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**A Study of the Single-ended Loop Characterization
for Special Services**

by

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A thesis submitted to the
faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of
Master of Applied Science

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Abstract

The objective of this research is to propose an approach for single-ended loop characterization by which the insertion loss (IL) over a subscriber loop can be estimated to within ± 1 dB accuracy based on some measurements from the central office (CO) only.

The estimation of transmission loss at 1 kHz is an essential requirement for both basic plain old telephone services (POTS) and special services provided by telephone companies (telcos). The loss at 1 kHz is used as an indication of the quality of the connection. To maintain the quality (loss) of the subscriber loops at a certain level, skilled technicians are conventionally needed to perform two-ended loss measurements at both the customer end and the central office. The latest methods used in the industry require large but unreliable data base. These result in substantial expenses to telephone companies. Our objective is to replace these by an automatic procedure. Estimation of the loop loss based on measurements from the Central Office only is complicated by the fact that the customer's terminal set may be one of a wide variety of terminations and will not, in general, be known to the operating companies.

The approach proposed in this thesis is intended for voice band special services for Carrier Serving Area (CSA) loops in digital loop carrier (DLC) systems. The problem is formulated as that of modelling a two port network using single port measurements. The parameters of the model representing the subscriber loop are

determined so as to minimize the input impedance error at several frequencies for arbitrary customer's termination. It is shown that using this model for insertion loss estimation results in errors within the required 1dB at 1 kHz. Next, a simple algorithm is proposed to use the same parameters in the model to determine insertion loss at higher voice frequencies. Finally, effect of error in input impedance measurement on loss estimation is studied.

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List of Symbols and Abbreviations

+ve	positive
-ve	negative
<LR, CX>	The termination of the off-hook model [(Figure 3.1b)] is assumed to be linear with its real part and constant with its imaginary part.
<LR, LX>	The termination of the off-hook model [(Figure 3.1b)] is assumed to be linear with its real part and linear with its imaginary part.
α	attenuation constant
A_i	current transfer function
ANSWR	Automated Network Services Workflow Resource
A_o	voltage transfer function
ARSB	Automated Repair Service Bureau
AT&T	American Telephone and Telegraph Corporation
ATAS	Automated Testing and Analysis System
ATM	Asynchronous Transfer Mode
AWG	American Wire Gauge
β	phase constant
BNR	Bell Northern Research
BW	bandwidth
C	capacitance
CAROT	Centralized Automatic Reporting on Trunks

CO	Central Office
COT	Central Office Terminal
CSA	Carrier Serving Area
D/A	Digital to Analog conversion
dB	decibel scale : $20 \log [v]$
DC	Direct Current
DLC	Digital Loop Carrier
DNHR	Dynamic NonHierarchical Routing
DTMF	Dual-Tone-Multi-Frequency
DUNLSJ	The optimization program used in this research is obtained from IMSL. The full name is Double precision Unconstrained Non-linear Least Square using Jacobian.
e.g.	for example
E911	Enhanced 911 service
EO	End Office
eqn.	equation
ERL	Echo Return Loss
etc.	et cetera
ETN	Electronic Tandem Network
F	Farad
FAX	Facsimile
FDI	Feeder-Distribution Interface
FDM	Frequency Division Multiplexing
FMAC	Facility Maintenance and Administration Center
FSA	Fiber Serving Area
FX	Foreign eXchange
G	conductance

γ	propagation constant
Hz	Hertz
I	complex current
i.e.	this is
IL	Insertion Loss
$\text{Im}(Z_{i0})$	imaginary part of the Z_{i0}
IP	Insertion Phase shift
kb/s	kilo bit per second
kft	kilo foot
kHz	kilo Hertz
KTS	Key Telephone System
L	inductance
LMOS	Loop Maintenance Operation Systems
mA	milli Ampere
Mb/s	Mega bit per second
MLT	Mechanized Loop Testing
MTN	Message Telephone Network
$M\Omega$	Mega Ohm
Np/m	Neper per meter
NPA	Numbering Plan Area
NT	Northern Telecom
OA&M	Operation Administration and Maintenance
OPX	Off-Premises eXtension
OS	Operations System
OSP	Outside Plan
π	pi
PBX	Private Branch eXchange

PCM	Pulse Code Modulation
PIC	Polyethylene-Insulated Cable
POTS	Plain Old Telephone Service
R	resistance
ρ	reflection coefficient
RC model	simplified lump transmission line model
$\text{Re}(Z_{i0})$	real part of the Z_{i0}
RL	Return Loss
RT	Remote Terminal
RTU	Remote Test Unit
SARTS	Switched Accessed Remote Test System
SSC	Special-Services Center
SSN	Switched Services Network
T1-T4	common multiplexing schemes of TDM in North America
TDM	Time Division Multiplexing
Telco	Telephone company
TL 1	Transaction Language 1
TSC	Test System Controller
V	complex voltage
VLSI	Very Large Scale Integration
ω	frequency in radian
WATS	Wide Area Telecommunications Service
WFA	Work Force and Administration
X	imaginary constant of the off-hook termination
Y_L	load admittance
Z_i	input impedance
Z_{i0}	Measured input impedance at CO when the far end is open

$Z_{i\text{off-hook}}$	Measured input impedance at CO when the far end is at off-hook state
$Z_{i\text{on-hook}}$	Measured input impedance at CO when the far end is at on-hook state
Z_L	load impedance
Z_0	characteristic impedance
Z_0'	output impedance
Z_{O3}	input impedance for the on-hook model
Z_S	source impedance
Z_{t3}	input impedance for the off-hook model
Ω	Ohm

1. Introduction

1.1. Introduction

Plain Old Telephone Services (POTS) are the most common telephone services offered by the telephone companies to ordinary households. Their counterpart services offered to business, government, and universities are called special services. Like POTS, the majority of special services are voice band applications. However, special services provide a range of services that POTS cannot provide, because the circuitry used by special services is more sophisticated. That is why the standards used by special services, in all aspects, are higher.

However, both these two type of services use the existing copper loop plants to provide services to customers. Several studies show that half of the annual telephone companies' (telcos) capital investments has been dedicated to the subscriber loops and over half of the budget for network expenses were associated with maintaining those loops. Among these loop related expenses, labor costs are the main categories. This distribution of cost is given in [Andrus et al 86] and is not expected to change in the 90s.

In order to utilize local loops efficiently, and thus minimize loop related expenses, a well defined loop system is essential. In the early 70s, Digital Loop Carrier (DLC) systems were established to serve rural subscribers. It was foreseen that in the long run, such a system will be cost effective in terms of loop provisioning, maintenance and conditioning. To deploy DLC system systematically, and hence

obtain additional advantages, the concept of Carrier Serving Area (CSA) was introduced and adopted by many telcos [Bellcore 88]. The concept of CSA designs limits the loop portion of the DLC system to satisfying the requirements of digital services (56 kb/s at that time) without any conditioning process. This systematic DLC approach allows telcos better control over the loops. Today's special-service engineers generally adopt the DLC system and the CSA loop design concepts.

Once a well-defined loop system is established, advanced loop testing systems are necessary. Telcos have deployed the automated loop testing systems since the 80s [Bellcore 86]. These testing systems for both POTS and special services support centralized loop testings. It was estimated that about 50% of labor savings can be achieved if such systems are used efficiently [Andrus et al 86].

This research work concentrates on the topic of single-ended loop characterization which is essential for the automated loop testing systems. Loop characterization refers to the estimation of frequency response or loss of a loop. It is easily achieved given a 2-port network model. Conventionally, determination of the parameters of a 2-port network requires end to end measurements, hence technicians are required at both CO and customer premises to take measurements simultaneously [Bellcore 91-v2]. Some recent approaches require all existing loop information to be stored in a huge database. The transmission parameters such as the frequency response are then retrieved from the data base for automated testing purposes [Fleckenstein 82], [Helsing et al 84], [Bellcore 86]. The information stored can be several years old and the accuracy of it reflecting the real loop condition is questionable. The single-ended loop characterization approach proposed here uses the limited resources of single port measurements to characterize the frequency response of the loop thus supporting the centralized loop management. This eliminates the use of huge and inaccurate data base deployed by the recent

approaches and the unnecessary dispatch of technicians to the customers' premises as well as technicians' coordination.

The approach proposed in this thesis assumes voice-band frequency operation for special services where CSA loops are used. As 1 kHz is the most important frequency for any voice band application [Blake et al 81], [AT&T 77-v1], the objective for the single-ended loop characterization studied in this thesis is to estimate the frequency response at 1 kHz for a CSA channel assuming the availability of input impedance measurements at the CO only. Results are then extended to higher voice frequencies.

1.2. Thesis Outline

In chapter 2, a review of the telephone network is given. It is followed by a discussion of special services and their different categories. This is followed by a discussion of the the Digital Loop Carrier (DLC) system and the Carrier Serving Area concept. The telephone companies' Operation Administration and Maintenance (OA&M) processes are described. This includes the description of the automated testing systems and their relationships with the single-ended loop characterization. Chapter 2 ends with a discussion of transmission fundamentals. These include the characteristics of voice signals, the insertion loss (IL) function, the frequency response, and the impedance mismatch in a transmission system. Then the two-port network analysis methods are introduced where ABCD parameters are primarily discussed.

In chapter 3, we formulate the objective of this thesis as an optimization problem to determine the optimum parameter models for insertion loss estimation. The termination model as well as the set-up of the initial guesses, the set-up of the constraints are discussed in detail.

In chapter 4, results of the insertion loss estimation using the optimization approaches described in chapter 3 are given. Besides discussing the results given by the three proposed optimization approaches, namely the on-hook, off-hook, and the combined on-hook and off-hook approaches, some simpler estimation methods are also described. An approach is also proposed to allow for using these results to estimate the insertion loss at other frequencies with the same accuracy. This makes the proposed model valid for the whole voice range. The effects of measurement errors on the insertion loss estimation is also given.

Chapter 5 gives the conclusions of the entire thesis as well as several suggestions for future work.

2. Telephone Networks

This chapter starts with a general review of current telephone systems. Next, the topic of special services is introduced and the most common special services offered by the telephone companies (telcos) are summarized. The loop systems that support the special services such as the Digital Loop Carrier (DLC) system, and the Carrier Serving Area (CSA) loop design concepts are discussed. The Operation Administration and Maintenance (OA&M) processes for these special services, such as using the automated loop testing systems are discussed. The objective of this review is to introduce the reader to current telephone systems and the need for improved automated loop testing systems. Addressing that need is the subject of this thesis. Chapter 2 ends with a discussion of transmission fundamentals and modelling of transmission lines.

2.1. Telephone System Overview

Speech is the most common form of communication. People can also communicate with other forms, e.g. hand signals etc.... At several miles apart, the primitives used audio or visual signals, e.g. hitting the drums or setting up the fire to communicate. Today, if two people wish to achieve a distant point-to-point communication, an obvious choice is the telephone. Unlike the primitives who used drum and fire signals, today's telephone systems use electrical signals in analog and/or digital form, optical signals are also deployed for the latest technology. The

differences between the primitives' methods and today's methods are that today's telephone communications are very reliable, accessible, and the formats of messages are very user understandable -- speech, words through terminals or even the image of the caller is shown. Today's telephone system supports millions of users. It is not surprising that new technologies have to be developed to satisfy the seemingly unlimited demand.

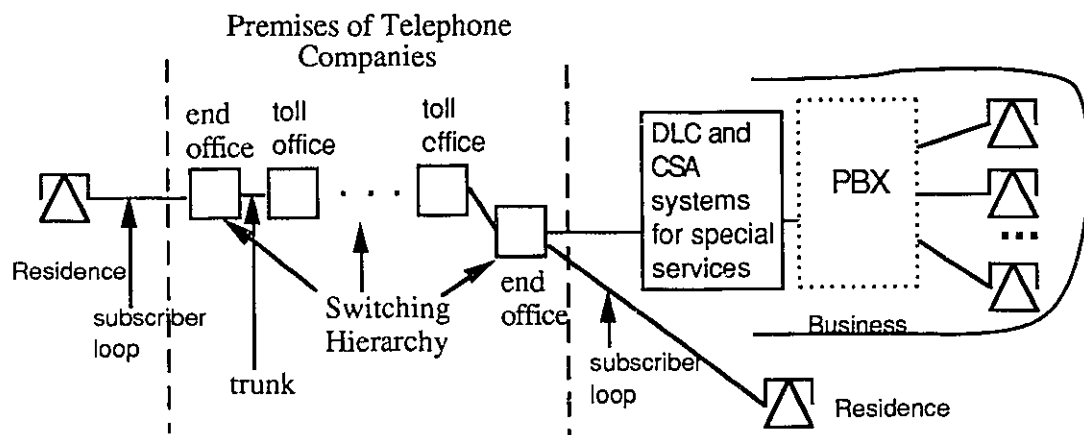


Figure 2.1 A simplified connection of a telephone system.

Note: A CO is called an EO (end office) if the CO is connected to the local loops, or the DLC and CSA systems.

Legend: DLC = Digital Loop Carrier; CSA = Carrier Serving Area

A simplified connection of a telephone system is shown in Figure 2.1. Depending on the case, the service required can be a simple connection to an end office (EO) (special services deploy the DLC system and sometimes CSA loop system to improve provisioning and maintenance of the services). Additional functions can be added on top of the basic line services, e.g. touch-tone, long distance discount packages, Bell Canada's invisible answering machine etc, with additional service charges. A small business can install a Key Telephone System (KTS) to allow several telephone stations to access the shared public lines. Government offices, universities and large corporations can install a fully functional Private Branch

Exchange (PBX) or Centrex system. Inside the two dotted lines is the telco premises where all the switching, routing, and special features are performed to serve the customers. The goal of a telephone company is to provide customers guaranteed access (low percentage of blocking) and satisfactory services.

This section will describe the telephone system starting from the user's end and proceeding to the CO switch. The DLC and CSA systems are discussed later in the special services section.

2.1.1. Telephone Set

When a caller picks up the telephone handset, the EO sends a dial tone to the caller via the dedicated subscriber loop. The caller then dials the number of the destination. Depending on the area called, the call can be routed through different COs and connected, if successfully, to the callee.

Once the call is successfully connected, the users start their conversation. Their speech vibrates the air in the form of waves and reaches the transmitter of the telephone set. The transmitter, composed of a vibrating diaphragm, carbon granules, and electric contacts, convert the sound waves to electrical signals. Depending on the loudness and the pitch of the person talking, different sound waves result. The vibrations apply pressure on the carbon granule and conduct electrical current according to the pressure¹. At the receiving end, the receiver of the telephone set converts the electrical signals back to the sound waves. The receiver of a telephone set composed of a voice coil and a vibrating speaker cone. The voice coil vibrates the

¹ If more pressure is applied to the carbon granules, they tend to squeeze together more tightly hence conduct electrical current better. If less pressure is applied, the granules move apart, and they will not conduct electrical current well. This is how alternating current is generated in the telephone set.

vibrating speaker cone according to the current that flows through it, and the sound waves are regenerated to the user.

2.1.2. Loop Signaling

A station set² is physically connected³ to the EO via the subscriber loop. The EO uses the Common Battery Operation [AT&T 77-v1] to supply a -48 V D.C. $\pm 4V$ to the subscriber's station set.

When a station set is on-hook, the loop is effectively terminated by the ringer of the station set. The on-hook DC resistance has to be larger than 5 M Ω , such that minimal or no current is drawn at this state [FCC 90]. Also the in-band⁴ on-hook impedance is high as described in [AT&T 52] and [EIA-470-A] for mechanical and electronic telephones respectively. The characteristics of those sets will be described in detail in chapter 3.

When a station set is off-hook, the loop is connected to the transmitter and the receiver of the station set. The EO sends a dial tone to let the caller know that it is ready to accept a call. The conventional dialing uses dial pulses where each number is assigned to a number of continuous pulses. Today, Dual-Tone-Multi-Frequency (DTMF) or Touch-tone, the trade name of Bell System, replaces most of the conventional dial pulse system. In DTMF, each digit is assigned two in-band frequency tones for a 12-button keypad as shown in Table 2.1 [AT&T 77-v1]. Touch-

² A station set indicates any kind of termination at the customers' premises. We normally refer those station sets as telephone sets.

³ There is also wiring inside the premises but this is insignificant compared to the outside wiring.

⁴ We define the in-band frequency from 200 Hz to 2800 Hz although the range can vary for different circuitries.

tone allows faster connections up to 10-15 times compared to pulse dialing as well as providing extra functions to the telephone service, e.g. touch-tone registration for courses, remote retrieval of messages from a voice message machine etc.

Table 2.1 A 12-button keypad dual tone assignment.

697 Hz	1	2	3
770 Hz	4	5	6
852 Hz	7	8	9
941 Hz	*	0	#
	1209 Hz	1336 Hz	1477 Hz

Once a number is pressed, two tones generated by two oscillators are sent to the EO. The caller will then receive one of the following messages from the EO: 1) a ringing signal -- when the CO has completed the call connection and the callee's telephone set is ringing, 2) a busy signal -- when the callee's telephone set is busy, 3) congestion signal (fast busy signal) -- when the CO trunks are busy.

If a call is connected and the callee picks up the phone, an off-hook signal is sent to the EO and it stops sending the ringing signals to the caller. When the call is finished, "hang-up" signals are sent to both the EOs and the circuit is disconnected. In case of long distance call, the callee's off-hook signal and the "hang-up" signals from both parties signify the start and the end of toll charges respectively. If a party does not hang up the handset properly, a combination of 4 tones is sent to the party with a relatively loud amplitude to alert the user.

These are the signals that the CO normally operates to communicate with subscribers. In plain old telephone service (POTS), these signals are transmitted in the same copper pair as the voice messages. For special services, Common Channel Signaling is generally used. This signaling scheme uses reserved loops to set up

telephone calls. Its advantages include: reducing the call set-up time, and freeing up the loop while connection is attempted [Rowe 91].

2.1.3. Switching Hierarchy of COs

In the old telephony era, telephones were fully connected to all users. This involves $N(N-1)/2$ dedicated loops for N users such that each user can communicate with the other $N-1$ users. This connection topology is obviously not practical for large number of users. Switching machines were used to solve the problem. Today's switching networks involve hierarchical structures. Different classes of switching COs are given in [AT&T 77-v1-Figure1-3]. According to this classification, the COs that terminate the local customers' loops are called the end office (EO). For switchings involving more than local switches, toll centers, primary centers, sectional centers and regional centers may be required. More details about the functions of these switching centers can be found in [AT&T 77-v1].

Bell System uses a North American Numbering Plan which consists of a 3-digit area code called the Numbering Plan Area (NPA) code and a 7-digit telephone number. The first 3 digits of the 7-digit telephone number represent the local exchange code and the last 4 digits identify the line number of a subscriber.

Depending on the density of a serving area, a local CO switch in a CO building may serve several miles of distance. Conversely, in a high density of telephone populated area, a local CO switch may serve 4 to 5 exchanges. It is common to have a CO building possessing multiple local CO switches and each switch serving multiple exchanges in a large metropolitan area.

A local call can be routed inside the same EO, if the EO serves the two customer's exchange number(s). If not, the call can be routed directly to the callee's EO through the direct connections of the 2 EOs or through a tandem (switching office

serves as connection purpose only) to the callee's EO. Otherwise a higher level of switching office is involved.

The routing algorithm is based on the shortest path approach. For long distance calls, AT&T proposed the Dynamic NonHierarchical Routing (DNHR) where the goal is to route a call at a maximum of 4 toll offices [Rowe 91]. Due to the traffic capacity of a CO, some incoming calls are blocked, and the shortest path approach is violated. A second shortest path is sought. If this is not found, a fast busy tone will indicate that the call is blocked.

2.1.4. CO Facilities

The medium for CO to CO communication can be copper pairs, coaxial cables, microwave radio, satellite link or optical fibers. Most subscriber loops are single-channel, while CO trunks are multiple-channel. Frequency multiplexing and time multiplexing allow multiple channels to be transmitted simultaneously on a cable pair. Analog signals are multiplexed in frequency domain, and the technique is called the Frequency Division Multiplexing (FDM); whereas digital signals are multiplexed in time domain, and the technique is called the Time Division Multiplexing (TDM).

An analog voice signal is bandlimited to 4 kHz. Twelve bandlimited analog voice signals are multiplexed to form a 12-channel 48 kHz bandwidth (BW) base group. Five base groups are multiplexed to form a 60-channel 240 kHz BW super group. Ten super groups are multiplexed to form a 600-channel 2400 kHz BW master group. A voice signal may be modulated and demodulated several times before it reaches the destination. As a result, the CO trunks are used efficiently.

As the digital technologies are becoming more popular, most analog carrier systems are replaced by the digital carrier systems. T1 carrier is commonly used in the digital switches. The incoming analog voice signals from a subscriber loop are first sampled into their corresponding discrete signals. The discrete signals are then

quantized linearly or nonlinearly to digital codes(Pulse Code Modulation PCM⁵). One T1 line can transmit 24 channels of these codes simultaneously. A bandlimited 4 kHz voice signal needs a rate of 64 kb/s (8 bit data x 8000/s sampling rate) to avoid aliasing. The 24 channels of codes are scanned by a rotary switch in sequence (8 bits at a time) and transmitted in a fixed time slot to the receiver end. At the receiver end, another rotary switch distributes each channel values to the appropriate terminal circuits as shown in Figure 2.2.

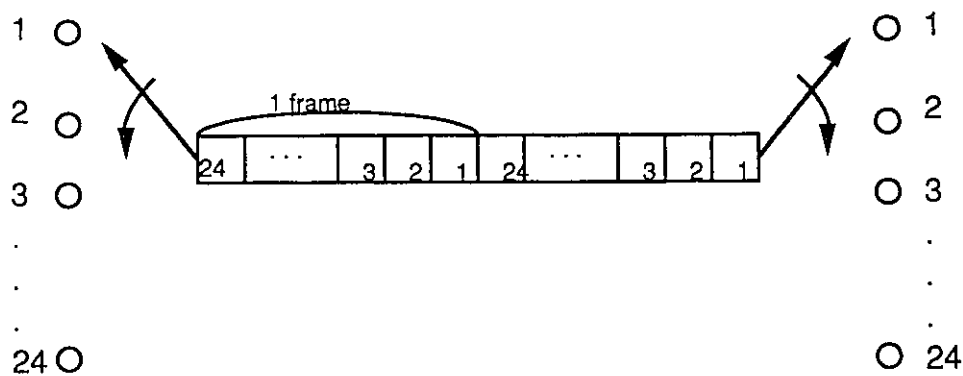


Figure 2.2 A schematic diagram for Time Division Multiplexing (TDM)

Due to the extra bits needed for signaling, the transmission rate of T1 is 1.544 Mb/s. Several T1s can be multiplexed to form T2, T3 or T4. In higher level, like T3, microwave or optical transmission is necessary for the high transmission bandwidth.

Besides circuit-based TDM switching, recently packet-based Frame Relay and Asynchronous Transfer Mode (ATM) transmissions are widely considered to support the broadband transmission.

⁵ Other digitizing techniques are also used, e.g. Differential PCM, Adaptive PCM and Delta Modulation (DM) etc.

2.2. Special Services

In the last section, we discussed briefly current basic telephone systems -- a subscriber can simply pick up a telephone handset, dial the number of the callee, and the telephone company will do the rest -- signaling, setting up the connection, supplying the power for the conversation... etc. Two classes of services are provided by a telco: 1) Plain Old Telephone Services (POTS), the basic telephone service for residential, coin, and basic business services. 2) Special services, primarily for business customers, government, and universities etc. This section describes the typical special services offered by a telco.

A large portion of telcos' annual revenue is earned from the special services. These services include terminals, channels, and network usage, support both voice and data services. They are facing rapid changes as a result of new technologies and competitions from other by-passes⁶. To maintain a high level service, new services and maintenance of existing services should respond to the present problems and future needs.

Residential, basic business, and coin telephone stations are the majority of POTS. These stations are connected directly to the serving central office (or end office) where ordinary telephone services are provided. No further treatments to these services are expected from the telephone companies. The special services, on the other hand, provide service capabilities beyond those ordinary telephone services. Services found in big business customers, government, and universities such as PBX and Centrex providing internal networking power, private lines providing direct connections to the servers, etc, are only offered by special services by telcos. Because these services are more complicated than POTS, the transmission and the quality requirements for these services are high.

⁶ Telecommunication services provided other than telcos.

To satisfy these requirements several strategies are used in special services. First, the customers' stations are directly connected to the DLC systems, and more generally, the loop portion deploy the CSA loops. The transmission quality using these systems is improved significantly. Second, the design for each special-service circuit is per line basis, i.e. the engineers design the loop and the electrical circuits (gain adjustments, balancing networks, etc) for each special service requested. Third, there are further engineering considerations such as circuit surveillance, maintenance etc... for these special services.

Special services can be either switched or nonswitched [Bellcore 91-v3]. If they are switched through the message network, they can be public switched or private switched; if they are not switched through the message network, they can be dedicated private line. Also, several special services can be interconnected together to form a network, such interconnection can provide many extra features.

2.2.1. Public Switched Services

911 service involves direct switching from the caller's exchange to the 911 stations, such that a dispatcher can send the police, fire, or medical help in the shortest time to the caller. To further reduce the time to identify the caller, the enhanced 911 (E911) can identify the name and address of the caller once a call is received.

It is often that a metropolitan area is served by more than one exchange carrier, such that some calls may need toll charges. An example is that of a call from Kanata to Orleans in the Metropolitan Ottawa area. The telcos offer the Foreign eXchange (FX) service which from the above example recognizes the caller in Kanata as an Orleans user, such that the toll charge between these two counties can be saved.

If a business has frequent customers in different regions, the Wide Area Telecommunications Service (WATS) allows this business to make calls to selected geographical regions for a fixed monthly charge. A familiar service is the inward 800/WATS which, for example, allows callers in the Eastern Ontario region to make complaints to the government. The WATS can be extended to out-going calls only and the Inward/outward two-way calls.

Off-Premises eXtension (OPX) and secretarial services both have an extension line added to the main station at CO. The difference is that the former one is extended to another station set whereas the later one is extended to a telephone answering service. Special steps should be made to isolate the main loop from its extension loop when maintenance is performed.

Voice band data and digital fax can also be supported by the local loops. Depending on the data rate required by the subscriber, conditioning may be needed with an associated tariff rate.

2.2.2. Private-Switched Services:

Private-switched services are a very important type of special services because they are suitable for any size of business. A small business can deploy an increasingly popular small PBX system called Key Telephone System (KTS) while a medium size to large size business can deploy the standard PBX or Centrex systems. These private-switched services account for a large portion of the total special services' revenue.

There are two types of private-switched services, the PBX and the Centrex systems. A PBX system interconnects station sets and terminals inside the customers' premises while Centrex provides the private switching system through the CO switching.

The idea of PBX is to allow the customer to own a self-contained switching system where most of the communication is internal. It is often not economical to have each telephone connected to the CO especially when the connection is several miles away. Using a PBX, a company can gain more control on its network, decrease the reliance on the CO operators and reduce the connection cost to CO.

To protect the telcos' public network revenues, Centrex is offered to compete with PBX. In order to be competitive, CO manufactures are focusing on increasing the power of Centrex to make it equivalent to PBXs.

The features of Centrex and the PBXs are quiet similar [Bellcore 91-v3], [Goleniewski et al 92]. They allow a variety of functions to be accessed by a user. For instance, a call can be made inside or outside the premises with or without the help of attendance and an outgoing call can be restricted (such as long distance calls) for billing purpose. Built-in functions such as call waiting, call transfer, and voice answering services are becoming standard; and the set-up of conference calls for a number of people is possible. These are only a few of the services offered.

However the biggest advantages are achieved when Centrex or PBX stations are interconnected together to form a huge private-switched network. Such connections strengthen the networking power within a private enterprise. Voice and data can then be multiplexed together. Higher bandwidth transmission are also possible. Because the service involves multiple circuit connections inside the network and access to the switched message network, very stringent standards are necessary. Examples of these interconnected private networks are the Electronic Tandem Network (ETN) and Switched Services Networks (SSN) [Bellcore 91-v3].

2.2.3. Private Lines

Private lines are dedicated lines involving no connection to switched message network. Channels are generally used for voice, voice band data (includes signaling), and higher bandwidth transmission (voice-data-voice network) etc. Since private lines are common for point to point and multi-point (several users connected together) communications, four-wire transmission is more desirable. This is because singing and echo produced by two-wire systems degrade considerably the multi-point communications, return loss and other measurements are often necessary. For multi-point lines involving large number of stations, a four-wire system is the only choice.

As examples of private lines, we recall dedicated lines from 911 stations or private firms to the police, fire, and fire stations. These lines provide immediate connections because there is no call setup time, no traffic blocking, and the emergency service being used knows exactly where the call originated [Bellcore 91-v3]. Other applications include lines for fire and burglar alarms, higher speed channels for studio to transmitter links, one-way television broadcast network, and high-capacity digital service.

2.3. Subscriber Loop

A loop is the physical connection between a customer's premises and the local CO. More than a decade ago the number of dedicated metallic subscriber loop pairs was estimated at about a hundred million in United States [Snelling et al 86]. This huge loop plant constituted half of telcos' capital investments. Similar investments are likely to continue today. The Operating Administration and Maintenance (OA&M) costs for these loops are growing rapidly. Half of the budget for the network expenses is reserved for these costs. Proper planning of new loop plants and reusing the existing loop plant efficiently are major concerns for operating companies.

General loop surveys were conducted in 1964, 1973 [AT&T 77-v3], and 1983 [Bellcore 91-v3]. For each loop survey, over 2000 loops were randomly chosen from each main station in the United States. The results show that early loop-plant planning was not systematic. The longest loops in the 1983 loop survey were over 114 kft. These long loops are difficult to be re-engineered to support any digital service or special service. More importantly, these long loops are very expensive to maintain. However, the majority of the loop population is relatively short as more than 90% of the loops were shorter than 20 kft. The average loop length was increasing in each of the last 3 surveys from over 10 kft to over 11 kft. The short loops were dominated by AWG 24 and 26. The AWG 22 became significant in the loop population for loops that were longer than 15 kft. The loop population was completely dominated by AWG 19 and 22 for loops longer than 25 kft.

Due to the large variation of loop lengths and the existence of long loops, the provisioning, administration, and maintenance of the loop system are extremely difficult and expensive. To limit the cost, existing long loops are sectioned while new loops are designed to meet new standards. In these schemes, the loops are more controllable. These loops become more manageable from a provisioning and maintenance point of view using today's automated loop testing systems.

This section primarily discusses two important classifications of loop systems, the DLC system and the CSA concept.

2.3.1. Digital Loop Carrier (DLC) Systems

Digital Loop Carrier (DLC) systems were first used on long, rural subscriber routes to avoid long runs of expensive coarse-gauge feeder relief cables [Bellcore 88] -- they were used as an economical substitute for new cables and structure placements on feeder routes [Greco et al 81].

Early loop designs were based on resistance limits [AT&T 77-v3]. For loops shorter than 18 kft, two finest consecutive standard gauge loops are connected such that the total loop resistance is less than 1300Ω . It is more economical to place the finer gauge cable closest to the CO. For loops longer than 18 kft, loaded cables were used. Later, a revised resistance design concept was given [Bellcore 91-v3]. In this design, loops between 18 and 24 kft long are left unloaded, however the resistance boundary is relaxed to 1500Ω . The DLC loops can follow the conventional 18 kft design or they can add the revised resistance design, but the DLC loops are never loaded.

A DLC system which is shown in Figure 2.3 consists of the Central Office Terminal (COT) (needed only when CO switches are analog), the Remote Terminal (RT), and the Feeder-Distribution Interface (FDI). They are administrated and engineered in two segments, feeder facilities and distribution facilities. Distribution cables are typically short. Individual subscribers are linked with distribution cables which are cross connected with the derived cable pairs at the FDI. The derived pairs or the DLC loops, are terminated at the RT. Early DLC systems had one RT at one site serving one FDI. When DLC systems were extended to densely populated urban area, multiple RTs at a single site have provided facilities to several FDIs. Such an installation scheme requires a higher transmission rate between COs and RTs. Very often, optical fibers are used.

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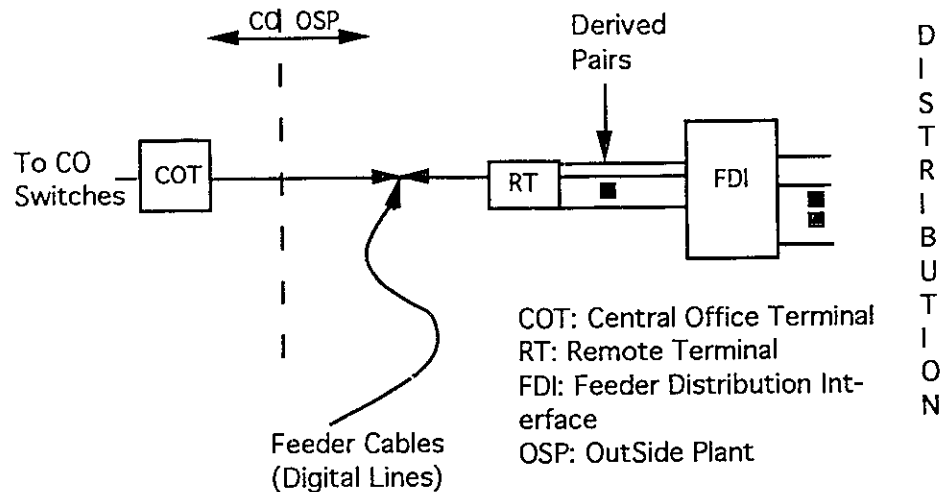


Figure 2.3 Standard DLC system

Deploying DLC systems for special services over the conventional loop system has many advantages. The customers' access lines are significantly shorter, and they are closer to the COs. The implications are: 1) The transmission constraints associated with copper facilities are reduced, hence special treatment for these circuits can be reduced; 2) More versatile special services can be implemented because the provisioning and maintenance of these services are more easily controlled.

For digital services, provisioning these services over the existing loop plant without DLC systems requires conditioning. The conditioning includes removing loading coils and excessive bridged taps. Repeaters are often required. The time elapsed for a service request can run up to several weeks or months. With DLC systems, a service request reduces to choosing the plug-in cards at the RTs or COs. The time elapsed is less than a week⁷ [Greco et al 81], [Byrne et al 82].

Today's DLC systems can result in substantial cost saving because of the popularity of digital switches and the advances in electronic technologies. In the old

⁷ This was estimated in 81 by [Greco et al 81].

CO environments when analog CO switches were dominant, central office terminals (COTs) were used as the interface to convert digital signals received from RTs to analog signals used by CO switches. This is known as the Universal Digital Loop Carrier system. The digital time division switches eliminate the need for COTs and the unnecessary D/A conversion. A direct digital connection can be made between CO and RT. This is known as the Integrated Digital Loop Carrier system. The elimination of COTs results in reduction in CO costs because battery, ringing, and supervision functions are required in RT only. Since digital switches are also less expensive than analog switches, the total cost is reduced when using Integrated Digital Loop Carrier system making it very attractive to the telephone companies [Greco et al 81], [Connolly 88].

Cost reduction in electronic technology and cables has dropped the per-line cost of DLC systems by a factor of 5 or more compared to their cost at their inception in early 70s [Snelling et al 86]. Progress in VLSI and micro-processor technology has reduced the operating cost of conditioning and provisioning of telephone services hence the labor-related cost in the loop portion has been reduced by as much as 50% [Andrus et al 86]. Due to these economical factors, the DLC systems have been deployed in heavily populated urban areas. Subsequently, DLC systems are deployed closer to CO, and the network becomes more flexible and adaptable to new services. The DLC systems which were primarily designed for the Message Telephone Network (MTN) are now handling a wide range of special services and digital services, e.g. Centrex lines, WATS services, voice band data transmission, and 56 kb/s digital data etc [Bellcore 88].

2.3.2. Carrier Serving Area (CSA)

Due to the increasing use of DLC systems and their abilities to provide new services, a more systematic approach to deploying DLC systems, the Carrier Serving Area (CSA) concept, was introduced. The concept of CSA was suggested to provide the most restrictive digital service at that time (56 kb/s) over loop with no repeaters. The maximum loop length of AWG 22, 24, and 26 that can be used to successfully transmit data at different rates without involving repeaters is given in [Byrne et al 82]. The maximum length for these cables for a data rate of 56 kb/s was found to be over 12 kft. Because the CSA concept considers a more stringent standard and takes into consideration of degradations that can occur in the distribution plant, the CSA rules confine the maximum length of AWG 26 to 9 kft, and AWG 22 and 24 to 12 kft. CSA loops are required to meet the following requirements [Bellcore 88]:

1. Only nonloaded cables can be used.
2. Multi-gauge cables are restricted to two gauges (excluding short cable sections used for stubbing or fusing).
3. Total bridged tap length may not exceed 2.5 kft. No single bridged tap may exceed 2.0 kft.
4. 26 gauge cables (used alone or in combination with another gauge cable) may not exceed a total length of 9 kft including any bridged tap.
5. For single gauge or multi-gauge cables containing only AWG 19, 22 or 24, the total cable length including bridged tap may not exceed 12 kft.
6. The total cable length, including bridged taps, of a multi-gauge cable that contains 26 gauge cable section may not exceed $12 - \frac{3(L_{26})}{9 - L_{BTAP}}$ kft, where L_{26} is the total length of AWG 26 in the cable (excluding any AWG 26 bridged tap) and L_{BTAP} is the total length of bridged tap in the cable. All lengths are in kft.

To apply CSA concept to the DLC systems, the conventional resistance design rules used for DLC loops are replaced by the CSA concept⁸. Because the loop length is further controlled and limited, the CSA concept improves the provisioning and maintenance of the digital services and the voice grade special services. The design of line units for CSA loops does not require option adjustments. Remote terminal (RT) in DLC systems can pre-equip these line units in bulk. Since these line units require no adjustment, the line circuit can be assigned in a fashion similar to POTS, where the usual special service design process is avoided [Bellcore 88].

The copper wire based CSA concept has been extended to its fiber based counterpart, Fiber Serving Area (FSA), to ensure a systematic approach to layout fiber in the outside plant [Karia et al 86] in the future.

Due to the lack of availability of CSA loop survey, we designed 56 CSA loops (given in appendix A) to satisfy the CSA requirements using the information of the general loop survey discussed in section 2.3. Loop series 14-23⁹, A, C, E, and F are arbitrarily designed to cover all possible CSA loops in the loop plants. Loop series B and D are designed according to general loop survey described in section 2.3. All the loops in these two series, when first extracted from the loop surveys, were over CSA limits. Loops in series B were designed by scaling down to CSA limits; while loops in series D were truncated to meet the CSA standards. This 7 series loop data base is used extensively for all the estimation methods described in chapter 4.

⁸ A detail CSA configuration is depicted in fig. 3 of [Byrne et al 82].

⁹ This loop series was originally designed by one of the co-workers in BNR. The loops were numbered from 1 to 23. We adopted 8 loops between loop #14 to loop #23 and named the loop series as 14-23.

2.4. Operation Administration and Maintenance (OA&M)

The objective of the maintenance service is to detect, adjust, and repair failure and substandard transmission circuits in the shortest time interval. Often, corrective action is taken before the problem is noticed by the customers. Maintenance activities include preparing new services (involves testing, gain adjustments etc), filing trouble reports, locating source of trouble, repairing and/or adjusting the circuit parameters to maintain the high transmission performance, removing failed circuits from service, performing record-keeping and administration procedures, and circuit surveillance, etc [Bellcore 91-v2], [Bellcore 91-v3].

Depending on the type of services, circuit surveillance can be continuous monitoring, periodic testing, or no surveillance (POTS). Continuous monitoring and periodic testing are possible because of the latest automated testing systems.

The conventional testing involves the coordination of two technicians, one transmitting test signals at one end (possibly EO) and the other receiving the signals at the other end (possibly customer end). This is a time consuming procedure, and is difficult to schedule efficiently because two technicians must be available simultaneously. The latest automated testing systems allow one person to perform automated testing remotely in a testing center. The testing center, called Facility Maintenance and Administration Center (FMAC), Automated Repair Service Bureau (ARSB), or Special-Services Center (SSC) for special services, centralizes circuit maintenance for a large geographic area. These centralized maintenance centers are capable of making all necessary measurements, including analog insertion loss, gain slope, echo return loss, singing return loss, C message noise, and impulse noise etc, by one person [Bellcore 91-v3]. However, these systems require large data base to store all information required such as the loop make-ups. The information stored in the system can be several years old and may not reflect the real loop conditions.

The situation would be better if optical fibers were used. However, due to the huge capital investment in copper wires, a more realistic approach is to strengthen the existing metallic loop plant by introducing advanced automated maintenance systems which will speed up the services and control the loop related network problems and expenses [Boulter et al 86], [Snelling et al 86], [Chagnon et al 86], and [Lau et al 86].

The inefficient manual maintenance methods used in the early stages are obsolete. Telephone companies like AT&T use automated testing machines like the Mechanized Loop Testing (MLT) system, the Switched Access Remote Test System (SARTS), and the Centralized Automatic Reporting on Trunks (CAROT) system to service the loops and trunks for both POTS and special services [Andrus et al 86], [Helsing et al 84], [Bellcore 86], [Plato et al 83]. To fully mechanize the testing systems, a large data base system [Fleckenstein 82] and an efficient system for the flow of information [Feuster et al 84] are required. Live call testing is one additional option to obtain some instant measurements by talking to the customers [Sutton et al 86], [Bell Lab 84]. However, those stand-alone systems are labor-intensive because many documents and decisions have to be handled manually. This is time consuming and expensive. Workflow automation integrates and mechanizes the manual operations, thus speed up the process [Mortensen 91], [Keathley et al 92].

2.4.1. Automated Testing Systems -- Bellcore Model

Bellcore has proposed an open architecture called Bellcore Model which allows different vendors to build their test equipments, and to interface them with the system using Transaction Language 1 (TL1) [Mortensen 91], [Sims 90]. This is shown in Figure 2.4. A typical automated testing system consists a data management system and the computerized testing systems. The testing is performed, for special services

in our case, in a centralized testing center called the Special-Services Center (SSC). The testing equipments in a CO are remotely controlled by the SSC.

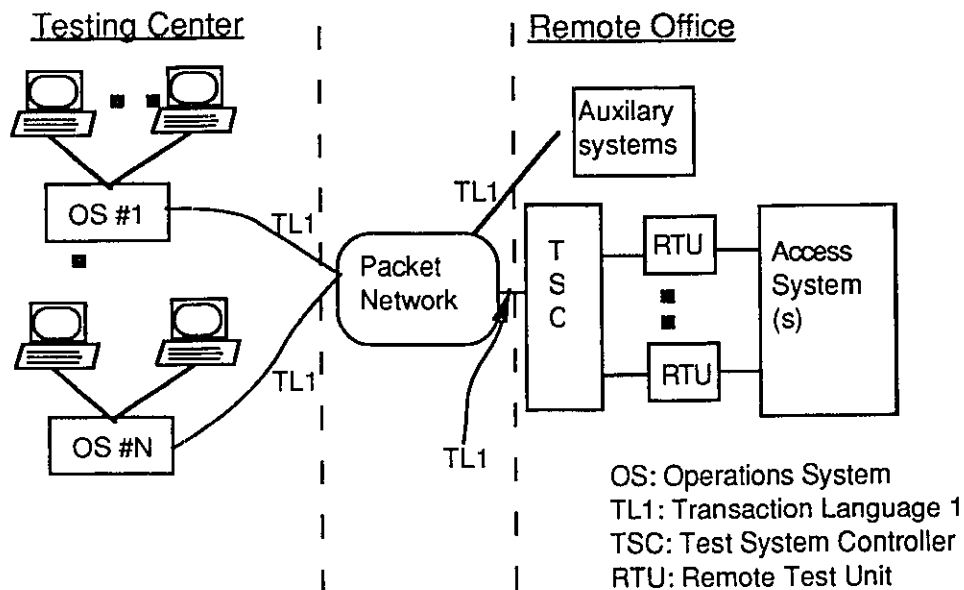


Figure 2.4 Bellcore Model

The Bellcore model lets planners tailor systems by allowing them to use equipment from different vendors. The heart of the model is the test Operations System (OS), the communication language -- Transaction Language 1 (TL1), the Test System Controller (TSC), the Remote Testing Unit (RTU), and the access system.

The test OS is a multi-user computer system. It can access a data base, e.g. the Loop Maintenance Operation Systems (LMOS), which contains all circuit related information (line record, maintenance record etc) for a test¹⁰. The test OS also transmits a circuit access request along with the circuit information to the remote

¹⁰ The full line record information is important because certain tests cannot be carried out if such information is not available [Bellcore 86].

office via a packet network. TL1 functions as an interface which allows different vendors' OSs to control different vendors' TL1-compatible remote test systems.

In the remote office, TSC manages RTUs, access systems, and other auxiliary systems. Knowing the resources available in the remote office, TSC assigns appropriate RTUs and access systems to a particular test request. While the access systems provide all the physical connections to the loops, RTUs perform all the required testings.

The system described above is fully mechanized. Both RTUs and TSC support remote administration. Change or modification of any code, password, or site dependent data base for these units is done through the operators in SSC.

2.4.2. Automated Work Flow

As mentioned earlier, current maintenance and installation operations are labor intensive and expensive. Although the loop testing systems are fully mechanized as described by the Bellcore's open architecture model, this approach involves several manual operations in the early stages. These slow down the entire process and proved to be very expensive. Due to the rapid growth of the special services, testing and provisioning of these circuits become more complicated. Adding personnel is not a viable solution. An automated work flow operation is needed to solve the above problems [Keathley et al 92], [Mortensen 91].

A software called the Automated Network Services Workflow Resource (ANSWR) was developed by Hekimian to integrate Southwestern Bell's Automated testing and Analysis System (ATAS) with its Work Force and Administration (WFA) [Keathley et al 92].

Trouble reports and pre-service testing requests, etc, are filed by operators, and tickets are generated in WFA. ANSWR scans WFA for these tickets. A test strategy is selected based on the type of trouble reported by the customer, and the

type of tests required -- installation or maintenance. Different SSCs have different test strategies, and they can be changed relatively easily -- by changing the codes of ANSWR. ANSWR performs a series of testing procedures. Depending on the outcome of the preliminary results, further actions are decided by ANSWR -- more tests may be performed by the testing vehicle, or technicians are dispatched to the outside plant etc. AT&T's Auto Test-2 [Mortensen 91] is similar to ANSWR. Auto Test-2 has an expert system to enhance its test strategies. This expert system has collected the information from many testers' feedback, observation, and experience for the past few years. The system is integrated into its Switched Access Remote Test System's (SARTS) software without expensive, specialized hardware.

2.4.3. Single-Ended Loop Characterization and Automated Testing Systems

Single-ended loop characterization refers to the estimation of frequency response or insertion loss (IL) of a subscriber loop based on measurements from the CO only. The loss estimation for the special services is important because many circuit adjustments require this piece of information. Knowing the loss of a loop, the signal level of a new special service can be adjusted properly. After the circuit is put into service, maintenance is essential. Being able to use automated testing systems to monitor loss estimation allows continuous or periodic circuit surveillance to minimize problems.

The current testing algorithms require a large data base to store the circuit information. When a circuit is tested, the first information to be acknowledged is the loss of the loop. This information allows proper adjustments to the signal levels and settings to the equalization of the circuit. Other loop-parameter adjustments require the knowledge of the circuit configurations are the loop balance settings, far end return loss estimation etc... However a loop's circuit configuration that is obtained from the

data base is not always precise. The actual circuit performance is affected by the weather, storage condition, and age such that the circuit parameters vary all the time. The current approach often uses this unreliable data base. When the data base is not complete, due to the loss of records or no record on a circuit, estimation of circuit parameters has to be done. The single-ended loop characterization allows testing and adjusting a circuit's IL according to its current measurements such that the changes in circuit parameters are reflected in each new update. Other loop adjustments that depend on the channel response can be done properly.

There are major disadvantages for the conventional manual approach and the current automated testing systems. The old manual approach requires all measurements to be done manually, an extremely slow and labor intensive process. Maintenance requires at least 2 technicians working simultaneously. The current automated testing systems rely heavily on large volumes of data base. As special services growing rapidly, the volume of loop information required is constantly increasing. Also the accuracy of the loop information is questionable after a few years.

The objective of single-ended loop characterization is to address these problems. The system for single-ended loop characterization can be integrated into the current automated testing systems such that the dispatch of a technician (due to the incorrect estimate of circuit parameters and subsequently wrong decision) is reduced, the excessive data base is eliminated, and the estimation of the circuit parameters is more accurate.

2800 Hz is passed (300 to 3000 Hz is also possible). The signals in this range are called the in-band signals. The ranges between 0 to 200 Hz and 2800 to 4000 Hz are referred to as the guard bands which provides buffer areas to reduce interference with adjacent channels (Figure 2.6).

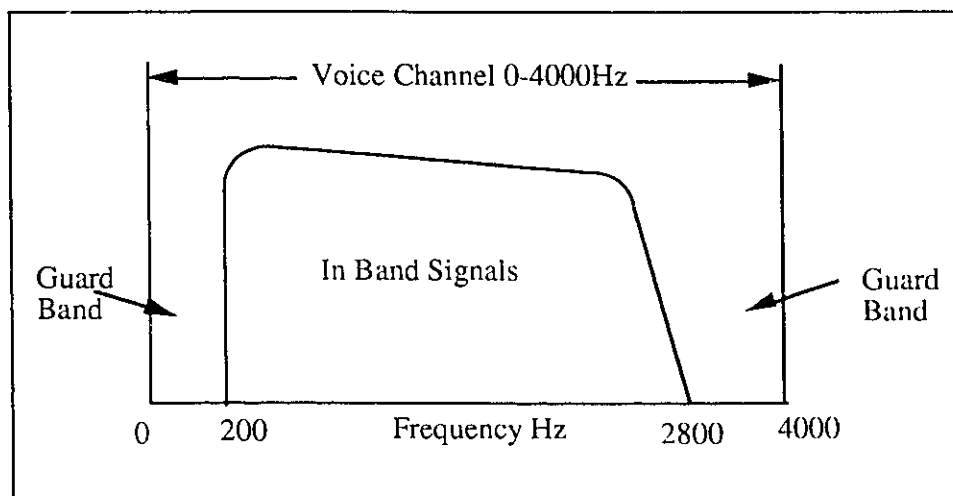


Figure 2.6 Frequency response of voice channel (0-4000 Hz).

In a telephone system, the transmission band for voice is defined as the frequency points at which the channel response is 10 dB down from a reference point, usually at 1000 Hz [AT&T 77-v1]. Hence 1000 Hz is the critical frequency for voice band transmission.

In the next section, we will discuss insertion loss, a common measure of possible channel impairments that could affect the quality and amplitude of voice signals transmitted over the channel.

2.5.2. Insertion Loss

Insertion loss is a very important function for evaluating the performance of a two-port network. If V_S in Figure 2.5 delivers power P_N to the load Z_L with the

network in place, and power P_O without the network, the insertion loss (IL) is defined as

$$IL = 10 \log \left(\frac{P_O}{P_N} \right) \quad \text{dB} \quad (2-1)$$

the insertion loss can also be expressed in terms of voltage ratio as

$$IL = 20 \log \left(\frac{|V_O|}{|V_N|} \right) \quad \text{dB} \quad (2-2)$$

$$IP = \frac{180}{\pi} (\phi_O - \phi_N) \quad \text{degree} \quad (2-3)$$

where IP is the insertion phase shift, and V_N and V_O are the amplitude of the signal voltage transferred to Z_L with and without the network in place, ϕ_N and ϕ_O are the associated phases.

The insertion loss function is particularly important to voice special services mentioned above. It describes the amount of extra signal loss if a system is inserted into a network. Because the special services have very stringent standards on its transmission requirements, such extra signal loss can easily degrade the service. It is thus necessary to determine this insertion loss function and compensate for it using equalization techniques.

The insertion loss can be attributed to two important two-port network parameters -- the frequency response of the channel and the impedance mismatch. These are discussed below.

2.5.3. Frequency Response

Transmission media such as twisted pair cables, and coaxial cables all exhibit lowpass characteristics. Figure 2.7 shows the frequency response $20 \log \frac{|V_O|}{|V_N|}$ (defined in eqn.(2-2)) for loop series A assuming standard 600 Ω source and termination impedance.

The characteristics of lowpass channels allow for no attenuation (or small attenuation) to its low frequency contents, while considerably reducing its high frequency contents. In Figure 2.7, loop 4a has 4 dB loss at 200 Hz, but 7 dB loss at 2800 Hz. Engineers have to control the degree of loss in a channel, otherwise a transmitted signal may be buried. Knowing the frequency response of the channel, engineers can equalize the channel characteristics by 'pulling' the frequency response curve back to, for example, the 1 dB vicinity. Recall that the task of this research is basically to estimate the unknown frequency response of the channel. This allows equalization and other circuit treatments to be applied to the channel.

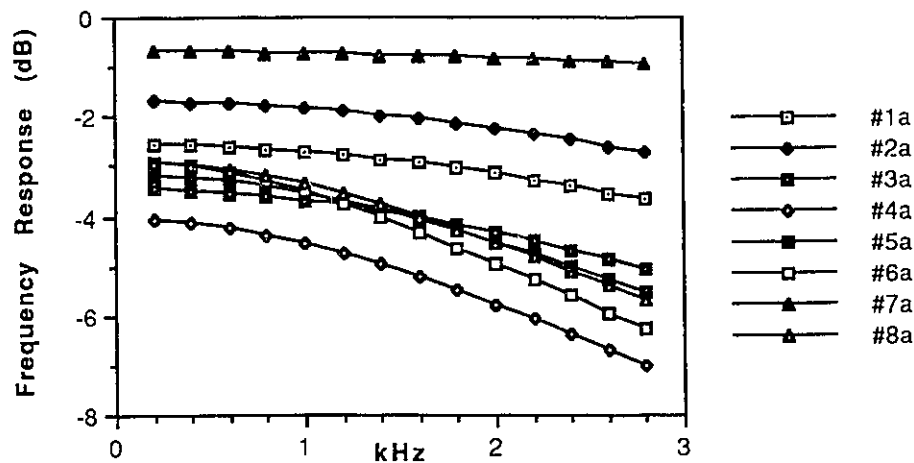


Figure 2.7 Lowpass characteristics of typical transmission channels at voice band.

Note : Here loop series A is used to represent the channels.

2.5.4. Impedance Mismatch

Impedance mismatch happens at the input port when there is a difference between Z_S and the network input impedance looking in from the input port. Mismatch can also happen when there is a difference between Z_L and the network input impedance looking in from the output port. The reflection coefficient (ρ) is a

measure of this mismatch. Referring to Figure 2.5, and assuming the two-port network a transmission line with output impedance Z_O' ,

$$\rho_S = \frac{Z_i - Z_S}{Z_i + Z_S} \quad (2-4)$$

$$\rho_L = \frac{Z_L - Z_O'}{Z_L + Z_O'} \quad (2-5)$$

where ρ_S and ρ_L are the reflection coefficients at the input port and at the output port respectively; and Z_i is the input impedance expressed in the next section as a function of ABCD parameters. This impedance mismatch results in smaller percentage of the transmitted power arriving at the load. This is usually referred to as return loss (RL) and expressed as

$$RL = -20 \log |\rho| \quad (2-6)$$

An alternate measure for the return loss is the echo return loss (ERL) given by:

$$ERL = -10 \log \left[\frac{\int_{f_2}^{f_1} |\rho|^2 W(f) df}{\int_{f_2}^{f_1} W(f) df} \right] \quad (2-7)$$

where f_1 and f_2 define the frequency range, and $W(f)$ is a non-negative weighting function given in [Bell Lab 82].

The return loss caused by the impedance mismatch can seriously affect the signal level at the output port. In some critical situations it can cause oscillations and destabilize the system [Bell Lab 82].

2.6. Circuit Analysis

2.6.1. Two-port Network Parameters

As mentioned earlier, transmission system is often described as a two-port network given in Figure 2.5. The characteristics of these two-port networks are often described by the input/output relationships or the appropriate transfer functions.

In Figure 2.5 there are four source variables at the two terminals of a two-port network, namely the $V_1(s)$, $V_2(s)$, $I_1(s)$, and $I_2(s)$ where $F(s)$ is the Laplace Transform of $f(t)$. From now on, it is implied that all functions are in the Laplace domain unless otherwise specified. A two-port network can be described by 2 equations in the general form:

$$U_1 = k_{11}W_1 + k_{12}W_2 \quad (2-8a)$$

$$U_2 = k_{21}W_1 + k_{22}W_2 \quad (2-8b)$$

where U_1 , U_2 , W_1 , and W_2 may be any of the voltage or current variables, and the k_{ij} s are the network parameters. There are various ways in which we can select two variables for U_1 and U_2 in eqn. (2-8). The six possible combinations are shown in Table 2.2.

Table 2.2 The six sets of two-port network parameters.

Parameter Type	Dependant Variables		Independent Variables	
	U_1	U_2	W_1	W_2
Open-Circuit Impedance (Z)	V_1	V_2	I_1	I_2
Short-Circuit Admittance (Y)	I_1	I_2	V_1	V_2
Hybrid (h)	I_1	V_2	V_1	I_2
Inverse Hybrid (g)	V_1	I_2	I_1	V_2
Chain (ABCD)	V_1	I_1	V_2	$-I_2$
Inverse Chain (ABCD)	V_2	I_2	V_1	$-I_1$

As an example, to obtain the open-circuit impedance (Z) parameters, eqn. (2-8) is rewritten as:

$$V_1 = z_{11}I_1 + z_{12}I_2 \quad (2-9a)$$

$$V_2 = z_{21}I_1 + z_{22}I_2 \quad (2-9b)$$

The Z functions can be obtained by appropriate choices of input functions and load termination. The system is then described by specifying z_{ij} , $i, j = 1, 2$ as:

$$\begin{aligned} z_{11} &= \left. \frac{V_1}{I_1} \right|_{I_2=0}, & z_{12} &= \left. \frac{V_1}{I_2} \right|_{I_1=0}, \\ z_{21} &= \left. \frac{V_2}{I_1} \right|_{I_2=0}, & z_{22} &= \left. \frac{V_2}{I_2} \right|_{I_1=0} \end{aligned} \quad (2-10)$$

One set of parameters is of particular importance in transmission analysis, this is the chain parameters or ABCD parameters. From Table 2.2, eqn.(2-8) is rewritten as:

$$V_1 = AV_2 - BI_2 \quad (2-11a)$$

$$I_1 = CV_2 - DI_2 \quad (2-11b)$$

To obtain A, port 2 is opened. Rearranging eqn (2-11a), we get:

$$A = \left. \frac{V_1}{V_2} \right|_{I_2=0} \quad (2-12)$$

A is obtained from its reciprocal to maintain the standard notation of always having the denominator as the source:

$$\frac{1}{A} = \left. \frac{V_2}{V_1} \right|_{I_2=0} \quad (2-13)$$

B, C, and D are obtained in a similar manner:

$$\frac{1}{B} = \left. \frac{-I_2}{V_1} \right|_{V_2=0} \quad (2-14)$$

$$\frac{1}{C} = \left. \frac{V_2}{I_1} \right|_{I_2=0} \quad (2-15)$$

$$\frac{1}{D} = \left. \frac{-I_2}{I_1} \right|_{V_2=0} \quad (2-16)$$

It is shown in [Huelsman 84] that the Z-parameter matrix for several networks connected in series is equal to the Z-parameter matrices added together to form a new Z-parameter matrix. For example, if two two-port networks connected in series have Z-parameter matrices:

$$Z_1 = \begin{bmatrix} s+5 & 1 \\ 1 & K_s \end{bmatrix}, \quad Z_2 = \begin{bmatrix} 3 & 3 \\ 3 & 3 \end{bmatrix},$$

the final Z parameters are:

$$Z = Z_1 + Z_2 = \begin{bmatrix} s+8 & 4 \\ 4 & K_s + 3 \end{bmatrix}$$

This is also true for the Y parameters: the Y-parameter matrices are added to form a new Y-parameter matrix if several networks are connected in parallel. For ABCD parameters, for a cascade of several networks, the final ABCD matrix is the product of the ABCD matrices in the cascading order. All 6 sets of parameters are readily convertible from one form to the other. [Huelsman 84 - Table 9-7.1].

The ABCD parameter presentation is natural for transmission analysis since transmission networks are normally cascaded stage by stage. Given the ABCD parameters of each stage, the overall characteristics can be obtained as the product of the ABCD matrices in the same order. Because the ABCD parameters are readily

applied to transmission system analysis, they are referred to as the transmission parameters.

As an example, consider the circuit shown in Figure 2.8

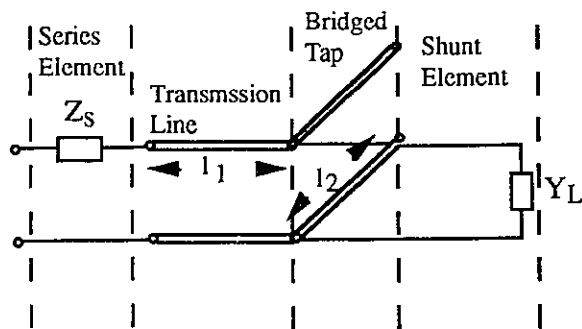


Figure 2.8 A sample circuit configuration that can be mapped easily onto the ABCD parameters.

This represents a typical transmission line with one bridged tap and termination Y_L . Consider the stages as shown in the figure, the overall transmission matrix is given by

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} A_3 & B_3 \\ C_3 & D_3 \end{bmatrix} \begin{bmatrix} A_4 & B_4 \\ C_4 & D_4 \end{bmatrix}$$

where $ABCD_1$ represents the source impedance section, $ABCD_2$ represents the transmission line section, $ABCD_3$ represents the bridged tap section, and $ABCD_4$ represents the termination section.

The representation of the series element for $ABCD_1$ and the shunt element for $ABCD_4$ can be found in [Huelsman 84], and the representation of the transmission line for $ABCD_2$ and the bridged tap for $ABCD_3$ can be found in [Bell Lab 82]. Substituting these values to the above matrix expressions, we have the final ABCD parameter:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z_s \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cosh \gamma_1 l_1 & (Z_{O1}) \sinh \gamma_1 l_1 \\ \frac{1}{Z_{O1}} \sinh \gamma_1 l_1 & \cosh \gamma_1 l_1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_{O2}} \tanh \gamma_2 l_2 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y_L & 1 \end{bmatrix}$$

where Z_S is the source impedance, Y_L is the load admittance, γ and Z_O are the propagation constant and the characteristic impedance of a transmission line section (both γ and Z_O will be discussed in the next section).

This method makes the analysis of transmission circuits using efficient computer coded programs possible. Examples are HOFF [Hung 81] developed by Bell Northern Research, and UNICCAP [DiBiasco et al 73] developed by Bell Telephone Laboratories.

Two-port network analysis is used to determine system parameters like input impedance (Z_i), output impedance (Z_o'), current transfer function (A_i), voltage transfer function (A_o), and insertion loss (IL) etc. These network functions are very important in analyzing a given transmission network. The input and output impedance are used to evaluate the mismatch of the impedance of the network at the source and at the load. Based on these impedance parameters, the efficiency of the power transfer can be calculated. The transfer functions and the insertion loss evaluate the response of the network that is inserted between the source and the termination. Proper gain can be adjusted to transmit sufficient signal to the load.

These network functions can be found in [Huelsman 84 - Table 9-7.1] and [DiBiasco et al 73]. The network parameters as functions of the ABCD coefficients are listed below:

$$Z_i = \frac{AZ_L + B}{CZ_L + D} \quad (2-17)$$

$$Z_o = \frac{DZ_S + B}{CZ_S + A} \quad (2-18)$$

$$A_i = \frac{1}{CZ_L + D} \quad (2-19)$$

$$A_v = \frac{Z_L}{AZ_L + B} \quad (2-20)$$

$$IL = 20 \log \left| \frac{AZ_L + B + (CZ_L + D)Z_S}{Z_S + Z_L} \right| \quad (2-21)$$

The above analysis is valid for low-frequency analysis. Other representations are used to describe two-port networks for high-frequency analysis because the required short and open circuit tests for the above parameters are difficult to achieve at high frequencies. Scattering parameters, for example, are used for microwave frequencies [Gonzalez 84].

2.6.2. Transmission Line Theory

The transmission loop is basically the path from the transmitter end to the receiver end. Transmission media such as twisted pair cables, coaxial cables, waveguides, atmosphere (for microwave and satellite systems), and optical fibers are used very often in telephone systems. The objective of these transmission media is to provide economical and efficient point-to-point transmission of power and information.

For message network (voice applications), the bandwidth is usually limited to 4000 Hz. Subscriber loops usually carry signals in the baseband thus rendering copper cables the most economical medium. Coaxial cables provide higher bandwidth than the twisted pair cables, but the shielding effect at low frequency is inefficient. Twisted pair cables are preferable for voice application due to the low cost and the fact that the 'twisting' effectively limits the electromagnetic interference at low frequencies [Paul et al 79].

Since early telephone systems were purely voice band applications, twisted pair cables were used extensively as dedicated subscriber loops. Today's applications demand high quality services, high data transmission rate, and high bandwidth. High bandwidth media like optical fibers are being increasingly used. Due to the existing loop population and the associated capital expense, twisted pair cables are still being

used to provide the new, more sophisticated services. The tight stringent standards of special services are met by using the CSA loop system as described in chapter 2. Despite all advances in services provided and possible transmission media, twisted pair copper loops are expected to continue to form the majority of loops for the foreseeable future.

In transmission line theory, two wire conductors such as twisted pair cables and coaxial cables are modelled as differential resistors (R'), conductors (G'), capacitors (C'), and inductors (L'). These differential elements are uniformly distributed over the length of the transmission line. Figure 2.9 shows the equivalent circuit of a differential length, Δl , of a transmission line.

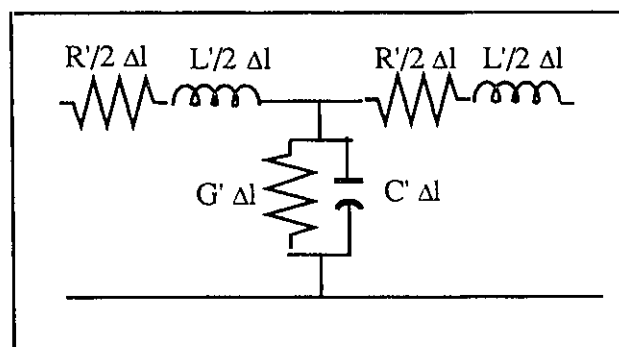


Figure 2.9 Equivalent circuit of a differential length, Δl , of a transmission line.

The differential elements R' , L' , G' , and C' are called the primary constants. Secondary constants such as the propagation constants (γ) and the characteristic impedance (Z_0) are derived from the primary constants as:

$$\gamma = \alpha + j\beta = \sqrt{(R' + j\omega L')(G' + j\omega C')} \quad \text{m}^{-1} \quad (2-22)$$

$$Z_0 = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}} \quad \Omega \quad (2-23)$$

where α is the attenuation constant (Np/m) and β is the phase constant (rad/m) [Cheng 83]. Both the primary and the secondary parameters are used to characterize transmission lines.

It was shown in [Cheng 83] that the transmission line can be modelled by lumped elements as shown in Figure 2.10 where the resistance, conductance, inductance and capacitance represent the total value for the specified length of the transmission line.

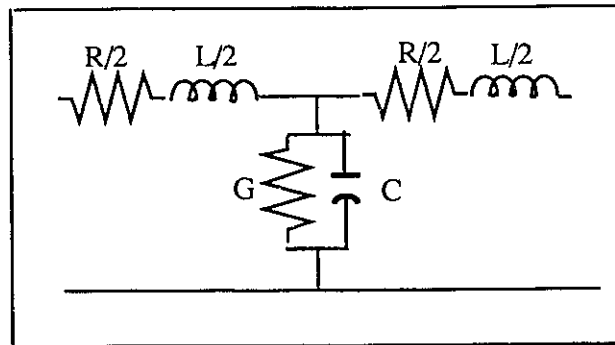


Figure 2.10 Lumped model of Figure 2.9.

Note: $R=R'l$, $L=L'l$, $G=G'l$, and $C=C'l$ (l is the length of the transmission line)

For voice band applications, the loop model can be further simplified. Since CSA loops use only AWG 19, 22, 24, and 26, and since the characteristics of the primary constants of the cables (Polyethylene-insulated cables (PIC) and pulp-insulated cables) given in [B.S.T.R. 83] at 70°F show that the impedance of R and C are significantly larger than L and G in the voice band, we can neglect L and G in the model in Figure 2.10. The resulting simplified model is shown in Figure 2.11.

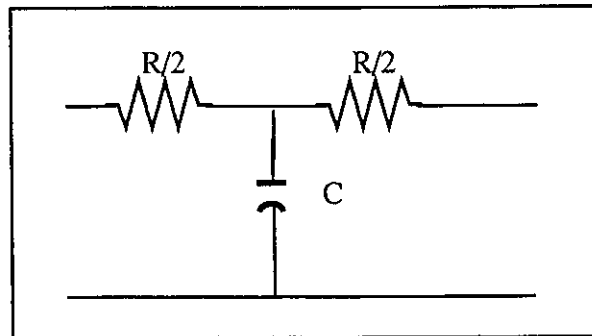


Figure 2.11 Simplified Lumped Model.

A general loop for voice band application can be approximately modelled by a cascade of sections of the form shown in Figure 2.11. Ideally we would use an infinite number of sections leading back to the model for a differential length. Practically, we found that a 2 stage section is sufficient to accurately model CSA loops (CSA loops are confined to a two gauge change). This is the model we will use to attempt to characterize the loop based on single-ended measurements. It is shown in Figure 2.12.

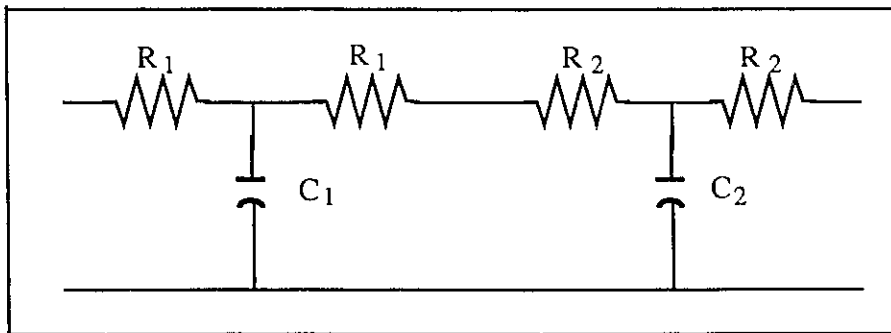


Figure 2.12 Loop model for the "Single-Ended Characterization".

3. Modelling of the Subscriber Loop

In this chapter, we present the problem to be addressed in this thesis: modelling a subscriber loop, in the voice range, based on measurements from the central office only. This model is to be used to estimate the insertion loss and should be able to do that within 1 dB. Since input impedance measurements are the most practically possible measurements at the central office end, the model parameters are to be chosen to "match" the measured input impedance at selected frequencies.

In this chapter, we will start by defining the performance measure to be used in optimizing the model parameters. The models used are those discussed based on chapter 2. We will then discuss the details of the terminations considered as well as explain some observations regarding the ambiguity of using Z_i : a single port measurement used to determine the insertion loss which is a two port function. Finally, we discuss the details of the optimization process: number of input impedance measurements, initial values for parameters and parameter constraints. Results of the modelling process are reported in chapter 4.

3.1. Problem Statement

The objective of this thesis is to estimate the insertion loss of a subscriber loop, at 1 kHz, given only input impedance measurements at the central office side and minimal, practically achievable, information on the termination at the customer's side. The error in IL estimation has to be less than ± 1 dB. The loop is modelled as

discussed in section 2.6. The details of the termination model and the process of choosing the optimum parameters for insertion loss estimation are discussed in the following sections. Thus, the problem is formulated as:

Find $\{R_1, R_2, R_3, R_4, R_5, R_6, C_7, C_8\}$ in Figure 3.1 to minimize

$$J = \sum_{\{\omega_i\}} |Z_{in}(\omega_i)|_{model} - Z_{in}(\omega_i)|_{measured}|^2 \quad (3-1)$$

where $\{\omega_i\}$ is the set of frequencies of interest in a limited voice frequency range.

The optimum parameters thus obtained are then used to estimate the insertion loss at this frequency. The actual insertion loss is computed based on exact knowledge of the loop and termination. Our aim is to keep the error between the actual and estimated losses to less than ± 1 dB.

The squared error in input impedance was chosen as the function to minimize since it was the only practically measurable quantity at the input port. However, it is to be expected that such a single port measurement cannot fully characterize a two-port transfer function like the insertion loss.

The optimization is carried out using DUNLSJ [IMSL-MATH Library]. This program requires the expressions for $Z_{in}(\omega_i)$ as well as its first derivatives. These expressions are provided in appendix C. The algorithm of DUNLSJ is based on the MINPACK routine LMDER [More et al 80]. It solves the nonlinear least squares problem with a modified Levenberg-Marquardt method defined as:

$$\text{minimize } \left(\frac{1}{2} \sum_{i=1}^m f_i(x)^2 \right), \quad (3-2)$$

where m is the number of functions, and $f_i(x)$ is the i -th function to be minimized (in our case, $f_i(x)$ is the error between the measured and modelled real/imaginary parts of the input impedance at a particular frequency as described in appendix C). The algorithm uses the trust region approach, which requires the function values and

Jacobian of the current points, to evaluate the new points. The procedure is repeated until the stopping criteria are satisfied [IMSL-MATH Library]. More details of the algorithm can be found in [Levenberg 44], [Marquardt 63].

Convergence is assumed when the residual error J is less than a user specified threshold. In our case, that threshold was set at 500. Thus, the sum of the squared input impedance errors at the specified frequencies had to be less than 500 for the parameters, R_1 , R_2 , R_3 , R_4 , R_5 , R_6 , C_7 , and C_8 , to be considered "optimum".

3.2. Impedance Models and IL Model for Optimization Approaches

The 2 section RC model of Figure 2.12 was selected to model the transmission line for our simulations. In this model, it is assumed that the network is at the left side and the customer is at the right. Depending on the termination on the customer's side we could have the on-hook model as in Figure 3.1a or the off-hook model in Figure 3.1b. Figure 3.2 shows the model used to calculate the insertion loss. Insertion loss values have to be estimated, in this case, for a customer termination R equal to the source termination. Other combinations for the source and customer's termination using the standard 600 or 900 Ω can be applied for different types of services [Blake et al 81 - section VI], [EIA/TIA-464-A - section 4.8.5]. In this thesis, we only consider insertion loss estimation assuming standard 600 Ω for source and customer terminations. The model for the customer's termination is selected as the best capable of matching actual terminations with a limited number of parameters as will be explained later.

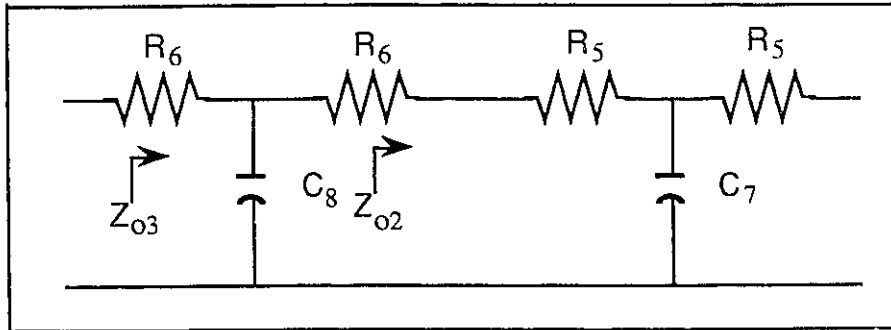


Figure 3.1a On-hook (open-circuited) Impedance Model.

Note that Z_{O2} and Z_{O3} are used to evaluate the analytical expressions for the input impedance function in the Appendix C.

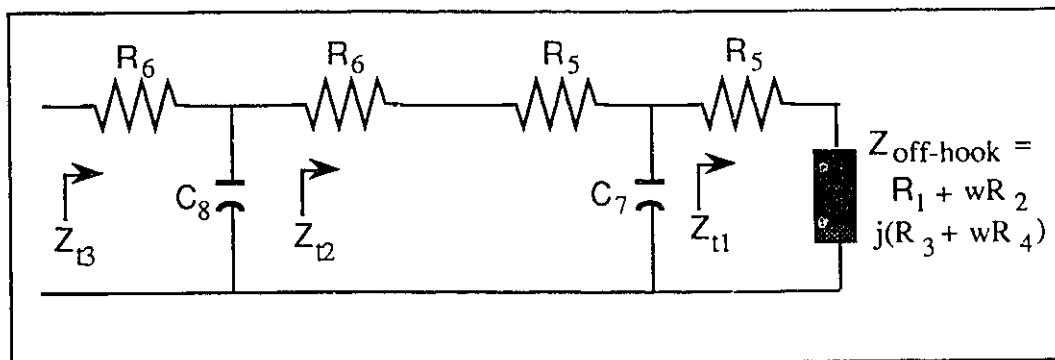


Figure 3.1b Off-hook (terminated) Impedance Model (Assume linear termination).

Note that Z_{I1} , Z_{I2} , and Z_{I3} are used to evaluate the analytical expressions for the input impedance function in the Appendix C.

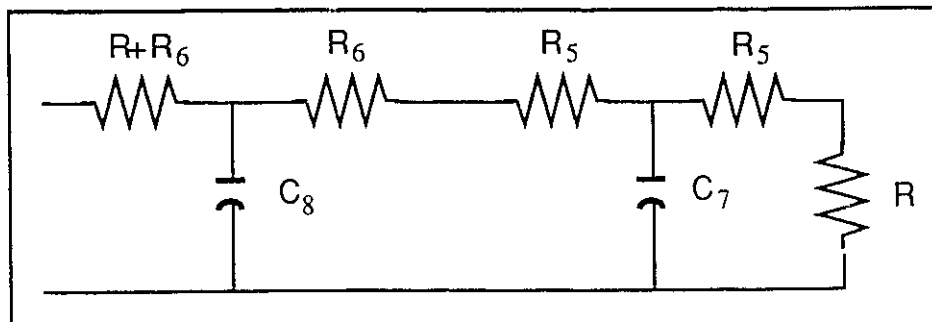


Figure 3.2 Model for calculation of insertion loss. R is the source resistance equal to 600Ω in this case.

The loop parameters R_5 , R_6 , C_7 , C_8 are essential in modelling the transmission line. The model would be used to estimate the insertion loss (IL) of the loop. These parameters, especially R_5 and R_6 , are very important in determining the IL for the CSA loops correctly. The results given in chapter 4 show that constraints applied to

these parameters are necessary whenever only single port information is known. This can prevent large IL estimation caused by the unrealistic values for the optimized parameters. The constraint set-ups to these 4 parameters are given later in section 3.6.

3.3. Output Port Termination

For the set-up considered in this thesis, it is assumed that the output port is terminated by a telephone set, electronic or mechanical. Three possible electronic sets were considered. Two of these have the ringer-impedance satisfying the standard given in [EIA/TIA-470-A]. The third was picked to have a ringer impedance that does not meet the standard. In such a way, all possible electronic ringers are tested. Since mechanical telephones (i.e., telephones with mechanical ringers) are still popular in some business offices, we also included one such set. The characteristics of a mechanical telephone with the standard mechanical ringer impedance are given in [AT&T 52 - Figure 13]. Several 500-type mechanical telephones in BNR were found to have the same ringer-impedance characteristics given by the above reference. This is shown by the 500-type curve in Figure 3.3a.

The three electronic telephones that we have used for the research are NTOC22AE 02 (NT product), TEL<OY> (Japanese product), and SPP 80 (SONY product); the mechanical telephone is an NT product with an electronic keypad. Their ringer-impedance characteristics for all sets are shown in Figure 3.3.

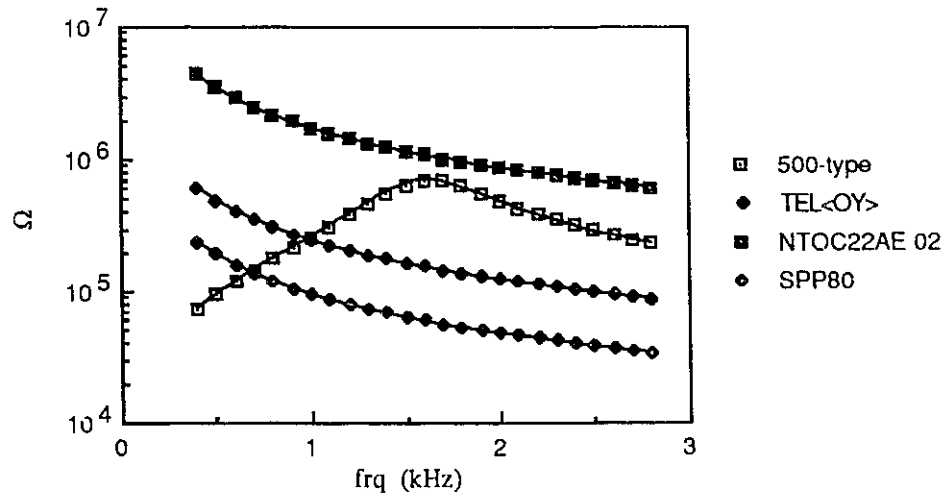


Figure 3.3a The magnitude of ringer impedance of the 3 electronic and 1 mechanical telephone.

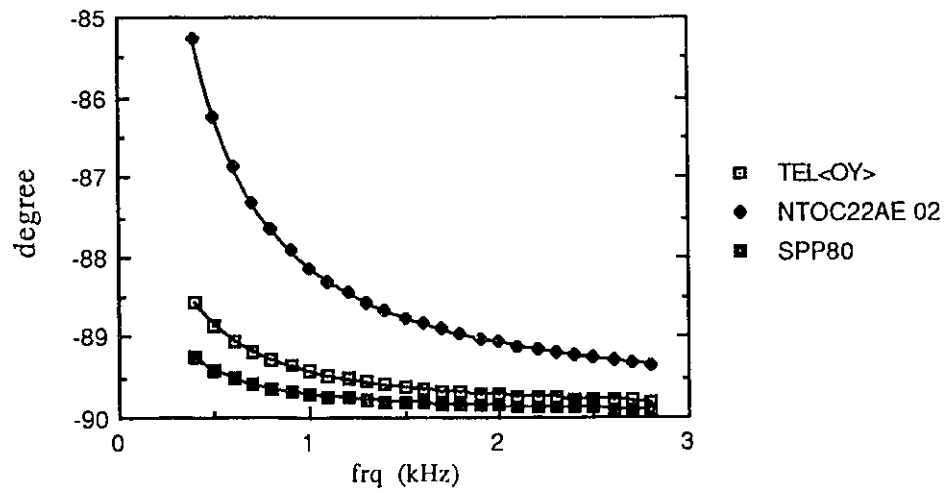


Figure 3.3b The phase of the impedance of the 3 electronic ringers.

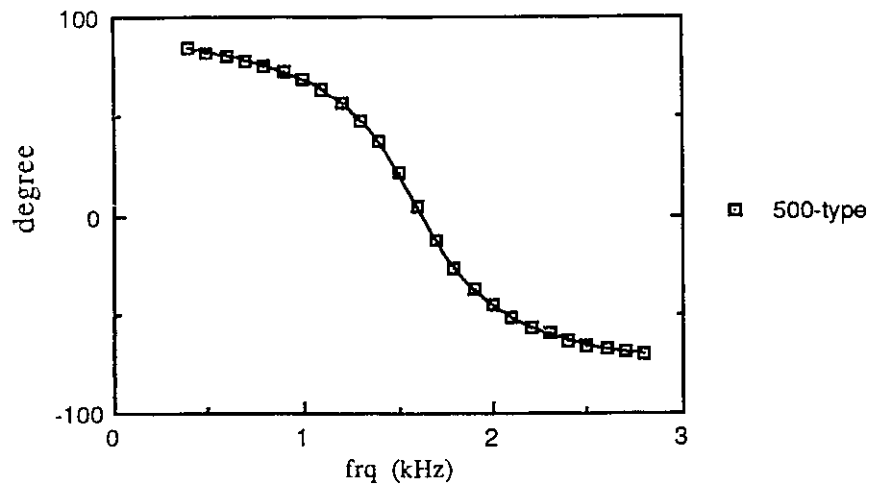


Figure 3.3c The phase of the impedance of the mechanical ringer.

Besides these four telephone devices which are mainly used for their ringer characteristics, we have chosen 4 telephone devices for their off-hook characteristics given in [Kahn 88]. They are the NT500, ET121, NTE2500, and CGE29100. Their off-hook characteristics are regenerated in appendix B.

These off-hook impedances were matched up with the ringer impedances in [Kahn 88]. It was decided this was the best approach since performing off-hook measurements is a very extensive process while the NT500, ET121, NTE2500, and CGE29100 were not accessible for measurements. We put the 500-type and NT500 together since both are mechanical telephones. The remaining electronic telephones were coupled arbitrarily as: ET121, TEL<OY>; ET121, NTOC22AE 02; CGE29100, SPP80.

3.4. Termination Models

3.4.1. Off-hook Case

It was shown in [Kahn 88] (reproduced in appendix B) that customer's off-hook terminations in general have real and imaginary parts that can be approximated by linear functions of frequency in limited ranges of frequencies. According to these linear characteristics, we model the termination of the off-hook model (Figure 3.1b) as $R_1 + \omega R_2 + j(R_3 + \omega R_4)$.

For a general termination, this linearized model can be used when the frequencies considered are reasonably close. This assumption is particularly useful for the combined on-hook and off-hook approach to be discussed in section 3.6. In that case, we need measurements for the two possible terminations at two frequencies. The termination used to model the off-hook case is assumed to be a linear function of frequency in between those two frequencies.

3.4.2. On-hook Case

[EIA/TIA-470-A - section 4.5] states that the magnitude of the ringer impedance¹¹ of any electronic telephone at frequencies between 697 and 1633 Hz should exceed 100 k Ω . Based on this standard, it is reasonable to assume an open-circuit model for the ringer impedance at the frequencies described above.

We have tested this assumption using the simulation program Hoff described in section 3.5 to simulate several designated CSA loops. The loop make-ups are AWG 26 of 1, 3, 6, and 9 kft. The ringers used were described in section 3.3.

The testing criterion was simple. The four designated testing loops described above are terminated at telephones with ringer impedances as described in Figure 3.3.

¹¹ Ringer impedance refers to the impedance of the telephone set for the on-hook state.

The input impedances measured at the near end of the loops are simulated (denoted as $Z_{l_{on-hook}}$). The same measurement is then repeated with these loops terminated at open circuit (denoted as $Z_{l_{open}}$). $Z_{l_{on-hook}}$ and $Z_{l_{open}}$ are compared. The differences are quantified to the absolute percentage (i.e. $\frac{|Z_{l_{on-hook}} - Z_{l_{open}}|}{|Z_{l_{open}}|} \times 100\%$), and the comparisons are made at different frequencies. The differences between $Z_{l_{on-hook}}$ and $Z_{l_{open}}$ are considered separately for the real part and the imaginary part. Figure 3.4 shows the differences for the imaginary part, and Figure 3.5 shows the differences for the real part.

For the imaginary part, Figure 3.4 shows that the average difference for short loops is larger than for long loops; and that the average difference is smaller at higher frequencies. The differences for the $\text{Im}(Z_{l_{open}})$ and $\text{Im}(Z_{l_{on-hook}})$ depend on the magnitude of the ringer impedance. From Figure 3.3a and 3.4a, we can see that the relative differences between $Z_{l_{on-hook}}$ and $Z_{l_{open}}$ for the 500-type telephone is minimum at 1.6 kHz. This frequency is where the 500-type telephone has the peak impedance magnitude. The differences for the three electronic telephones are quite constant with frequency. We believe the SPP 80 has the biggest average difference because it has the lowest ringer impedance in magnitude. Figure 3.4b shows that when loops are longer than 3 kft and the frequencies are above 1 kHz, the worst difference for SPP 80 is around 3%.

For the real part, Figure 3.5 shows that on the average the difference for short loops is larger than long loops; and it decreases with frequency. These observations are similar to those made for the imaginary part. When comparing the mechanical telephone with the electronic ones, it was found that for electronic telephones, the error between $\text{Re}(Z_{l_{on-hook}})$ and $\text{Re}(Z_{l_{open}})$ was significantly smaller. It was believed that this was a result of the electronic telephone having a pure imaginary ringer impedance. This assumption was verified by computing $\text{Re}(Z_{l_{on-hook}})$ and

$\text{Re}(Z_{\text{ilopen}})$ for various terminations, real, imaginary, and complex. Figure 3.6 summarizes the results showing that the percentage error was smaller for all frequencies for cases of pure imaginary termination. In fact, for loops longer than 3 kft, Figure 3.5 (b,c,d) shows that the error was less than 10% for frequencies over 1 kHz (an actual difference of less than 10Ω).

Thus, we conclude that we can approximate the on-hook termination by an open circuit if

1. The loop is sufficiently long (>3 kft),
2. The frequency is sufficiently high (≥ 1 kHz),
3. The magnitude of the ringer impedance is sufficiently large,
4. The phase of the ringer impedance is close to $-\pi/2$ (electronic ringers)¹².

In fact, the optimization approach involving the on-hook model utilizes the open-circuit model and has no trouble estimating the IL for short loops. This is because the range of the primary parameters for these short loops are small.

¹² Not needed when 1, 2, and 3 are satisfied.

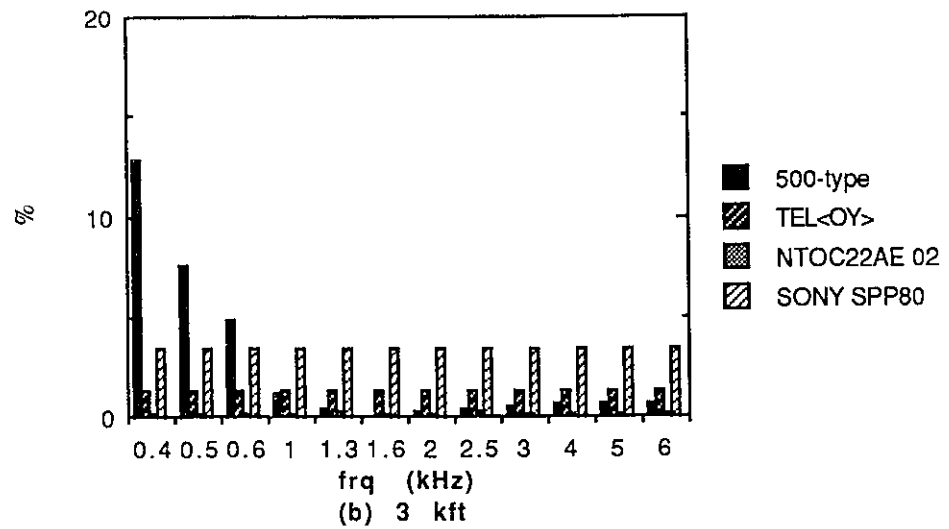
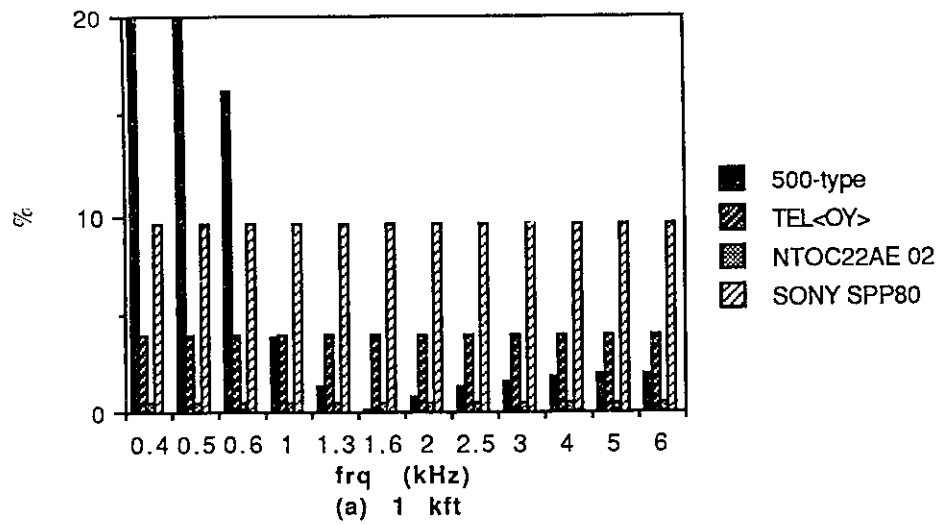
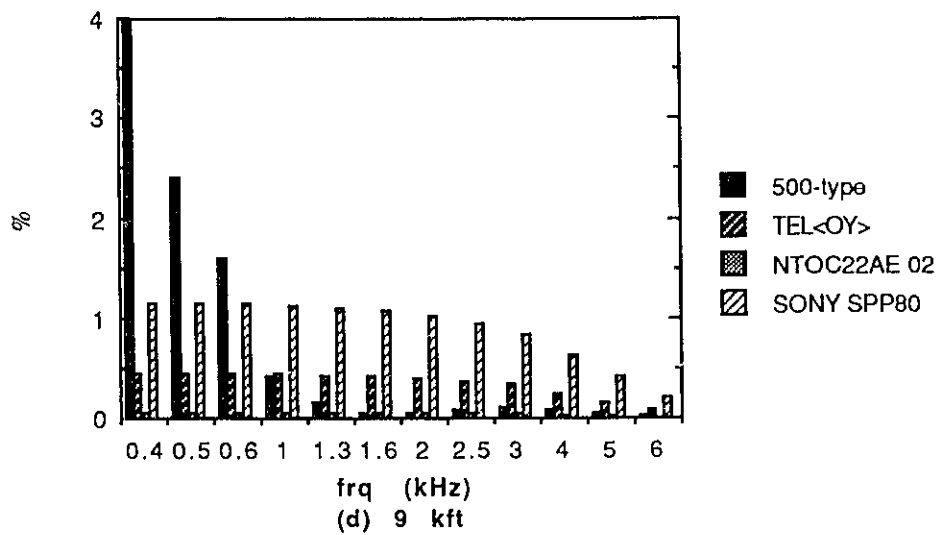
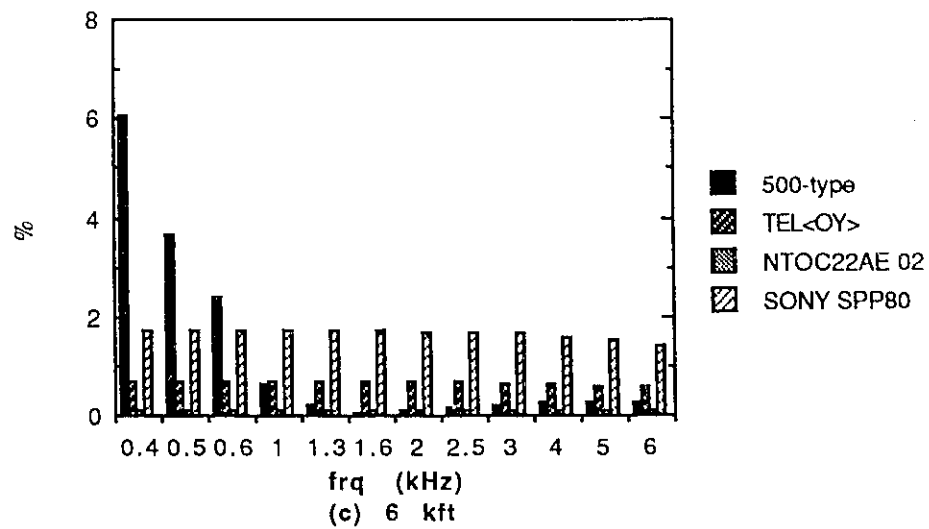


Figure 3.4 a,b,c,d) $\frac{|\text{Im}(Z_{\text{lon-hook}}) - \text{Im}(Z_{\text{lopen}})|}{|\text{Im}(Z_{\text{lopen}})|} \times 100\%$ for 1,3,6, and 9 kft, AWG26.



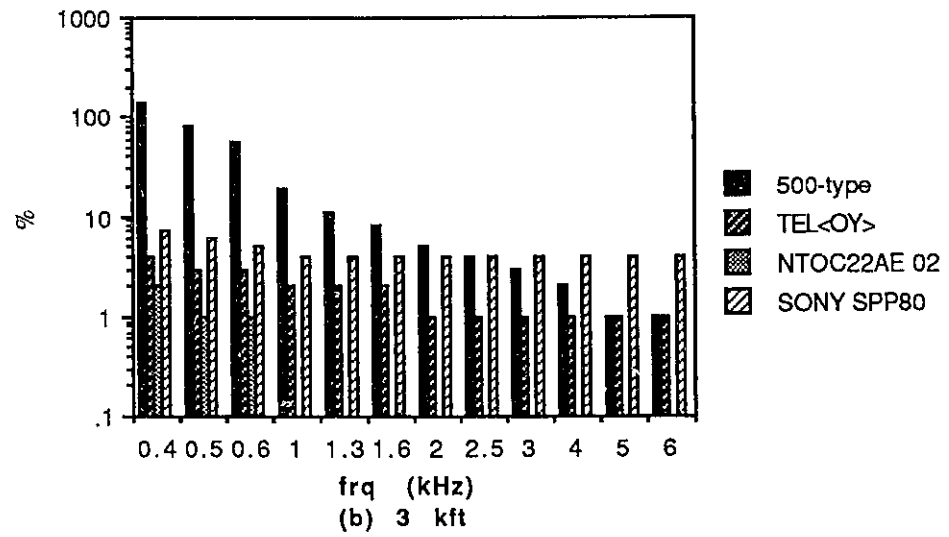
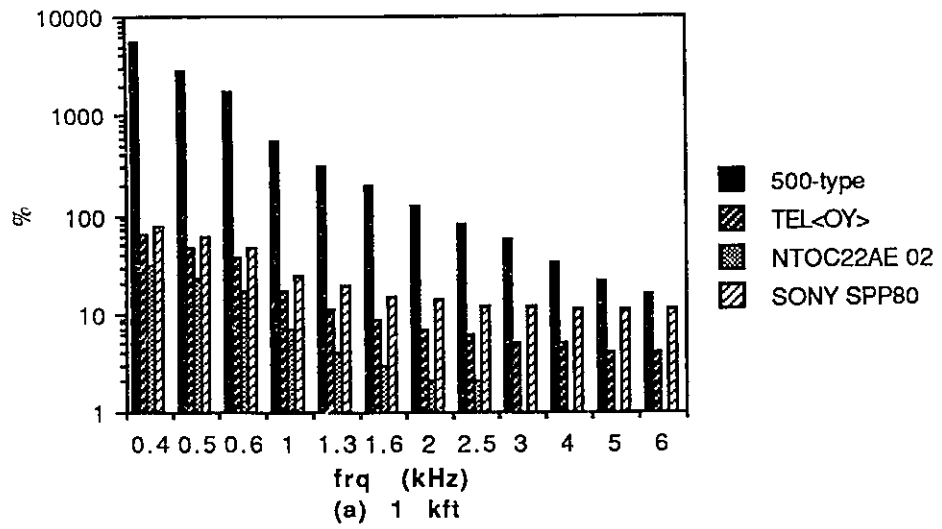
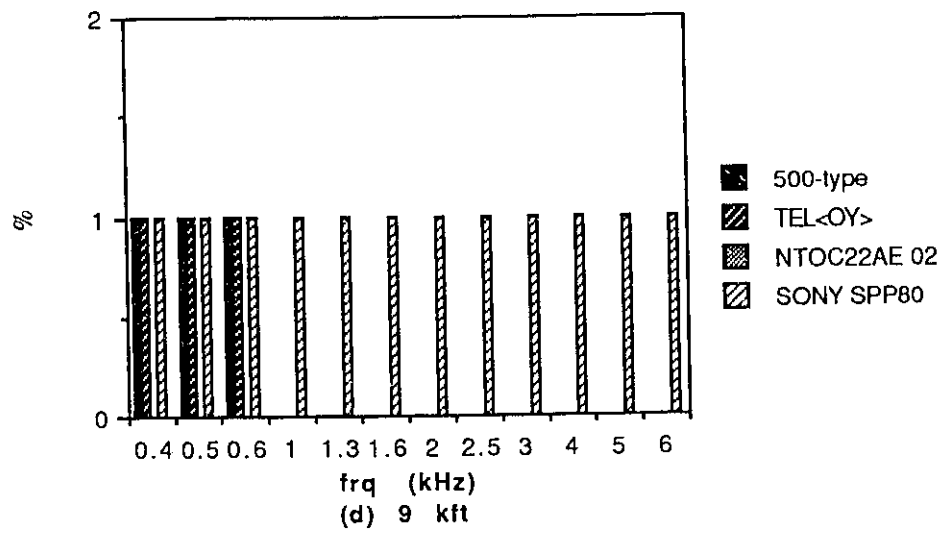
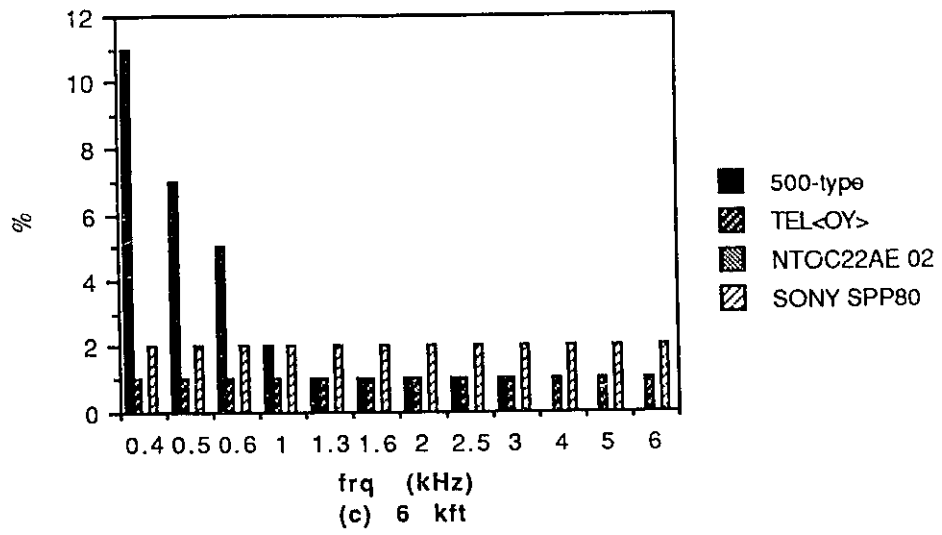


Figure 3.5 a,b,c,d) $\frac{|\text{Re}(Z_{\text{lon-hook}}) - \text{Re}(Z_{\text{lopen}})|}{|\text{Re}(Z_{\text{lopen}})|} \times 100\%$ for 1,3,6, and 9 kft, AWG26.



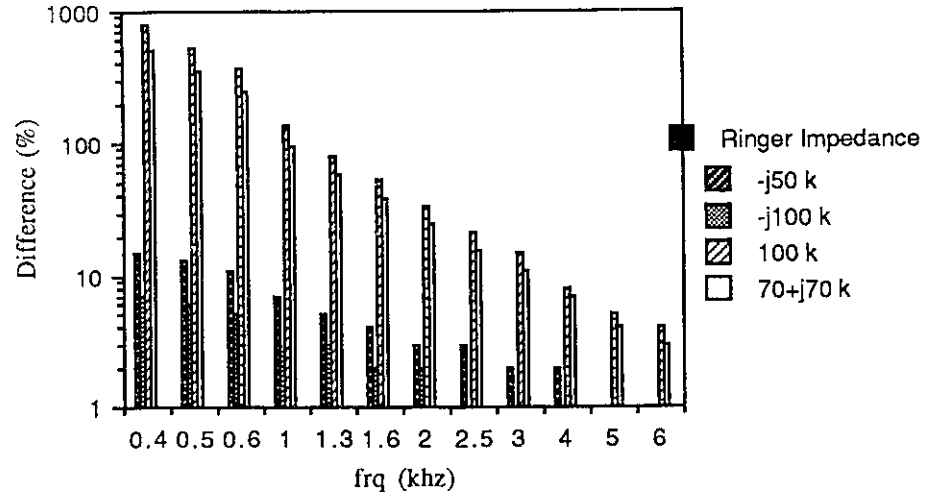


Figure 3.6 Differences (in percentage) between the $\text{Re}(Z_{i|open})$ and the $\text{Re}(Z_{i|on-hook})$ for 3 kft AWG26 using ringer impedance $-j50k$, $-j100k$, $100k$, and $70 + j70 k$ for the terminations.

3.4.2.1. Use of $Z_{i|open}$ in Determining Loop Length

In this section we will discuss how to use $Z_{i|on-hook}$ to determine loop length and capacitance. Since we have already shown that $Z_{i|open}$ can be used in place of $Z_{i|on-hook}$ if the four conditions of section 3.4.2 were satisfied, we will base our discussion here on $Z_{i|open}$ as obtained from Hoff. Table 3.2 gives the values of $Z_{i|open}$ for the 4 testing loops (AWG26 of 1,3,6,9 kft).

As we can see from Table 3.1, $\text{Re}(Z_{i|open})$ does not change with frequency in most cases. The $\text{Im}(Z_{i|open})$ shows the characteristics of $\frac{-1}{\omega C}$ where " ω " is frequency in radian/s and " C " is the loop capacitance. Because PIC cables are designed to have a constant capacitance at $0.083 \mu\text{F}$ per mile [B.S.T.J. 83], we can combine this characteristic and the fact that $\text{Im}(Z_{i|open}) = \frac{-1}{\omega C}$ to find the loop length including bridged taps as $L = \frac{C}{0.083 \times 10^{-6}} \times 5.28 \text{ kft}$ (5.28 is the conversion factor from mile to kft). Consider as an example from Table 3.1, $\text{Im}(Z_{i|open}) = -1024 \Omega$ at 1.0 kHz for a 1 kft loop. C can thus be calculated as

$$C = \frac{-1}{\omega \cdot \text{Im}(Z_{\text{Iopen}})} = \frac{1}{2\pi \cdot 1000 \cdot 10124} = 1.57 \cdot 10^{-8} \text{ F}$$

and the loop length can be calculated as

$$L = \frac{C}{0.083 \cdot 10^{-6}} \cdot 5.28 = \frac{1.57 \cdot 10^{-8}}{0.083 \cdot 10^{-6}} \cdot 5.28 = 1.0 \text{ kft}$$

The determination of the loop length will be later used to set some constraints on the range of variation in the coefficients.

Table 3.1 The characteristics of Z_{Iopen} .

freq (khz)	1kft (Z_{Iopen})		3 kft (Z_{Iopen})		6 kft (Z_{Iopen})		9 kft (Z_{Iopen})	
	Real	Imag	Real	Imag	Real	Imag	Real	Imag
low frequency range								
0.4	38	-25267	87	-8422	168	-4212	251	-2811
0.5	33	-20250	85	-6750	168	-3376	251	-2254
0.6	32	-16881	85	-5627	168	-2814	251	-1880
medium low frequency range								
1.0	29	-10124	84	-3374	167	-1688	250	-1133
1.3	29	-7784	84	-2594	167	-1299	250	-874
1.6	29	-6328	84	-2108	167	-1056	250	-715
medium high frequency range								
2.0	29	-5061	84	-1686	167	-846	249	-578
2.5	29	-4045	84	-1347	167	-677	248	-468
3.0	28	-3374	84	-1123	167	-565	247	-397
high frequency range								
4.0	28	-2526	84	-839	167	-425	244	-310
5.0	28	-2023	84	-671	167	-342	241	-261
6.0	28	-1685	84	-558	167	-287	238	-230

3.4.2.2. Ambiguity of $Z_{i\text{open}}$ in Completely Defining the Loop

During our preliminary investigation, it was also noticed that very different loops can have almost identical $Z_{i\text{open}}$ while having widely varying IL. Table 3.2 shows some such cases. The IL changes from 1.97 dB (loop 6e) to 4.02 dB (loop 4e) at 1.0 kHz. The difference is 2.05 dB while $Z_{i\text{open}}$ remains almost unchanged. This will later help in explaining the problems faced when attempting to determine IL based on on-hook measurements only. This input impedance ambiguity is minimized when measurements are based on both on-hook and off-hook terminations.

Table 3.2 Example of loops that have similar input impedance but different IL.

Loop	Loop make-up	IL	Re($Z_{i\text{open}}$)	Im($Z_{i\text{open}}$)
3e	5 kft AWG22	3.09	118	-1011
	5 kft AWG24			
4e	3.4 kft AWG19	4.02	119	-1014
	6.6 kft AWG26			
5e	0.4 kft AWG24	2.56	118	-1010
	9.6 kft AWG22			
6e	1.1 kft AWG26	1.97	119	-1009
	8.9 kft AWG19			

3.4.3. Standard Source and Termination for IL model

The source impedance and the terminal impedance given in the IL model can be any of the standard resistive impedances, 600Ω or 900Ω , depending on the applications [Blake et al 81 - section VI], [EIA/TIA-464-A - section 4.8.5]. Since modelling process is basically for the loop and the termination irrespective of the source impedance, we choose the source and the terminal resistive impedance for the IL model as 600Ω in all cases considered here.

3.5. Tools for Simulation and Optimization

Simulations in this thesis make extensive use of two programs: HOFF [Hung 81] used to provide the simulated equivalent of input impedance and insertion loss measurements, and DUNLSJ [IMSL-Math Library] used for optimizations to find the loop and termination parameters providing best match for measured and modelled input impedances. The purpose of using Hoff is to simulate the input impedance, insertion loss and other functions for different kinds of CSA loops given the loop make-up and primary constants. Since CSA is a relatively new concept for special services, as yet there is no established loop survey similar to the general loop survey discussed in section 2.3. Thus, we constructed 56 CSA loops (discussed in section 2.3.2) to be used in this thesis. Hoff was used to simulate the input impedance for these 56 CSA loops with different terminations at different frequencies; in addition, the IL of the 56 loops is also determined by Hoff.

DUNLSJ is an optimization program supported by the [IMSL-Math Library]. It is used here to match the input impedance of the impedance model(s) (Figure 3.1) to the input impedance of the 56 CSA loops with different terminations as simulated by Hoff. When this is achieved, the parameters in the impedance model(s) are

optimized in the sense that the error between the two sets of input impedances is minimized. The loop parameters in the impedance model(s) are then used to calculate the IL. This can be done using Hoff.

Optimization programs for non-linear least square problems generally require users to supply subroutines to evaluate the function to be optimized as well as the first derivatives (Jacobians) [Dennis et al 83]. Initial guesses for the variables are particularly important since multiple optima could exist. DUNLSJ requires all the information mentioned above. The function to be minimized and its Jacobians are derived in appendix C, with Fortran program given in appendix D.

The same general problems associated with nonlinear optimizations exist in our case. The solutions given by the optimization are not necessarily unique and the optimization process may converge to a local minimum depending on the initial conditions [Dennis et al 83]. Varying the initial guesses at the beginning of the optimization can change the final solution dramatically. The complexity of the function to be optimized is also a concern as it could limit the number of frequencies at which the function is evaluated.

3.6. Details of the Optimization Setup

3.6.1. Possibilities for Customer Termination

3.6.1.1. On-hook Approach

In this case, it is assumed that the telephone company will measure the input impedance at the CO port while the far end customer's termination is at on-hook state. The on-hook approach uses the on-hook model given in Figure 3.1a. Since there are 4 variables in this model, 2 complex frequency measurements between 1.0 and 1.5 kHz are required¹³.

The measured input impedances are then fed into the on-hook model. DUNLSJ optimizes the solution by changing the variables R_5 , R_6 , C_7 , C_8 to minimize the squared error between the measured input impedance and the input impedance for the model. R_5 , R_6 , C_7 , C_8 are then used in the IL model given in Figure 3.2 to calculate the IL.

3.6.1.2. Off-hook Approach

Here, it is assumed that telephone company will measure the input impedance at the CO port while the far end customer's termination is at off-hook state. The off-hook approach uses the off-hook model given in Figure 3.1b. Two possibilities are considered for the termination model -- $\langle LR, LX \rangle$ and $\langle LR, CX \rangle$ where $\langle LR, CX \rangle$ is a simplified form by assuming the imaginary part of the off-hook impedance is constant. Since there are either seven or eight variables, depending on whether the $\langle LR, LX \rangle$ or $\langle LR, CX \rangle$ model is used, 4 complex impedance measurements at four frequencies between 1.0 and 1.5 kHz are required.

¹³ The number of measurements required is discussed in the next section.

The measured input impedances are then fed into the off-hook model. DUNLSJ optimizes the solution by changing the variables $R_1, R_2, R_3, R_4, R_5, R_6, C_7, C_8$ to minimize the squared error between the measured input impedance and the input impedance for the model. R_5, R_6, C_7, C_8 are then used in the IL model given in Figure 3.2 to calculate the IL.

3.6.1.3. Combined On-hook and Off-hook Approach

In this last approach, it is assumed the telephone company will measure the input impedance at the CO port once with the far end customer's termination at on-hook state and again for the off-hook state. This approach uses both the on-hook model given in Figure 3.1a and the off-hook model given in Figure 3.1b. The general case of the off-hook model, namely $\langle LR, LX \rangle$, is used. Since there are 8 variables in this model, 2 complex frequency measurements for each one of the on-hook and off-hook cases between 1.0 and 1.5 kHz are required.

The measured input impedances are then fed into these two models. DUNLSJ optimizes the solution by changing the variables $R_1, R_2, R_3, R_4, R_5, R_6, C_7, C_8$ to minimize the squared error between the measured input impedance and the input impedance for the models. R_5, R_6, C_7, C_8 are then used in the IL model given in Figure 3.2 to calculate the IL.

3.6.2. Number of Measurements Required

Due to the complexity of evaluating the impedance function and its derivatives as given in appendix C, we use the minimum number of measurements possible. For each of the above cases, the number of variables is determined. The number of input impedance measurements is then taken as 1/2 the number of variables since each impedance measurement provides a real and imaginary function to be minimized. Matching the input impedances at a larger number of frequencies will obviously

provide a better model but will result in excessively complex computations and may not be manageable by DUNLSJ.

3.6.3. Constraints Applied to the Loop Parameters

When the optimization parameters were unconstrained, it was found that the system converged to highly unrealistic values (-ve resistances or effectively open circuit resistances) resulting in excellent impedance match and unacceptable IL errors. It was thus decided to constrain the variables to their practical ranges of values.

The constraints applied to C_7 and C_8 are determined by the loop capacitance obtained from the on-hook impedance measurements as shown in section 3.4.2.1. We first equally divide the measured loop capacitance between C_7 and C_8 . Then a $\pm 10\%$ margin of variation around this value is allowed. The 10% margin was chosen since it was observed that when the margin was set too small, the optimization program had difficulty converging for some of the 56 loops. When the margin was set too wide, some final results were unrealistic.

The constraints applied to resistive elements of the loop are determined based on the length of the loop and the differential resistance, R' , of the finest (AWG26) and the thickest (AWG19) gauges of the twisted pair wires used in CSA loops. The loop resistance was thus restricted to a lower bound equal to the resistance of the pure-gauged AWG 19, and an upper bound equal to the resistance of the pure-gauged AWG 26 of equal length¹⁴. Since there are 4 resistive elements (2 R_5 s and 2 R_6 s) in the loop model, each element is assigned one-fourth of the bound, such that each

¹⁴ Because the maximum loop resistance for a CSA loop is defined by the AWG26 9 kft CSA loop, for loops of other gauges, any loop length estimated longer than 9 kft has to have the same upper bound for loop resistance (each resistor in Fig. 3.1 (a,b) has the maximum value of 187.5 Ω).

resistive element is lower bounded by $\frac{R'l}{4} \Big|_{\text{AWG19}}$, and upper bounded by $\frac{R'l}{4} \Big|_{\text{AWG26}}$, where l is the length of the loop.

3.6.4. Selection of Initial Parameter Values

For the off-hook model, the initial estimates for the termination parameters R_1 , R_2 , R_3 and R_4 are:

- R_1 and R_3 are arbitrarily chosen to 500 and 400 respectively. These values are some y-intercept points for the graph given by [Kahn 88] giving the off-hook impedance as a function of frequency for different telephone sets.
- R_2 and R_4 are assigned small values (10^{-2}) to characterize the small impedance change with respect to frequency.

The initial estimates for the loop capacitive elements, C_7 and C_8 , are determined by equally dividing the measured loop capacitance among the two variables. These estimates are always used irrespective of the choices of the other parameters.

As mentioned in section 3.5, changing initial estimates for the optimization may change the final solution. It was thus decided to repeat the optimization process for every set of measurements five times with five different initial estimates for R_5 and R_6 . If the solution obtained from an individual run has an error less than a certain threshold, it is considered successful. At the end, the variables obtained from the successful runs are averaged to produce the final solution. In other words, for a given loop and a given optimization set-up (on-hook for example), five optimization runs are conducted.

The initial estimates for R_5 and R_6 for these five runs are determined as follows:

- (i) The range of the initial estimates is bounded by the loop resistive constraints discussed in section 3.6.3, i.e., they are lower bounded by $R_L = \frac{R'l}{4} \Big|_{\text{AWG19}}$, and upper bounded by $R_U = \frac{R'l}{4} \Big|_{\text{AWG26}}$, where l is the loop length and R' is the differential resistance of a loop.
- (ii) 4 equal intervals between R_L and R_U , such that values for each interval differ by $\frac{R_U - R_L}{4}$. The five estimates, $R_5(k)$, $k=0, \dots, 4$, for R_5 are chosen as

$$R_5(k) = R_L + \frac{R_U - R_L}{4} \times k \quad ; \quad k=0, \dots, 4$$

- (iii) Similarly, for R_6

$$R_6(k) = R_L + \frac{R_U - R_L}{4} \times k \quad ; \quad k=0, \dots, 4$$

If more than one final solution from the 5 runs have total error smaller than 500, then the final solution is obtained by averaging the results from those "successful" runs only. However if all the solutions from the 5 runs have errors larger than 500, the solution is simply obtained by averaging the results for all 5 runs for lack of better results.

4. Simulations and Optimizations

In chapter 1, we discussed the importance of automated testing systems used on the loop portion of the telephone companies' (telcos) Operation Administration and Maintenance (OA&M) processes. Old maintenance methods require at least two technicians to make measurements simultaneously. Although current methods can reduce the need to dispatch field technicians to the customer premises, the huge data base needed and the out-of-date and possibly inaccurate data make this approach expensive and unreliable. The proposed single-ended loop characterization enhances the current method by providing the necessary accurate estimation of loop parameters while eliminating the huge data base required.

Telcos provide a variety of services to customers. Special services are one of the most competitive and wide growing areas. The standards for these services are tight and the quality demanded by the customers is high. For voice band applications, the IL of a loop at 1 kHz becomes particularly important. New special-services loops are designed based on the Carrier Serving Area (CSA) requirements as discussed in section 2.3.2. As a result, our objective can be more specifically restated as the estimation of the IL of a given unknown CSA loop as defined in section 2.3.2 using single-port impedance measurements to within ± 1 dB error.

In this chapter, we present an approach to attain this objective based on estimating the loop parameters in the model of Figure 3.1. This is achieved basically by minimizing the error between the input impedance function as measured on the

actual loop and the input impedance function of the model with the appropriate termination.

In our simulations, we used a BNR proprietary simulation program, Hoff, to provide the equivalent of the measured values given the loop make-up and specific termination. Specifically, the role of Hoff is to provide the actual measured input impedance at the CO port for 56 generated CSA loops with different terminations. Hoff also provides the IL for these 56 generated CSA loops.

The function of the proposed optimization program is to obtain the optimum loop parameters in the lumped model described in section 3.2 so as to match the input impedance simulated by Hoff by minimizing the error functions described in section 3.1. The estimated loop IL can again be evaluated by Hoff for those optimum parameters.

In general, the loop resistances and capacitances in Figure 3.1 as well as the customer's termination are unknown. Since we are dealing with a two-port network, missing information from the far end imposes a definite handicap for estimating two-port parameters using single-port information only. In this chapter, we propose several approaches to determine the loop parameters to be used in the estimation of insertion loss based on different assumptions about the customer's termination. We will first begin by assuming exact knowledge of customer termination. Given this information, it will be shown that the insertion loss can be estimated very accurately using only input impedance measurements at the CO site.

However, since practically speaking it may not be possible to obtain this information, we next consider loss estimation based on more realistically available information of input impedance for the on-hook and off-hook cases. These measurements are easily achievable and will be shown to lead to insertion loss estimation to within the required 1 dB.

The above approaches result in loss estimation at 1 kHz. Using the same parameters to estimate the loss at 2.8 kHz could result in unacceptable error. We thus proposed a simple approach to estimate the IL at 2.8 kHz maintaining the same error as for 1 kHz.

We conclude by discussing the effect of measurement errors on the accuracy of insertion loss estimation.

4.1. IL Estimation Based on the Availability of Two-port Information

4.1.1. Determination of Loop Model Parameters Assuming Availability of D.C. Loop Resistance Measurement

Here, we start by assuming real short circuit at the customer's termination. In this case, given the loop capacitance and loop D.C. resistance, we can easily determine the loop parameters as

$$R_5 = R_6 = \frac{\text{D.C. Resistance}}{4}$$

$$C_7 = C_8 = \frac{\text{Capacitance}}{2}$$

The loop capacitance can be obtained from the $\text{Im}(Z_{\text{loop-hook}})$ measurements discussed in section 3.4.2.1. The loop D.C. resistance is obtained as the D.C. input impedance from the CO and assuming short circuit at the customer's end.

Consider the differential length of a transmission line in Figure 2.9, if we measure the circuit at D.C., the inductor (L) will be shorted, the capacitor (C) will be

opened, and since the conductor (G) is inherently small (open circuit), the only element left in the transmission line model is the resistor. If the transmission line is terminated at the short circuit, the near-end input impedance measured is equivalent to the D.C. resistance¹⁵ of the loop. Table 4.1 shows the actual loop D.C. resistance (as simulated by Hoff) and the approximated loop D.C. resistance obtained by the input impedance measured at the central office with the customer's end short circuited.

Table 4.1 Simulated and Estimated loop D.C. resistance.

Note: "Simulated" is the loop D.C. Resistance simulated by Hoff to represent the actual loop D.C. Resistance; "Estimated" is the loop D.C. Resistance approximated by the near-end input impedance measurements at low frequencies and the far end is shorted.

Loop	1a	2a	3a	4a	5a	6a	7a	8a
Simulated	405	253	583	707	525	467	97	472
Estimated	408	256	584	711	527	473	98	473

The values of R_5 , R_6 , C_7 , and C_8 obtained as such are used to calculate the insertion loss using the model described in Figure 3.2. Figure 4.1 summarizes the errors obtained for all loops in loop series A given in appendix A. It is clear that excellent results can be obtained based on this available information. The errors at 1 kHz are below 0.05 dB. The largest error is estimated for loop 4a at 2.8 kHz for 0.32 dB only.

However, there are two practical problems involved in this method:

1. To achieve short circuit termination, a technician has to be dispatched to the customer's location. It should be noted that off-hook is not equivalent to short circuit.

¹⁵ Since bridged taps are assumed "open" all the time, the resistive elements in the bridged taps do not contribute to the loop D.C. resistance.

2. Measurements at frequencies below 200 Hz are not easily achievable because the frequencies below 200 Hz are attenuated to become the guard band discussed in section 2.5.1.

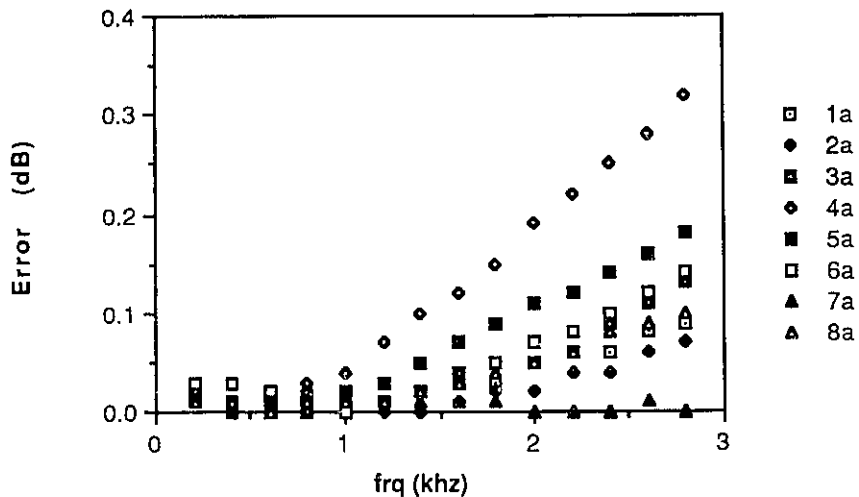


Figure 4.1 The errors of the IL estimations using the loop D.C. resistance obtained by the approximation method; and the loop capacitance is obtained by the $\text{Im}(Z_{\text{in-hook}})$ measurements.

4.1.2. Determination of Loop Model Parameters Based on Exact Knowledge of Customer's Off-hook Termination

In this section, we assume that the impedance of the customer's off-hook termination is known exactly (we have used ET121 as the known termination to simulate the result). The values of R_1 , R_2 , R_3 , and R_4 which characterize the off-hook impedance are used in the off-hook impedance model given in Figure 3.1b. The loop parameters R_5 , R_6 , C_7 , and C_8 are then varied to minimize the error function as defined in section 3.1. Hoff is again used to obtain the measured values of input impedance at two frequencies (1.0 and 1.5 kHz).

The errors for the IL estimations for various loops in loop series A are shown in Figure 4.2. Again, excellent results are obtained. The errors at 1 kHz are smaller than 0.1 dB, and the maximum error at 2.8 kHz (with no projection method used) is smaller than 0.30 dB.

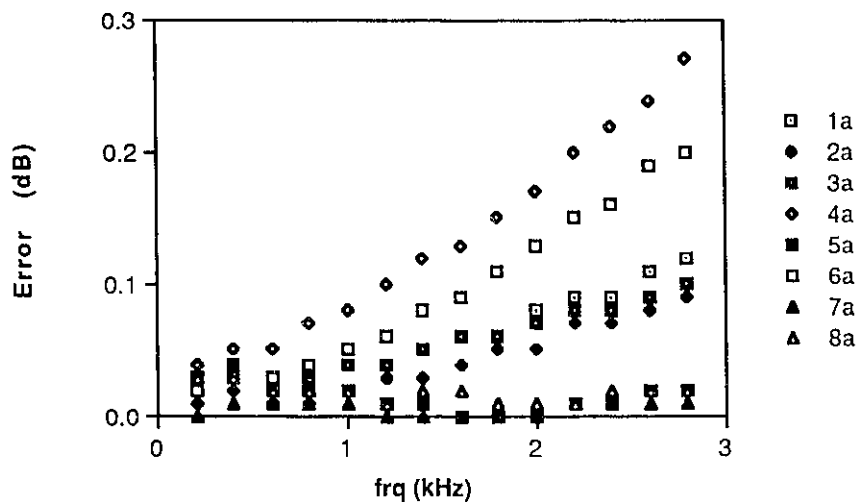


Figure 4.2 The errors for the IL estimations based on the known off-hook termination. Unconstrained optimizations are used.

However, determining the parameters for customer's off-hook termination would require a technician's presence there. Thus an assumption of availability of knowledge of parameter values for the termination is not very practical.

4.2. IL Estimation for Short Loops (<4.5 kft)

The insertion loss of a given loop is upper bounded by that of a pure AWG 26 loop of equal length and lower bounded by that of a pure AWG 19 loop of equal length. It was noticed from extensive simulations that for loops of length <4.5 kft, these upper and lower bounds differ by less than 2 dB. Based on this, the insertion loss of short loops of length < 4.5 kft can be directly estimated as the average of these two bounds at the required frequency.

For example, the IL for 4.5 kft of AWG 19 and AWG 26 are 0.6 dB and 2.46 dB (1.86 dB difference) respectively at 1 kHz, and 1.08 dB and 3.03 dB respectively (1.95 dB difference) at 2.8 kHz¹⁶. Thus the IL estimate for a 4.5 kft loop is obtained as the average of the IL for pure AWG 26 and AWG 19 of this length and is given by $\frac{0.6+2.46}{2} = 1.53$ dB at 1 kHz, and $\frac{1.08+3.03}{2} = 2.06$ dB at 2.8 kHz. In this case, the IL is estimated directly without explicitly determining the model parameters.

We can increase the loop length beyond 4.5 kft if certain loop statistics are given. For example, if we use the general loop survey results discussed in section 2.3 (which shows that short loops are dominated by AWG 24 and AWG 26), the short-loop definition can be redefined to approximately 6 kft.

4.3. IL Estimation for a General Loop Based on Single-port Information

In this section, we deal with the more general case of estimating the IL for a loop of any length based on input impedance measurements from the CO and no knowledge of the customer termination. We are assuming the input impedance measurements are available at up to four frequencies in the voice range of 0.2 kHz - 2.8 kHz.

First, we will consider loss estimation based on on-hook measurements only. We have implemented the unconstrained and constrained optimizations as described in section 3.6. It was found that unconstrained optimizations usually give unrealistic loop parameters resulting in large IL errors despite excellent impedance matching. This approach is subsequently dropped and replaced by constrained optimization. The

¹⁶ The IL calculated here use standard 600Ω source and termination. Other kind of terminations have different IL.

next approach considered is the loss estimation based on off-hook measurements only. It will be shown that for both the on-hook and the off-hook cases, the desired accuracy is not always achieved. It was clear that considering only input impedance knowledge imposes a definite handicap. This was to be expected since we were using single-port measurements to determine multi-port characteristics. More specifically, this was to be expected since it was verified from on-hook measurements (section 3.4.2.2) that very different loops with different IL can have the same input impedance. Also in the off-hook impedance model given in Figure 3.1b, R_5 and the real part of the termination show up together as a unit in the input impedance expressions but not in IL expressions. Based on this, we are proposing using both on-hook and off-hook measurements simultaneously since this allows the model parameters to be identifiable from the terminal parameters and thus makes the junction between R_5 and the real part of the termination less transparent in the expressions. Based on these two pieces of information, we show that we can accurately estimate the loop IL within ± 1 dB (generally well within the limits) for most loops.

We have tested each optimization approach with 7 loop series (8 loops in a series) for a total of 56 loops. Since each loop is terminated by one of four different telephone devices described in section 3.3, such that each optimization approach will test $56 \times 4 = 224$ loop combinations.

4.3.1. Loss Estimation Using On-hook Impedance Measurements

4.3.1.1. Unconstrained Optimizations

Section 3.6 has described the optimization algorithm where the loop parameters were not constrained. We have tested this approach using loop series A. The loops are terminated at the 500-type mechanical telephone. The on-hook model shown in Figure 3.1a is used with 2 different frequencies (1.0 and 1.5 kHz).

Table 4.2 shows the result of the optimization program matching the model's input impedance to the measured ones for loop 3a, 5a, and 8a. It is clear that we have almost perfect impedance matching to within 1Ω (Table 4.2). The IL was estimated using the parameters obtained from the optimization. Table 4.3 summarizes the results. As we can see, the IL estimates are totally unacceptable. The results can be explained from the optimized loop parameters given in Table 4.4. Some "optimum" values for the resistance are negative resulting in R_5 and R_6 for loop 3a canceling out each other, causing a very small IL estimation (0.15 dB). The resistive parameter R_5 , for loop 5a and 8a are very large, 1676Ω and 3497Ω , causing the impedance model to effectively become a 1 stage model (because the 2nd stage is effectively opened). At the same time, the large values for R_5 result in large IL estimates for these 2 loops (13.64 dB and 18.96 dB).

The values, $-196\ \Omega$, $1676\ \Omega$, and $3497\ \Omega$ given in Table 4.4 for R_5 are obviously unrealistic because the physical CSA loops will never have negative resistive values nor resistive values as large as $1676\ \Omega$. To eliminate the possibility of these unrealistic parameters, constrained optimizations was carried out for the remaining simulations.

Table 4.2 Errors of impedance matching using unconstrained optimization

Loop	Frq(kHz)	Simulated		Optimized		Absolute Error	
		Re(Zi)	Im(Zi)	Re(Zi)	Im(Zi)	Re(Zi)	Im(Zi)
3a	1.0	197	-1457	196	-1456	1	1
	1.5	196	-969	196	-970	0	1
5a	1.0	247	-1137	248	-1137	1	0
	1.5	247	-761	247	-761	0	0
8a	1.0	239	-1021	239	-1021	0	0
	1.5	239	-682	239	-683	0	1

Table 4.3 Errors of IL estimations using unconstrained optimization

Loop	Frg (kHz)	Simulated IL (dB)	Optimized IL (dB)	Absolute Error (dB)
3a	1.0	3.69	0.15	3.54
	2.8	5.06	1.03	4.03
5a	1.0	3.55	13.64	10.09
	2.8	5.54	18.15	12.61
8a	1.0	3.37	18.96	15.59
	2.8	5.70	24.44	18.74

Table 4.4 Optimized loop parameters using unconstrained optimizations

Loop	R ₅	R ₆	C ₇	C ₈
3a	-196	196	5.50x10 ⁻⁶	5.44x10 ⁻⁶
5a	1676	224	1.59x10 ⁻⁶	1.25x10 ⁻⁵
8a	3497	227	8.87x10 ⁻⁷	1.47x10 ⁻⁵

4.3.1.2. Constrained Optimizations

The same optimization was conducted as in section 4.3.1.1 except for the fact that realistic constraints were imposed on the loop parameters as explained in section 3.6. We have tested this approach with the 224 loop combinations (56 loops terminated with four types of ringers) discussed in section 4.3. Table 4.5 shows the mean and standard deviation of the IL errors calculated at 1 kHz for these 224 loop combinations. We group the errors to each type of telephone ringer termination. We have found from Table 4.5 that all 3 electronic ringers have average mean error below 0.36 dB, and the 500-type mechanical ringer has the largest, 0.41 dB, mean error. The overall average error is calculated by averaging the errors of the 224 loop combinations. The result is 0.36 dB.

overall average error is calculated by averaging the errors of the 224 loop combinations. The result is 0.36 dB.

Table 4.5 The mean and standard deviation of the IL error at 1.0 kHz for the 224 loop combinations using constrained optimizations on on-hook approach

Ringer Device	Mean (dB)	Standard Deviation (dB)
500-type	0.43	0.38
TEL<OY>	0.34	0.26
NTOC22AE 02	0.33	0.27
SPP80	0.33	0.26
Overall	0.36	0.29

If we look closely at the distribution of the IL error in Figure 4.3, we find that 74% (166/224) loop combinations have errors smaller than 0.5 dB, 91% (204/224) loop combinations have errors smaller than 0.8 dB, and 3.6% (8/224) have errors larger than 1 dB.

Table 4.6 shows the 20 loop combinations with errors larger than 0.8 dB. Of these, eight involve the 500-type mechanical ringers. Five of these eight loop combinations involving the 500 type ringer have errors larger than 1 dB. This suggests that the mechanical ringer can cause unacceptable errors for this approach.

Considering the actual loops in Table 4.6, we can also see that the errors on loops 1a, 3e, 5a are large (around 0.90 dB) independent of the terminations. Loop 1a and 3e are reversed gauge¹⁷ design. Reversed gauge loops make up half of the loops

¹⁷ Loop design which is not economical because the thicker gauge wire-pair is connected closer to CO and will occupy more space. This kind of loop design is also not recommended as we will see in all three optimization approaches that this design causes problems in IL estimations.

in Table 4.6 (1a, 4a, 8c, 3e, and 4e). Loops with long bridged taps can also cause problems-- loop 5a has a bridged tap 2.5 kft (over the CSA limit).

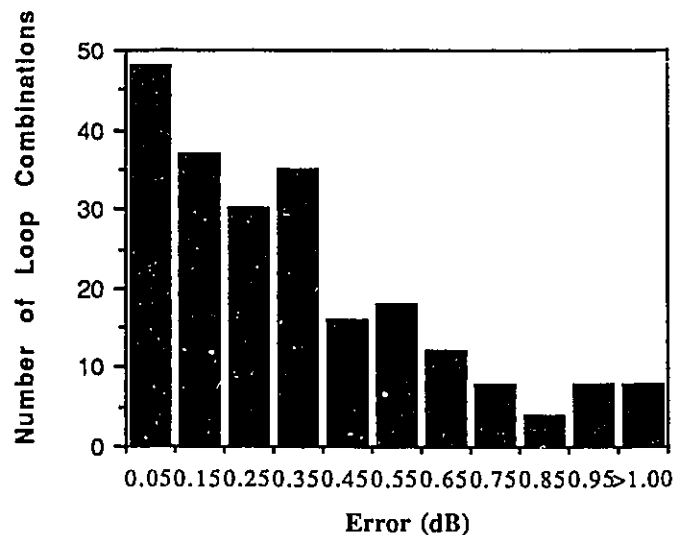


Figure 4.3 The distribution of the IL error at 1.0 kHz for the 224 loop combinations using constrained optimizations of on-hook measurements

Loop 3a, 1d, and 2d all use extensively AWG 26 which could possibly have problems with mechanical ringers for this approach. Loops 4e and 8e have multi-gauge jump design. In addition to this, loop 4e is also reversed gauge design. When loop 4e is terminated at the 500-type ringer, the IL error is the largest with 1.88 dB. This large error can be explained by its unusual loop design plus the fact that on-hook measurements are ambiguous as was discussed in section 3.4.2.2.

Based on the above discussions, we can see that this approach does not provide the required accuracy of loss estimation for:

1. reverse gauge loops (thicker gauge followed by finer gauge),
2. multi-gauge jump loops,
3. loops that extensively use AWG 26 .

When the optimum parameters obtained above were used to estimate the insertion loss at 2.8 kHz (rather than 1 kHz), the results in Figure 4.4 and Table 4.7 were obtained. The results should be predictable. We have found that the overall average mean IL error for 2.8 kHz (Table 4.7) increased from 0.36 dB to 0.50 dB. Figure 4.4 shows that 49 loop combinations (compared to 20 at 1 kHz) have errors larger than 0.8 dB, and 32 of them (compared to 8) have over 1 dB error.

In section 4.4, we will introduce the Frequency projection method to project the IL at 1.0 kHz to 2.8 kHz, such that the IL error at 2.8 kHz is as small as at 1.0 kHz.

Table 4.6 The loop combinations that have IL error over 0.80 dB using constrained optimizations on on-hook approach.

Loop	Terminations : 1= 500-type, 2=TEL<OY>, 3=NTOC22AE02, 4= SPP80	Error (dB) -- in the sequence of the terminations column
1a	1, 2, 3, 4	1.05, 1.06, 1.07, 1.04
3a	1	0.92
4a	1	0.94
5a	2, 3, 4	0.91, 0.89, 0.93
8c	1	1.22
1d	1	1.29
2d	1	1.18
3e	1, 2, 3, 4	0.95, 0.96, 0.95, 0.94
4e	1	1.88
8e	2, 4	0.83, 0.85

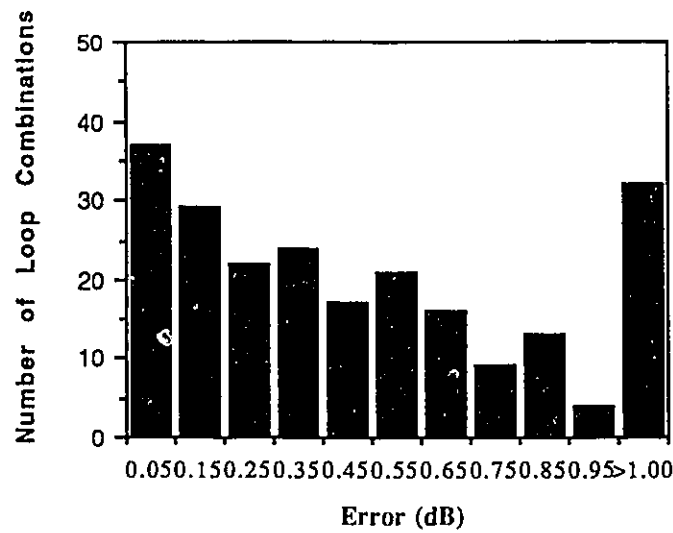


Figure 4.4 The distribution of the IL error at 2.8 kHz for the 224 loop combinations using the optimized parameters of constrained optimizations of on-hook approach at 1.0 kHz.

Table 4.7 The mean and standard deviation of the IL error at 2.8 kHz for the 224 loop combinations using the optimized parameters from constrained optimizations of on-hook approach at 1.0 kHz.

Ringer Device	mean (dB)	Standard Deviation (dB)
500-type	0.52	0.41
TEL<OY>	0.49	0.40
NTOC22AE 02	0.48	0.39
SPP80	0.50	0.42
Overall	0.50	0.41

4.3.2. Constrained Loss Estimation Using Off-hook Input Impedance Measurements

In this section, we assume the availability of off-hook input impedance measurements. The simulations were conducted for the same 224 loop combination. In section 3.4.1 we have discussed the use of $(R_1 + \omega R_2) + j(R_3 + \omega R_4)$ as the off-hook model. We also noted that the imaginary part of the telephones' off-hook impedance given by [Kahn 88] is relatively constant with respect to frequencies. We thus proposed a simplified off-hook model $(R_1 + \omega R_2) + jR_3$. The results of using this simplified model are referred to as <LR, CX>. To preserve the generality, the unsimplified model is also discussed. The results are referred to as <LR, LX>.

Table 4.8 and 4.9 show that the IL error for <LR, LX> and <LR, CX> are very similar at 1 kHz. The difference mostly comes for the case of the NTE2500 termination. However the mean error is obviously a function of the termination. For <LR, LX>, the smallest mean error is 0.23 dB (for CGE29100), but the largest mean error is 0.70 dB (for ET121). However studying the curve of the off-hook input impedance given by [Kahn 88], the curve for ET121 is quite close to the curve for NTE2500 while the IL errors are quite different. This raises some questions about the consistency of this approach.

Table 4.8 The mean and standard deviation of the IL error at 1.0 kHz for the 224 loop combinations using constrained optimizations of off-hook measurements <LR, LX>.

Off-hook Device	mean (dB)	Standard Deviation (dB)
NT500	0.26	0.18
ET121	0.70	0.33
NTE2500	0.32	0.23
CGE29100	0.23	0.18
Overall	0.38	0.23

Table 4.9 The mean and standard deviation of the IL error at 1.0 kHz for the 224 loop combinations using constrained optimizations of off-hook measurements <LR, CX>.

Off-hook Device	mean (dB)	Standard Deviation (dB)
NT500	0.26	0.19
ET121	0.72	0.29
NTE2500	0.19	0.13
CGE29100	0.25	0.18
Overall	0.36	0.20

Figure 4.5 and 4.6 show the distribution of error for <LR, LX> and <LR, CX>. 218 of the 224 loop combinations converged for <LR, LX> and 223 of the 224 loop combinations converged for <LR, CX>. The percentage of convergent loops is somehow related to the constraints imposed on C₇ and C₈. We found that relaxing constraint on C₇ and C₈ results in faster convergence rates and higher completion rates, but the final IL errors are larger. A constraint of $\pm 50\%$ change on C₇ and C₈ was simulated. Loop series A was tested using <LR, CX>, and all combinations converge. However, the average IL error was 0.90 dB as opposed to 0.77 dB for $\pm 10\%$ constraint on C₇ and C₈.

For the <LR, LX> case where 218 loop combinations converged, 26 of those 218 loop combinations have errors larger than 0.8 dB, and 13 of them are larger than 1 dB. For <LR, CX>, only one loop combination did not converge. Of those that did converge, 24 loops have errors larger than 0.8 dB, and the error for 8 of them is larger than 1 dB.

From the above discussion, we can see that the results of this approach are a function of terminations. We have found that large errors happened mostly for loops terminated at ET121. Since the characteristics of ET121 are quite typical, this termination by itself could not be considered the cause of the large error. It was felt

that these errors resulted primarily from the approach itself where the model resistance and $R_1 + \omega R_2$ of the termination were effectively lumped together in the impedance matching stage but were very independent in the insertion loss estimation.

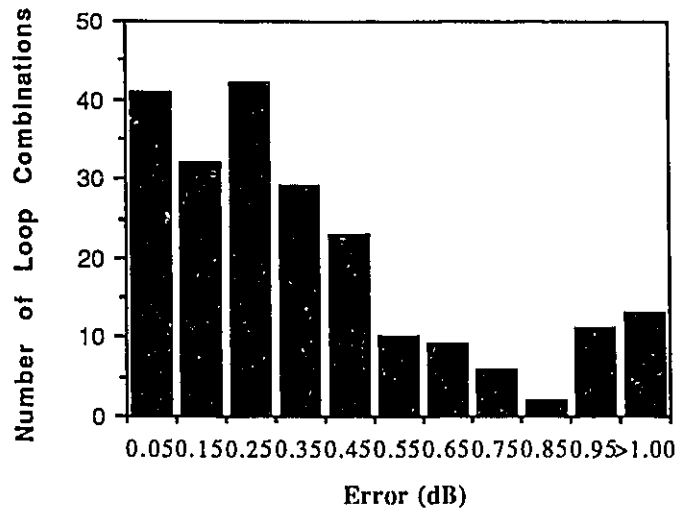


Figure 4.5 The distribution of the IL error at 1.0 kHz for the 224 loop combinations using constrained optimizations of off-hook approach <LR, LX>. Only 218 loop combinations are converged.

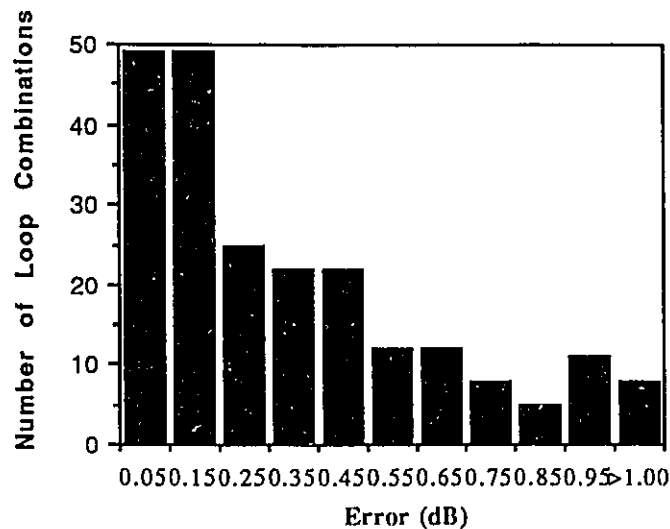


Figure 4.6 The distribution of the IL error at 1.0 kHz for the 224 loop combinations using constrained optimizations of off-hook approach <LR, CX>. Only 223 loop combinations are converged.

4.3.2.1. Identifying the Break-point between the Model and Termination Resistance at the Far End

The simulation results using the off-hook impedance model demonstrate a very serious weakness in this approach for the proper determination of the loop and termination parameters. The resistor at the second stage of the model, namely R_5 , is connected in series with the real part of the off-hook model, namely $R_1 + \omega R_2$. In the input impedance expressions, R_5 and $R_1 + \omega R_2$ show up together as a unit. But the IL expressions require these two parts be properly separated.

In Table 4.10, we list the results from the optimization approach in section 4.3.2 for loop 1a to demonstrate this point. Column 2 gives the actual values for the parameters. Column 3 gives the values obtained by the optimization assuming prior knowledge of termination (section 4.1.2). Column 4, 5 give results obtained using only off-hook measurements as discussed in this section. As expected, we can see that exact knowledge of termination results in an almost perfect match and negligible IL estimation error (column 2 and 3). In contrast, column 4, 5 result in loop parameters that are very different from the actual values despite the close matching of input impedance.

We will now compare the loop resistive parameters, R_5 and R_6 , for $\langle LR, LX \rangle$ (column 5) and those obtained from using the exact loop make-up and termination (column 2).

$$\text{Total loop resistance (column 2)} = 125.2 \times 2 + 78.8 \times 2 = 408 \Omega$$

and for $\langle LR, LX \rangle$ we get,

$$\text{Total loop resistance (column 5)} = 31.4 \times 2 + 74.9 \times 2 = 212.6 \Omega$$

with a difference of -195.4Ω. Now let us turn our attention to the termination. To calculate the real part of the termination, we use $R_1 + \omega R_2$. For column 2 we get,

$$\text{Termination (column 2)} = 255 + 2\pi \times 1000 \times 2.86 \times 10^{-2} = 434.7 \Omega$$

and for $\langle LR, LX \rangle$ we get,

$$\text{Termination (column 5)} = 453 + 2\pi \times 1000 \times 2.80 \times 10^{-2} = 628.9\Omega$$

and the difference of the real part of the termination is 194.2Ω.

We see that this positive 194.2Ω error in the termination resistive value is almost cancelled by the negative 195.4Ω error in the loop total resistance for the <LR, LX>. This suggests that the break-point given by the optimization method is actually located inside the loop, causing the 1.15 dB underestimated error. Results for <LR, CX> are similar to those for <LR, LX>.

Table 4.10 The example that <LR, CX> and <LR, LX> fail to determine the proper break-point at the far end.

Parameters in the model	Actual Loop 1a	Known Termination	Results from <LR, CX> optimizations	Results from <LR, LX> optimizations
R ₁	255	255	472	453
R ₂	2.86x10 ⁻²	2.86x10 ⁻²	2.10x10 ⁻²	2.80x10 ⁻²
R ₃	50	50	121	51
R ₄	4.77x10 ⁻³	4.77x10 ⁻³	0.00	0.80x10 ⁻²
2R _{5s}	125.2x2	117.4x2	68.4x2	31.4x2
2R _{6s}	78.8x2	88.3x2	50.2x2	74.9x2
C ₇	4.72x10 ⁻⁸	3.83x10 ⁻⁸	4.28x10 ⁻⁸	4.51x10 ⁻⁸
C ₈	4.72x10 ⁻⁸	5.30x10 ⁻⁸	4.28x10 ⁻⁸	4.29x10 ⁻⁸
Total R ₅ and R ₆	408	411.4	237.2	212.6
Total C ₇ and C ₈	9.44x10 ⁻⁸	9.13x10 ⁻⁸	8.56x10 ⁻⁸	8.80x10 ⁻⁸
Loop resistance error (Ω)	-----	3.4	-170.8	-195.4
IL Error (dB)	-----	0.03	-1.00	-1.15

In conclusion, when matching input impedance, the output port point is not properly identified leading to large errors for the off-hook case. Since we had seen earlier that results from on-hook case were not acceptable either, it is clear that loss estimation based on either off-hook or on-hook impedance matching methods individually has problems. In the following section, we propose using both on-hook and off-hook measurements simultaneously to improve the estimation.

4.3.3. Constrained Loss Estimation Based on Combined On-hook and Off-hook Input Impedance Measurements

In this section, we propose combining both previous approaches based on on-hook and off-hook measurements to obtain accurate loss estimation for the loops considered. The on-hook measurements are added to the off-hook measurements to help the off-hook impedance model identify the break-point between R_5 and $R_1 + \omega R_2$ at the customer's end. It will be shown that by applying both the on-hook impedance model and the off-hook impedance model simultaneously, the previous problems are minimized. In this case, since we have two possible terminations, input impedance measurements are made at two frequencies for each of the two terminations (as opposed to four frequencies for one termination) -- resulting in 4 complex functions.

Again, we test this approach with the same 224 loop combinations described in section 4.3. Significant improvement was obtained. Figure 4.7 shows the overall average mean error given in Table 4.11 has dropped to 0.32 dB. The dependence on the terminations for this approach is minimized (compared to the previous 2 approaches) as evidenced by the fact that the average error for all termination is about the same. Finally, the number of loop combinations that has loss estimation error over 0.80 dB has been reduced to 8 with only 2 of them over 1 dB. Details of these

offending loops are given in Table 4.12. We also note that the 8 loop combinations with errors in excess of 0.8 dB result from 3 loops (1a, 3e, 4e) that have reversed gauge designs. These are highly uncommon and unrecommended loops. The largest error comes from loop 4e which is a reversed gauge loop with multi-gauge jumps. Both properties are highly unlikely.

Thus, this approach is proposed as a highly reliable way of estimating insertion loss to within ± 1 dB using only measurements at the central office for the on-hook and off-hook customer's termination.

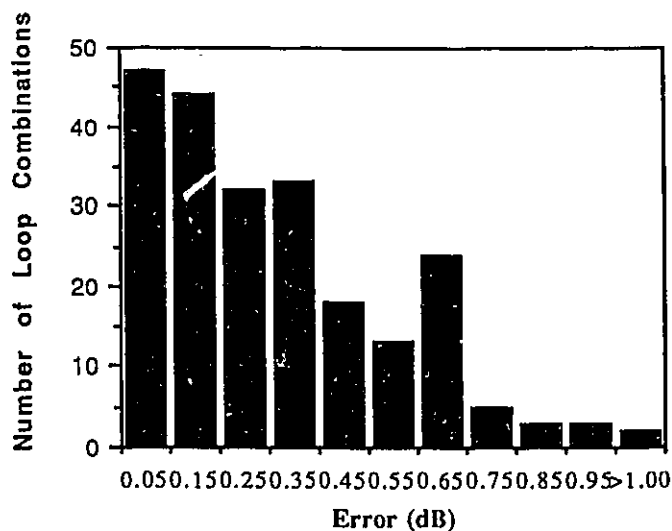


Figure 4.7 The distribution of the IL error at 1.0 kHz for the 224 loop combinations using constrained optimizations of combined on-hook and off-hook approach.

Table 4.11 The mean and standard deviation of the IL error at 1.0 kHz for the 224 loop combinations using constrained optimizations of combined on-hook and off-hook approach.

Ringer Device	mean (dB)	Standard Deviation (dB)
500-type	0.34	0.29
TEL<OY>	0.31	0.24
NTOC22AE 02	0.32	0.24
SPP80	0.31	0.22
Overall	0.32	0.25

Table 4.12 The loop combinations that have IL error over 0.80 dB using constrained optimizations of combined on-hook and off-hook approach.

Loop	Terminations : 1= 500-type, 2=TEL<OY>, 3=NTOC22AE02, 4=SPP80	Error (dB) -- in the sequence of the terminations column
1a	1, 2, 3	0.95, 1.06, 0.97
3e	1, 2, 3, 4	0.90, 0.94, 0.90, 0.87
4e	1	1.54

4.4. Loss Estimation for Frequencies Higher than 1 kHz -- Frequency Projection Method

Earlier, in section 2.5.1 we discussed the importance of accurate estimation of the insertion loss at 1 kHz. However, there is also a need to estimate the insertion loss at other frequencies throughout the voice range. The obvious method to achieve this would be to repeat the proposed combined on-hook and off-hook approach using input impedance measurements at the vicinity of the desired frequency. This would be required since using the parameters obtained through input impedance matching at 1

kHz to estimate loss at 2.8 kHz for example will definitely result in higher errors. Here, we propose to "project" the loss at 1.0 kHz into an estimate of the loss at 2.8 kHz while maintaining the 1 dB accuracy.

The proposed approach is based on some observations made in the process of modelling the subscriber loop. It was noted that if the loop is modelled using a single RC section as shown in Figure 4.8 at a given frequency f_0 , then the insertion loss computed using these values R and C at higher frequencies will have the same error as that at the original frequency, f_0 .

R and C are defined as

$$R = \text{Re}[Z_{in}(\omega_0)|_{\text{on-hook}}] \quad (4-1a)$$

$$C = \frac{1}{\omega_0 \text{Im}(Z_{in}(\omega_0)|_{\text{on-hook}})} \quad (4-1b)$$

where $\omega_0 = 2\pi f_0$, and $Z_{in}(\omega_0)|_{\text{on-hook}}$ is the measured input impedance at ω_0 with customer's termination on-hook.

From Figure 4.9, we can see that using R and C as defined in eqn.(4-1) to calculate insertion loss at different frequencies in the voice band will result in basically a constant error at all frequencies. Thus, if we can accurately determine one point on the curve (i.e. estimate the IL accurately at one frequency), then, we can use the same values for R and C to estimate the IL at higher frequency using Figure 4.8 to within the same error.

This is a significant result since it expands the accuracy of our model to the whole voice range. Thus, rather than repeating the optimization process for every frequency: we only need to perform the optimization and determine the insertion loss accurately from the optimum values of R_5 , R_6 , C_7 , C_8 at one frequency. From that frequency we measure and calculate R and C in Figure 4.8. Insertion loss is then calculated using this model at other voice-band frequencies while preserving the same error.

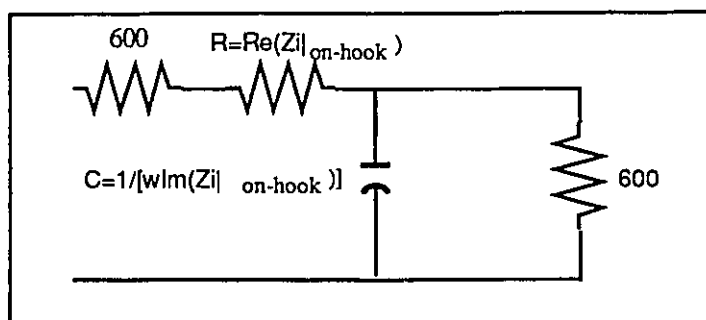


Figure 4.8 The Frequency projection model

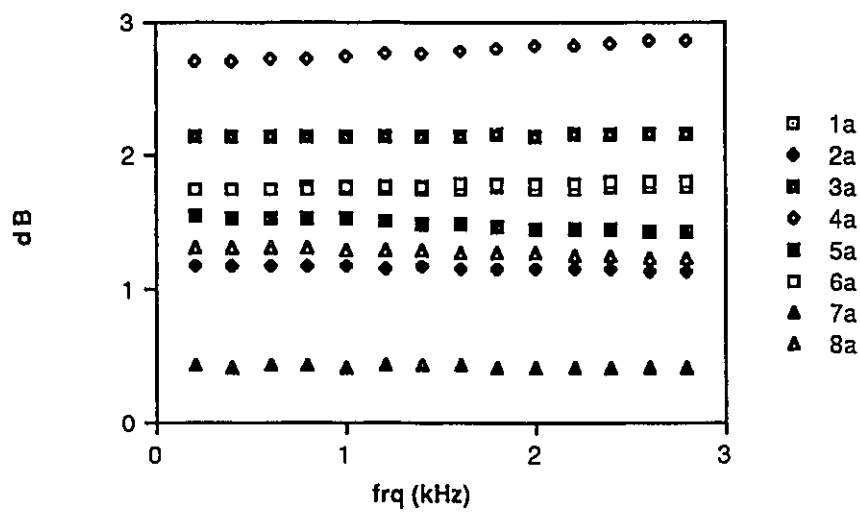


Figure 4.9 The error of the insertion loss estimated by the Frequency projection model

4.5. Effects of Error in Impedance Measurements on Loss Estimation

All the above optimization results are based on the input impedance measurements at various frequencies and various terminations. In our work, these "measurements" were obtained using the simulation package Hoff, thus were determined accurately. To conclude this work, we study the effects of errors in impedance measurements on the loss estimation. Numerous simulations were carried out based on "inaccurate" measurements of input impedance used in the optimization.

In [Bellcore 90], it is suggested that the accuracy of the input impedance measurements be defined according to return loss (RL):

$$RL = -20 \log \frac{|Z_{in} - Z_{ref}|}{|Z_{in} + Z_{ref}|} \text{ dB} \quad (4-2)$$

where Z_{in} is the measured input impedance and Z_{ref} is the actual impedance of the network. The measured return loss between 500 and 3400 Hz [Bellcore 90 -- Table 7.4-2] should be greater than 26 dB. Substituting in eqn.(4-2),

$$-20 \log \frac{|Z_{in} - Z_{ref}|}{|Z_{in} + Z_{ref}|} > 26 \quad (4-3)$$

$$\frac{|Z_{in} - Z_{ref}|}{|Z_{in} + Z_{ref}|} < 0.05 \quad (4-4)$$

$$0.90 < \frac{Z_{in}}{Z_{ref}} < 1.10 \quad (4-5)$$

Thus the measurements can have up to $\pm 10\%$ error. In this section, we will study the performance of the different approaches proposed in section 4.3 when errors exist in some or all of the measured values.

Numerous runs were conducted where the optimization program is provided with inaccurate input impedance measurements. The following remarks are based on the results of these runs:

1. For cases when only on-hook measurements were assumed available, very small changes were observed in the loss estimates when all input impedance measurements had an error of -10%. However, this small change could push the error over 1 dB for those cases with initially large error.
2. Small changes were also observed for simultaneous on-hook and off-hook measurements when all measurements had an error of +10%. In some cases those small changes helped bring large initial errors to less than 1 dB.
3. For on-hook case, an error of 10% in the real part of input impedance at 1 kHz resulted in a significant change in the loss estimation error from -ve to +ve while still being less than 1 dB in amplitude. In other cases, this leads to the error exceeding 1 dB.

Table 4.13 summarizes, in general, the effects of errors in the "measured" values of the input impedance on the loss estimation using each of the three approaches proposed (assuming no knowledge of customer's termination set).

Based on Table 4.13, we can see that for the on-hook and combined on-hook and off-hook cases, the effects of measured impedance errors depend to a large extent on whether all, partly, or one measurement is inaccurate.

It was also found that the off-hook approach is very sensitive to any kind of measurement errors. The average IL change is over 0.50 dB. The on-hook approach and the combined on-hook and off-hook approach are affected mostly by the single on-hook measurement error (0.37 dB and 0.35 dB respectively). The effects are reduced to 0.16 dB and 0.13 dB when all measurements are bearing the same percentage of error. If we look closely at the combined on-hook and off-hook approach, we find that errors found from either the on-hook or off-hook measurements have even smaller effects (0.08 dB). Note also that errors related to off-hook measurements have minimal effect on the IL estimation (0.04 dB change).

The above observations suggest that the off-hook approach is very sensitive to any kind of measurement errors; the on-hook and the combined on-hook and off-hook approach are sensitive to a single error in the on-hook measurements. Overall, we find that the combined approach is the most robust one.

Table 4.13 The summary of IL change for each type of termination and for each approach due to the measurement errors.

<u>On-hook approach</u>		
Error format	Effects on IL	Average change
(i) All measurements	small change	0.16 dB
(ii) Single measurement	big change	0.37 dB
Comment : Sensitive to the single measurement error		
<u>Off-hook approach</u>		
Error format	Effects on IL	Average change
(i) All measurements	big change	0.54 dB
(ii) Single measurement	big change	0.55 dB
Comment: Sensitive to any kind of error		
<u>Combined On-hook and Off-hook</u>		
Error format	Effects on IL	Average change
(i) All measurements	small change	0.13 dB
(ii) Either on-hook or off-hook	small change	0.08 dB
(iii) Single measurement in on-hook	big change	0.35 dB
(iv) Single measurement in off-hook	small change	0.04 dB
Comment: Sensitive to the single on-hook measurement error. Off-hook error does not affect the IL estimation.		

4.6. Conclusions

In this chapter, we have proposed three approaches to characterize the IL of an unknown CSA loop. The first approach assumes knowledge of exact off-hook customer's termination or possibility of having actual short circuit at the customer end. Based on either one of those assumption, excellent loss estimation was obtained in agreement with well known principles of characterizing two-port networks based on two-port information. The IL errors estimated at 1.0 kHz are well below 1 dB. In fact, for the loops that we have tested, the IL errors are all below 0.1 dB. For some services where customers' sites require the operating companies to install equipments for interface purposes, the impedance for such equipments, such as the PBX, are generally known. The impedance characteristics of the trunk interfaces such as the channel banks can also be determined. This approach is useful in such cases. However short-circuited termination at the customer's end is unachievable without a technician presence and the impedance of the off-hook termination is generally unknown.

The second proposed approach is intended to simplify the loss estimation for loops shorter than 4.5 kft. This method involves no complicated optimization methods. For a given loop with loop length shorter than 4.5 kft, the IL of the loop can be estimated by averaging the IL for AWG 19 and AWG 26. This was shown to result in IL error less than 1 dB. This approach would be useful for loss estimation on cables inside buildings where the cable length is limited to 3.5 kft.

The third approach constitutes the heart of this thesis since it requires practically available information at the CO port to characterize the CSA loops and it works for both short loops and long loops. Three methods are proposed, namely the on-hook approach, the off-hook approach, and the combined on-hook and off-hook approach. They all use the appropriate input impedance models given in Figure 3.1a

and 3.1b. By matching the input impedance of these model(s) and the on-hook and off-hook measurements, the parameters in the impedance model(s) are optimized and later used for IL calculation. The IL errors obtained as such are shown to be mostly low and the overall average error for each approach was below 0.40 dB. Table 4.14 summarizes the average IL error for each type of termination, the overall average error, the number of loop combinations that are over 0.80 dB, and the number of loop combinations that are over 1.0 dB for the three approaches. Detailed simulations showed that reverse-gauged loops or loops with multi-gauge jumps consistently gave the worst errors for different terminations.

It was thus concluded that using combined on-hook and off-hook approach, the insertion loss can be estimated to within 1 dB error at 1 kHz. Next, a simple method of using the loop parameter values based on which the loss was estimated at 1 kHz to obtain accurate projection of insertion loss at 2.8 kHz was given.

Finally the effect of errors in the measurement of input impedance on the loss estimation was considered. Preliminary results show that the result depends on whether all or some of the errors are erroneous as well as on the approach used. The combined on-hook and off-hook approach proved to be the most robust even though it is sensitive to single errors in impedance measurement.

Table 4.14 The summary of the IL error given by the three optimization approaches (i.e. the on-hook, off-hook, and the combined on-hook and off-hook approaches).

Termination	Optimization Approaches			
	On-hook (dB)	Off-hook <LR, LX> (dB)	Off-hook <LR, CX> (dB)	On-hook + Off-hook (dB)
500-type	0.43	0.26	0.26	0.34
ET121+TEL<OY>	0.34	0.70	0.72	0.31
NTE2500+NTOC22AE	0.33	0.32	0.19	0.32
CGE29100+SPP80	0.33	0.23	0.25	0.31
Overall average error	0.36	0.38	0.36	0.32
# of loop combinations over 0.80 dB	20	26	24	8
# of loop combinations over 1.0 dB	8	13	8	2

5. Conclusions and Future Works

5.1. Conclusions

In this thesis, we have discussed different approaches to estimate the insertion loss (IL) of an unknown Carrier Serving Area (CSA) loop for special services. The greatest concern to the telephone companies (telco) is how to design, provision, and maintain the copper loop plants properly and efficiently. Such concern is the motivation for this research. The methods mentioned in this thesis offer approaches that are more economical than the conventional and the current methods for estimating the loop characteristics, within the prescribed error, resulting in significant savings for the telcos.

The fundamental idea of the "Single ended loop characterization" is to estimate the IL of CSA loops in the more general and practical situation where only single port information, the input impedance at the Central Office (CO) port, is measurable. Two types of input impedance are easily available, namely the on-hook and off-hook measurements. These measurements are matched by the on-hook and/or off-hook impedance models (composed of 2-section RC model and a proper termination model) by minimizing the error between the impedance function of the impedance model(s) and the measured input impedance at several frequencies.

Three approaches are proposed, namely the on-hook approach, the off-hook approach, and the combined on-hook and off-hook approach. Results show that the off-hook approach has the largest IL estimation error, the highest probability of

convergence problems and the highest sensitivity to termination and measurement errors. This was true for both termination models when both R and X are assumed linear functions of ω or when R was a linear function of ω but X was constant. The on-hook results were found to be better than the off-hook results in all aspects mentioned above. However, the on-hook approach had problem with mechanical telephones, and the number of loop combinations whose IL error is close to or over 1 dB error was still large. The combined on-hook and off-hook approach has been shown to outperform the other two approaches -- the overall average IL error is the lowest, the approach is least dependent on the termination, and the optimization is least sensitive to measurement errors.

The above approaches yield an estimate of insertion loss at 1 kHz to within 1 dB. Next, a simple approach (Frequency Projection Method) is proposed to estimate IL at higher frequencies to within the same error of ± 1 dB using the loop parameters obtained from the proposed optimizations.

In general, only the input impedance is measurable at CO. However, in some special cases, telcos are able to obtain some extra information about the customer's termination. In such cases, very precise estimations characterizing the CSA loops were shown to be possible. IL over short loops (loops shorter than 4.5 kft) can be estimated by the simplest method without using optimization. The method can guarantee the IL error below 1 dB while IL for known terminations can be estimated with almost zero error.

5.2. Recommendation for Future Works

Nonlinear least square optimizations, such as the optimization approaches proposed in chapters 3 and 4, all have the same problem of the non-uniqueness of the solution. Different set-ups for the initial guesses and the constraints of variables can lead the optimization to different solutions. The set-ups given in section 3.6 produce

the best solutions to estimate the wide varieties of CSA loops we designed. This set-up works particularly well for the combined on-hook and off-hook approach. However, other practical ways of ensuring proper convergence should be investigated for the real CSA loop survey (to be released soon). One should carefully study the loop survey and design a set of CSA loop data base based on it. The new data base should reflect the actual CSA loop plant. We expect the type of loop designs to be more limited than the ones used here and given in appendix A. A tighter set of constraints, compared to the range of constraints given in section 3.6, can be applied to the loop variables. Better selection of initial guess and determination of the final solution should be studied. These would lead to better IL estimations.

The combined on-hook and off-hook approach showed better performance due to establishing a break-point between R_5 and $R_1 + \omega R_2$ in Figure 3.1b. One can modify the 2-section RC model in many ways to separate R_5 from $R_1 + \omega R_2$. One possible alternative is to emulate the existence of a bridged tap between the 2nd section of the RC model and the termination. In doing so, a capacitor is inserted in parallel between R_5 and $R_1 + \omega R_2$. The results using this model should be studied.

The sensitivity of a single measurement error affecting the IL estimations needs to be further studied. Possible solutions may be found if an in-depth analysis on the sensitivity of the input impedance to variations in the parameters of the RC model. The study should also involve the analysis of the convergence characteristics, and the error functions for the optimization approaches.

Finally, the algorithm should be simplified such that the codes for the algorithm can be allocated onto the line unit to perform real time measurements and IL estimation.

References:

- [Andrus et al 86] "Advances in digital loop carrier systems to meet evolving service needs", P.W. Andrus, L.C.J. Roscoe, G.E. Harrington, W.L. Shafer, ISSLS 86, p223-7.
- [AT&T 52] "500 series combined telephone sets", Bell system Practices AT&T Co standard, 1952.
- [AT&T 77-v1] "Telecommunications transmission engineering--principles", AT&T, v1, ch(1, 13), 1977.
- [AT&T 77-v3] "Telecommunications transmission engineering--networks and services", AT&T, v3, ch(3, 4), 1977.
- [B.S.T.R. 83] "High capacity digital service channel interface specification", Bell System Technical Reference, AT&T, Sept. 1983.
- [Bell Lab 82] "Transmission system for communications", Bell Lab 82.
- [Bell Lab 84] "MLT-2: advanced system for interactive loop testing", AT&T Bell Lab Record, Aug 1984, p16-7.
- [Bellcore 86] "Generic automatic loop test systems", TR-TSY-000231, 1986
- [Bellcore 88] "Functional criteria for DLC systems", TR-TSY-000057, 1988.
- [Bellcore 90] "LATA switching systems generic requirements, LSSGR, section 7, TR-TSY-000507, Jun 1990.
- [Bellcore 91-v2] "Telecommunications transmission engineering--Facilities", Bellcore, v2, ch23, 1991.
- [Bellcore 91-v3] "Telecommunications transmission engineering--networks and services", Bellcore, v3, ch(4-5, 11-18, 20-21), 1991.

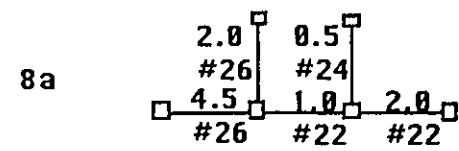
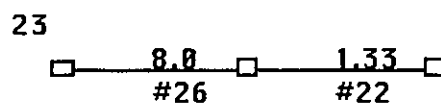
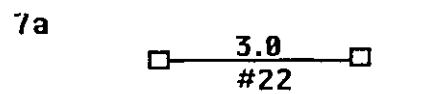
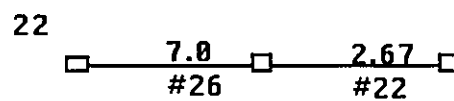
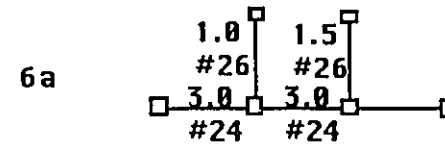
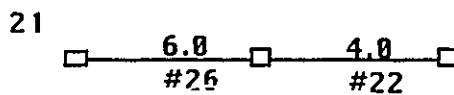
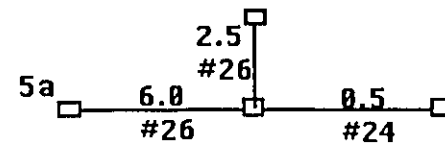
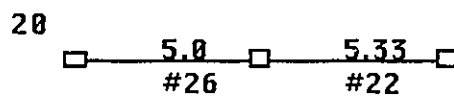
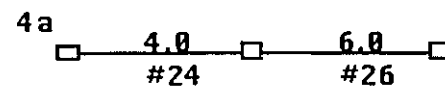
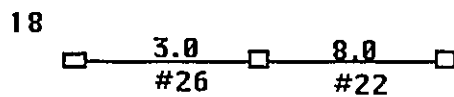
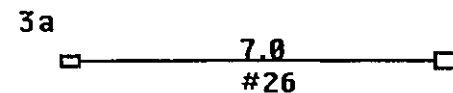
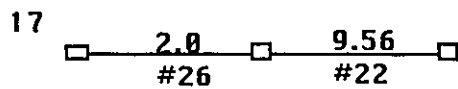
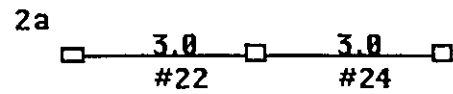
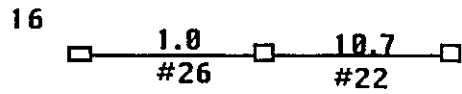
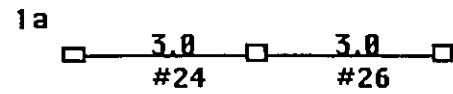
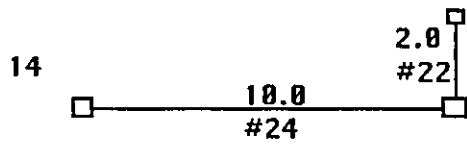
- [Blake et al 81] "Digital signal processor: voice-frequency transmission treatment for special-service telephone circuits", by R.B. Blake, A.C. Bolling, and R.L. Farah, B.S.T.J., vol.60, no.7, pt.2, Sept 81, p1585-619.
- [Boulter et al] "An electronically configurable local optical network", by R.A. Boulter, J.R.W. Ames, ISSLS 86, p.175-80.
- [Byrne et al 82] "Positioning the subscriber loop network for digital services", by T.P. Byrne, R. Coburn, H.C. Mazzoni, G.W. Aughenbaugh, J.L. Duffany, ISSLS 82, p71-75.
- [Chagnon et al 86] "Bell Canada access network evolution plan", by P.J. Chagnon, D. Poirier, ISSLS 86, p.7-11.
- [Cheng 83] "Field and wave electromagnetics", D.K. Cheng, Adelson-Wesley, 1983.
- [Connolly 88] "Using today's equipment for tomorrow's network", by R.D. Connolly, TE&M, Dec 1988, p75-8.
- [Dennis et al 83] "Numerical methods for unconstrained optimization & nonlinear equations", by J.E. Dennis and R.B. Schnabel, Chap 1,2,10.
- [DiBiao et al 73] "A conversational program for telephone circuit analysis", L.S. DiBiao, R.A. McDonald, Bell Telephone Laboratories, 1973.
- [EIA/TIA-464-A] "Private Branch Exchange (PBX) switching equipment for voice applications", Electronic Industries Association, EIA/TIA-464-A.
- [EIA/TIA-470-A] "Telephone instruments with loop signaling", Electronic Industries Association, EIA/TIA-470-A.

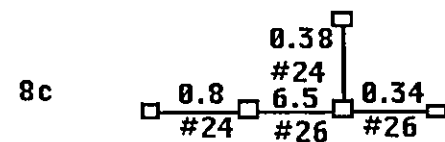
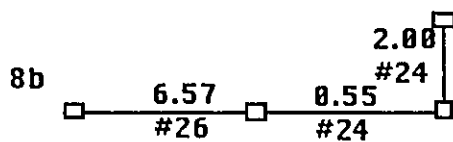
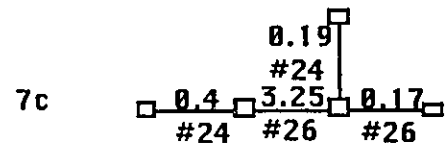
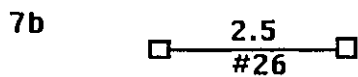
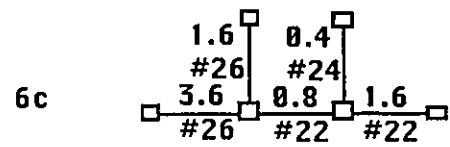
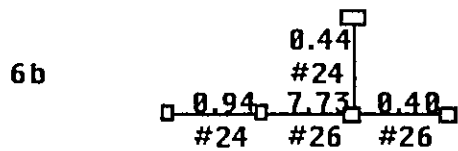
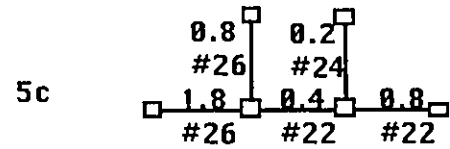
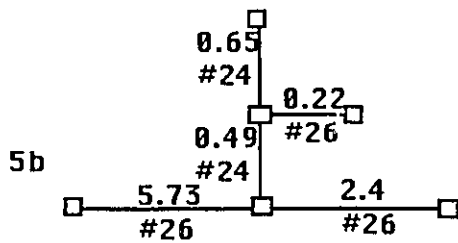
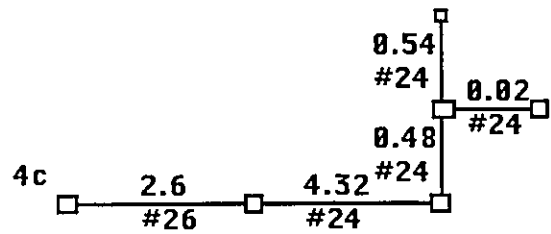
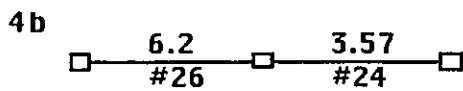
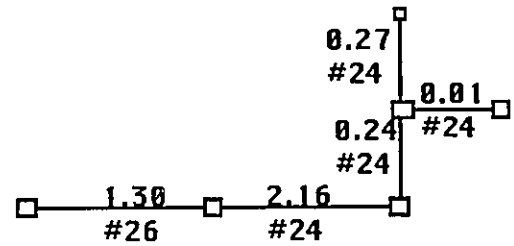
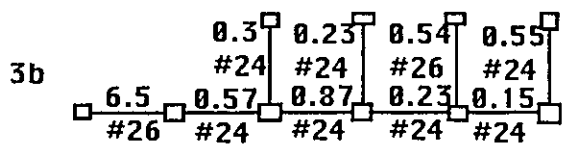
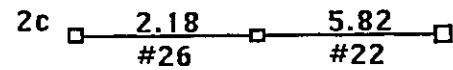
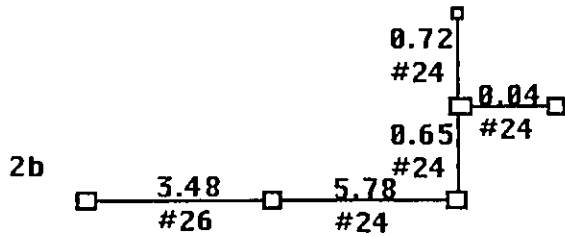
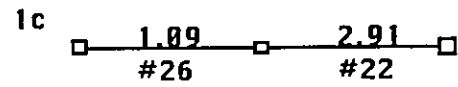
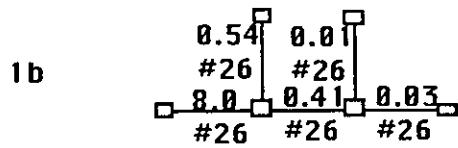
- [FCC 90] "Connection of terminal equipment to the telephone network", Federal Communications Commission (FCC) Rules and Regulations, Part 68 (68.312), 1990, p.68.501-5.
- [Feuster et al 84] "Speeding up the 'service' in special services circuits", by I.R. Feuster and D.C. Radeschi, AT&T Bell Lab Record, May 1984, p8-12.
- [Fleckenstein 84] "Operations support systems: computer aids for the local exchange" by W.O. Fleckenstein, Bell Lab Record, Sept 1982, p185-93.
- [Goleniewski et al 92] "PBX versus Centrex comparison", by L. Goleniewski, R. Horak, The LIDO Organization Inc, 1992.
Reproduced by Datapro Information Services group, Communication Series: Voice network systems V1 (5270), MGH.
- [Gonzalez 84] "Microwave transistor amplifiers analysis and design", G. Gonzalez, Prentice-Hall, 1984.
- [Greco et al 81] "Application of digital loop carrier in the 80's", by G.J. Greco, D.H. Morgen, Bell Lab, N.T.C., Nov 1981, D3.1.1-7.
- [Helsing et al 84] "Reach out and test something special", by D.V. Helsing, L.V. Pannone, T.K. Srinivas, AT&T Bell Lab Record, Nov 1984, p10-14.
- [Huelsman 84] "Basic circuit theory", L.P. Huelsman, 2nd edition, Prentice-Hall, 1984.
- [Hung 81] "A computer program for digital loop systems simulation", by P. Hung, BNR internal document, 1981.
- [IMSL-Math Library] "DUNLSJ", IMSL MATH/LIBRARY v3, 8.1.3., p.841.

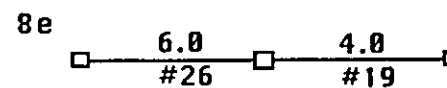
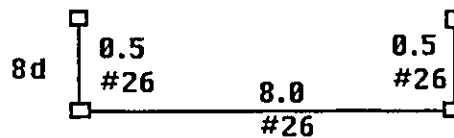
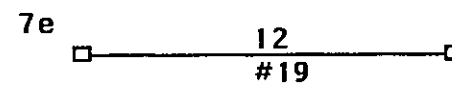
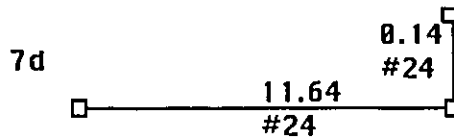
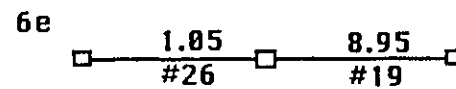
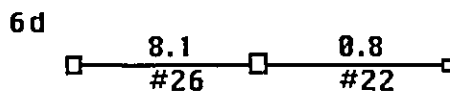
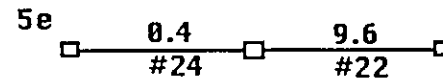
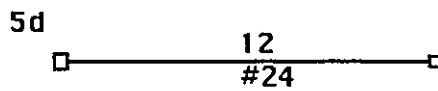
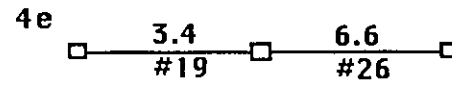
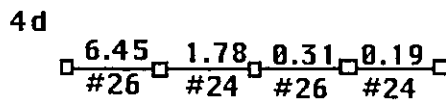
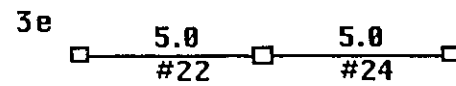
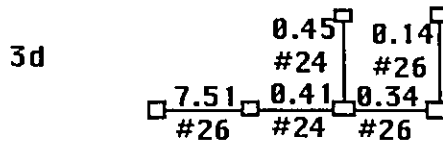
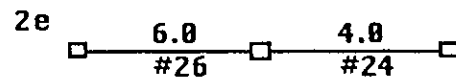
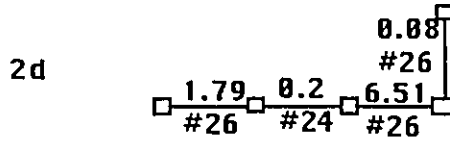
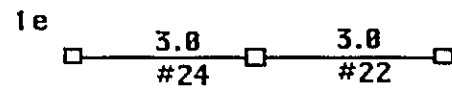
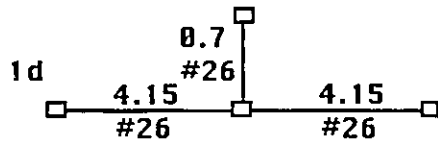
- [Kahn 88] "Impedance characteristics diagrams", by Kahn, BNR, 1988.
- [Karia et al 86] "Digital loop carrier evolution", by A.J. Karia, R.J. Richardson, S.J. Edwards, ISSLS 86, p.228-32.
- [Keathley et al 92] "Venture breaks barrier to special service testing", by T. Keathley, W.H. Duncan, TE&M, Mar 1992, p58-60.
- [Lau et al 86] "Evolution of digital remotes in the access plant", by R. Lau, M.P. Ludlow, P.J. Maciaren, Northern Telecom, ISSLS 86, p.71-76.
- [Levenberg 44] "A method for the solution of certain problems in least squares", by K. Levenberg, Quarterly of Applied Mathematics, 2, 164-168, 1944.
- [Marquardt 63] "An algorithm for least-squares estimation of nonlinear parameters", by D. Marquardt, SIAM Journal on Applied Mathematics, 11, 431-441, 1963.
- [More et al 80] "User guide for MINPACK-1", by More, Jorge, Garbow, and Hillstrom, Argonne National Labs Report ANL-80-74, Argonne, Illinois, 1980.
- [Mortensen 91] "Special service Automation", by M.H. Mortensen, AT&T Technology, v4, no.1, 1991, p44-9.
- [Paul et al 79] "Prediction of crosstalk involving twisted pairs of wires -- Part II : A simplified low-frequency prediction model", C.R. Paul and J.W. McKnight.
- [Plato et al 83] "CAROT's new features expand maintenance and administrative functions", by J.J. Plato, B.S. Robb, Bell Lab Record vol 61, no.9, (July/Aug 1983), p.18-24.
- [Rowe 91] "Voice communication", by S.H. Rowe, Business Telecommunications, Macmillian publishing Co, 2nd ed, 1991, p.133-62.

- [Sims 90] "Centralize special services testing through a DCS", by J.L. Sims, TE&M, Dec 15, 1990, p54-7.
- [Snelling et al 86] "The revolution in the loop network: The evolving broadband technology", R.K. Snelling, J. Chernak, Issls 86, p210-15.
- [Sutton et al 86] "Tracing quality with live calls", by R.A. Sutton, K.W. Evans, J.P. Wagh, D.M. Hornbuckle, TE&M, Nov 15, 1986, p88-96.

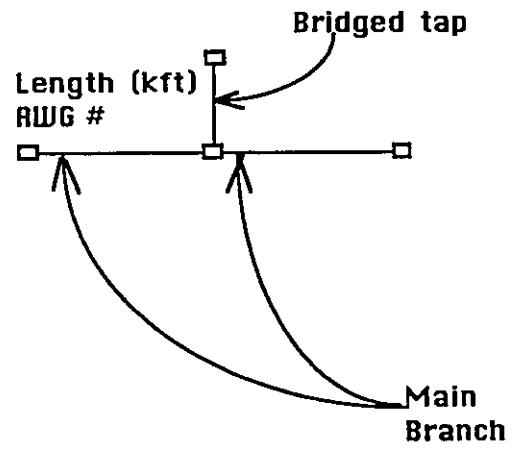
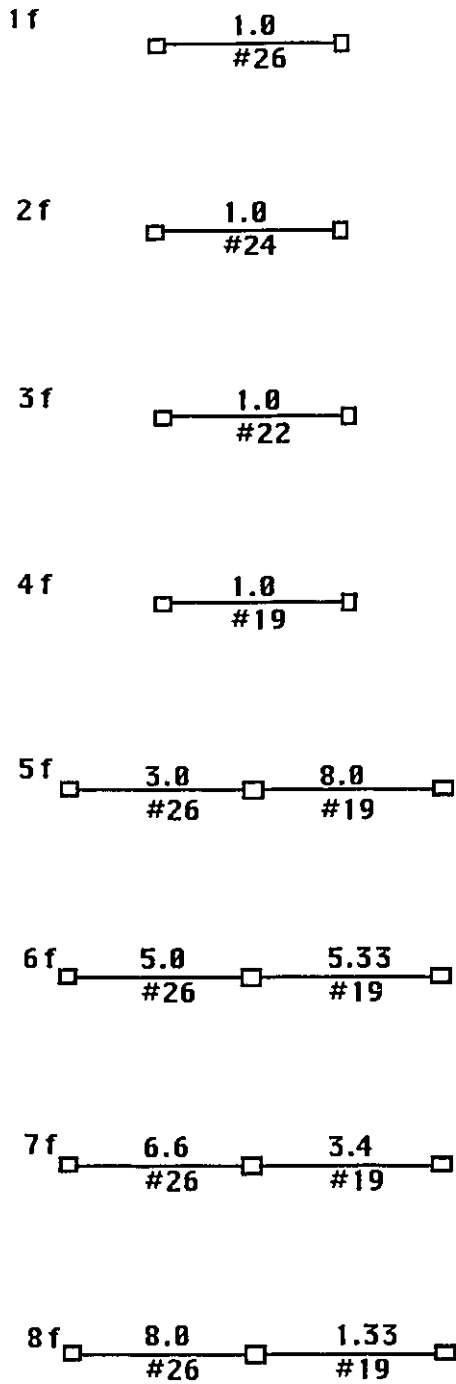
Appendix A Loop Make-ups







Legends:



Appendix B Off-hook Impedance from [Kahn 88]

The off-hook impedance curves for NT500, ET121, NTE2500, and CGE29100 are given in [Kahn 88]. The real and imaginary parts of the impedance are regenerated from 0.5 to 3.0 kHz. They are shown in Figure B.1a and B.1b.

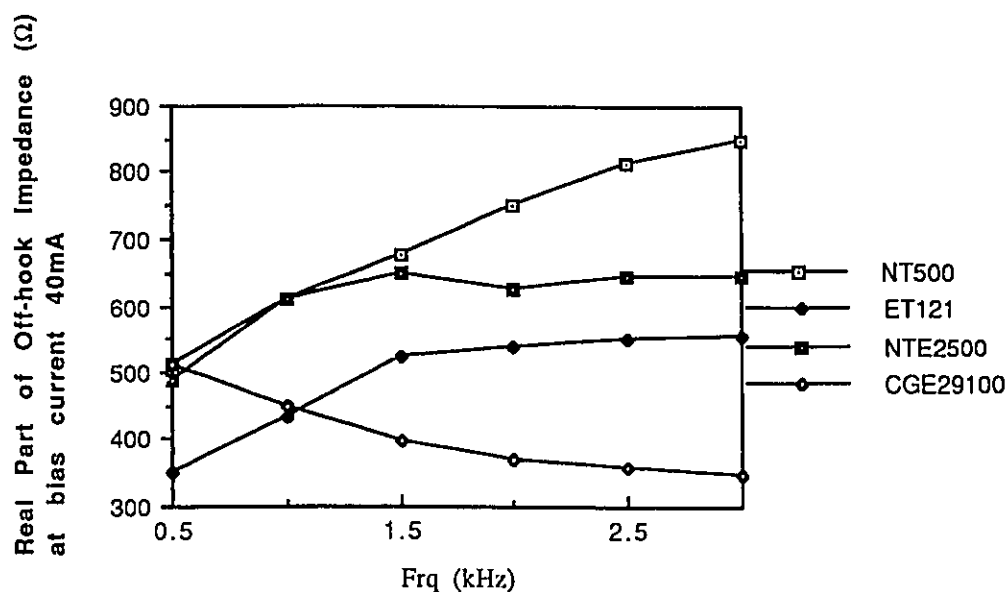


Figure B.1a The real part of off-hook impedance for NT500, ET121, NTE2500, and CGE29100 given by [Kahn 88] at bias current 40mA.

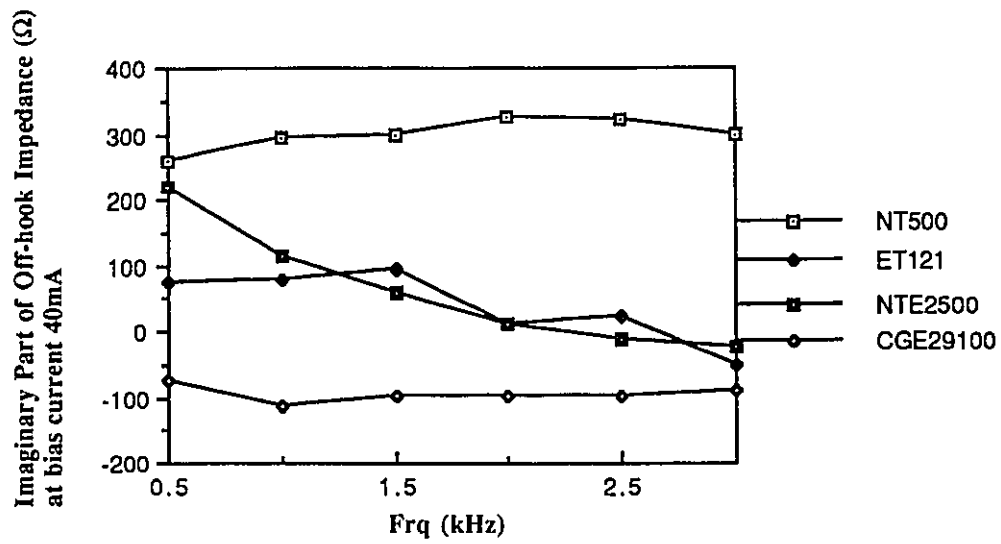


Figure B.1b The Imaginary part of off-hook impedance for NT500, ET121, NTE2500, and CGE29100 given by [Kahn 88] at bias current 40mA.

Appendix C Analysis of Input Impedance Functions and the Jacobians

C.1. Analysis of the On-hook Model

The on-hook model shown in Figure 3.1a can be analyzed stage by stage from right to left. The analysis is made in complex domain in 2 stages, namely Z_{O2} and Z_{O3} , where Z_{O2} is the impedance of the intermediate stage of the model, and Z_{O3} is the impedance of the model. The steps are followed:

C.1.1. Equations for the Input Impedance :

$$Z_{O2} = R_5 + R_6 + S_7$$

$$Z_{O3} = R_6 + \frac{Z_{O2} \cdot S_8}{Z_{O2} + S_8}$$

$$\text{where } S_7 = \frac{1}{j\omega C_7},$$

$$\text{and } S_8 = \frac{1}{j\omega C_8}$$

C.1.2. Equations for the Jacobians:

$$\frac{\partial Z_{O3}}{\partial R_5} = \frac{\partial Z_{O3}}{\partial Z_{O2}} \cdot \frac{\partial Z_{O2}}{\partial R_5} = \frac{S_8^2}{(Z_{O2} + S_8)^2} \cdot 1$$

$$\frac{\partial Z_{O3}}{\partial R_6} = 1 + \frac{\partial Z_{O3}}{\partial Z_{O2}} \cdot \frac{\partial Z_{O2}}{\partial R_6} = 1 + \frac{S_8^2}{(Z_{O2} + S_8)^2} \cdot 1$$

$$\frac{\partial Z_{O3}}{\partial C_7} = \frac{\partial Z_{O3}}{\partial Z_{O2}} \cdot \frac{\partial Z_{O2}}{\partial S_7} \cdot \frac{\partial S_7}{\partial C_7} = \frac{S_8^2}{(Z_{O2} + S_8)^2} \cdot 1 \cdot \frac{-j}{\omega C_7^2}$$

$$\frac{\partial Z_{O3}}{\partial C_8} = \frac{\partial Z_{O3}}{\partial S_8} \cdot \frac{\partial S_8}{\partial C_8} = \frac{Z_{O2}^2}{(Z_{O2}+S_8)^2} \cdot \frac{j}{\omega C_8^2}$$

C.2. Analysis of the Off-hook Model

Similarly the analysis of the terminated model have 3 stages. The steps are followed:

C.2.1. Equations for the Input Impedance:

$$Z_{t1} = R_5 + (R_1 + \omega R_2 + j(R_3 + \omega R_4))$$

$$Z_{t2} = R_5 + R_6 + \frac{Z_{t1} \cdot S_7}{Z_{t1} + S_7}$$

$$Z_{t3} = R_6 + \frac{Z_{t2} \cdot S_8}{Z_{t2} + S_8}$$

$$\text{where } S_7 = \frac{1}{j\omega C_7},$$

$$\text{and } S_8 = \frac{1}{j\omega C_8}$$

C.2.2. Equations for the Jacobians :

$$\frac{\partial Z_{t3}}{\partial Z_{R1}} = \frac{\partial Z_{t3}}{\partial Z_{t2}} \cdot \frac{\partial Z_{t2}}{\partial Z_{t1}} \cdot \frac{\partial Z_{t1}}{\partial Z_{R1}} = \frac{\partial Z_{t3}}{\partial Z_{t2}} \cdot \frac{\partial Z_{t2}}{\partial Z_{t1}}$$

$$\frac{\partial Z_{t3}}{\partial Z_{R2}} = \frac{\partial Z_{t3}}{\partial Z_{t2}} \cdot \frac{\partial Z_{t2}}{\partial Z_{t1}} \cdot \frac{\partial Z_{t1}}{\partial Z_{R2}} = \frac{\partial Z_{t3}}{\partial Z_{t2}} \cdot \frac{\partial Z_{t2}}{\partial Z_{t1}} \cdot (w)$$

$$\frac{\partial Z_{t3}}{\partial Z_{R3}} = \frac{\partial Z_{t3}}{\partial Z_{t2}} \cdot \frac{\partial Z_{t2}}{\partial Z_{t1}} \cdot \frac{\partial Z_{t1}}{\partial Z_{R3}} = \frac{\partial Z_{t3}}{\partial Z_{t2}} \cdot \frac{\partial Z_{t2}}{\partial Z_{t1}} \cdot (j)$$

$$\frac{\partial Z_{t3}}{\partial Z_{R4}} = \frac{\partial Z_{t3}}{\partial Z_{t2}} \cdot \frac{\partial Z_{t2}}{\partial Z_{t1}} \cdot \frac{\partial Z_{t1}}{\partial Z_{R4}} = \frac{\partial Z_{t3}}{\partial Z_{t2}} \cdot \frac{\partial Z_{t2}}{\partial Z_{t1}} \cdot (jw)$$

$$\frac{\partial Z_{t3}}{\partial Z_{R5}} = \frac{\partial Z_{t3}}{\partial Z_{t2}} \cdot \left(1 + \frac{\partial Z_{t2}}{\partial Z_{t1}}\right)$$

$$\frac{\partial Z_{t3}}{\partial Z_{R6}} = \left(1 + \frac{\partial Z_{t3}}{\partial Z_{t2}}\right)$$

$$\frac{\partial Z_{t3}}{\partial C_7} = \frac{\partial Z_{t3}}{\partial Z_{t2}} \cdot \frac{\partial Z_{t2}}{\partial S_7} \cdot \frac{\partial S_7}{\partial C_7}$$

$$\frac{\partial Z_{t3}}{\partial C_8} = \frac{\partial Z_{t3}}{\partial S_8} \cdot \frac{\partial S_8}{\partial C_8}$$

where $\frac{\partial S_7}{\partial Z_{C7}} = \frac{j}{wC_7^2}$

$$\frac{\partial S_8}{\partial Z_{C8}} = \frac{j}{wC_8^2}$$

$$\frac{\partial Z_{t2}}{\partial Z_{t1}} = \frac{S_7^2}{(Z_{t1} + S_7)^2}$$

$$\frac{\partial Z_{t3}}{\partial Z_{t2}} = \frac{S_8^2}{(Z_{t2} + S_8)^2}$$

$$\frac{\partial Z_{t3}}{\partial S_7} = \frac{Z_{t1}^2}{(Z_{t1} + S_7)^2}$$

$$\frac{\partial Z_{t3}}{\partial S_8} = \frac{Z_{t2}^2}{(Z_{t2} + S_8)^2}$$

Appendix D Program Listing (Fortran)

The program listing for the combined on-hook and off-hook approach is given. By excluding the off-hook or the on-hook part in this program, the program will work for the on-hook or the off-hook approach.


```

C      READ ON-HOOK AND OFF-HOOK MEASUREMENTS FOR EACH LOOP          ON000560
C      L : LOOP COUNTER (1-8)                                         ON000570
      DO 1 L=1,8                                                       ON000580
      WRITE (2,9) L                                                    ON000590
      CALL IMPED(W,OW,REZI,IMZI,OREZI,OIMZI)                            ON000600
                                                                           ON000610
C      INITIALIZATION                                                 ON000620
      CNT=0                                                            ON000630
      DO 15 I=1,5                                                       ON000640
      DO 16 J=1,8                                                       ON000650
      BXX(I,J)=0.                                                       ON000660
      BYY(I,J)=0.                                                       ON000670
16     CONTINUE                                                         ON000680
      BERR(I)=0.                                                         ON000690
15     CONTINUE                                                         ON000700
                                                                           ON000710
C      ON000720
C      TL : LENGTH OF LOOP L                                          ON000730
C      C : CALCULATED CAPACITANCE FOR EACH CAPACITOR OF LOOP L      ON000740
C      CU : UPPER LIMIT FOR EACH CAPACITOR OF LOOP L                ON000750
C      CL : LOWER LIMIT FOR EACH CAPACITOR OF LOOP L                ON000760
C      RU : UPPER LIMIT FOR EACH RESISTOR OF LOOP L                 ON000770
C      RL : LOWER LIMIT FOR EACH RESISTOR OF LOOP L                 ON000780
C      ON000790
      C(L)=0.5/(OW(2)*(-OIMZI(2)))                                     ON000800
      TL=2.DO*5.28*C(L)/0.083D-6                                       ON000810
      CU(L)=1.10D0*C(L)                                                 ON000820
      CL(L)=0.90D0*C(L)                                                 ON000830
      RU(L)=440.8*TL/5.28/4.DO                                          ON000840
      RL(L)=87.DO*TL/5.28/4.DO                                          ON000850
C      CSA LIMIT FOR EACH RESISTOR                                     ON000860
      IF (RU(L).GT.187.5D0) THEN                                       ON000870
      RU(L)=187.5                                                       ON000880
      ENDIF                                                             ON000890
                                                                           ON000900
C      LL : COUNTER FOR RUNS (0-4)                                     ON000910
7      DO 2 LL=0,4                                                      ON000920
                                                                           ON000930
      XGUESS(1)=500.DO                                                  ON000940
      XGUESS(2)=1.D-2                                                  ON000950
      XGUESS(3)=400.DO                                                  ON000960
      XGUESS(4)=1.D-2                                                  ON000970
      XGUESS(5)=(RU(L)-RL(L))/4.DO*LL+RL(L)                            ON000980
      XGUESS(6)=(RU(L)-RL(L))/4.DO*LL+RL(L)                            ON000990
      XGUESS(7)=C(L)                                                    ON001000
      XGUESS(8)=C(L)                                                    ON001010
                                                                           ON001020
C      SET EQUAL WEIGHT TO ALL FUNCTIONS AND VARIABLES              ON001030
      DO 10 J=1,M                                                       ON001040
      FSCALE(J)=1.                                                       ON001050
      XSCALE(J)=1.                                                       ON001060
10     CONTINUE                                                         ON001070
                                                                           ON001080
C      SET MAXIMUM ITERATIONS                                         ON001090
      CALL DU4LSF (IPARAM, RPARAM)                                     ON001100

```

```

IPARAM(3) = 200000 ON001110
IPARAM(4) = 200000 ON001120
IPARAM(5) = 200000 ON001130
ON001140
C CALLING OPTIMIZATION PROGRAM TO OPTIMIZE LOOP PARAMETERS ON001150
CALL DUNLSJ (FONOFF, JONOFF,M, N, XGUESS, XSCALE, FSCALE, ON001160
$ IPARAM,RPARAM, X, FVEC, FJAC, LDFJAC) ON001170
ON001180
C STORE THE NUMBER OF ITERATIONS FOR EACH RUN ON001190
DO 19 J=1,3 ON001200
PARAM(LL+1,J)=IPARAM(J+2) ON001210
19 CONTINUE ON001220
ON001230
C CALCULATE THE SUM SQUARE ERROR FOR ONE RUN ON001240
ERR(LL+1)=0. ON001250
DO 20 J=1,M ON001260
ERR(LL+1)=ERR(LL+1)+FVEC(J)**2 ON001270
20 CONTINUE ON001280
ON001290
C CNT: NUMBER OF FAILURE RUNS ON001300
IF (ERR(LL+1).GT.500.) THEN ON001310
CNT=CNT+1 ON001320
ENDIF ON001330
ON001340
C KEEP TRACK OF THE SUCCESSFUL AND UNSUCCESSFUL RUNS ON001350
C XX(5 SUBRUNS, 8 VAR) : STORE THE OPTIMIZED X(S) FOR EACH RUN ON001360
C YY(5 SUBRUNS, 8 FVEC) : STORE THE RESULTANT FVEC(S) FOR EACH RUN ON001370
C ERR(8) : SUM SQUARE OF FVEC(S) FOR EACH SUCCESSFUL RUN ON001380
C BERR(8): SUM SQUARE OF FVEC(S) FOR EACH UNSUCCESSFUL RUN ON001390
C BXX(5 SUBRUNS, 8 VAR) : TO EXCLUDE THE X VALUES FOR THE ON001400
C RUN SINCE THE SUM SQUARE OF ON001410
C FVEC(S) FOR THE RUN IS GREATER THAN ON001420
C THRESHOLD=500. ON001430
C BYY(5 SUBRUNS, 8 FVEC) : TO EXCLUDE THE FVEC VALUES FOR ON001440
C THE RUN SINCE THE SUM SQUARE OF ON001450
C FVEC(S) FOR THE RUN IS GREATER THAN ON001460
C THRESHOLD=500. ON001470
ON001480
DO 5 J=1,N ON001490
XX(LL+1,J)=X(J) ON001500
YY(LL+1,J)=FVEC(J) ON001510
IF (ERR(LL+1).GT.500.) THEN ON001520
BXX(LL+1,J)=X(J) ON001530
BYY(LL+1,J)=FVEC(J) ON001540
BERR(LL+1)=ERR(LL+1) ON001550
ELSE ON001560
BXX(LL+1,J)=0. ON001570
BYY(LL+1,J)=0. ON001580
BERR(LL+1)=0. ON001590
ENDIF ON001600
5 CONTINUE ON001610
2 CONTINUE ON001620
ON001630
C USE THE SOLUTIONS FROM THE 5 UNSUCCESSFUL SUBRUNS ON001640
IF (CNT.EQ.5) THEN ON001650

```

```

CNT=0
DO 25 J=1,N
DO 26 I=1,5
BXX(I,J)=0.DO
BYY(I,J)=0.DO
BERR(I)=0.DO
26 CONTINUE
25 CONTINUE
ENDIF

C EXCLUDE THE SOLUTIONS FROM UNSUCCESSFUL RUNS
C AXX : AVERAGE OF EACH VARIABLE IN XX WITH THE SUCCESSFUL SUBRUNS
C AYY : AVERAGE OF EACH FVEC IN YY WITH THE SUCCESSFUL SUBRUNS
C AERR : AVERAGE ERROR FOR A LOOP
DO 23 J=1,8
AXX(J)=0.
AYY(J)=0.
DO 22 I=1,5
AXX(J)=AXX(J)+XX(I,J)-BXX(I,J)
AYY(J)=AYY(J)+YY(I,J)-BYY(I,J)
22 CONTINUE
AXX(J)=AXX(J)/(5-CNT)
AYY(J)=AYY(J)/(5-CNT)
23 CONTINUE
AERR=0.
DO 24 J=1,5
AERR=AERR+ERR(J)-BERR(J)
24 CONTINUE
AERR=AERR/(5-CNT)

C OUTPUT TO FILE #2
C OUTPUT R1 TO R6 FOR LOOP L OF ALL 5 RUNS
WRITE (2,995)
DO 35 J=1,6
WRITE (2,999) J,XX(1,J),XX(2,J),XX(3,J),XX(4,J),XX(5,J),
$ AXX(J)
35 CONTINUE

C OUTPUT C7 TO C8 FOR LOOP L OF ALL 5 RUNS
DO 34 J=7,8
WRITE (2,997) J,XX(1,J),XX(2,J),XX(3,J),XX(4,J),XX(5,J),
$ AXX(J)
34 CONTINUE

C OUTPUT THE FVECS FOR ALL RUNS
WRITE (2,994)
DO 36 J=1,8
WRITE (2,999) J,YY(1,J),YY(2,J),YY(3,J),YY(4,J),YY(5,J),
$ AYY(J)
36 CONTINUE

C OUTPUT THE SUM SQAURED FVEC FOR SUCCESSFUL RUNS, AND THE
C AVERAGE AS AERR
WRITE (2,993)
WRITE (2,999) J,ERR(1),ERR(2),ERR(3),ERR(4),ERR(5),AERR

```

```

ON001660
ON001670
ON001680
ON001690
ON001700
ON001710
ON001720
ON001730
ON001740
ON001750
ON001760
ON001770
ON001780
ON001790
ON001800
ON001810
ON001820
ON001830
ON001840
ON001850
ON001860
ON001870
ON001880
ON001890
ON001900
ON001910
ON001920
ON001930
ON001940
ON001950
ON001960
ON001970
ON001980
ON001990
ON002000
ON002010
ON002020
ON002030
ON002040
ON002050
ON002060
ON002070
ON002080
ON002090
ON002100
ON002110
ON002120
ON002130
ON002140
ON002150
ON002160
ON002170
ON002180
ON002190
ON002200

```

```

C OUTPUT THE FUNCTIONS ITERATED
  WRITE (2,991)
  DO 54 J=1,5
  WRITE (2,992) J,PARAM(J,1),PARAM(J,2),PARAM(J,3)
54 CONTINUE
  WRITE (2,996)

C OUTPUT FORMATS OF FILE#2
9  FORMAT('LOOP #',I2)
999 FORMAT(I1,2X,6(F9.3,1X))
997 FORMAT(I1,2X,6(E9.4,1X))
996 FORMAT(//)
995 FORMAT('THE VALUES OF THE OPTIMIZED PARAMETER ARE:')
994 FORMAT(/,'THE RESIDUAL ERRORS ARE:')
993 FORMAT(/,'THE SUMED SQUARED ERRORS ARE:')
992 FORMAT(I2,2X,3I7)
991 FORMAT(/,'NUM OF ITERATIONS, FUNCTIONS AND JACOBIANS EVALUATED
  $ ARE:')

C OUTPUT TO FILE#1 (HOFF) FOR IL CALCULATIONS
  WRITE (1,55) L,600+AXX(6),AXX(8),AXX(6)+AXX(5),AXX(7),AXX(5)
55  FORMAT('$* LOOP# ',I2,/, '$*',/,
  $ 'R   ''N1'' ''N2'' 0 ',E10.4,/,
  $ 'C   ''N2'' ''N3'' 0 0.0+',E10.4,'I',/,
  $ 'R   ''N3'' ''N4'' 0 ',E10.4,/,
  $ 'C   ''N4'' ''N5'' 0 0.0+',E10.4,'I',/,
  $ 'R   ''N5'' ''N6'' 0 ',E10.4,/,
  $ 'G   ''N6'' ''N7'' 0 600',/,
  c $ 'C   ''N6'' ''N7'' 0 ',e10.4,'+',e10.4,'I',/,
  c $ 'R   ''N7'' ''N8'' 0 ',E10.4,/,
  c $ 'C   ''N3'' ''N4'' 0 ',E10.4,'+2.16e-6I',/,
  c $ 'C   ''N3'' ''N4'' 0 600+2.16e-6I',/, 'END')
  $ 'END')
1  CONTINUE
  END

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C SUBROUTINE TO EVALUATE THE ON-HOOK AND OFF-HOOK FUNCTIONS C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C PLEASE REFER TO APPENDIX C FOR FUNCTION EXPRESSIONS
      SUBROUTINE FONOFF (M, N, X, F)
      INTEGER M, N,K,K1,CNT,L
      COMPLEX*16 Z(8,8),S(8,8),Z02(2),Z03(2)
      DOUBLE PRECISION F(M),X(N),W(4),REZI(4),IMZI(4),OREZI(4),
  $ OIMZI(4),RU(8),RL(8),CU(8),CL(8)
      COMMON CU,CL,RU,RL,W,REZI,IMZI,OREZI,OIMZI,K,K1,L

C CONSTRAINTS APPLIED TO LOOP PARAMETERS
  IF (X(5).LT.RL(L)) THEN
    X(5)=RL(L)
  ELSE IF (X(5).GT.RU(L)) THEN
    X(5)=RU(L)

```

ON002210
 ON002220
 ON002230
 ON002240
 ON002250
 ON002260
 ON002270
 ON002280
 ON002290
 ON002300
 ON002310
 ON002320
 ON002330
 ON002340
 ON002350
 ON002360
 ON002370
 ON002380
 ON002390
 ON002400
 ON002410
 ON002420
 ON002430
 ON002440
 ON002450
 ON002460
 ON002470
 ON002480
 ON002490
 ON002500
 ON002510
 ON002520
 ON002530
 ON002540
 ON002550
 ON002560
 ON002570
 ON002580
 ON002590
 ON002600
 ON002610
 ON002620
 ON002630
 ON002640
 ON002650
 ON002660
 ON002670
 ON002680
 ON002690
 ON002700
 ON002710
 ON002720
 ON002730
 ON002740
 ON002750

```

ENDIF
IF (X(6).LT.RL(L)) THEN
  X(6)=RL(L)
ELSE IF (X(6).GT.RU(L)) THEN
  X(6)=RU(L)
ENDIF
IF (X(7).LT.CL(L)) THEN
  X(7)=CL(L)
ELSE IF (X(7).GT.CU(L)) THEN
  X(7)=CU(L)
ENDIF
IF (X(8).LT.CL(L)) THEN
  X(8)=CL(L)
ELSE IF (X(8).GT.CU(L)) THEN
  X(8)=CU(L)
ENDIF
C CALCULATED THE ADMITTANCE FOR C7 AND C8, Sm...m=7,8
C Sm IS THE SAME FOR THE ON-HOOK AND OFF-HOOK CASES BECAUSE THE
C ON-HOOK AND OFF-HOOK MEASUREMENTS ARE TAKEN AT THE SAME FREQUENCIES
C S(2,J) : S7 CALCULATED AT FREQUENCY J
C S(3,J) : S8 CALCULATED AT FREQUENCY J
      DO 100 I=2,K1
      DO 110 J=1,K/2
      S(I,J)=CMPLX(0.DO,-1/(W(J)*X(N-K1+I)))
110    CONTINUE
100    CONTINUE
C
C OFF-HOOK INPUT IMPEDANCE
C IT WAS ORIGINALLY PROGRAMMED TO ALLOW MODELS FOR DIFFERENT
C NUMBER OF RC SECTIONS
C Z(I,J) : (REFER TO FIG. 3.10b AND APPENDIX C) INPUT IMPEDANCE FOR
C THE 3 STAGES
C Z(K1=3,J) : Zo3 FOR FREQUENCY J
      DO 120 J=1,K/2
      DO 130 CNT=1,K1
      IF (CNT.EQ.1) THEN
        Z(1,J)=X(5)+X(1)+W(J)*X(2)+(0.DO,1.DO)*(X(3)+W(J)*X(4))
      ELSE IF (CNT.GT.1.AND.CNT.LT.K1) THEN
        Z(CNT,J)=X(CNT+3)+X(CNT+4)+Z(CNT-1,J)*S(CNT,J)/
$      (Z(CNT-1,J)+S(CNT,J))
      ELSE IF (CNT.EQ.K1) THEN
        Z(CNT,J)=X(CNT+3)+Z(CNT-1,J)*S(CNT,J)/(Z(CNT-1,J)+S(CNT,J))
      ENDIF
130    CONTINUE
C ON-HOOK INPUT IMPEDANCE FOR 2 SECTIONS ONLY
      ZO2(J)=X(5)+X(6)+S(2,J)
      ZO3(J)=X(6)+ZO2(J)*S(3,J)/(ZO2(J)+S(3,J))

```

```

ON002760
ON002770
ON002780
ON002790
ON002800
ON002810
ON002820
ON002830
ON002840
ON002850
ON002860
ON002870
ON002880
ON002890
ON002900
ON002910
ON002920
ON002930
ON002940
ON002950
ON002960
ON002970
ON002980
ON002990
ON003000
ON003010
ON003020
ON003030
ON003040
ON003050
ON003060
ON003070
ON003080
ON003090
ON003100
ON003110
ON003120
ON003130
ON003140
ON003150
ON003160
ON003170
ON003180
ON003190
ON003200
ON003210
ON003220
ON003230
ON003240
ON003250
ON003260
ON003270
ON003280
ON003290
ON003300

```

```

120      CONTINUE
C  FUNCTIONS DEFINE THE DIFFERENCE OF THE MEASURED AND THE MODELS'
C  INPUT IMPEDANCES
      DO 150 J=1,K/2
        F(J)=DREAL(Z(K1,J))-REZI(J)
        F(J+2)=DIMAG(Z(K1,J))-IMZI(J)
        F(J+4)=DREAL(ZO3(J))-OREZI(J)
        F(J+6)=DIMAG(ZO3(J))-OIMZI(J)
150     CONTINUE
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C  SUBROUTINE TO EVALUATE THE JACOBIANS OF ON-HOOK AND OFF-HOOK FNS C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C  PLEASE REFER TO APPENDIX C FOR JACOBIAN EXPRESSIONS

      SUBROUTINE JONOFF(M,N,X,FJAC,LDFJAC)
      INTEGER M,N,LDFJAC,K,K1,CNT,L
      COMPLEX*16 ZO2(2),ZO3(2),Z(8,8),S(8,8),DSC(8,8)
      COMPLEX*16 T,TT,TTT(8)
      COMPLEX*16 DZZ(8,8,8),DZS(8,8),DZC(8,8),DZR(8,8),
$      DZRL1(8),DZRL2(8),DZRL3(8),DZRL4(8)
      COMPLEX*16 DZO2S(2),DZO3Z(2),DZO3R5(2),DZO3R6(2),DZO3C7(2),
$      DZO3C8(2)
      DOUBLE PRECISION X(N),FJAC(LDFJAC,N)
      DOUBLE PRECISION W(4),REZI(4),IMZI(4),OREZI(4),OIMZI(4)
      DOUBLE PRECISION RU(8),RL(8),CU(8),CL(8)
      COMMON CU,CL,RU,RL,W,REZI,IMZI,OREZI,OIMZI,K,K1,L

C  CONSTRAINTS APPLIED TO LOOP PARAMETERS
      IF (X(5).LT.RL(L)) THEN
        X(5)=RL(L)
      ELSE IF (X(5).GT.RU(L)) THEN
        X(5)=RU(L)
      ENDIF

      IF (X(6).LT.RL(L)) THEN
        X(6)=RL(L)
      ELSE IF (X(6).GT.RU(L)) THEN
        X(6)=RU(L)
      ENDIF

      IF (X(7).LT.CL(L)) THEN
        X(7)=CL(L)
      ELSE IF (X(7).GT.CU(L)) THEN
        X(7)=CU(L)
      ENDIF

      IF (X(8).LT.CL(L)) THEN
        X(8)=CL(L)
      ELSE IF (X(8).GT.CU(L)) THEN
        X(8)=CU(L)
      ENDIF

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      ENDIF
      ON003860
C Sm : S, DSm/DCm : DSC...m=7,8
      ON003870
C Sm AND DSm/DCm ARE THE SAME FOR THE ON-HOOK AND OFF-HOOK CASES
      ON003880
C BECAUSE THE MEASUREMENTS ARE MADE AT THE SAME FREQUENCIES.
      ON003890
      DO 500 I=2,K1
      ON003900
      DO 510 J=1,K/2
      ON003910
      S(I,J)=CMPLX(0.D0,-1/(W(J)*X(N-K1+I)))
      ON003920
      DSC(I,J)=CMPLX(0.D0,1/(W(J)*X(N-K1+I)**2))
      ON003930
510 CONTINUE
      ON003940
500 CONTINUE
      ON003950
      ON003960
      ON003970
C OFF-HOOK INPUT IMPEDANCE (SAME AS IN FONOFF)
      ON003980
      DO 520 J=1,K/2
      ON003990
      DO 530 CNT=1,K1
      ON004000
      IF (CNT.EQ.1) THEN
      ON004010
      Z(1,J)=X(5)+X(1)+W(J)*X(2)+(0.D0,1.D0)*(X(3)+W(J)*X(4))
      ON004020
      ELSE IF (CNT.GT.1.AND.CNT.LT.K1) THEN
      ON004030
      Z(CNT,J)=X(CNT+3)+X(CNT+4)+Z(CNT-1,J)*S(CNT,J)/
      ON004040
      $ (Z(CNT-1,J)+S(CNT,J))
      ON004050
      ELSE IF (CNT.EQ.K1) THEN
      ON004060
      Z(CNT,J)=X(CNT+3)+Z(CNT-1,J)*S(CNT,J)/(Z(CNT-1,J)+S(CNT,J))
      ON004070
      ENDIF
      ON004080
530 CONTINUE
      ON004090
      ON004100
C ON-HOOK INPUT IMPEDANCE (SAME AS IN FONOFF)
      ON004110
      Z02(J)=X(5)+X(6)+S(2,J)
      ON004120
      Z03(J)=X(6)+Z02(J)*S(3,J)/(Z02(J)+S(3,J))
      ON004130
520 CONTINUE
      ON004140
      ON004150
      ON004160
C INTERMEDIATE STEPS TO CALCULATE JACOBIANS
      ON004170
      ON004180
C OFF-HOOK CASE
      ON004190
C DZtn/DZt(n-1) n=2,3
      ON004200
C DZtn/DZt(n-1) : DZZ
      ON004210
      DO 550 J=1,K/2
      ON004220
      DO 560 CNT=2,K1
      ON004230
      DZZ(CNT,CNT-1,J)=S(CNT,J)**2/(Z(CNT-1,J)+S(CNT,J))**2
      ON004240
560 CONTINUE
      ON004250
      ON004260
C ON-HOOK CASE
      ON004270
C DZo3/DZo2 : DZO3Z
      ON004280
      DZO3Z(J)=S(3,J)**2/(Z02(J)+S(3,J))**2
      ON004290
550 CONTINUE
      ON004300
      ON004310
      ON004320
C OFF-HOOK CASE
      ON004330
C DZt3/DSm m=7,8
      ON004340
C DZt3/DSm : DZS
      ON004350
      DO 580 J=1,K/2
      ON004360
      DO 570 CNT=1,K1
      ON004370
      IF (CNT.EQ.1) THEN
      ON004380
      DZS(CNT,J)=1D0
      ON004390
      ELSE
      ON004400
      DZS(CNT,J)=Z(CNT-1,J)**2/(Z(CNT-1,J)+S(CNT,J))**2
      ON004400

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      ENDIF                                ON004410
570    CONTINUE                            ON004420
                                           ON004430
C ON-HOOK CASE                             ON004440
C DZo2/DS7 : DZ02S                        ON004450
      DZ02S(J)=Z02(J)**2/(Z02(J)+S(3,J))**2 ON004460
580    CONTINUE                            ON004470
                                           ON004480
C CALCULATIONS OF FINAL JACOBIANS FOR ON-HOOK AND OFF-HOOK FUNCTIONS ON004490
C DZt3/DRn : DZR          n=1,2,...6      ON004500
C DZt3/DCm : DZC          m=7,8          ON004510
C DZo3/DRp : DZRLp       p=1,2,...4      ON004520
C DZo3/DRi : DZ03Ri     i=5,6          ON004530
C DZo3/DCj : DZ03Cj     j=7,8          ON004540
                                           ON004550
C T : INTERMEDIATE CALCULATIONS FOR DZt3/DCm ON004560
C TT : INTERMEDIATE CALCULATIONS FOR DZt3/DRn ON004570
C TTT: INTERMEDIATE CALCULATIONS FOR DZt3/DRp ON004580
      DO 600 J=1,K/2                        ON004590
      DO 610 CNT = 1,K1                     ON004600
      IF (CNT.EQ.1) THEN                   ON004610
          TT=1D0                           ON004620
      ELSE                                  ON004630
          TT=1D0+DZZ(CNT,CNT-1,J)          ON004640
      ENDIF                                 ON004650
          T=DZS(CNT,J)*DSC(CNT,J)          ON004660
      DO 620 I=CNT+1,K1                    ON004670
          T=T*DZZ(I,I-1,J)                 ON004680
          TT=TT*DZZ(I,I-1,J)               ON004690
620    CONTINUE                            ON004700
                                           ON004710
          DZC(CNT,J)=T                      ON004720
          DZR(CNT,J)=TT                    ON004730
610    CONTINUE                            ON004740
                                           ON004750
          DZ03R5(J)=DZ03Z(J)               ON004760
          DZ03R6(J)=1D0+DZ03Z(J)          ON004770
          DZ03C7(J)=DZ03Z(J)*DSC(2,J)     ON004780
          DZ03C8(J)=DZ03S(J)*DSC(3,J)     ON004790
600    CONTINUE                            ON004800
                                           ON004810
          DO 650 J=1,K/2                   ON004820
          TTT(J)=1.D0                       ON004830
          DO 640 I=2,K1                    ON004840
          TTT(J)=TTT(J)*DZZ(I,I-1,J)       ON004850
640    CONTINUE                            ON004860
650    CONTINUE                            ON004870
                                           ON004880
          DO 660 J=1,K/2                   ON004890
          DZRL1(J)=TTT(J)                   ON004900
          DZRL2(J)=TTT(J)*W(J)             ON004910
          DZRL3(J)=TTT(J)*(0.D0,1.D0)     ON004920
          DZRL4(J)=TTT(J)*(0.D0,1.D0)*W(J) ON004930
660    CONTINUE                            ON004940
                                           ON004950

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C PUT JACOBIANS ONTO THE CORRESPONDING OFF-HOOK AND ON-HOOK
C JACOBIAN MATRICE (FJAC)
C OFF-HOOK CASE
  DO 700 J=1,K/2
    FJAC(J,1)=DREAL(DZRL1(J))
    FJAC(J,2)=DREAL(DZRL2(J))
    FJAC(J,3)=DREAL(DZRL3(J))
    FJAC(J,4)=DREAL(DZRL4(J))
    DO 710 I=2,K1
      FJAC(J,3+I)=DREAL(DZR(I,J))
      FJAC(J,N-K1+I)=DREAL(DZC(I,J))
710   CONTINUE
      FJAC(J+2,1)=DIMAG(DZRL1(J))
      FJAC(J+2,2)=DIMAG(DZRL2(J))
      FJAC(J+2,3)=DIMAG(DZRL3(J))
      FJAC(J+2,4)=DIMAG(DZRL4(J))
      DO 720 I=2,K1
        FJAC(J+2,3+I)=DIMAG(DZR(I,J))
        FJAC(J+2,N-K1+I)=DIMAG(DZC(I,J))
720   CONTINUE
C ON-HOOK CASE
  FJAC(J+4,1)=0.DO
  FJAC(J+4,2)=0.DO
  FJAC(J+4,3)=0.DO
  FJAC(J+4,4)=0.DO
  FJAC(J+4,5)=DREAL(DZO3R5(J))
  FJAC(J+4,6)=DREAL(DZO3R6(J))
  FJAC(J+4,7)=DREAL(DZO3C7(J))
  FJAC(J+4,8)=DREAL(DZO3C8(J))
  FJAC(J+6,1)=0.DO
  FJAC(J+6,2)=0.DO
  FJAC(J+6,3)=0.DO
  FJAC(J+6,4)=0.DO
  FJAC(J+6,5)=DIMAG(DZO3R5(J))
  FJAC(J+6,6)=DIMAG(DZO3R6(J))
  FJAC(J+6,7)=DIMAG(DZO3C7(J))
  FJAC(J+6,8)=DIMAG(DZO3C8(J))
700  CONTINUE
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C SUBROUTINE TO READ MEASUREMENTS
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
SUBROUTINE IMPED(W,OW,REZI,IMZI,OREZI,OIMZI)
DOUBLE PRECISION PI,W(4),OW(4),REZI(4),IMZI(4),OREZI(4),
$ OIMZI(4)
C MEASUREMENTS ARE MADE AT FREQUENCIES 1.0 AND 1.5 KHZ
C W : FREQUENCY POINTS FOR OFF-HOOK MEASUREMENTS
C OW: FREQUENCY POINTS FOR ON-HOOK MEASUREMENTS
C REZI : THE VALUE OF REAL PART OF OFF-HOOK MEASUREMENTS

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