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Traffic Flow Monitoring in PBX Networks

by

Mark Sestak, B.Sc.

A thesis submitted to

the Faculty of Graduate Studies and Research

in partial fulfillment of

the requirements for the degree of

Master of Computer Science (M.C.S.)

Department of Systems and Computer Engineering

Carleton University

Ottawa, Ontario

May 10, 1990

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submitted by Mark Sestak, B.Sc.

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ABSTRACT

This thesis applies Call Detail Record (CDR) architectures to solve the problem of traffic flow monitoring in PBX networks from a central monitoring station. The functional requirements for the traffic flow monitoring system are described and two alternative CDR architectures are proposed, applied and analysed to meet the outlined requirements. The first CDR architecture approximates what is currently used in the industry; the second CDR architecture has not been applied in the industry. As a basis for the analysis, a traffic model for PBX networks is proposed.

This work demonstrates that:

- * Two CDR architectures can be applied to provide a wide range of traffic flow monitoring capabilities in real time or on a historical basis.
- * The second CDR architecture requires significantly less resource to support the monitoring system in terms of disk storage, processing power and transmission bandwidth between the network and the monitoring center.

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GLOSSARY OF TECHNICAL TERMS AND ABBREVIATIONS

Call Forwarding - A PBX feature in which a station can be programmed to forward all or a subset of received calls to another location prior to the calls being answered.

CDR - Call Detail Record - data about calls occurring in switching systems, typically used as the basis for generating call billing reports. See also: SMDR.

CPH - Calls per Hour.

CO - Central Office - A switching system which, in general, provides phone service to the general public.

CENTREX - CENTRAL EXchange. CO systems which provide PBX-like features.

CO Trunk - A trunk which terminates or originates at a CO. For the purpose of this thesis, this trunk connects a PBX to a CO.

DASS2 - Digital Access Signalling System #2 - A PBX to CO ISDN-like protocol, used primarily in the UK marketplace.

Device - Equipment attached to a PBX through which voice or data is transmitted. Examples of devices include trunks, telephones and data sets.

DPNSS - Digital Private Networking Signalling System - A PBX to PBX ISDN-like protocol, used primarily in the UK marketplace.

Feature Transparency - Describes the situation when features (eg: call forwarding) operate identically in single PBX environments as well as PBX network environments.

Fully Connected Network - A network configuration in which all elements (in this case, PBXs) of the network are directly connected to all other elements of the network.

Functional Requirements - Those requirements describing functions that a system must provide.

Horizontal Applications - In the PBX market, those applications which appeal to all or most market segments (eg: networking).

Incoming External Call - A PBX call type, an incoming C.O. trunk call.

Incoming Network Call - A PBX call type, an incoming network trunk call.

Intra PBX Call - A PBX call type in which the originating and terminating stations are attached to the same PBX.

Linearly Connected Network - A network connected along a single path which traverses each network element once and has two network elements as endpoints. Conceptually, the topology of such a network is a straight line with attached network elements.

Network - A network of PBXs.

Network Element - A PBX.

NMC - Network Management Center - the workstation(s) from which management of a network occurs.

Network Management System - A network and the system which manages it.

Network Trunk - A trunk which interconnects network elements.

Outgoing External Call - A PBX call type, an outgoing CO trunk call.

Outgoing Network Call - A PBX call type, an outgoing network trunk call.

PBX - Private Branch Exchange - A switching system designed to support business needs.

PBX Call Type - A generic type of call which occurs in PBX environments (eg: Intra PBX call).

SMDR - Station Module Detail Recording - data about calls occurring in switching systems, typically used as the basis for generating call billing reports. See also: CDR.

Switching System - An electronic system designed to switch calls (eg: PBX, CO).

Tandem Calls - A PBX call type, an incoming network trunk call which terminates on an outgoing network trunk.

Transfer - A PBX feature which enables a user to direct (transfer), via the telephone, a call to another destination.

Trunk - The physical connection and associated protocol between two switching systems.

Vertical Applications - In the PBX market, those applications which appeal to a specific market segment (eg: hospitals) but are not generally required by other market segments.

1 INTRODUCTION

In recent years there have been significant changes in the expectations of Private Branch Exchange (PBX) customers. Fuelled by Central Exchange (CENTREX) competition and technological advances such as digital trunks, common channel signalling techniques, the world migration to the Integrated Services Digital Network (ISDN), and European PBX protocol initiatives (Digital Private Networking Signalling System (DPNSS) and Digital Access Signalling System #2 (DASS2)), PBX suppliers have shifted from providers of isolated standalone systems to suppliers of sophisticated private networks connecting corporate branch offices anywhere in the world. Supporting feature transparency, vertical and horizontal applications, these networks satisfy corporate voice and low speed data switching needs.

The demand to simplify the management of PBX networks has increased in proportion to the growth in PBX network sales. Facilities for managing these networks have not kept pace with the demand. As a result, even though PBX networks offer many advantages, each PBX in the network is still typically managed as an isolated standalone system. This is becoming increasingly unacceptable to the market and, consequently, PBX suppliers are under great pressure to deliver functionality to alleviate the complexities associated with managing networks.

"Network Management" is a popular expression that is used by many companies to describe various functions which simplify the

management of a network. A subcategory of network management is "monitoring", encapsulating those functions which monitor network activity. A further subcategory of monitoring is the function of monitoring traffic flow. This is the focus of this thesis in the context of PBX networks.

Monitoring Traffic Flow

Monitoring traffic flow may be defined as the surveillance of the call carrying capacity of those voice and data channels which connect PBXs together in a network or to Central Offices (COs). The capability to monitor these channels:

- * can directly affect the cost of the network. Dedicated trunks between PBX systems are typically leased and expensive. For a business, traffic monitoring capability is key to ensuring the efficient allocation and utilization of trunking resources.
- * supports decisions on the physical allocation of trunks and the logical order of trunk selection for call processing activity.
- * is crucial when attempting to solve traffic related problems in the network. Trunk congestion on a single node, for example, may have an adverse impact on the performance of other nodes in the network - traffic flow monitoring capability will assist the network manager in identifying the real cause of the problem by providing a perspective of the complete network.
- * is required before network control and readjustment can be automated. The automation of network parameter adjustments assists in the efficient utilization of the network resources.

The detailed requirements for a PBX network traffic monitoring package are outlined in Chapter 3. In literature surveys,

nothing which describes traffic flow monitoring requirements for PBX networks was found. Based on this and the experience of the author, it appears that a traffic flow monitoring package which meets the requirements of Chapter 3 is not available.

1.1 Objectives

This thesis has three primary objectives:

- * To demonstrate that the requirements of a traffic flow monitoring package for PBX networks can be achieved by the use of a Call Detail Record (CDR) architecture which approximates what is used in the industry. This is referred to in this thesis as "CDR Architecture A". (CDR information is currently produced by PBX systems and used to create billing reports as described in detail in Section 2.1.2).
- * To present algorithms which use CDR Architecture A to meet the traffic flow monitoring requirements and to estimate the corresponding computing and telecommunications resource requirements.
- * To present a new "CDR Architecture B" which meets the traffic flow monitoring requirements while requiring significantly less resources.

Using CDR information to achieve traffic flow monitoring requirements has three practical benefits:

- * As a result of relying on a single source of data to satisfy the requirements of the traffic monitoring package, the software complexity associated with the network management center is reduced.
- * CDR information is already produced by PBX systems. Extending this to meet the needs of the traffic flow monitoring package is more cost effective than developing an alternate mechanism.

- * Using CDR information satisfies an additional PBX market requirement of centralized CDR collection. Although centralized CDR collection is not directly related to monitoring traffic flow, it would be cost effective for any PBX supplier to use the same system architecture to satisfy both requirements.

1.2 Outline

Chapter 2 presents background information on PBX networks and PBX network management. It also proposes a traffic model and uses it to estimate calls per hour rates for PBX networks of various sizes and topologies. In subsequent chapters, calls per hour rates are used as a basis for deriving CDR generation rates for PBX networks.

Chapter 3 outlines the author's assessment of the requirements of a traffic monitoring package for PBX networks.

Chapter 4 applies CDR Architecture A to solve the traffic flow monitoring problem.

Chapter 5 proposes and applies the new CDR Architecture B to solve the traffic flow monitoring problem.

Chapter 6 presents and analyses graphs which were created by the application of the theories of previous chapters. This quantifies and compares the results of applying the two CDR architectures.

Chapter 7 relates the results of the thesis back to the original

objectives and suggests possible extensions to the thesis.

Appendix A includes further graphs following the format presented in Chapter 6 but varying certain key parameters. These graphs result from the application of the theories of the thesis to a wide range of network sizes and topologies. The graphs should be used for reference purposes.

1.3 Literature Survey

Several references on telecommunication networks [2], [3], [4] discuss industry products which address traffic related problems. The use of CDRs in the telecommunications industry is presented in [5], [6], [7] and [8]. Functions of a telecommunications management network are discussed in [9].

Tsiotras [2] describes the architecture of the Network Traffic Management Subsystem of the AT&T's Multifunction Operations System (MFOS/NTMS). This subsystem detects and identifies both network and network element overload. CDR information is not used for this purpose; Rather, data collection is done by the NTMS on a five-minute basis for traffic counts and on a thirty-second basis for discrete (event) information.

Hurley et al. [3] discusses the development of automatic routing methods and describes the two main North American contenders, AT&T's Dynamic NonHierarchical Routing (DNHR) and Northern Telecom's Dynamically Controlled Routing (DCR).

Neither system uses CDR information as a basis for automatic rerouting decisions.

Bierman [4] describes Northern Telecom's Dynamic Network Controller (DNC) family of products. Dynamic network control is achieved by each intelligent switch in the network reporting to the network controller several times per minute. Based on this non-CDR data, the network controller distributes routing changes to the network.

Field [5] discusses Station Message Detail Recording (SMDR) as the most important tool in managing telecommunications resource. (Note: SMDR and "CDR recording" can be used interchangeably.) Various products are described including AT&T's Centralized Station Message Detail Recording (CSMDR), Teldata Systems Corporation's Telephone Accounting and Control System - Instant Information (TACS ii), Com Dev, Inc.'s SMDR Multiplexor and SMDR Translator Units (STUs), etc., all of which provide some type of polling structure for centralized collection of SMDR information. This is not done in real time and the results are not tailored to satisfying those traffic flow monitoring requirements outlined by Chapter 3.

Ahmadi et al. [6] describes the Netview/PC approach to network management. Noted in this article is Rolm's Call Detail Collector application which collects CDR data from up to ten PBXs, saves the data in a file and later forwards it to a host for processing. This is not done in real time; the output from

the host is not described.

Fuchs et al. [7] discusses GTE's private network management service, NETSCAN. This provides a central point for information retrieval of information such as CDRs (not in real time). Two way communication capability is used to monitor traffic through individual switches; CDR information is not used for this purpose.

Gorman et al. [8] reviews the design of AT&T's Horizon Communications System. This notes the use of Station Message Detail Recording (SMDR) and the availability of hardcopy print-out of all incoming and outgoing calls. No allusion is made to using SMDR information for the purpose of satisfying traffic flow monitoring requirements.

Scherer et al. [9] divides the functions of a telecommunication management network into nine distinct areas, including the "Network Operations and Management" and "Performance Monitoring" functions. The former of these is concerned with the transmittal of network traffic data between network elements and the Telecommunication Management Network. The latter is concerned with the real-time collection of data that is indicative of the performance of the telecommunications network elements. The "Monitoring Traffic Flow" focus of this thesis addresses a subset of these two functions.

2 BACKGROUND

This chapter presents background information to establish context for the analysis performed in subsequent chapters.

Section 2.1 discusses PBX network characteristics which are relevant to this thesis. Within this section, PBX network call types are identified and the current application of CDRs in PBX networks is discussed.

Section 2.2 identifies the network management architecture on which this thesis is based. Within this context, a traffic flow monitoring system is outlined.

Section 2.3 presents a traffic model for PBX networks. This section forms the basis for subsequent analysis on the effect of using CDR information to satisfy traffic flow monitoring requirements.

2.1 PBX Networks

The PBX networks considered by this thesis are randomly connected, ranging in size from 2 to 255 PBXs. The upper boundary of 255 is an arbitrary number, chosen because networks larger than 255 PBXs are, to the author's knowledge, not common and also because the range of 2 to 255 has proven adequate to show the trends resulting from the analysis of this thesis. In order to support higher network sizes, the formulas presented in

this thesis can simply be recalculated with the boundary of choice.

Within the PBX network, each PBX may consist of 8 possible configurations:

- * 500 lines, 71 trunks.
- * 1000 lines, 122 trunks.
- * 1500 lines, 176 trunks.
- * 2000 lines, 230 trunks.
- * 2500 lines, 283 trunks.
- * 3000 lines, 336 trunks.
- * 3500 lines, 388 trunks.
- * 4000 lines, 441 trunks.

These configurations are a sample of those derived from AT&T traffic statistics [1] which assess typical PBX configurations and the associated call processing traffic patterns. They have been chosen since they represent a broad spectrum of possible configurations. Again, however, this thesis is not constrained to these numbers - new numbers can simply be substituted into the proposed theories to obtain new sets of results.

2.1.1 PBX Network Call Types

Depicted below are 6 call types which can occur in a PBX network and are particularly relevant to this thesis. Call types include:

- * INCOMING EXTERNAL calls (external off network device calling a station). In this example, 592-7300 is received by a PBX from a CO trunk.

Figure 2.1 - Incoming External Call

- * INCOMING NETWORK calls (on network station to station). In this example, a PBX receives 7300 from an intra network device.

Figure 2.2 - Incoming Network Call

- * INTRA PBX calls (station to station calling on the same PBX).

Figure 2.3 - Intra PBX Call

- * **OUTGOING EXTERNAL** calls (station calling external off network destination). In this example, a PBX user dials an off network device via 9-592-7300.

Figure 2.4 - Outgoing External Call

- * **OUTGOING NETWORK** calls (station to on network station). In this example, a PBX user dials 7300 to reach an intra network device.

Figure 2.5 - Outgoing Network Call

- * **TANDEM or TRANSIT** calls. These are also known as incoming network calls to outgoing network calls (network to network) implying that the PBX servicing the call is not acting as a network termination point. In this example, a PBX receives 7300 on a network trunk and signals 7300 over another network trunk.

Figure 2.6 - Tandem or Transit Call

These call types are referenced by later sections of this thesis.

2.1.2 Call Detail Records (CDRs)

A mandatory feature of any PBX system is the ability to produce call detail records (CDRs). These are generated as calls occur and are processed to produce call billing/charging reports (ie: reports which correlate call charges with the individual responsible for the call). To allow such billing to occur, CDRs must contain information such as:

- * the identity of the device originating the call.
- * the identity of the device on which the call terminated.
- * whether the call was voice or data.
- * the digits dialled.
- * the date and time that the call was originated.
- * the date and time that the call terminated.

For outgoing external calls, the billing report generation package can determine the destination of the call based on the digits dialed and can estimate the cost of the call based on the time of day and call duration information. The call can then be billed to the owner of the device who originated the call.

The call billing system must also be able to determine the originating device independent of the path that the call followed through the network. This problem has been solved in PBX networks by billing systems that correlate CDRs from many PBXs in order to determine the identity of the originating device. The CDR architecture which requires this approach is outlined in Chapter 4.

This thesis extends the utility of CDR records such that, in addition to satisfying the billing function, they can be used to satisfy traffic flow monitoring requirements. Two CDR architectures are discussed and analysed in Chapter 4 and Chapter 5.

2.2 Network Management

This section defines those aspects of network management which serve as background to this thesis.

2.2.1 Hardware Architecture

The following diagram depicts the hardware architecture of the proposed network management system on which this thesis is based.

Figure 2.7 - Network Management System Hardware Architecture

In Figure 2.7:

- * The Network-Management-Center (NMC) is comprised of two key components: workstations and associated databases. There are various ways to arrange the workstations. They may be arranged, for example, as a hierarchy such that a single workstation controls all network management facilities for a portion of the network. An

alternative approach is to have a single workstation dedicated to a single network management facility. Yet another approach is to have a combination of the previous approaches. The workstation and database arrangement will be based on the CPU and disk space required to support the traffic flow monitoring package.

- * The NMC-to-PBX-Network-Link is the connection between the NMC and the PBX network. This may be multiple or single links to multiple or single PBXs. The number of connections will be influenced by the CPU and disk space required to support the proposed traffic flow monitoring package. The two way arrow indicates two way communication between the NMC and the PBX.

2.2.2 Traffic Flow Monitoring System

As identified in Chapter 1, the focus of this thesis is to propose and analyse a solution to the problem of traffic flow monitoring in PBX networks by using CDRs. As such, the traffic flow monitoring system operates as follows:

- * PBX systems produce CDR data to enable the billing function. When produced, this information is routed to the PBX(s) connected to the NMC.
- * The NMC processes this data to satisfy the traffic flow monitoring requirements.

The processing of CDR data is described in Section 4.3.

2.3 PBX Network Traffic Model

In order to make quantitative comparisons of computing and telecommunications resource required for traffic flow

monitoring, it is necessary to have estimates of CDR generation rates in networks of various sizes and types. CDR generation rates are directly related to the number of calls occurring in a PBX network. "Calls per hour" (CPH) is the measure used in the PBX industry to indicate traffic. Since there is no published data which describes PBX network traffic, it has been necessary to develop a method of forming these estimates. The following discussion presents a model for estimating the calls per hour rates for randomly connected PBX networks by the following steps:

1. determine calls per hour for a single PBX environment.
2. determine calls per hour for a two-PBX network.
3. determine calls per hour for a fully connected N-PBX network.
4. determine calls per hour for a randomly connected N-PBX network.

Based on a synthesis of published literature [1], Step 1 presents calls per hour data for the single PBX environment. Step 2 introduces the author's theory for extending the data from the single PBX environment into a simple two-PBX network. Step 3 generalizes the theory presented in Step 2 to produce a calls per hour theory which is applicable to any fully connected PBX network. Step 4 eliminates the fully connected restriction and extends the theory of Step 3 to produce calls per hour data for a randomly connected PBX network. These steps are based on the author's knowledge and experience of PBX networks. While

the model cannot be exact, it is representative and is sufficient for the comparisons of different CDR architectures in the remainder of this thesis.

Step 1: Single PBX Environment

The number of calls per hour in a single PBX environment, based on the number of stations, the number of central office trunks and the traffic load, is given in [1]. This specification yields calls per hour numbers for three PBX call types: INTRA PBX calls, EXTERNAL OUTGOING calls and EXTERNAL INCOMING calls (see Section 2.1.1). For heavy traffic loads in single PBX environments, the calls per hour statistics from [1] are presented in Table 2.1.

Lines Trunks		Heavy Originating Traffic (calls per hour)			
		Intra PBX	Outgoing External	Incoming External	Total
500	71	765	707	521	1993
1000	122	1638	1420	981	4039
1500	176	2402	2228	1466	6096
2000	230	3159	2971	1954	8084
2500	283	3901	3707	2438	10046
3000	336	4642	4448	2926	12016
3500	388	5378	5189	3414	13981
4000	441	6109	5931	3902	15942

Table 2.1 - Heavy Traffic Load - Calls Per Hour

Table 2.1 indicates, for example, that a PBX equipped with

500 stations and 71 central office (CO) trunks when under heavy traffic will, on average, handle:

- * 765 station to station calls (INTRA PBX),
- * 707 station to CO trunk calls (OUTGOING EXTERNAL) and
- * 521 CO to station calls (INCOMING EXTERNAL) per hour.

Step 2: Two-PBX Network Environment

The two-PBX network environment introduces the additional complexity of OUTGOING NETWORK and INCOMING NETWORK calls. To extend the data introduced by Table 2.1 into a two-PBX network environment, we assume that:

- * The PBXs in the network have identical configuration;
- * 70% of all PBX originated calls terminate on the same PBX (INTRA PBX calls) while the remaining 30% are evenly distributed throughout the network (that is, a 70% intra PBX community of interest exists);
- * An INCOMING EXTERNAL call will terminate anywhere in the network with equal probability;
- * OUTGOING EXTERNAL calls are not originated via the network but rather are originated locally (that is, a user on PBX A who wishes to dial an external destination will not be routed via the PBX network but rather will be routed via the external trunks connected directly to PBX A).

Formula 2.0 - PBX Network Characteristics

Then, in calculating the traffic distribution for each PBX in the two PBX network:

- * 70% of what were INTRA PBX calls in Table 2.1 will remain INTRA PBX in the two-PBX network model while the remaining 30% will terminate in the network, thereby becoming PBX to OUTGOING NETWORK calls;
- * 50% of the what were INCOMING EXTERNAL calls in Table 2.1 remain INCOMING EXTERNAL while the remaining 50% will terminate in the network, thereby becoming INCOMING EXTERNAL TO OUTGOING NETWORK calls;
- * All OUTGOING NETWORK calls generated by one of the PBX systems will be handled as INCOMING NETWORK calls by the other PBX.

Formula 2.1 - Two-PBX Network CPH per PBX

Applying Formula 2.1 to the data table for the single PBX environment depicted by Table 2.1, the traffic distribution for each PBX in a two-PBX network is depicted in Table 2.2.

		Heavy Originating Traffic (calls per hour)					
		Incoming External To					
Lines	Trunks	Intra PBX	Outgoing External	Incoming External	Outgoing Network	Outgoing Network	Incoming Network
500	71	535	707	260	260	230	490
1000	122	1147	1420	490	490	492	982
1500	176	1681	2228	733	733	721	1454
2000	230	2211	2971	877	877	948	1925
2500	283	2731	3707	1219	1219	1170	2389
3000	336	3249	4448	1463	1463	1393	2856
3500	388	3765	5189	1707	1707	1613	3320
4000	441	4276	5931	1951	1951	1833	3784

Table 2.2 - Result of Formula 2.1 - Two-PBX Network

This matrix indicates that, on average, each PBX in a heavy traffic two-PBX network equipped with, for example, 500 stations and 71 central office (CO) trunks will handle:

- * 535 station to station calls (INTRA PBX),
- * 707 station to CO trunk calls (OUTGOING EXTERNAL),
- * 260 CO to station calls (INCOMING EXTERNAL),
- * 260 INCOMING EXTERNAL TO OUTGOING NETWORK calls and
- * 230 OUTGOING NETWORK calls and
- * 490 INCOMING NETWORK calls per hour.

Comparing Table 2.2 to Table 2.1, the total number of calls handled by each PBX in the two-PBX network is greater than in the single PBX environment. For each row of the table, the total calls value has increased by the number of INCOMING NETWORK calls. For example, row 1 of Table 2.2 has increased by 490. This increase is due to the theory, presented by Formula 2.0, used to create the two-PBX network model.

Step 3: Fully Connected N-PBX Network Environment

This section extends the two-PBX network model to an N-PBX network with the restriction that the network is fully connected. This eliminates the possibility of tandem calls occurring in the network during normal call establishment situations. Tandem calls will only occur due to congestion or feature activation (eg: call forwarding). Eliminating

tandem calls simplifies the calls per hour calculations; this restriction will be removed in the next section.

Using Formula 2.0 as a basis, the calls per hour per PBX statistics for each PBX call type in the fully connected N-PBX network are derived from Table 2.1 as follows:

INTRA PBX calls =
 $(\text{Table 2.1 INTRA PBX calls})(.7).$

OUTGOING EXTERNAL calls =
 $(\text{Table 2.1 OUTGOING EXTERNAL calls}).$

INCOMING EXTERNAL calls =
 $(\text{Table 2.1 INCOMING EXTERNAL calls})/N.$

INCOMING EXTERNAL TO OUTGOING NETWORK calls =
 $(\text{Table 2.1 INCOMING EXTERNAL calls})/N (N-1).$

OUTGOING NETWORK calls =
 $(\text{Table 2.1 INTRA PBX calls})(.3).$

INCOMING NETWORK calls =
 $(\text{Table 2.1 INTRA PBX calls})(.3) +$
 $(\text{Table 2.1 INCOMING EXTERNAL calls})/N (N-1).$

Formula 2.2 - N-PBX Network CPH per PBX Call Type

OUTGOING NETWORK reflects the portion of Formula 2.0 which states that 30% of all INTRA PBX calls from Table 2.1 will be distributed throughout the network. INCOMING EXTERNAL TO OUTGOING NETWORK reflects the portion of Formula 2.0 which states that all INCOMING EXTERNAL calls will be evenly distributed between the PBXs in the network. This results in 1/N of INCOMING EXTERNAL calls being serviced by the PBX

itself while $(N-1)/N$ calls are distributed throughout the network.

The number of INCOMING NETWORK calls is always equal to the total OUTGOING NETWORK calls. This is due to the assumptions that all PBXs in the network are identical (thereby each PBX generates the same number of OUTGOING NETWORK calls), the calls are evenly distributed and the network is fully connected.

Applying Formula 2.2 to the data in Table 2.1, the traffic distribution for each PBX in a four-PBX fully connected network is depicted in Table 2.3.

Lines Trunks		Heavy Originating Traffic (calls per hour)					
				Incoming External To			
		Intra PBX	Outgoing External	Incoming External	Outgoing Network	Outgoing Network	Incoming Network
500	71	535	707	130	390	230	620
1000	122	1147	1420	245	736	492	1228
1500	176	1681	2228	367	1100	721	1821
2000	230	2211	2971	489	1466	943	2414
2500	283	2731	3707	610	1829	1170	2999
3000	336	3249	4448	732	2195	1393	3588
3500	388	3765	5189	854	2561	1613	4174
4000	441	4276	5931	976	2927	1833	4759

Table 2.3 - Result of Formula 2.2 - Four-PBX Network

Based on Formula 2.2, the total number of calls per hour per PBX (CPH per PBX) in a fully connected N-PBX network is given by:

$$\begin{aligned} & (\text{Table 2.1 INTRA PBX calls}) + \\ & (\text{Table 2.1 OUTGOING EXTERNAL calls}) + \\ & (\text{Table 2.1 INCOMING EXTERNAL calls}) + \\ & (\text{Table 2.1 INTRA PBX calls})(.3) + \\ & (\text{Table 2.1 INCOMING EXTERNAL calls})/N(N-1). \end{aligned}$$

Formula 2.3 - N-PBX Network CPH per PBX

The total calls per hour in the N-PBX network is given by:

$$(N)(\text{Result of Formula 2.3})$$

where N is the number of PBXs in the network.

Formula 2.4 - N-PBX Network CPH

Step 4: Randomly Connected N-PBX Network Environment

Eliminating the fully connected restriction introduces additional complexity in calculating PBX network calls per hour. This complexity is caused by the fact that calls per hour statistics in randomly connected networks must take tandem calls into account. To illustrate this, consider the network of Figure 2.8. Any calls originating at PBX 4

destined for PBX 1 will add tandem traffic to PBX 2 and 3. Due to the topology, calls per hour calculations for PBX 2 and 3 must include provision for tandem calls.

Figure 2.8 - Example Four-PBX Network

Further analysis of the above network shows that:

- * All calls originated at PBX 1 intended for PBX 4 will traverse PBX 2 and 3. The tandem traffic generated by PBX 1 is given by the:

$$(\text{number of calls from PBX 1 to PBX 4})(L),$$

where:

$$L = (\text{the number of network hops between PBX 1 and PBX 4}) - 1.$$

In this case $L = 2$.

- * All calls originated at PBX 1 intended for PBX 3 will traverse PBX 2. The tandem traffic generated at PBX 2 by PBX 1 in this situation is given by the:

$$(\text{number of calls from PBX 1 to PBX 3})(L),$$

where:

$$L = (\text{the number of network hops between PBX 1 and PBX 3}) - 1.$$

In this case $L = 1$.

Similar analysis may be performed on all PBX (x,y) combinations in the above network. In all cases, the tandem

traffic generated may be calculated by the same means as presented in the above example (x,y) combinations.

For any N-PBX network, the tandem traffic caused by calls made from PBX x to any other PBX y in any network is equal to:

(the number of calls made from x to y)
 ((the number of network hops between x and y) - 1).

Formula 2.5 - Tandem CPH due to Calls from X to Y

The above formula quantifies the number of tandem calls by determining how many are caused by a PBX.

Based on the above, the total tandem traffic generated in a network is given by the summation of Formula 2.5 for all (x,y) combinations. This may be expressed as:

$$\sum_{x=1}^N \sum_{y=1}^N \text{Result of Formula 2.5}$$

Formula 2.6 - Network Tandem CPH

The calculation can be simplified by reasserting the assumption proposed in the two-PBX network discussion, that

all PBXs in the network are identical in configuration.
With this, the average number of tandem calls generated per
PBX is given by:

(Total outgoing network calls)
(Average network path length - 1).

Formula 2.7 - Tandem CPH per PBX

The average network path length is equal to:

(total network hops between each PBX (x,y) combination)/
(the number of PBX (x,y) combinations where $x \neq y$).

Formula 2.8 - Average Network Path Length

The number of PBX (X,Y) combinations is given by:

$N(N-1)$

where N is the number of PBXs in the network.

Formula 2.9 - Number of PBX Combinations

Extending Formula 2.7, the number of tandem calls per
network is given by:

$(N)(\text{Result of Formula 2.7})$

where N is the number of PBXs in the network.

Formula 2.10 - Tandem CPH per Network

For the simple network depicted in Figure 2.8:

The total network hops between each PBX (x,y) combination is 20, given by:

(hops between 1,2) +
 (hops between 1,3) +
 (hops between 1,4) +
 (hops between 2,1) +
 (hops between 2,3) +
 (hops between 2,4) +
 (hops between 3,1) +
 (hops between 3,2) +
 (hops between 3,4) +
 (hops between 4,1) +
 (hops between 4,2) +
 (hops between 4,3).

Applying Formula 2.9, the number of PBX (x,y) ($x \neq y$) combinations is 12, given by $(4)(3)$.

Applying Formula 2.8, the average network path length = $20/12 = 1.6666$.

Applying Formula 2.7, the total number of tandem calls is:

$(\text{number of outgoing network calls})(.6666)$.

Utilizing Formula 2.7 on the total-calls data from Table 2.3 for a four-PBX network, Table 2.4 depicts additional tandem call generation per PBX based on a variety of average path lengths. Note that Figure 2.8 depicts the topology which will, for a four-PBX network, yield the maximum average path length of 1.6666. As a result, Table 2.4 does not record

data for any path length exceeding the maximum.

Lines (Ref: Table 2.3)	Additional Tandem Traffic When Average Path Length =					
	1.1	1.2	1.3	1.4	1.5	1.6666
500	62	124	186	248	310	413
1000	123	246	369	492	615	818
1500	182	364	546	728	910	1213
2000	241	482	723	964	1205	1609
2500	300	600	900	1200	1500	2000
3000	359	718	1077	1436	1795	2391
3500	417	834	1251	1668	2085	2782
4000	476	952	1428	1904	2380	3172

Table 2.4 - Result of Formula 2.7 - Four-PBX Network

The data of Table 2.4 indicates that additional tandem calls processed can be quite significant depending on the topology of the network. In the four-PBX network with the maximum average path length (1.6666), processed tandem calls will add 15.3% to 15.8% of additional network traffic depending on the topology of the network. This percentage figure is only applicable to the four-PBX network situation. Worst case additional tandem traffic percentages will vary depending on the number of PBXs in the network and the topology of the network.

Summary

This section developed a traffic model for calculating network calls per hour rates for any type of network topology. To summarize, calls per hour rates are calculated by the following steps:

1. Use Table 2.1 as the basis for calculation.
2. Given the PBX network under consideration, apply Formula 2.2 to yield a matrix such as that depicted by Table 2.3.
3. Apply Formula 2.4 to yield calls per hour per network, excluding tandem calls.
4. Apply Formula 2.7 to yield tandem traffic per PBX.
5. Apply Formula 2.10 to yield tandem traffic per network.
6. Calculate total network calls by summing the results of steps 3 and 5.

3 TRAFFIC MONITORING REQUIREMENTS

This chapter outlines the author's proposed functional requirements for a PBX traffic monitoring package. Areas such as user interface requirements and compliance to standards requirements are outside of the scope of this thesis. Each requirement is supported by a brief justification.

Functional Requirements

The functional requirements of a traffic monitoring package are:

1. To provide the ability to view the call path associated with a specific device or collection of devices. This functionality allows the network manager to easily verify the call path programming of the network and to find programming errors. Alternatively, the network manager may wish to know what path is followed if a user dials a string of digits from a particular device in the network.
2. To provide the ability to view all traffic in the network. This functionality assists the network manager in understanding traffic patterns, detecting changes in traffic patterns and identifying potential or real congestion points.

3. To provide the ability to observe network call paths for voice or data calls or both simultaneously. Decisions made to the operating parameters of a network environment are affected by whether a particular link is being used for voice or data. If a path between PBX B and C is congested, for example, data to the network manager may indicate that 50% of the link is being used for data calls from PBX C to a terminal server via PBX B. In this situation the best solution to the problem may be to provide a dedicated link between PBX C and the terminal server rather than supplying additional trunking resources between B and C. Without the ability to easily appreciate the types of calls being made via the congested route, the network manager is susceptible to solving problems with less than optimal solutions.
4. To provide the ability to observe the call paths for all traffic affecting a PBX or collection of PBXs. With such capability, the network manager can more comfortably assess the reason for PBX or subnetwork problems caused by high traffic levels. Consider the situation where users connected to PBX B and PBX C are complaining of poor service response times. A possible reason for such a complaint is that the PBXs are receiving more traffic than they can handle and, consequently, running out of CPU resource. A technique used to circumvent this problem is to alter the routing of traffic from other PBXs such that the overloaded areas are bypassed. In order to make

correct alternate routing decisions, the network manager must understand the origination points of the traffic which is affecting the overloaded PBXs.

5. To provide the ability to view all traffic originating from or terminating on a specific PBX or collection of PBXs. Such functionality has many applications. For example, the network manager may be interested in recording the distribution of calls from all or a subset of PBXs in the network. The manager may be interested in assessing the percentage of calls originating from a PBX to another PBX in the network or the percentage of calls originating from a PBX to an off-network destination. Such information is essential when adjusting further operating and configuration characteristics of the network. If, for example, users on PBX B are making many off-network calls via PBX C, it may be advantageous to increase the number of external central office trunks connected directly to B.
6. To provide the ability to view the complete call path of traffic occurring on links between a pair of PBXs. This requirement is essential to assist a network manager in understanding the cause of a congestion or other anomalous condition. Assume, for example, that a congestion condition is observed between two PBXs, B and C, in the network. The most likely uneducated fix to this problem would be to add additional trunks to increase the

connection capacity between B and C. Although satisfying short term requirements, the chosen solution may be hiding the real problem. To correctly diagnose the solution to this problem the network manager must be able to acquire more information about the congestion condition. In particular, the network manager must be able to see the entire call path of all established calls traversing the congested route. Such a view might indicate that 60% of the congested route between B and C is caused by traffic originating at PBX D. Clearly, such a perspective would affect the solution chosen to fix the problem.

In addition, the traffic flow monitoring package must:

1. Provide the ability to observe any of the above items in real time. This facility has numerous applications, particularly when applying automatic software controlled adjustments to the operating parameters of the network. Such dynamic adjustments are only effective if based on the current state of the network. For the human observer, a real time perspective facilitates similar, but less dynamic, adjustment.
2. Provide the ability to observe any of the above items on a historical basis. This perspective allows a network manager to look at the past events of network operation and thus supports post mortem analysis of a network situation.

If a network PBX collapsed, for example, this functionality would allow the network manager to observe, after the fact, the traffic characteristics which might have caused the collapse.

Summary

This chapter has defined six key functional requirements of a PBX traffic flow monitoring package. Each of these must be satisfied in real time or on a historical basis.

4 MONITORING USING CDR ARCHITECTURE A

This chapter analyzes the application of CDR Architecture A to meet the traffic monitoring requirements outlined in Chapter 3.

Section 4.1 describes CDR Architecture A in detail. Differences between this architecture and those commonly used in the industry are described. Also included are a description of when CDRs are generated, contents of CDRs, an example CDR generation scenario and how to calculate CDR generation statistics for any PBX network topology. This serves as a framework for the analysis performed in the remainder of the chapter.

Since data produced by the PBX network is processed by the NMC, the NMC must have provision for storing CDR information to subsequently satisfy traffic flow monitoring requirements. Section 4.2 outlines the internal RAM and disk storage structures required at the NMC. The storage structures later serve as a basis for traffic flow monitoring algorithms and for determining storage requirements at the NMC.

Section 4.3 describes how traffic flow monitoring requirements are satisfied at the NMC by outlining the algorithms that would be executed at the NMC in response to user queries. These algorithms operate on the RAM storage structures of the NMC.

Section 4.4 identifies and analyzes potential bottlenecks to determine the physical (hardware) requirements of the traffic monitoring system.

4.1 CDR Architecture A

In Architecture A, CDRs are generated by a PBX to indicate call establishment, call termination and call transfer. They are not generated for intra PBX calls.

A call establishment CDR is generated on a PBX whenever a non-intra PBX call is being established. An incoming external call which terminates on a network trunk, for example, causes the generation of a call establishment CDR identifying two trunks as being involved in the call. A station calling out on an external trunk causes the generation of a call establishment CDR identifying a station and a trunk as being involved in the call. Further non-intra call types were identified in Section 2.1.1.

A call termination CDR is generated on a PBX whenever a call is completed. For every call establishment CDR, there will be a call termination CDR. The delay between the call establishment CDR and corresponding call termination CDR depends on the duration of the call.

Call transfer CDRs are generated on PBXs where a call transfer involving a trunk has occurred. These CDRs indicate that the call has been transferred and identify the resultant call connections. The key purpose of these records is to ensure that the call is billed to the party originating the call (if device A calls device B and B, as an intermediate party, transfers A to

a new device C, the charge of the C call should be billed to device A rather than to device B).

There are differences between Architecture A and that which is commonly used in the industry. The key similarity between the two is that a CDR is generated on each PBX traversed by a call. The key difference is that common CDR architectures generate a CDR at each PBX only when the call terminates. This CDR contains information which, in Architecture A, is spread over multiple CDRs.

The reason for this difference is that, as noted in Section 2.1.2, the current primary use of CDRs is for billing reports. For such reports, no CDR information is needed prior to the termination of the call. A requirement of traffic flow monitoring, however, is the real time display of calls in progress. To facilitate this via CDRs, CDR information must be generated when the call is established.

4.1.1 CDR Content

The content of a CDR record is dictated by whether call establishment, call transfer or call termination is being indicated. The required record content for each of these events is presented below. Each record is derived from the assessment of the functional requirements.

In deriving fields of CDRs, attention was given to

maintaining nibble and byte boundaries. For the ensuing discussion, this occasionally causes an allocation of space which may slightly exceed the real requirements of the record field.

Call Establishment CDRs

A call establishment CDR is depicted in Figure 4.1.

Bits	Field Description
1-8	Record Length (based on "digits dialed")
9-10	Record Function (CALL ESTABLISHMENT)
11	Type of Call (Voice or Data)
17-32	Date
33-56	Start Time HH:MM:SS
57-96	Calling Party (Trunk number or Extension)
	Called Party (Trunk number or Extension)
97-104	PBX id
105-136	Digits Dialed (variable; 26 digits max)

Figure 4.1 - Call Establishment CDR

Details on the fields of the call establishment record are:

- * Record-length is the total length of the record. This is variable since the digits-dialed field is of variable length.
- * Record-function identifies the record as a call-establishment record. To accomodate 3 possible values, 2 bits are allocated for this field.
- * Type-of-call indicates whether the call is voice or data. 1 bit is allocated for this field.

- * Date is stored as days to conserve space. Allocated space is 16 bits to accomodate a span of approximately 179 years (65535 days / 365 days per year).
- * Start-time is stored in HH:MM:SS format. Allocated space is 8 bits for hours, 8 bits for minutes and 8 bits for seconds (total = 24 bits). Combined with the date field, this field is used to determine the duration of the call for billing purposes.
- * If the CDR is describing a tandem call, both the calling and called parties will describe a trunk; in all other situations, one of the parties will be an extension and the other will be a trunk. Adequate space must be reserved in this CDR to accomodate either of these situations. The bounds defined by this thesis are that trunk numbers will not exceed 4 digits and extension numbers will not exceed 6 digits (ie: trunk numbers range from 0000 to 9999; extension numbers range from 000000 to 999999). As a result, 16 bits of storage are required for trunks, the first bit to indicate "trunk", the remaining bits to identify the trunk number. 24 bits of storage are required for extensions, the first bit to indicate "extension", the remaining bits to identify the extension number. Summing these, the total storage required for the calling and called party fields is 40 bits.
- * PBX-id uniquely identifies the PBX from which the CDR was generated. Allocated storage is 8 bits, implying that there will not be more than 255 PBXs in the network.
- * Digits-dialled contains the digits dialled by the PBX. This may be variable length up to 26 digits. The average length is assumed to be 8 digits, requiring a storage allocation of 32 bits (4 bits per digit).

Call Termination CDRs

A call termination CDR is depicted in Figure 4.2.

Bits	Field Description
1-2	Record Function (CALL TERMINATION)
3-8	Time to Answer in Seconds
9-24	Date
25-48	End Time HH:MM:SS
49-64	Trunk Party (Trunk number)
65-72	PBX id

Figure 4.2 - Call Termination CDR

Details on the fields of the call termination record are presented below. Where not mentioned, the storage structure of a field in this record is identical to the storage structure outlined for the similar field in the call establishment record

- * Record-function identifies this as being a call-termination record.
- * Time-to-answer identifies the seconds of time between when the requested device was seized and when it was answered. If the call was not answered, this field is set to 0. Maximum allocated space for this function is 6 bits implying that time-to-answer will not exceed 63 seconds.
- * Date is the date on which the call terminated.
- * End-time is the time of day at which the call terminated.
- * Trunk-party is the trunk party of the call which has cleared (if both parties in the call are trunks, either of the trunks are indicated). It is not necessary for this record to indicate both devices involved in the call since that association can be derived based on the data that was produced by the corresponding call establishment record.
- * PBX-id identifies the PBX from which the record was

generated.

Call Transfer CDR

A call transfer CDR is depicted in Figure 4.3.

Bits	Field Description
1-2	Record Function (CALL TRANSFER)
9-48	Calling Party (Trunk number or Extension)
	Called Party (Trunk number or Extension)
49-72	Transferring Party
73-80	PBX id

Figure 4.3 - Call Transfer CDR

Details on the fields of the call transfer record are presented below. Where not mentioned, the storage structure of a field in this record is identical to the storage structure outlined for the same field in the call establishment record.

- * Record-function identifies this as a call-transfer CDR.
- * Calling-party, called-party and transferring-party identify the three parties involved in the transfer. The transferring party will always be an extension, thereby requiring 24 bits of storage.
- * PBX-id identifies the PBX on which the transfer occurred.

4.1.2 CDR Generation: Example

Figure 4.4 illustrates an intra network call. Station 1200 on PBX 1 dials 7300, trunk 23 is seized and 7300 is forwarded to PBX 2. On PBX 2, the call comes in via trunk 62, trunk 91 is seized and 7300 is forward to PBX 3. Eventually PBX 4 receives 7300 and rings the requested station. Figure 4.4(b) depicts the CDRs generated during the call establishment phase of the call (date and time information is not shown). A CDR is generated at each PBX through which the call is routed.

(a) Call Path

PBX	Type of Call	Caller	Digits Dialed	Callee
1	Voice	1200	7300	Trunk 2
2	Voice	Trunk 62	7300	Trunk 91
3	Voice	Trunk 18	7300	Trunk 311
4	Voice	Trunk 147	7300	7300

(b) Resultant Call Establishment CDRs

PBX	Trunk
1	Trunk 2
2	Trunk 62
3	Trunk 181
4	Trunk 147

(c) Resultant Call Termination CDRs

Figure 4.4 - Intra Network Call Example

Figure 4.4(c) shows the call termination CDRs which will be generated when the call terminates (date and time information is not shown). This implicitly describes the clearing sequence as station 1200 hanging-up first with the hang-up propagated through the network prior to station 7300 hanging-up. In practice, the order of call termination CDRs

varies depending on the hang-up sequence. Independent of the hang-up sequence, however, the generated CDRs will have content as indicated below but the order in which they appear will vary.

4 1.3 CDRs Per Hour

The number of CDRs generated per hour in a PBX network is required in order to assess the resource limitations of the proposed network management system. Using the traffic model of Section 2.3 as a basis, the following section derives CDR generation rates in PBX networks using Architecture A.

Call transfer CDRs were discussed previously to give a complete picture of CDR Architecture A. In a network, however, the number of call transfer CDRs will be insignificant relative to the number of call establishment and call termination CDRs because only a small percentage of the total number of calls are transferred. Consequently, call transfer records will not be considered in CDRs per hour calculations.

A CDR is generated both at call establishment and call termination in each of the PBX network call types (Section 2.1.1):

- * a local device call terminates on an outgoing external trunk (OUTGOING EXTERNAL).
- * an incoming external trunk call terminates on a local

device (INCOMING EXTERNAL).

- * an incoming external trunk call terminates on a network trunk (INCOMING EXTERNAL TO OUTGOING NETWORK).
- * a local device call terminates on an outgoing network trunk (OUTGOING NETWORK).
- * an incoming network trunk call terminates on a local station (INCOMING NETWORK).
- * an incoming network trunk call terminates on an outgoing network trunk (TANDEM).

Calls per hour for the first five of these call types can be taken directly from a matrix such as that depicted by Table 2.3. Referencing Table 2.3, the total number of CDRs, ignoring tandem calls, which are generated per PBX during both call establishment and call termination is given by:

$$(2)((\text{OUTGOING EXTERNAL}) + (\text{INCOMING EXTERNAL}) + (\text{INCOMING EXTERNAL TO OUTGOING NETWORK}) + (\text{OUTGOING NETWORK}) + (\text{INCOMING NETWORK})).$$

Formula 4.1 - CDRs per PBX per Hour

The factor 2 is included since a CDR is generated both at call establishment and call termination.

The number of CDRs generated per network per hour, ignoring tandem calls, is:

(Result of Formula 4.1)(N)

Formula 4.2 - CDRs per Network per Hour

where N is the number of PBX systems in the network.

To address tandem calls, Formula 2.7 is utilized. The additional number of CDRs caused by each PBX due to tandem calls is given by:

(2)(Result of Formula 2.7).

Formula 4.3 - Tandem CDRs per PBX per Hour

The additional number of CDRs per network due to tandem calls is given by:

(Result of Formula 4.3)(N)

Formula 4.4 - Tandem CDRs per Network per Hour

where N is the number of PBX systems in the network.

CDR generation rates for two scenarios (with and without tandem calls) of the four-PBX network described by Table 2.3 are presented in Table 4.1. As explained in Section 2.3, an average path length of 1.6666 is the maximum possible in a

four-PBX network.

Lines Trunks		CDRs per Hour per Network (No Tandem Traffic) (Avg. Path Length = 1)	Tandem Calls Caused Per PBX (Tandem Traffic) (Avg. Path Length = 1.6666)	Additional CDRs/Hour Network
500	71	16616	413	3306
1000	122	32952	818	6543
1500	176	49880	1213	9706
2000	230	66288	1609	12869
2500	283	82504	2000	15989
3000	336	98832	2391	19130
3500	388	115112	2782	22255
4000	441	131400	3172	25381

Table 4.1 - CDR Rates for a Four-PBX Network

The no-tandem-traffic section of Table 4.1 describes a fully connected network. Within that section of the table, CDRs/Hour/PBX and CDRs/Hour/Network are calculated by the application of Formula 4.1 and Formula 4.2, respectively. The tandem-calls-caused column, calculated by the application of Formula 2.7, identifies the number of tandem calls generated per PBX in a four-PBX network when the average path length for network calls is 1.6666. The additional-CDRs/hour/network is calculated by the application of Formula 4.4.

In the worst case 4-PBX network configuration, tandem calls

add between 19.3 and 19.9% of additional CDR traffic to the network. Similar to calls per hour data, this percentage will vary with the number of PBXs in the network and the average path length per network call.

Summary

The process for calculating CDR generation rates for Architecture A is:

1. For a PBX network, calculate a matrix such as that illustrated by Table 2.3 by the application of theories outlined in Section 2.3.
2. Calculate tandem traffic by application of Formula 2.7. The average path length portion of the formula is what enables the consideration of any network topology.
3. Ignoring tandem calls, calculate CDR generation rates per PBX by application of Formula 4.1 to the data matrix created by Step 1.
4. Calculate CDR generation rates per network by the application of Formula 4.2.
5. Calculate CDR generation rates for tandem calls per PBX by application of Formula 4.3.
6. Calculate CDR generation rates for tandem calls per network by application of Formula 4.4.

At completion of the first 2 steps of this process, calls per hour rates for the PBX network are known. At the end of the next 4 steps, CDRs per hour rates for the PBX network are known. With this data, resource requirements for the network management system can be derived. The process for this is outlined in Section 4.4.

4.2 Storage Of CDR Data

This section describes the set of storage structures required at the NMC to store and manage CDR data. This description will be

utilized later in this chapter when discussing algorithms to satisfy traffic flow monitoring queries (Section 4.3) and when assessing CPU, RAM and disk requirements at the NMC (Section 4.4).

CDR data is stored in RAM and on disk. The RAM data is used to satisfy real time queries on traffic flow conditions. Disk data is used to satisfy queries about past events.

4.2.1 RAM Data Structures

Since NMC RAM data will be accessed to satisfy real time queries, performance (rapid access in particular) is a key consideration in the design of RAM data structures. An analysis of the CDR architecture yields two key attributes of each generated CDR. First of all, each CDR is associated with a single PBX. Secondly, since CDRs are not generated on intra PBX calls, each CDR references at least one trunk.

Taking advantage of these characteristics, Figure 4.5 illustrates the RAM data structure for storing CDR information. This matrix is indexed by trunk-number (1...N) and PBX-id (1...M). The expanded content of matrix element [2,1], [62,2] and [91,2] is shown in the matrix to reflect a portion of the call path depicted by Figure 4.4. The intersection of [2,1] indicates that the other-party involved in the call is station 1200 and that the call is voice. [62,2] indicates an other-party involved in the call as trunk

91, reflecting the fact that trunk 91 is in conversation with trunk 62. [91,2] indicates an other-party of trunk 62. Similar path information can be plotted for any calls.

		PBX					
		1	2	3	4	...	M
T R U N K #	1					...	
	2	1200 Voice				...	
	62		T 91 Voice			...	
	91		T 62 Voice			...	
	N					...	

Figure 4.5 - RAM Storage of CDRs

At the NMC, data for the matrix in Figure 4.5 is taken directly from CDRs indicating call establishment or call transfer. Upon reception of call termination CDRs, the corresponding matrix elements are cleared (indicating that the [trunk-number, PBX-id] combination is no longer in use). Since the data structure is based on the trunk and PBX combinations, the matrix is accessible directly from information contained in the received CDRs.

In Figure 4.5, each element of the matrix indicates the other-party. This can be a six digit extension number or a six digit trunk number. In addition, each element contains an indication of whether the call is voice or data. As a result, each element of this data structure is comprised of:

- * a single bit to differentiate between voice and data.
- * a single bit to indicate whether the other party is a trunk or a device.
- * 20 bits to hold up to six digits.

The total storage required per element, then, is approximately 3 bytes.

Algorithms which may be applied to satisfy the real time requirements of the traffic flow monitoring package are discussed in Section 4.3. These algorithms are designed to operate on the matrix in Figure 4.5.

4.2.2 Disk Data Structures

As noted at the beginning of this section, CDR disk information must support historical analysis of network traffic flow.

Each CDR record will be stored on disk as an element of a direct access file. Depending on the size of the network and the corresponding number of CDRs being generated, there could be many such files. There could be, for example, a new file

created every hour or every day or every week, etc. This is an important point to note to avoid the misperception that this design requires all CDRs to be stored in a single file. Figure 4.6 depicts the conceptual file structure that each direct access file would have. In this diagram, X represents the index into the direct access file where the last CDR was written.

Figure 4.6 - Disk Storage of CDRs

Since there is a one-to-one relationship between the number of CDRs generated for call termination and call establishment, the average size of each element in Figure 4.6 is the average size of these two CDRs.

The number of elements in Figure 4.6 is controlled by the length of time for which CDR collection is occurring. This time will vary depending on how much historical information

the network manager requires.

In addition to storing CDRs on disk, the RAM data structure defined in Figure 4.5 will be periodically written to disk. Along with this, the current value of X from Figure 4.6 and the name of the file indexed by X will be written to disk. This will create the conceptual file structure depicted by Figure 4.7. As in Figure 4.5, the size of each element in Figure 4.7 is 3 bytes. The storage required for X and the file name is negligible relative to the matrix being written out and is not considered in subsequent calculations.

1	<ul style="list-style-type: none"> - Figure 4.5 structure at time A - Value of X at time A - File name indexed by X at time A
2	<ul style="list-style-type: none"> - Figure 4.5 structure at time B - Value of X at time B - File name indexed by X at time A
3	<ul style="list-style-type: none"> - Figure 4.5 structure at time C - Value of X at time C - File name indexed by X at time A
:	:
:	:
:	:

Figure 4.7 - Disk Storage of RAM Matrix

The need for the data structures of Figure 4.6 and Figure 4.7 are clarified by example in Section 4.3.

4.2.3 Additional Storage Requirements

The RAM matrix in Figure 4.5 is indexed by trunk-number and PBX-id. As CDR information is processed, it is possible to look into an element of the matrix (see Figure 4.5) and determine, for example, that local to PBX 2, trunk 62 and trunk 91 are connected in conversation. What cannot be determined from the RAM/disk data structures presented so far is the termination points of either of these trunks. Referring to Figure 4.4, trunk 62 on PBX 2 terminates on trunk 2 on PBX 1; trunk 91 on PBX 2 terminates on trunk 18 on PBX 3.

It is essential to have this information prior to solving many of the possible traffic flow monitoring queries. An example of such a query is "show the call path involving station 1200 on PBX 1 through the network". Without trunk termination information, call paths cannot be determined.

Another matrix, indexed by trunk-number and PBX-id, can be used to store the required data. This is presented in Figure 4.8 and is required both in RAM for rapid access and on disk for permanent storage. This matrix contains the termination point of a trunk. For example, the matrix element at the intersection of trunk 62 and PBX 2 ([62,2]) is set to 2:1. This identifies trunk 2 on PBX 1 as the end of on trunk 62 on PBX 2. Similarly, at the intersection of trunk 2 and PBX 1 ([2,1]), 62:2 is indicated.

Figure 4.8 - Additional RAM/disk storage

Each element in Figure 4.8 contains a PBX identifier and a trunk number. Based on CDR contents, a trunk number will not exceed 4 digits and the number of PBXs in the network will not exceed 255. As a result, 8 bits of storage are required for the PBX identifier and 16 bits for the trunk number. This results in 24 bits (3 bytes) of required storage per matrix element.

The need for this data structure is clarified by example in Section 4.3.

4.3 Traffic Flow Monitoring Algorithms

This section describes the traffic flow monitoring algorithms which can be applied on the NMC to retrieve the data needed to meet the requirements described by Chapter 3. All algorithms

operate on the data maintained by the RAM structures depicted by Figure 4.5 and Figure 4.8.

To assist in establishing the context for these algorithms, assume that a network manager is querying the network management system from the NMC, looking at a high resolution screen which depicts the network topology, network elements and links between them.

As noted in Chapter 3, the traffic flow monitoring system must provide the ability to view network traffic in real time or on a historical basis. For real time monitoring, the RAM matrix of Figure 4.5 will be updated as the NMC receives CDR data from the PBX network. At the time that real time display is requested, the RAM data structures will be accessed to display the current traffic situation. Once the initial view is presented, the display and the RAM matrix will be continually updated as CDRs are received.

If a historical view is requested, a matrix identical to Figure 4.5 will be updated from disk data. Assume, for example, the query: "Show all traffic on 89/09/11 at 22:15". To update the RAM matrix with the status of the network at that date and time, the following algorithm is used. This algorithm is applied as the first step for all queries involving historical data.

- * Access disk to retrieve the structure depicted by Figure 4.7 at the nearest available time prior to the requested time. If the matrix was saved every hour, for example, the nearest structure would be the 89/09/11, 22:00 snapshot. Copy this matrix into an identical structure as

that depicted by Figure 4.5.

- * Using X and the file name, both available from Figure 4.7, access the file name (the structure described depicted by Figure 4.6) beginning at X+1. Read CDR records from disk, update the RAM structure retrieved in the previous step, until the 22:15 time stamp is surpassed (note: depending on the number of files in Figure 4.6 format, more than one file may have to be opened and read). Reading and updating the RAM matrix can be accomplished using the same software that drives the update of Figure 4.5 in real time.
- * The RAM structure now contains the traffic state of the network at the requested time. Using algorithms described below, the user's query will be satisfied.

Given the RAM matrix of Figure 4.5, updated from real time or historical data, the following algorithms will be applied to retrieve the data to meet the traffic flow monitoring requirements. These requirements follow the order outlined by Chapter 3.

View a Specific Call

Example query: Show the call affecting station 1200 on PBX 1.

To satisfy this query, the following algorithm is applied:

- * Scan through each element of column 1 (representing PBX 1) of the RAM data structure of Figure 4.5 until station 1200 is found. Finding 1200 at [2,1], for example, indicates that station 1200 is in conversation with trunk 2. Assume that the station is found at ["trunk #", "PBX-id"].
- * To find the termination point of ["trunk #", "PBX-id"], index the matrix depicted by Figure 4.8 at ["trunk #", "PBX-id"]. If the matrix element is nil, the trunk referenced by ["trunk #", "PBX-id"] is a CD trunk and does not terminate within the PBX network. Otherwise, the referenced trunk terminates on the [trunk #, PBX-id] combination stored within the matrix

element.

- * If the previous step shows that the trunk terminates within the network, the step can be reapplied with the new [trunk #, PBX-id] combination to find the next step in the call path. This process can be continued until another non-trunk termination point is found or until the trunk no longer terminates within the PBX network. Once this occurs, the complete call path is known and can be displayed appropriately.

Example query: Show the call affecting trunk 91 on PBX 2.

To satisfy this query, the following algorithm is applied:

- * access the RAM structure of Figure 4.5 at [91,2].
- * If the element in the RAM structure indicates that the trunk is in conversation with a station, the call path can be traced and displayed by following the previous algorithm.
- * If the element in the RAM structure indicates that the trunk is in conversation with another trunk, the call path must be traced along both trunks. For each trunk, the call path can be traced and displayed by following the previous algorithm.

Viewing All Traffic

Example query: Show all traffic in the network

For each non-nil element [trunk #, PBX-id] of the matrix depicted by Figure 4.5:

- * If the content of the element is an extension number, an incoming trunk call has terminated on the PBX or an outgoing trunk call has been originated by the PBX. Using the [trunk #, PBX-id], access Figure 4.8 to determine the termination point of the trunk. If the accessed element in Figure 4.8 is nil, this is a CO trunk call; Otherwise, this call involves a network trunk and the trunk terminates on the PBX indicated in the element of Figure 4.8.
- * If the content of the element is a trunk, this is a

tandem call. One of the trunks in the call is given by the current [trunk #, PBX-id] indexes; the other is stored in the accessed element. The termination points for each of these trunks must be determined by application of the same mechanism described by the previous step, namely by using the [trunk #, PBX-id] combinations to access Figure 4.8.

This simple algorithm will yield all the data necessary to provide a visual display of all traffic in the network.

View Voice and/or Data Calls

Example query: Show all Data Calls in the Network.

The algorithm is identical to that described above for "Viewing All Traffic" with the exception that the display of information is governed by an additional check, namely whether the call is voice and/or data. This check is made by looking at the appropriate field within each element of Figure 4.5.

View Paths of Calls Affecting a PBX(s)

Example query: Show all Calls Affecting PBX 20.

For each trunk of the PBX(s), access the matrix depicted by Figure 4.5 at [trunk #, PBX-id]. If the element is non-nil, display the call following the algorithm outlined above in "View a Specific Call".

View Calls Originating or Terminating on a PBX(s)

Example query: Show all calls which originate or terminate at PBX 20.

Given the PBX id(s), traverse Figure 4.5 for all trunks of the requested PBX. If the matrix element is non-nil and does not reference a network trunk (ie: the trunk is not in conversation with another trunk), the call is either terminating or originating at the PBX. Display the call using the algorithm outlined above in "View a Specific Call".

View Calls Associated with a PBX Connection

Example query: Show calls affecting trunks connecting PBX 2 to PBX 3.

Access Figure 4.8 at one of the supplied PBX-ids. For each trunk on that PBX, access the matrix of Figure 4.8 to determine whether it terminates on the other supplied PBX-id. If it does, use that information to access Figure 4.5 and display the call path as per the algorithm outlined above in "View a Specific Call".

4.4 Resource Requirements

This section discusses potential bottlenecks that exist in the outlined traffic monitoring system.

Figure 2.7 depicts the network management topology on which the

traffic monitoring system is based. With this system structure, four bottlenecks are identifiable. These include:

- * the amount of disk and RAM space required at the NMC.
- * the bandwidth required to support PBX-network to NMC communication.
- * the processing capability required at the NMC to handle the amassing, evaluation and storage of CDR data arriving from the PBX network. Also, the processing capability required to handle user queries.
- * the bandwidth required to enable the transfer of CDR information within the PBX network, assuming that each PBX does not have a direct connection to the NMC.

The severity of each of these potential bottlenecks is determined by the amount of data being transferred. In turn, the amount of data being transferred is a function of the size and number of generated CDR records. The following paragraph derives the average CDR size for Architecture A.

Average CDR Size

As shown by Figure 4.1 and 4.2, the average size of the call establishment CDR is 17 bytes and the size of the call termination CDR is 9 bytes. Since these records are always generated in pairs, the average size of CDRs being generated by the system is the average of these two records, equating to 13 bytes

4.4.1 NMC Storage Requirements

This section determines the amount of disk and RAM space

required at the NMC for any network size and topology.

RAM Requirements

RAM data structures were outlined by Figures 4.5 and 4.8.

Total RAM requirements are given by:

$$(\# \text{ PBXs in network})(\# \text{ of Trunks})(6 \text{ bytes}).$$

Formula 4.5 - RAM Requirements

For each of Figures 4.5 and 4.8, the #-of-PBXs-in-network and #-of-trunks yields the dimensions of the depicted matrices. Each element of both matrices requires three bytes of storage.

Applying Formula 4.5, Table 4.2 depicts RAM requirements for the four-PBX network described by Table 4.1.

Lines Trunks		RAM Requirements (Bytes)
500	71	1704
1000	122	2928
1500	176	4224
2000	230	5520
2500	283	6792
3000	336	8064
3500	388	9312
4000	441	10584

Table 4.2 - Four-PBX Network RAM Requirements

Disk Requirements

Disk storage is required for the conceptual file structures depicted by Figures 4.6, 4.7 and 4.8. This section presents formulas for determining disk space requirements for each of these structures given any network topology.

The disk storage, in bytes per hour, required to store Figure 4.6 is derivable by the following formula:

$$(\# \text{ of CDRs per network per hour})(13 \text{ bytes}).$$

Formula 4.6 - Disk Storage Required for Figure 4.6

In this formula, "13 bytes" is the average size of call establishment and call termination CDRs.

Substituting the four-PBX network data depicted by Table 4.1 into Formula 4.6, Table 4.3 shows the disk required per hour to store the disk structure depicted by Figure 4.6. As in Table 4.1, this depicts best case (no tandem traffic) and worst case results for a four-PBX network.

CDRs/ Hour/ Network (No Tandem Traffic - Table 4.1)	Disk Required/ Hour (Bytes)	Additional CDRs/Hour/ Network (Worst Case Tandem Traffic - Table 4.1)	Additional Disk Required/ Hour (Bytes)
16616	216008	3306	42978
32952	428376	6543	85059
49880	648440	9706	126178
66288	861744	12869	167297
82504	1072552	15989	207857
98832	1284816	19130	248690
115112	1496456	22255	289315
131400	1708200	25381	329953

Table 4.3 - Disk Required to Store Figure 4.6

The disk storage, in bytes per hour, required to store Figure 4.7 is derivable by the following formula:

$$(\# \text{ PBXs})(\# \text{ of Trunks per PBX})(3 \text{ bytes})$$

Formula 4.7 - Disk Storage Required for Figure 4.7

The dimensions of the depicted matrix are #-of-PBXs-in-network and #-of-trunks. The size of each matrix element is three bytes. This storage is independent of CDR generation rates.

Applying Formula 4.7 to any four-PBX network, Table 4.4 shows the disk required per hour to store the RAM matrix

described by Figure 4.7.

Lines Trunks		Disk Required/Hour (Bytes)
500	71	852
1000	122	1464
1500	176	2112
2000	230	2760
2500	283	3396
3000	336	4032
3500	388	4656
4000	441	5292

Table 4.4 - Disk Required to Store Figure 4.7

The disk storage, in bytes, required for Figure 4.8 is derivable by the following formula:

$$(\# \text{ PBXs})(\# \text{ of Trunks per PBX})(3 \text{ bytes})$$

Formula 4.8 - Disk Storage Required for Figure 4.8

The dimensions of the depicted matrix are #-of-PBXs-in-network and #-of-trunks. The size of each matrix element is 3 bytes. This storage is independent of CDR generation rates, is static and multiple copies are not required.

Applying Formula 4.8 to a four-PBX network, Table 4.5

shows the disk required per hour to store the RAM matrix described by Figure 4.8.

Lines Trunks		Disk Required/Hour (Bytes)
500	71	852
1000	122	1464
1500	176	2112
2000	230	2760
2500	283	3396
3000	336	4032
3500	388	4656
4000	441	5292

Table 4.5 - Disk Required to Store Additional Matrix

Summary

It is clear that the RAM structures do not occupy significant RAM storage even if the network is at its maximum size (255 PBXs, each configured with 441 trunks). As a result, these structures will not be considered in the subsequent analysis of Chapter 6.

It is also clear that the storage required for the structure depicted by Figure 4.6 is the dominant factor in disk storage requirements. As a result, the disk requirements for Figure 4.7 and Figure 4.8 will not be considered in the subsequent analysis of Chapter 6.

4.4.2 PBX-Network To NMC Bandwidth Requirements

PBX network to NMC (see Figure 2.7) bandwidth requirements are derivable by the following formula:

$$(\# \text{ of CDRs per hour})(13 \text{ bytes})(8)/3600.$$

Formula 4.9 - Bandwidth Requirements (bps)

The #-of-CDRs-per-hour is the number of CDRs being generated in the PBX network per hour. The average size of the call establishment and call termination CDR is 13 bytes.

This formula yields the bandwidth requirement without considering any overhead associated with a link protocol.

Substituting the four-PBX network data depicted by Table 4.1 into Formula 4.9, Table 4.6 shows the bandwidth required for the PBX network to NMC connection. As in Table 4.1, this depicts best case (no tandem traffic) and worst case results for a four-PBX network.

CDRs/ Hour/ Network (No Tandem Traffic - Table 4.1)	Required Bandwidth (bps)	Additional CDRs/Hour/ Network (Worst Case Tandem Traffic - Table 4.1)	Additional Required Bandwidth (bps)
16616	480	3306	96
32952	952	6543	189
49880	1441	9706	280
66288	1915	12869	372
82504	2383	15989	462
98832	2855	19130	553
115112	3325	22255	643
131400	3796	25381	733

Table 4.6 - NMC to PBX-Network Bandwidth Requirements

4.4.3 NMC Processor Requirements

There are four events which require processor time at the NMC, including:

- * handling call establishment CDRs.
- * handling call termination CDRs.
- * periodically updating the disk structure of Figure 4.6.
- * satisfying user traffic flow monitoring queries.

Each of these is discussed further below.

For each call establishment and call termination CDR, the processor will:

- * collect the CDR (via interrupt or some other means).

- * analyse the CDR to update RAM matrix information.
- * update the RAM matrix. Each CDR will cause the update of a single element of the RAM matrix element.
- * write the CDR to disk.

For call establishment and call termination CDRs, it is clear that the effect on processor requirements is governed by the size and number of CDRs being processed. For a four-PBX network, Table 4.1 depicts the number of CDRs; Table 4.3 depicts the amount of data that these numbers translate to. Of the four activities that must occur for each CDR, it is likely that the analysis of the CDR to update RAM matrix information and the update of the RAM matrix are both trivial operations. The first of these is trivial since the CDR is in fixed format and the required data is a simple retrieval operation. The second of these is trivial since the RAM matrix is directly indexable from the CDR information. Given this, the largest effect on the processor is due to the handling and storing of the received data.

The third event which demands processor time is the periodic writing of the RAM structure to disk. Assuming that this occurs once per hour or even once per 15 minutes, the corresponding processor effect is negligible relative to the handling of the CDRs because of the volume of data involved.

The fourth event requiring processor time is satisfying user traffic flow monitoring queries. This is, in effect, the

problem of applying an algorithm to the RAM data structure and producing visual displays with the resultant data. Based on Section 4.3, it is clear that the traversal of the data structure is a simple operation. Since the visual displays are not defined by this thesis, it is not possible to assess the processor time necessary to manage them. Also, this thesis has not established that the processor which handles CDRs would be the same one used to update displays. Thus, based on what is known, this event is insignificant relative to the handling of CDRs.

Summary

The primary demand on the processor is the receipt and storage of CDRs. This will be analysed further in Chapter 6.

4.4.4 Intra Network Bandwidth Requirements

Intra network bandwidth is the bandwidth required on PBX to PBX connections to support CDR traffic destined for the NMC. This bandwidth requirement depends on the topology of the PBX network. Minimum intra network bandwidth is achieved on those links supporting CDR traffic for a single PBX and directly connecting that PBX to the PBX attached to the NMC. If all PBXs in the network were so connected, all intra network links would require adequate bandwidth capacity to support the CDR traffic generated by a single PBX. A network

topology with minimum intra network bandwidth requirements is depicted in Figure 4.9, assuming that the NMC is connected to the center PBX. Any link in Figure 4.9 represents the best case intra network link.

Figure 4.9 - Minimum Intra Network Bandwidth

Maximum intra network bandwidth is required in networks configured such as Figure 4.10, assuming the NMC is connected to PBX 1. Link 1 must have adequate bandwidth to handle all CDR traffic from PBX 2, PBX 3 and PBX 4. Link 2 must support CDR traffic from PBX 3 and PBX 4. Link 3 must support CDR traffic from PBX 4.

Figure 4.10 - Worst Case Intra Network Bandwidth

Link 1 of Figure 4.10 represents the worst case bandwidth requirement for an intra network link. It must handle CDR traffic from (N-1) PBXs in the network.

For any topology, the intra network bandwidth requirements will always be a function of the number of PBXs being supported by the link. The general formula for calculating intra network bandwidth requirements is:

(# of PBXs supported by the link)
 (# of CDRs generated by a PBX per hour)
 (13 bytes per CDR)
 (8 bits per byte)/
 (3600 sec per hour).

Formula 4.10 - Intra Network Bandwidth (bps)

The average size of the call establishment and call termination CDRs is 13 bytes. As discussed above, the number

of PBXs supported by the link can never exceed $N-1$, where N is the number of PBXs in the network.

This thesis will not examine intra network bandwidth in any more detail. Rather, since the intra network requirement is always less than the NMC to PBX requirement, this thesis will focus on analyzing NMC to PBX bandwidth requirements.

4.4.5 Summary

Based on the resource requirements analysis, there are three key resource bottlenecks:

- * Disk storage required to store CDRs received at the NMC (Figure 4.6).
- * NMC to PBX network bandwidth.
- * The processor requirements at the NMC.

The requirements for these resources are graphed and discussed for a wide variety of network sizes and topologies in Chapter 6 and Appendix A.

5 MONITORING USING CDR ARCHITECTURE B

This chapter introduces a new CDR Architecture B and assesses the corresponding effect on the resource bottlenecks identified and quantified in Chapter 4. The intention of this proposal is to reduce the monitoring resource requirements for a network of given size and topology.

Section 5.1 describes CDR Architecture B in detail, following the organization of Section 4.1.

Section 5.2 revisits the storage structures proposed by Section 4.2 to determine their applicability to the new CDR architecture.

Section 5.3 revisits the traffic flow monitoring algorithms outlined in Section 4.3 to determine their applicability to the new CDR architecture.

Section 5.4 analyses the bottlenecks outlined by Section 4.4 to determine the physical (hardware) requirements of the traffic monitoring system when using the new CDR architecture.

5.1 CDR Architecture B

In CDR Architecture A, a CDR was generated for all calls which were not local to a PBX. In addition, a CDR was generated on each PBX traversed by a call when the call was either established or terminated. CDRs were sent to the NMC and assembled there to satisfy traffic flow monitoring requirements.

Using CDR Architecture B, a CDR is still generated for all calls which are not local to a PBX. Rather than having a CDR generated on each PBX traversed by a network call, however, a single CDR is generated when the call is established and a single CDR when the call is terminated. As in Architecture A, CDRs are still sent to the NMC.

As a result of Architecture B, the total number of CDRs that are generated by the network is reduced. Figure 4.4 illustrates a call that has traversed four PBX systems. In CDR Architecture A this call would have caused four CDRs (see Figure 4.4) when the call was established and four CDRs when the call was terminated. Using CDR Architecture B, this same call will result in the generation of one CDR when the call is established and one CDR when the call terminates.

The key difference, then, between Architecture B and Architecture A is in the number of CDRs generated during a PBX network call (ie: a call involving at least 2 PBXs). In Architecture A, the number of CDRs generated is directly related to the number of PBXs involved in the call. In Architecture B, the number of CDRs generated for any call is independent of the number of PBXs traversed by the call.

To appreciate the migration to Architecture B, there are two key issues that should be clarified:

Issue 1

How can the path of a call through the network be traced using the new architecture?

Call path information (PBX id and the devices involved in the call) is added to the call establishment signalling messages as they traverse PBXs. An effect of this solution is that call establishment messages become longer as they progress through a PBX network. This is explained in more detail in Section 5.1.2.

Issue 2

Architecture B appears to be more efficient than Architecture A due to the fact that fewer CDR records are being generated on any call involving more than one PBX. If Architecture B is superior, why is it not already used in the industry?

Prior to the early 1980s, call establishment was achieved over analogue trunks by using channel associated signalling techniques. In the late 1970s and early 1980s, the telecommunications industry began to adopt sophisticated protocols that used common channel signalling techniques and digital trunks. These factors have been key in increasing available signalling bandwidth, thus providing the ability to pass more call information between telecommunications systems.

CDR Architecture B relies on the availability of increased signalling bandwidth since call path information is added to call establishment messages. Prior to the availability of increased signalling bandwidth, the adoption of such an architecture would have been technically infeasible due to the inefficiencies of older signalling techniques. Currently, even with increased signalling bandwidth, inertia and a huge installation of low bandwidth wiring prevents the telecommunications industry from adopting advantageous and innovative changes quickly.

Finally, the efficiency of one CDR architecture over another is not based on the number of CDRs generated but rather on the amount of CDR data generated. This is a function of the number of records generated and the size of the records. As will be seen in subsequent analysis, however, Architecture B will generate less data for all network sizes and topologies.

5.1.1 CDR Content

CDRs are generated during call establishment, call termination and call transfer. The record content for each of these situations is presented below.

Call Establishment CDRs

The call establishment CDR required for this architecture is different from the one required by Architecture A in that several fields have been deleted and a new call-path field added. A call establishment CDR is presented below.

Bits	Field Description
1-8	Record Length (based on "digits dialed")
9-10	Record Function (CALL ESTABLISHMENT)
11	Type of Call (Voice or Data)
17-32	Date
33-56	Start Time HH:MM:SS
57-64	Digits Dialed Length
65-96	Digits Dialed (variable length)
97-	Call Path (variable length)

Figure 5.1 - Call Establishment CDR

Fields are identical to corresponding fields outlined in Section 4.1.1 except as follows:

- * Digits-dialed-length denotes the length of the digits dialed field. This new length field is required due to the fact that there are two variable length fields (rather than one as in Architecture A) in the call establishment CDR for Architecture B. As in chapter 4, the average number of digits dialed is assumed to be 10 (10 digits at 4 bits per digit = 40 bits of required storage).
- * Call-path contains the path that the call has followed through the network. For each PBX that the call traverses, this field will contain a PBX ID (8 bits), an originating device and a

terminating device. The originating and terminating device will both be trunks (tandem call) or an extension and a trunk. The total space required to store this information is 40 bits (16 bits for a trunk, 24 bits for an extension). Call-path will thus be 48 bits for each PBX involved in the call.

Call Termination CDRs

There is no difference between the call termination CDR and the one used by CDR Architecture A.

Bits	Field Description
1-2	Record Function (CALL TERMINATION)
3-8	Time to Answer in Seconds
9-24	Date
25-48	End Time HH:MM:SS
49-64	Trunk Party (Trunk number)
65-72	PBX id

Figure 5.2 - Call Termination CDR

Call Transfer CDRs

There is no difference between the call termination CDR and the one used by CDR Architecture A.

Bits	Field Description
1-2	Record Function (CALL TRANSFER)
9-48	Calling Party (Trunk number or Extension)
49-72	Called Party (Trunk number or Extension)
73-80	Transferring Party
	PBX id

Figure 5.3 - Call Transfer CDR

5.1.2 CDR Generation: Example

Architecture B is achieved by a fundamental change to the call establishment CDR and the associated call establishment signalling protocol. Figure 5.4 illustrates a network call where station "1200" on PBX 1 is calling station "7300" on PBX 4.

2

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(a) Call Path

PBX	Type of Call	Call Path
4	Voice	1:X1200,2 2:62,91 3:18,311 4:147,X7300

(b) Resultant Call Establishment CDR

PBX	Trunk
4	Trunk 147

(c) Resultant Call Termination CDR

Figure 5.4 - Intra Network Call Example

During the call establishment phase of this call, CDR information will be generated (date and time information is not shown) as depicted by Figure 5.4(b). For the call termination phase of the call CDR information will be generated as depicted by Figure 5.4(c).

For call establishment, the single CDR is generated by PBX 4. Extension 1200 on PBX 1 called extension 3700 via trunk 2; PBX 2 received the call on incoming trunk 62 and called out via trunk 91; PBX 3 received the call on incoming trunk 18

and called out on trunk 311; and so on. PBX 4 generated a call establishment CDR since it was the terminating PBX for the call.

To appreciate how PBX 4 acquires the information necessary to generate the CDR, the call establishment phase must be described in some detail. Using today's signalling techniques, assuming a reasonably sophisticated, ISDN-like protocol utilizing digital trunking and common channel signalling, the call referenced above would be established as follows:

- * Station 1200 dials station 7300.
- * Trunk 2 is reserved for the call by PBX 1. A message is sent via common channel signalling to PBX 2. The message indicates that station 1200 is calling station 7300.
- * PBX 2 receives the message via incoming trunk 62, interprets the message and determines that station 7300 is being called. PBX 2 reserves trunk 91 for the call and forwards the message to PBX 3.
- * The process described by the previous step continues until PBX 4 receives the message and rings station 7300. This completes the call establishment phase of the call.

By a slight modification to this signalling protocol, it is possible to supply PBX 4 with all the information needed to generate a CDR. By having each traversed PBX add call path information to signalling messages, PBX 4 would receive a call establishment message containing the data required to produce the CDR illustrated in Figure 5.4(b).

This technique is not without implications. On the positive side, it allows a reduction in the number of CDRs generated in a network call. On the negative side, there is an increase in the length of messages exchanged between PBXs during call establishment. This may result in increased bandwidth requirements for signalling channels depending on the characteristics of the associated signalling protocol (in particular, the bandwidth of the signalling channel and the number of channels controlled by it). (Note: This implication is not significant for the purposes of this thesis but should be considered prior to implementing Architecture B.)

5.1.3 CDRs Per Hour

As in Architecture A, the generation rates of Architecture B are directly related to the calls per hour calculations of Section 2.3. Using that as a basis, this section derives CDRs per hour rates. It also highlights example differences in CDRs per hour rates between Architecture A and Architecture B.

As in Architecture A, the number of call transfer CDRs in Architecture B are insignificant in comparison to the call establishment and call termination numbers. As a result, call transfer CDRs are not considered in CDR generation calculations.

A CDR is generated both at call establishment and call termination in each of the following PBX call types (Section 2.1.1):

- * an incoming external trunk call terminates on a local device (INCOMING EXTERNAL).
- * a local device call terminates on an outgoing external trunk (OUTGOING EXTERNAL).
- * an incoming network trunk call terminates on a local station (INCOMING NETWORK).

The calls per hour for these call types can be taken directly from a matrix such as that illustrated by Table 2.3. Referencing Table 2.3, the total number of CDRs generated per PBX per hour is:

$$(2)((\text{OUTGOING EXTERNAL}) + (\text{INCOMING EXTERNAL}) + (\text{INCOMING NETWORK})).$$

Formula 5.1 - CDRs per PBX per Hour

The "2" is included because a CDR is generated both when a call is established and when the call terminates.

The number of CDRs generated per network per hour (CDRs/Network/Hour) is:

$$(\text{Result of Formula 5.1})(N)$$

Formula 5.2 - CDRs per Network per Hour

where N is the number of PBX systems in the network.

The key to this architecture is that the above equations hold not only for the fully connected network topology but also for the non-fully connected network topology. In Architecture A, additional CDRs were generated for each tandem call which occurred in the network. In Architecture B, tandem calls do not result in the generation of CDR information. Each traversed PBX does, however, increase the size of the call establishment CDR. This implication is considered in Section 5.4.

Table 5.1 calculates CDR Architecture B generation rates for the four-PBX network described by Table 2.3. It also includes the CDR generation rates for Architecture A (taken directly from Table 4.1).

Lines Trunks		CDRs per Hour per Network	CDRs/ Hour/ Network	Additional CDRs/Hour/ Network (Worst Case)
		(Independent of Tandem Traffic - Architecture B)	(From Table 4.1 - CDR Architecture A)	
500	71	11656	16616	3306
1000	122	23136	32952	6543
1500	176	35320	49880	9706
2000	230	46984	66288	12869
2500	283	58520	82504	15989
3000	336	70136	98832	19130
3500	388	81728	115112	22255
4000	441	93328	131400	25381

Table 5.1 - CDR Rates for a Four-PBX Network

As can be seen from Table 5.1, there is a significant difference in Architectures A and B with respect to CDR generation rates. Percentage difference shows that:

- * With no tandem calls, Architecture B produces 70 to 71% of the CDRs produced by Architecture A (calculated by dividing column 3 by column 4).
- * With worst case tandem calls in a four-PBX network, Architecture B produces 58.5 to 59.5% of the CDRs produced by Architecture A (calculated by dividing column 3 by the addition of column 4 and 5).

As a result, in any four-PBX network topology, CDR generation rates for Architecture B will be 58.5 to 71% of those in Architecture A. The effect of this on the total amount of data being transferred is further analysed in Section 5.4.

These percentage differences apply only to a four-PBX network

situation. Each network size and topology will yield different percentage results between Architecture A and B. This variation is developed in Chapter 6.

Summary

The process for calculating CDR generation rates for Architecture A is:

1. For a PBX network, calculate a matrix such as that illustrated by Table 2.3 by the application of the theories outlined in Section 2.3.
2. Calculate CDR generation rates per PBX by application of Formula 5.1 to the data matrix created by step 1.
3. Calculate CDR generation rates per network by the application of Formula 5.2.

At completion of the first step of this process, calls per hour rates for the PBX network are known. At the end of the next 2 steps, CDRs per hour rates for the PBX network are known. At this stage, resource requirements for the network management system can be derived. The process for this is outlined in Section 5.4.

5.2 Storage Of CDR Data

The conceptual storage structures required by Architecture B are identical to those described in chapter 4 by Figures 4.5 to 4.8. The structure used for RAM management of CDRs remains as described by Figure 4.5, namely a matrix indexed by trunk-number and PBX-id. A difference between the two architectures occurs in the way that the matrix is updated. For Architecture A, a single CDR causes the update of a single matrix element. For

Architecture B, a single CDR may cause the update of many matrix elements, the exact number depending on the length of the call path contained in the CDR. A single CDR will not update more than a single element in a specific column as this would imply that a single PBX was being traversed twice by the same call.

Two structures were outlined in Section 4.2.2 for disk management of CDRs. The first, depicted by Figure 4.6, is a simple array-like structure which collects CDR information in the order that it is received. The second structure, depicted in Figure 4.7, is a snapshot of the RAM storage structure. Both of these are required to support CDR Architecture B.

Figure 4.8 depicts a mapping table used to determine the termination points of trunks. This is required in RAM and on disk for both CDR architectures.

5.3 Traffic Monitoring Algorithms

The traffic flow monitoring algorithms introduced in Section 4.3 are designed to operate on the RAM and disk storage structures and, consequently, are independent of the CDR architecture. Since Architecture B and Architecture A are supported by identical RAM and disk data structures, the algorithms for traffic flow monitoring using CDR Architecture A are directly applicable to CDR Architecture B.

5.4 Resource Requirements

As in Section 4.4, there are 4 primary resource requirements:

- * the amount of disk and RAM storage required at the NMC.
- * the bandwidth required to support PBX-network to NMC communication.
- * the processing capability required at the NMC to handle the amassing, evaluation and storage of CDR data arriving from the PBX network.
- * the bandwidth required to enable the transfer of CDR information within the PBX network, assuming that each PBX does not have a direct connection to the NMC.

Average CDR Size

As shown in Figure 5.2 and Figure 5.1, the size of the call termination CDR is 9 bytes and the size of the call establishment CDR varies based on the number of PBXs traversed by the call. The number of PBXs traversed is governed by the network topology and call characteristics. Based on Figure 5.1, the size of each call establishment CDR equals:

$$12 \text{ bytes} + ((6 \text{ bytes})(\# \text{ of PBXs traversed by the call})).$$

Formula 5.3 - Call Establishment CDR Size

The following explains how the average size of a call establishment record can be derived.

Given a matrix such as that depicted by Table 2.3 and using Architecture B, CDRs are only generated on OUTGOING EXTERNAL, INCOMING EXTERNAL and INCOMING NETWORK calls. For all network topologies, all OUTGOING EXTERNAL and INCOMING EXTERNAL calls involve a single PBX and affect the call establishment CDR accordingly (ie: the size of the call establishment CDR for these calls is 18 bytes, given by application of Formula 5.3 - (12 bytes + (6 bytes)(1)). The complexity in determining CDR size, then, is in determining the number of PBXs that have been traversed by the INCOMING NETWORK calls.

For any fully connected network, all INCOMING NETWORK calls involve two PBXs. Consequently, the average size, in bytes, of the call establishment CDR for such a network is given by (reference Table 2.3):

$$\frac{((\text{INCOMING EXTERNAL} + \text{OUTGOING EXTERNAL})(18 \text{ bytes}) + ((\text{INCOMING NETWORK})(24 \text{ bytes})))}{(\text{INCOMING EXTERNAL} + \text{OUTGOING EXTERNAL} + \text{INCOMING NETWORK})}$$

Formula 5.4 - Average Call Establishment Size In Fully Connected Network

The "18 bytes" is derived from the fact that a single PBX adds 6 bytes to the call establishment record (12 bytes + 6 bytes = 18 bytes). The "24 bytes" is calculated by (12 bytes + 2(6 bytes)) since, in a fully connected network, all

network calls involve 2 PBXs.

For a randomly connected network, INCOMING NETWORK calls occur as a result of one or more network hops. In this situation, the average call establishment CDR size for a network is calculated by:

$$\frac{((\text{INCOMING EXTERNAL} + \text{OUTGOING EXTERNAL})(18 \text{ bytes}) + ((N-1 \text{ hop INCOMING NETWORK})(12 \text{ bytes} + (6 \text{ bytes})(N))) + ((N-2 \text{ hop INCOMING NETWORK})(12 \text{ bytes} + (6 \text{ bytes})(N-1))) + \dots + ((1 \text{ hop INCOMING NETWORK})(12 \text{ bytes} + (6 \text{ bytes})(2))))}{(\text{INCOMING EXTERNAL} + \text{OUTGOING EXTERNAL} + \text{INCOMING NETWORK})}$$

Formula 5.5 - Average Call Establishment Size In Randomly Connected Network

The INCOMING EXTERNAL, OUTGOING EXTERNAL and INCOMING NETWORK calls of this formula are the total number of such calls occurring in the network. The "N-x hop INCOMING NETWORK" are the number of INCOMING NETWORK calls that travel "N-x" network hops. In the fully connected network, Formula 5.5 equates to Formula 5.4.

Applying Formula 5.5 to the fully connected Four-PBX network and to the randomly connected network depicted by Figure 5.4, the average call establishment size for all line/trunk combinations is depicted in Table 5.2. These values are used in subsequent calculations.

Lines Trunks		Call Establishment Size (bytes)	
		Best Case (No Tandem Traffic)	Worst Case (Worst case Tandem Traffic)
500	71	21	22
1000	122	21	22
1500	176	20	22
2000	230	20	22
2500	283	20	22
3000	336	20	22
3500	388	20	22
4000	441	20	22

Table 5.2 - Four-PBX Network Call Establishment Sizes

In summary, the average CDR size, in bytes, for Architecture B is given by:

$(\text{Result of Formula 5.5} + 9 \text{ bytes})/2$

Formula 5.6 - Average CDR size

The "9 bytes" is the size of the call termination CDR.

5.4.1 NMC Storage Requirements

RAM Requirements

Since the RAM data structures are independent of CDR size, the RAM requirements do not change between

Architecture A and Architecture B. For the four-PBX network example, Table 4.2 depicts the RAM requirements for both architectures.

Disk Requirements

Since the disk storage structures required to support Architecture A or B are identical and since Figures 4.7 and 4.8 are independent of CDR size, there will be no change in storage requirements for them. Consequently, the disk required for these two structures using Architecture B is depicted by Tables 4.4 and 4.5, respectively.

The remaining disk storage structure is the collection of received CDRs depicted by Figure 4.6. While conceptually equivalent in both architectures, the disk space requirements are affected by the number of CDRs and the size of each CDR. As a result, independent of the network topology, there will be a change in storage requirements for this structure between Architecture A and Architecture B. Although Architecture B will produce call establishment CDRs which are larger than those produced in Architecture A, B will produce fewer call establishment and call termination CDRs for all network calls.

The disk storage, in bytes per hour, required for Figure

4.6 is derivable by the following formula:

(# of CDRs per network per hour)(Result of Formula 5.6).

Formula 5.7 - Disk Storage Required for Figure 4.6

"Formula 5.6" yields the average size of call establishment and call termination records. Building on the CDR generation rates depicted by Table 5.1, Table 5.3 depicts the disk space required to store the conceptual structure depicted by Figure 4.6. Note that there are two sets of numbers for Architecture B; one reflects the worst case network topology, the other reflects the fully connected network topology. The change in disk requirements is due to the fact that the size of the call establishment record of Architecture B varies with the network topology.

CDRs/ Hour/ Network Independent of Tandem Traffic Table 5.1)	Architecture B Disk Required/Hour (Bytes)		Worst Case Disk Storage Required using Architecture A (From Table 4.3)
	Best Case (No Tandem Traffic)	Worst Case Tandem	
11656	174840	174840	258986
23136	347040	347040	513435
35320	494480	529800	774618
46984	657776	704760	1029041
58520	819280	877800	1280409
70136	981904	1052040	1533506
81728	1144192	1225920	1785771
93328	1306592	1399920	2038153

Table 5.3 - Disk Required to Store Figure 4.6

In the worst case four-PBX network, the disk space per hour required to store Figure 4.6 in Architecture B is 67.5 to 68.7% of that required using Architecture A. In the best case four-PBX network, the disk space requirement of Architecture B is 76.5 to 81% of that required using Architecture A.

5.4.2 PBX-Network To NMC Bandwidth Requirements

A significant reduction in bandwidth requirements over CDR Architecture A is realized by introducing Architecture B. As would be expected, however, the amount of reduction varies with the size and topology of the network. Since Architecture B produces fewer CDRs for all network calls, the

percentage reduction in bandwidth requirements over Architecture A will increase as network and tandem calls increase.

Bandwidth requirements are derivable by the following formula:

$$(\# \text{ of CDRs per hour})(\text{Results of Formula 5.6})(8)/3600.$$

Formula 5.8 - Bandwidth Requirements (bps)

Formula 5.6 yields the average size of the call establishment and call termination CDRs.

Table 5.4 shows the bandwidth requirements for the four-PBX network described by Table 5.1. Again, there are two sets of numbers for CDR Architecture B to reflect the variation of the call establishment record size as the network topology changes. Note that this table depicts effective bandwidth requirements.

CDRs/ Hour/ Network (Independent of Tandem Traffic Table 5.1)	Architecture B Required Bandwidth (bps)		Worst Case Bandwidth Required using Architecture A (From Table 4.6)
	Best Case (No Tandem Traffic)	Worst Case Tandem	
11656	389	389	576
23136	771	771	1141
35320	1099	1177	1721
46984	1462	1566	2287
58520	1821	1951	2845
70136	2182	2338	3408
81728	2543	2724	3968
93328	2904	3111	4529

Table 5.4 - NMC to PBX-Network Bandwidth Requirements

In the worst case four-PBX network, the bandwidth required to support Architecture B is 67.5 to 68.7% of that required to support Architecture A. In the best case network, the bandwidth required by Architecture B is 76.5 to 81% of that required to support Architecture A.

5.4.3 NMC Processor Requirements

As for CDR Architecture A, there are four events which require processor(s) time at the NMC. These are:

- * The handling of call establishment CDRs;
- * The handling of call termination CDRs;
- * Periodically updating the disk structure depicted by Figure 4.6.
- * Satisfying user traffic flow monitoring queries.

The positive effect of Architecture B on processor requirements will vary with the size and topology of the network. Gains in processor utilization for a specific network topology will always be realized as the number of tandem and network calls increase.

Of the above events, the first two are affected significantly by the migration from Architecture A to B. Since the processing required is directly related to the volume of received CDR data, it is clear that by reducing the CDR volume, a positive effect on processor requirements will be realized. Updating the RAM data structure from call establishment and call termination CDRs will be a bit more processor intensive per CDR in Architecture B since such CDRs may result in the update of many elements in the RAM matrix (rather than a single element as in Architecture A). This will be offset, however, by the fact that fewer CDRs are being processed.

For each call establishment or call termination CDR, the processor will:

- * collect the CDR (via interrupt or some other means).
- * analyse the CDR to update RAM matrix information.
- * update the RAM matrix. For the call establishment CDR, call data will be entered into the matrix. For the call termination CDR, elements of the matrix will be cleared.
- * write the CDR to disk.

Table 5.1 compares the number of CDRs processed in four-PBX networks as a result of Architectures A and B. Table 5.3 compares the corresponding volume of data generated. In both numbers and data volume, the savings between B in comparison to A are significant.

The processor cost of periodically updating the disk structure of Figure 4.6 or of satisfying user queries does not change as a result of the new architecture. This is due to the fact that data to satisfy all real time queries is taken from the RAM data structure, utilized by both CDR architectures. The processor cost of satisfying historical queries will be reduced by Architecture B since fewer CDR records will have to be processed to recreate the network status. However, since historical queries do not have real-time constraints, the processor cost associated with them is not particularly relevant.

Summary

As for Architecture A, the primary demand on the processor is in the receipt and storage of CDRs. This will be discussed further in Chapter 6.

5.4.4 Intra Network Bandwidth Requirements

With one exception, the intra network bandwidth discussion presented in Section 4.4.4 for Architecture A is directly

applicable to Architecture B. The exception occurs in Formula 4.7 which identifies the average size of the call establishment and call termination CDRs as being 13 bytes. In this architecture, the average size of the CDRs is calculated by application of Formula 5.6.

Once again, the resource required for intra network bandwidth will always be less than the NMC to PBX bandwidth requirement and, consequently, will not be considered further.

5.4.5 Summary

As for Architecture A, there are three key resource bottlenecks:

- * Disk storage required to store CDRs received at the NMC (Figure 4.6).
- * NMC to PBX network bandwidth.
- * The processing capability at the NMC for handling the receipt and storage of received CDRs.

The requirements for these resources are further evaluated for a wide variety of network sizes and topologies in Chapter 6.

6 RESULTS

This chapter applies the analysis of Chapters 4 and 5 to a wide variety of network sizes. The four primary objectives of this chapter are:

- * to quantify, via graphs, the resource requirement boundaries for any PBX network using CDR Architecture A or B.
- * to compare the two CDR architectures by quantifying the difference in resource requirements between them for any PBX network.
- * to show resource requirement trends which occur using Architectures A and B when a fixed number of PBXs are in the network but the physical capacity of the PBXs is varied.
- * to perform sensitivity analysis on the results by varying the key assumption of the traffic model outlined by Chapter 2. This is documented in Section 6.4.

The three key resource bottlenecks identified in Sections 4.4.5 and 5.4.5 were:

- * the disk storage required to store CDRs received at the NMC.
- * the NMC to PBX network bandwidth requirements.
- * the processing power required to handle the data at the NMC.

The graphs introduced in this chapter illustrate data results for one of these resources while varying either the number of PBXs in the network or the physical capacity of the PBXs.

To meet the first three objectives of this chapter, each of Sections 6.1, 6.2 and 6.3 present and discuss three graphs. The first graph plots the number of PBXs in the network (range of 2 to 255) against the resource under consideration. To increase the graph resolution of smaller networks, the second graph also plots

the number of PBXs in the network against the resource under consideration but varies the number of PBXs from 2 to 100. Both graphs assume a fixed capacity of 2000 lines and 230 trunks for each PBX in the network. This capacity is one of the eight line and trunk configurations, described in Section 2.1, that has been considered throughout this thesis. For each resource, a graph depicting similar data for the other seven configurations is included in Appendix A.

The third graph in each of the above sections shows, for a network of eighty PBXs, the capacity of each PBX in the network against the resource under consideration. That is, the size of the network remains constant while the capacity of the PBXs within the network is varied.

Within each graph, four sets of points are plotted to indicate:

- * B_C_A (Best Case using Architecture A), represented in the graphs by the letter "a".
- * B_C_B (Best Case using Architecture B), represented in the graphs by the letter "b".
- * W_C_A (Worst Case using Architecture A), represented in the graphs by the letter "A".
- * W_C_B (Worst Case using Architecture B), represented in the graphs by the letter "B".

Best and worst case network architectures are defined as follows:

The best case network architecture for CDR data generation is the fully connected network since, in such a network, no tandem calls occur.

The worst case network architecture for CDR data generation is the linearly connected network. A linearly connected four-PBX network is depicted by Figure 5.4.

Neither best or worst case network configurations are generally practical for any network exceeding four to eight PBXs. That is, it is unlikely that a geographically dispersed eight-PBX network would be either fully or linearly connected. It is even more unlikely that a one-hundred-PBX network would be either fully or linearly connected. This is due to the number of links required, the associated hardware costs to support the links at the PBXs, the cost of the links, etc.

Although these network configurations are generally impractical, they do define the bounds of resource requirements. That is, ANY network topology using CDR Architecture A or B will require resources that fall between the bounds highlighted by the best case and worst case graphs.

The data for the graphs is calculated by application of the theory outlined in previous chapters. Someone attempting to apply this research can use these boundaries to get an appreciation for the resource requirements. If data specific to a topology is required, the theories of this thesis can be followed to define more precise resource requirements.

All graphs show that:

$$b < a < B < A.$$

Or that, per resource:

- * best case B is always better than best case A.

- * worst case B is always better than worst case A.

In summary, given any network size and topology, CDR Architecture B will require less resource than CDR Architecture A.

6.1 Disk Storage Requirements

Figure 6.1 depicts best and worst case disk storage requirements using CDR Architectures A and B for a PBX network ranging in size from 1 to 255 PBXs. Figure 6.2 depicts the same for networks ranging in size from 1 to 100 PBXs. For both graphs, each PBX in the network is configured with 2000 lines and 230 trunks.

For all sizes of network, the disk required to support B_C_B is between 77.3 and 81.1% of that required to support B_C_A. The disk required to support W_C_B is between 24.8 and 81.1% of that required to support W_C_A.

Figure 6.1 - Disk Space Requirements
PBX Size: 2000 lines, 230 trunks.

Figure 6.2 - Disk Space Requirements
PBX Size: 2000 lines, 230 trunks.

Figure 6.3 depicts best and worst case disk storage requirements using CDR Architecture A and B for an 80 PBX network when varying PBX configuration from 500 to 4000 lines (eight configurations as outlined in Table 2.1).

As shown by this graph, the relationship of:

$$b < a < B < A$$

holds independent of what PBX configuration is being used within the network.

In the best case 80 PBX network for all eight PBX configurations, the disk required to support Architecture B is 76.4 to 77.6% of that required to support Architecture A. In the worst case eighty PBX network for all eight PBX configurations, the disk required to support Architecture B is 28.6 to 28.8% of that required to support Architecture A.

Figure 6.3 - Disk Space Requirements
of PBXs = 80.

6.2 NMC To PBX Network Bandwidth Requirements

Figure 6.4 depicts best and worst case bandwidth requirements using CDR Architectures A and B for a PBX network ranging in size from 2 to 255 PBXs. Figure 6.5 depicts the same for networks ranging in size from 2 to 100 PBXs. For both graphs, each PBX in the network is configured with 2000 lines and 230 trunks.

For all sizes of network, the bandwidth required to support B_C_B is between 77.3 and 81.1% of that required to support B_C_A. The bandwidth required to support W_C_B is between 24.8 and 81.1% of that required to support W_C_A.

Figure 6.4 - Bandwidth Requirements
PBX Size: 2000 lines, 230 trunks.

Figure 6.5 - Bandwidth Requirements
PBX Size 2000 lines, 230 trunks.

Figure 6.6 depicts best and worst case bandwidth requirements using CDR Architecture A and B for an 80 PBX network when varying PBX configuration from 500 to 4000 lines (eight configurations as outlined in Table 2.1).

As shown by this graph, the relationship of:

$$b < a < B < A$$

holds independent of which PBX configuration is being used within the network.

In the best case eighty PBX network for all eight PBX configurations, the bandwidth required to support Architecture B is 76.4 to 77.6% of that required to support Architecture A. In the worst case eighty PBX network for all eight PBX configurations, the bandwidth required to support Architecture B is 28.6 to 28.8% of that required to support Architecture A.

Figure 6.6 - Bandwidth Requirements
Network Size: 80 PBXs.

6.3 NMC Processing Power Requirements

As noted in Sections 4.4.3 and 5.4.3, two key issues govern the processing requirements at the NMC. These include:

- * the number of CDRs received at the NMC.
- * the amount of data that these CDRs translate to.

The amount of data received at the NMC has already been depicted by Figures 6.1 and 6.2.

To address the first of these, Figure 6.7 depicts best and worst case number of CDRs using CDR Architectures A and B for a PBX network ranging in size from 1 to 255 PBXs. Figure 6.8 depicts the same for networks ranging in size from 1 to 100 PBXs. For both graphs, each PBX in the network is configured with 2000 lines and 230 trunks.

For all sizes of network, the best case number of CDRs received using Architecture B is between 66.9 and 75.3% of those received using A. Worst case number of CDRs received using Architecture B are between 2.3 and 75.3% of those received using A.

Figure 6.7 - CDRs Received
PBX Size: 2000 lines, 230 trunks.

Figure 6.8 - CDRs Received
PBX Size: 2000 lines, 230 trunks.

Figure 6.9 depicts best and worst case CDR generation rates using CDR Architecture A and B for an 80 PBX network when varying PBX configuration from 500 to 4000 lines (eight configurations as outlined in Table 2.1).

As shown by this graph, the relationship of:

$$b < a < B < A$$

holds independent of what PBX configuration is being used within the network.

In the best case eighty PBX network for all eight PBX configurations, the number of CDRs generated in Architecture B is 66.2 to 67.2% of the number generated in Architecture A. In the worst case eighty PBX network for all eight PBX configurations, the number of CDRs generated in Architecture B is 6.8 to 7.0% of the number generated in Architecture A.

Figure 6.9 - CDRs Received
Network Size: 80 PBXs.

6.4 Sensitivity Analysis

The results of this thesis are based on the PBX traffic model described by Section 2.3. Within that section, Formula 2.2 is the method by which the traffic table of the single PBX environment is utilized to derive a traffic table for an N-PBX network. This section describes the effect of altering the key component of Formula 2.2, the distribution of INTRA PBX calls.

Based on Formulas 2.0 and 2.1, Formula 2.2 assumed that:

70% of what were INTRA PBX calls in the single PBX environment will remain INTRA PBX in the N-PBX network while the remaining 30% will terminate uniformly throughout the network.

To test the sensitivity of this assumption, the 70% was varied from 50% to 90%. As would be expected, the number of CDRs, disk storage requirements and bandwidth requirements changed as the percentage changed. Of interest, however, is that CDR architecture B continued to offer significant improvements over architecture A, regardless of the adjustment.

The number of received CDRs in a network configured with 2000 line and 230 trunk PBXs

when the 70% was changed to 50%:

the best case number of CDRs received using Architecture B is between 64.9 and 71.7% of those received using A. Worst case number of CDRs received using B are between 2.1% and 71.7% of those received using A.

when the 70% was unchanged:

the best case number of CDRs received using Architecture B is between 66.9 and 75.3% of those received using A.

Worst case number of CDRs received using B are between 2.3% and 75.3% of those received using A.

when the 70% was changed to 90%:

the best case number of CDRs received using Architecture B is between 69.9 and 80.2% of those received using A. Worst case number of CDRs received using B are between 2.6% and 80.2% of those received using A.

The bandwidth or disk space requirements in a network configured with 2000 line and 230 trunk PBXs:

when the 70% was changed to 50%:

the best case requirements using Architecture B are between 74.8 and 77.3% of A. Worst case requirements using B are between 24.7 and 77.3% of A.

when the 70% was unchanged:

the best case requirements using Architecture B are between 77.3 and 81.1% of A. Worst case requirements using B are between 24.8 and 81.1% of A.

when the 70% was changed to 90%:

the best case requirements using Architecture B are between 80.6 and 86.4% of A. Worst case requirements using B are between 25.2 and 86.4% of A.

In all cases, the direction of change in percentage is what would be expected. Changing the 70% to 50%, for example, increases the number of tandem calls occurring in the network. This increases the benefit of architecture B relative to A as indicated by the decrease in the percentage of the number of CDRs received, the bandwidth requirements and disk space requirements.

In summary, the results of this thesis are not significantly affected by altering the principle assumption of Formula 2.2.

7 CONCLUSIONS

7.1 Have The Objectives Been Met?

Chapter 1 states the three primary objectives of this thesis:

- * To demonstrate that the requirements of a traffic flow monitoring package for PBX networks can be achieved by the use of a Call Detail Record (CDR) architecture which approximates what is used in the industry.
- * To present algorithms which use CDR Architecture A to meet the traffic flow monitoring requirements and to estimate the computing and telecommunications resources required.
- * To present a new "CDR Architecture B" which meets the traffic flow monitoring requirements while requiring significantly less resource.

The analysis to achieve the first objective is presented in Chapter 4. By a slight modification to the architecture commonly used in the industry, it is demonstrated that the requirements of the traffic flow monitoring package are achievable.

Algorithms which use CDR architecture A are presented in Chapter 4. Based on the RAM and data structures outlined by that chapter, the algorithms demonstrate that all traffic monitoring data is attainable from the CDRs. The approach to determining computing and telecommunications resource requirements is also described by Chapter 4. Data resulting from the application of the formulas of Chapter 4 is presented in Chapter 6 and Appendix A.

The analysis to achieve the third objective was presented in

Chapter 5. Resultant data was presented in Chapter 6 and Appendix A. From this data, it is clear that, for minimizing the resource needed to support traffic flow monitoring, Architecture B is superior to Architecture A.

7.2 Applying The Thesis

The work in this thesis has practical application:

- * The CDR architectures can be built into PBXs.
- * The traffic flow monitoring system can be built and applied to PBX networks.
- * If this approach to traffic flow monitoring is adopted, the resource requirements for a specific PBX network can be calculated by the application of the theories presented by this thesis or by mapping the PBX network onto the graphs presented in Chapter 6 or Appendix A.

7.3 Further Extensions

This section presents ideas for the extension of the work begun by this thesis. These are listed below.

- * The theories of this thesis have been constructed in the context of the assumption that all PBXs in the network are identical in configuration, having the same number of lines and trunks. An extension to this work would eliminate that assumption and rework the theories to accommodate any network of a hybrid collection of PBX configurations. Such a rework would allow the direct application of the new theories to any PBX network rather than having to alter the characteristics of the PBX network to fit the current theories.
- * The data for the thesis was derived from Table 2.1 which depicts heavy traffic load statistics. In practice, PBX networks will be comprised of PBXs which experience levels of traffic ranging from heavy to light. An extension to this work would be to rework the theories to consider the specific or predicted traffic levels for each PBX.

- * From the discussions on resource requirements for both CDR architectures, it is clear that resource limitations are determined by the amount of CDR data being transmitted, received, processed and saved. Clearly, if equivalent functionality could be achieved with less data, the resource requirements would be less. An extension to this work would be to look at creative ways to reduce the amount of CDR data. Some areas to investigate might be:
 - * compacting information at the NMC prior to saving it on disk.
 - * using the timestamp of the NMC rather than the timestamp of the PBX. This would save several bytes of data per call establishment and call termination CDR but affect the timing accuracy. The implications of this approach, however, are not clear.
- * Processor requirements at the NMC are assessed by determining the number of records and the amount of data that the NMC must process. These values have not been related to any particular processor platform, primarily due to the fact that planning the hardware configuration at the NMC is beyond the scope of the thesis. An extension to this thesis would be to plan the hardware configuration and measure the number of records and volume of data that the planned configuration could handle.
- * An interpretive user interface using graphics techniques for the proposed traffic flow monitoring facility would be an interesting study.
- * The proposed traffic flow monitoring facility provides complete data on network traffic. A logical next step would be to automate the reconfiguration of network parameters based on analysis of the data.
- * Protocols for receiving CDRs or for automatic response to them have not been analysed.

APPENDIX A: ADDITIONAL GRAPHS

This appendix depicts graphs which are the result of applying the analysis from Chapters 4 and 5 to a wide variety of network sizes and PBX configurations.

Each of Sections A.1, A.2 and A.3 depict fourteen graphs, all plotting network size against a particular resource.

The first fourteen graphs follow the format of Figures 6.1 and 6.2, plotting the number of PBXs in the network against disk storage requirements.

The second fourteen graphs follow the format of Figures 6.4 and 6.5, plotting the number of PBXs in the network against bandwidth requirements.

The last fourteen graphs follow the format of Figures 6.7 and 6.8, plotting the number of PBXs in the network against CDR generation rates.

For each resource category, each pair of graphs shows a different configuration of the PBXs within the network. The "2000 line, 230 trunk" configuration was used in Figures 6.1, 6.2, 6.4, 6.5, 6.7 and 6.8 and, consequently, is not reshowed here.

The graphs are shown in pairs; the first graph of the pair varies the number of PBXs in the network from 2 to 255; to increase the resolution of the first graph, the second graph of the pair varies the number of PBXs in the network from 2 to 100 systems.

A.1 Disk Storage Graphs

Figure A.1 - Disk Space Requirements
PBX Size: 800 lines, 71 trunks.

Figure A.2 - Disk Space Requirements
PBX Size: 500 lines, 71 trunks.

Figure A.3 - Disk Space Requirements
PBX Size: 1000 lines, 122 trunks.

Figure A.4 - Disk Space Requirements
PBX Size: 1000 lines, 122 trunks.

Figure A.5 - Disk Space Requirements
PBX Size: 1800 lines, 176 trunks.

Figure A.6 - Disk Space Requirements
PBX Size: 1500 lines, 175 trunks.

Figure A.7 - Disk Space Requirements
PBX Size: 2500 lines, 283 trunks.

Figure A.8 - Disk Space Requirements
PBX Size: 2500 lines, 283 trunks.

Figure A.9 - Disk Space Requirements
PBX Size: 3000 lines, 336 trunks.

Figure A.10 - Disk Space Requirements
PBX Size: 3000 lines, 336 trunks.

Figure A.11 - Disk Space Requirements
PBX Size: 3500 lines, 388 trunks.

Figure A.12 - Disk Space Requirements
PBX Size: 3800 lines, 388 trunks.

Figure A.13 - Disk Space Requirements
PBX Size: 4000 lines, 441 trunks.

Figure A.14 - Disk Space Requirements
PBX Size: 4000 lines, 441 trunks.

A.2 NMC To PBX Network Bandwidth Graphs

Figure A.15 - Bandwidth Requirements
PBX Size: 500 lines, 71 trunks.

Figure A.16 - Bandwidth Requirements
PBX Size: 500 lines, 71 trunks.

Figure A.17 - Bandwidth Requirements
PBX Size: 1000 lines, 122 trunks.

Figure A.18 - Bandwidth Requirements
PBX Size: 1000 lines, 122 trunks.

Figure A.19 - Bandwidth Requirements
PBX Size: 1500 lines, 176 trunks.

Figure A.20 - Bandwidth Requirements
PBX Size: 1800 lines, 176 trunks.

Figure A.21 - Bandwidth Requirements
PBX Size: 2800 lines, 283 trunks.

Figure A.22 - Bandwidth Requirements
PBX Size: 2500 lines, 283 trunk.

Figure A.23 - Bandwidth Requirements
PBX Size: 3000 lines, 336 trunks.

Figure A.24 - Bandwidth Requirements
PBX Size: 3000 lines, 336 trunks.

Figure A.25 - Bandwidth Requirements
PBX Size: 3500 lines, 388 trunks.

Figure A.26 - Bandwidth Requirements
PBX Size: 3500 lines, 388 trunks.

Figure A.27 - Bandwidth Requirements
PBX Size: 4000 lines, 441 trunks.

Figure A.28 - Bandwidth Requirements
PBX Size: 4000 lines, 441 trunks.

A.3 CDR Generation Rate Graphs

Figure A.29 - CDRs Received
PBX Size: 500 lines, 71 trunks.

Figure A.30 - CDRs Received
PBX Size: 500 lines, 71 trunks.

Figure A.31 - CDRs Received
PBX Size: 1000 lines, 122 trunks.

Figure A.32 - CDRs Received
PBX Size: 1000 lines, 122 trunks.

Figure A.33 - CDRs Received
PBX Size: 1500 lines, 176 trunks.

Figure A.34 - CDRs Received
PBX Size: 1500 lines, 176 trunks.

Figure A.35 - CDRs Received
PBX Size: 2500 lines, 283 trunks.

Figure A.36 - CDRs Received
PBX Size: 2500 lines, 283 trunks.

Figure A.37 - CDRs Received
PBX Size: 3000 lines, 336 trunks.

Figure A.38 - CDRs Received
PBX Size: 3000 lines, 336 trunks.

Figure A.39 - CDRs Received
PBX Size: 3500 lines, 388 trunks.

Figure A.40 - CDRs Received
PBX Size: 3500 lines, 388 trunks.

Figure A.41 - CDRs Received
PBX Size: 4000 lines, 441 trunks.

Figure A.42 - CDRs Received
PBX Size: 4000 lines, 441 trunks.

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