ABSTRACT

Satellite ATM networks have significant advantages over terrestrial ATM networks. Satellites provide unique advantages such as remote coverage with rapid deployment, distance insensitivity, bandwidth on demand, immunity to terrestrial disasters, and offering broadband links. Satellite ATM networks will play an important role in the rapidly evolving information infrastructure. However, there are several obstacles which need to be overcome so that satellite ATM networks can operate in full service. The objective of this survey is to present the state of the art in satellite ATM networks and to point out open research problems.

Satellite ATM Networks: A Survey

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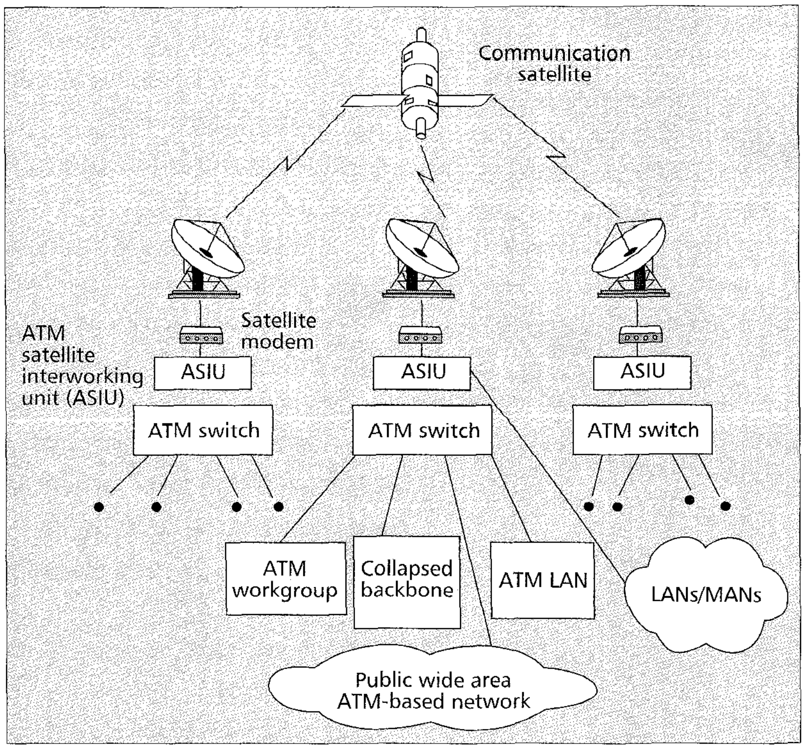
Asynchronous transfer mode (ATM) is the switching and multiplexing technique for B-ISDN (broadband integrated services for digital networks) and is widely accepted as the networking technology of the future. ATM technology offers users integration of voice, video, and data services, and the flexibility of accessing bandwidth on demand. On the other hand, there is increasing recognition of the benefits and advantages of using satellite transmission systems which, in our opinion, will play a significant role in establishing the global information infrastructure.

Furthermore, satellites can be the key component in both the communication infrastructure of developing countries and the multimedia communication and information superhighway of technically more advanced countries [1].

The growing interest in the interconnection of satellite and ATM networks is based on the following additional reasons:

- By using satellite, ATM services can be provided over a wide geographical area, including remote, rural, urban, and inaccessible areas.
- Satellite communication systems have a global reach with very flexible bandwidth-on-demand capabilities. This significant strength of satellite communications ideally matches the main characteristics of ATM networks which provide bandwidth-on-demand and multimedia services.
- Satellites offer flexibility in terms of network configuration and capacity allocation to different sites which use ATM networks in various geographical areas.
- Satellites provide broadcast and multipoint-to-multipoint capabilities as well as fast network setup which can be useful in deploying multipoint-to-multipoint communication of ATM networks.
- Alternative channels can be provided for connections for which the bandwidth demands and traffic characteristics are unpredictable which may result in maximum resource utilization.
- New users can easily be added to the system by simply installing the ATM stations at customer premises. As a result, possible network expansions will be a simple task.
- Satellites can act as a safety valve for optical fiber ATM networks. Fiber failure, or network congestion problems, can be recovered easily by routing traffic through a satellite channel on a demand basis.

However, there are several obstacles which need to be overcome so that satellite ATM networks can operate in full



■ **Figure 1.** *Satellite ATM network architecture.*

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service. The objective of this survey is to present the state of the art in satellite ATM technology and point out some research problems.

In the second section, we explain the satellite ATM network architecture. The remaining sections will cover the requirements and technical barriers for seamless integration of ATM and satellite networks in detail. Specifically, the third section describes the feasibility of the existing ATM cell transport methods; the fourth section deals with conventional and new satellite link access methods, and some error control schemes for the satellite environment. We then describe the problems of the already proposed traffic and congestion control schemes, followed by the error performance of the Transmission Control Protocol (TCP) and Service-Specific Connection-Oriented Protocol (SSCOP) for the satellite ATM network in the sixth section. In the seventh section, we present basic requirements and a possible architecture for local area-metropolitan area network (LAN-MAN) interconnection using satellite ATM and then discuss the requirements for multimedia services in satellite ATM networks in the eighth section. In the ninth section, we give an overview of several satellite ATM projects launched in recent years, and finally we conclude the article by presenting future research directions.

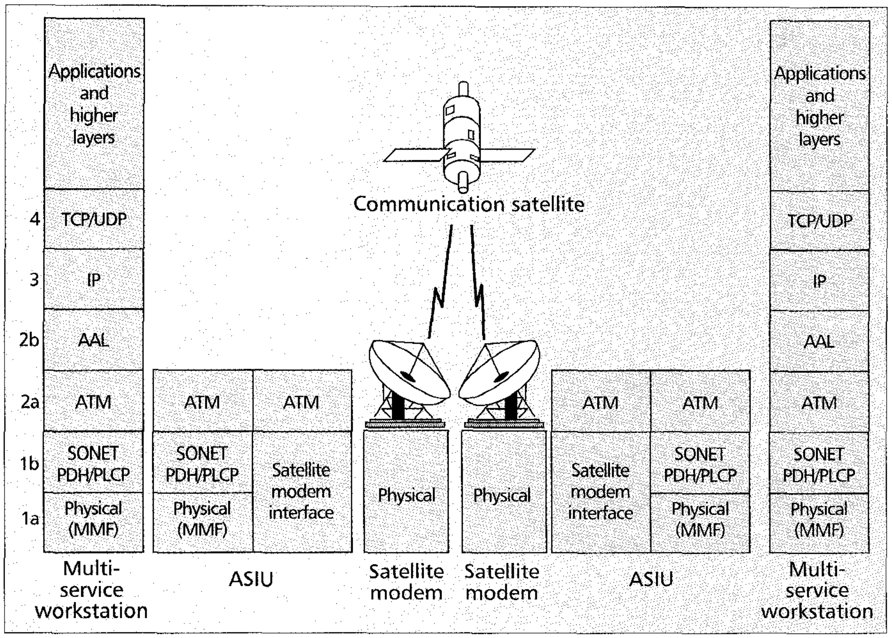


Figure 2. *Protocol stack for the satellite ATM network.*

SATELLITE ATM NETWORK

Figure 1 illustrates a possible architecture of satellite ATM networks, and Figure 2 shows its protocol stack.

As shown in Fig. 1, the ATM satellite interworking unit (ASIU), the key component of the architecture, interconnects ATM and satellite networks. The ASIU is responsible for management and control of system resources, and overall system administrative functions. The key functions of the ASIU include real-time bandwidth allocation, network access control, system timing and synchronization control, call monitoring, error control, and traffic control.

Figures 3 and 4 show the detailed interface between the ASIU and other modules, and the internal architecture of the ASIU, respectively. To accommodate ATM networks seamlessly, the ASIU needs to support the existing ATM cell transport methods such as SONET (synchronous optical network)/SDH (synchronous digital hierarchy), PDH (plesiochronous digital hierarchy), and PLCP (Physical Layer Convergence Protocol), explained later.

As shown in Fig. 4, when SONET/PDH/PLCP frames conveying ATM cells arrive at an ASIU, ATM cells are extracted from the frames. Extracted ATM cell streams are classified according to the traffic classes, and each classified cell stream is placed into a buffer with a certain priority before transmission into the satellite channel.

An effective error correction coding scheme should be employed in the ASIU because satellite networks often introduce multiple bit errors. Furthermore, in order to operate with the existing high-speed ATM networks which use optical fiber as a transmission medium, the bit error ratio (BER) of satellite links should be comparable to the BER of optical fiber links. The coding scheme can be applied over ATM cells after they are extracted from the received frames.

Since the satellite bandwidth is a limited resource and should be shared between earth stations fairly, a flexible and efficient bandwidth management scheme is required in the ASIU. In other words, it is important to assign the bandwidth dynamically and efficiently based on the various user requirements.

The ASIU also needs to support an appropriate satellite link access scheme to send data into satellite channel. Link access schemes should be chosen to provide high efficiency of the satellite bandwidth utilization. The demand-assignment multiple access (DAMA) scheme is preferred because it allows each earth station to request only the bandwidth that will actually be used.

Another important factor which should be considered for overall performance of satellite ATM networks is the quality of satellite links. The willingness of the ATM users to adopt satellite communication will largely depend on providing high-quality, cost-effective satellite links. The elements of satellite link quality which can affect the network performance include link budget process, satellite equipment latency, data rate, modem type, buffer management scheme, coding/modulation, throughput, interface, and satellite type

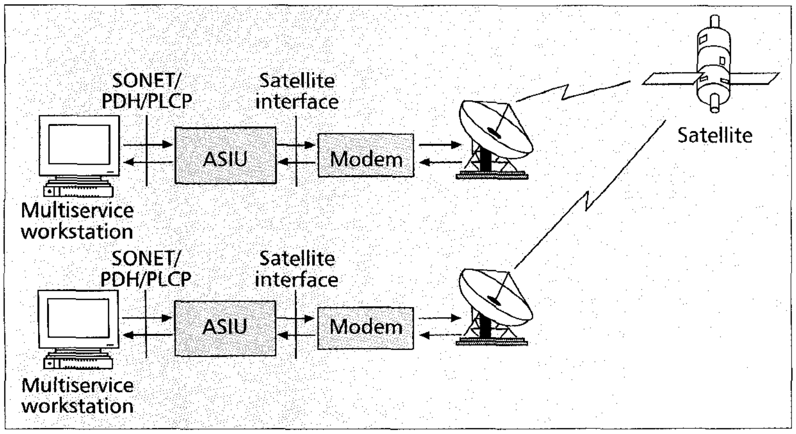
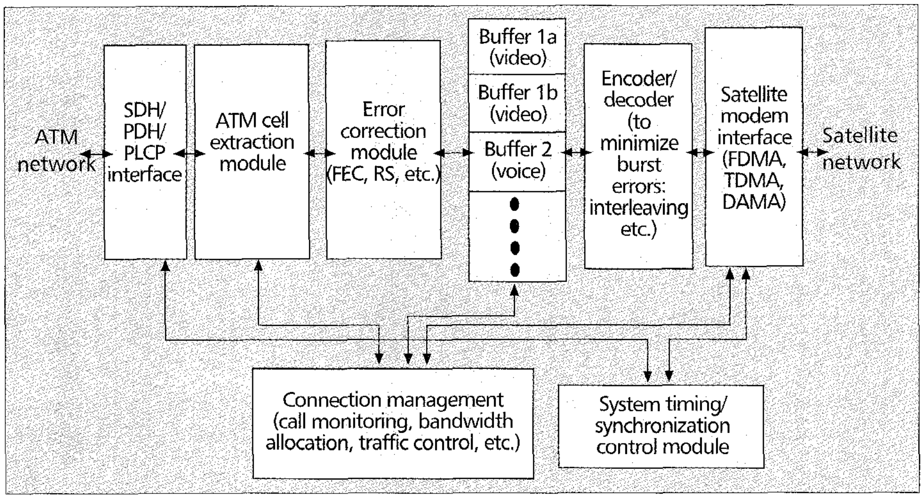


Figure 3. *Interface between the ASIU and other modules.*



■ **Figure 4.** *Internal architecture of ASIU.*

[2]. They should be chosen properly according to user and network requirements.

THE CELL TRANSPORT METHOD

ATM cells can be transported by using the existing digital transmission format over the satellite systems. The national and international standardization committees recommended the transport of ATM cells using plesiochronous digital hierarchy (PDH), synchronous digital hierarchy (SDH), and physical layer convergence protocol (PLCP) [3]. The following two sections describe the feasibility of these methods in further detail.

PLESIOCHRONOUS DIGITAL HIERARCHY AND SYNCHRONOUS DIGITAL HIERARCHY

PDH was developed to carry digitized voice efficiently in major urban areas. Figure 5a shows the PDH multiplexing method. At each step, the multiplexer should take into account that each tributary clock is allowed to have a certain range of speeds.

The multiplexer reads each tributary at the highest allowed clock speed and, when there are no bits in the input buffers, adds a stuffing bit to stuff the signal up to the higher clock speed. It also has a mechanism to signal to the demultiplexer that it has performed stuffing, and the demultiplexer should know which bits to throw out.

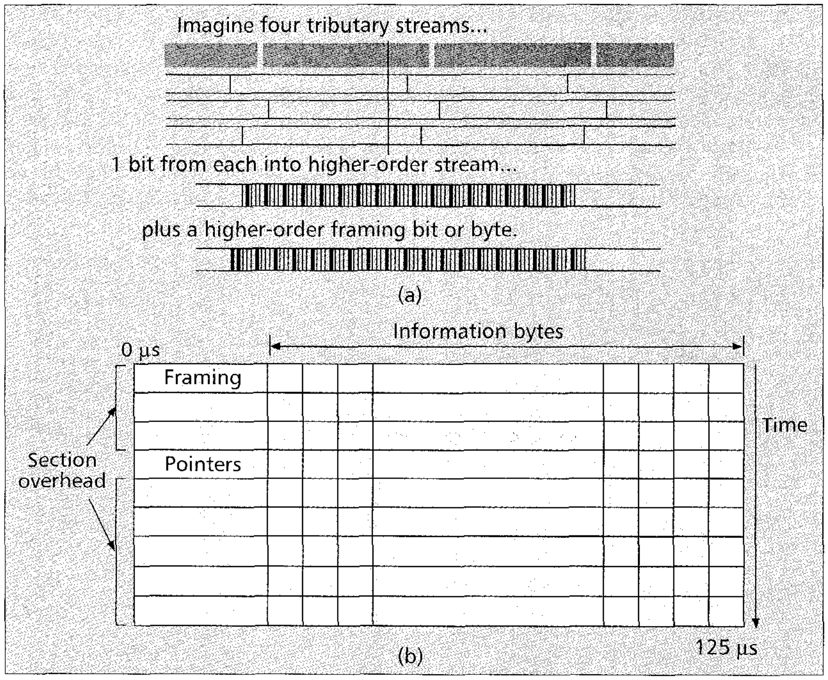
PDH has some inefficiencies. Each time it is necessary to pick out (or insert) a stream (e.g., DS1) from a high-order stream (e.g., DS3), the multiplexer needs to perform the redundant operations ADD to add a stuffing bit and DROP to drop the stuffed bit. In addition, rerouting signals after network failures and managing remote network elements are extremely difficult.

On the other hand, SDH, shown in Fig. 5b, was developed to take advantage of the totally synchronized network. Some intelligence was put in the multiplexers for solving operations and maintenance problems. SDH is preferred because it has the following advantages over PDH:

- Higher rates are well defined, and direct multiplexing is possible without an intermediate multiplexing stage.
- Direct multiplexing is realized by using pointers in the multiplexing overhead which directly identifies the position of the payload.
- The fiber optic transmission signal transfers a very accurate clock rate along the transmission path all the way to the end systems.
- SDH provides easier and lower-cost multiplexing/demultiplexing of various levels and increased provision of network management.

The key feature of SDH transmission is the inclusion of pointer bytes which are used to indicate the location of the first byte in the payload of the SDH frame, and also to avoid slips and their associated data losses due to slight phase or frequency variations between the SDH payload and the frame. ATM cell transmission using SDH further incorporates a cell delineation mechanism for the acquisition and synchronization of ATM cells on the receiver side of the network.

However, there is an important problem with SDH. An incorrect pointer detection may produce an incorrect payload extraction, so the error monitoring function realized by the comparison between signals produces an errored block. As a result, all received blocks may be incorrect and severely errored. In order to avoid this problem, satellite systems with SDH-based interfaces should employ efficient techniques that can spread out errors and an enhanced error performance monitoring function. Using this approach, a reduction of incorrect pointer detection can be ensured and the path integrity due to pointer corruption preserved when burst errors occur.



■ **Figure 5.** *The a) PDH and b) SDH formats.*

PHYSICAL LAYER CONVERGENCE PROTOCOL (PLCP)

Another possible cell transport method is to use PLCP. The PLCP was defined in the IEEE P802.6 specification and ATM Forum User-Network Interface (UNI) Specification [4] to carry ATM cells over existing DS3 44.736 Mb/s communication facilities. Mapping ATM cells into the DS3 is accomplished by inserting the 53-byte ATM cells into the DS3 PLCP. The PLCP frame has a format with a 125 μs interval containing a sequence of 12 ATM cells, as illustrated in Fig. 6.

PLCP payload	Framing	POI	POH	PLCP	
A1	A2	P11	Z6	1st ATM cell	
A1	A2	P10	Z5	2nd ATM cell	
A1	A2	P9	Z4	3rd ATM cell	
A1	A2	P8	Z3	4th ATM cell	
A1	A2	P7	Z2	5th ATM cell	
A1	A2	P6	Z1	6th ATM cell	
A1	A2	P5	X	7th ATM cell	
A1	A2	P4	B1	8th ATM cell	
A1	A2	P3	G1	9th ATM cell	
A1	A2	P2	X	10th ATM cell	
A1	A2	P1	X	11th ATM cell	
A1	A2	P0	CI	12th ATM cell	Trailer
1 byte	1 byte	1 byte	1 byte	53 bytes	13–14 nibbles

A1, A2: PLCP framing bytes
P0–P11: Path overhead identifier (POI)
POH: Path overhead
Z1–Z6: Reserved byte (growth byte)
X: Unassigned byte
B1: PLCP bit-interleaved parity-8 (BIP-8)
G1: PLCP path status byte
C1: Cycle/stuff counter

Figure 6. *PLCP frame format.*

Each cell is preceded by four bytes of PLCP overhead: A1, A2, POI (path overhead indicator), and POH (path overhead). A1 and A2 are the framing octets; they use the same framing pattern used in SONET/SDH. The POI byte is used to identify the associated POH byte. POH bytes (Z1–Z6) are currently user-definable bytes which can be used to identify the interleaver frame interval and for C1 byte protection. Nibble stuffing is required after the 12th cell in each frame to maintain the nominal 125 μs interval. The trailer duration is modulated over a three-frame interval. The C1 byte in the overhead of the 12th frame is used as a cycle/stuff counter. The cycle/stuff counter provides a nibble-stuffing opportunity cycle and length indicator for the PLCP frame. A stuffing opportunity occurs every third frame of a three-frame (375 μs) stuffing cycle. The value of C1 is used as an indication of the phase of the 375-μs stuffing opportunity cycle. It indicates whether 13 or 14 nibbles are included in the trailer of the PLCP frame.

If the PLCP frame overhead is not interleaved prior to transmission, it is susceptible to corruption caused by burst errors. Corruption of C1 byte may result in loss of frame (LOF), an incorrect determination of the number of nibbles in the trailer of the PLCP frame. This, in turn, results in nibble misalignment of the beginning of the next frame interval and ultimate loss of frame synchronization of the PLCP device.

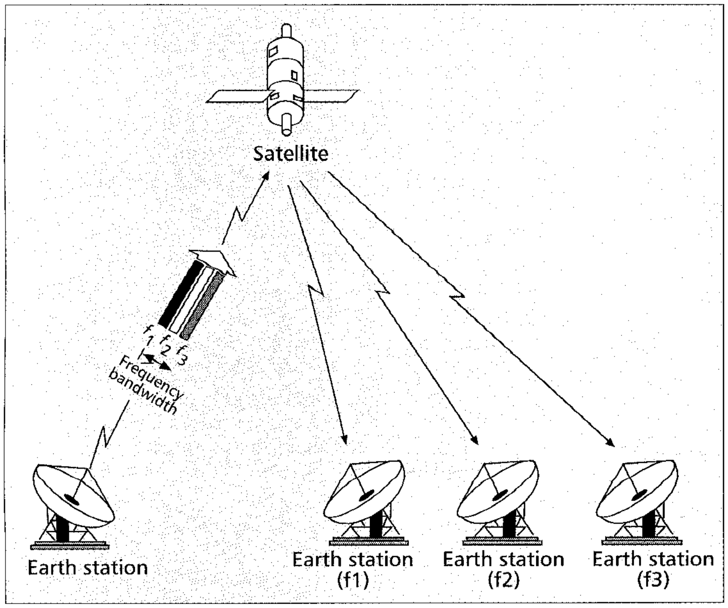


Figure 7. *Frequency-division multiple access.*

From the observations above, it can be concluded that the PLCP is not suitable in the burst error environment because a single burst error may affect the path overhead octets for framing and cycle/stuff counter, which results in causing LOF or OOF (out-of-frame) state. In order to avoid the important problems, an efficient mechanism for preventing the corruption of critical octets or recovering corrupted octets should be employed.

LINK LAYER

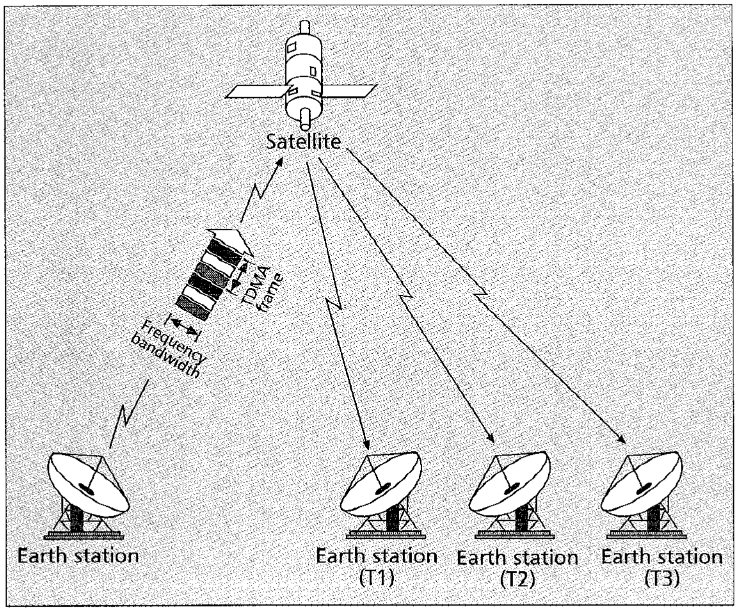
SATELLITE LINK ACCESS METHODS

The access methods [5] used in LANs and MANs depend on short transmission times and are not useful for broadband satellite systems where the propagation delay is around 250–280 ms for GEO (geosynchronous earth orbit) satellites, 110–130 ms for MEO (medium earth orbit) satellites, and 20–25 ms for LEO (low earth orbit) satellites. The traditional contention-based access schemes are not suitable because the limited satellite channel bandwidth should be utilized at maximum capacity, and future offered multimedia traffic will be highly variable [3].

There are basic satellite link access schemes, including frequency-division multiple access (FDMA), time-division multiple access (TDMA), and DAMA. However, these existing schemes are not optimized for ATM technology. In this section, we describe the key features and problems of these basic access schemes and also discuss new efficient access schemes for satellite ATM networks.

Frequency-Division Multiple Access — With FDMA, the total bandwidth is divided into equal-size portions (i.e., the subchannels), and each earth station is assigned one portion, as shown in Fig. 7. Since each earth station has its own private frequency band to use, there is no interference between earth stations and the system operates without error or collision. Another advantage is that smaller antennas can be used with FDMA. However, FDMA requires guard bands to keep the signals well separated, and there is little flexibility.

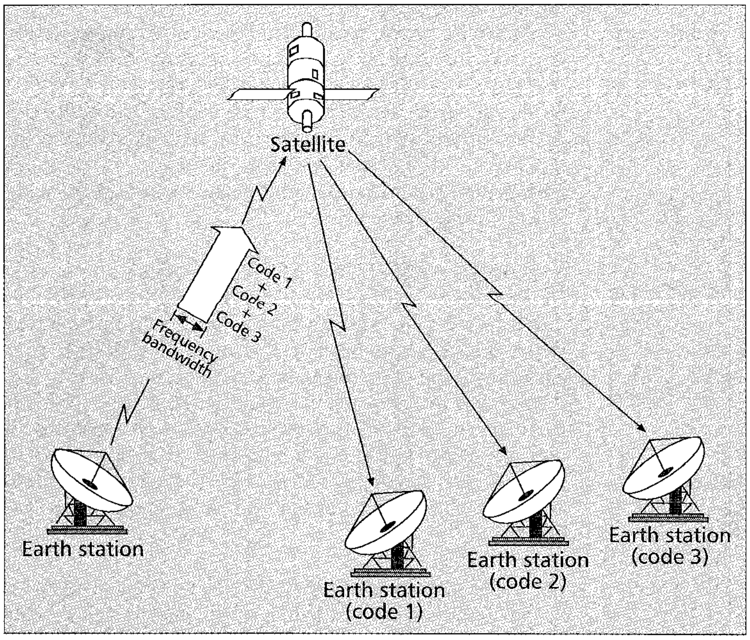
Time-Division Multiple Access — Compared to FDMA, the total bandwidth of TDMA is not divided into subchannels by frequency but by time, as shown in



■ **Figure 8.** *Time-division multiple access.*

Fig. 8. The channel is usually divided into fixed and equal-size time slots. Variable time slots or allocation on demand are also possible. The earth stations take turns in a round robin fashion, and each periodically gets the entire bandwidth for a little burst of time. TDMA is very flexible for packet traffic. However, a problem with TDMA is the antenna size. In addition, it requires careful time slot synchronization in each earth station of the satellite network, and therefore the complexity of earth station equipment may increase.

Code-Division Multiple Access (CDMA) — With CDMA, shown in Fig. 9, the transmissions from each earth station are spread over the time-frequency plane by a code transformation. These techniques are referred to as *spread-spectrum systems*. In addition to their multiple access capabilities, they are useful in combating jamming and are principally used in military satellite systems.



■ **Figure 9.** *Code-division multiple access.*

Multifrequency TDMA (MF-TDMA) — Conventional TDMA uses only one frequency; all earth stations transmit and receive on a single frequency, whatever the destination of the bursts. Therefore, it does not provide power efficiency, and the satellite link speed is limited. To solve this inefficiency, MF-TDMA was proposed. MF-TDMA reduces satellite antenna sizes and transmission power, and increases satellite network bandwidth [6]. Most future satellites will use MF-TDMA. Each earth station may transmit on any one frequency at a given time. If the ATM cell payload capacity on each frequency is B Mb/s and the number of frequencies is N, the overall payload capacity is $N \times B$ Mb/s. Figure 10 shows the MF-TDMA frame format.

Demand-Assignment Multiple Access — DAMA technology allows dynamic allocation and reallocation of satellite power and bandwidth based on the communication needs of network users. For applications where high-speed connectivity is required, but not required all the time, it may be more cost effective to employ DAMA technology rather than a full-time single channel per carrier (SCPC). Therefore, if a network has multiple sites with voice and data service requirements, but not a 24 hour-a-day need for all sites to be in communication with other sites, a smaller amount of satellite power and bandwidth can be shared by all users. This will lower the recurring monthly space-time costs.

DAMA with MF-TDMA or SCPC — In order to achieve a greater efficiency in satellite ATM networks, the DAMA scheme can be employed with other access schemes such as MF-TDMA[7, 8] or SCPC [17, 31]. By exchanging ATM signaling cells, the process of call setup involves the negotiation among the earth station, the satellite, and a master control station (MCS) which controls the satellite network. The signaling cells are transmitted in the synchronization area, which is a fixed portion in the MF-TDMA frame. Once the connection is established, a certain amount of memory and bandwidth onboard is allocated to the new connection.

DAMA with SCPC is given in [8]. With this scheme, dedicated SCPC channels are used for ATM signaling procedure. When a user wants to make a call, a call setup message is generated by the user-side ATM UNI interface. This message is then segmented into ATM cells, and the cells are transmitted to the satellite network via dedicated SCPC channels. After the call setup procedure is complete, ATM user cells are transmitted via the available SCPC channels.

ERROR CONTROL

Problems regarding reliable data transmission via satellite links are very important because they can affect user applications significantly. In this section, we discuss the impact of the burst error characteristics of satellite links and several schemes, including the interleaving mechanism, error recovery algorithm, and efficient coding scheme, for improving error performance.

The Impact of Burst Error Characteristics — Burst error is a well-known problem in the satellite environment due to the variations in satellite link attenuation and the use of convolutional coding to compensate for channel noise.

ATM is well defined for a fiber optic transmission link with random error characteristics rather than error burstiness. Since ATM header error check (HEC) is able to correct only single-bit errors, the burst errors in the ATM header cannot be corrected. Therefore, there might be a significant increase in ATM cell discard probability, which is defined as the ratio of the number of ATM cells that are discarded due to uncorrectable errors to the total number of cells received.

The burst error characteristics can also affect the performance of ATM adaptation layer (AAL) protocols. In general, N-bit cyclic redundancy check (CRC) can detect burst errors as long as the length of burst errors is ″ N. AAL1 and 3/4 employ 3-bit and 10-bit CRC, respectively. If the length of burst error is beyond 10 the error may not be detected, and the undetected error may affect the synchronization mechanism on the receiver side and degrade the quality of user applications severely. On the other hand, AAL5 employs a 32-bit CRC which is more powerful in burst error detection than AAL1 and 3/4. Hence, AAL5 is much less sensitive to burst errors because it is capable of detecting all burst errors with length ″ 32. As a result, the undetected error rate can be decreased significantly. However, the use of only AAL5 cannot be considered the optimal solution for improving error characteristics because there can be still severe cell discard at the physical level. In the following three sections, we discuss possible solutions to the problem: an interleaving mechanism, error recovery algorithms, and efficient coding schemes for error correction.

Interleaving Mechanism — It has been shown that the ATM cell discard probability and the probability of undetected errors can be reduced significantly if interleaving is performed on the ATM cell header and/or payload [3, 9, 10]. Interleaving may be performed for ATM cell header or payload.

The full bit interleaving of ATM cell headers can decrease the probability of an ATM cell header being in error by 2 bits or more because it distributes the bit errors between ATM cell headers. Furthermore, errored cells can have single-bit errors rather than burst errors, which can be corrected easily by ATM HEC code.

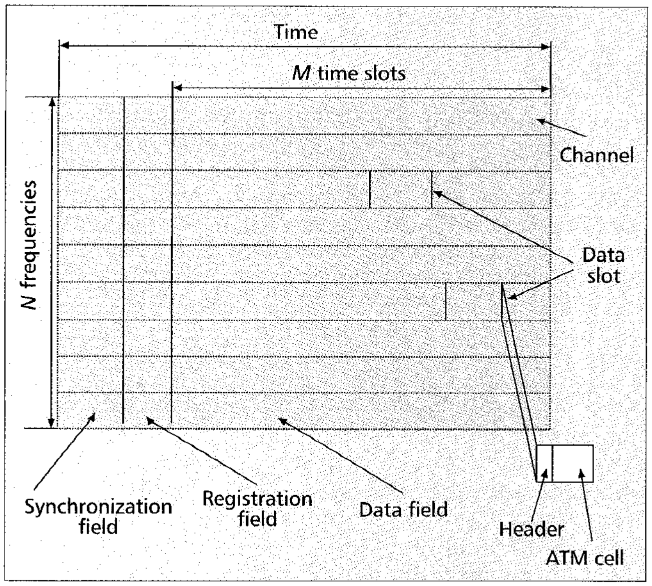


Figure 10. *The MF-TDMA frame format.*

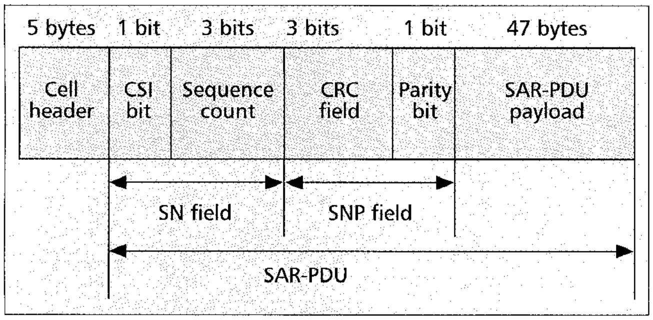


Figure 11. *The SAR-PDU format of AAL1.*

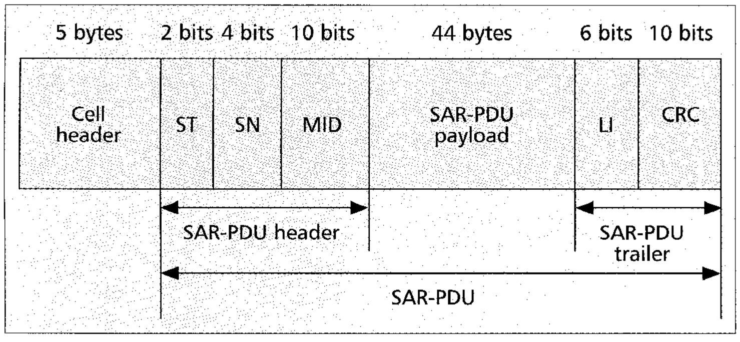


Figure 12. *The SAR-PDU format of AAL3/4.*

The ATM cell payload interleaving scheme can be employed differently according to the properties of AAL types. AAL1 supports the transmission of user traffic with constant bit rate (CBR). Figure 11 illustrates the segmentation and reassembly (SAR)-protocol data unit (PDU) for AAL1. As shown in Fig. 11, the first octet of the SAR header is broken into two major fields: sequence number (SN) and sequence number protection (SNP). The SNP field contains a 3-bit CRC and a parity bit. This field protects the SN field, which includes a 3-bit sequence number and a convergence sublayer indication (CSI) bit. The importance of the first octet in the SAR header is very similar to the ATM cell header; therefore, full bit interleaving of the first octet can protect the ATM cell payload from burst errors effectively.

AAL3/4 supports transmission of user traffic. Figure 12 depicts the SAR PDU for AAL3/4. The SAR-PDU header contains a 2-bit segment type (ST), 4-bit SN, and 10-bit multiplexing identification (MID). The SAR-PDU trailer consists of a 6-bit length indicator (LI) and 10-bit CRC. The 10-bit CRC detects all single bursts of length ″ 10. In this case, it is necessary to protect all bits included in the SAR-PDU header and trailer to guarantee normal AAL operation. Therefore, full byte interleaving for the SAR-PDU is more effective than first byte interleaving in reducing the probability of undetected errors.

As described above, the interleaving mechanism is an efficient way to solve the burst error problem which can cause severe data corruption. After interleaving, however, one or more cells may still contain errors due to error bursts which can corrupt the interleaved cells. One solution to this problem may be the use of an efficient error identifier on the receiver side to detect the occurrence of multiple bit errors; however, in reality it is not easy to identify exactly which bits are in error. Another problem is that the appropriate interleaving depth for optimal error performance still needs to be determined.

Error Recovery Algorithm — At the link layer, the automatic repeat request (ARQ) technique can be useful in reducing the error ratio because it can provide a low error ratio for loss-sensitive, delay-insensitive services. There are three basic versions of ARQ: stop-and-wait, Go-Back-N, and selective-repeat.

In general, the stop-and-wait ARQ scheme is used to support acknowledged connectionless service, and the Go-Back-N ARQ scheme is used to support connection-oriented service. The stop-and-wait ARQ scheme has the advantage of being simple, but is not effective in the satellite environment where the propagation delay is relatively long and the sender will wait for an acknowledgment for each transmission.

The Go-Back-N ARQ scheme is more efficient than the stop-and-wait ARQ scheme because there is no need to wait for an acknowledgment from the receiver after sending an ATM cell, which results in enhanced throughput performance. The next ATM cell can be sent immediately after sending one. However, whenever there is a negative acknowledgment (NAK) from the receiver, which means cell loss or errored cell, the sender should send N previous cells instead of sending new cells. This may cause significant transmission delay and therefore degrade throughput performance; thus, this scheme is also ineffective in the satellite ATM environment.

Better throughput and error performance can be achieved by using selective-repeat ARQ because the sender retransmits only those cells for which an NAK is received. This advantage, resulting from fewer retransmissions, seems to be useful for the satellite environment. However, there are still several problems to be solved in selective-repeat ARQ: this scheme increases complexity at the sender and receiver. In addition, cells may be received out of order. Due to these reasons, the Go-Back-N ARQ scheme is often preferred in existing networks.

Coding Scheme for Improving Error Performance — In order to enhance the satellite link reliability, efficient error correction coding scheme can be employed which may compensate for the weakness of the ARQ scheme. Currently, many satellite modems employ mainly convolutional code with Viterbi decoding to achieve a typical BER ranging from 10^{-3} to 10^{-5} [8]. However, this is regarded unreliable for satellite ATM networks which should support loss-sensitive ATM traffic. To improve the error performance of satellite links, an efficient coding scheme called *concatenated coding* was investigated in [10]. The key feature of concatenated coding is that an outer code is added before the convolutional encoder, which means that the convolutional inner code is concatenated with the outer code before transmission. By using these combined codes, satellite links would show very long intervals between errors.

The success of the concatenated coding depends on the choice of the outer code. The following items present guidelines to choose the appropriate outer code:

- The coding delay should be maintained low (especially for delay-sensitive applications); that is, the block size of the outer code should be as small as possible.
- The outer code should work well with the chosen inner code. In order to obtain optimum performance of the combined codes, the error distribution caused by the inner code should be taken into account.
- The code rate should be as high as possible to maximize the use of the satellite capacity while still providing the required performance.

Forward error correction (FEC) code is usually employed as a convolutional inner code over satellite links. In concatenation with this FEC inner code, Reed Solomon (RS) code has been identified as performing particularly well because it is capable of correcting burst errors [11]. It is also known that RS code can be added to the transmission modem without requiring any additional power on the transmission link [12], which can provide a cost-effective solution.

Since the RS code is based on symbols, symbol interleaving and deinterleaving with long depth is typically required to distribute bursts of symbol errors as if they were spread in a random manner. As a matter of fact, this helps the RS decoder on the receiver side to handle errors more efficiently; therefore, the outer code performance can be improved. In this case, however, the optimal interleaving depth for satellite ATM networks should still be determined to maximize error performance.

TRAFFIC MANAGEMENT

Generic traffic management functions can be classified as either traffic control or congestion control functions. A clear distinction whether a traffic management mechanism is traffic control or congestion control is difficult. Traffic control functions are network functions that take actions to avoid congestion conditions. Congestion is defined as the state of the network elements in which the network is not able to meet the negotiated performance objectives for already established connections and/or new connections. Congestion control functions are network functions that take actions to minimize the intensity spread and duration of congestion [13]. Congestion control actions are triggered by the onset of congestion in one or more network elements.

A range of traffic and congestion control functions are necessary to maintain the quality of service (QoS) of ATM connections over satellite. For satellite ATM networks, more elaborate traffic and congestion control procedures are required since satellite links are bandwidth-limited compared to optical fiber links. Furthermore, due to long propagation delay which is the nature of satellite communications, the control functions should be performed faster and more efficiently. In the following sections, we will describe the performance aspects in terms of performance parameters and the impact of transmission delay characteristics in the satellite ATM environment, and then discuss the feasibility of the existing traffic and congestion control schemes, and satellite bandwidth management issues.

PERFORMANCE ASPECTS

Basically, the validity of seamless integration between ATM and satellite networks should be evaluated on the basis of QoS. The QoS expected by end users in terrestrial ATM networks should not be affected or degraded, due to either delay or specific bit error distribution, when the user's end-to-end connection includes a satellite link. The traffic and congestion control functions should be able to satisfy the QoS requirements sufficient for all foreseeable satellite ATM services. The QoS can be measured by a set of parameters intended to characterize the performance of satellite ATM networks. These QoS parameters quantify the end-to-end performance at the ATM layer.

The basic QoS parameters that correspond to a network performance objective in satellite ATM networks may include cell loss ratio (CLR), maximum and mean cell transfer delay (CTD), and cell delay variation (CDV). Due to the impact of error bursts caused by the nature of satellite networks, CLR is one of the most stringent criteria for determining the performance of satellite ATM networks [2, 12]. Another critical QoS parameter is the CTD, which marks the difference between ATM and satellite links, including satellite hops and ATM nodes. A long CTD can affect real-time applications because they are more sensitive to long delay than pure data applications. CDV also cannot be neglected since it may degrade the quality of applications which require synchronization between different connections.

The cell error ratio (CER), severely errored cell block ratio (SECBR), and cell misinsertion ratio (CMR) are recommended to be taken into account to measure the actual performance of satellite ATM networks because the satellite link is subject to multiple bit errors and undetected errors. The CER is defined for ATM connection as the ratio of errored cells to the sum of successfully transferred cells and errored cells, and the SECBR is defined as the ratio of severely errored cell blocks to total transmitted cell blocks. For practical purposes, a cell block will normally correspond to the number of user information cells transmitted between successive operation and management (OAM) cells [13]. Finally, CMR, which is defined as the ratio of misinserted cells to time interval, needs to be considered because cell misinsertion is often caused by an undetected cell header error.

THE IMPACT OF TRANSMISSION DELAY CHARACTERISTICS

There is no doubt that most of the capabilities of ATM technology will be used to provide future application services. However, in satellite ATM networks, the long delay caused by satellite communications has a significant impact on delay-sensitive services such as request and response services, real-time voice and video services, and high-speed data services [1, 3]. The impact of satellite delay characteristics on a few basic services are briefly summarized as follows.

Video and Voice Service — Real time services such as video and voice service are very sensitive to the long delay and the waiting time for acknowledgment in the communication protocols. They sometimes generate long burst traffic. As long as the delay variation is restricted to a very small value or the signal timing can be recovered at the destination exactly, the satellite can provide a connection of high quality.

Text or Data Service — As a matter of fact, text or data service is not very sensitive to satellite delay but often requires reliable transport protocols instead. However, the throughput can be restricted by long delays.

Video Telephony — The coding and decoding time of the coding technique of video telephony specified in International Telecommunications Union — Telecommunications Standardization Sector (ITU-T) Recommendation H.261 [14] is greater than the satellite delay, so the impact of the satellite delay may not be so significant. However, future video telephony will demand more stringent delay requirements.

CSCW Applications — When computer-supported cooperative work (CSCW) applications run on a workstation over TCP/IP, the delay introduced by the satellite may be acceptable from the application's point of view. However, the poor performance of the TCP/IP protocol in a high-delay environment increases application setup time and therefore degrades the entire performance.

In order to minimize the transmission delay effect and support real-time applications efficiently, the adjustment of existing protocols or development of new ones is required [15]. For example, the value of a time-out parameter or window size of protocols which require acknowledgments of cell arrival might be increased to accommodate the long propagation delay. In particular, to support a certain QoS of the above services, new robust feedback mechanisms should be employed because large propagation delays of ATM cells can significantly increase the latency of feedback mechanisms of congestion control.

TRAFFIC CONTROL

Especially in the satellite ATM environment, congestion can be regarded as a critical problem because the data rate of a satellite link is very low compared to a fiber link of ATM networks. Traffic control functions which manage and control traffic to avoid congestion in ATM networks have been specified by ITU-T [16] and the ATM Forum [13]. These functions should also be considered in satellite ATM networks to support terrestrial ATM users without performance degradation. In this section, we briefly discuss the feasibility of traffic control procedures proposed for terrestrial ATM networks.

Traffic shaping is a mechanism that changes the traffic characteristics of a cell stream to achieve a desired modification of those traffic characteristics. Traffic shaping should maintain cell sequence integrity on an ATM connection. Basic examples of traffic shaping are peak cell rate reduction, burst length limiting, and reduction of CDV by suitably positioning cells in time and queue service schemes. This scheme is, however, limited to procedures that maintain the established QoS of the connection. Furthermore, when the network is congested, the traffic parameters cannot be changed dynamically.

In priority control and selective cell discard mechanism, the cell loss priority (CLP) bit is used as a means of traffic control to discard the ATM cells with lower priority in order to prevent congestion. However, this mechanism is not efficient in ensuring data delivery, which often requires retransmission of the lost data. In fact, dependence on the priority can magnify the congestion problem in the satellite ATM network since losses due to the congestion may cause retransmissions frequently and degrade throughput performance.

For networks that experience occasional congestion, connection admission control (CAC) can be an effective traffic control scheme. CAC is defined as the set of actions taken by a network to establish whether an ATM connection can be accepted or rejected in order to avoid congestion. In a satellite ATM environment, this scheme seems to be useful only at the call setup phase because the renegotiation procedure operates on the time scale of the long round-trip propagation delay even if a fast resource management scheme is used.

In summary, the currently defined preventive traffic control schemes such as traffic shaping, CAC, and the use of deliberate cell dropping are useful in the terrestrial ATM network, but need to be modified somehow to be acceptable in satellite ATM networks. Traffic control procedures should be designed to avoid congestion more quickly so that the requested QoS can be satisfied in the satellite environment.

CONGESTION CONTROL

In this section, various congestion control schemes are briefly described; then we examine the feasibility of these schemes for satellite ATM networks.

A frequently discussed congestion control scheme is selective cell discard, which allows a congested network element to selectively discard cells that belong to a noncompliant ATM connection and those with CLP set to 1. This operation protects cells that have CLP = 0. Although this method can be rather efficient from a control standpoint, dropping data on an ensured connection will lead to retransmission, which will delay the delivery of a substantial number of cells in the satellite ATM network. Furthermore, it is difficult to guarantee a relatively good QoS for CLP = 1 flows if a substantial probability of discard exists.

Another popular congestion control scheme is the use of EFCI (explicit forward congestion indication) incorporated with a feedback mechanism. The main objective of the feedback is to provide the traffic sources causing congestion with information about the congestion event so that the sources can take appropriate action to temporarily reduce the current traffic load. EFCI is used to convey congestion notification to the source. A network element in an impending congested or congested state may set an EFCI in the cell header of particular virtual paths or virtual channels contributing to or causing the congestion so that this indication may be examined by the destination end system. At the destination end system, this indication is sent to the higher protocol layer, which is instructed to notify its peer protocol entity to reduce its traffic load. This entire mechanism is called forward explicit congestion notification (FECN). FECN seems to be inappropriate for effective congestion control in satellite ATM environment because at least a one-way propagation delay is required to notify the source.

For solving the inefficiency of FECN, a faster mechanism, backward explicit congestion notification (BECN), was proposed in [17]. With this mechanism, a congested network element can send a notification in the reverse direction of the congested path. The effectiveness of BECN could be significantly better than FECN if satellite links are involved and sources can respond quickly to congestion notification. However, network configurations should be taken into account for more reliable congestion control because the congestion may occur on the destination side of a satellite link or other trunk with long propagation delay.

Buffering and VC prioritization were also proposed to control congestion [18]. Buffering can make the congestion problem less severe at the expense of delay for buffered traffic. While delay-sensitive data is being served, delay-insensitive and loss-sensitive data can be placed into buffers of an ATM satellite interworking unit. The buffers for delay-sensitive traffic should be distinguished from those of delay-insensitive traffic in order to be served differently. The delay and jitter of delay-sensitive traffic should be maintained as requested by the user.

VC prioritization can be used for mitigating congestion. The satellite links supporting different VC connections have different VC priority levels assigned. The higher priority levels are assigned for traffic that is time-sensitive compared to other traffic. Using this approach, real-time applications can be supported in the congested network. This scheme can also be incorporated with buffering.

Besides the congestion control mechanisms described above, many mechanisms were proposed and analyzed [17]. These congestion control functions, however, need to be modified for a satellite ATM environment so that they can operate on a very short time interval in order to be successful in that environment. The control algorithms should not interfere with delay-sensitive traffic because satellite ATM networks require a higher degree of network efficiency to provide a certain QoS and minimal cell loss.

SATELLITE BANDWIDTH MANAGEMENT

The limited satellite bandwidth can impose a restriction on applications that require high bandwidth. Thus, efficient bandwidth management in the satellite ATM network is a very important issue. The network control center which controls the entire satellite network should be able to allocate bandwidth capacity to each connection according to traffic characteristics and user requirements.

Satellite bandwidth allocation can be performed during the connection setup phase using a burst time plan (BTP) in a typical TDMA network [18]. A BTP is a map that indicates the position and lengths of bursts in the transmission frame. Since bursts and subbursts in BTP carry traffic such as video, voice, and data, the BTP can be considered as a simple traffic assignment format within a frame. Within each BTP, burst times are specified for each earth station, which restricts the number of ATM cells in bursts or subbursts to be transmitted by each earth station. A BTP is limited to a certain number of cells.

In [16], the virtual path (VP) is considered a key element for resource management in ATM networks. The allocation of satellite bandwidth can be performed in terms of VPs because the number of VPs are restricted by BTPs. That is, reservation of ATM bandwidth capacity on VPs can be mapped into reservation of satellite bandwidth capacity on bursts or subbursts in BTP. The virtual channel (VC) can also be managed according to the status of the VP because it is subject to the bandwidth available to the VP.

However, it is not easy to use a satellite channel efficiently and control the maximum cell delay when providing high-speed data communication services using a satellite ATM network that employs the TDMA scheme, because the bandwidth of each channel in TDMA is fixed and high-speed data communication traffic is very bursty and unpredictable. If the satellite bandwidth is assigned constant based on the average transmission bit rate of the input traffic, the satellite channel efficiency is acceptable but the maximum cell delay increases. On the other hand, if the satellite bandwidth is assigned constant based on the maximum transmission bit rate of the input traffic, the maximum cell delay decreases but the satellite channel efficiency decreases significantly.

TCP AND SSCOP

TCP: LESSONS LEARNED

TCP is a widely used transport protocol in terrestrial networks. In the satellite ATM environment, however, the efficiency of the error control mechanism of TCP should be carefully examined in order not to degrade user services.

TCP is basically responsible for error control to provide an error-free flow of packets from source to destination. To achieve this purpose, TCP employs a retransmission strategy. Retransmission occurs when a packet is damaged in transit but nevertheless arrives at its destination. In this case, a large number of packets are retransmitted even if only a single packet is damaged due to error.

If a packet does not arrive successfully, a timeout-based approach is used to recover the lost packet. A timer is associated with each packet as it is sent. This approach is inefficient because it allows a large retransmission period to prevent flooding the network with useless retransmissions.

Another factor that makes TCP inadequate is the window size. The window size is the number of outstanding data units allowed for a connection. It is limited by the numbering space allotted to the sequence number of a data unit. The default TCP window size value is only 16 kB, which can severely restrict the throughput efficiency over a satellite link [3].

The disadvantages of the TCP protocol described above makes it unacceptable in satellite ATM networks. It may be desirable to tune the timeout and window size parameters of TCP to the satellite link or employ other efficient protocols.

AN EFFICIENT PROTOCOL FOR ERROR RECOVERY: SSCOP

SSCOP was defined by ITU-T Recommendation Q.2110 [19] (previously Q.SAAL.1) for reliable end-to-end delivery of data in the ATM environment and designed to compensate for long propagation delay, which is the case in satellite ATM networks.

The key features of SSCOP are a 24-bit sequence space and selective retransmission protocol. The large sequence space allows the window size to be set to a size much larger than needed for a satellite network, which results in improved throughput performance.

SSCOP provides an ensured delivery service to its user by using a selective retransmission mechanism which prevents unnecessary retransmission and therefore provides quick recovery of lost data. If missing data is detected at the receiver, the transmitter is requested to retransmit the lost data. The transmitter periodically polls the receiver as a keep alive action and only resends the missing data. This selective reject type of retransmission protocol significantly reduces unproductive retransmissions for a very high-speed, high-delay environment. Thus, it is expected that SSCOP will provide acceptable performance in the satellite ATM network.

LAN/MAN INTERCONNECTION USING SATELLITE ATM

THE BASICS

There has been rapid growth in the use of LANs and MANs for interconnecting computers within industry, academia, companies, and research institutes. Consequently, there has been an increasing need for the interconnection of remotely located LANs and MANs.

The wide-area networking to interconnect remote LANs/MANs is very inefficient because of the lack of global area coverage. Although wide area networks (WANs) are being modernized by wireline facilities in certain regions, satellite can prove to be a much more affordable solution for interconnecting widely dispersed areas.

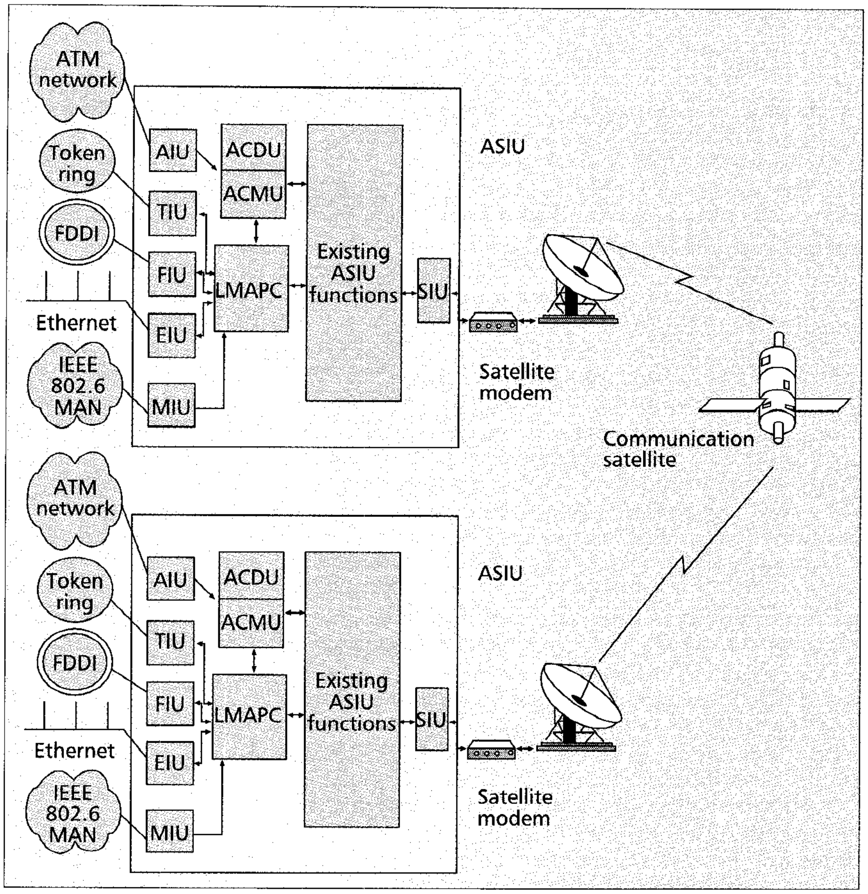


Figure 13. *LAN/MAN interconnection architecture.*

Satellite ATM networks can serve as an effective operational network interconnecting LANs/MANs by using the benefits of both ATM and satellite technology [20]. This kind of integration can offer very rapid deployment and flexibility in the amount of bandwidth allocated to the interconnection service. However, there are some constraints on LAN/MAN interconnection. The following items are basic issues which should be considered when designing the LAN/MAN interconnection architecture [1, 15, 20]:

- The significant performance parameters for LAN/MAN applications include delay and delay jitter of the LAN/MAN packets. The long transmission delays inherent in satellite communication systems can affect the throughput of LAN/MAN protocols. The delay jitter can especially affect voice/multimedia traffic of LAN/MAN users. Thus, new mechanisms to optimize delay jitter performance and delay characteristics are required.
- One of the most important functions to be performed for LAN/MAN interconnection using satellite ATM is frame translation. All the LANs/MANs being considered employ completely different data frame structures, each of which in turn is incompatible with ATM cells. Consequently, an efficient conversion protocol without severe processing delay is required to achieve the mapping between these frame structures and the ATM cell format.
- Particular restrictions regarding frame buffering at the ASIU and end-to-end transmission delay should be minimized by solving the problems of satellite link access, management of satellite frames, and bandwidth limitations.
- The ASIU is required to interconnect heterogeneous networks as well as homogeneous networks for providing various services to LAN/MAN users.
- The ASIU should be able to support existing protocols based on the existing network architectures. In fact, since the ASIU can make conversions between LAN/MAN packets and ATM cells, almost all services and applications implemented on the existing LAN/MAN architecture can be supported transparently. In addition, the ASIU should also be able to support new protocols based on the newly developed ATM architectures.

In the following section, a possible architecture for LAN/MAN interconnection using satellite ATM is presented.

ARCHITECTURE

LAN/MAN interconnection can be achieved by using satellite ATM with the capability of bridging/routing in the ASIU. Figure 13 depicts a possible interconnection architecture, and Fig. 14 shows its protocol stack. Here, we focus our discussion on the architecture of ASIU for interconnecting LANs/MANs.

An ASIU can be used as an interconnection unit for LANs/MANs as well as ATM networks by adding necessary functions and modules for the interconnection. In this case, it has two interfaces from the interconnection perspective: LAN/MAN interface and satellite link interface. In order to support conventional LAN/MAN services, the ASIU should be able to interface the existing terrestrial LAN/MAN, such as Ethernet, token ring, fiber distributed data interface (FDDI), and IEEE 802.6 MAN. The ASIU also needs to interface the satellite link with a specific link access method.

The ASIU knows the network configuration of LAN/MAN and satellite, and manages the received frames in order to transmit to the final destination. Frames with an unknown address for the local LAN/MAN are automatically forwarded to the remote LAN/MAN over satellite; on the other hand, the frames with a known address for the local LAN/MAN are not forwarded to the satellite channel. This simple filtering function can provide a basis for efficient use of the satellite link. As shown in Fig. 13, the ASIU with the capability of LAN/MAN interconnection consists of an ATM interface unit (AIU), Ethernet interface unit (EIU), token ring interface unit (TIU), FDDI interface unit (FIU), IEEE 802.6 MAN interface unit (MIU), LAN/MAN-to-ATM protocol converter (LMAPC), ATM cell multiplexer unit (ACMU), ATM cell demultiplexer unit (ACDU), and satellite interface unit (SIU).

The EIU, TIU, FIU, and MIU can be implemented in a similar manner as the existing LAN/MAN bridges. They filter the traffic in the local LAN/MAN and forward only traffic that is destined to nonlocal addresses (i.e., a remote address on another site). The filtering can be achieved by maintaining a bridging table in the ASIU which has information about local addresses. The destination addresses of incoming traffic are compared to the addresses contained in the table.

After LAN/MAN frames are forwarded to the LMAPC by the EIU, FIU, TIU, and MIU, the address of the LAN/MAN traffic should be converted to an ATM address. Namely, the media access control (MAC) address should be converted to the corresponding ATM VP/VC identifier (VPI/VCI). The address conversion information should be maintained in the address mapping table of the ASIU. If there is no corresponding VPI/VCI in the table, the LAN/MAN packet is transmitted using a newly defined VPI broadcast path to all other networks.

The main role of the LMAPC is to convert LAN/MAN frames into ATM cells, then transfer the converted ATM cells to the ACMU. The fragmentation and reassembly processes should be carried out at the speed of the satellite link while controlling the memory buffers.

ACMU multiplexes the ATM cell streams from the LAN/MAN into one ATM cell stream. It transfers the multiplexed cells to a satellite interface unit (SIU). This SIU provides a satellite link interface. Usually, there is a speed mismatch between the low satellite link speed and the high aggregate speed from the LANs/MANs; therefore, an efficient multiplexing scheme is needed in order to avoid cell clumping due to CDV which may be caused by the multiplexer operation. A novel flow control scheme is also required to prevent severe cell losses due to the limited buffer capacity in the ASIU.

REQUIREMENTS FOR MULTIMEDIA SERVICES

With the recent progress in digital data compression technology, large-bandwidth video data can now be reduced to a few megabits per second and transmitted in combination with different signals to form multimedia data. In the telecommunications field, there is increasing demand to support a variety of multimedia services that can provide access to such multimedia data.

In the near future, a satellite ATM network is expected to be used to offer these multimedia services promptly and inexpensively over wide areas because satellite networks are superior to terrestrial networks in coverage of users and will gain increasing importance in the multimedia era by having access to information sources dispersed over the country and will broadcast information to users. Therefore, satellite communication systems will be one of the first telecommunication infrastructures to allow future multimedia services to a large population. In this section, basic requirements are described for multimedia services that should be supported by satellite ATM networks [1–3].

First, *multimedia services* should be provided promptly and in a cost-effective manner, especially for users separated by long distances, including rural areas and remote islands.

Second, the satellite ATM network architecture should be designed to provide universal access to interactive multimedia broadband capabilities. It should provide a wide range of multimedia services, including health care, education, and so on. To support this purpose, multirate digital data should be provided by multiplexing and distribution by satellites.

Third, video transmission imposes different and, in many ways, stricter requirements for a satellite ATM network. These requirements include video timing recovery, minimization of the effect of delay jitter, video data prioritization to cope with cell loss and cell delay, and error-resilient techniques that have not been carefully studied for the specific satellite environment. Retransmission is not appropriate for real-time video transmission; therefore, harsher constraints may arise. To ensure that satellites can provide transparent ATM service for video traffic, these problems are being studied by the ATM Forum and ITU.

Finally, even if satellites have a number of advantages over terrestrial systems, such as multiple access capability, wide coverage of service area, multiple distribution capability, and *rapid/flexible network rearrangement*, satellite transmission capacity is smaller than terrestrial. Thus, in order to satisfy users' various high-bandwidth requirements and provide fair sharing of the limited capacity among many users, an efficient dynamic satellite channel assignment scheme and a high-performance satellite transponder are required.

SATELLITE ATM PROJECTS

In this section we discuss general issues about satellites such as the types of satellites and frequency bands, and then summarize satellite ATM projects launched in recent years.

TYPES OF SATELLITES

Satellites are usually classified according to the type of orbit they are in. Here we describe three basic types of satellites.

Low Earth Orbit Satellites — LEO satellites are normally military reconnaissance satellites that can pick out tanks or armored cars from 500 to 1000 mi above the Earth. The typical propagation delay of LEO satellites is 20–25 ms due to the relatively short distance. Proposed LEO satellites are divided into three categories: little LEOs, big LEOs, and mega-LEOs. Little LEOs will operate in the 800 MHz range, big LEOs will operate in the 2 GHz or above range, and mega-LEOs will operate in the 20–30 GHz range. The higher frequencies associated with mega-LEOs translate into more information-carrying capacity and the capability of real-time low-delay video transmission. LEOs are more complex to operate than geosynchronous satellites.

Medium Earth Orbit Satellites — Over the last few years, technological innovations in space communications have given rise to new orbits and totally new systems designs. MEO satellite networks have been proposed that will orbit at distances of about 8000 mi. Signals transmitted from a MEO satellite travel a shorter distance, which translates to improved signal strength at the receiving end. This means that smaller, lighter-weight receiving terminals can be used. Also, since the signal travels a shorter distance to and from the satellite, there is less transmission delay (i.e., the time it takes for a signal to travel up to a satellite and back down to a receiving station). For real-time communications, the shorter the transmission delay, the better the performance. For example, a GEO satellite requires 0.25 s for a round-trip; a MEO satellite requires less than 0.15 s to complete the job. MEOs operate in the 2 GHz and above frequency range. The typical propagation delay of MEO satellites is 110–130 ms.

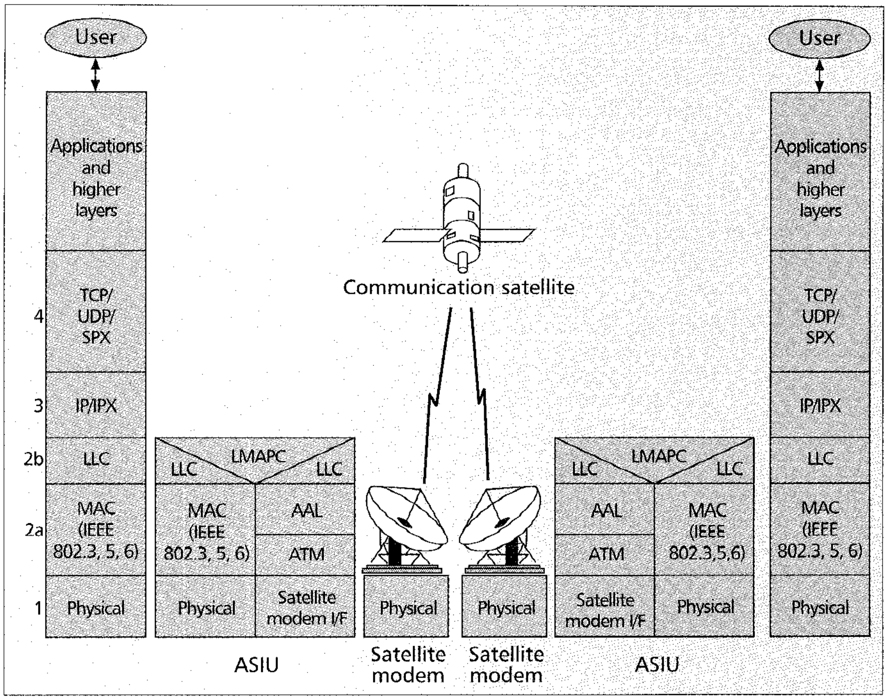


Figure 14. *Protocol stack for LAN/MAN interconnection.*

Geosynchronous Earth Orbit Satellites — Earth-synchronous or geosynchronous satellites are placed into orbit so that their period of rotation exactly matches the Earth's rotation. Today, the overwhelming majority of satellites in orbit around the Earth are positioned at a point 22,238 mi above the Earth's equator in GEO. It is at the precise distance of 22,238 mi that a satellite can maintain an orbit with a period of rotation around the earth exactly equal to 24 hr.

Since the satellites revolve at the same rotational speed of the earth, they appear stationary from the surface of the Earth. That is why most earth station antennas do not need to move once they have been properly aimed at a target satellite in the sky.

The plane of orbit for these satellites is generally not the equatorial plane. The satellites are used for communications at high latitudes, particularly in Russia and Canada. The orbits are called *Molniya* orbits.

GEO satellites experience long delays compared to LEO and MEO satellites. The typical propagation delay of GEO satellites is 250–280 ms. GEO satellites are easy to deploy but will need some time before they can offer global services.

THE FREQUENCY BANDS

The three most commonly used satellite frequency bands are the Ku band, Ka band, and C band. The Ku and C bands are the two most common frequency spectra used by today's satellites. To help understand the relationship between antenna diameter and transmission frequency, it is important to note that there is an inverse relationship between frequency and wavelength: when frequency increases, wavelength decreases. As wavelength increases, larger antennas are necessary to gather the signal.

Ku-band satellite transmissions occupy the 11–17 GHz frequency range. These relatively high-frequency transmissions correspond to shorter wavelengths; therefore, a smaller antenna can be used to receive the minimum signal strength. Ku-band antennas can be as small as 18 inches in diameter. The Ku band is currently being used for DirecTV.

Ka-band satellite transmissions occupy the 20–30 GHz frequency range. These very high-frequency transmissions mean very small wavelengths and very-small-diameter receiving antennas. The Ka band has more capacity than Ku, but is also more rain-attenuated.

C-band satellite transmissions occupy the 4–8 GHz frequency range. These relatively low frequencies translate to larger wavelengths than the Ku or Ka bands. The larger wavelengths of the C band mean that a larger satellite antenna is required to gather the minimum signal strength; therefore, the minimum size of an average C-band antenna is approximately 2–3 m in diameter.

SATELLITE ATM PROJECTS

In order to demonstrate the feasibility of ATM networks based on satellite links, several satellite ATM projects have been launched in recent years. Table 1 summarizes some projects.[1]

CONCLUSIONS AND RESEARCH DIRECTIONS

In this article, we first presented a possible satellite ATM network architecture and then discussed issues and challenges which need to be solved so that satellite ATM networks can operate full-service.

A satellite ATM network can play an important role in the rapidly evolving information infrastructure and also in future integrated broadband communication networks by using the benefits of satellite and ATM technology. However, there are still many open research issues that need to be addressed, discussed below, in order to achieve seamless integration of ATM and satellite networks.

In the laboratory (Network Applications Integration Lab, NAIL) at Georgia Tech, we have the following equipment: a Hewlett Packard broadband analyzer with dual network impairment modules, two OC-3 modules, and two DS-3 modules. A research network is already in place for simulating satellite links via a DS-3 microwave link from NAIL on the Georgia Tech campus to NAIL equipment at Clark Atlanta University (approximately 2.5 mi away). The network impairment modules will be used to provide the LEO, MEO, and GEO channel delays as well as noise characteristics. Also in place in the laboratory are numerous ATM switches and workstations for generating end-to-end network operations.

The following research challenges in satellite ATM networks are currently being investigated by our research group.

The existing ATM cell transport methods, such as SONET/SDH, PDH, and PLCP, can be employed in a satellite ATM environment. However, efficient techniques are needed to spread out errors, protect important overhead bytes, minimize the number of incorrect pointer detections, and preserve path integrity even when pointer corruption occurs due to burst errors.

Since satellite channel capacity is expensive and bandwidth-limited, we need an efficient satellite link access scheme. In other words, new multiple access schemes are necessary in order to improve transmission power efficiency, reduce satellite antenna sizes, and use satellite network bandwidth efficiently.

Once a cell from a connection has been chosen to be assigned to a certain mutiple access scheme like MF-TDMA,

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[1] *There are several other satellite ATM projects worldwide. We randomly selected some of the projects and describe them in Table 1.*

Project name	Development team	Transponder	Access method	Speed	Terrestrial network interface
ICAROS [21]	Telefonica, Swiss PTT, Telia Research AB, EUTELSAT	EUTELSAT II (GEO)/ HISPASAT	Aloha/FDMA	34 Mb/s (PDH) EUTELSAT or 2 Mb/s HISPASAT (QPSK WITH FEC)	ATM/LAN emulation
AKT ATM Tech Trial [22]	AT&T, KDD, Telstra with equipment from COMSAT and INTELSAT	INTELSAT V (GEO, inclined orbit) connecting three sites	SCPC FDM	45 Mb/s (optional RS coding and COMSAT ALE or ATM Star Link Enhancer	B-ISDN using CBR or circuit emulation
TTCP STP6/STP8 [23]	ROME (U.S.), DRA (U.K.), NRAD (U.S.), DISA (U.S.), *et al.*	Various satellites on SCPC connections, including ACTS	SCPC	Various 64 kb/s to 155 M/s (typically 1.54 M/s)	Various
NASA ACTS (UMD) [24]	University of Maryland	Ka-band using ACTS Satellite 3 m or 5 m antenna, built by Harris	ACTS OBP, bandwidth allocation based on the queue in the FRACS	*n* x 64 kb/s	Via Frame Relay Access Circuit Switch (FRACS) built by COMSAT
EC ACTS VANTAGE [25]	Alcatel Bell, Bradford Univ., BT Lab, Salford Univ., *et al.*	A conventional transparent satellite	N/A	256 kb/s ~ 34 Mb/s	ATM networks
RACE Catalyst R2074 [1]	Alcatel, EUTELSAT Salford Univ., Surrey Univ., *et al.*	Ku-band using EUTELSAT II (GEO)	SCPC FDM	12 Mb/s	B-ISDN, Ethernet
RACE Exploit [26]	ASCOM Technology, Swiss PTT, *et al.*	Simulated satellite	SCPC	2 Mb/s PDH	B-ISDN to PC ATM card using AAL3/4
XVSAT [27]	ESTEC, SAIT, NERA A/S, Telenor, MPR TelTech	Ku-band on INTELSAT VII (GEO) with NORSAT-B terminal, 3.5 m antenna	Adaptive FDMA	*n* x 64 kb/s ~ 3 Mb/s	Internally ATM LAN
Teledesic Broadband Global Net. [28]	Teledesic	Ka-band satellite (LEO) constellation	Frequency cell scanning	Standard 16 kb/s to 2 Mb/s	B-ISDN
COST 226 [20]	Jaoneum Graz, CNUCE, *et al.*	Ku-band/Ka-band using DFS-Kopernikus	Symbol-Synchronous TDMA	2 Mb/s	IP/X.25,FDDI, and ATM interfaces

■ **Table 1.** *Satellite ATM projects.*

TDMA, or FDMA, it is necessary for the lower-layer functions to choose a specific slot on the MF-TDMA/FDMA/TDMA frame for the cell. All these functions constitute the MAC implementation. Therefore, a satellite-specific MAC sublayer needs to be defined.

An optimal interleaving depth for RS code must still be determined to maximize error detection performance. In addition, an optimal interleaving depth for interleaving the ATM cell header and payload should be determined to reduce the impact of the burst error characteristics of satellite modems.

At the link layer, ARQ techniques can be used to reduce error rate because it provides a low error rate for loss-sensitive and delay-insensitive services (i.e., quality-critical services). Acceptable throughput and error performance can be achieved by using selective-repeat ARQ scheme because the sender retransmits only those cells for which an NAK is received. This advantage, resulting from fewer retransmissions, seems to be useful for the satellite environment. However, this scheme may increase complexity at the sender and receiver; also, each cell should be acknowledged.

For seamless interconnection of LANs/MANs using satellite ATM, several challenges need to be solved. First, a fast and efficient conversion protocol between LANs/MANs and ATM is needed to improve the interconnection performance. Second, a mechanism to minimize delay is required to support real-time applications. Third, an efficient multiplexing scheme is needed in order to avoid cell clumping due to the CDV which may be caused by poor multiplexing operation. Fourth, an efficient flow control mechanism is needed to minimize the cell losses due to the limited capacity of the ASIU. Finally, a new interworking scheme in the ASIU is needed to interconnect heterogeneous and homogeneous networks efficiently.

Although many traffic control mechanisms have been proposed and analyzed to date, they appear to be unacceptable for the satellite environment. Preventive traffic control schemes, such as traffic shaping, CAC, and the use of deliberate cell dropping, seem to be inadequate. For example, traffic shaping is limited to the procedures that maintain the established QoS of the connection. Preventive traffic control schemes which have long propagation delays need to be modified for the satellite ATM network so that they can operate in a very short time interval. The traffic control algorithms should also not interfere with delay-sensitive traffic because satellite ATM networks require a higher degree of network efficiency to provide a certain QoS and minimal cell loss.

It may be desirable to modify standard TCP to eliminate the problems of TCP such as retransmission of packets based on the timeout approach and limited window size. SSCOP is a part of AAL functions and is considered a more efficient error control scheme than TCP.

An efficient mechanism for satellite bandwidth management is needed in order to use a satellite channel efficiently and dynamically and to control the maximum cell delay when supporting high-speed data communication traffic which is very bursty and unpredictable.

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