Next-Generation Satellite Networks: Architectures and Implementations

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ABSTRACT A new generation of satellite networks is being developed to handle highly bursty Internet and multimedia traffic. In these networks, satellite links are used for interconnecting remote network segments as well as for providing direct network access to homes and businesses. In this environment, the satellite network must support not only circuit switched traffic, but also packet services with highly bursty traffic patterns. The traditional circuit switched approach based on the user or network signaling is inadequate to carry dynamically varying packet traffic efficiently, necessitating faster bandwidth allocation solutions. Standard interworking solutions and air interfaces are very important for interoperability leading to proliferation of satellite networks to potentially millions of home and business users. In this article we provide an overview of the standardization effort that has recently started at the TIA in the area of satellite ATM networks. Subsequently, a bandwidth-on-demand multiservice satellite network architecture implementation is described.

We are in the midst of a global information revolution brought about by the evolution of digital technology. The enormous strides in digital technology and its applications have fundamentally changed the way in which information is generated, processed, stored, and transported. The resulting information infrastructure will produce profound changes in all aspects of life, such as health care, education, crisis management, environmental monitoring, and electronic commerce. Telecommunications networks, as the arteries of this infrastructure, are evolving rapidly in response to the complex and stringent requirements of the new environment. Satellite communications networks can be an integral part of the newly emerging national and global information infrastructures provided the issues of interoperability of satellite and terrestrial networks are resolved. The rapidly evolving information infrastructure will play a critical role in realizing the "global village" concept of the world. Satellite communications systems are essential in establishing the global information infrastructure (GII).

There are two major developments in fixed telecommunication networks: Internet and asynchronous transfer mode (ATM). Satellite communications systems can play a multifaceted role in these evolving telecommunications networks and vastly strengthen the capabilities of the national information infrastructure (NII) and the GII in a number of ways:

- Providing global connectivity anywhere and anytime.
- Providing cost-effective broadcast/multipoint services.
- Reaching remote, inaccessible areas.
- Providing connectivity in areas where the terrestrial infrastructure has been damaged.

Satellite communications networks, if designed properly, can be a seamlessly interoperable part of global telecommunications networks. Satellite communications systems have a global reach, with very flexible bandwidth-on-demand capabilities, from the agility of the spot beams to the accessibility of the satellite channel from any earth station in the coverage area. Because of these features, coupled with the inherent multipoint/broadcast nature of satellite links, satellite communications systems can serve an important role in the information superhighway.

However, a new generation of satellite networks is needed to handle the Internet and multimedia traffic. The traditional circuit switched approach, based on the user or network signaling, is rather inadequate to efficiently carry dynamically varying packet traffic. This article describes a series of satellite based ATM network architectures and implementations. Subsequently, a multi-protocol satellite network architecture with bandwidth on demand is described.

SATELLITE/ATM NETWORK ARCHITECTURES AND IMPLEMENTATIONS

As satellite networks move closer to end users where potentially millions of home and business users can be served, development of standard solutions for interworking with the terrestrial network and standard air interfaces becomes critical. Based on demand from the industry, the Communications and Interoperability Section (CIS) of TIA's Satellite Communications Division has started this standardization process. TR34.1, the standards committee for CIS, has defined a set of satellite based ATM network architectures for future physical layer specification [1]. These network architectures cover both on-board switching and transparent satellites, network access and network interconnect scenarios, and mobile and fixed terminals and networks. TR34.1 has subsequently embarked on developing the physical layer specification for one of these architectures, point-to-point fixed ATM network interconnection.

The architectures defined by TR34.1 can be broadly grouped into two categories: satellite ATM (SATATM) architectures for transparent satellites, and SATATM architectures for satellites with on-board switches. The former applies to SATATM networks that can be implemented using today's satellites, while the latter applies to SATATM networks that can be implemented using the future on-board processing satellites. In addition to the type of processing on the satellites, the architectures defined by TR34.1 differ in terms of offered data rates, required protocol processing, mobility support provided by the network, and whether the satellites are used at the access or for transit.

SATELLITE/ATM ARCHITECTURES FOR TRANSPARENT SATELLITES

In transparent satellite networks no processing is done at the ATM layer or above on the satellites. All protocol processing is performed on the ground at user terminals (UT), gateway earth stations (GES), and the Network Control Center (NCC). These architectures provide the fastest way of deploying ATM to remote locations and interconnecting ATM

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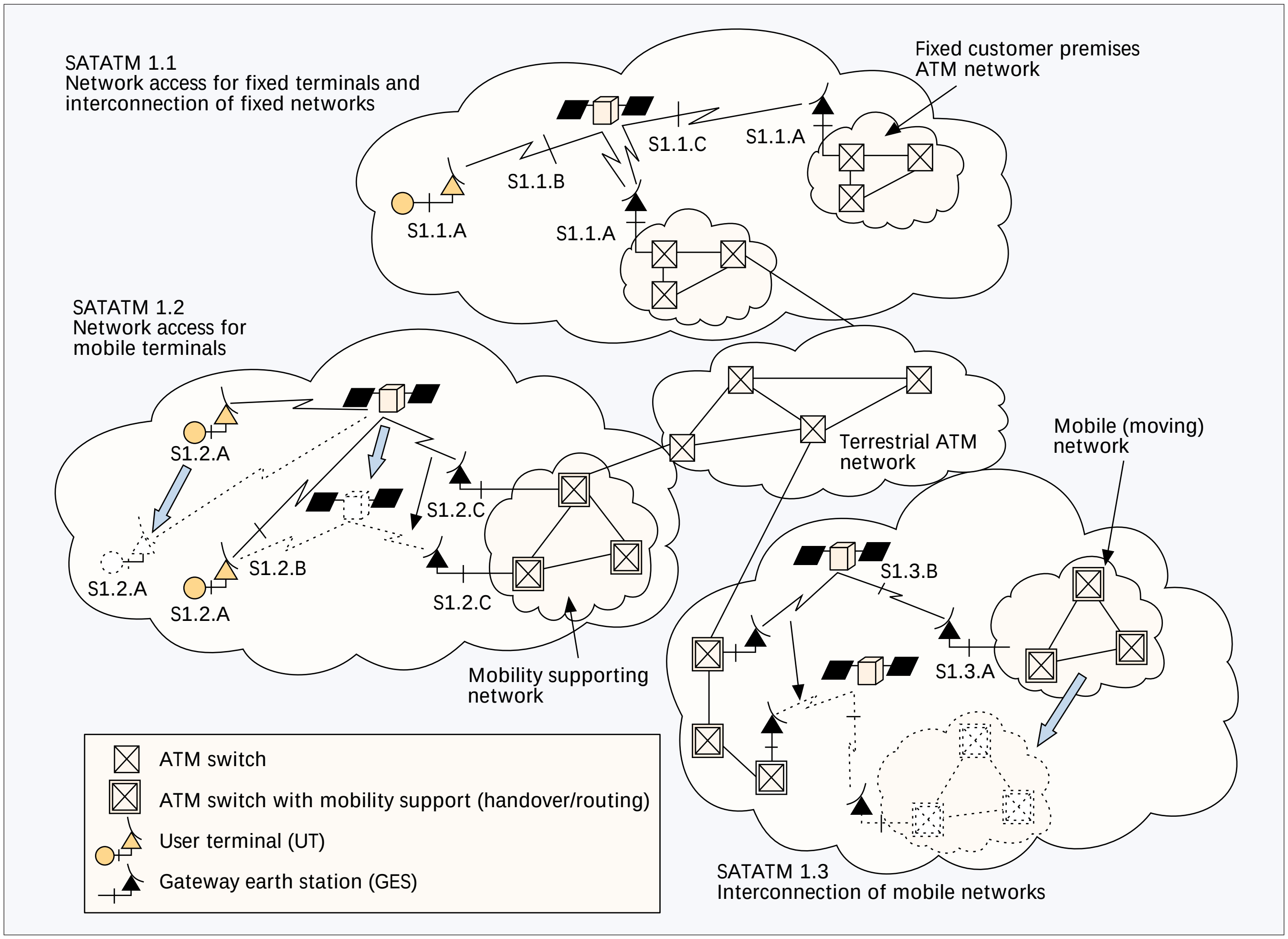


Figure 1. *Satellite ATM network architectures for transparent satellites.*

islands by using today's satellites. Although the lack of on-board processing and switching prevents full integration between a satellite network and the terrestrial ATM network, the advantages of ubiquitous coverage, inherent broadcast capability, cost effectiveness for long distances, suitability for providing mobile services, and flexibility in network configuration and capacity allocation, make these architectures a viable complement to high speed terrestrial networks.

These network architectures are further divided into three categories according to the type of mobility supported by the satellite network:

- SATATM 1.1 – Fixed ATM Network Architecture.
- SATATM 1.2 – Terminal Mobility Supporting ATM Network Architecture.
- SATATM 1.3 – Network Mobility Supporting ATM Network Architecture.

Figure 1 shows the reference configurations for these network architectures.

SATATM 1.1 – Fixed ATM Network Architecture — In the fixed ATM network architecture, satellites are used mainly in two scenarios:

- High-speed network access by user terminals.
- High-speed interconnection of remote ATM networks.

In the network access scenario the satellite network resides at the access portion of the broadband network. The satellite earth stations at the customer premises are typically small and low-cost terminals and referred to as "user terminals" (UT). The indoor unit (IDU) of these user terminals interfaces with the customer premises ATM network through a standard ATM User Network Interface (UNI) [2]. The satellite earth station at the other end of the satellite links is a gateway earth station (GES). According to the architecture described in [1] the GES does not perform ATM switching or concentration functions, and therefore the interface between the GES and the terrestrial broadband network is also a UNI. Optionally, the GES could provide ATM switching functions, in which case the interface to the terrestrial ATM network could be a Network-Network-Interface (NNI) such as the ATM Forum Private Network-Node Interface (PNNI) [3].

Satellite networks at the access are characterized by a large number of UTs and few GESs. Owing to the large number of UTs, terminal size, cost, and bandwidth efficiency become critical for successful deployment of these networks. Bandwidth efficiency implies both efficiency of the physical layer, i.e., advanced coding and modulation techniques, and innovative bandwidth management and capacity allocation techniques.

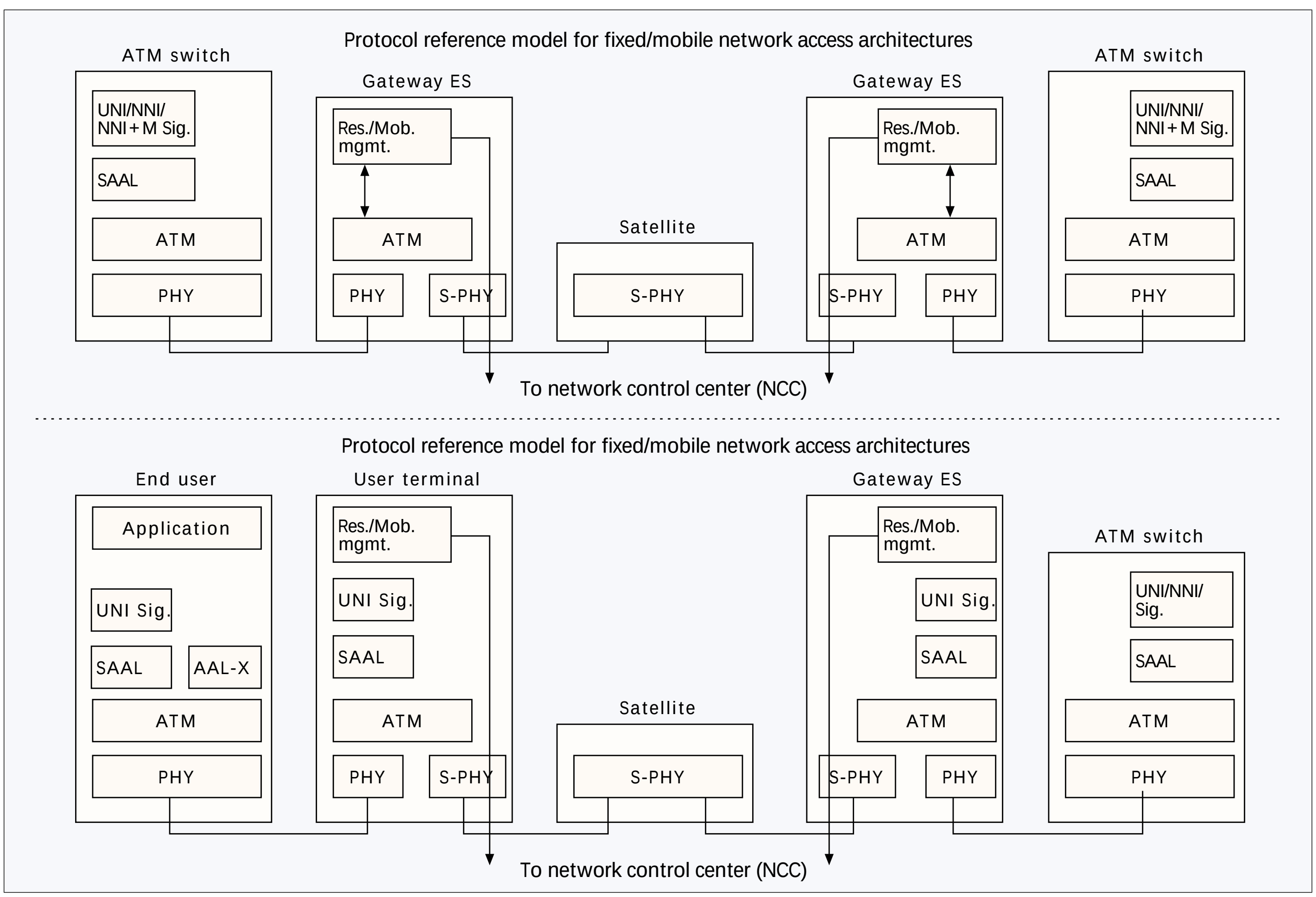
In the network interconnection scenario, the satellite network resides at the transit portion of the broadband network. The GESs do not perform switching or concentration functions. Since a certain level of statistical multiplexing gain is achieved at the terrestrial ATM network, the traffic arriving at the GES is less bursty. Although dynamic bandwidth management is still possible, it is not as critical as in the user access scenario. The satellite links provide high-speed interconnection among ATM islands at fixed transmission speeds.

The reference points of the fixed ATM network architecture are shown in Fig. 1. Reference point S1.1.A represents a standard UNI or NNI ATM interface between the earth stations and the terrestrial network. In the case of network access, this interface is a standard ATM UNI, while in the case of network interconnection this interface is a standard ATM NNI. Reference point S1.1.B is the air interface between the UT and GES for the network access scenario. The physical layer data rates envisioned for this interface are in the 64 Kb/s – T1 range. Reference point S1.1.C is the air interface between two GESs for the network interconnection scenario. The physical layer data rate envisioned for this interface is in the T1 – 1.2 Gb/s range.

The protocol reference models for fixed ATM network access and network interconnection are shown in Fig. 2. The resource management function implemented at the UT and GES allow the bandwidth assigned to connections to change dynamically based on demand, available capacity, quality of service requirements, and fair share of bandwidth. In this architecture, it is assumed that bandwidth management functions are centralized at the Network Control Center (NCC). In the network access scenario, the UT can also interwork with ATM UNI signaling to establish switched connections. In this case, the UNI signaling messages are transported transparently over the satellite network; however, the information carried in these messages is used by the resource management function to allocate/deallocate necessary satellite capacity for ATM traffic. The UT and GES can use internal signaling to request capacity from the Network Control Center (NCC) or release capacity based on this information. For network access that uses permanent connections (PVCs or PVPs) the resource management function is much simpler and does not interwork with ATM signaling.

TR34.1 is currently in the process of standardizing the common air interface for ATM over a point-to-point satellite link, and consideration is being given to a number of features found in current implementations, such as the COMSAT Link Enhancer (ALE-2000) and Link Accelerator (CLA-2000/ATM). These implementations provide an essentially error-free satellite link in a bandwidth efficient manner at fractional T1 to DS3 rates. ALE-2000 is a networking device that allows customers to interconnect ATM networks over satellite and wireless links, at DS3 and E3 rates. It provides efficient bandwidth utilization, provides fiber-like link quality, and significantly improves the performance of applications operating over satellite and wireless ATM networks by dynamically inserting Reed-Solomon forward error correction into the data stream and introducing interleaving. Cell Loss and Cell Error ratio improvements by several orders of magnitude are achieved. The CLA-2000/ATM is designed for use over satellite or terrestrial wireless links operating at fractional T1 to 8.448 Mb/s, symmetric or asymmetric, data rates. It includes a number of innovative features to improve link quality and application throughput, such as rate adaptation, adaptive forward error correction, interleaving, ATM cell header compression, and lossless ATM cell payload compression.

***SATATM 1.2 Terminal Mobility Supporting Satellite ATM Network Architecture* —** This network supports portable UTs as well as UTs that appear to be in continuous motion with respect to the satellite due to the orbit of the satellite (i.e., in the case of middle/low earth orbiting satellites). While portability of the UTs requires the satellite net-



■ **Figure 2.** *Satellite ATM network protocol reference models for transparent satellites.*

work to support location management, the motion of the satellite requires the satellite network to support handovers. Handovers can be:

- From one satellite to another as the UT or GES leaves the coverage area of one satellite and enters the other.
- From one satellite beam to another as the UT or GES leaves the coverage area of one beam and enters the other.
- From one GES to another as the satellite leaves the line of sight of one GES and enters the other.

The first two types of handovers do not require rerouting at the ATM layer and can be performed at the satellite physical layer. However, the third handover type requires rerouting of the ATM connection at the ATM layer since the two GESs are connected to the terrestrial ATM network via two separate switches. This is illustrated in the lower left side of Fig. 1. Inter-beam handover rates can be much higher than the other two types of handovers depending on the system configuration. For example, a medium earth orbiting satellite at about 8000 km altitude will have about a five-hour orbit period. The minimum number of satellites required for full coverage along the orbital plane would be five. A single satellite would be in view from one spot on the earth for about one hour. If the satellite has 100 beams in a symmetrical pattern (i.e., 10 x 10 square), there will be approximately 10 beam-to-beam handovers within a satellite during this one hour. This would translate to a rate of one handover every six minutes for one connection. For the low earth orbiting satellites, the handover rate is even higher. As a single satellite may be in view for up to 12 minutes or so, a similar satellite configuration (100 beams in a symmetrical pattern) would lead to a rate of 10 handovers every 12 minutes for each connection.

Development of location management and ATM connection rerouting procedures are not within the current scope of work of TR34.1. The wireless ATM (WATM) specification that is being developed by the ATM Forum [4] will address location management and ATM handovers and can be used for mobility management in satellite ATM networks.

The network reference model for this architecture is shown on the lower left side of Fig. 1. This figure illustrates the following two cases:

- Where the user terminal is portable, requiring mobility management functions to support its migration from one satellite beam coverage to another.
- Where the user terminal can be fixed, but the satellite is mobile, requiring mobility management functions to support handover of the connection from one satellite, beam, or GES to another satellite, beam, or GES.

Reference point S1.2.A is an ATM UNI, possibly with enhancements and additional mobility support protocols (+M) if handovers and location management are incorporated into ATM UNI signaling. Reference point 1.2.B is the air interface between the mobile terminal and the gateway earth stations. Reference point S1.2.C is an NNI with mobility support (+M). The protocol reference model for SATATM 1.2 is similar to that of fixed ATM network access with the additional functionality and protocols to support mobility.

SATATM 1.3 Network Mobility Supporting Satellite ATM Network Architecture — In this network architecture, the satellite network provides high-speed interconnectivity between a mobile network and a fixed network or between two mobile networks. One application for this network architecture is interconnecting the communications network of mobile multi-user platforms such as airplanes, ships, and trains with the terrestrial ATM network via satellite links. The mobile network comprises one or more switches that are fixed with respect to each other, end user terminals that are attached to these switches, and a satellite earth station. The mobile network can be a stand-alone network with no connectivity to the terrestrial network, or it can communicate with the terrestrial network via several NNI links. On the ground this network comprises GESs and ATM switches that interface with the terrestrial ATM network. A global satellite system provides continuous coverage to the mobile platform.

The most compelling requirement of this network architecture is to support the mobility of a network that is moving as a whole. Network mobility ideally requires support for both handovers and dynamic routing (i.e., the ability to join in the routing hierarchy of the fixed network). As the mobile platform moves outside the coverage area of one satellite and enters that of another, the ongoing connections are handed off from the previous satellite and GES to a new satellite and GES. This can be a one-step process where all connections are rerouted toward the new GES from an appropriate node (crossover switch) along the original path, or a two-step process where first all connections are extended from the previous GES toward the new GES and subsequently path optimization is performed and all connections are rerouted according to the optimal path. In a large mobile network many connections may have to be handed over simultaneously while the mobile network is in the overlapping coverage area of two satellite beams.

The ATM Forum is currently working toward including the mobility extensions to its routing mechanism in version 2 of its PNNI specification [5]. According to the work currently in progress, each mobile network will be able to add itself in the routing hierarchy of the fixed network. This will be achieved by mobility-enhanced ATM switches in the mobile network that get the routing hierarchy information of the fixed network from the border nodes and propagate this information higher in the mobile network hierarchy. The node highest in the hierarchy of the mobile network then decides whether to join the fixed network or not. If this node decides to join the fixed network, it updates the mobile network hierarchy list accordingly and this update is propagated to all the nodes, including the border node. The border node advertises the updated hierarchy list of the mobile network to the neighboring node in the fixed network. Then appropriate routing links are established to the mobile network from the fixed network.

SATELLITE/ATM ARCHITECTURES FOR ONBOARD PROCESSING SATELLITES

In ATM networks with on-board processing satellites, the payload switch performs ATM switching functions. The control functions are typically distributed between the on-board ATM switch and the NCC on ground. The ATM interfaces between the payload switch and ground terminals can be of both the UNI and NNI type. The proposed future satellite systems of Astrolink and Teledesic fall into this architecture.

TR34.1 further divides these networks into three architectures according to the type of connectivity provided by these networks:

- SATATM 2.1 (ATM Network Access) — In this network architecture low-speed satellite links are used to connect remote ATM hosts to a terrestrial network. The ATM interface between the ATM hosts and the on-board switch is a UNI, and the ATM interface between the on-board switch and the terrestrial ATM network is an NNI.
- SATATM 2.2 (ATM Network Interconnectivity) — In this network architecture, the satellite is an ATM node interconnecting multiple terrestrial ATM networks via high speed links. The interfaces are of the NNI type.

• SATATM 2.3 (Mesh ATM) — In this network architecture, several satellites form an ATM network in the sky via intersatellite links. This network provides both ATM network access and network interconnectivity. The ATM interface between the satellites is of the NNI type.

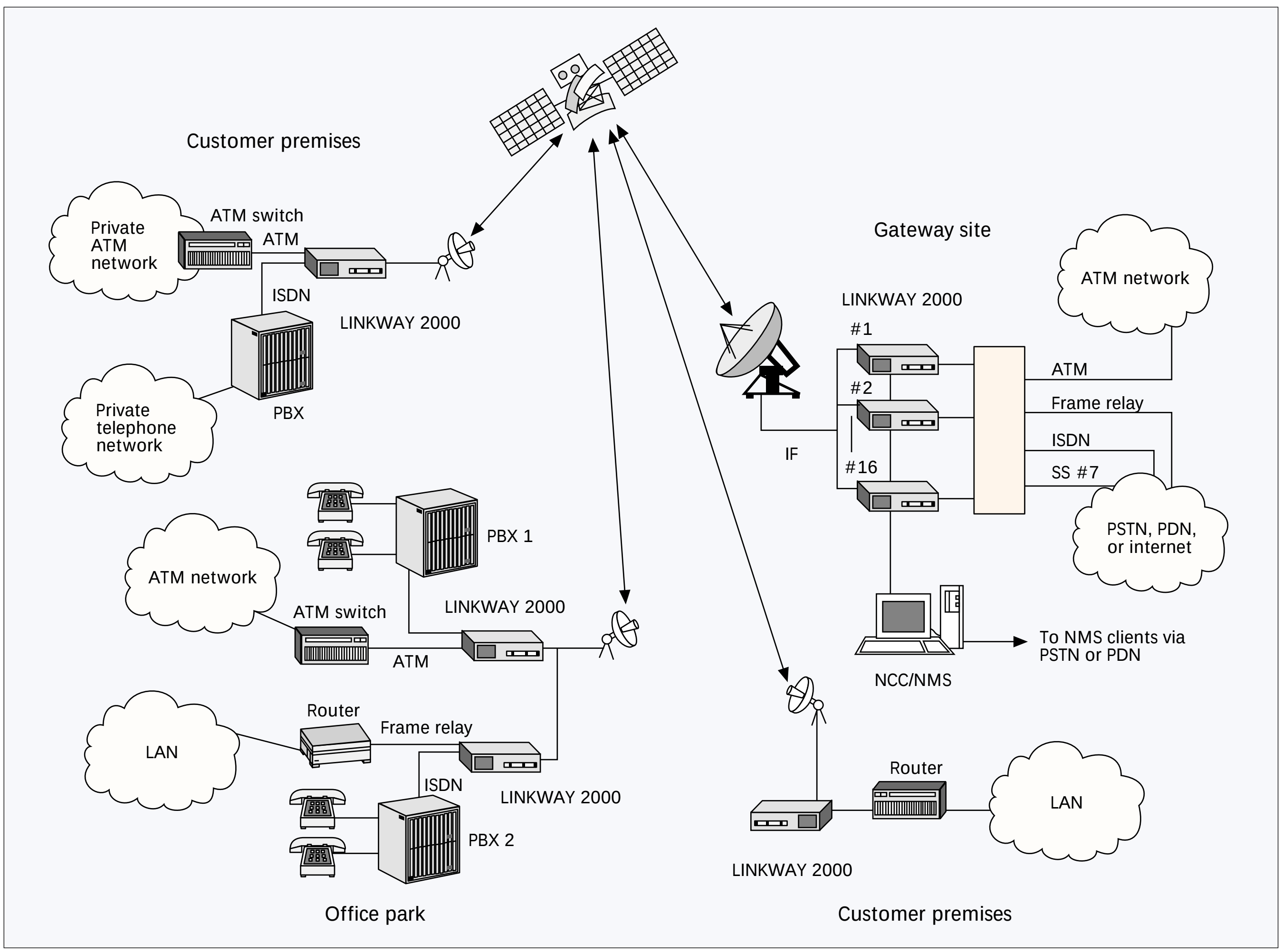
MULTISERVICE BANDWIDTH-ON-DEMAND SATELLITE NETWORKS

A number of standards bodies (such as ATM Forum, ITU, Internet Engineering Task Force) are developing protocols and standards for handling dynamically varying bandwidth requirements for new applications and services. ATM and Internet networks are designed to handle applications that require variable bandwidth on demand. A demand assigned multiple access (DAMA) satellite network, if designed properly, is an ideal platform to provide ATM and Internet services at required Quality of Service (QoS) levels in a very bandwidth efficient manner. One such network is the COMSAT Linkway 2000 wide area networking and switching system that provides access and transport for packet switched services (ATM, IP/LAN, and Frame Relay), and circuit switched services (ISDN and Signaling System No. 7) as shown in Fig. 3.

NETWORK OVERVIEW

Linkway 2000 provides a full-mesh multi-service satellite network with a multi-frequency TDMA satellite air interface and unified frame, cell, and circuit mode transport services. Equipped with a high-performance 2 Mb/s burst modem, the user terminals provide single-hop, bandwidth-on-demand access and transport for Frame Relay, ATM, IP/LAN, ISDN, and SS #7 user interfaces in a full-mesh, symmetric or asymmetric manner. Using stackable units, scaleable network solutions can be deployed with per-node transport capacity from 2 Mb/s to 32 Mb/s.

The transmission format is burst-by-burst dynamically selectable, supporting QPSK and BPSK modulation waveforms with many settings of concatenated coding. The inner code is convolutional FEC with rates 1/2, 2/3, 3/4, and 7/8; the outer code uses variable block length Reed-Solomon with a maximum block length of 255 bytes. With 1/2 rate FEC, (236,216) Reed-Solomon, and QPSK at 2.5 Msymbols/s, a BER threshold 10^{-8} is achieved at E_b/N_0 = 5.5dB. The TDMA frame length can be selected between 12 msec and 48 msec on a network basis. A burst can contain multiple channels whose structure depends on the type of traffic carried by the channel: circuit channel, packet channel, or ATM channel. A configurable amount of Reed-Solomon coding can be applied to each channel within the burst, thus permitting different levels of error protection for different services. Bandwidth efficiency



■ **Figure 3.** *Linkway 2000 — a multiservice satellite network with bandwidth on demand.*

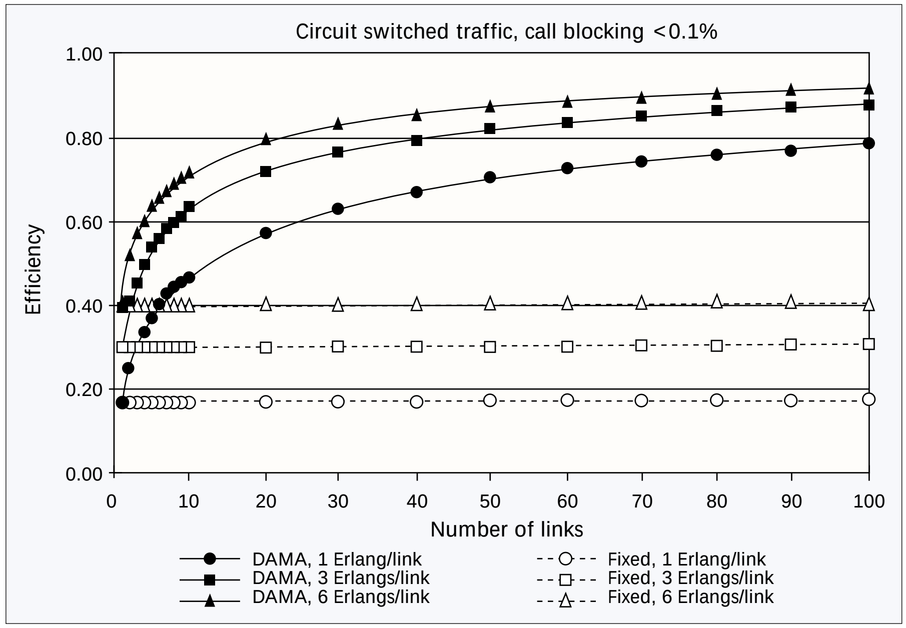


Figure 4. *Bandwidth efficiency comparison of DAMA and fixed bandwidth assignment for circuit switched traffic.*

is enhanced with demand assignment of circuit services — call by call DAMA and demand assignment of data services — offering both committed information rates and incremental bandwidth allocation dynamically adapting to the traffic changes. Frame efficiency is increased by allocating multi-channel bursts for the reserved/guaranteed portion of PVC/call bandwidth. The network supports carrier frequency hopping on a burst-by-burst basis.

A Web-based Network Management System using JAVA client-server technology provides network configuration, operation, control, and monitoring capability. Built-in traffic management mechanisms for frame and ATM services provide per-VC Quality-of-Service tuned to application requirements. PVCs provisioned and SVCs can thus be optimized for user applications ranging from jitter sensitive voice/video and delay sensitive transactions to best effort Internet services. A centralized Network Control Center (NCC) workstation attached to a reference terminal performs network control and also runs the Network Management System (NMS) server. Multiple NMS browser clients may connect to the NMS server with predefined authentication and access privilege levels for complete or restricted views of the network. The NMS includes an easy to navigate, hierarchical set of screens for network configuration, status, alarms, performance, and security functions. The NMS can set up nailed-up cell/frame bandwidth between sites by provisioning extra PVCs.

BANDWIDTH MANAGEMENT

The NCC runs a central bandwidth management algorithm, which is crucial to the efficient usage of the space segment and ensuring a high level of end-user data throughput. The NCC runs a bandwidth management and capacity allocation algorithm that ensures fair and efficient bandwidth allocation. The network supports both fixed bandwidth allocation and dynamic bandwidth allocation, depending on the type of connection.

Dynamic bandwidth assignment can be at both the call level and packet level. The multiservice bandwidth-on-demand satellite network supports various user interfaces: IP, ATM, FR, ISDN, and SS #7. The bandwidth assignment mechanism is different for each service. Constant Bit Rate (CBR) and real-time Variable Bit Rate (rt-VBR) connections can only be handled by fixed assignment of bandwidth during the lifetime of the Permanent Virtual Circuit (PVC). Other ATM service categories, Frame Relay, and ISDN traffic can best be handled by assigning bandwidth on demand. While for ISDN traffic, a fixed amount of bandwidth is assigned on a per-call basis, for variable-bit rate packet traffic the dynamic bandwidth assignment algorithm runs continuously and reacts to changes in the buffer levels and instantaneous arrival rates at the transmit terminals.

The dynamic bandwidth allocation algorithm uses three levels of fairness in assigning bandwidth to each terminal:

- Outgoing fairness
- Incoming fairness
- System fairness

Outgoing fairness ensures that all VCs originating from a particular terminal get a fair share of bandwidth assigned to the terminal. Incoming fairness ensures that all VCs terminating at a particular terminal get a fair share of the downlink bandwidth to that terminal. System fairness ensures that all VCs in the entire network get a fair share

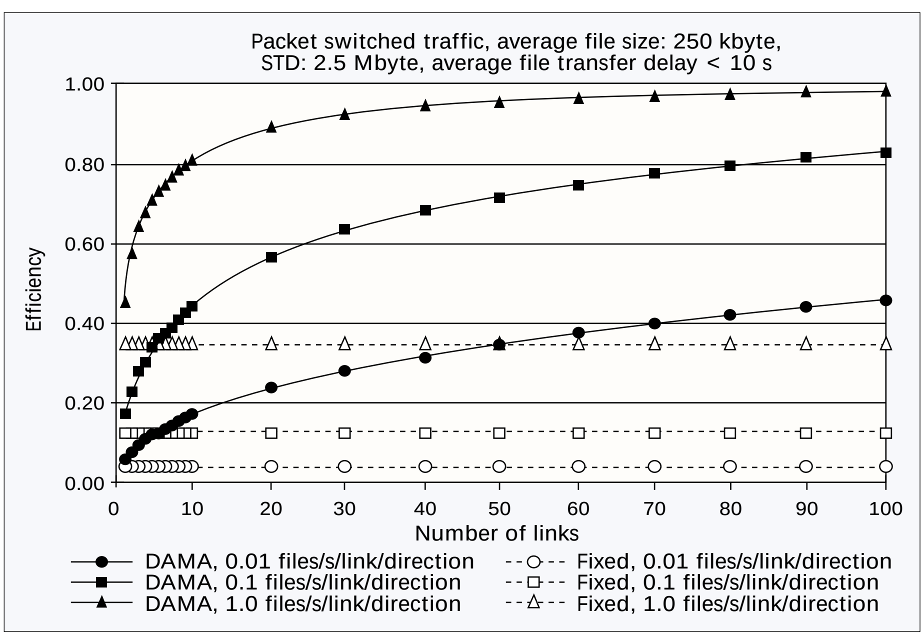


Figure 5. *BAndwidth efficiency comparison of DAMA and fixed bandwidth assignment for packet traffic.*

of the total system capacity (number of carriers x 2 Mb/s) in a fair manner. The execution of this algorithm on a periodic basis results in bandwidth allocation and deallocation in response to changing incoming user traffic rates in a dynamic and fair way.

In Figs. 4 and 5 the bandwidth efficiency of a DAMA satellite system is compared to that of a fixed-assignment satellite system. In Fig. 4 the comparison is for circuit switched traffic. Each call requires a full-duplex 64 Kb/s channel. Calls arrive according to a Poisson distribution. On the horizontal axis, the connectivity of the network is increased by increasing the number of links. On the vertical axis, the bandwidth efficiency is plotted. Bandwidth efficiency is defined as the ratio of total throughput (in Mb/s) to total bandwidth (in Mb/s) dedicated for the network. The total bandwidth required is determined by using the Erlang-B formula. The total number of 64 Kb/s channels required to meet a call blocking probability of 0.001 is computed for a given traffic load in Erlangs (calls per second multiplied by average call duration). With fixed assignment, a number of 64 Kb/s channels are dedicated to each link whether there is an ongoing call or not, whereas with demand assignment, bandwidth is dedicated to the whole network and is shared among all links. Figure 4 shows that the bandwidth efficiency of a bandwidth-on-demand satellite network is approximately twice that of a fixed-assignment network for a moderate size network of 10 links.

In Fig. 5 a similar comparison is made for packet switched traffic. The application that is chosen is a large file transfer between two sites. File transfer requests arrive according to a Poisson distribution on each link. File size has a general distribution with mean 250 kbytes and a large standard deviation (2.5 Mbytes). With fixed assignment the transmission queue on each direction of a link behaves as an M/G/1 queue. The required transmission capacity for each link is determined such that the total delay (queuing + transmission + propagation) for an average file transfer is less than 10 s. With bandwidth on demand, the whole network is modeled as an M/G/1 queuing system. This is equivalent to assuming that file transfer requests on all links are placed in a common queue and served by the satellite network one at a time. Figure 5 illustrates the significant improvement in bandwidth efficiency obtained by using demand assignment.

CONCLUSIONS

The growing demand for bandwidth for network access has defined a new role for satellite networks where dynamic bandwidth allocation and interoperability with the new network technologies and protocols are critical. Moreover, in this new role, standard interworking solutions and common air interfaces have become extremely important to proliferate these networks to potentially millions of home and business users in a cost effective way. Standardization activities have started both in the areas of ATM over satellite and IP over satellite. The Communications and Interoperability Section of the Satellite Communications Division of TIA and its standards committee, TR34.1, has defined a set of ATM network architectures for future physical layer specification. These network architectures cover both on-board switching and transparent satellites, network access and network interconnect scenarios, and mobile and fixed terminals and networks. TR34.1 has subsequently embarked on developing the physical layer specification for one of these architectures — point-to-point fixed ATM network interconnection. While these standardization activities have started recently, the industry has implemented and tested various solutions for carrying ATM traffic over satellites in a bandwidth-efficient and virtually error-free way. These solutions are believed to foster the development of these standards.

When satellite links are used at the access network, one of the challenges is to cope with the heterogeneity of network protocols and interfaces and develop satellite network solutions that can accommodate these in a bandwidth-efficient manner. In this article we gave an overview of one such network that offers IP, ATM, Frame Relay, ISDN, and SS No. 7 services in fully-meshed mode at data rates ranging from 64 Kb/s to 32 Mb/s. This network uses multifrequency TDMA to achieve very high efficiency and flexibility in satellite bandwidth management. Unlike conventional VSAT systems, this network allocates system capacity to both circuit and packet switched traffic in a dynamic and fair manner among different terminals.

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BIOGRAPHIES

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