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Bundling Internet Traffic over VBR ATM Networks

Canada – Germany Research Activity

Louise Lamont, Luis Villasenor, Nawel Chefai
and Ilka Miloucheva



This work described in this document was sponsored by the
Department of National Defence under Task 04160.

Defence Research Establishment Ottawa

Technical Report
DREO TR 1999-020
CRC Report No. 98-007
December 1998



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Abstract

An initiative between DeTeBerkom in Berlin and the Communication Research Centre (CRC) in Ottawa was undertaken to determine realistic resource reservation requirements when Internet Protocol (IP) telephony applications are multiplexed with bulk data applications in an Asynchronous Transfer Mode (ATM) network.

In our work, we considered different ways of bundling voice (i.e. IP telephony) and data traffic. We analyse the throughput achieved for the data traffic and the rate, packet loss and delay variance for the voice traffic for each bundle type.

We illustrate the specific effects that different performance factors such as Variable Bit Rate (VBR) traffic parameters, the Transmission Control Protocol (TCP) flow control and send window size, network delay, system scheduling and application traffic have on the Quality of Service (QoS) provision in an ATM Wide Area Network (WAN) and Local Area Network (LAN) environment.

Trans-Atlantic connections, using national high-speed test networks and Teleglobe's trans-Atlantic submarine fibre CANTAT-3 are used to obtain the ATM WAN measurements. LAN measurements are performed using an ATM LAN testbed at CRC.

The experiments are performed and evaluated with the CM Toolset, which provides for the automation of QoS analysis of selected applications under different ATM network environments.

Résumé

Une étude a été effectuée conjointement par le Centre des Recherches sur les Communications (CRC) à Ottawa et par DeTeBerkom à Berlin. L'objectif de cette étude était d'exploiter les ressources du réseau de Mode de Transmission Asynchrone (MTA) de façon efficace en multiplexant des applications de voix utilisant le protocole Internet avec des applications de données.

Differentes méthodes de multiplexage de la voix et des données ont été considérées. Les tests consistaient à mesurer les paramètres de qualité de service MTA tels que la largeur de bande atteinte en fonction du trafic des données ainsi que le débit, la perte de paquets et la variation du délai du trafic de la voix et ce, pour chaque type de multiplexage.

Les résultats révèlent que certains facteurs tels que les paramètres de trafic du débit binaire variable, la dimension de la fenêtre du protocole de contrôle de transmission (TCP), le contrôle du débit TCP, les délais encourus dans le réseau et la répartition du temps de calcul par le système d'exploitation entre les processus concurrents ont un effet spécifique sur la qualité de service des réseaux MTA.

Les mesures trans-Atlantic ont été obtenues en utilisant des réseaux nationales ATM et le câble sous-marin CANTAT-3 de Téléglobe. Les mesures locales ont été effectuées au CRC sur un réseau local MTA.

Un outil dénommé CM tool a été utilisé pour effectuer et évaluer les mesures. Cet outil permet la sélection des caractéristiques du trafic à générer et l'analyse des résultats obtenus.

Executive Summary

A collaboration between the Communication Research Centre (CRC) in Ottawa Canada and DeTeBerkom in Berlin Germany was undertaken to study the Quality of Service (QoS) requirements of User Datagram Protocol (UDP) Internet voice traffic when multiplexed with Transmission Control Protocol (TCP) data traffic over a trans-Atlantic Asynchronous Transfer Mode (ATM) Wide Area Network (WAN) and an ATM Local Area Network (LAN) Variable Bit Rate (VBR) service. The purpose of this investigation was to determine realistic resource reservation requirements when Internet Protocol (IP) telephony applications are multiplexed with bulk data applications.

A series of performance measurement tests were carried out, between Berlin and Ottawa, in the March and April 1998 timeframe. Local ATM measurements were performed at CRC between June and August.

For the purpose of this joint Canada-Germany research activity, national ATM networks were interconnected via the CANTAT-3 trans-Atlantic submarine fibre cable. Teleglobe Canada provided use of the CANTAT-3 submarine fibre cable system. Access to the CANTAT-3, via the national ATM Test Network facilities, was supported by the CANARIE Test Network Operations Committee (TNOC) in Canada and by Deutsche Telekom and DeTeBerkom in Germany. From Pennant Point, Nova Scotia, the CANTAT-3 submarine cable lands at Sylt Germany. Permanent Virtual Circuit (PVC) links supporting a VBR QoS class were set up between the CRC BADlab in Ottawa and DeTeBerkom in Berlin.

The research team also had access to a local ATM testbed at CRC. LAN measurements provided a valuable baseline for comparison with the measurements for the trans-Atlantic ATM WAN. For the LAN measurements, PVCs supporting a VBR QoS class were established.

The experiments focused on two types of Internet applications: bulk applications, which are sensitive to minimum throughput, and voice applications, which are sensitive to delays.

The measurements were taken using the CM toolset which was developed by Automated Testing Solutions (ATS) Research & Consulting GmBh in Berlin. It was used to measure the throughput of the bulk data applications and the voice applications together with the packet loss for the voice applications. The delay variance measurements were taken using the Adtech AX/4000 ATM testset (Adt97).

The objective of the research was to explore how the bandwidth in ATM networks can be used more efficiently. The goal was to demonstrate that by reserving network resources, not only for individual connections, but for groups of connections and while maintaining the traffic and QoS requirement limitations of each connection that network bandwidth resources could be used more efficiently. For instance, it is important that each UDP voice connection that has been grouped together to form a bundle experiences a minimum packet loss, that the transmitting and receiving rate are maintained and that the delay variance is kept to a minimum. We demonstrated that transport level connections can be multiplexed or bundled to improve resource reservation, QoS provisioning and bandwidth cost. We also demonstrated that when connections are bundled at the end-system, many factors affect the performance of the voice and data traffic over a VBR service. These include the type of traffic as well as the network delay, the system scheduling, the rate at which the information is transmitted, the TCP window sizes and the TCP slowstart and congestion avoidance mechanisms.

In our experiments, transport connections are grouped together to form a bundle and the traffic is sent over an ATM virtual connection. The results show that when bundles are built using only UDP connections the UDP throughput starts to decrease when more than twelve UDP audio streams are multiplexed on the WAN. This same behaviour occurs on the LAN when ten UDP audio streams are bundled. When a single TCP connection is bundled with UDP connections, the UDP throughput decreases faster. The TCP window size and slow-start mechanism have a direct impact on the UDP throughput. With a large window size, for instance 50 KB, up to four UDP sessions can be multiplexed so that the required rate for the UDP connections is maintained. By selecting a smaller window size, more UDP connections can be bundled. Finally when a bundle includes many TCP connections the UDP throughput decreases even faster. As the number of TCP sessions is increased, the UDP throughput

decreases. With a large window size, for instance 50 KB, only two TCP connections can be multiplexed with one UDP connection so that the required UDP rate is maintained. Nevertheless by choosing a small window size up to six TCP connections can be bundled with one UDP connection without considerably affecting the throughput of the UDP connection.

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Introduction

The Canada-Germany project "Bundling Internet Traffic over VBR ATM Networks" was undertaken to study the Quality of Service (QoS) requirements of User Datagram Protocol (UDP) Internet voice traffic when multiplexed with Transmission Control Protocol (TCP) data traffic over a trans-Atlantic Asynchronous Transfer Mode (ATM) Wide Area Network (WAN) and an ATM Local Area Network (LAN) supporting a Variable Bit Rate (VBR) service. Different ways of bundling voice (i.e. Internet Protocol (IP) telephony) and data traffic were considered. This investigation was designed to determine realistic resource reservation requirements when IP telephony applications are multiplexed with bulk data transmissions over an ATM network.

One of the primary benefits of ATM networks is that they offer different service classes to differentiate between specific types of connections, each with a particular mix of traffic and QoS parameters. The VBR service class is well-suited for voice applications where the delay requirements are stringent. When the UDP voice traffic is multiplexed with TCP data traffic over a single virtual channel connection, the ATM VBR traffic parameters must be selected carefully in order to provide efficient throughput for the TCP traffic. The traffic parameters that can be set when using the VBR service class are the Peak Cell Rate (PCR), the Cell Delay Variation Tolerance (CDVT), the Sustainable Cell Rate (SCR) and the Maximum Burst Size (MBS)[Atmf96]. The TCP flow control mechanism has a direct impact on the SCR and MBS and the traffic parameters must therefore be set in a way to not degrade the TCP throughput [Ano97][Bon96]. When the traffic parameters are exceeded, the ATM network can enforce the traffic contract by performing traffic policing. Non-conforming cells may be discarded. When cells that carry TCP traffic are discarded, the TCP throughput can go down to zero. In order to ensure that cells are not discarded, traffic shaping is done at the source by limiting the traffic rate at the source to the selected SCR.

Continuous speech of acceptable quality must be reconstructed from voice packets that have experienced variable delays at the sending station and through the network. Various techniques for packet-loss recovery and for jitter compensation have been proposed to improve the

quality of the voice at the receiver [Perk98] [Chen89]. The loss, delay characteristics and the transmitting and receiving voice rates are the voice QoS parameters that are of interest and therefore monitored in our experiments.

Recently a large-scale measurement infrastructure has been proposed in the Internet community that allows for performance and QoS management. Features belonging to such measurement infrastructure include tools and facilities that provide different kinds of performance and traffic analysis, daemons that provide measurement requirements and data bases to store the results. Automated Testing Solutions (ATS) Research & Consulting GmbH in Berlin is working on such an infrastructure. Its infrastructure was used to complete our study of the performance of Internet applications over ATM networks. This measurement infrastructure includes facilities to analyse the factors affecting the Quality of Service of specific classes of applications and provides for the automation of QoS analysis of selected applications under different ATM network infrastructures (trans-Atlantic ATM and Local ATM).

Tele globe Canada provided use of their CANTAT-3 submarine fibre cable. The CANARIE Test Network Operations Committee (TNOC) in Canada and Deutsche Telekom and DeTe-Berkom in Germany supported access to the CANTAT-3 via national ATM test network facilities. The research team also had access to a local ATM testbed at the Communications Research Centre (CRC) in Ottawa. LAN measurements provided a valuable baseline for comparison with the measurements for the trans-Atlantic ATM WAN.

1 UPC Mechanism for VBR

The traffic parameters that can be set when using the VBR service class are the Peak Cell Rate (PCR), the Cell Delay Variation Tolerance (CDVT), the Sustainable Cell Rate (SCR) and the Maximum Burst Size (MBS) [Atmf96]. The PCR specifies the maximum number cells that can arrive at an endpoint per time. The CDVT controls how much time is allowed to pass between consecutive cells. The SCR gives the long-term average number of cells that can arrive at an endpoint. The MBS is the maximum number of cells that can arrive on an endpoint at the peak information rate without violating the sustained information rate. The SCR and

MBS traffic parameters enable the end-system to describe the future cell flow of an ATM connection in greater detail than just the PCR. If an end-system is able to specify the future cell flow in greater detail than just the PCR, then the network may be able to use the network resources more efficiently.

An ATM connection that is set up with specified traffic parameters constitutes a traffic contract between the user and the network. The network can enforce the traffic contract by a mechanism known as Usage Parameter Control (UPC), better known as traffic policing. UPC is a set of algorithms used by an ATM switch on the receipt of cells within a connection to determine whether or not the cell stream is compliant with the negotiated traffic contract. The Generic Cell Rate Algorithm (GCRA) is used to define conformance with respect to the traffic contract. For each cell arrival, the GCRA determines whether the cell conforms to the traffic contract of the connection. The UPC function may implement the GCRA, or one or more equivalent algorithms to enforce conformance. In general terms, the GCRA is used to define the relationship between the PCR and the CDVT, as well as the relationship between the SCR and the MBS. Traffic sent across ATM connections that is controlled by a UPC is sometimes shaped using the GCRA. This ensures that cells will not be inadvertently marked as non-conformant. Traffic shaping can also be done in the traffic source, e.g., workstation.

Conformance for a real-time-VBR (rt-VBR) or non-real-time-VBR (nrt-VBR) connection is characterised by a SCR parameter and corresponding MBS in addition to a PCR parameter and corresponding CDVT. Rt-VBR and nrt-VBR connections are distinguished by their QoS parameters and by the magnitude of the MBS supported. Larger MBSs are more typical for nrt-VBR connections. The QoS parameters are the Peak-to-peak Cell Delay Variation (CDV), the Maximum Cell Transfer Delay (Max CTD), the Mean Cell Transfer Delay (Mean CTD) and the Cell Loss Ratio (CLR). With rt-VBR the CLR, CDV and Max CTD are the QoS parameters of interest while for nrt-VBR the CLR and Mean CTD are the relevant parameters.

Upon the detection of a non-conformant cell, switches in an ATM network can pass, tag, or discard any cells that exceed the configured peak or sustained information rate. When the tagging option is used, cells identified by the UPC function to be non-conforming are modified

by setting the CLP bit to 1. The cells that are tagged will get discarded further within the ATM network if further congestion is experienced. When the discard option is used, cells identified by the UPC function to be non-conforming are discarded.

2 TCP Window Control

TCP [Jaco88], [Post81] was designed to provide reliable best-effort service over a connectionless network layer such as IP. The protocol mechanisms of TCP are described in the following sub-sections along with the problems that occur when trying to ensure reasonable performance over an ATM VBR service.

2.1 TCP Window Based Flow

TCP uses a window based flow and congestion control [Jaco88]. The maximum window that a connection is allowed to use is called the send window. The size of the send window can be set according to the receiver's buffer, the user's throughput requirements or the network bandwidth to be used by the connection. The actual window in TCP is determined by the minimum of the send window and the congestion window. The congestion window is dynamically adapted to the available bandwidth-delay product by the TCP congestion control mechanism (e.g., Slowstart, Congestion Avoidance). TCP sends traffic in a sliding window up to 64 KB. The source has to wait until it receives an acknowledgement from the target before sending further Packet Data Units (PDUs). TCP requires one acknowledgement per PDU.

2.2 Slowstart and Congestion Avoidance

The purpose of Slowstart and Congestion Avoidance is to adapt the PDU flow to the available bandwidth since the transport agent has no idea of the available resources at connection establishment. Slowstart begins with the congestion window set to one PDU. At the arrival of an acknowledgement (ACK), the window slides by one PDU and the congestion window is incremented by one PDU, so two PDUs are sent. This results in an exponential increase in the number of transport layer PDUs sent over one Round Trip Time (RTT). When the congestion window has reached the Slowstart-threshold, Congestion Avoidance takes over. A PDU is only sent in response to an ACK as the receipt of an ACK means that a PDU has left the network (i.e., the "conservation of packets principle"). Sending PDUs only in response to

ACKs adds a "self-clocking property" to TCP. Congestion Avoidance increases the congestion window slightly by one PDU per RTT to determine if there is more bandwidth available (linear increase).

Slowstart takes $RTT * \log_2(\text{congestion window})$ seconds [Jaco88]. Slowstart can cause burst and retransmission problems if TCP exceeds the MBS and the SCR when trying to reach the optimal window. The TCP throughput can degrade to almost zero as the UPC discards non-conforming cells. This causes the situation where the TCP data is retransmitted due to timeouts and is discarded again until the TCP connection is lost due to too many timeouts [Ano97]. In our experiments, in order to avoid such performance degradation, the traffic is shaped at the source to ensure that the UPC mechanism does not discard any cells.

3 Objectives

In order to use ATM networks more efficiently, resources can be reserved not only for individual connections but also for groups of connections [Lamo97] [Lamo96]. The objectives of our experiments are to characterise voice (i.e. IP telephony) and data traffic based on their respective QoS requirements (i.e., minimum throughput, minimum delay variance, minimum packet loss) when different bundling strategies are used. QoS limits (thresholds) are established for IP telephony applications and for bulk data applications for the various bundling experiments. This investigation allows us to determine realistic resource reservation requirements when IP telephony applications are multiplexed with bulk data transmissions. The bundles are built using different types of transport connections:

1. A UDP voice connection is multiplexed with an increasing number of TCP connections;
2. A TCP connection is multiplexed with an increasing number of UDP connections;
3. An increasing number of UDP connections are multiplexed.

4 ATM Testbeds

4.1 Trans-Atlantic Testbed Configuration

Classical IP Permanent Virtual Circuits (PVCs) supporting VBR service were established between CRC in Ottawa and DeTeBerkom in Berlin. The Classical IP PVCs use Logical Link Control/Subnetwork Attachment Point (LLC/SNAP) encapsulation as specified in RFC 1483 [Hein93] and are supported per RFC 1577 [Laub94]. The Internet-Protocol-to-ATM address translation table entries were programmed manually. The IP traffic destined for the remote host was sent via the FORE ATM Adapter card, located in the Solaris workstation at CRC and DeTeBerkom, on the specified Virtual Channel Identifier (VCI) and Virtual Path Identifier (VPI) using the ATM Adaptation Layer (AAL) type 5. The Maximum Transmission Unit (MTU) was set to 9180 bytes. A round trip time delay (RTT) of 103 msec was observed throughout the measurements. The PCR and SCR were set to 6 Mb/s and 2 Mb/s. The CDVT and MBS were set to their default values. For instance, in the MainStreetXpress 36170 switches the CDVT was set to 250 msec while the MBS was set to 32 cells. The default traffic policing values were selected. The MainStreetXpress 36170 switches for example were set to discard any non-conforming cells. The PCR in the Fore ATM Adapter card was set to 1594 kbits/s. Traffic was submitted to the network such that the PCR in the Fore card was not exceeded. The IP traffic was segmented/reassembled into ATM cells in the FORE card and sent on the trans-Atlantic link as shown in Figure 1. A trans-Atlantic submarine fibre cable system, the CANTAT-3 [Lamo96] interconnected CA*net II, the Canadian national ATM network, with Deutsche Telekom the German ATM network.

Trans-Atlantic ATM Infrastructure

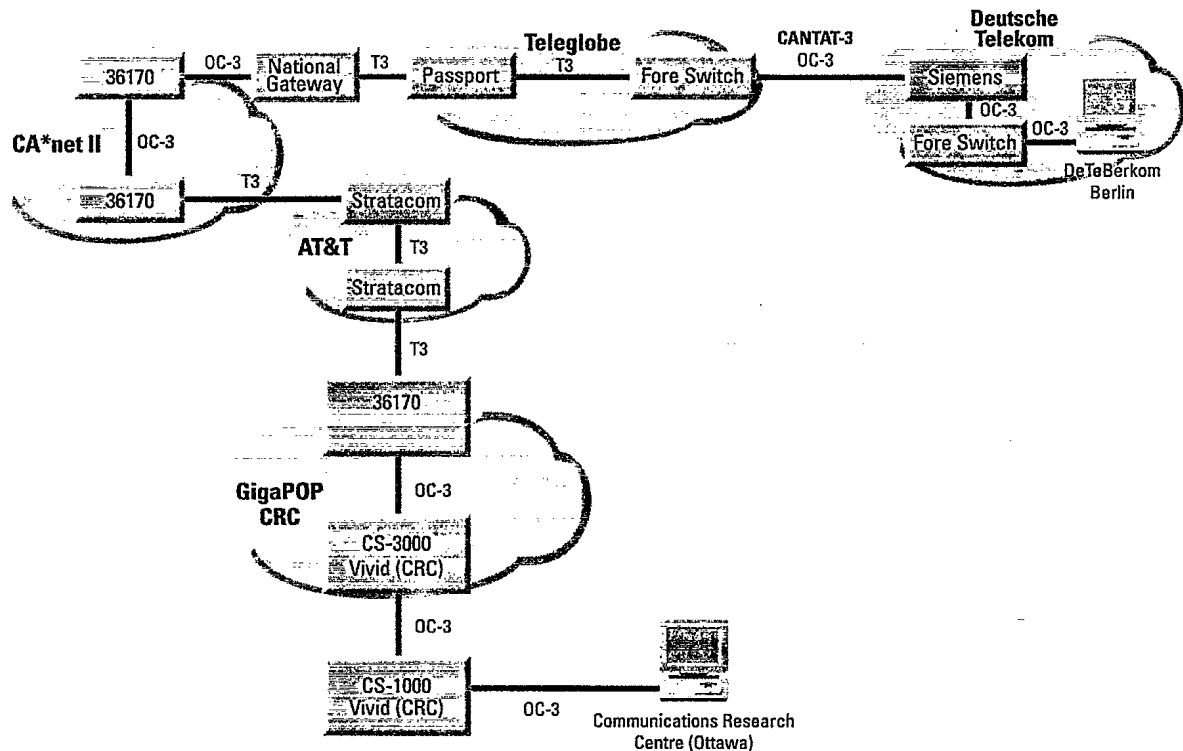


Figure 1: Trans-Atlantic ATM infrastructure

4.2 Local ATM Testbed Configuration

Classical IP PVCs supporting VBR service were established in a ATM LAN at CRC in Ottawa. The Classical IP PVCs use LLC/SNAP encapsulation as specified in RFC 1483 and are supported per RFC 1577. The Internet-Protocol-to-ATM address translation table entries were programmed manually. The IP traffic destined to the remote host was sent via the FORE ATM Adapter card, located in the Solaris workstations at CRC, on the specified VCI and VPI using AAL type 5. The MTU size was set to 9180 bytes. A RTT of 2 msec was observed throughout the measurements.

Local ATM Infrastructure

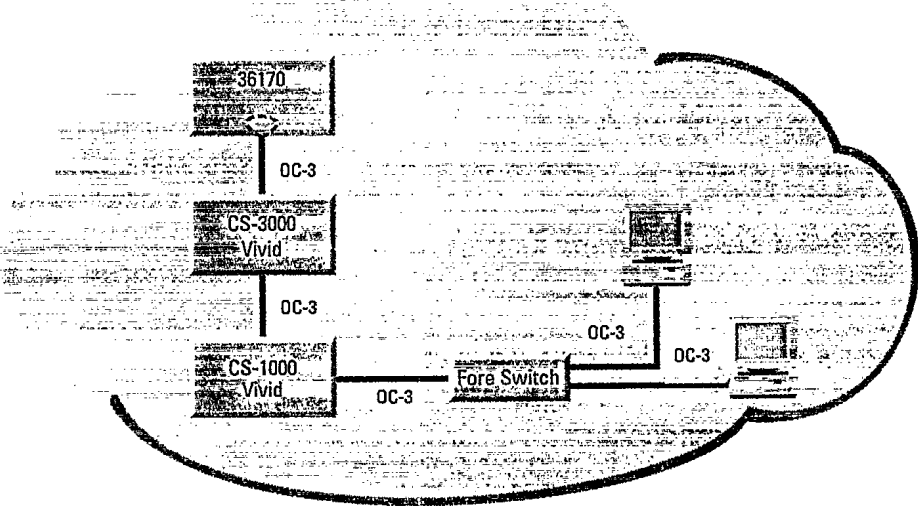


Figure 2: Local ATM infrastructure

5 Advanced Toolset for Measurement of ATM Networks - CM Toolset

5.1 CM Toolset

The Protocol Tuning Box (PROTB) [Milo95], [Milo97] presented at the Workshop for new Multimedia Protocols in Salzburg, 1995, introduced new aspects for measuring applications and protocols. It allows for instance the automation of measurements with different protocol parameters and network configurations.

The CM Toolset is an extension of the PROTB and uses an object-oriented approach (based on application and networking components) to measuring the performance of application classes and their specific QoS. It is based on a remote test measurement infrastructure that allows distributed measurements within different kinds of networking components. CM toolset includes:

1. GUI for the manipulation of remote measurement objects (network configuration, specification of application classes and their bundling, protocol parameter settings);
2. Daemons for remote execution of measurement tasks between the specified objects;
3. Local performance evaluation system and a simple data base to store measurement results.

5.2 Protocol Tuning Box

The main part of the actual CM Toolset version is the Protocol Tuning Box. It allows the automation of the performance analysis of application classes based on the UDP and TCP protocols.

5.2.1 Setting of Network Architecture

The Protocol Tuning Box provides an object-oriented approach for specifying measurement components. The application class is defined with its entities, for instance data transfer with the sending and receiving entities. The user assigns a host address to each entity when the entities are created. Depending on the application class, further parameters such as traffic characteristics (distributions to describe Transport Service Data Units (TSDU) lengths and interarrival times) and underlying protocol (TCP, UDP) can be specified. For data transfer all

parameters are given at the sending entity. The CM Toolset allows different configurations of such application entities, for example point-to-point, bundling of application classes, to be specified. The following picture specifies a bi-directional data transfer for a specific network architecture:

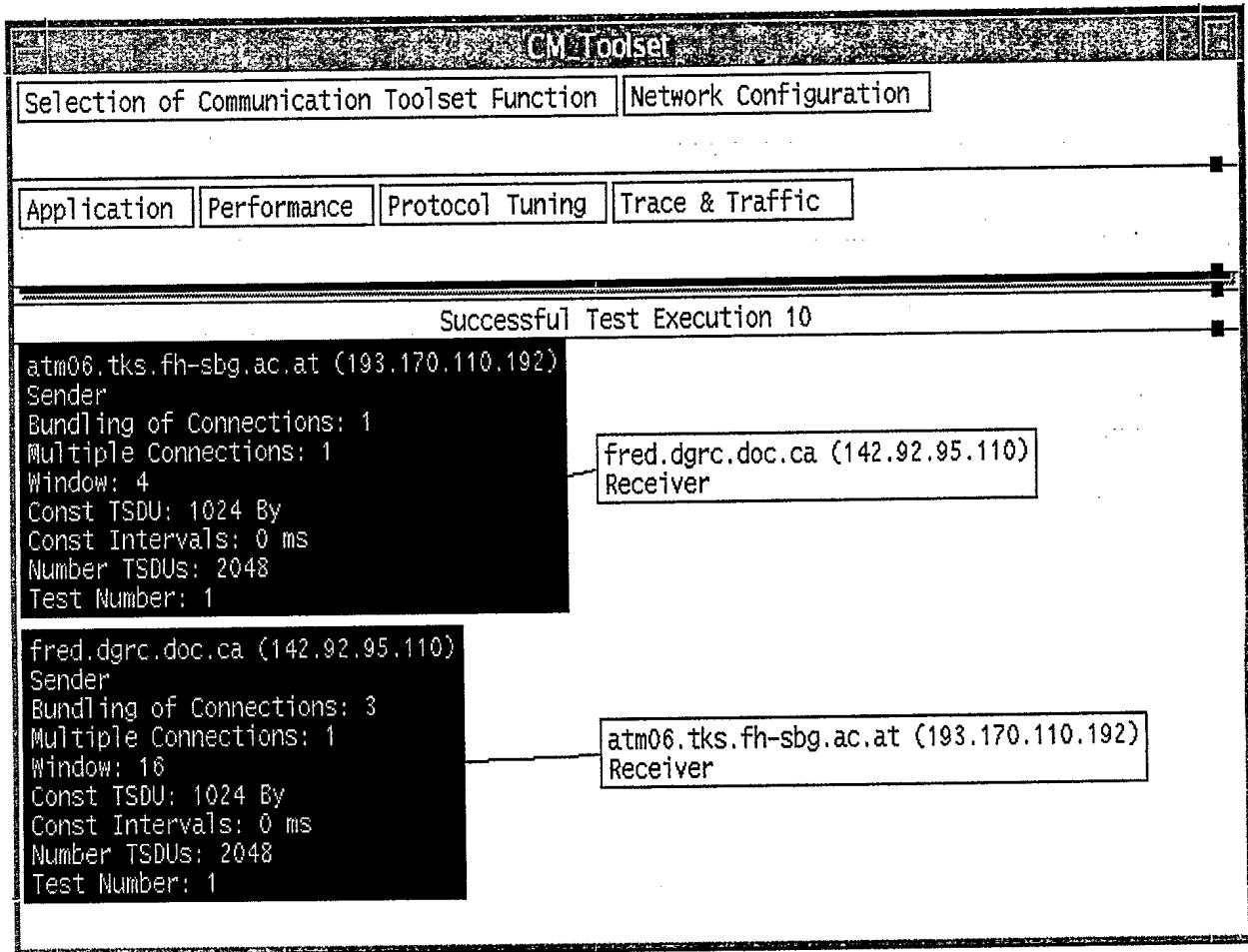


Figure 3: Bidirectional data transfer

More measurement definition parameters can be viewed in Figure 3. For instance, the user can give the number of measurements for the specified test suites in order to obtain mean values and standard deviations of the measured statistic.

Furthermore, it is possible to specify the transferred data volume as either the number of bytes or the number of TSDUs.

5.2.2 Specification of Application Classes and QoS Analysis

Application classes are described with their traffic characteristics. The menu of the Protocol Tuning Box allows the specification of distributions for the TSDU sizes and the TSDU interarrival times of applications. The system will be enhanced in the near future with session modelling. An example of a traffic specification currently supported by the CM Toolset is shown in Figure 4.

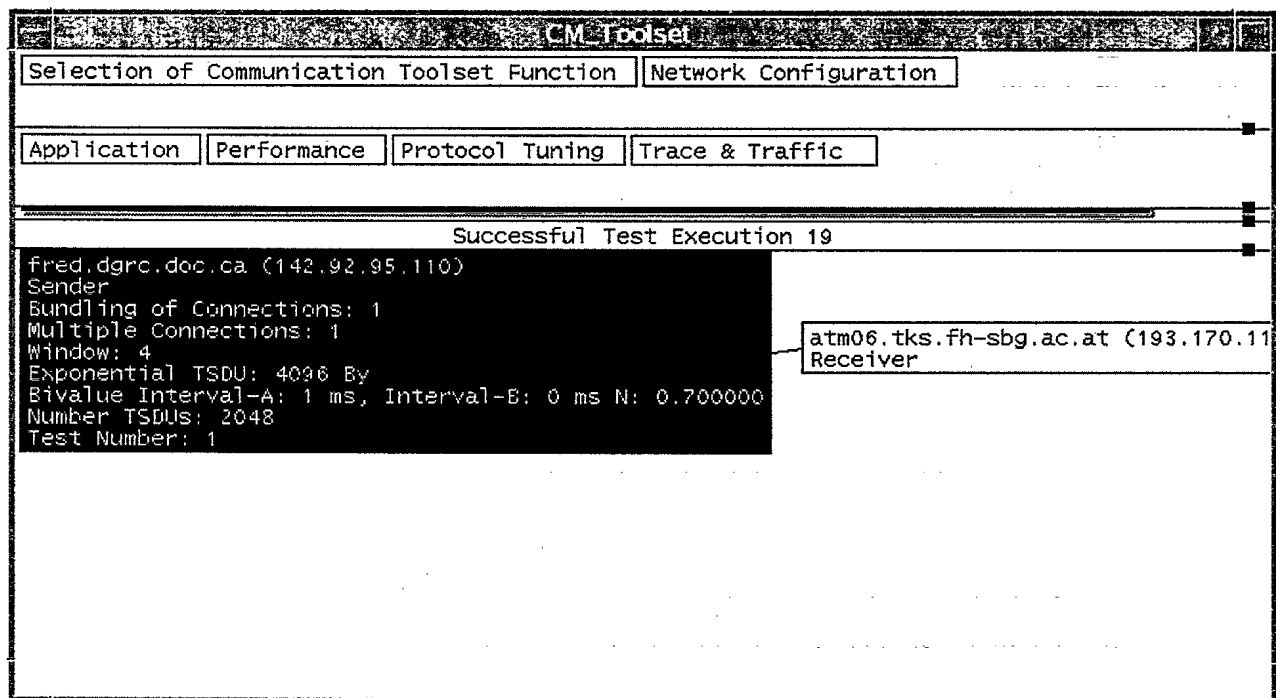


Figure 4: Example of traffic specification using the CM Toolset

Currently only point-to-point and point-to-multipoint application traffic can be modelled, which is enough to support a wide area of application classes such as bulk data transfer, Internet telephony, real-time audio and video.

The application traffic characteristics are specified for the active sender of the application traffic. The QoS measurements of a specified application class and the protocol used for the

provision of its communication service will depend on the specified application class. Bulk data transfer, i.e. file transfer, is used with the TCP protocol [Post81]. The CM Toolset calculates the throughput for TCP application classes. For UDP application classes, such as real-time video and Internet Telephony, the packet loss rate is evaluated.

5.2.3 Bundling of Application Classes

The Protocol Tuning Box supports different approaches for bundling of application classes.

The simplest way is to bundle application classes with the same traffic characteristics. For this purpose the menu item “Bundling” can be used.

Bundling of different application classes can be specified by invoking the “New bundle” menu item. Figure 5 shows an example for bundling several application classes and sessions.

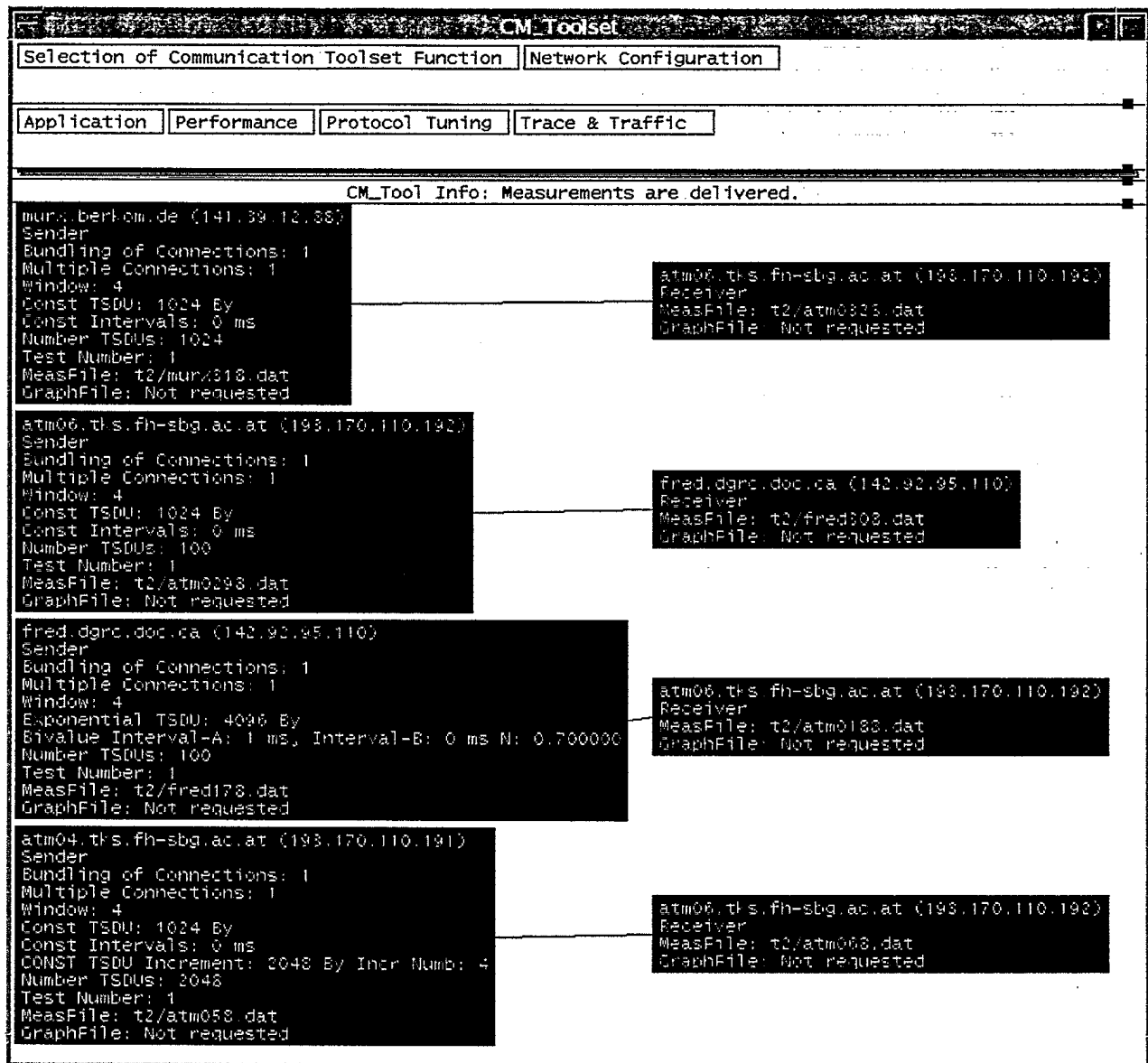


Figure 5: Bundling of application classes and sessions

5.2.4 Setting of Protocol Parameters

The user of the CM Toolset can select the protocol for the emulation of the service with the menu item "Protocol". Currently, TCP and UDP protocols are supported. For TCP, the window size parameter is required (menu item 'Window').

5.2.5 Incremental Parameter Measurements

The CM Toolset allows the user to automate measurements with varying parameters. This is called incremental measurements. From the menu items for incremental parameter settings, the user can get the first value and the distribution to calculate and evaluate the increments.

Currently, incremental measurements are provided for the window size, the number of bundled connections and the TSDU size. Figure 6 illustrates the settings for incremental TSDU size measurements:

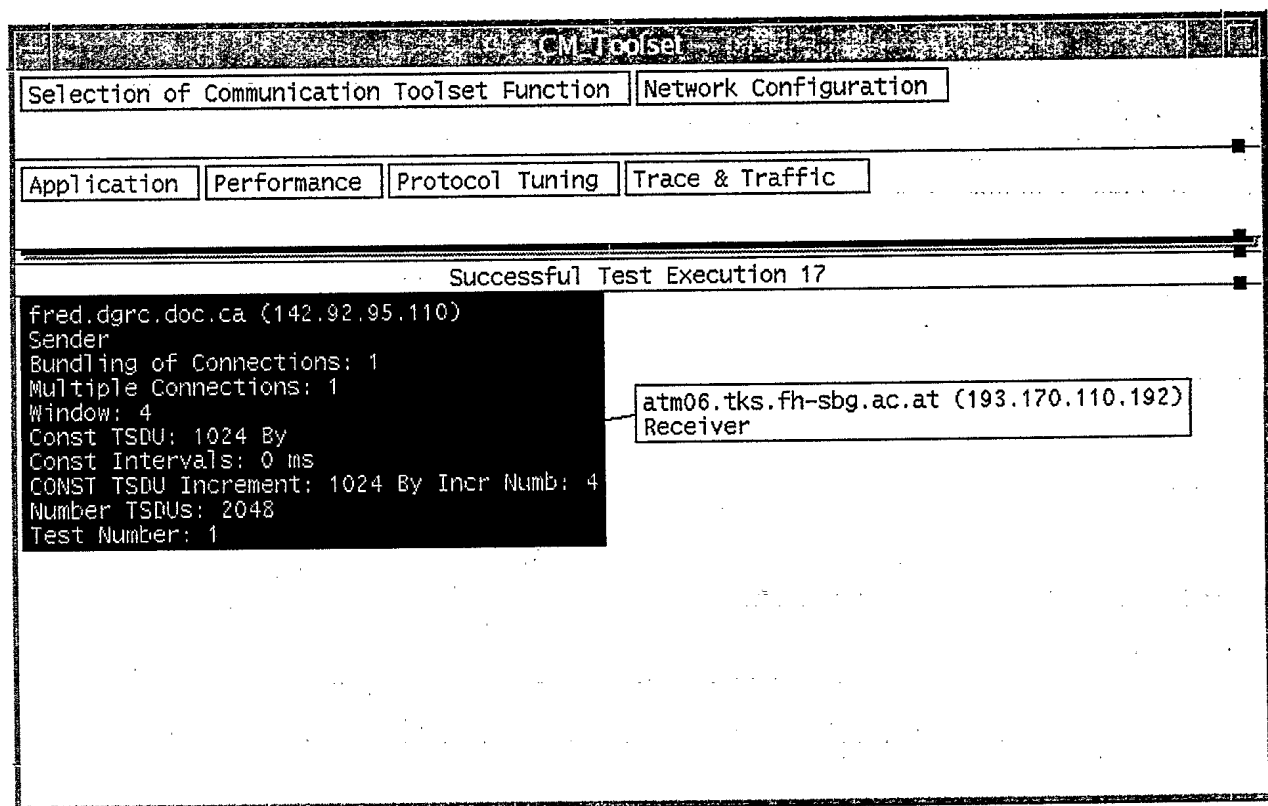


Figure 6: Incremental measurement scenario

The increment shows the number of bytes that will be added with each new measurement. The increment number defines the number of incremental measurements.

6 Characterisation of voice and data when the SCR is restricted

The focus of these measurements is to determine efficient strategies for using ATM resources efficiently when UDP and TCP traffic are multiplexed onto one Virtual Channel Connection (VCC). The emulated applications include bulk data and real time voice, i.e. Internet Telephony. Traffic is shaped at the source by limiting the peak rate at the end-system to that of the SCR for the connection which is set to 2 Mbits/s. This ensures that the SCR is not exceeded and that cells are not discarded. The PCR in the FORE card is set to 1594 kb/s.

The voice traffic is sent using the UDP protocol with a TSDU size of 80 bytes and a constant interarrival time of 10 ms. The duration of the UDP session was set to 3 minutes. Typical bit rates used for Internet Telephony vary from 8 to 12 kb/s. In our experiments, the worse case scenario is selected.

$$\frac{80 \text{ [Byte]}}{0.01 \text{ [s]}} = 8000 \text{ [Byte / s]} = 64 \text{ [kBit / s]}$$

The TCP traffic consists of bulk data with no interarrival time. The number of TSDUs was calculated such that the duration of the TCP session was 3 minutes. Again a worse case scenario is selected for the bulk data where no interarrival time is considered between TSDUs.

The Adtech AX/4000 ATM test system [Adt97] was used to measure the cell delay variations and the CM Toolset to obtain the throughput and byte loss measurements at the transport level. The CM Toolset did not provide the facility to obtain the end-to-end delay. Consequently, this measurement has not been considered in this current study.

6.1 Trans-Atlantic Measurements

The trans-Atlantic measurement were completed using a Classical IP PVC supporting VBR as described in section 4.1. Several measurement test scenarios in which TCP and UDP traffic were multiplexed were considered. The bundles were built using different types of transport connections:

1. A bulk data session (TCP) is multiplexed with an increasing number of voice sessions (UDP).
2. A voice session (UDP) is multiplexed with an increasing number of bulk data sessions (TCP).
3. An increasing number of voice sessions (UDP) are multiplexed.

Several measurement test scenarios in which TCP and UDP traffic were multiplexed were considered. As the number of connections increased, the mean value of the throughput was calculated by summing the throughput of each connection belonging to the same transport connection type and dividing the result by the number of connections. For instance, when bundling one TCP connection with an increasing number of UDP connections, the mean value of the UDP throughput was calculated by summing the throughput of each UDP connection and dividing the result by the number of UDP connections.

6.1.1 Bundling one TCP connection with an increasing number of UDP connections

Measurement Scenario:

Description	Goal	- TCP Throughput vs. number of UDP bundles - UDP Throughput vs. number of UDP bundles - UDP loss rate vs. number of UDP bundles
	Test tool	CM-Toolset, Protocol Tuning Box, Adtech AX/4000
	Applications	Bulk data (TCP), 64 kbps audio stream (UDP)
	Protocols	TCP, UDP
Traffic Parameters	TCP	Constant TSDU length: 4 Kbytes, 8 Kbytes, 10 Kbytes and 20 Kbytes TSDU interarrival: 0 ms (unconstrained traffic) Number of TCP TSDUs: variable
	UDP	Constant TSDU length: 80 bytes TSDU interarrival: 10 ms Number of TSDUs: 18000 (3 minutes duration at 64 kb/s)
	Number of UDP Bundles	1,2,3,4,6,8,12,16
	Sender	Workstation: endor-cip SPARC-10, Solaris 2.5.1, Berkomp Germany NIC: ForeRunner SBA-200 Peak cell rate: 1594 kb/s (limitation of the FORE card)
	Receiver	Workstation: fred-cip SPARC-10, Solaris 2.4, CRC Canada NIC: ForeRunner SBA-200 Peak cell rate: 2000 kb/s
	ATM WAN	VBR PVC connection PCR = 6 Mbits/s MBS = 32 cells SCR = 2 Mbits/s CDVT = 250 msec
	ATM Link	OC-3c (155.52 Mb/s), T3 (45Mb/s)
	RTT	103 ms
	Adaptation Layer	ATM AAL 5, MTU 9180 Bytes
Details	Data	See Appendix A, Tables 5 through 16

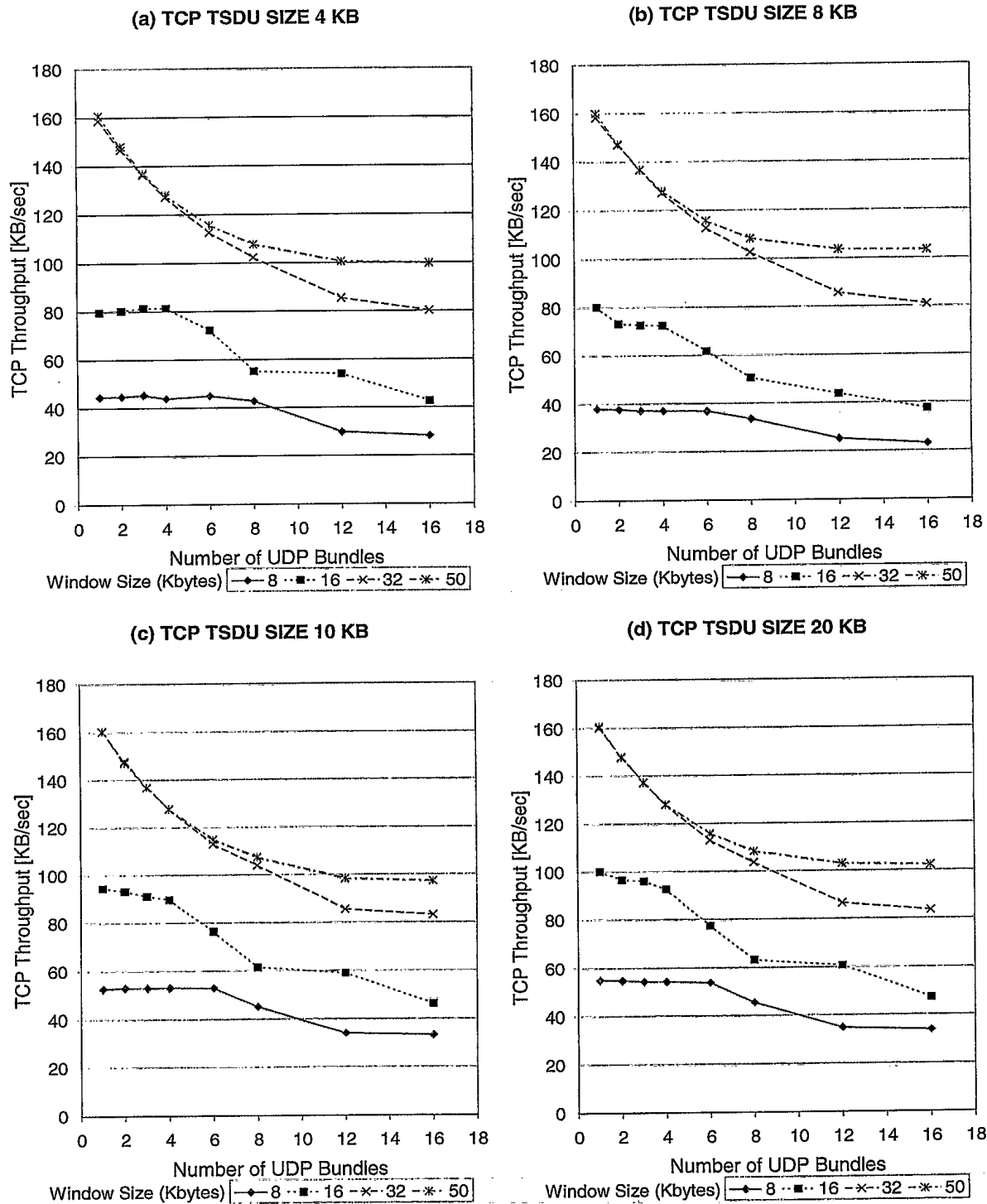


Figure 7: TCP Throughput vs. number of UDP bundles for different TCP TSDU lengths: (a) 4 KB, (b) 8 KB, (c) 10 KB and (d) 20 KB on an ATM WAN

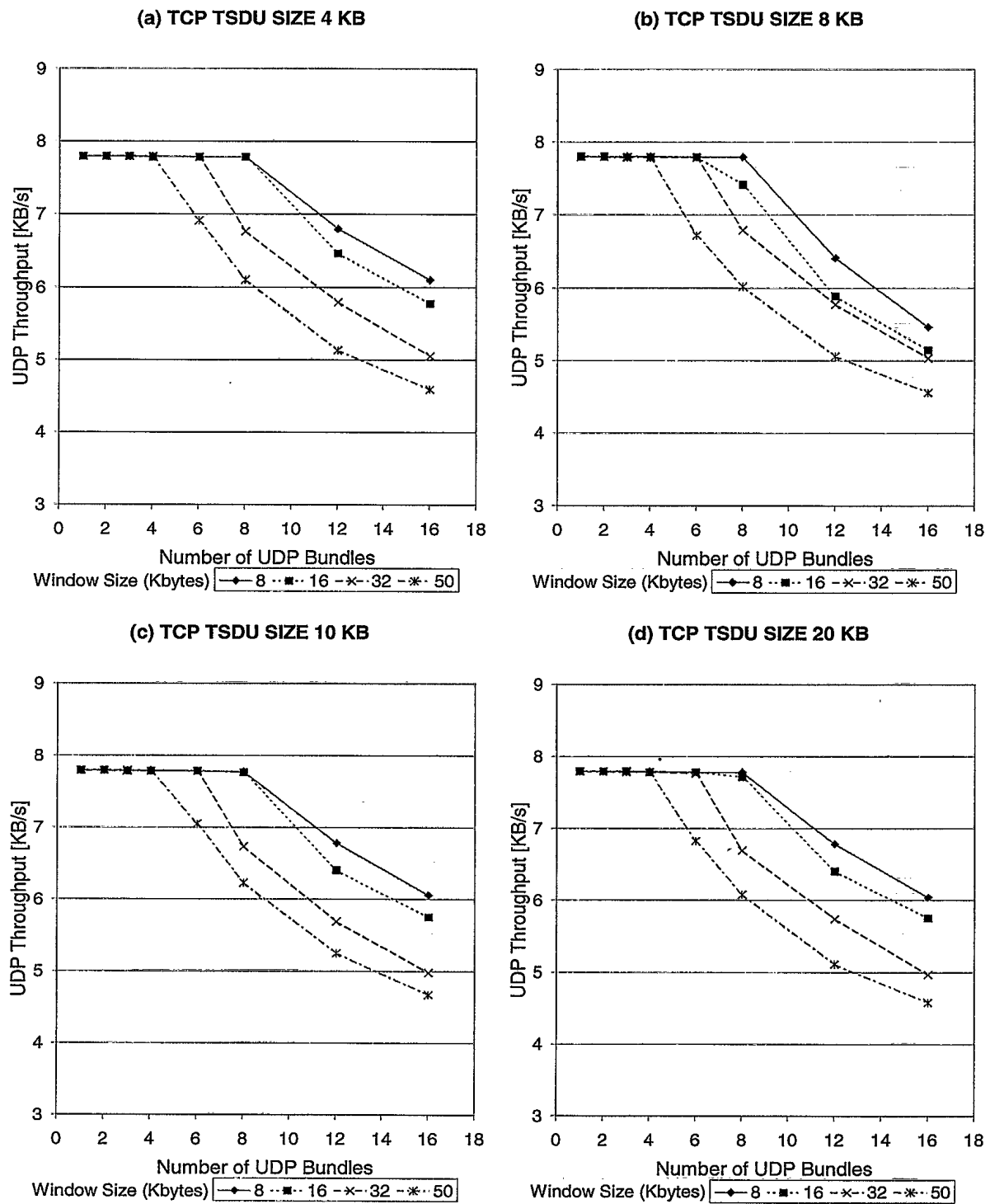


Figure 8: UDP Throughput vs. number of UDP bundles for different TCP TSDU lengths: (a) 4 KB, (b) 8 KB, (c) 10 KB and (d) 20 KB on an ATM WAN

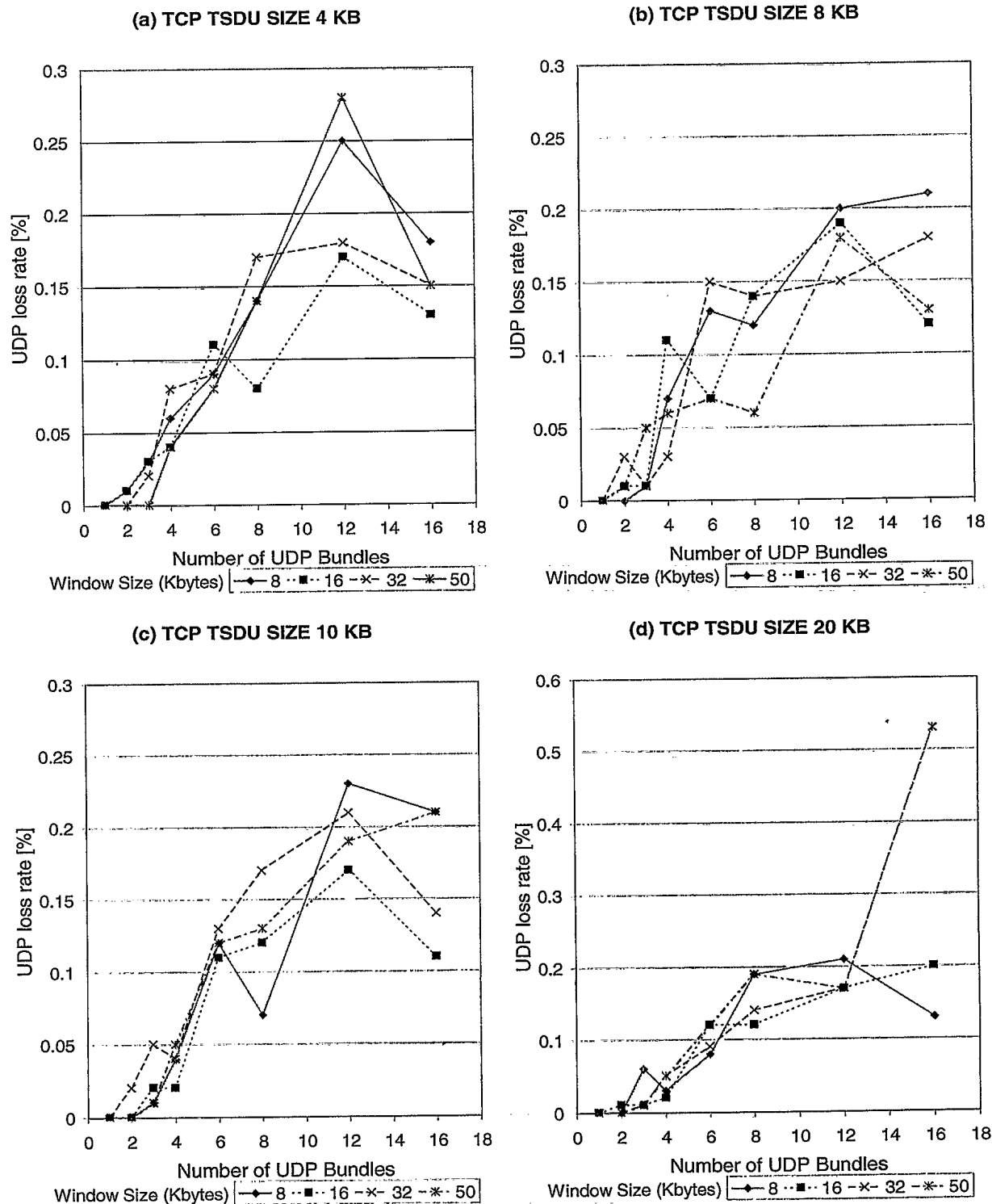


Figure 9: UDP loss rate vs. number of UDP bundles on an ATM WAN

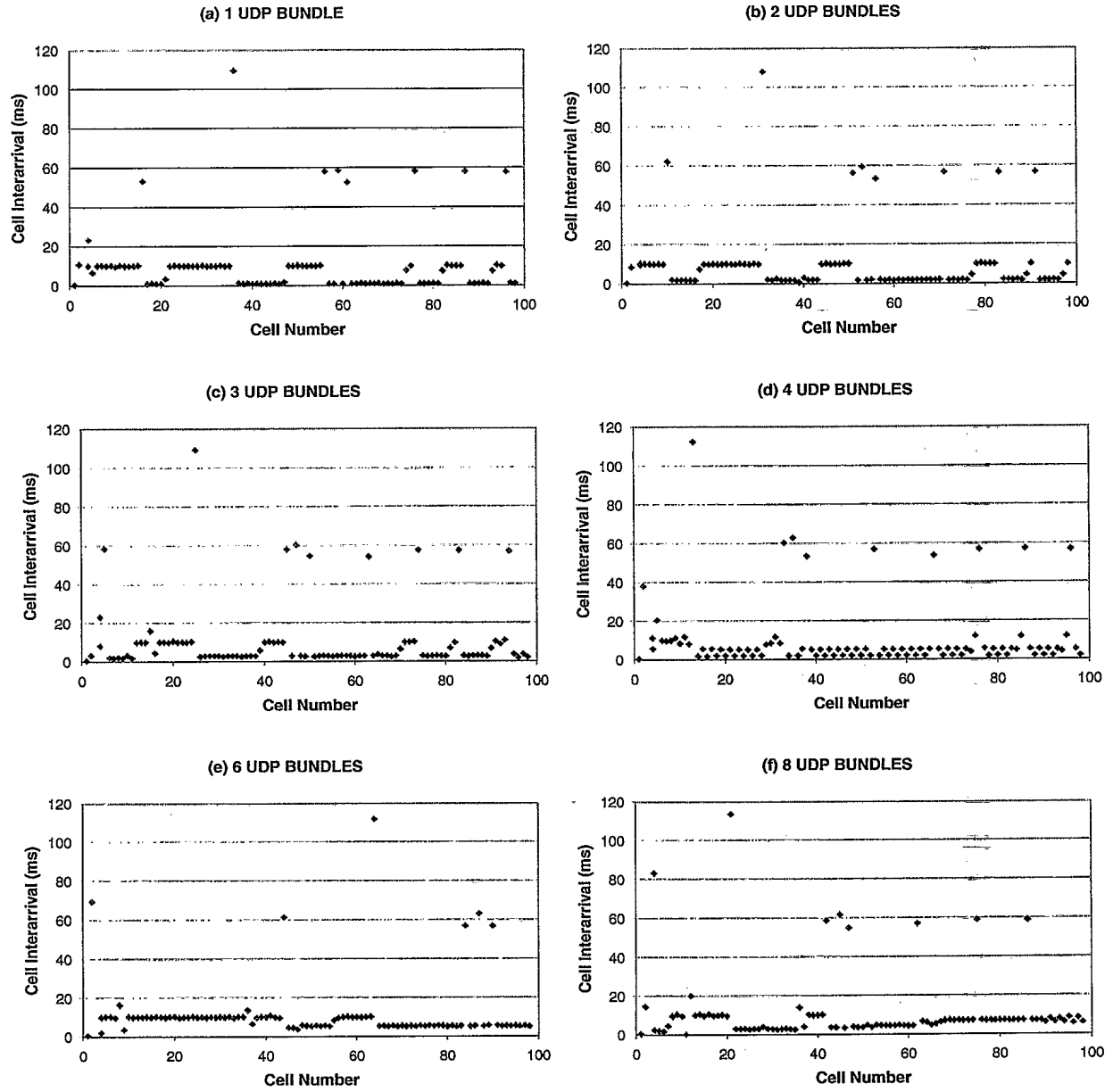


Figure 10: Cell interarrival variation when bundling one TCP connection, using a window size of 16 KB, with different number of UDP bundles: (a) 1 UDP bundle, (b) 2 UDP bundles, (c) 3 UDP bundles, (d) 4 UDP bundles, (e) 6 UDP bundles and (f) 8 UDP bundles on ATM WAN

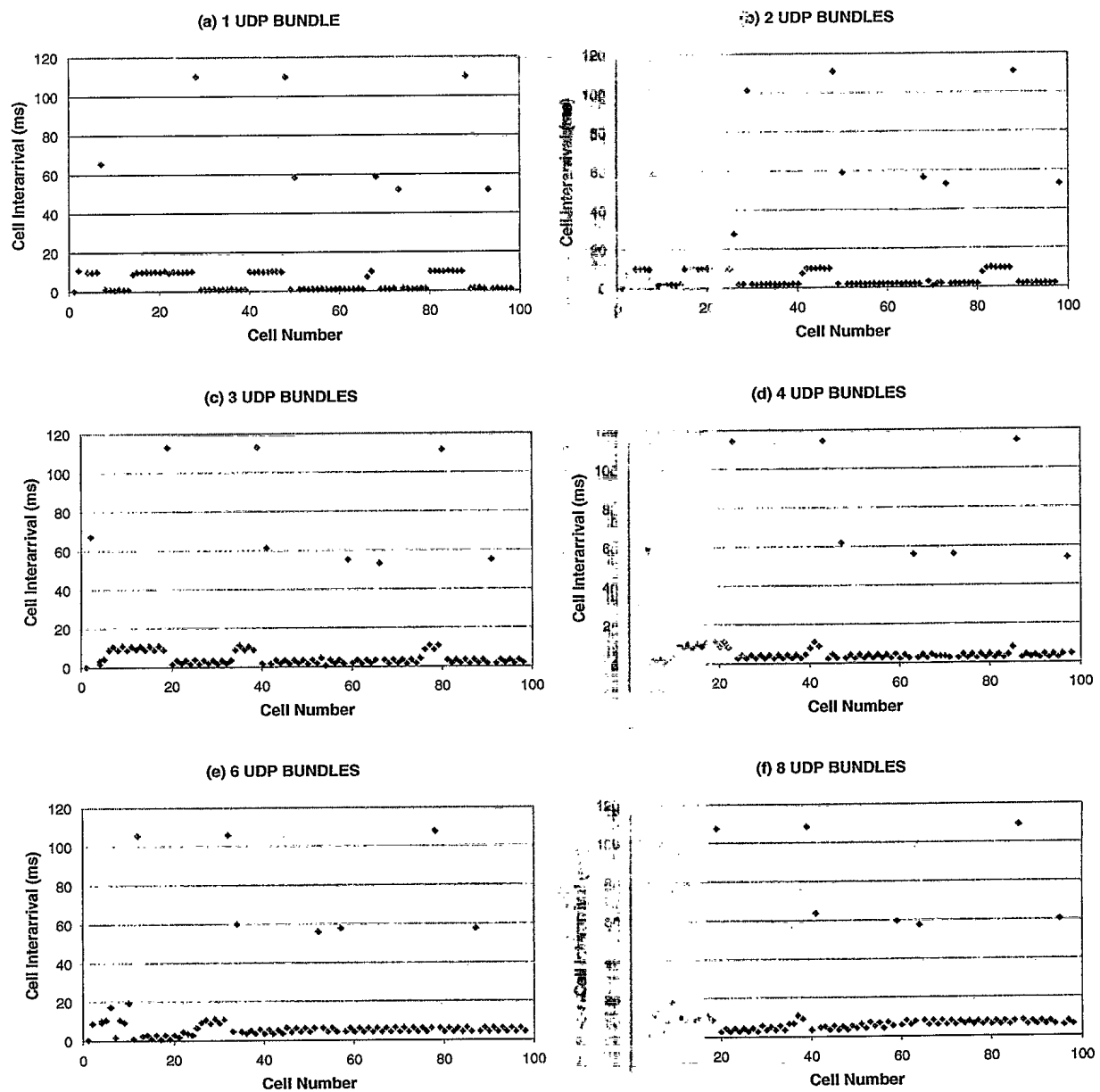


Figure 11: Cell interarrival variation when bundling in a UDP connection, using a window size of 50 KB, with different number of UDP bundles: (a) 1 UDP bundle, (b) 2 UDP bundles, (c) 3 UDP bundles, (d) 4 UDP bundles, (e) 6 UDP bundles, (f) 8 UDP bundles on ATM WAN

Observations for figure 7:

In Figure 7 one can see the effect of an increasing number of multiplexed voice connections (UDP) on the bulk data (TCP) throughput. The RTT delay and the window size affect the throughput of a TCP connection. When bundling one TCP connection with several UDP connections, the TCP throughput is also affected by the time required to send the UDP traffic, as show in Figure 12. That is:

$$TCP_Throughput \approx \frac{Window_Size}{T_{TCP} + T_{UDP}}$$

With different window sizes, different levels of throughput are achieved [Lamo96a]. It is clear, from Figures 7(a) through 7(d) that the throughput achieved by the TCP connection is greater when larger window sizes are used.

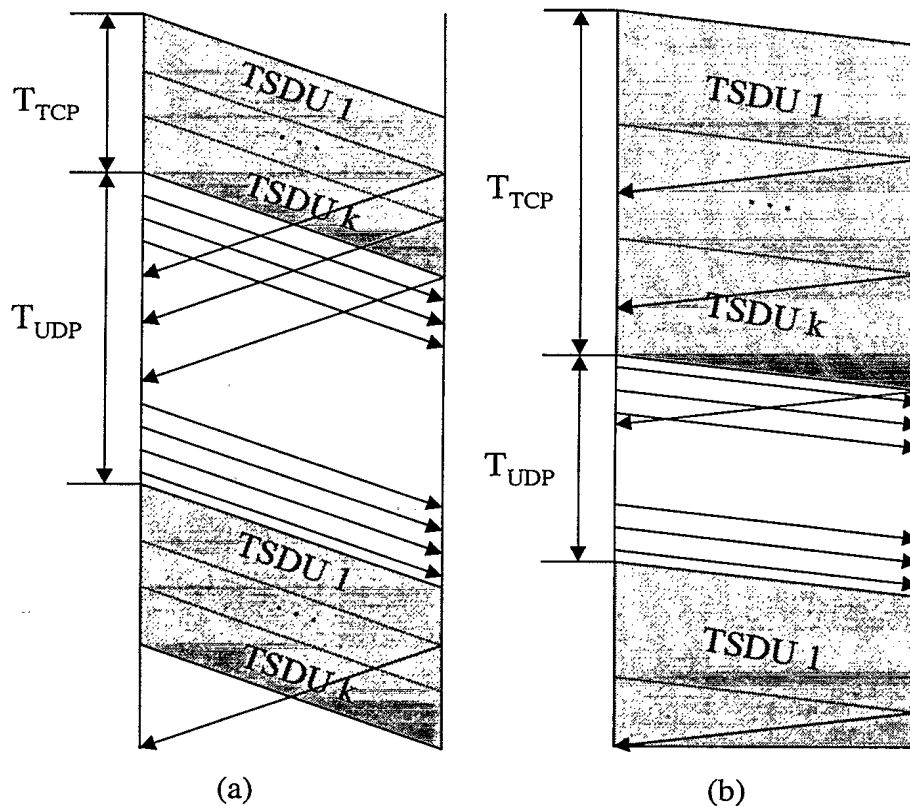


Figure 12 Bundling one TCP connection with many UDP connections on an ATM WAN

From figure 12(a) and 12(b), we can see that the TCP throughput is affected by the time required to transmit a complete window (T_{TCP}) and the time it takes to send the UDP information (T_{UDP}) before the next TCP window is sent.

The peak rate of the FORE card was set to 1594 kb/s, that is, 194.58 KB/s. With ATM we have 5 bytes of overhead per cell, thus the maximum data throughput is 176.22 KB/s.

When using a large window size (i.e. 50 KB or 32 KB window size), the TCP throughput is almost 160 KB/s, which is close to the connection's bandwidth limit. For these cases, the time it takes to send one window ($T_{TCP} \cong 280$ ms for a window size of 50 KB and $T_{TCP} \cong 180$ ms for a window size of 32 KB) is greater than the RTT (103 ms for the trans-Atlantic link), thus a maximum throughput can be achieved.

As the number of UDP bundles increases, the TCP throughput decreases because the required time to transmit the UDP (T_{UDP}) increases as shown in figure 12(a) and 12(b).

Observations for figure 8:

The throughput of each UDP audio stream is 64 kb/s or 7.81 KB/sec. As we can see in Figures 8(a) through 8(d), we can bundle up to four UDP audio connections with one TCP connection and maintain the required 7.81 KB/s for the UDP connections, independently of the TCP TSDU length and TCP window size used.

For all scenarios, when one TCP connection is bundled with several UDP audio connections, a better UDP throughput performance is always obtained when smaller window sizes for the TCP connection are used. This can be explained in terms of the time, T_{TCP} , required to send one complete TCP window. To achieve a 64 kb/s data rate, each UDP TSDU, 80 bytes in size, is transmitted every 10 ms. As the TCP window size is increased, the required time to transmit the window, T_{TCP} , increases as shown in Figure 12. A large T_{TCP} increases the delay of the UDPs, as they are required to wait while the TCP window is being sent, and therefore a lower UDP throughput is achieved. When a small window size is used, as opposed to a large window, the TCP throughput is naturally lower. Thus, more bandwidth is available on the link for the UDP connections and this provides a better UDP throughput performance.

Observations for figure 9:

One can notice from Figures 9(a) through 9(d), that when one TCP connection is bundled with an increasing number of UDP audio streams, there is a tendency of increased UDP loss rate as the number of UDP bundles increase. In most cases, the loss rate is less than 0.5 %. Packet loss rates between 1 and 10% can be tolerated, depending on the manner in which voice is coded and missing packets masked [Ramj94]. Therefore in our scenario, the performance parameter that becomes a critical factor is the delay encountered by the UDP TSDUs as they are being transmitted.

Observations for figure 10 and 11:

Figures 10 and 11 show the cell interarrival time, in milliseconds, for a sequence of 100 ATM cells of one UDP connection when an increasing number of UDP connections are bundled with one TCP connection. All UDP connections are being generated with a TSDU size of 80 bytes every 10 ms. The TCP session was created using a TSDU size of 8 KB and a window size of 16 KB for Figure 10 and 50 KB for Figure 11.

UDP Bundles	Mean Interarrival (ms)	Standard Deviation
1	10.31	17.25
2	9.89	17.26
3	10.43	17.88
4	10.61	18.25
6	11.49	15.93
8	11.27	18.20

Table 1 Mean cell interarrival times and corresponding standard deviations

Two case studies have been considered. Case 1: one TCP session set to a TSDU size of 8 KB and a window size of 16 KB. Case 2: one TCP session set to a TSDU size of 8 KB and a

window size of 50 KB. For the two cases, we calculated the mean interarrival time and the standard deviation (Table 1 and Table 2). From Table 1 it is clear that the cell interarrival times increase as the number of UDP bundles increase. Note also that the standard deviation increases as the number of UDP bundles is increased.

These results show that when four UDP connections are bundled with one TCP connection, the cell interarrival time variation for the UDP connection is 0.61 ms from the optimum value of 10 ms. When six and eight UDP connections are bundled with one TCP connection, the cell interarrival time is greater than the expected 10 ms. This observation corresponds with the observation made on Figure 8, where it was shown that up to four UDP connections can be bundled with one TCP connection and the UDP throughput can still be maintained to the required rate of 7.81 KB/s.

UDP Bundles	Mean Interarrival (ms)	Standard Deviation
1	10.53	21.75
2	10.59	21.25
3	10.50	22.02
4	10.97	22.11
6	10.85	20.22
8	12.85	22.62

Table 2 Mean cell interarrival times and corresponding standard deviations

From Table 2 it is clear that the cell interarrival times also increase as the number of UDP bundles is increased. This same relationship holds for the standard deviation. It increases as the number of UDP bundles is increased. Comparing the results in Table 2 with the ones in Table 1, one sees that the mean cell interarrival time is closer to the expected 10 ms, but the standard deviation is greater than that obtained in Table 1. Therefore the use of a larger TCP window size causes the interarrival times for cells carrying the UDP traffic to increase. More TCP traffic is sent on the TCP connection before any data is sent on a UDP connection.

6.1.2 Bundling one UDP connection with an increasing number of TCP connections

Measurement Scenario:

Description	Goal	- TCP Throughput vs. number of TCP bundles - UDP Throughput vs. number of TCP bundles
	Test tool	CM-Toolset, Protocol Tuning Box, Adtech AX/4000
	Applications	Bulk data (TCP), 64 kb/s audio stream (UDP)
	Protocols	TCP, UDP
Traffic Parameters	TCP	Constant TSDU length: 4 Kbytes, 8 Kbytes, 10 Kbytes and 20 Kbytes TSDU interarrival: 0 ms (unconstrained traffic) Number of TSDUs: variable
	TCP Bundles	1,2,3,4,6,8,10
	UDP	Constant TSDU length: 80 bytes TSDU interarrival: 10 ms Number of TSDUs: 18000 (3 minutes duration at 64 kb/s)
	Sender	Workstation: endor-cip SPARC-10, Solaris 2.5.1, Berkomp Germany NIC: ForeRunner SBA-200 Peak Cell Rate: 1594 kb/s
	Receiver	Workstation: fred-cip SPARC-10, Solaris 2.4, CRC Canada NIC: ForeRunner SBA-200 Peak Cell Rate: 2000 kb/s
	ATM WAN	VBR PVC connection PCR = 6 Mbits/s MBS = 32 cells SCR = 2 Mbits/s CDVT = 250 msec
	ATM Link	OC-3c (155.52 Mbits/s) T3 (45 Mb/s)
	RTT	103 ms
	Adaptation Layer	ATM AAL 5, MTU 9180 Bytes
Details	Data	See Appendix B, Tables 17 through 24

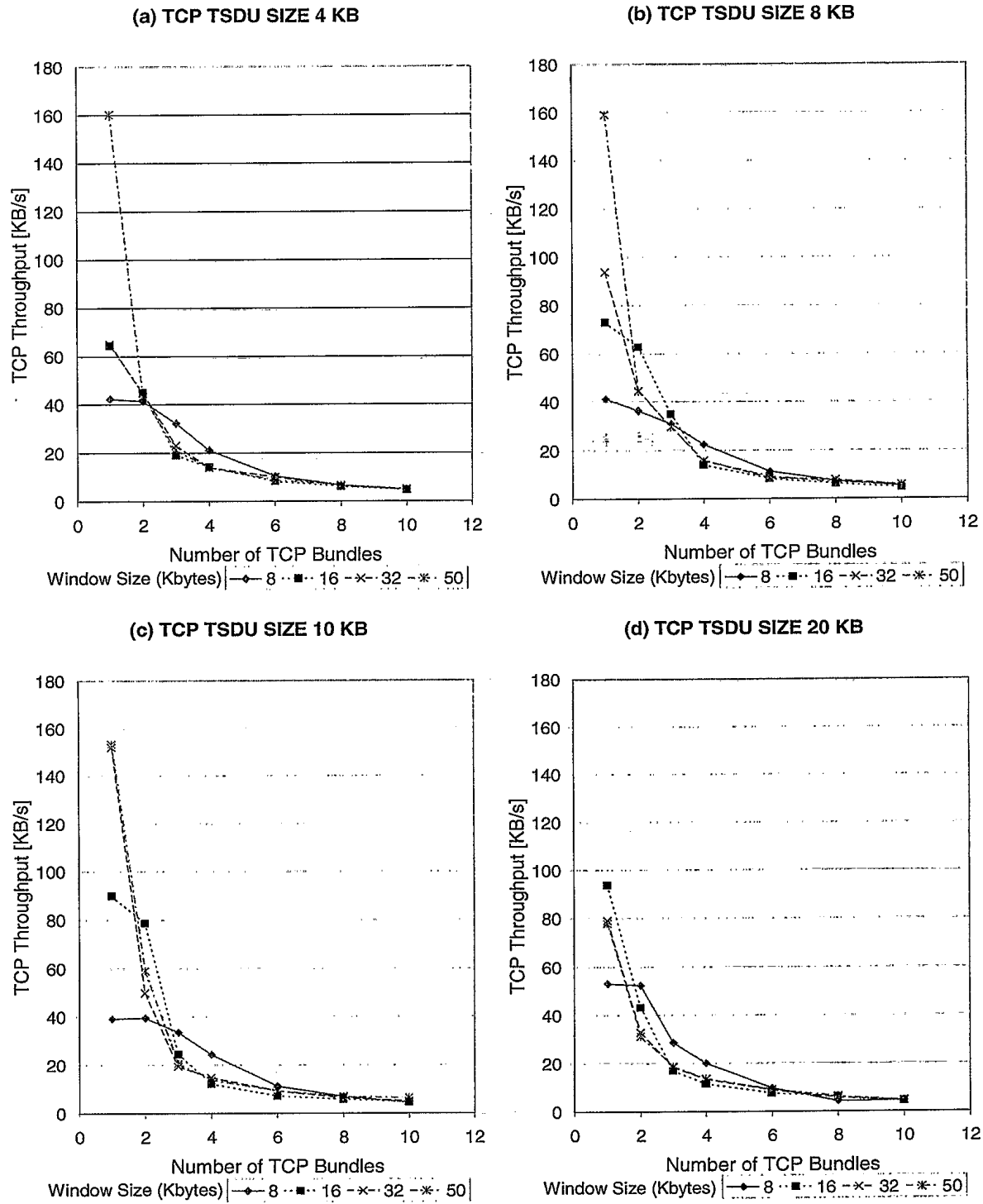


Figure 13: TCP Throughput vs. number of TCP bundles for different TCP TSDU lengths: (a) 4 KB, (b) 8 KB, (c) 10 KB and (d) 20 KB on an ATM WAN

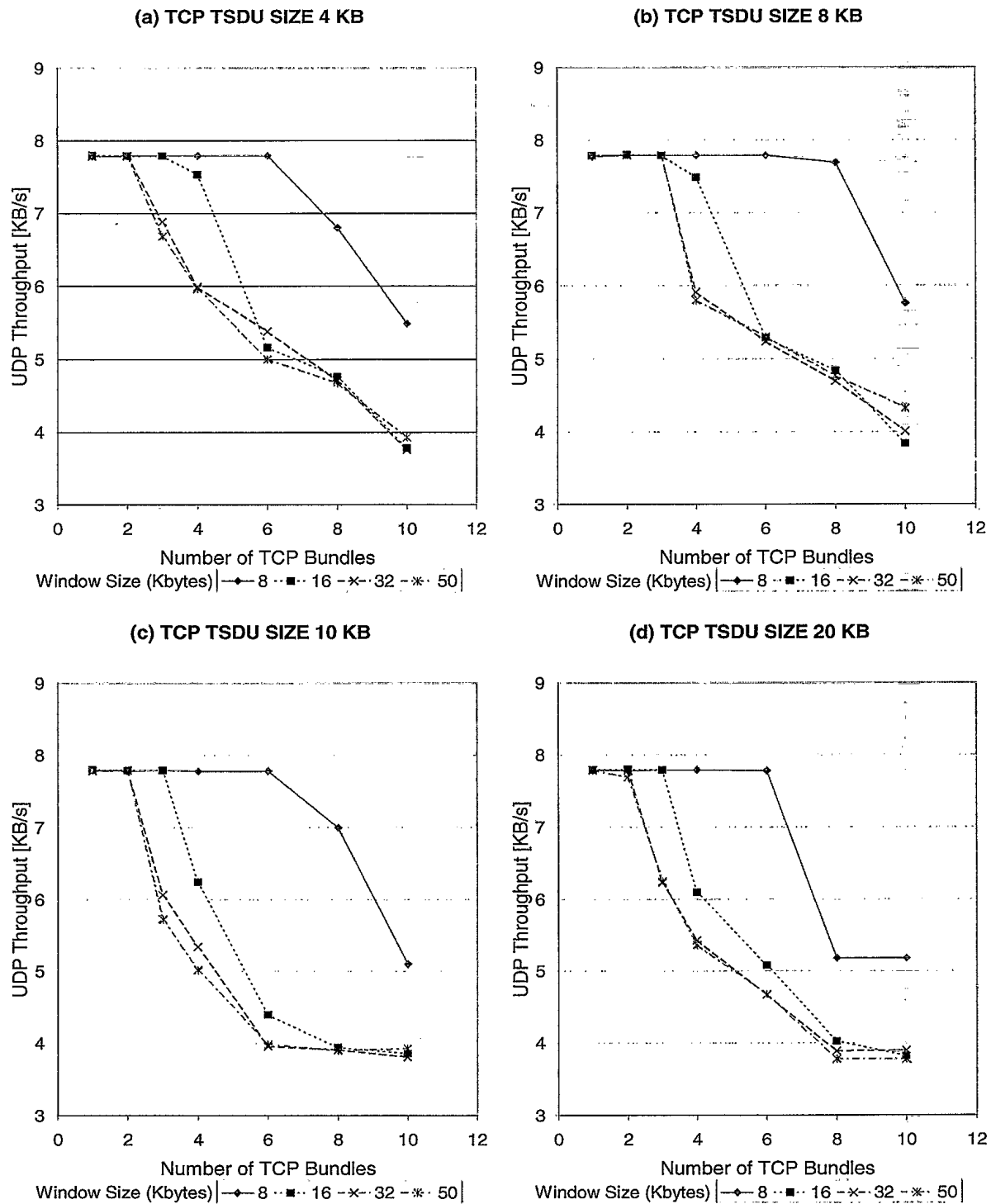


Figure 14: UDP Throughput vs. number of TCP bundles for different TCP TSDU lengths: (a) 4 KB, (b) 8 KB, (c) 10 KB and (d) 20 KB on an ATM WAN

Observations for figure 13:

From Figures 13(a) through 13(d) we can see that when several TCP connections are bundled with one UDP audio stream, the TCP throughput decreases as the number of TCP connections increases. This can be explained in terms of the bandwidth required by each TCP connection and the delay incurred by the UDP connection. As more TCP connections are bundled, the total link bandwidth must be shared between the TCP sessions. On the other hand, while the TCP information is being sent, the UDP information must wait to be transmitted, thus increasing the UDP delay and T_{UDP} which directly affects the TCP throughput, Figure 12. All these factors affect the throughput of each TCP connection. Also, as the number of TCP processes in the transmitting workstation increases, the end-system takes longer to address the TCPs requests for data transfer.

Observations for figure 14:

From Figure 14(a) through 14(d) we can see that up to two TCP connections can always be bundled with one UDP without affecting the required 7.81 KB/s throughput for the UDP audio stream. With the TCP window size set to 8 or 16 KB, the number of TCP bundles can be increased to three without affecting the UDP throughput performance. Additionally up to six TCP connections can be bundled with one UDP audio stream without considerably affecting the UDP throughput performance by setting the window size to 8 Kbytes.

The reason why more TCP connections with a small window size can be bundled with one UDP audio stream without affecting the UDP throughput performance is that the TCP throughput is lower when using a smaller window size than when a larger window size is used. Because of this the total link bandwidth can be shared with more TCP connections without affecting the UDP connection.

6.1.3 Bundling an increasing number of UDP connections

Measurement Scenario:

Description	Goal	• UDP Throughput vs. number of UDP bundles • UDP loss rate vs. number of UDP bundles
	Test tool	CM-Toolset, Protocol Tuning Box, Adtech AX/4000
	Applications	64 kbps audio stream (UDP)
	Protocols	UDP
Traffic Parameters	UDP	Constant TSDU length: 80 bytes TSDU interarrival: 10 ms. Number of TSDUs: 18000 (3 minutes duration at 64 kbit/s)
	UDP Bundles	1, 2, 3, 4, 6, 8, 10, 12, 14 and 16
	Sender	Workstation: endor-cip SPARC-10, Solaris 2.5.1, Berkomp Germany NIC: ForeRunner SBA-200 Peak Cell Rate: 1594 kb/s
	Receiver	Workstation: fred-cip SPARC-10, Solaris 2.4, CRC Canada NIC: ForeRunner SBA-200 Peak Cell Rate: 2000 kb/s
	ATM WAN	VBR PVC connection PCR = 6 Mbits/s MBS = 32 cells SCR = 2 Mbits/s CDVT = 250 msec
	ATM Link	OC-3c (155.52 Mbits/s) T3 (45 Mb/s)
	RTT	103 ms
	Adaptation Layer	ATM AAL 5, MTU 9180 Bytes
Details	Data	See Appendix C, Table 25 and 26

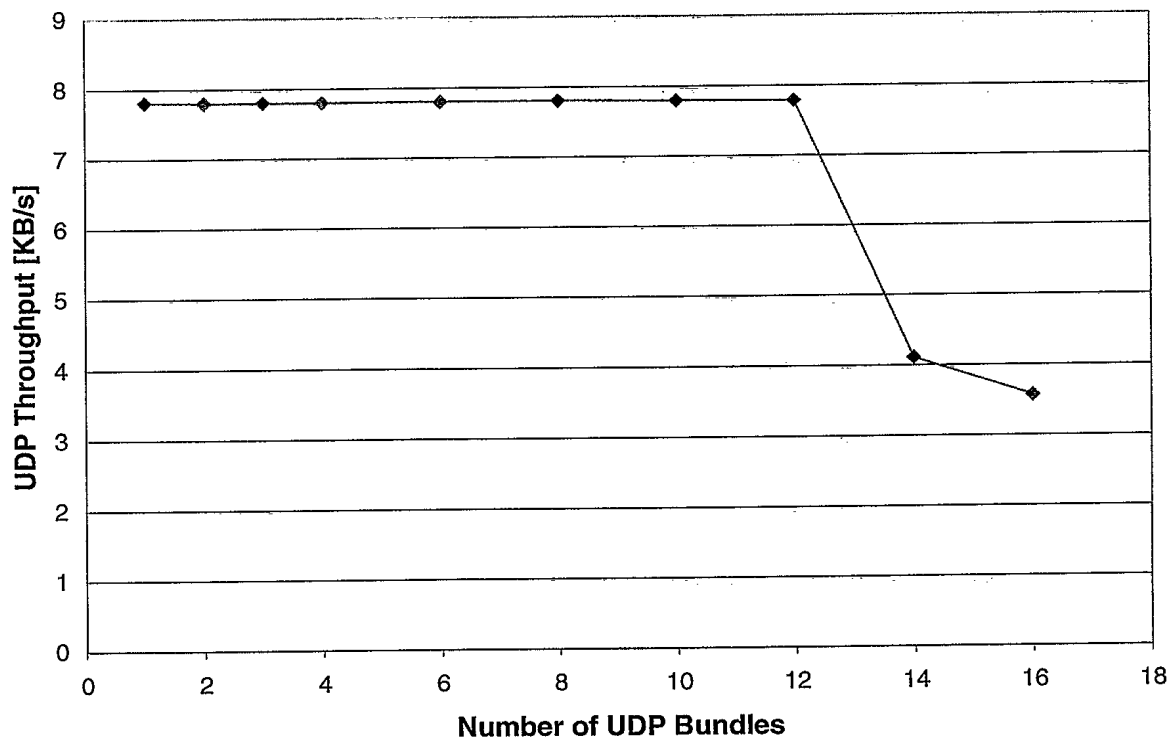


Figure 15: UDP Throughput vs. number of UDP bundles on an ATM WAN

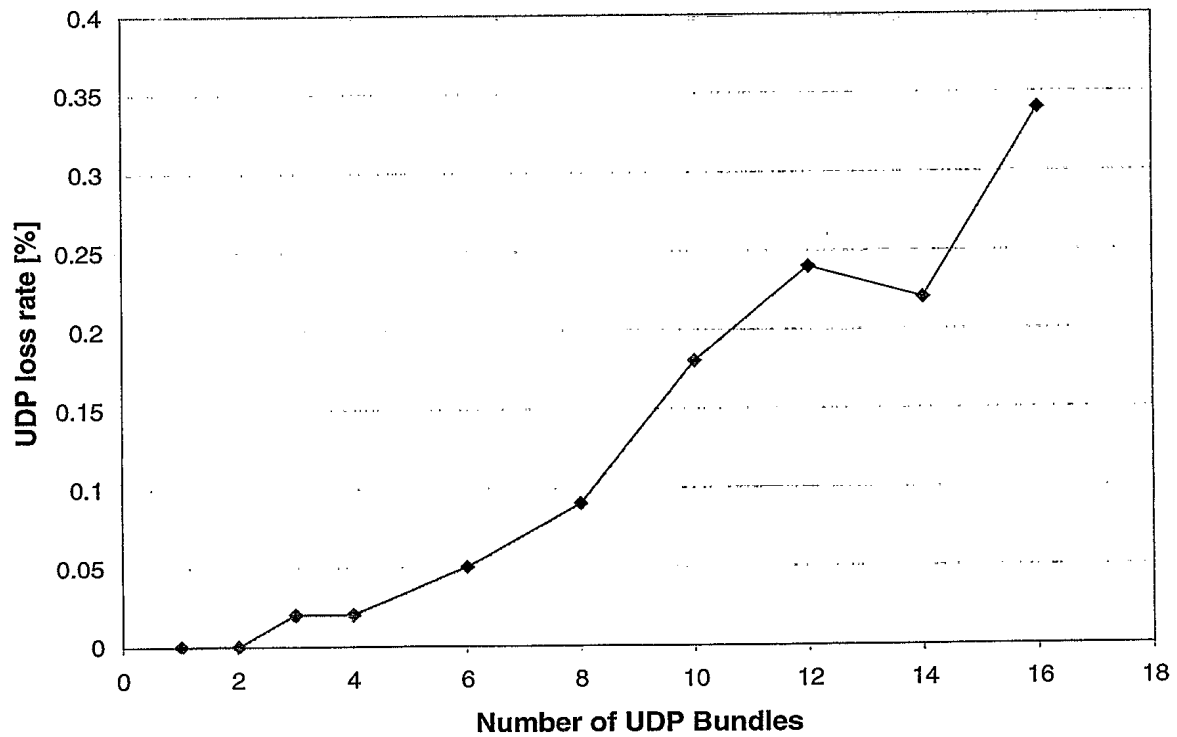


Figure 16: UDP loss rate vs. number of UDP bundles on an ATM WAN

Observations for figure 15:

In the WAN measurements, the number of UDP audio streams that can be bundled is affected by the PCR limit. For the trans-Atlantic measurements, the PCR in the FORE card was set to 1594 kb/s or 194.58 KB/s. Each UDP voice session has a data rate of 64 kb/s or 7.8 KB/s. During our measurements, each UDP voice session was characterised by a UDP data stream with a TSDU size of 80 bytes and an interarrival time of 10 ms. However each UDP TSDU is encapsulated using AAL5 and therefore one ATM cell is required to encapsulate the UDP header and two more ATM cells are required for the 80 bytes of UDP data. As each UDP TSDU is sent, three ATM cells are required per TSDU, thus the actual data rate is 300 cells/s or 15.53 KB/s per UDP connection. In Figure 15 the mean UDP throughput starts to decrease when more than 12 UDP audio streams are sent together. This can be explained in terms of the cell rate per UDP audio stream. Twelve audio streams require a bandwidth of 186.33 KB/s which is under the 194.858 KB/s PVC's bandwidth. As more UDP streams are bundled, the PVC's bandwidth is exhausted and the UDP throughput performance is affected and a lower throughput is obtained.

Observations for figure 16:

For the WAN measurements up to 16 UDP bundles were multiplexed. In every scenario the loss rate was less than 1%. From Figure 16, it is clear that there is an increase in cell loss as the number of UDP bundles is increased. This can be explained in terms of the workload that is generated at the receiving station. As more UDP connections are being bundled the Operating System's scheduler at the receiving workstation must deal with more UDP connections, therefore some of the UDP information gets discarded by the Kernel buffer and/or the ATM device buffer as it is not serviced in time.

6.2 LAN Measurements

The LAN measurements were done using a Classical IP PVC supporting VBR as described in section 4.1. Several measurement scenarios were tested for multiplexing TCP and UDP traffic. The bundles are built using different types of transport connections:

- A bulk data session (TCP) is multiplexed with an increasing number of voice sessions (UDP).
- A voice session (UDP) is multiplexed with an increasing number of bulk data sessions (TCP).
- An increasing number of voice sessions (UDP) are multiplexed.

As in the WAN measurements, the mean value of the throughput for the same types of transport connections is calculated by summing the throughput of each connection and dividing the result by the number of connections. For instance, when bundling one TCP connection with an increasing number of UDP connections, the mean value of the UDP throughput was calculated by summing the throughput of each UDP connection and dividing the result by the number of UDP connections.

6.2.1 Bundling one TCP connection with an increasing number of UDP connections

Measurement Scenario:

Description	Goal	- TCP Throughput vs. number of UDP bundles - UDP Throughput vs. number of UDP bundles - UDP loss rate vs. number of UDP bundles
	Test tool	CM-Toolset, Protocol Tuning Box, Adtech AX/4000
	Applications	Bulk data (TCP), 64 kb/s audio stream (UDP)
	Protocols	TCP, UDP
Traffic Parameters	TCP	Constant TSDU length: 4 Kbytes, 8 Kbytes and 20 Kbytes TSDU interarrival: 0 ms (unconstrained traffic) Number of TCP TSDUs: variable
	UDP	Constant TSDU length: 80 bytes TSDU interarrival: 10 ms. Number of TSDUs: 18000 (3 minutes duration at 64 kb/s)
	UDP Bundles	1,2,3,4,6,8,10
	Sender	Workstation: lucifer-cip SPARC-10, Solaris 2.4 , CRC Canada NIC: ForeRunner SBA-200 Peak cell rate: 1594 kb/s
	Receiver	Workstation: fred-cip SPARC-10, Solaris 2.4 , CRC Canada NIC: ForeRunner SBA-200 Peak cell rate: 1594 kb/s
	ATM LAN	VBR PVC connection PCR = 6 Mbits/s MBS = 32 cells SCR = 2 Mbits/s CDVT = 250 msec
	ATM Link	OC-3c (155.52 Mbits/s), T3 (45 Mb/s)
	RTT	2 ms
Details	Adaptation Layer	ATM AAL 5, MTU 9180 Bytes
	Data	See Appendix D, Tables 28 through 35

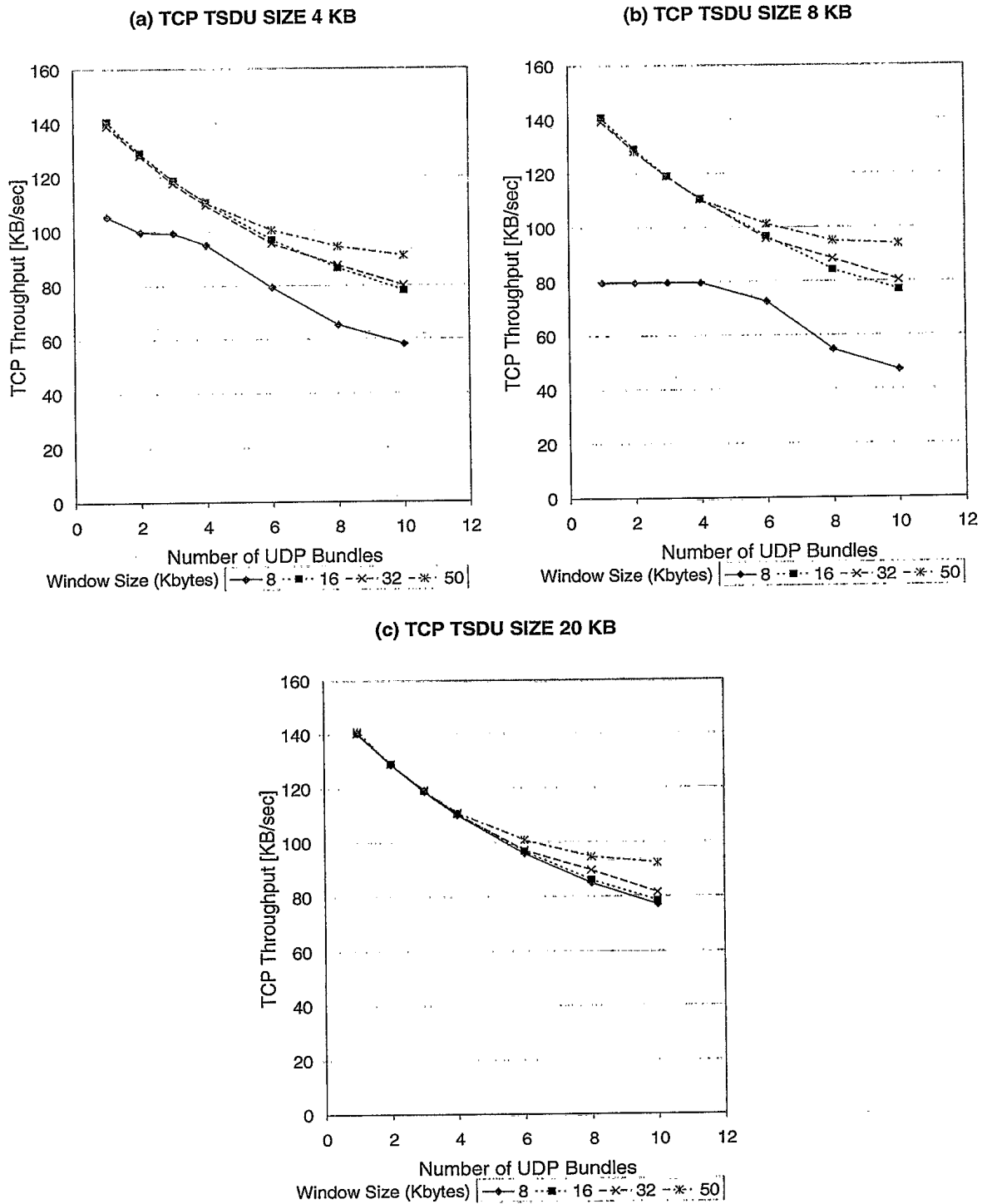


Figure 17: TCP Throughput vs. number of UDP bundles for different TCP TSDU lengths: (a) 4 KB, (b) 8 KB and (c) 20 KB on an ATM LAN

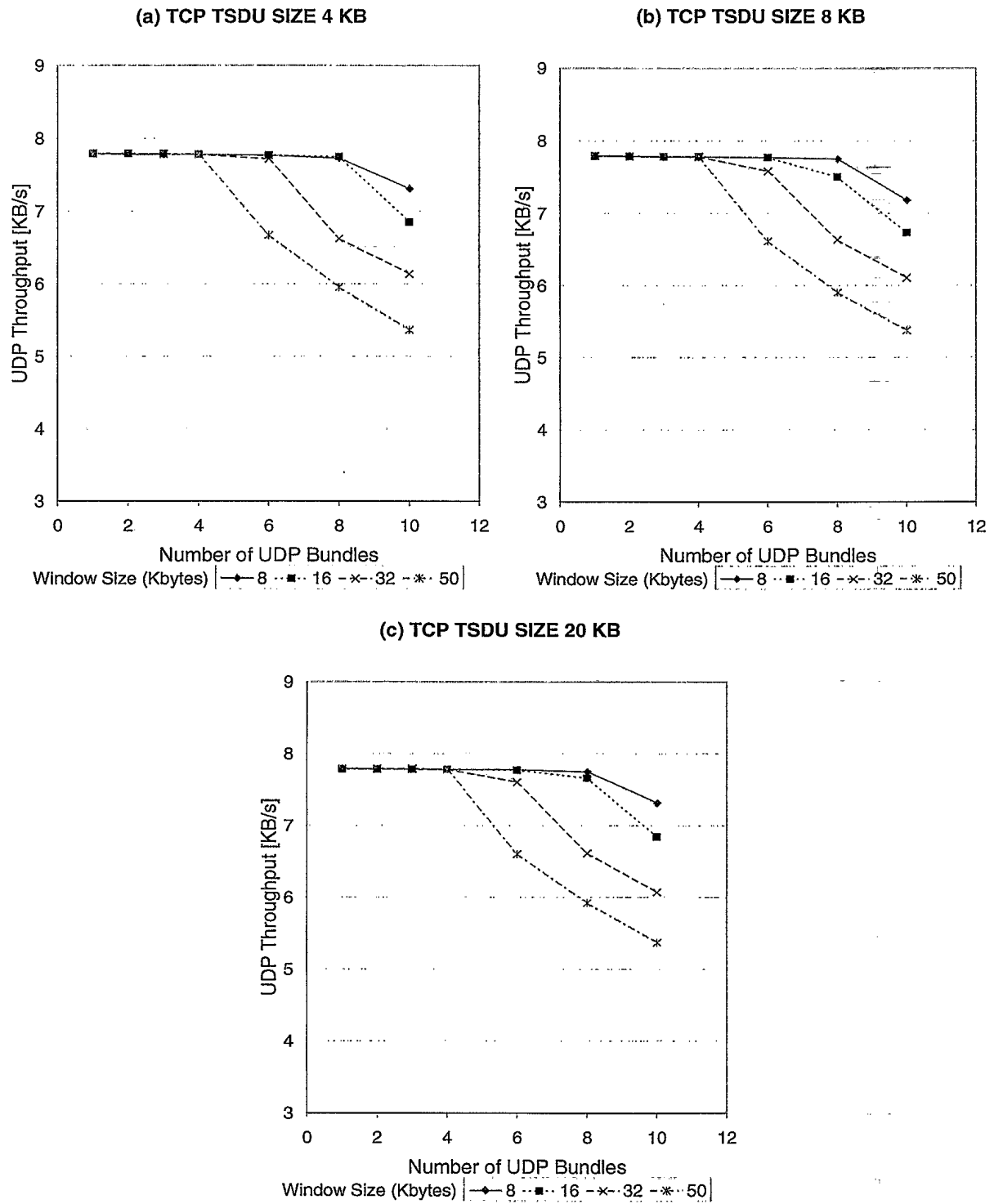


Figure 18: UDP Throughput vs. number of UDP bundles for different TCP TSDU lengths: (a) 4 KB, (b) 8 KB and (c) 20 KB on an ATM LAN

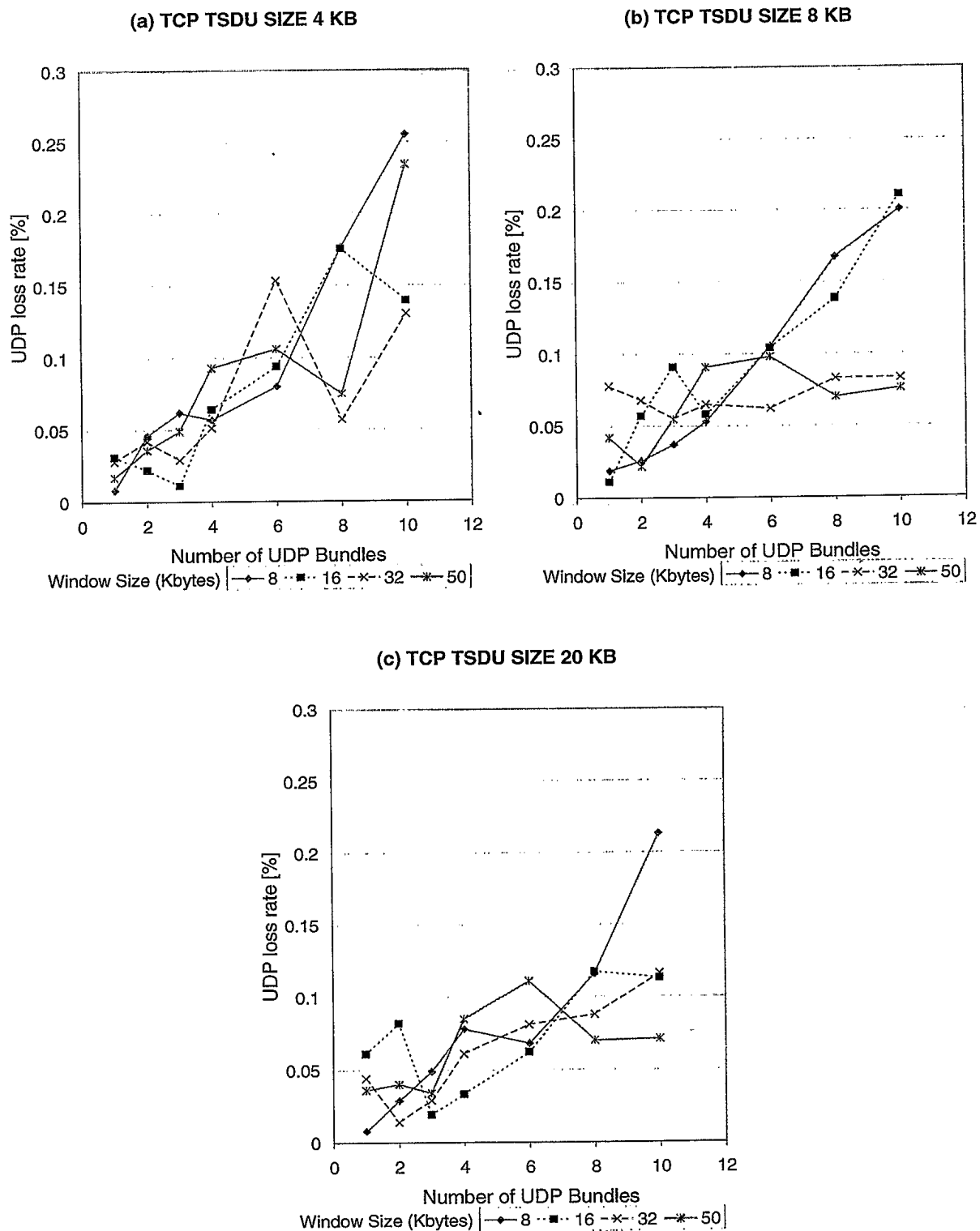


Figure 19: UDP loss rate vs. number of UDP bundles on an ATM LAN

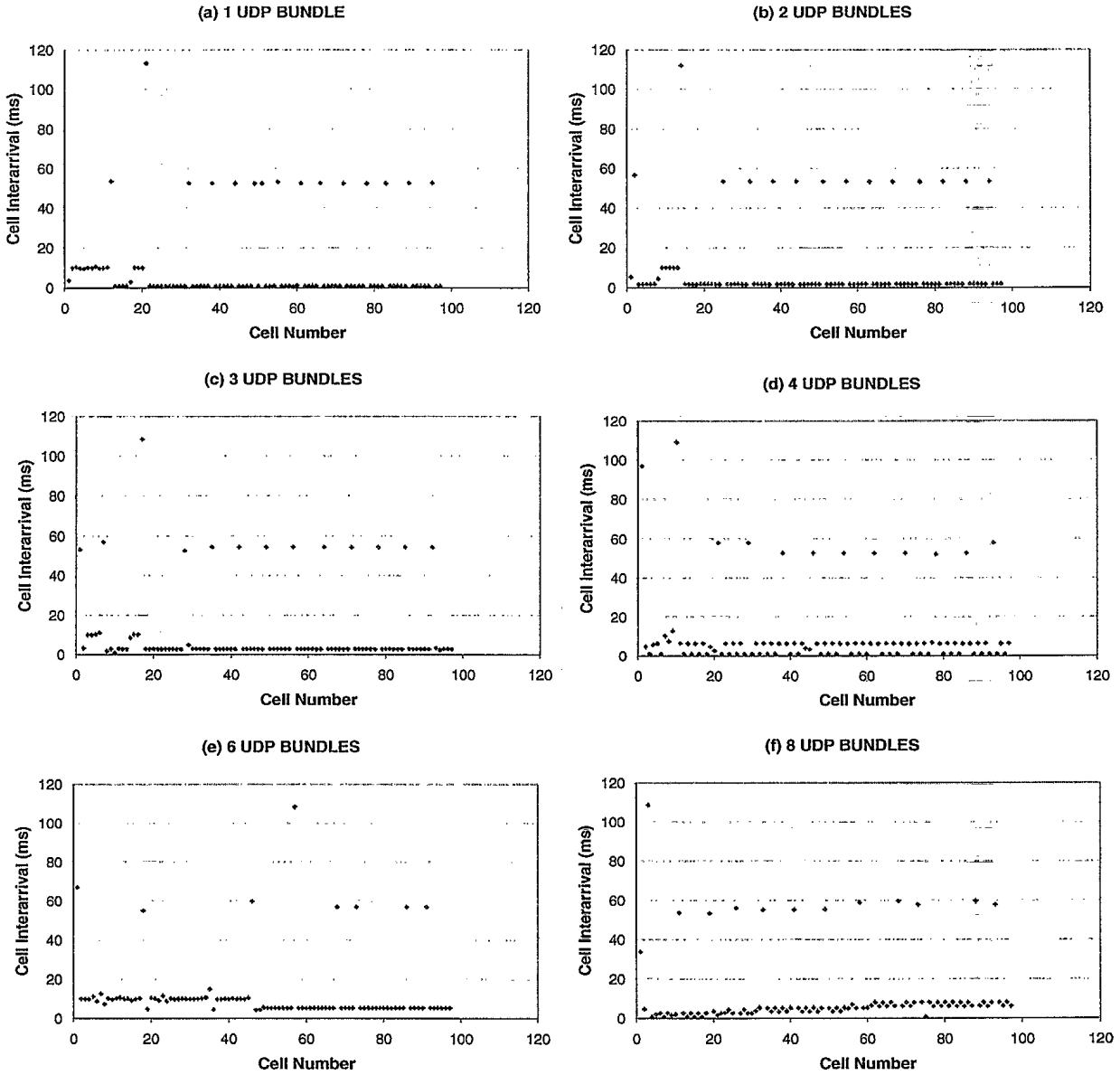


Figure 20: Cell interarrival time variation when bundling one TCP connection, using a window size 16 KB with different number of UDP bundles: (a) 1 UDP bundle, (b) 2 UDP bundles, (c) 3 UDP bundles, (d) 4 UDP bundles, (e) 6 UDP bundles, (f) 8 UDP bundles on an ATM LAN

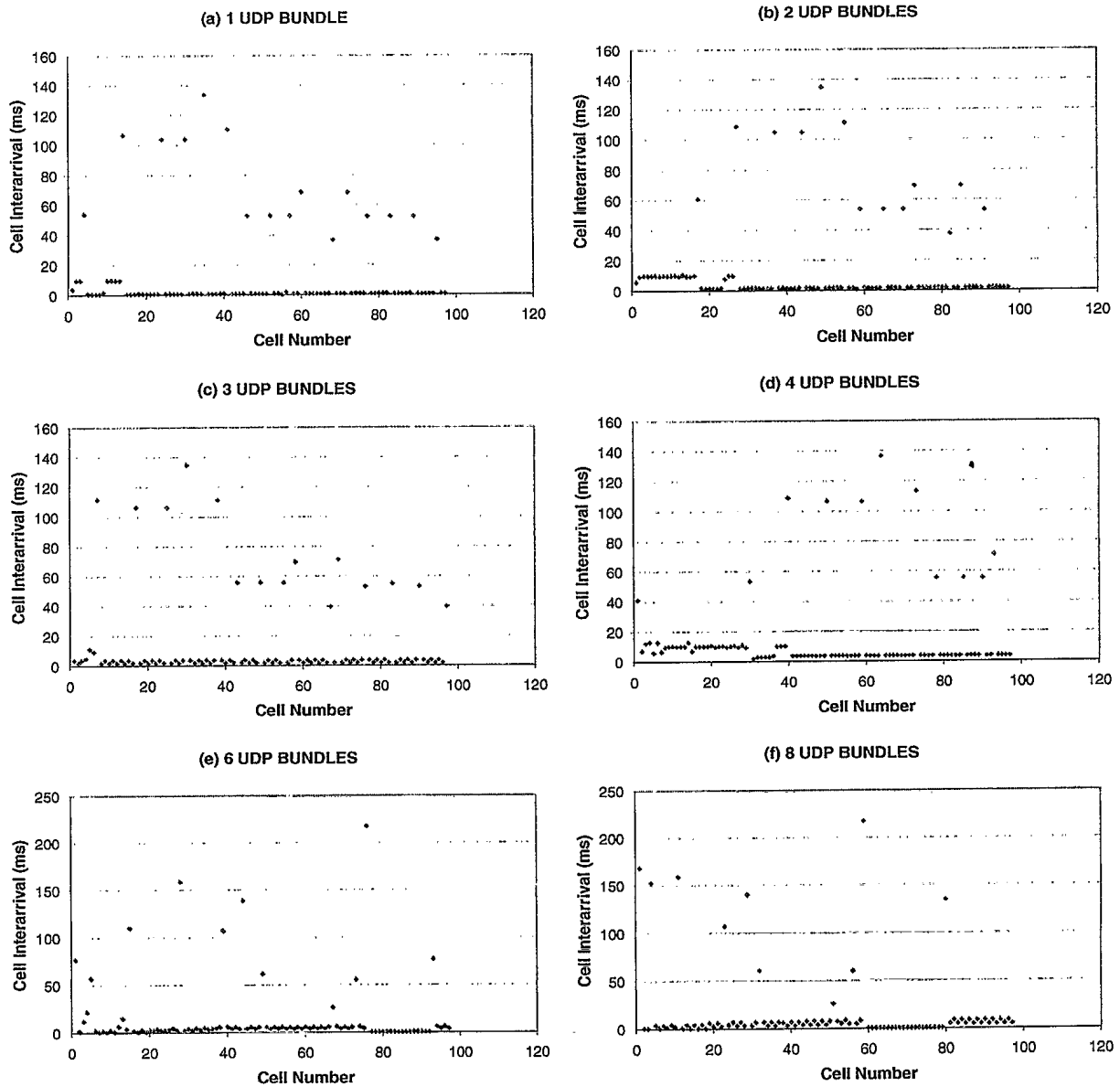


Figure 21: Cell interarrival time variation when bundling one TCP connection, using a window size 50 KB with different number of UDP bundles: (a) 1 UDP bundle, (b) 2 UDP bundles, (c) 3 UDP bundles, (d) 4 UDP bundles, (e) 6 UDP bundles, (f) 8 UDP bundles on an ATM LAN

Observations for figure 17:

As in the WAN, an increasing number of multiplexed UDP voice connections results in a decrease in the TCP throughput (Figure 17). However, in the LAN case, two distinct behaviours have been distinguished. The first behaviour occurs when less than four UDP sessions are bundled with a TCP session. An identical TCP throughput is reached irrespective of the window sizes (16 KB, 32 KB, 50 KB) or the TCP TSDU sizes (4 KB, 8 KB and 20 KB). The second behaviour, which occurs when more than four UDP sessions are bundled with a TCP session, shows different levels of throughput achieved for different window sizes, regardless of the TCP TSDU sizes.

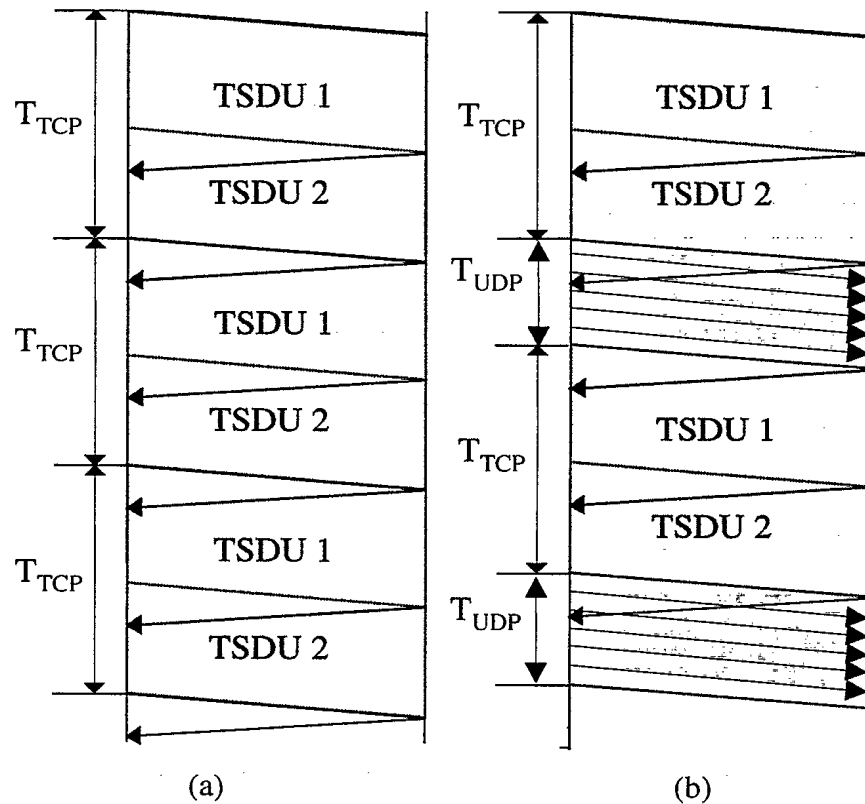


Figure 22: Bundling one TCP connection with many UDP connections on an ATM LAN

The peak rate of the FORE card was set to 1594 kb/s; that is, 194.58 KB/s. In an ATM cell there is 5 bytes of overhead. Therefore the maximum data throughput is 176.22 KB/s.

The link is fully utilised on the LAN when only the TCP traffic is present (see Figure 22(a)) because of the very small RTT. If we consider only TCP traffic, the throughput can be calculated in the following way:

$$TCP_Throughput \approx \frac{Window_Size}{T_{TCP}}$$

Therefore when using a window size of 50 KB, the time to send the window is $T_{TCP} \approx 280$ ms. For a window size of 16 KB, it takes ≈ 90 ms to send the window. For all the window sizes considered, the time it takes to send the window greatly exceeds the RTT delay (2 ms for the LAN link), therefore the pipe is always full. The source scheduler is always busy sending TCP traffic. However, since UDP sessions are bundled with a TCP session, the source scheduler has to take into consideration the additional UDP traffic. In our system, the UDP traffic is transmitted just after sending a whole window (see Figure 22(b)). However it should be noted that the TCP traffic, when using a window size of 8 KB with TCP TSDU sizes of 4 KB and 8 KB, presents a different behaviour (see Figure 17(a) and Figure 17(b)). The throughput achieved is less in the other scenarios due to the extra processing overhead that it is generated when the TCP TSDU sizes are smaller than the window size.

When more than four UDP connections are bundled with a TCP connection, the effects of the window size become apparent. As the number UDP connections increases, a larger gap between the TCP “send” operations is created and the effect of different window sizes become more significant. As the TCP window size gets larger, more TCP information is sent and the TCP throughput achieved becomes greater. The small RTT does not favour the bundling of UDP sessions when they exceed a certain number because the window size influences the TCP and UDP throughput.

Observations for figure 18:

As in the WAN case, the throughput of each UDP audio stream is 64 kb/s or 7.81 KB/s. From Figures 18(a) through 18(c), one can notice that four UDP audio connections can be bundle with one TCP connection without affecting the throughput of the UDP traffic, independent of the TCP TSDU length and TCP window size used.

In addition as already observed in the WAN case, when one TCP connection is bundled with several UDP audio connections, a better UDP throughput is obtained when smaller window sizes are used. This situation can be explained by the fact that the sender has more network bandwidth available for the UDP connections when smaller window sizes are used.

However, it should be noted that in the LAN results, the TCP TSDU size does not affect the UDP throughput for any number of UDP sessions. The reason as mentioned before (see observation for Figure 17) is the fact that the pipe gets full and the only factor which affects the UDP throughput is the TCP window size.

If we compare the TCP and the UDP throughput, we can notice complementary results. When larger windows are used, we get a better TCP throughput and a diminished UDP throughput. When smaller windows are used the opposite situation occurs. This is a direct result of the small RTT in the LAN that leads to a full pipe which is in turn governed by the window size parameter.

Observations for figure 19:

One can notice, as in the WAN case, that when one TCP connection is bundled with an increasing number of UDP audio streams, there is an increase of UDP loss rate as the number of UDP bundles increases (Figures 19 (a) through 19 (d)). In most cases, the loss rate is less than 0.25%. Although these loss rates are acceptable, the delay characteristics also have to be considered.

Observations for figure 20 and 21:

As in the WAN case, in order to calculate the cell inter-arrival times, we have considered a sequence of 100 ATM cells from one UDP connection when several UDP connections are bundled with one TCP connection. All UDP connections have been generated using a TSDU size of 80 bytes and an interarrival time of 10 ms. Two case studies have been considered. Case 1: one TCP session with a TSDU size of 8 KB and a window size of 16 KB. Case 2: one TCP session with a TSDU size of 8 KB and a window size of 50 KB. For the two cases, we calculated the mean interarrival time and the standard deviation (Table 3 and Table 4).

UDP Bundles	Mean Inter-arrival (ms)	Standard Deviation
1	10.66	20.81
2	10.25	20.46
3	10.57	19.68
4	11.07	20.50
6	12.15	16.72
8	12.08	19.42

Table 3: Mean cell interarrival time and standard deviation for the Case 1

UDP Bundles	Mean Inter-arrival (ms)	Standard Deviation
1	13.00	28.67
2	13.44	27.92
3	13.83	28.65
4	14.34	26.71
6	14.79	35.27
8	16.40	40.53

Table 4: Mean cell interarrival time and standard deviation for the Case 2

From these tables, the cell interarrival time, as well as the standard deviation, increases as the number of UDP connections increases. In the first case, the cell interarrival delays, which are of a few milliseconds greater than the expected 10 ms, are considered acceptable [Ramj94]. However, the large standard deviations indicate that some cells are arriving much later than the expected 10 ms. This statement can be confirmed by examining Figure 20 which shows that some cells have a delay of 50 or 60 ms and even reach a delay of 115 ms. These delays might be caused by network devices or perhaps I/O bottlenecks at the workstations or both.

The standard deviations, which reflect the cell delay variation, may not be considered acceptable and therefore should be adjusted to meet the delay requirements of a voice stream. One solution would be to ensure that the sending workstation discards any cells that have been waiting too long for transmission if the I/O at the source is causing a bottleneck. One could also use a buffer at the receiver, which would work as a regulator to smooth out the variations. The size of this buffer would depend on the interarrival of UDP cells at the receiver and on the end-to-end-delay [Perk98].

For larger window sizes, such as the 50 KB, the mean cell interarrival times as well as the standard deviations are larger. This is due to the fact that more information is sent in each TCP window and therefore the UDP connections must wait longer to be processed. The same buffer solution, as detailed above, should be applied to meet the delay requirements of the UDP voice traffic.

If the results obtained in the LAN (Table 3 and 4) are compared to those obtained in the WAN (Table 1 and 2), one can notice that the delay variances are more important in the former case. The small RTT (2 ms) in the LAN, compared to the much larger one (103 ms) in the WAN, has the effect of saturating the receiving end-system faster.

6.2.2 Bundling one UDP connection with an increasing number of TCP connections

Measurement Scenario:

Description	Goal	- TCP Throughput vs. number of TCP bundles - UDP Throughput vs. number of TCP bundles
	Test tool	CM-Toolset, Protocol Tuning Box, Adtech AX/4000
	Applications	Bulk data (TCP), 64 kb/s audio stream (UDP)
	Protocols	TCP, UDP
Traffic Parameters	TCP	Constant TSDU length: 4 Kbytes, 8 Kbytes and 20 Kbytes TSDU interarrival: 0 ms (unconstrained traffic) Number of TSDUs: variable
	TCP Bundles	1,2,3,4,6,8,10
	UDP	Constant TSDU length: 80 bytes TSDU interarrival: 10 ms Number of TSDUs: 18000 (3 minutes duration at 64 kb/s)
	Sender	Workstation: lucifer-cip SPARC-10, Solaris 2.4 , CRC Canada NIC: ForeRunner SBA-200 Peak Cell Rate: 1594 kb/s
	Receiver	Workstation: fred-cip SPARC-10, Solaris 2.4 , CRC Canada NIC: ForeRunner SBA-200 Peak Cell Rate: 1594 kb/s
	ATM WAN	VBR PVC connection PCR = 6 Mb/s MBS = 32 cells SCR = 2 Mb/s CDVT = 250 msec
	ATM Link	OC-3c (155.52 Mbits/s) T3 (45 Mb/s)
	RTT	2 ms
	Adaptation Layer	ATM AAL 5, MTU 9180 Bytes
Details	Data	See Appendix E, Tables 36 through 41

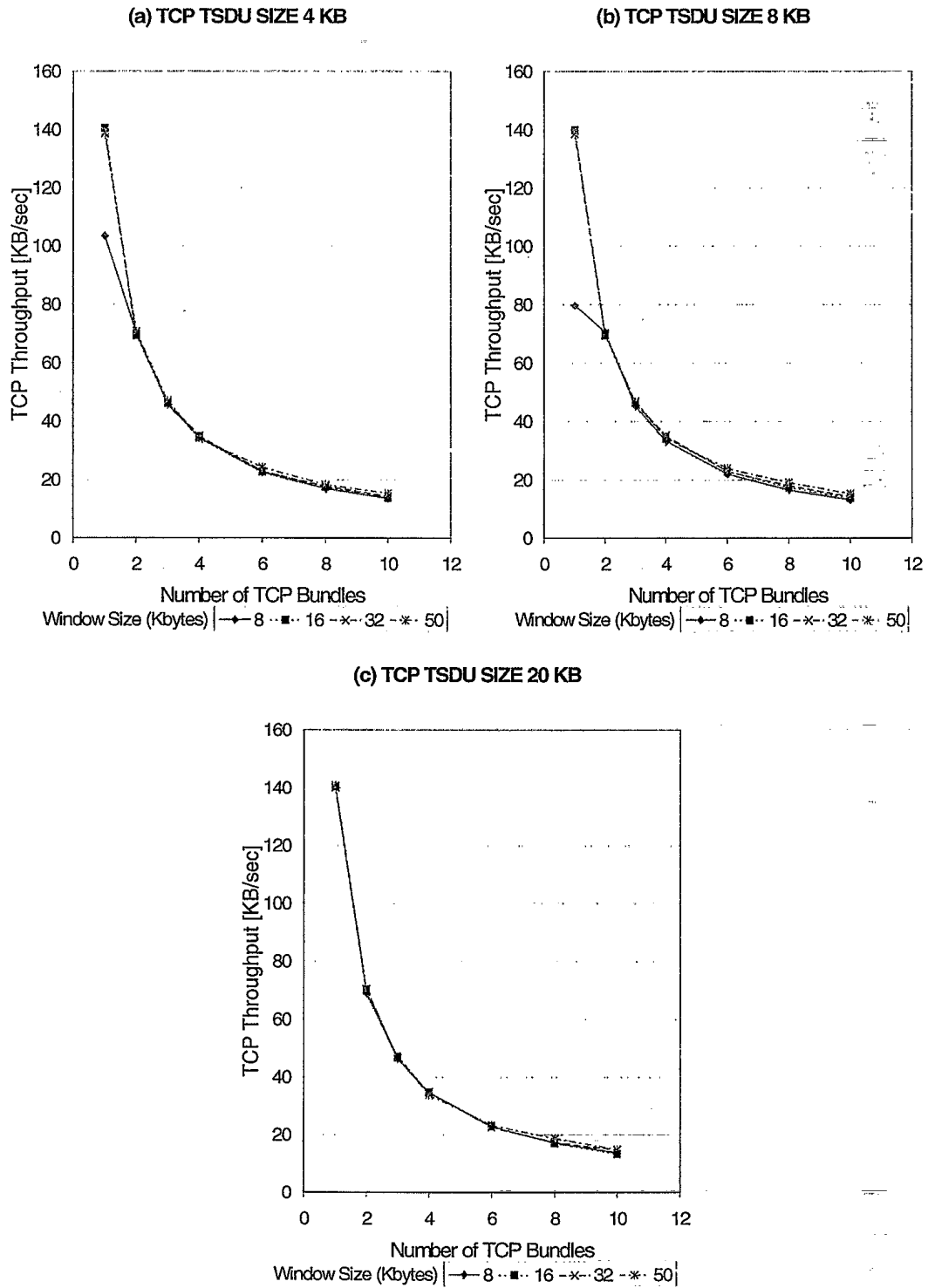


Figure 23: TCP Throughput vs. number of TCP bundles for different TCP TSDU lengths: (a) 4 KB, (b) 8 KB and (c) 20 KB on an ATM LAN

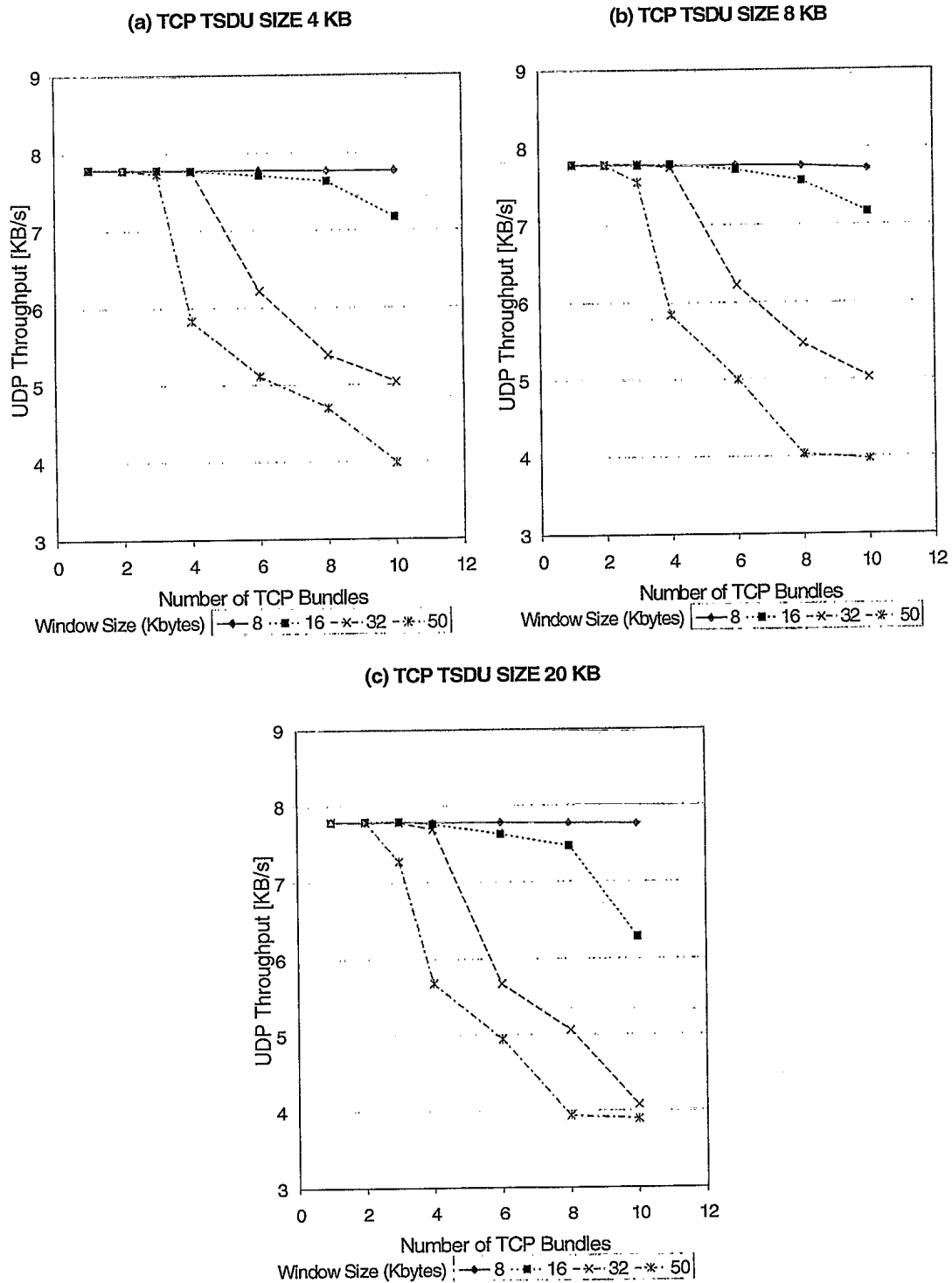


Figure 24: UDP Throughput vs. number of TCP bundles for different TCP TSDU lengths: (a) 4 KB, (b) 8 KB and (c) 20 KB on an ATM LAN

Observations for figure 23:

As in the WAN case, when several TCP connections are bundled with one UDP audio stream, the mean TCP throughput decreases as the number of TCP connection increases (Figures 23(a) through 23(c)). This can be explained in terms of the bandwidth required by each of the TCP and UDP connections (see “Observation on Figure 13”). However, in the LAN case, the curves are very similar because the link is fully utilised for all TCP TSDU sizes considered due to the very small RTT (2 ms). However, when many TCP sessions are bundled with one UDP session, the window size does not affect the TCP throughput. Recall that when many UDP sessions were bundled with one TCP session (Section 6.2.1), the window size did not have an impact on the TCP throughput. This can be explained by the fact that the link becomes fully utilised sooner when many TCP connections are bundled and the influence of the window size is therefore reduced.

Observations for figure 24:

Note that, just as in the WAN case, up to two TCP connections can always be bundled with one UDP connection without affecting the required 7.8 KB/s throughput for the UDP audio stream. When the TCP window size is set to 8 or 16 KB, the number of TCP bundles can be increased to ten and six bundles, respectively, without affecting the UDP connection’s throughput. (Figure 24(a) through 24(c)). The same reasoning, as in the WAN case, can be applied to the LAN case to explain the behaviour of the UDP throughput performance: smaller TCP window sizes yield lower TCP throughput therefore leaving more bandwidth for the UDP audio stream.

If the results obtained on the LAN are compared with those obtained for the WAN, it is clear that the LAN case shows a better performance regarding the number of TCP bundles. For instance, with a window size of 8 KB, a maximum of ten and six TCP connections, in the LAN and WAN, respectively, can be added to the UDP traffic without affecting the UDP connection’s performance. This difference can be attributed to the fact that the ACKs arrive much faster on the LAN than on the WAN and as a result the end-system is able to process more UDP traffic.

6.2.3 Bundling an increasing number of UDP connections

Measurement Scenario:

Description	Goal	• UDP Throughput vs. number of UDP bundles • UDP loss rate vs. number of UDP bundles
	Test tool	CM-Toolset, Protocol Tuning Box, Adtech AX/4000
	Applications	64 kb/s audio stream (UDP)
	Protocols	UDP
Traffic Parameters	UDP	Constant TSDU length: 80 bytes TSDU interarrival: 10 ms Number of TSDUs: 18000 (3 minutes duration at 64 kb/s)
	UDP Bundles	1, 2, 3, 4, 6, 8, 10, 12, 14, 16, 18, 20, 26
	Sender	Workstation: lucifer-cip SPARC-10, Solaris 2.4 , CRC Canada NIC: ForeRunner SBA-200 Peak Cell Rate: 1594 kb/s
	Receiver	Workstation: fred-cip SPARC-10, Solaris 2.4 , CRC Canada NIC: ForeRunner SBA-200 Peak Cell Rate: 1594 kb/s
	ATM WAN	VBR PVC connection PCR = 6 Mb/s MBS = 32 cells SCR = 2 Mb/s CDVT = 250 msec
	ATM Link	OC-3c (155.52 Mbits/s) T3 (45 Mb/s)
	RTT	2 ms
	Adaptation Layer	ATM AAL 5, MTU 9180 Bytes
Details	Data	See Appendix F, Table 38 and 39

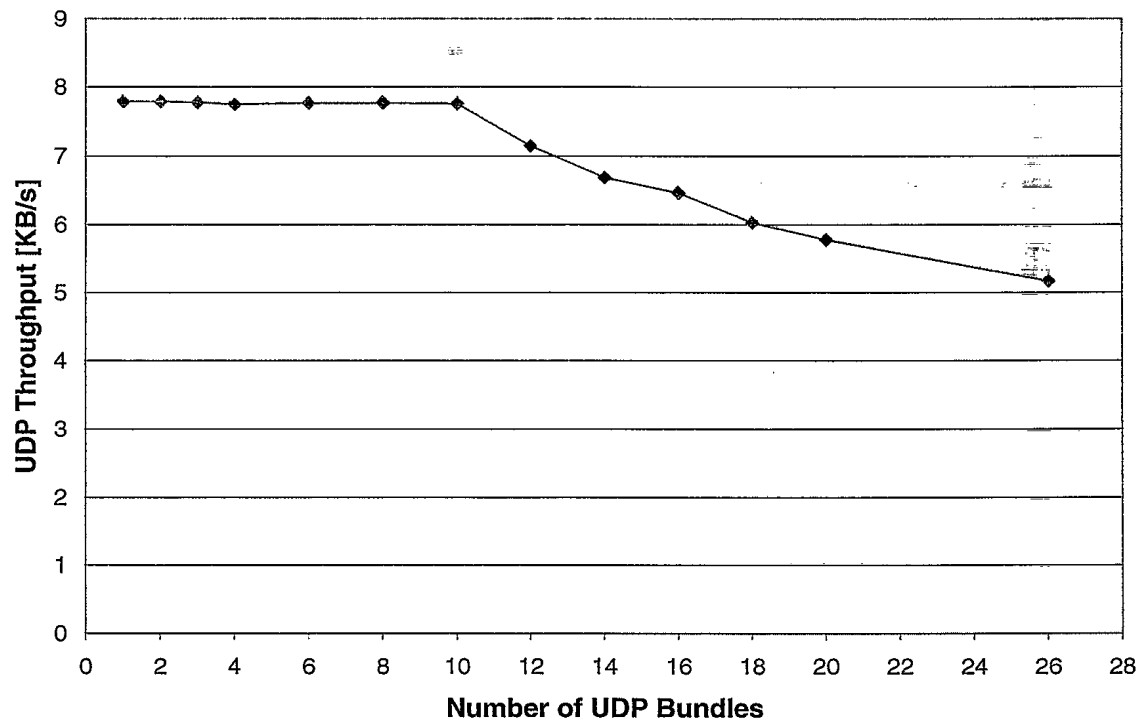


Figure 25: UDP Throughput vs. number of UDP bundles on an ATM LAN

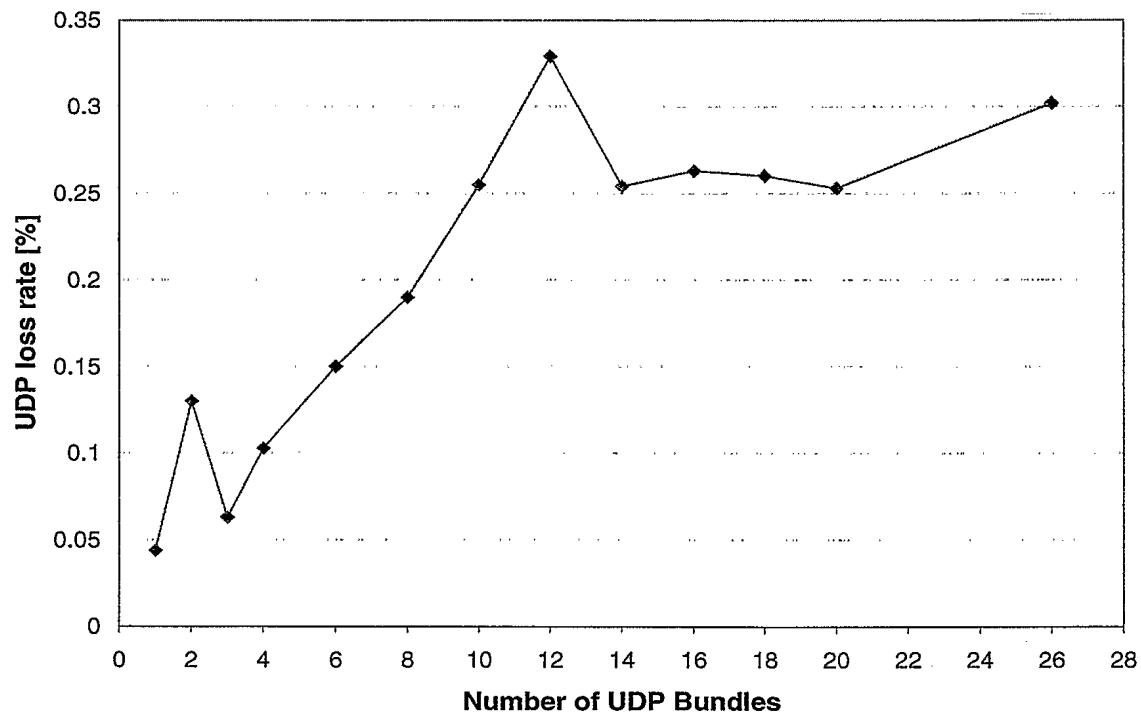


Figure 26: UDP loss rate vs. number of UDP bundles on an ATM LAN

Observations for figure 25:

As in the WAN measurements, the PCR in the FORE card was set to 1594 Kb/s (or 194.58 KB/s) and each UDP session was characterised by a TSDU size of 80 bytes and an interarrival time of 10 ms. In the experiments, each TSDU requires three ATM cells in order to be sent. Therefore, the effective data rate is 300 cells/s or 15.53 KB/s for each UDP connection. In Figure 25, one can notice that the mean UDP throughput starts to decrease when more than 10 UDP audio streams are bundled.

In the WAN measurements, twelve UDP sessions were bundled without a decrease in the mean UDP throughput. Therefore, when more than ten audio streams are bundled (equivalent to 155.3Kb/s) with the TCP stream, the receiver's workstation gets overloaded. In this case, the bottleneck becomes the workstation, instead of the PCR set in the FORE card as stated in the WAN measurements (see "Observations for Figure 13"). This is a result of the much smaller RTT in the LAN.

Observations for figure 26:

As seen in the WAN measurements, an increase in the number of UDP bundles, results in an increase in the byte loss rate (Figure 26,) even though the overall loss rate did not exceed 1%. As in the WAN case, the receiving station's workload can be attributed to the byte loss rate behaviour (see "Observations for Figure 14").

7 Conclusion

When bundles are built using only UDP connections, the mean UDP throughput starts to decrease when more than twelve UDP audio streams are multiplexed on the WAN and when ten UDP audio streams are multiplexed on the LAN. As soon as a bundle includes a TCP connection the UDP throughput decreases faster. The TCP window size and the TCP slowstart and congestion avoidance mechanisms have a direct impact on the UDP throughput. With a large window size, for example 50 KB, up to four UDP sessions can be multiplexed, in both the LAN and WAN case, and still maintain the required rate for the UDP connections. By selecting a smaller TCP window size, more UDP connections can be bundled while maintaining the required UDP throughput. Finally, when a bundle includes many TCP connections, the UDP throughput decreases even faster. As the number of TCP sessions is increased, the UDP throughput decreases. With a large window size, 50 KB, at most two TCP connections can be multiplexed with one UDP connection while still maintaining the required UDP's connection rate. Nevertheless, choosing a small window size permits up to six TCP connections to be bundled with one UDP connection without considerably affecting the UDP connection's throughput performance. Another parameter that influenced the TCP and the UDP throughput throughout our measurements was the RTT delay of the network. We observed that the smaller the RTT, the better the UDP throughput when one UDP session is bundled with many TCP sessions. This is due to the fact that the TCP acknowledgements are received faster and therefore allows the source end-system to process the UDP traffic sooner. On the other-hand, the delay variations observed on the LAN are more pronounced than in the WAN due to the smaller RTT which has the effect of causing saturation at the end-system sooner.

8 Abbreviations of Technical Terms

AAL	ATM Adaptation Layer
ACK	acknowledgement
ATM	Asynchronous Transfer Mode
CDV	Cell Delay Variation
CDVT	Cell Delay Variation Tolerance
CLR	Cell Loss Ratio
CTD	Cell Transfer Delay
GCRA	Generic Cell Rate Algorithm
GUI	Graphical User Interface
IP	Internet Protocol
LAN	Local Area Network
LLC	Logical Link Control
Max CTD	Maximum Cell Transfer Delay
MBS	Maximum Burst Size
MTU	Maximum Transport Unit
Mean CTD	Mean Cell Transfer Delay
NIC	Network Interface Card
nrt-VBR	non-real-time-Variable Bit Rate
PCR	Peak Cell Rate
PDU	Packet Data Unit
PVC	Permanent Virtual Circuit
QoS	Quality of Service
rt-VBR	real-time-Variable Bit Rate
RTT	Round Trip Time
SCR	Sustainable Cell Rate
SNAP	Subnetwork Attachment Point
TCP	Transmission Control Protocol
TSDU	Transport Service Data Unit
UDP	User Datagram Protocol
UPC	Usage Parameter

VBR	Variable Bit Rate
VCC	Virtual Channel Connection
VCI	Virtual Channel Identifier
VPI	Virtual Path Identifier
WAN	Wide Area Network

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Appendix A: One TCP bundled with several UDP Connections on trans-Atlantic ATM

UDP Bundles	TCP TSDU LENGTH = 4 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]
1	44.34	79.2	158.55	160.68
2	44.48	79.77	146.45	147.95
3	45.13	80.96	136.19	137.1
4	43.6	80.95	126.85	127.8
6	44.76	71.76	112.27	115.4
8	42.53	54.69	101.89	107.45
12	29.67	53.58	84.96	100.33
16	27.99	42.32	79.71	99.5

Table 5

UDP Bundles	TCP TSDU LENGTH = 8 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]
1	37.84	79.84	158.25	160.04
2	37.62	72.94	146.82	147.26
3	37.12	72.37	136.48	136.8
4	36.97	72.2	127.1	127.99
6	36.83	61.53	112.42	115.52
8	33.59	50.26	102.34	108.19
12	25.12	43.59	85.35	103.53
16	22.96	37.32	80.56	103.21

Table 6

UDP Bundles	TCP TSDU LENGTH = 10 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]
1	52.58	94.06	160.05	160.2
2	52.83	92.71	147.52	146.91
3	52.89	90.69	136.56	136.83
4	52.96	89.34	127.38	127.59
6	52.77	75.93	112.64	114.62
8	44.84	61.19	103.58	107.09
12	33.97	58.61	85.19	98.02
16	33.13	45.9	82.86	97.04

Table 7

UDP Bundles	TCP TSDU LENGTH = 20 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]
1	54.74	99.76	159.88	160.7
2	54.6	96.25	147.87	147.68
3	54.04	95.67	137.02	137.26
4	54.11	92.19	127.61	127.98
6	53.62	76.91	112.68	115.61
8	45.31	62.81	103.33	108.14
12	34.86	60.35	86.15	102.74
16	33.82	47.02	83.13	101.99

Table 8

UDP Bundles	TCP TSDU LENGTH = 4 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]
1	7.79	7.79	7.79	7.79
2	7.79	7.79	7.79	7.79
3	7.79	7.79	7.79	7.79
4	7.79	7.78	7.79	7.78
6	7.78	7.78	7.78	6.91
8	7.78	7.78	6.76	6.1
12	6.8	6.46	5.79	5.13
16	6.1	5.77	5.05	4.59

Table 9

UDP Bundles	TCP TSDU LENGTH = 8 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]
1	7.8	7.8	7.79	7.79
2	7.79	7.8	7.79	7.79
3	7.8	7.79	7.79	7.78
4	7.8	7.79	7.79	7.78
6	7.79	7.79	7.78	6.72
8	7.79	7.41	6.79	6.02
12	6.41	5.88	5.77	5.06
16	5.46	5.14	5.03	4.56

Table 10

UDP Bundles	TCP TSDU LENGTH = 10 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]
1	7.79	7.79	7.79	7.79
2	7.79	7.79	7.79	7.79
3	7.79	7.78	7.79	7.78
4	7.79	7.78	7.78	7.78
6	7.78	7.78	7.78	7.05
8	7.77	7.76	6.73	6.23
12	6.78	6.4	5.69	5.25
16	6.06	5.75	4.98	4.67

Table 11

UDP Bundles	TCP TSDU LENGTH = 20 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]
1	7.79	7.79	7.79	7.79
2	7.79	7.79	7.79	7.79
3	7.79	7.79	7.79	7.78
4	7.79	7.78	7.78	7.78
6	7.78	7.78	7.76	6.82
8	7.78	7.71	6.69	6.08
12	6.78	6.4	5.74	5.11
16	6.04	5.75	4.97	4.58

Table 12

UDP Bundles	TCP TSDU LENGTH = 4 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]
1	0	0	0	0
2	0.01	0.01	0	0
3	0.03	0.03	0.02	0
4	0.06	0.04	0.08	0.04
6	0.09	0.11	0.09	0.08
8	0.14	0.08	0.17	0.14
12	0.25	0.17	0.18	0.28
16	0.18	0.13	0.15	0.15

Table 13

UDP Bundles	TCP TSDU LENGTH = 8 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]
1	0	0	0	0
2	0	0.01	0.03	0.01
3	0.01	0.01	0.01	0.05
4	0.07	0.11	0.03	0.06
6	0.13	0.07	0.15	0.07
8	0.12	0.14	0.14	0.06
12	0.2	0.19	0.15	0.18
16	0.21	0.12	0.18	0.13

Table 14

UDP Bundles	TCP TSDU LENGTH = 10 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]
1	0	0	0	0
2	0	0	0.02	0
3	0.01	0.02	0.05	0.01
4	0.04	0.02	0.04	0.05
6	0.12	0.11	0.13	0.12
8	0.07	0.12	0.17	0.13
12	0.23	0.17	0.21	0.19
16	0.21	0.11	0.14	0.21

Table 15

UDP Bundles	TCP TSDU LENGTH = 20 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]
1	0	0	0	0
2	0	0.01	0	0
3	0.06	0.01	0.01	0.01
4	0.03	0.02	0.05	0.05
6	0.08	0.12	0.09	0.12
8	0.19	0.12	0.14	0.19
12	0.21	0.17	0.17	0.17
16	0.13	0.2	0.53	0.53

Table 16

Appendix B: One UDP bundled with several TCP connections on trans-Atlantic ATM

TCP Bundles	TCP TSDU LENGTH = 4 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]
1	42.21	64.63	65.17	160.18
2	41.35	45.32	44.63	43.28
3	32.15	18.94	23.09	21.2
4	21.12	14.01	13.73	13.66
6	10.27	8.07	9.95	8.74
8	6.54	5.94	6.29	6.49
10	4.62	4.53	4.66	4.87

Table 17

TCP Bundles	TCP TSDU LENGTH = 8 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]
1	41.35	73.18	94.18	159.02
2	36.41	62.98	44.69	44.41
3	31.05	35.08	29.85	29.75
4	22.56	14	15.9	15.77
6	11.24	8.22	8.52	9.18
8	7.28	6.16	7.7	6.69
10	5.05	4.55	5.58	5.66

Table 18

TCP Bundles	TCP TSDU LENGTH = 10 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]
1	39.16	90.15	152.16	153.5
2	39.51	78.89	49.99	59.06
3	33.65	24.5	19.37	20.55
4	24.36	11.87	14.51	13.63
6	11.07	6.98	9.09	9.03
8	6.77	5.61	6.13	6.79
10	4.38	4.39	4.8	6.12

Table 19

TCP Bundles	TCP TSDU LENGTH = 20 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]
1	53.08	93.91	79.17	77.97
2	52.46	43.2	32.8	31.33
3	28.74	16.85	18.48	18.77
4	20.19	11.41	13.36	13.57
6	9.5	7.52	8.76	9.02
8	4.28	5.94	5.56	6.31
10	4.54	4.34	4.49	4.54

Table 20

TCP Bundles	TCP TSDU LENGTH = 4 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]
1	7.78	7.8	7.78	7.79
2	7.79	7.79	7.79	7.78
3	7.79	7.79	6.88	6.68
4	7.79	7.53	5.98	5.96
6	7.79	5.15	5.37	4.99
8	6.8	4.75	4.7	4.67
10	5.48	3.77	3.75	3.92

Table 21

TCP Bundles	TCP TSDU LENGTH = 8 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]
1	7.77	7.79	7.79	7.79
2	7.79	7.8	7.79	7.79
3	7.79	7.79	7.79	7.79
4	7.79	7.49	5.91	5.8
6	7.79	5.28	5.23	5.3
8	7.69	4.83	4.69	4.76
10	5.76	3.83	4	4.32

Table 22

TCP Bundles	TCP TSDU LENGTH = 10 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]
1	7.79	7.8	7.78	7.79
2	7.78	7.79	7.79	7.79
3	7.79	7.79	6.06	5.72
4	7.78	6.24	5.33	5.01
6	7.78	4.38	3.95	3.98
8	7	3.93	3.9	3.89
10	5.1	3.85	3.8	3.92

Table 23

TCP Bundles	TCP TSDU LENGTH = 20 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]
1	7.79	7.79	7.79	7.78
2	7.78	7.8	7.78	7.69
3	7.79	7.79	6.23	6.25
4	7.79	6.09	5.42	5.36
6	7.78	5.07	4.66	4.67
8	5.18	4.02	3.88	3.77
10	5.18	3.81	3.89	3.77

Table 24

Appendix C: UDP bundled connections on trans-Atlantic ATM

UDP Bundles	PCR 2 Mbps
	UDP Throughput [Kbytes/s]
1	7.8
2	7.79
3	7.79
4	7.79
6	7.8
8	7.8
10	7.79
12	7.78
14	4.11
16	3.57

Table 25

UDP Bundles	PCR 2 Mbps
	Mean UDP Loss Rate [%]
1	0
2	0
3	0.02
4	0.02
6	0.05
8	0.09
10	0.18
12	0.24
14	0.22
16	0.34

Table 26

Appendix D: One TCP bundled with several UDP Connections on LAN ATM

UDP Bundles	TCP TSDU LENGTH = 4 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]
1	105.42	140.81	139.22	140.17
2	99.68	129.18	128.1	128.52
3	99.28	118.93	117.82	118.93
4	94.94	110.89	109.89	110.73
6	79.32	96.85	95.47	100.42
8	65.25	86.44	87.44	94.27
10	58.16	78.08	79.98	90.91

Table 27

UDP Bundles	TCP TSDU LENGTH = 8 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]
1	79.76	140.97	139.4	140.16
2	79.75	129.34	128.45	128.24
3	79.76	119.31	119.1	119.09
4	79.7	110.75	110.82	110.51
6	72.49	96.8	95.9	101.3
8	54.63	84.23	88.35	94.89
10	47.09	76.87	80.36	93.72

Table 28

UDP Bundles	TCP TSDU LENGTH = 20 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]	TCP Throughput [Kbytes/s]
1	140.35	140.68	140.42	141.21
2	128.72	129.12	129.02	128.86
3	118.76	119.15	119.25	119.46
4	110.15	110.78	110.73	111.01
6	95.88	96.68	97.06	100.94
8	84.9	86	89.61	94.61
10	77.02	78.42	81.42	92.4

Table 29

UDP Bundles	TCP TSDU LENGTH = 4 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]
1	7.79	7.79	7.79	7.79
2	7.78	7.79	7.79	7.79
3	7.78	7.79	7.79	7.78
4	7.78	7.78	7.78	7.78
6	7.77	7.77	7.72	6.67
8	7.73	7.75	6.62	5.95
10	7.31	6.85	6.13	5.36

Table 30

UDP Bundles	TCP TSDU LENGTH = 8 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]
1	7.79	7.79	7.79	7.78
2	7.79	7.78	7.78	7.79
3	7.78	7.78	7.78	7.78
4	7.78	7.78	7.78	7.77
6	7.77	7.77	7.58	6.61
8	7.75	7.5	6.63	5.9
10	7.18	6.73	6.1	5.37

Table 31

UDP Bundles	TCP TSDU LENGTH = 20 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]	Mean UDP Throughput [Kbytes/s]
1	7.79	7.78	7.79	7.79
2	7.79	7.78	7.79	7.78
3	7.78	7.78	7.79	7.78
4	7.78	7.78	7.78	7.78
6	7.78	7.77	7.6	6.6
8	7.75	7.66	6.61	5.92
10	7.32	6.84	6.07	5.37

Table 32

UDP Bundles	TCP TSDU LENGTH = 4 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]
1	0.008	0.031	0.028	0.017
2	0.046	0.022	0.042	0.036
3	0.062	0.011	0.029	0.049
4	0.057	0.064	0.051	0.093
6	0.08	0.094	0.153	0.106
8	0.176	0.175	0.057	0.075
10	0.255	0.139	0.13	0.234

Table 33

UDP Bundles	TCP TSDU LENGTH = 8 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]
1	0.019	0.011	0.078	0.042
2	0.026	0.057	0.068	0.022
3	0.037	0.091	0.055	0.055
4	0.053	0.058	0.065	0.091
6	0.105	0.104	0.062	0.098
8	0.167	0.138	0.083	0.07
10	0.2	0.21	0.083	0.076

Table 34

UDP Bundles	TCP TSDU LENGTH = 20 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]	Mean UDP Loss Rate [%]
1	0.008	0.061	0.044	0.036
2	0.029	0.082	0.014	0.04
3	0.049	0.019	0.029	0.034
4	0.078	0.033	0.061	0.085
6	0.068	0.062	0.081	0.111
8	0.116	0.117	0.088	0.07
10	0.213	0.113	0.116	0.071

Table 35

Appendix E: One UDP bundled with several TCP connections on LAN ATM

TCP Bundles	TCP TSDU LENGTH = 4 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]
1	103.5	140.71	138.9	139.65
2	70.21	69.27	69.8	70.57
3	45.55	46.03	46.29	46.98
4	34.24	34.54	34.88	34.19
6	22.49	22.74	22.81	24.19
8	16.84	17.35	17.67	18.25
10	13.54	13.7	14.25	15.23

Table 36

TCP Bundles	TCP TSDU LENGTH = 8 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]
1	79.65	140.1	138.87	139.67
2	70.43	69.34	69.81	70.19
3	45.08	46.06	46.4	46.78
4	33.18	34.53	35.05	34.14
6	21.91	22.86	22.8	23.88
8	16.37	17.2	17.85	18.97
10	13.05	13.71	14.07	15.14

Table 37

TCP Bundles	TCP TSDU LENGTH = 20 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]	Mean TCP Throughput [Kbytes/s]
1	140.28	140.54	140.25	140.81
2	68.79	70.24	70.29	70.14
3	46.26	46.89	46.53	46.55
4	34.3	34.58	34.67	33.73
6	22.71	22.75	22.48	23.22
8	17.07	16.94	17.2	18.61
10	13.69	13.2	14.62	14.83

Table 38

TCP Bundles	TCP TSDU LENGTH = 4 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]
1	7.79	7.79	7.79	7.79
2	7.79	7.78	7.78	7.78
3	7.78	7.78	7.78	7.73
4	7.78	7.77	7.77	5.83
6	7.78	7.71	6.21	5.11
8	7.77	7.63	5.38	4.7
10	7.77	7.16	5.03	3.99

Table 39

TCP Bundles	TCP TSDU LENGTH = 8 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]
1	7.79	7.79	7.79	7.78
2	7.78	7.78	7.79	7.78
3	7.79	7.78	7.79	7.56
4	7.77	7.79	7.75	5.84
6	7.78	7.72	6.22	5
8	7.77	7.57	5.46	4.03
10	7.73	7.16	5.02	3.97

Table 40

TCP Bundles	TCP TSDU LENGTH = 20 Kbytes			
	TCP Window 8 Kbytes	TCP Window 16 Kbytes	TCP Window 32 Kbytes	TCP Window 50 Kbytes
	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]	UDP Throughput [Kbytes/s]
1	7.79	7.78	7.79	7.79
2	7.78	7.79	7.78	7.78
3	7.79	7.79	7.78	7.27
4	7.78	7.76	7.69	5.68
6	7.78	7.62	5.67	4.94
8	7.77	7.46	5.06	3.94
10	7.76	6.28	4.08	3.9

Table 41

Appendix F. UDP bundled connections on LAN ATM

UDP Bundles	PCR 2 Mbps
	UDP Throughput [Kbytes/s]
1	7.79
2	7.79
3	7.78
4	7.75
6	7.77
8	7.77
10	7.76
12	7.15
14	6.69
16	6.46
18	6.03
20	5.78
26	5.17

Table 42

UDP Bundles	PCR 2 Mbps
	Mean UDP Loss Rate [%]
1	0.044
2	0.13
3	0.063
4	0.103
6	0.15
8	0.19
10	0.255
12	0.329
14	0.254
16	0.263
18	0.26
20	0.253
26	0.302

Table 43

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An initiative between DeTeBerkom in Berlin and the Communication Research Centre (CRC) in Ottawa was undertaken to determine realistic resource reservation requirements when IP telephony applications are multiplexed with bulk data applications in an ATM network.

In our work, we considered different ways of bundling voice (i.e. IP telephony) and data traffic. We analyse the throughput achieved for the data traffic and the rate, packet loss and delay variance for the voice traffic for each bundle type.

We illustrate the specific effects that different performance factors such as VBR traffic parameters, the TCP flow control and send window size, network delay, system scheduling and application traffic have on the QoS provision in an ATM Wide Area Network (WAN) and Local Area Network (LAN) environment.

Trans-Atlantic connections, using national high-speed test networks and Teleglobe's trans-Atlantic submarine fibre CANTAT-3 are used to obtain the ATM WAN measurements. LAN measurements are performed using an ATM LAN testbed at CRC.

The experiments are performed and evaluated with the CM Toolset, which provides for the automation of QoS analysis of selected applications under different ATM network environments.

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