{A + \frac{B}{Z_L}}{C + \frac{D}{Z_L}} = \frac{A \cdot Z_L + B}{A \cdot Z_L + B} \quad (1.7)$$

1.3 Two-Port Characterization of Transmission Lines

The two-port model of a twisted-pair line can be derived from the per-unit length two-port model as shown in Figure 1.2. The R , L , C , and G parameters indicate resistance, inductance, capacitance and conductance per unit length of the transmission line, respectively. Now, let a segment of the transmission line be regarded as the cascade of such sections that are infinitesimally small in length. At any point y , the two-port voltages and currents are related through the following differential equations at any given frequency $\omega = 2\pi f$

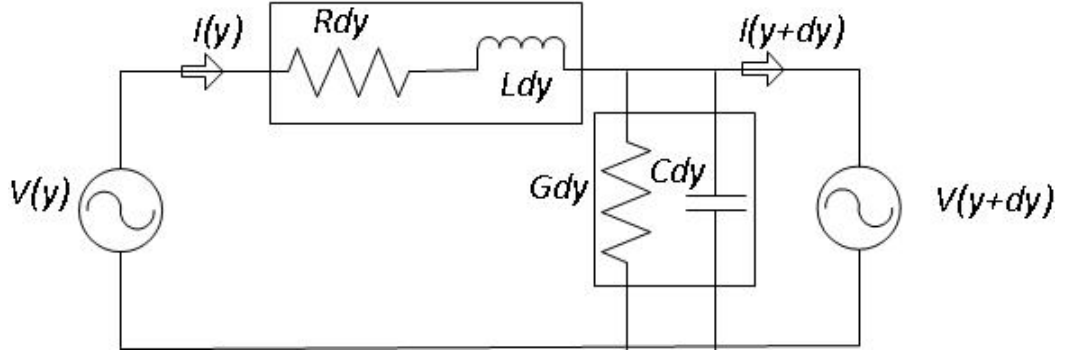


Figure 1.2: Incremental section of the twisted-pair transmission line.

[1]:

$$-\frac{dV}{dy} = (R + j\omega L).I \quad (1.8)$$

$$-\frac{dI}{dy} = (G + j\omega C).V \quad (1.9)$$

where V and I are phasor quantities indicating peak amplitudes of sinusoids at frequency f (the R, L, C, G parameters also vary with frequency). The above equations are also equivalent to the following second-order differential equations:

$$-\frac{d^2V}{dy^2} = \gamma.V \quad (1.10)$$

$$-\frac{d^2I}{dy^2} = \gamma.I \quad (1.11)$$

In particular:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (1.12)$$

where γ is the frequency-dependent propagation constant for the twisted-pair, which is used to characterize each segment of the transmission line. The solutions to the differential equations (1.10) and (1.11) are the sum of positive and negative-direction waves that vary with position as $e^{+\gamma y}$ and $e^{-\gamma y}$, where the sign of the exponent depends on direction.

The real part α and the imaginary part β in equation (1.12) are called the attenuation constant and the phase constant, respectively. For a lossless line ($R = 0, G = \infty$), the attenuation constant is zero. The solution to the differential equations (1.10) and (1.11) are as follow [1]:

$$V(y) = V_0^+ .e^{-\gamma y} + V_0^- .e^{+\gamma y} \quad (1.13)$$

$$I(y) = I_0^+ .e^{-\gamma y} + I_0^- .e^{+\gamma y} \quad (1.14)$$

By substituting either of these solutions into (1.8) and (1.9), the ratio of the positive-going voltage to the positive-going current, and the ratio of the negative-going voltage to the negative-going current are obtained, which provide a constant characteristic impedance of the transmission line. Suppose that a transmission line of length d has the solution $V_L = V(d)$ and $I_L = I(d)$, which leads to the following equations:

$$V_L = V(d) = V_0^+ .e^{-\gamma d} + V_0^- .e^{+\gamma d} \quad (1.15)$$

$$I_L = I(d) = I_0^+ .e^{-\gamma d} + I_0^- .e^{+\gamma d} \quad (1.16)$$

As the two voltage waves in each direction are related to the same direction current waves by the characteristic impedance Z_0 , one can solve the above two equations for V_0^+ and V_0^- to arrive at:

$$V_0^+ = \frac{1}{2}(V_L + I_L .Z_0) .e^{\gamma d} \quad (1.17)$$

$$V_0^- = \frac{1}{2}(V_L - I_L .Z_0) .e^{-\gamma d} \quad (1.18)$$

Now, putting these constants into the solutions of (1.15) and (1.16) and evaluating voltage and current at $y = 0$ in terms of those at $y = d$, the following $ABCD$ representation for the

transmission line is obtained [1]:

$$\begin{bmatrix} V(0) \\ I(0) \end{bmatrix} = \begin{bmatrix} \cosh \gamma d & Z_0 \sinh \gamma d \\ \frac{1}{Z_0} \sinh \gamma d & \cosh \gamma d \end{bmatrix} \cdot \begin{bmatrix} V(d) \\ I(d) \end{bmatrix} \quad (1.19)$$

where γ and Z_0 are the propagation constant and the characteristic impedance of the line, respectively.

1.4 Two-Port Characterization of Bridged Taps

A bridged tap is an open-circuited twisted pair providing flexibility for future additions and changes in service demands, and can be viewed as a three-port network. However, one of the ports appears as a load impedance to the line between the two segments on each side of the bridged tap. Thus, a bridged tap can be described by the following two port characterization model [1]:

$$\begin{bmatrix} 1 & 0 \\ \frac{1}{Z_{bt}} & 1 \end{bmatrix} \quad (1.20)$$

where Z_{bt} denotes the characteristic impedance of the line for bridged tap section.

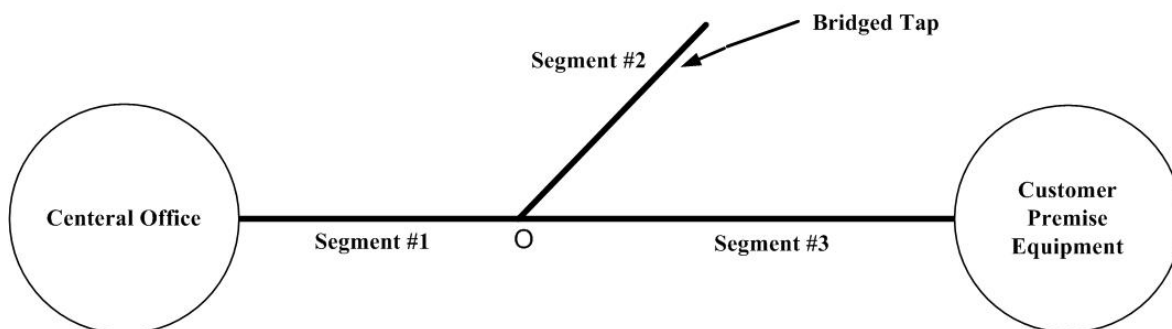


Figure 1.3: An example of a subscriber loop from the central office to the customer premise equipment, with only one bridged tap connected to the main line.

1.5 Frequency Response of a Subscriber Loop with Multiple Segments

It is shown in this section how to derive the frequency response of a subscriber loop with multiple segments. Consider first a transmission line with one bridged tap, which consists of three segments as shown in Figure 1.3: segment #1 between the CO and the point O where the bridged tap is connected to the main line; segment #2 which is the bridged tap, and segment #3 between the connection point O and the customer premise equipment (CPE). The main line or main channel connecting the CO to the CPE in this case consists of segments #1 and #3, and is the primary contributor to the attenuation of the signal passing through the line (both uplink and downlink). The effect of the bridged tap, as discussed later, is the reflection of the signal passing through the main channel from the connection point. Figure 1.4 depicts the line configuration for the case of two bridged taps, and the five segments associated with it. The problem of the characterization of the line configuration is concerned with identifying the length and gauge of each segment of

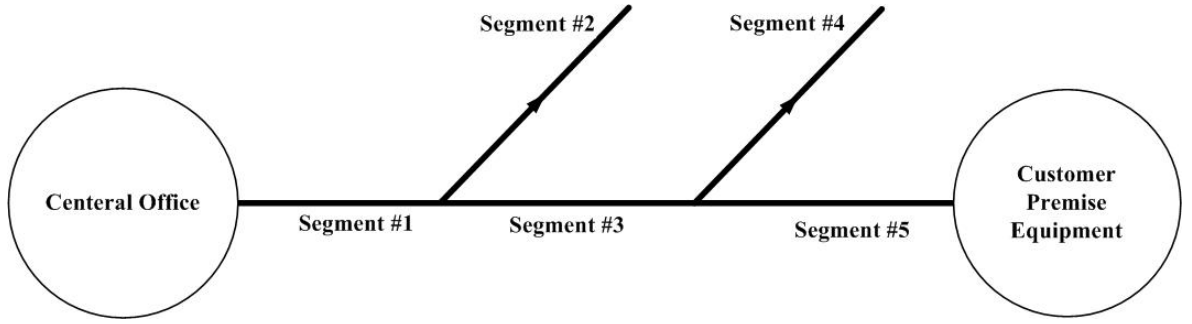


Figure 1.4: Subscriber loop with two bridged taps.

the transmission line (bridged taps and main-channel segments).

The frequency response of a subscriber loop with multiple segments can be found by multiplying the corresponding two-port $ABCD$ matrices of different segments, which are, in fact, connected in series [1]. The matrices are multiplied in the natural order of appearance from the CO to CPE. As an example, for the transmission line with two bridged taps shown in Figure 1.4, one can write:

$$\phi = \phi_1 \cdot \phi_2 \cdot \phi_3 \cdot \phi_4 \cdot \phi_5 \quad (1.21)$$

where ϕ_i represents the frequency response of segment $\#i$, $i = 1, \dots, 5$. The two-port model for the voltage source, on the other hand, is given by:

$$\begin{bmatrix} 1 & Z_S \\ 0 & 1 \end{bmatrix} \quad (1.22)$$

where Z_S is the source impedance. Moreover, the output voltage and current are related by the following scalar equation:

$$V_L = I_L \cdot Z_L \quad (1.23)$$

where Z_L is the load impedance. From the above equation, one can obtain the transfer function of the transmission line as follows:

$$H = \frac{V_L}{V_S} \quad (1.24)$$

Now, by using the $ABCD$ model for every segment of the line, the transfer function of the subscriber loop is obtained as [1]:

$$H = \frac{V_L}{V_S} = \frac{Z_L}{(A \cdot Z_L + B + C \cdot Z_S \cdot Z_L + D \cdot Z_S)} \quad (1.25)$$

The segment numbers adopted in Figures 1.3 and 1.4 will be used hereafter to specify each segment of the line.

1.6 Frequency-Dependency of the $RLCG$ Parameters

The parameters R, L, C and G are the primary constants, namely resistance, inductance, capacitance and conductance, respectively, of the transmission line which are expressed in per unit length. These parameters also depend on frequency, and are found for twisted-pairs through measurement. Practical measurements, however, are subject to error; that is why the measured $RLCG$ values may not follow smooth curves with frequency [1]. Therefore, parameterized smooth fitting models are used to represent the measured values.

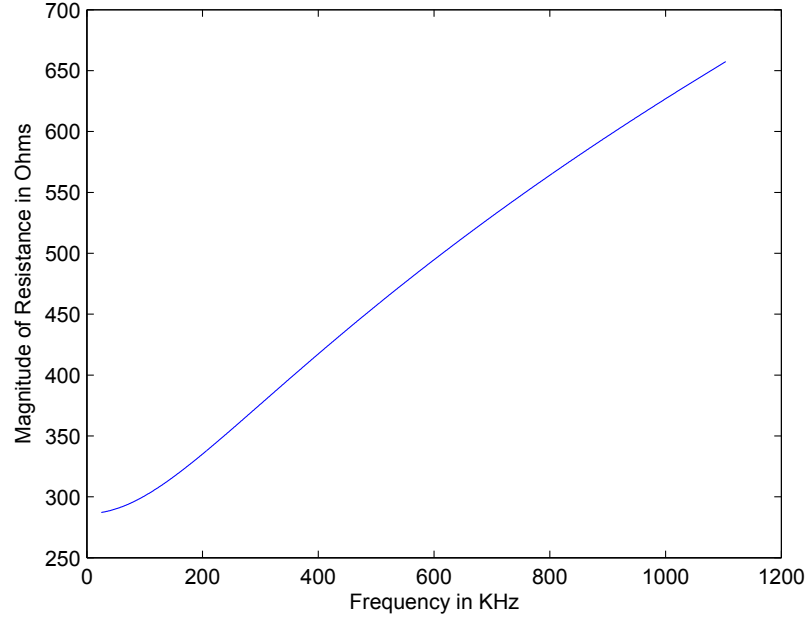


Figure 1.5: Resistance vs frequency for a 26 gauge cable.

The parameterized model for resistance with the frequency dependency is:

$$R(f) = \frac{1}{\frac{1}{\sqrt[4]{r_{OC}^4 + a_C \cdot f^2}} + \frac{1}{\sqrt[4]{r_{OS}^4 + a_S \cdot f^2}}} \quad (1.26)$$

where r_{OC} and r_{OS} are the copper and steel *DC* resistances, respectively. Furthermore, a_C and a_S are the constants indicating the rise of resistance with frequency in the skin effect. The frequency dependency of resistance are shown in Figures 1.5 and 1.6. From these figures, it is evident that resistance is an increasing function of frequency, and at low frequencies (typically from 0 to 10 KHz) its value is almost constant.

The parameterized model for inductance showing the frequency dependency is:

$$L(f) = \frac{l_0 + l_\infty \cdot \left(\frac{f}{f_m}\right)^b}{1 + \left(\frac{f}{f_m}\right)^b} \quad (1.27)$$

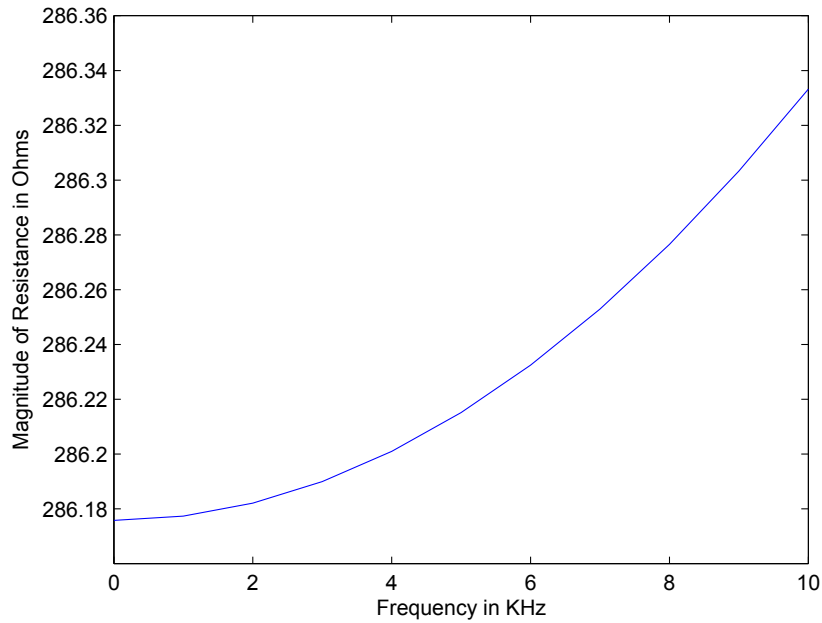


Figure 1.6: Resistance at low frequencies for a 26 gauge cable.

where l_0 and l_∞ are the low-frequency and high-frequency inductance, respectively, and b is a parameter chosen to characterize the transition between low and high frequencies in the measured inductance values. The frequency dependency of inductance can be clearly visualized from Figures 1.7 and 1.8. These figures show that inductance is a decreasing function of frequency, and at low frequencies its value is also almost constant [1].

The parameterized model for capacitance is:

$$C(f) = c_\infty + c_0 \cdot f^{-c_e} \quad (1.28)$$

where c_∞ is the contact capacitance, and c_0 , c_e are constants used to fit the measurement.

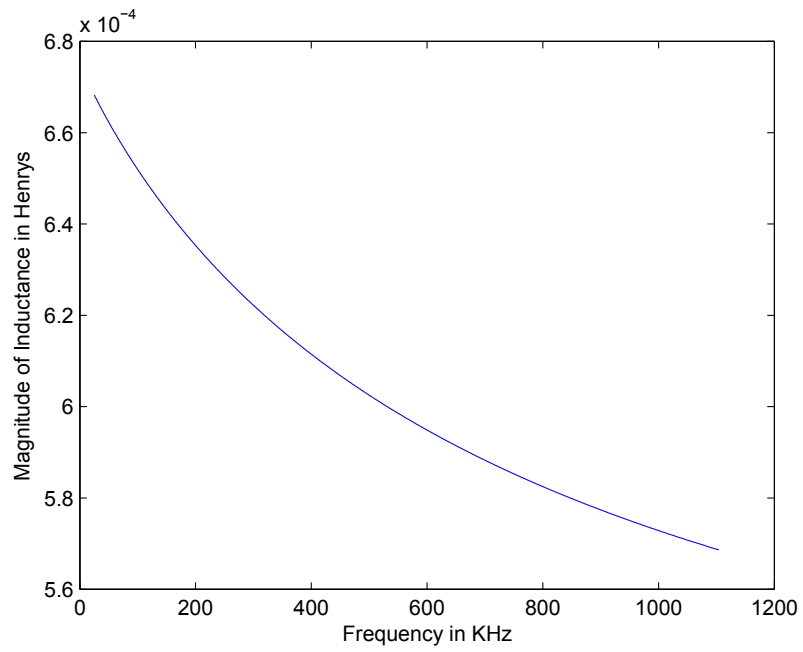


Figure 1.7: Inductance vs frequency for a 26 gauge cable.

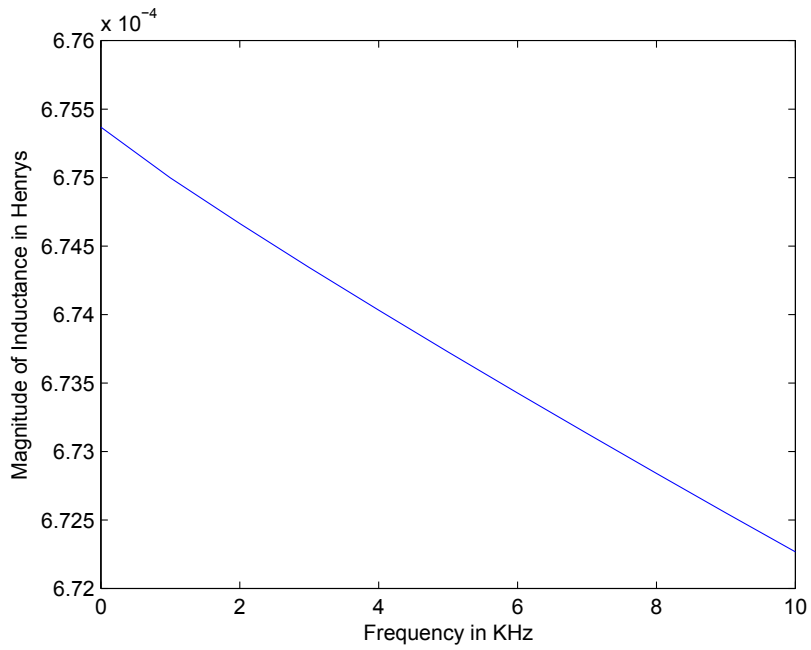


Figure 1.8: Inductance at low frequencies for a 26 gauge cable.

The parameterized model for conductance is:

$$G(f) = g_0 \cdot f^{+g_e} \quad (1.29)$$

where the constants g_0 and g_e are used to fit the measurement. The parameter values for 26 and 24 gauge twisted-pairs are given in Tables 1.1 and 1.2, respectively.

Table 1.1: Parameter values for a 26 gauge twisted pair cable

Resistance (value)	r_{OC} 286.17578 Ω/Km	r_{OS} $\infty \Omega/Km$	a_C 0.14769620	a_S 0.0
Inductance (value)	l_0 675.36888 $\mu H/Km$	l_∞ 488.95186 $\mu H/Km$	b 0.92930728	f_m 806.33863 KHz
Capacitance (value)	C_∞ 49 nF/Km	C_0 0.0 nF/Km	C_e 0.0 nF/Km	—
Conductance (value)	g_0 43 nS/Km	g_e 0.70	—	—

Table 1.2: Parameter values for a 24 gauge twisted pair cable

Resistance (value)	r_{OC} 174.55888 Ω/Km	r_{OS} $\infty \Omega/Km$	a_C 0.053073481	a_S 0.0
Inductance (value)	l_0 617.29539 $\mu H/Km$	l_∞ 478.97099 $\mu H/Km$	b 1.1529766	f_m 553.760 KHz
Capacitance (value)	C_∞ 50 nF/Km	C_0 0.0 nF/Km	C_e 0.0 nF/Km	—
Conductance (value)	g_0 234.87476 nS/Km	g_e 1.38	—	—

1.7 Objective

The objective of the present work is to develop an algorithm to identify the full configuration of a twisted-pair transmission line from its frequency response. The algorithm can be

used as a single-ended line testing. In other words, the line can be characterized using the information collected at the CO by performing a simple test. The problem of identifying the line configuration is concerned with determining each segment (main line segments and bridged taps) in terms of its length and gauge. It is assumed that the line can have up to two bridged taps. Each bridged tap divides the main line to two segments, and with two bridged taps there will be at most three segments in the main line. Furthermore, each segment of the main line and the bridged taps can have three different gauges (please see Figures 1.3 and 1.4).

1.8 Contribution and Publication

The problem has been solved using a proper optimization technique (which finds the closest configuration by minimizing the error in the frequency response). The core concept to solve the problem has been explained in Chapter 3. The method used to determine the lengths of the bridged taps has been explained in Chapter 2. The results of this work appeared in the following conference:

Kazi Moinul Islam, Mohammad Salehizadeh and Amir G. Aghdam, "Characterization of the Line Configuration in Wired Communication Networks," in *Proceedings of ACM Research in Applied Computation Symposium (RACS)*, Miami, USA, November 2011.

Chapter 2

Determination of the Lengths of the Bridged Taps and the Total Length of the Line

2.1 Effects of Different Transmission Line Segments

Optical fiber is used in modern very high speed DSL (VDSL) networks to connect the CO to an optical network unit (ONU). Up to about one mile of the existing copper-based telephone network infrastructure is then used from the ONU to CPE [48]. When a signal is transmitted through a twisted-pair, some of its energy leaks out from the main channel and some is reflected back to the bridging location by the open circuited twisted-pair as

shown in Figure 2.1. The reflected signal (which is a delayed and distorted version of

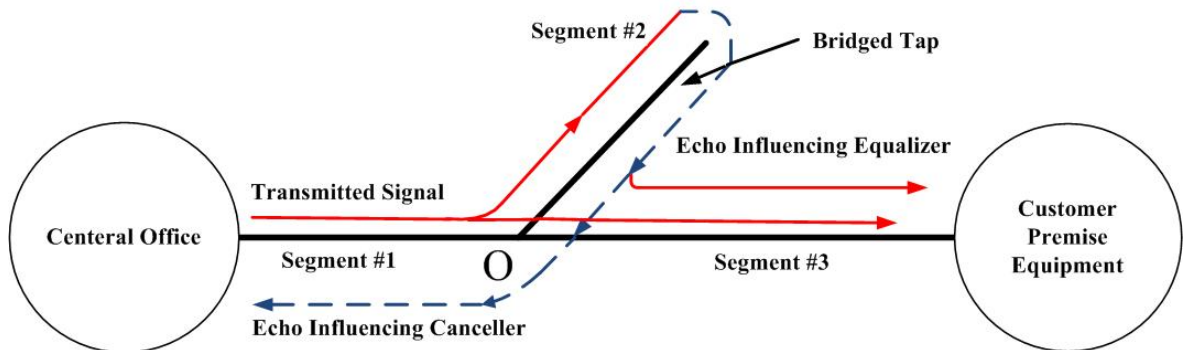


Figure 2.1: The effect of a bridged tap in the transmission line.

the main signal) creates two types of interferences as shown in the figure and discussed below:

- i) The first component of interference is the one that travels in the same direction as the main signal, which is added to it and will appear as noise to the receiver.
- ii) The second component of interference is the one that propagates back and will appear as an echo to the transmitter.

In addition to the above two interference components, there is another damaging effect of the bridged tap, namely net loss caused by nulls (dips) in the frequency response of the loop. In fact, for certain frequencies a sinusoidal wave reflected by the bridged tap can arrive at the bridging location with a phase shift of 180 with respect to the corresponding sinusoidal wave in the main signal. When this occurs, the two frequency components subtract in amplitude and the result is a noticeable dip in the overall magnitude response of the loop around this frequency. These dips occur at frequencies for which the bridged tap

length d_{bt} is equal to an odd multiple of one quarter of the wavelength of that frequency. Let $v(f) = \frac{1}{\tau_\phi(f)}$ and $\lambda(f) = \frac{v(f)}{f}$, where $v(f)$ is the phase velocity, $\tau_\phi(f)$ is the phase delay, and $\lambda(f)$ is the wavelength. The first null occurs at [5]:

$$f_0 = \frac{v(f_0)}{\lambda(f_0)} = \frac{v(f_0)}{4d_{bt}} = \frac{1}{4d_{bt}\tau_\phi(f_0)} \quad (2.1)$$

Other nulls occur at the following frequencies [5]:

$$f = (2j + 1)f_0, \quad j = 1, 2, 3, \dots \quad (2.2)$$

The expression (2.1) is highly nonlinear; however, it can be solved by approximation for bridged taps up to a certain length (less than 2 Kft). In such a configuration, the nulls occur in a frequency range where the phase delay is approximately constant and equal to about 8.7 micro sec/mile [5]. This leads to the following equality:

$$d_{bt} = \frac{150}{f_0} \quad (2.3)$$

where f_0 and d_{bt} are in KHz and Kft, respectively.

2.2 Determine the Lengths of the Bridged Taps

Figure 2.2 depicts the magnitude response of a transmission line with one bridged tap, where the segments are characterized as:

Segment #1 (CO-side of the main channel): 2500 ft, 26 gauge

Segment #2 (bridged tap): 500 ft, 24 gauge

Segment #3 (CPE-side of the main channel): 1500 ft, 24 gauge

This figure shows the first null occurs approximately at 304 KHz (and the second one at

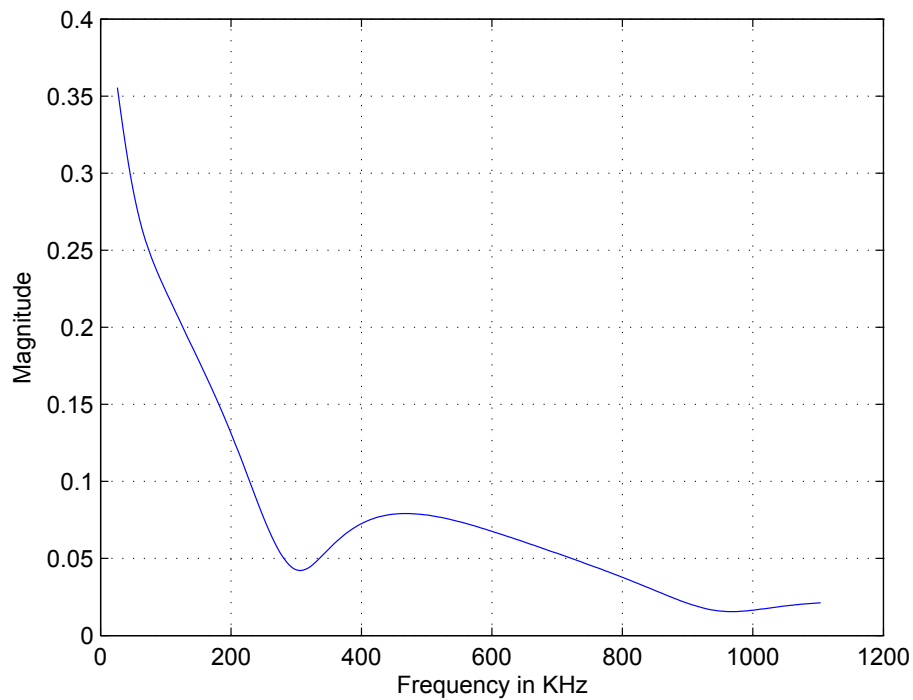


Figure 2.2: The magnitude response of a loop with single bridged tap.

around 912 KHz, which is equal to 304×3). Thus, from equation (2.3) the length of the bridged tap is obtained to be 494 ft, which is very close to the exact value.

By generalizing the method presented in the previous section, the lengths of multiple bridged taps in a loop can be heuristically determined from equation (2.3). First of all,

one needs to identify distinct groups of dips which meet the condition expressed by equation (2.2). The number of such groups is, in fact, the number of bridged taps in the loop. The length of each bridged tap can then be obtained from the smallest frequency in each group. However, such groupings can be made only if the length of a bridged tap is not an odd multiple of the length of another bridged tap (because in such cases the corresponding nulls coincide). Throughout this work, it is assumed that the length of a bridged tap is not an odd multiple of the length of another bridged tap (note that the length of a line segment is by assumption nonzero).

As an example, the magnitude response of a transmission line with two bridged taps

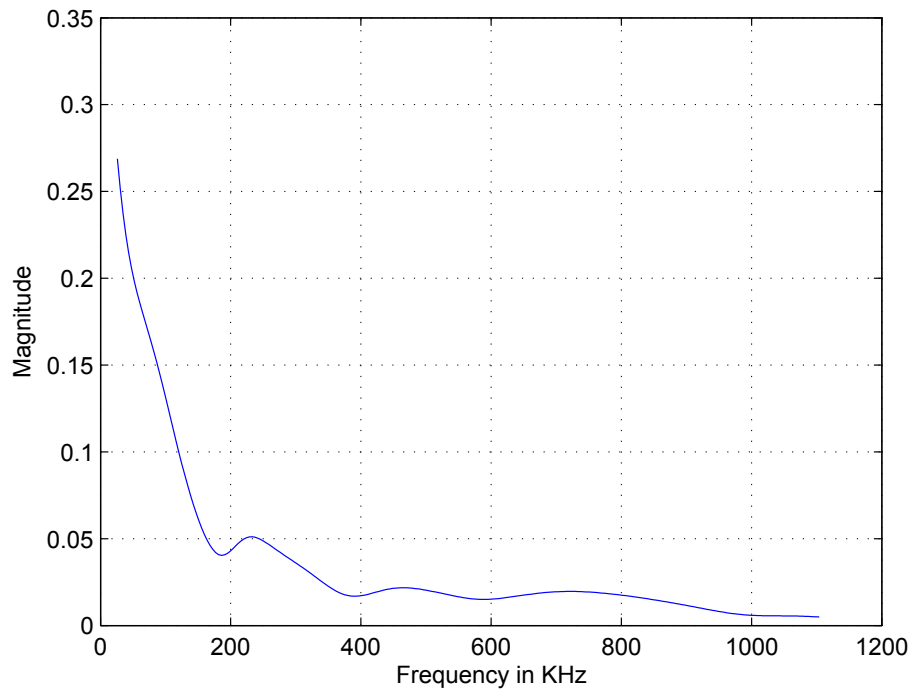


Figure 2.3: The magnitude response of a loop with two bridged taps.

is given in Figure 2.3. The smallest null frequencies corresponding to these bridged taps

are 183 KHz and 390 KHz. Hence, from equation (2.3) the bridged tap lengths are obtained as 818 ft and 385 ft.

2.3 A Method to Determine the Total Length of the Transmission Line

As shown in the previous section, the frequency response of a twisted-pair is a gradually decaying function of frequency. It can be observed from Figure 2.2 that there are some oscillations in the curve at high frequencies, which is, in fact, due to the presence of the bridged tap. However, the curve is smooth at low frequencies, which contains very important information. An estimation of the total line length can be made by fitting the low-frequency curve with a smooth curve. Detailed procedure for this is given below in a step-by-step manner.

- i) Step 1: Fit the magnitude response with a polynomial of sufficiently high degree.
- ii) Step 2: To obtain a rough estimate of the total line length, it is assumed that there is no bridged tap connection. The frequency response of the simplified line is approximated subsequently by applying the two-port network model of communication line as described in Chapter 1. The frequency response is a function of frequency with unknown line length, i.e.:

$$H = g(f, d) \tag{2.4}$$

where f is the frequency and d is the total length of the line.

iii) Final step: Now, there are two equations: one from the best fitted curve (which is a function of frequency) and the other from the simplified line applying the two-port network model. An estimate of the line length can now be obtained by using a proper optimization procedure, e.g., *Nelder – Mead's* simplex search method.

2.3.1 Simulation Result for Initial Length Estimate of the Main Line

In this subsection two different line configurations with two bridged taps are considered: one with relatively short segments, and one with longer segments. The procedure given earlier will be used to estimate the total length of the main line.

Configuration 1: Consider a wired communication line with the following characteristics (see Figure 1.4 for segment numbers):

Segment #1: 1500 ft, 26 gauge

Segment #2: 700 ft, 22 gauge

Segment #3: 1000 ft, 24 gauge

Segment #4: 400 ft, 22 gauge

Segment #5: 500 ft, 22 gauge

Note that the total length of the main line in this configuration (segments #1, 3, 5) is 3 Kft. The magnitude response of this line along with the 10th-order fitting polynomial for that obtained by MATLAB is given in Figure 2.4. Now, using the algorithm provided in Section 2.3, the total length of the main line is estimated to be 3.0412 Kft, which is very

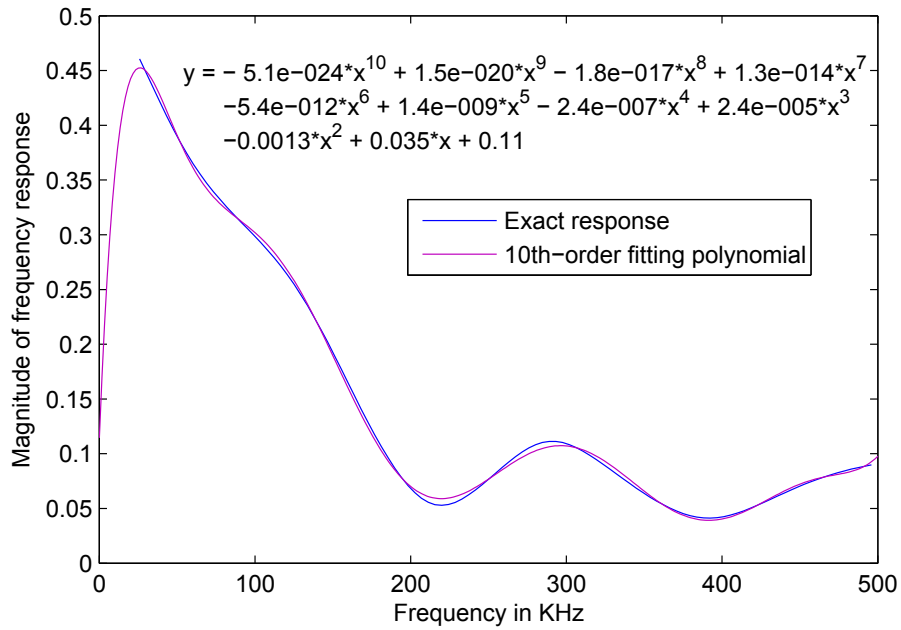


Figure 2.4: The real magnitude response and the associated fitting polynomial of order 10 for Configuration 1.

close to the exact line length.

Configuration 2: Consider now a line configuration with longer segments as follows:

Segment #1: 4000 ft, 26 gauge

Segment #2: 1500 ft, 24 gauge

Segment #3: 2500 ft, 24 gauge

Segment #4: 1000 ft, 24 gauge

Segment #5: 1500 ft, 22 gauge

The magnitude response of this line is provided in Figure 2.5 together with the corresponding 10th-order fitting polynomial . Using the algorithm given in Section 2.3, an

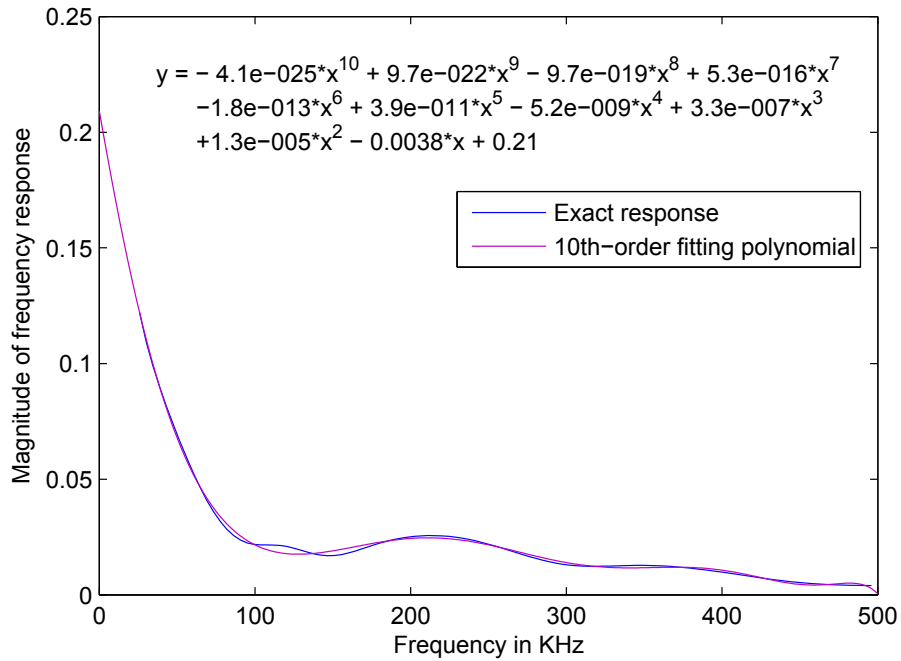


Figure 2.5: The real magnitude response and the associated fitting polynomial of order 10 for Configuration 2.

estimate of the total length of the main line is obtained to be 8.0297 Kft, which means the estimation error in this case is 0.371%.

2.4 Frequency-Dependency of the *RLCG* Parameters

Any technique used to identify the line configuration should take the frequency dependency of the line model, namely resistance R , inductance L , capacitance C and conductance G , into account. This dependency is not the same for different line gauges, as noted earlier. In this thesis, the frequency dependency of the parameters of the transmission line is taken into consideration in the optimization procedure introduced in the next chapter.

To improve the speed of the procedure, look-up tables will be used to compute the frequency response of the line in the underlying procedure. The look-up tables for the three line gauges are given in Tables 2.1-2.3.

Table 2.1: *RLGC* values for a 26 gauge twisted pair cable

Frequency(Hertz)	R(Ohms/mile)	L(Henrys/mile)	G(Siemens/mile)	C(Farads/mile)
1	440.75	0.9861	0.0	0.083
5	440.75	0.9861	0.001	0.083
10	440.75	0.9861	0.002	0.083
15	440.76	0.9861	0.003	0.083
20	440.76	0.9861	0.004	0.083
30	440.76	0.9861	0.005	0.083
50	440.76	0.9861	0.008	0.083
70	440.76	0.9861	0.011	0.083
100	440.76	0.9861	0.016	0.083
150	440.76	0.9861	0.022	0.083
200	440.76	0.9860	0.028	0.083
300	440.76	0.9860	0.040	0.083
500	440.77	0.9859	0.063	0.083
700	440.78	0.9859	0.084	0.083
1000	440.79	0.9858	0.115	0.083
1500	440.81	0.9856	0.164	0.083
2000	440.83	0.9854	0.210	0.083
3000	440.88	0.9850	0.299	0.083
5000	441.01	0.9843	0.466	0.083
7000	441.15	0.9836	0.625	0.083
10000	441.39	0.9825	0.853	0.083
15000	441.87	0.9807	1.213	0.083
20000	442.88	0.9789	1.558	0.083
30000	443.88	0.9753	2.217	0.083
50000	447.81	0.9660	3.458	0.083
70000	453.09	0.9546	4.634	0.083
100000	463.39	0.9432	6.320	0.083
150000	485.80	0.9306	8.993	0.083
200000	513.04	0.9212	11.550	0.083
300000	575.17	0.9062	16.436	0.083
500000	699.61	0.8816	25.633	0.083
700000	812.95	0.8614	34.351	0.083
1000000	956.65	0.8381	46.849	0.083
1500000	1154.38	0.8146	66.665	0.083
2000000	1321.07	0.8001	85.624	0.083
3000000	1600.68	0.7823	121.841	0.083
5000000	2044.07	0.7638	190.021	0.083

Table 2.2: *RLGC* values for a 24 gauge twisted pair cable

Frequency(Hertz)	R(Ohms/mile)	L(Henrys/mile)	G(Siemens/mile)	C(Farads/mile)
1	277.19	0.9861	0.0	0.083
5	277.19	0.9861	0.001 0.083	
10	277.19	0.9861	0.002	0.083
15	277.19	0.9861	0.003	0.083
20	277.19	0.9861	0.004	0.083
30	277.19	0.9861	0.005	0.083
50	277.19	0.9861	0.008	0.083
70	277.19	0.9861	0.011	0.083
100	277.19	0.9861	0.016	0.083
150	277.20	0.9860	0.022	0.083
200	277.20	0.9860	0.028	0.083
300	277.20	0.9860	0.040	0.083
500	277.21	0.9859	0.063	0.083
700	277.22	0.9858	0.084	0.083
1000	277.23	0.9857	0.115	0.083
1500	277.25	0.9854	0.164	0.083
2000	277.28	0.9852	0.210	0.083
3000	277.34	0.9848	0.299	0.083
5000	277.48	0.9839	0.466	0.083
7000	277.66	0.9829	0.625	0.083
10000	277.96	0.9816	0.853	0.083
15000	278.58	0.9793	1.213	0.083
20000	279.35	0.9770	1.558	0.083
30000	281.30	0.9723	2.217	0.083
50000	286.82	0.9577	3.458	0.083
70000	294.29	0.9464	4.634	0.083
100000	308.41	0.9347	6.320	0.083
150000	337.22	0.9204	8.993	0.083
200000	369.03	0.9087	11.550	0.083
300000	431.55	0.8885	16.436	0.083
500000	541.69	0.8570	25.633	0.083
700000	632.08	0.8350	34.351	0.083
1000000	746.04	0.8146	46.849	0.083
1500000	902.84	0.7947	66.665	0.083

Table 2.3: *RLGC* values for a 22 gauge twisted pair cable

Frequency(Hertz)	R(Ohms/mile)	L(Henrys/mile)	G(Siemens/mile)	C(Farads/mile)
1	174.27	0.9861	0.000	0.083
5	174.27	0.9861	0.001	0.083
10	174.27	0.9861	0.001	0.083
15	174.27	0.9861	0.001	0.083
20	174.27	0.9861	0.002	0.083
30	174.27	0.9861	0.003	0.083
50	174.27	0.9861	0.005	0.083
70	174.27	0.9861	0.006	0.083
100	174.27	0.9861	0.009	0.083
150	174.27	0.9860	0.013	0.083
200	174.27	0.9860	0.017	0.083
300	174.28	0.9860	0.024	0.083
500	174.29	0.9858	0.040	0.083
700	174.29	0.9857	0.054	0.083
1000	174.31	0.9856	0.076	0.083
1500	174.34	0.9853	0.110	0.083
2000	174.37	0.9850	0.145	0.083
3000	174.44	0.9844	0.211	0.083
5000	174.62	0.9833	0.341	0.083
7000	174.83	0.9821	0.467	0.083
10000	175.22	0.9804	0.652	0.083
15000	176.06	0.9778	0.954	0.083
20000	177.11	0.9744	1.248	0.083
30000	179.86	0.9672	1.824	0.083
50000	187.64	0.9491	2.943	0.083
70000	197.71	0.9372	4.032	0.083
100000	215.55	0.9237	5.630	0.083
150000	247.57	0.9055	8.229	0.083
200000	277.95	0.8898	10.772	0.083
300000	333.39	0.8642	15.744	0.083
500000	421.57	0.8309	25.396	0.083
700000	493.24	0.8123	34.796	0.083
1000000	583.59	0.7950	48.587	0.083
1500000	707.91	0.7783	71.014	0.083

Chapter 3

Identification of Line Configuration

3.1 Finding an Initial Estimate for Line Configuration

Given the frequency response (magnitude only) of a transmission line, it is desired now to characterize its configuration by finding the length and gauge of each segment of the line. To this end, an optimization procedure is developed which aims to find a configuration with the closest magnitude response to the given function (in the sense of integral of the squared error in the frequency domain). As the first step of the underlying optimization procedure, it is important to find an initial estimate of the length of each segment within about 20% accuracy. If the initial estimate is not in a reasonable neighborhood of the exact values, the algorithm can converge to different local minima, or even diverge. The following assumptions will be used in the development of the procedure.

Assumption 1: The length of each bridged taps is assumed to be either 0 or between 400 ft and 1500 ft.

Assumption 2: There can be only one or two bridged taps. In the latter case, both bridged taps have the same gauge.

Assumption 3: The overall length of the main channel does not exceed 20 Kft.

Assumption 4: The frequency response of the line is given in a bin-by-bin basis (each frequency bin is 4.3125 KHz), from the 6th bin (25.875 KHz) to the 256th bin (1.104 MHz).

It is to be noted that Assumption 1-3 are in accordance with the standard loop configurations [4]. Assumption 4, on the other hand, reflects the practical constraints in measuring the frequency response of the line from the CO. To obtain an initial estimate for the length of the bridged tap, the frequency of the first null caused by each bridged tap in the frequency response will be used in equation 2.3, as discussed in Chapter 2. To check different line configurations, 5 line segments are considered as the most general case (two bridged taps and three main line segments). Note that the case of one bridged tap or no bridged tap in the configuration, are special cases of a 5-segment line, where the length of one or two segments is zero. The number of different combinations of line segments which one needs to check is as follows:

- i) Each segment can have 3 different gauges. Since both bridged taps are assumed to

have identical gauges, the total number of possible gauge combinations for the five segments is equal to $3^4 = 81$ [29].

- ii) In order to obtain a reasonably accurate initial estimate, the main line will be divided to 12 units. It is straightforward to verify that the total number of different combinations for this units (corresponding to a line with two bridged taps) is $1 + 2 + \dots + 12 = 78$ [29]. Note that the real length of each unit can be obtained by dividing the overall length of the channel by 12. Note also that using the above technique the minimum number of units for a segment is zero, and the maximum number for it is 12.

The initial configuration search is accomplished by a *MATLAB* code which finds the frequency response of a total of $81 \times 78 = 6318$ combinations in a bin-by-bin format. The difference between the magnitude of this frequency response and that of the given frequency response is then computed as a measure of error (integral of the squared error over frequency). The combination corresponding to the minimum error will be chosen as the initial condition for the optimization procedure.

3.2 Search for the Optimum Configuration

The initial line parameters generated in the previous stage will now be used in the main optimization program to find the closest match for the line configuration. The performance index is the numerical integral of the squared error (the difference between the

magnitude responses of the real line and the configuration considered by the optimization program in each iteration). The program uses Nelder-Mead's simplex search method [20]-[27], and examines different line gauges for different segments in a way similar to the initialization program. If the performance index resulted by the optimization program for a specific configuration is less than a reasonable margin, the program will stop and the corresponding configuration will be the final result.

The problem solved here is, in fact, a constrained optimization problem, as the length of each segment must be positive, and by assumption, should not exceed certain limits. These constraints are implemented by considering a penalty function in the corresponding MATLAB code. On the other hand, in order to avoid long execution times, reasonable limits have been considered for the number of iterations and also for the accuracy of the results in the optimization procedure, as the termination conditions.

Remark 1: If the initial estimates provided to the main optimization program are too far from the exact values, they may not lie in the global optimum's domain of attraction in which case the algorithm does not converge to the desired configuration as noted before. This shows the importance of the initialization phase. A similar problem also occurs when the real line configuration does not satisfy required assumptions (e.g., has more than five segments). In any case, the algorithm returns a configuration with the closest frequency response to the real line.

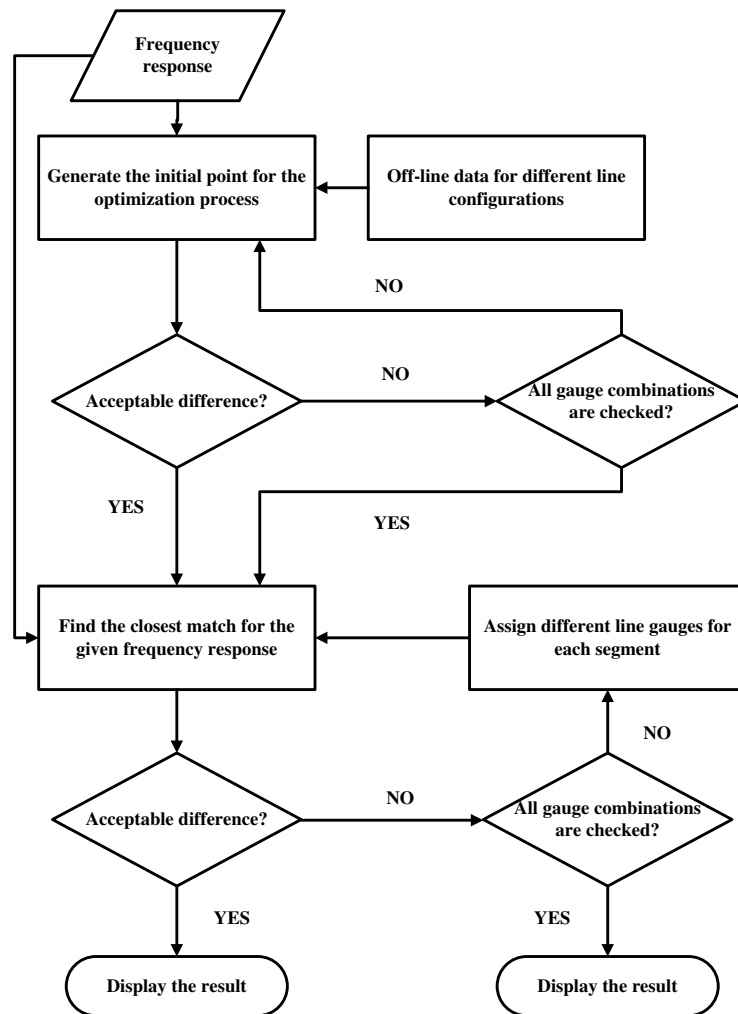


Figure 3.1: The flowchart of the proposed algorithm.

3.3 Reducing Program Execution Time

An important practical issue in the line identification program is the execution time. Due to the complexity of the equations, it can take up to a few weeks for the whole program to run for a typical line with two bridged taps. Using different tricks, however, one can reduce the execution time to about 30 minutes. To accomplish this, the following steps are taken:

- i) The MATLAB code generating the frequency response of the transmission line was written in a way to avoid repeated time consuming command. This reduced the execution time about four times.
- ii) Some of MATLAB commands in the optimization program were written to avoid several function callings. This reduced the execution time about two times.
- iii) By experiment, the most informative points in frequency were identified. By computing the frequency response and error index over the identified points of frequency, the overall execution time was reduced to about 70% of the normal execution time.
- iv) Several programs were written to generate off line data, which can be used in the main program to save some time in online computation. It takes about 10 days for the off line data to be generated and it saves almost the same amount of time in the

online algorithm.

3.4 MATLAB Programs

The main programs are called *initialLineMatch* and *finalLineMatch* and the data files are *length_coef*, *lengthSimulationData_22*, *lengthSimulationData_24* and *lengthSimulationData_26*. The data files are generated by *lengthSimulation* and *initialEstimateTest_10000* programs. The total number of lines written in *MATLAB* is about 1200 lines for the main programs and 950 lines for the data generating codes. The steps of the program execution are given in the following subsections.

3.4.1 Steps or Pseudocode of the Initialization Phase

This program obtains an initial estimate of the line configuration. This estimate needs to be sufficiently close to the exact configuration in order for the optimization procedure (in the next phase) converge. The steps of the algorithm are given below:

- i) Finding the initial estimate for the bridged tap lengths.

- ii) Using part of the low-frequency axis which is more informative.

- iii) Loading the primary constants (*RLGC*) files for the frequency response generator program corresponding to different gauges.
- iv) Loading the restored values from the data files for different lengths and gauges corresponding to different bridged tap gauges.
- v) Choosing the lines corresponding to the approximately calculated bridged tap lengths.
- vi) Finding the initial estimate for the line length (one estimate for each combination of bridged tap lengths), considering segments with different gauges and different lengths in the main line.
- vii) Rearranging the gauges of the main line segments.
- viii) Rearranging the gauges of the bridged taps.
- ix) Generating the output of the initialization phase.

3.4.2 Steps or Pseudocode of the Optimization Phase

This program finds the closest line configuration for a given frequency response. It checks three different line gauges (22, 24, 26) for each segment of a line with one or two bridged

taps. The steps of the optimization phases are as follow:

- i) Getting data for different gauge combinations.
- ii) Setting the optimization Parameters.
- iii) Defining the function that calculates the error to be minimized.
- iv) Setting up a simplex near the initial guess. Iteration takes place until the diameter of the simplex is less than a prescribed termination tolerance value, and the function values are sufficiently close to zero (within a prescribed error margin) or the max function evaluations are exceeded.
- v) Using the *fminsearch* function to get the configuration with minimum error.
- vi) Providing the optimum configuration for the given frequency response.

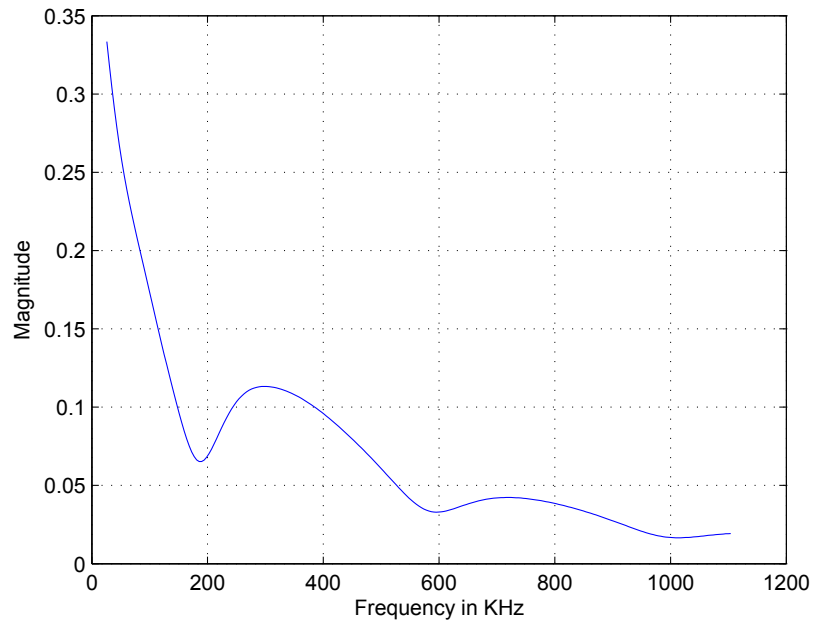


Figure 3.2: Magnitude response for the transmission line of Example 1.

3.5 Simulation Results

Four examples are given in this section for the characterization of a transmission line from the bin-by-bin magnitude response. In the first example a transmission line with one bridged tap and in the second example a transmission line with two bridged taps is considered.

Example 1: Consider a transmission line with three segments as follows (for segment numbers see Figure 1.3):

Segment #1: 3000 ft, 26 gauge

Segment #2: 800 ft, 24 gauge

Segment #3: 1000 ft, 24 gauge

The magnitude response of this transmission line is shown in Figure 3.2, and the corresponding information is provided in a bin-by-bin fashion to the initialization and optimization procedures developed in this work. The outcome of the initialization procedure is as follows (for segment numbers see Figure 1.4):

Segment #1: 2689 ft, 26 gauge

Segment #2: 768 ft, 26 gauge

Segment #3: 672.25 ft, 26 gauge

Segment #4: 0.0 ft, 26 gauge

Segment #5: 672.25 ft, 22 gauge

It can be verified that maximum discrepancy of the initial estimates from the exact values is within 20%. These values are subsequently provided to the main optimization procedure, which arrives at the following values:

Segment #1: 3002 ft, 26 gauge

Segment #2: 800 ft, 24 gauge

Segment #3: 996 ft, 24 gauge

This demonstrates that the procedure has converged to the exact values for this configuration. The initialization and optimization procedures for this example take 2.20 min and 1.38 min, respectively, on a personal computer with a 2.33 GHz Intel Core 2 Duo CPU and 2.00 GB RAM.

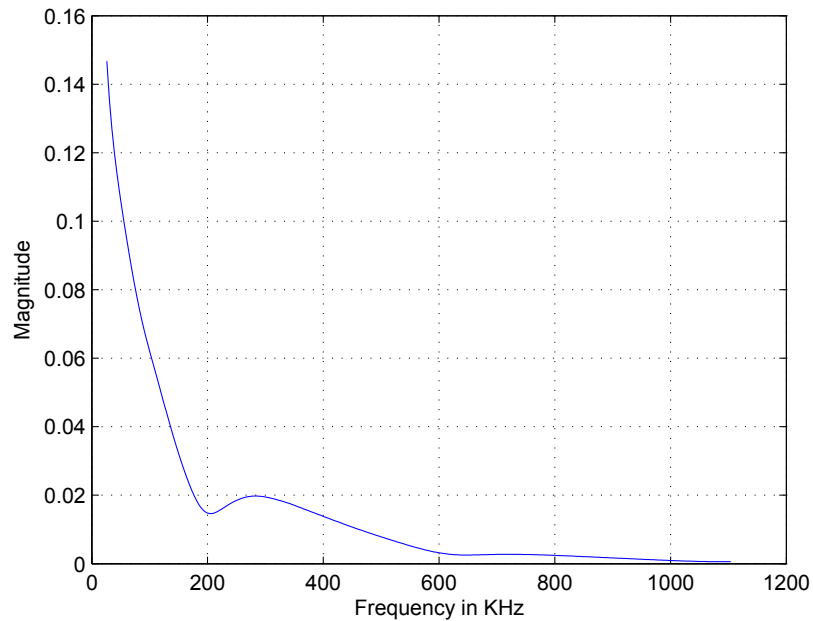


Figure 3.3: Magnitude response for the transmission line of Example 2.

Example 2: Consider a transmission line with three segments as follows (for segment numbers see Figure 1.3):

Segment #1: 4050 ft, 26 gauge

Segment #2: 750 ft, 24 gauge

Segment #3: 5042 ft, 22 gauge

The magnitude response of this transmission line is shown in Figure 3.3, and the corresponding information is provided in a bin-by-bin fashion to the initialization and optimization procedures developed in this work. The outcome of the initialization procedure is as follows (for segment numbers see Figure 1.4):

Segment #1: 3161.5 ft, 26 gauge

Segment #2: 768 ft, 24 gauge

Segment #3: 3161.5 ft, 26 gauge

Segment #4: 0.0 ft, 26 gauge

Segment #5: 393.2 ft, 22 gauge

It can be verified that maximum discrepancy of the initial estimates from the exact values is within 20%. These values are subsequently provided to the main optimization procedure, which arrives at the following values:

Segment #1: 4050 ft, 26 gauge

Segment #2: 750 ft, 24 gauge

Segment #3: 5041 ft, 22 gauge

This demonstrates that the procedure has converged to the exact values for this configuration. The initialization and optimization procedures for this example take 2.20 min and 1.2 min, respectively, on a personal computer with a 2.33 GHz Intel Core 2 Duo CPU and 2.00 GB RAM.

Example 3: Consider a transmission line with five segments as follows (for segment numbers see Figure 1.4):

Segment #1: 5030 ft, 26 gauge

Segment #2: 1320 ft, 24 gauge

Segment #3: 2078 ft, 24 gauge

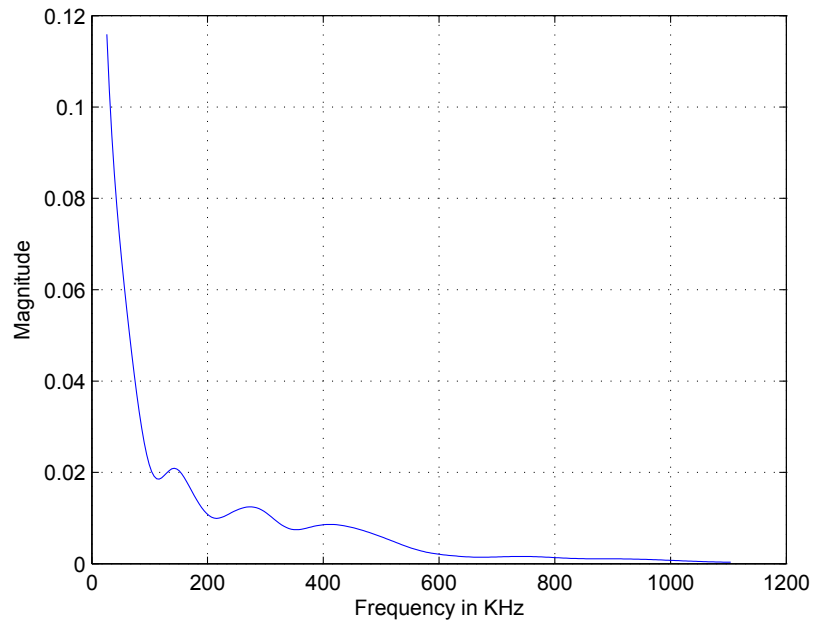


Figure 3.4: Magnitude response for the transmission line of Example 3.

Segment #4: 709 ft, 24 gauge

Segment #5: 1013 ft, 22 gauge

The magnitude response of this transmission line is shown in Figure 3.4, and the corresponding information is provided in a bin-by-bin fashion to the initialization and optimization procedures developed in this work. The outcome of the initialization procedure is as follows (for segment numbers see Figure 1.4):

Segment #1: 4798.6 ft, 26 gauge

Segment #2: 1200 ft, 26 gauge

Segment #3: 2056.5 ft, 24 gauge

Segment #4: 768 ft, 26 gauge

Segment #5: 1371 ft, 22 gauge

It can be verified that maximum discrepancy of the initial estimates from the exact values is within 20%. These values are subsequently provided to the main optimization procedure, which arrives at the following values:

Segment #1: 5031 ft, 26 gauge

Segment #2: 1320 ft, 24 gauge

Segment #3: 2077 ft, 24 gauge

Segment #4: 709 ft, 24 gauge

Segment #5: 1012 ft, 22 gauge

This demonstrates that the procedure has converged to the exact values for this configuration. The initialization and optimization procedures for this example take 2.27 min and 0.23 min, respectively, on a personal computer with a 2.33 GHz Intel Core 2 Duo CPU and 2.00 GB RAM.

Example 4: Consider a transmission line with five segments as follows (for segment numbers see Figure 1.4):

Segment #1: 3000 ft, 26 gauge

Segment #2: 800 ft, 22 gauge

Segment #3: 1500 ft, 24 gauge

Segment #4: 400 ft, 22 gauge

Segment #5: 2000 ft, 22 gauge

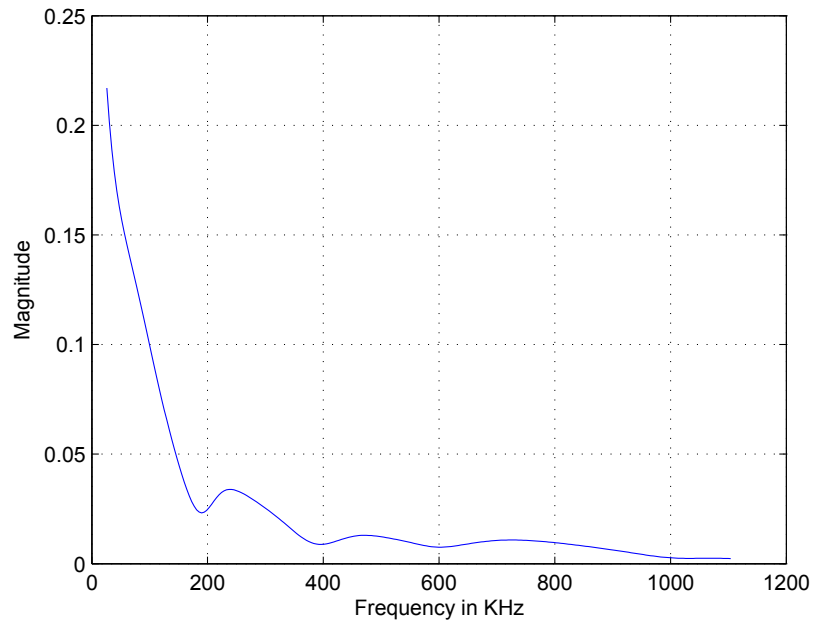


Figure 3.5: Magnitude response for the transmission line of Example 4.

The magnitude response of this transmission line is shown in Figure 3.5, and the corresponding information is provided in a bin-by-bin fashion to the initialization and optimization procedures developed in this work. The outcome of the initialization procedure is as follows (for segment numbers see Figure 1.4):

Segment #1: 3544.1 ft, 26 gauge

Segment #2: 768 ft, 22 gauge

Segment #3: 1518.9 ft, 24 gauge

Segment #4: 393.2 ft, 22 gauge

Segment #5: 1012.6 ft, 22 gauge

It can be verified that maximum discrepancy of the initial estimates from the exact values

is within 20%. These values are subsequently provided to the main optimization procedure, which arrives at the following values:

Segment #1: 3000 ft, 26 gauge

Segment #2: 800 ft, 22 gauge

Segment #3: 1501 ft, 24 gauge

Segment #4: 400 ft, 22 gauge

Segment #5: 2000 ft, 22 gauge

This demonstrates that the procedure has converged to the exact values for this configuration. The initialization and optimization procedures for this example take 2.27 min and 0.23 min, respectively, on a personal computer with a 2.33 GHz Intel Core 2 Duo CPU and 2.00 GB RAM.

Chapter 4

Conclusions

4.1 Summary

This thesis presents a technique to identify the configuration of a transmission line in a wired communication network from its frequency response. The proposed technique aims to find the closest match for the given magnitude response, using the integral of squared error as the measure of closeness. The procedure consists of two phases: initialization and optimization. The initialization phase provides a reasonable initial estimate of line parameters for the optimization program which uses direct search method to find the optimal solution. It is assumed that the transmission line consists of not more than two bridged taps, and that the length of bridged taps and main channel are within certain ranges in accordance with the DSL loop standards.

Chapter 2 provides a technique to estimate the total length of the main line. To this end, the magnitude response of the line is approximated by a polynomial of a sufficiently high degree. A procedure is subsequently used to find an estimate of the line length, mainly from the magnitude response in lower frequencies. While this estimate is not used in the technique presented later in the thesis, it is very useful as it provides an estimate of the distance between the customer and central office, which is very important for the DSL service providers.

The main contribution of the work is provided in Chapter 3, where a technique is presented to identify the configuration of the line (in terms of length and gauge of each segment). An initial estimate of the line configuration is made first, and then an optimization procedure is used to tune the parameters of the model to minimize the difference between the real frequency response of the line and that of the model.

The results of this work can be used as a single-ended testing of the line from the central office to characterize it and determine any sources of possible problems in the signal transmission. Simulations demonstrate the effectiveness of the proposed technique.

4.2 Future Work

The proposed algorithm fully characterizes the twisted-pair transmission line with high accuracy from its frequency response. The following issues can be considered for future work:

- i) The overall performance of the procedure depends on the accuracy of the optimal parameters, and how fast they are obtained. This, in turn, depends on the accuracy of the initialization process and how fast it is completed. A more accurate initial estimate would require a longer time, but leads to more accurate parameters (as the output of the optimization procedure) in a shorter period of time. This introduces a trade-off between the accuracy of initialization algorithm and the speed of the optimization procedure, which needs to be addressed by simulations for a more efficient algorithm.

- ii) If the lengths of a bridged tap is equal (or very close) to the length of another bridged tap, the initialization algorithm may not distinguish them. A different approach should be used in such cases to estimate the number of bridged taps in the line, before the initialization algorithm is performed.

Bibliography

- [1] T. Starr, J.M. Cioffi and P.J. Silverman, *Understanding Digital Subscriber Line Technology*, New York: Prentice Hall, 1999.
- [2] S. Galli and K.J. Kerpez, "Single-Ended Loop Make-Up Identification-Part I: Improved Algorithms and Performance Results," *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 2, pp. 528–537, April 2006.
- [3] S. Galli and K.J. Kerpez, "Single-Ended Loop Make-Up Identification-Part II: A Method of Analyzing TDR Measurements," *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 2, pp. 538–549, April 2006.
- [4] G. Hong, "Performance of a 51.84-Mb/s VDSL Transceiver Over the Loop with Bridged Taps," *IEEE Transactions on Communications*, vol. 50, no. 5, May 2002.
- [5] J.J. Werner, "The HDSL Environment," *IEEE Journal on Selected Areas in Communications*, vol. 9, no. 6, August 1991.
- [6] P. Boets, T. Bostoen, L.V. Biesen and T. Pollet, "Pre-Processing of Signals for Single-Ended Subscriber Line Testing," *IEEE Transactions on Instrumentation and*

- Measurement*, vol. 55, no. 5, pp. 1509–1518, 2006.
- [7] S. Galli and D.L. Waring, "Loop Makeup Identification Via Single Ended Testing: Beyond Mere Loop Qualification," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 5, June 2002.
- [8] International Telecommunication Union, *Telecommunication G.996.1*, Test Procedures for Digital Subscriber Line (DSL) Transceiver, 2001.
- [9] S. Galli, "Exact Conditions for the Symmetry of a Loop," *IEEE Communications Letters*, vol. 4, no. 10, October 2000.
- [10] K.J. Kerpez, "The Telcordia DSL Spectral Compatibility Computer website," <http://net3.argreenhouse.com>, available online.
- [11] K. Kerpez and S. Galli, "Joint Optimization of Single-Carrier and Multi-Carrier DSL Spectra," *IEEE Int. Conf. on Communications*, pp. 1347-1351, May 2005.
- [12] K.B. Song, S.T. Chung, G. Ginis and J.M. Cioffi, "Dynamic Spectrum Management for Next-Generation DSL Systems," *IEEE Communications Mag.*, vol. 40, no. 10, pp. 101-109, October 2002.
- [13] K. Kerpez, D. Waring, J. Dixon, P. Mandon and S. Galli, "Advanced DSL Management," *IEEE Communications Mag.*, vol. 41, no. 9, pp. 116-123, September 2003.
- [14] W.Y. Chen, *DSL-Simulation Techniques and Standards Development for Digital Subscriber Line Systems*, Indianapolis, Macmillan Technical Publishing.
- [15] I. Kalet and S. Shamai-Shitz, "On the Capacity of a Twisted-Wire Pair: Gaussain Model," *IEEE Transactions on Communications*, vol. 38, no. 3, pp. 379-383, March 1990.

- [16] *Transmission Systems for Communications*, Holmdel, NJ: Bell Laboratories, 1982.
- [17] J.M. Cioffi, "Very-High-Speed Digital Subscriber Lines-System Requirements," *ANSI Contribution TIE1.4/98-172*, June 1998.
- [18] T. Vermeiren, T. Bostoën, F. Louage, P. Boets and X.O. Chehab, "Subscriber Loop Topology Classification by Means of Time Domain Reflectometry," *IEEE Int. Conf. on Communications*, vol. 3, pp. 1998-2002, May 2003.
- [19] P. Boets, T. Bostoën, D. Gardan and L.V. Biesen, "Single Ended Line Testing-A White Box Approach," in *Proceedings of 4th IASTED Int. Multi-Conf. Wireless and Optical Communications*, pp. 393-398, July 2004.
- [20] P.D. McFadden, *Interpolation Techniques for the Time Domain Averaging of Vibration Data with Application to Helicopter Gearbox Monitoring*, Dept. of Defence, Defence Science and Technology Organisation, Aeronautical Research Laboratories, 1986.
- [21] J.C. Lagarias, A.J. Reeds, M.H. Wright and P.E. Wright, "Convergence Properties of the Nelder Mead Simplex Method in Low Dimensions," *SIAM Journal on Optimization*, vol. 9, no. 1, pp. 112-147, 1998.
- [22] A.P. Gurson, *Simplex Search Behavior in Nonlinear Optimization*, Bachelors Honors Thesis, Computer Science Department, College of William and Mary, Williamsburg, Virginia, 2000.
- [23] T.G. Kolda, R.M. Lewis and V. Torczon, "Optimization by Direct Search: New Perspectives on Some Classical and Modern Methods," *SIAM Review*, no. 45, pp. 385-482, 2003.

- [24] R.M. Lewis, V. Torczon and M.W. Trosset, "Direct Search Methods: Then and Now, in Numerical Analysis," *SIAM Journal on Optimization*, vol. 4, pp. 191-207, 2001.
- [25] K.I.M. McKinnon, "Convergence of the Nelder Mead Simplex Method to a Non-Stationary Point," *SIAM Journal on Optimization*, vol. 9, pp. 148-158, 1998.
- [26] J.A. Nelder and R. Mead, "A Simplex Method for Function Minimization," *Computer Journal*, no. 7, pp. 308-313, 1965.
- [27] J.M. Ortega and W.C. Rheinboldt, *Iterative Solution of Nonlinear Equations in Several Variables*, Academic Press, New York, 1970.
- [28] A. Schrijver, *Theory of Linear and Integer Programming*, John Wiley and Sons, New York, 1987.
- [29] A.L. Garcia, *Probability, Statistics, and Random Processes for Electrical Engineering*, Prentice Hall, 2008.
- [30] A.M. Stuart and A.R. Humphries, *Dynamical Systems and Numerical Analysis*, Cambridge University Press, Cambridge, UK, 1996.
- [31] M.H. Wright, *Direct Search Methods: Once Scorned, Now Respectable*, Addison-Wesley Longman, pp. 191-208, 1996.
- [32] V. Torczon, "On the Convergence of Pattern Search Algorithms," *SIAM Journal on Optimization*, no. 7, pp. 1-25, 1997.
- [33] W.H. Press, B.P. Flannery, S.A. Teukolsky and W.T. Vetterling, *Numerical Recipes in Fortran: the Art of Scientific Computing*, Cambridge University Press, Cambridge, UK, 1992.

- [34] C.J. Price, I.D. Coope and D. Byatt, "A Convergent Variant of the Nelder Mead Algorithm," *Journal of Optimization Theory and Applications*, no. 113, pp. 5-19, 2002.
- [35] A.S. Rykov, "Simplex Algorithms for Unconstrained Optimization," *Problems of Control and Information Theory*, no. 12, pp. 195-208, 1983.
- [36] P. Tseng, "Fortified-Descent Simplicial Search Method: A General Approach," *SIAM Journal on Optimization*, vol. 10, no. 1, pp. 269-288, 1999.
- [37] L.J. Nazareth and P. Tseng, "Gilding the Lily: A Variant of the Nelder Mead Algorithm Based on Golden Section Search," *Computational Optimization and Applications*, vol. 22, pp. 133-144, 2002.
- [38] *MATLAB User Guide*, R2010b Documentation, The Mathworks Inc., Natick, Massachusetts, 2010.
- [39] F. Klein, *Elementary Mathematics from an Advanced Standpoint: Geometry*, Dover Publications: New York, 1939.
- [40] L. Han and M. Neumann, "Effect of Dimensionality on the Nelder Mead Simplex Method," *Optimization Methods and Software*, vol. 21, pp. 1-16, 2006.
- [41] A.R. Conn, K. Scheinberg and L.N. Vicente, "Introduction to Derivative-Free Optimization," *SIAM Journal on Optimization*, no. 53, pp. 395-396, 2009.
- [42] I.D. Coope and C.J. Price, "On the Convergence of Grid-Based Methods for Unconstrained Optimization," *SIAM Journal on Optimization*, vol. 11, pp. 859-869, 2001.
- [43] C. Audet and J.E. Dennis, "Analysis of Generalized Pattern Searches," *SIAM Journal on Optimization*, vol. 13, pp. 889-903, 2003.

- [44] C. Audet and J.E. Dennis, "Mesh Adaptive Direct Search Algorithms for Constrained Optimization," *SIAM Journal on Optimization*, vol. 17, pp. 188-217, 2006.
- [45] *Characterization of Subscriber Loops for Voice and ISDN Services (1983 subscriber loop survey results)*, Bellcore, Science and Technology Series, ST-TSY-000 041, 1987.
- [46] *Transmission and Multiplexing (TM); Access Transmission Systems on Metallic Access Cables; Very High Speed Digital Subscriber Line (VDSL); Part 2: Transceiver Specification*, ETSI TS 101 270-2, 2001.
- [47] G. Ginis and J.M. Cioffi, "Vectored Transmission for Digital Subscriber Line Systems," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 5, pp. 1085-1104, June 2002.
- [48] A. Wang, J.J. Werner and S. Kallel, *Effect of Bridged Taps on Channel Capacity at VDSL Frequencies*, Bell Laboratories, Holmdel, USA.
- [49] B. Porat and D. Schmucking, "The Achievable Capacity of First-Generation FDD Symmetric VDSL Under the FSAN Noise Model," *ETSI Contribution*, TD-30, January 1998.
- [50] T. Bostoen, P. Boets, M. Zekri, L.V. Biesen, T. Pollet and D. Rabijns, "Estimation of the Transfer Function of a Subscriber Loop by Means of a One-Port Scattering Parameter Measurement at the Central Office," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 5, pp. 936-948, June 2002.
- [51] W.D. Block, R. Pintelon and Y. Rolain, "Identification of Transmission Lines: From Time Domain Measurements to Frequency Domain Models," *IEEE Instrumentation and Measurement Technology Conference*, May 2002.

Appendix A

Appendix

A.1 MATLAB Code to Determine the Length of Bridged Taps

%Finding the initial estimate for the bridged-tap length

```
lp_cfg = [2000 26 0; 900 22 1; 1600 24 0; 500 22 1; 2300  
22 0];
```

```
ZL = 100; ZG = 100; f1 = [6*4.3125:4.3125:1104];
```

```
[Ay,By,Cy,Dy] = g_loop(f1,lp_cfg,1); H_cb = (ZL + ZG) ./ (ZG  
.*(Cy.*ZL + Dy) + Ay.*ZL + By); H = abs(H_cb);
```

```
lp_cfg_real = lp_cfg;
```

```
%
```

```

%
%
subplot(211),
plot(f1,H), grid on;
title('lp-cfg =[900 26 0;1500 22 1;4000 24 0;500 22
1;5000 24 0]')
%
Dif=diff(H);
fd=f1(1:length(f1)-1);
subplot(212),plot(fd,Dif)
title('derivative of transfer function')
grid on;
save Dif;
save fd;
j=1;
for i=1:length(Dif)-1

    if ((Dif(i)*Dif(i+1))<0)
        freq(j)=((f1(i)+f1(i+1))/2);
        j=j+1;
    end
end
disp('zero-cross freqs are: ');
freq
disp('Length of 1st bridged tap is in feet: ');

```

```

yy1=150000./freq(1)
disp('Length of 2nd bridged tap is in feet: ');
yy2=150000./freq(3)

```

A.2 MATLAB Code to Determine the Total Length of Line

```

%Equation generated by the fitting curve.
% function y=CF(f)
% p1 = -5.9324e-008;
% p2 = 2.0479e-005;
% p3 = -0.0043668;
% p4 = 0.64293;
%
% y=p1*f^3 + p2*f^2 +p3*f + p4 ;
% % Equation generated by theory.
% function h=LL(f,x)
% lp_cfg = [x/3 26 0;x/3 24 0;x/3 22 0];
% ZL = 100; ZG = 100;
% [Ay,By,Cy,Dy] = g_loop(f,lp_cfg,1); H_cb = (ZL + ZG)./(ZG
% .* (Cy.*ZL + Dy) + Ay.*ZL + By);
% h=abs(H_cb);
% % Function generation for direct search.
% function F=LLF(y)

```

```

% f=[6*4.3125:4.3125:200];
% F=0;
% for i=1:length(f)
%     F=(LL(f(i),y)-CF(f(i)))^2;
% end
% g1=43*10^(-9);
% g2=0.7;
% G=g1*(f^g2);

%per unit value of 24 AWG
% R=175;
% L=616e-6;
% C=50e-9;
% G=0.0;
%
% d1=3;
% d2=0.1;
% d3=1.0;
% d4=0.1;
% d5=1;
%
%
% gamma=sqrt((R+i*6.283185*f*L)*(G+i*6.283185*f*C));
% Z=sqrt((R+i*6.283185*f*L)/(G+i*6.283185*f*C));
% Zs=Z;

```

```

% Zl=Z;
% phi1=[cosh(gamma*d1) Z*sinh(gamma*d1);(1/Z)*sinh(gamma*d1
) cosh(gamma*d1)];
% phi2=[1 0;(1/Z)*tanh(gamma*d2) 1];
% phi3=[cosh(gamma*d3) Z*sinh(gamma*d3);(1/Z)*sinh(gamma*d3
) cosh(gamma*d3)];
% phi4=[1 0;(1/Z)*tanh(gamma*d4) 1];
% phi5=[cosh(gamma*d5) Z*sinh(gamma*d5);(1/Z)*sinh(gamma*d5
) cosh(gamma*d5)];
% phi=phi1*phi2*phi3*phi4*phi5;
% %phi=phi1*phi3*phi5;
% H=abs(Zl/((phi(1,1)*Zl)+phi(1,2)+phi(2,1)*Zl*Zs+phi(2,2)*
Zs))

```

A.3 MATLAB Code to Deal with the Variable Nature of RLCG Values with Frequency

```

clc
clear all
%per unit value of 26AWG
%syms f
f = [6*4.3125*1000:4.3125:1104*1000];
r1=286.17578;
r2=inf;

```

```

a1=0.14769620;
a2=0.0;
R=1./((1./(r1^4+a1*f.^2).^ (1/4))+(1./(r2.^4+a2*f.^2).^ (1/4)
));
plot(f,R)
xlabel('Frequency in KHz')
ylabel('Magnitude of Resistance in Ohms')
l1=675.36888*10^(-6);
l2=488.95186*10^(-6);
b=0.92930728;
fm=806338.63;
L=(l1+l2.*(f./fm).^b)/(1+(f./fm).^b);
figure(2)
plot(f,L)
xlabel('Frequency in KHz')
ylabel('Magnitude of Inductance in Henrys')

% g1=43*10^(-9);
% g2=0.7;
% G=g1*(f^g2);

%per unit value of 24 AWG
% R=175;
% L=616e-6;
% C=50e-9;

```

```

% G=0.0;
%
% d1=3;
% d2=0.1;
% d3=1.0;
% d4=0.1;
% d5=1;
%
%
% gamma=sqrt((R+i*6.283185*f*L)*(G+i*6.283185*f*C));
% Z=sqrt((R+i*6.283185*f*L)/(G+i*6.283185*f*C));
% Zs=Z;
% Zl=Z;
% phi1=[cosh(gamma*d1) Z*sinh(gamma*d1);(1/Z)*sinh(gamma*d1
) cosh(gamma*d1)];
% phi2=[1 0;(1/Z)*tanh(gamma*d2) 1];
% phi3=[cosh(gamma*d3) Z*sinh(gamma*d3);(1/Z)*sinh(gamma*d3
) cosh(gamma*d3)];
% phi4=[1 0;(1/Z)*tanh(gamma*d4) 1];
% phi5=[cosh(gamma*d5) Z*sinh(gamma*d5);(1/Z)*sinh(gamma*d5
) cosh(gamma*d5)];
% phi=phi1*phi2*phi3*phi4*phi5;
% %phi=phi1*phi3*phi5;
% H=abs(Zl/((phi(1,1)*Zl)+phi(1,2)+phi(2,1)*Zl*Zs+phi(2,2)*
Zs))

```


Appendix B

Appendix

B.1 Modified Section of MATLAB Code for the Initialization Phase

```
%Modification subcode in the initialization phase.  
% Using a portion of frequency points which is more  
informative  
ff = 1000*f1(1:1:round(length(f1)/2))'; % This change of  
scale is necessary because g-loop uses frequency in KHz.  
f1 = f1(1:1:round(length(f1)/2))';  
H = H(1:1:round(length(H)/2));  
%size(H)  
f_length = length(ff);
```

```

% load the files for g_loop corresponding to different
    gauges
fid=fopen(['rlgc\' '22' 'pic70.txt'], 'r');
[y1, cc]=fscanf(fid, '%f', [5, 37]);
fclose(fid);
fid=fopen(['rlgc\' '24' 'pic70.txt'], 'r');
[y2, cc]=fscanf(fid, '%f', [5, 37]);
fclose(fid);
fid=fopen(['rlgc\' '26' 'pic70.txt'], 'r');
[y3, cc]=fscanf(fid, '%f', [5, 37]);
fclose(fid);
% Set the error index to a big initial value
Error = 1.e10;
config = [];
kk = 1;
for b_g = 22:2:26,
    % Load prestored values for different lengths and
        gauges corresponding to different bridged-tap gauges
    if b_g == 22,
        load lengthSimulationData_22
    elseif b_g == 24,
        load lengthSimulationData_24
    else
        load lengthSimulationData_26

```

end

*% Choosing the lines corresponding to the above bridged
-tap length (in both locations)*

%y0 = min(abs(Y(1:8,2) - yy));

*i1 = find(abs(Y(:,1) - yy1) == min(abs(Y(1:8,2) - yy1))
& abs(Y(:,2) - yy2) == min(abs(Y(1:8,2) - yy2))));*

Y = Y(i1 ,:);

H0_22 = H0_22(:, i1);

H0_24 = H0_24(:, i1);

H0_26 = H0_26(:, i1);

% Main line segment gauges

g1 = [22 24 26];

g2 = [22 24 26];

g3 = [22 24 26];

g4 = [22 24 26];

g5 = [22 24 26];

% Bridged-tap gauges

G_y = [b_g b_g];

*% Finding the initial estimate for the line length (one
estimate for each combination of bridged-tap
lengths)*

h0_22 = min(abs(H0_22 - H(1)));

for i = 1:length(h0_22),

```

        d1(i) = d(find(abs(H0_22(:,i) - H(1)) == h0_22(i)))
        ;
    end

    h0_24 = min(abs(H0_24 - H(1)));
    for i = 1:length(h0_24),
        d2(i) = d(find(abs(H0_24(:,i) - H(1)) == h0_24(i)))
        ;
    end

    h0_26 = min(abs(H0_26 - H(1)));
    for i = 1:length(h0_26),
        d3(i) = d(find(abs(H0_26(:,i) - H(1)) == h0_26(i)))
        ;
    end

    dd = [d1' d2' d3'];
end

```