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Quality of service for satellite IP networks: a survey

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SUMMARY

The future media rich applications such as media streaming, content delivery distribution and broadband access require a network infrastructure that offers greater bandwidth and service level guarantees. As the demand for new applications increases, 'best effort' service is inadequate and results in lack of user satisfaction. End-to-end quality of service (QoS) requires the functional co-operation of all network layers. To meet future application requirements, satellite is an excellent candidate due to features such as global coverage, bandwidth flexibility, broadcast, multicast and reliability. At each layer, the user performance requirements should be achieved by implementation of efficient bandwidth allocation algorithms and satellite link impairment mitigation techniques.

In this paper, a QoS framework for satellite IP networks including requirements, objectives and mechanisms are described. To fully understand end-to-end QoS at each layer, QoS parameters and the current research are surveyed. For example at physical layer (modulation, adaptive coding), link layer (bandwidth allocation), network layer (IntServ/DiffServ, MPLS traffic engineering), transport layer (TCP enhancements, and alternative transport protocols) and security issues are discussed. Some planned system examples, QoS simulations and experimental results are provided. The paper also includes the current status of the standardization of satellite IP by ETSI, ITU and IETF organizations. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: QoS; satellite IP; TCP; UDP; MPLS; DAMA; DiffServ; IntServ; spread ALOHA

1. INTRODUCTION

A satellite communications network is distinguished by several characteristics such as global coverage, scalability, broadcast capability, bandwidth-on-demand flexibility, multicast capability and reliability. This makes it an excellent candidate to provide broadband integrated Internet access. The next generation satellite multimedia networks can be divided into two classes. The first is broadband satellite *connectivity network* in which full end-to-end user connectivity is established on a global level. On the other hand, regional *access networks* are intended to provide Internet access over a regional level. Many of the global networks use on-board processing and fast switching payload while the access systems employ non-regenerative

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payloads. The critical requirement is to provide high data rate Internet access, global connectivity and provisioning of quality of service (QoS) within the next generation satellite network systems. For example, a user initiates a voice-over-IP call and expects the call to be intelligible. From a human point of view, call quality is subjective but objective measures of packet rate, delay, jitter and loss are required for an intelligible call and must be supplied by the network.

The current satellite systems operate in C and Ku frequency bands.[§] The growing congestion of the C and Ku bands and the success of the Advanced Communications Technologies Satellite (ACTS) program [1] increased the interest of satellite system developers in the Ka-band satellite communications network for growing Internet access applications. The proposed satellite systems use geosynchronous orbit (GSO), non-geosynchronous orbits (NGSO) and multi-spot beams, adaptive power control and adaptive coding for propagation error impacts mitigation, efficient routing with on-board processing/switching and resource allocation/demand assignment multiple access (DAMA). These are planned to employ small terminals with high gain antennas overcoming the path loss and fades. Examples of the global satellite networks being developed include Euroskyway, Spaceway, IntelSat, Eutelsat and Astrolink, and broadband access networks include Starband, Cyberstar, iPStar and Wildblue [2]. Each one of these systems is being designed to support the user level QoS guarantees.

The Internet has evolved through many changes in traffic characteristics and applications and in link bandwidths and utilizations, as opposed to a simple telephone system. Even though the transmission bandwidths increased from speeds of kilobits to several hundreds of megabits and even gigabits, still some of the residential users receive speeds less than 56 Kbps. A proliferation of new bandwidth hungry applications is expected in future. Periods of congestion on Internet will increase more than what is experienced today. A given link or router of the Internet will carry thousands and millions of sessions from a wide variety of applications whose service levels of (satisfaction) requirements are different. Increase in bandwidth will not fully alleviate the problem of congestion. Methods of traffic management, congestion control and QoS approaches become an important issue in future.

Currently, most of the Internet applications use a transmission control protocol (TCP [3])/ Internet protocol (IP [4]) protocol suite. Although the TCP protocol was developed for terrestrial networks, a number of TCP enhancements have been proposed by the Internet engineering task force (IETF) to accommodate the satellite specific link characteristics such as propagation delay, bandwidth asymmetry, channel impairments and congestion [5]. For example, performance degradation due to weather and fading in a satellite environment has been addressed in some of the TCP enhancements [6].

QoS approaches have been proposed to leverage the congestion controls of TCP used by all Internet traffic. Unfortunately, not all applications can reasonably make use of TCP with its elastic response to congestion. These are not particularly suited for real-time applications, which are built around user datagram protocol (UDP), real-time protocol (RTP) or recently stream control transmission protocol (SCTP) [7]. For real-time and non-real-time applications, QoS approaches must be studied further to provide user service level guarantees.

The IETF has proposed QoS architectures to provide guaranteed service level to different applications over terrestrial networks. These architectures include, integrated services (IntServ),

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[§] Ka—uplink: 27.5–30.0 GHz; downlink: 17.7–20.2 GHz, C—uplink: 5.925–6.425 GHz; downlink: 3.7–4.2 GHz and Ku—uplink: 12.75–13.25, 13.75–14.5 GHz; downlink: 10.7–12.75 GHz.

differentiated services (DiffServ) and multiprotocol label switching (MPLS) traffic engineering. There is an urgent need for developing QoS architectures for broadband satellite network, multicast services and identifying the challenges for realizing Ka-band satellite systems [8–10]. The critical issue of QoS—its framework, reference models, architectures and performance examples form the main focus of this paper.

This paper is organized as follows. Section 2 provides the market potential for broadband satellite IP networks and future applications. The QoS framework including QoS parameters and objectives, and end-to-end QoS is described in Section 3. Section 4 provides an overview of broadband satellite network architectures, protocol architecture, QoS functional allocation and an IP satellite network example. For completion purposes, a brief discussion on the physical layer QoS parameters is described in Section 5. Section 6 provides a survey of bandwidth allocation research and different satellite IP. QoS architecture candidates and technologies at the network layer are surveyed in Section 7. At the transport layer, current research on TCP enhancements, QoS results for TCP and UDP traffic and modified TCP and performance results are provided in Section 8. Section 9 includes a brief overview of present satellite IP projects and some of the programs. The paper concludes in Section 10 with future research issues.

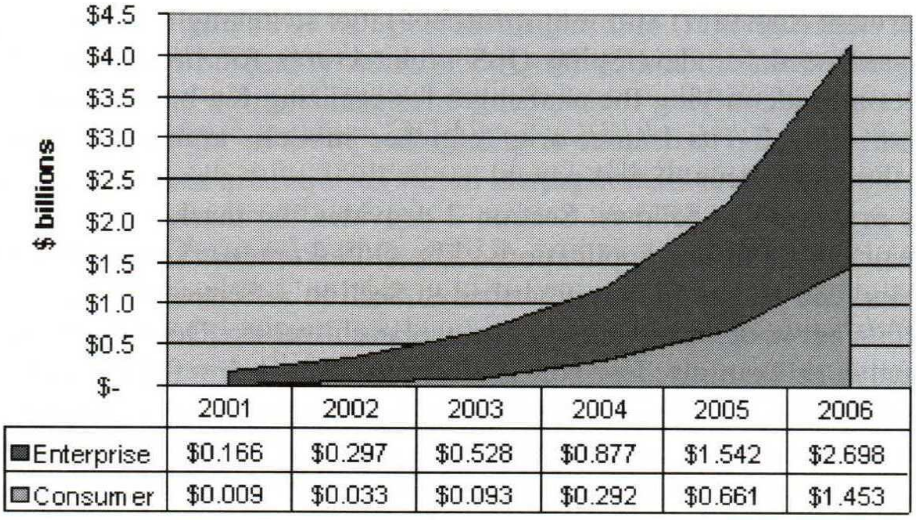
2. MARKET POTENTIAL AND APPLICATIONS

2.1. Market potential

The total worldwide market opportunity for broadband satellite service providers is expected to reach nearly $27 billion by 2008 [11]. This includes three major applications: content distribution and delivery (CDD), broadband access and trunking and backbone. Satellites being by nature multicast enabled, CDD services could be efficiently supported by satellite links. The scalability of the network could be ensured through multicast streams to several users via the same satellite link with no additional cost. In addition, satellite networks reduce the number of router hops and intermediate exchange points thereby improving the reliability and content quality. Thus, IP content distribution market is effectively a niche market for satellite communication systems developers. As shown in Figure 1, the potential market for satellite-based broadband enterprise and residential access users is expected to grow up to $4 billion by 2006 for (CDD) [11].

2.2. Applications

The potential applications for CDD for enterprise services contribute a greater share of the potential market over broadband satellite networks. Examples of the enterprise applications include executive communications with internal organizations—training and human resources, marketing and sales, engineering and service; database distribution, remote shopping, audio and video entertainment distribution, financial data delivery, telemedicine (transmission of clinical tests, X-rays, electrocardiograms, magnetic resonance) and teleeducation. Future satellite applications are not limited to the Internet but also include new environments such as managing activity of the Public Administration, bank and financial services and remote industrial control and management. For example, industries having open peripheral offices in remote locations where telecommunication infrastructure is often limited and not very reliable, can be connected to the headquarters using satellite network.



	2001	2002	2003	2004	2005	2006
■ Enterprise	$0.166	$0.297	$0.528	$0.877	$1.542	$2.698
▨ Consumer	$0.009	$0.033	$0.093	$0.292	$0.661	$1.453

Figure 1. Satellite CDD service growth.

2.2.1. Teleeducation example. Seventy-one per cent of the American students aged between 12 and 17 years download material from the Internet for their studies. These students living in remote areas could access the teleeducation systems via 90 cm rooftop antenna with Ka-band satellite network. The first phase of teleeducation was essentially based on non-interactive services were lectures where distributed through videocassettes, CDs and also special TV channels. The interaction of students with the teacher was limited to snail mail, and/or phone when available and e-mail. Even the few teleeducation systems providing limited interaction became expensive due to the high cost of the bandwidth and limited number of sites.

Best effort Internet: The previous teleeducation system has been improved by the growth of Internet and remote connectivity of the local area networks of different universities employing TCP/IP-based applications. It enables the students to receive the lectures via their computers both at home and campus and the teachers to deliver lectures not only from their offices without special teleeducation classrooms but from any locations such as hotel rooms if the instructor is on the move. The services of teleeducation not only include delay sensitive audio and video UDP applications but also data supported by TCP where the students can access the databases providing the lecture material, review questions and papers. The scenario is limited by the available Internet technology, which, on the one hand, offers the mentioned opportunities, but, on the other hand, has a limited bandwidth and lack of resource allocation algorithms to guarantee a user level of quality. This results in limited interactive services for audio and video streaming applications.

QoS Internet: To fully realize such global multimedia applications, the current research includes asynchronous transfer mode (ATM) and IP technologies, different satellite configurations, GigEthernets, wireless networks and even optical backbones. Specifically, for a successful teleeducation application, research is warranted in the areas of: fading and weather effect mitigation techniques, dynamic bandwidth allocations, bandwidth reservation schemes, QoS architectures, enhanced TCP or new TCP protocols, multicast protocols. Some of these research results are surveyed for satellite IP networks with QoS architectures and performance results, which forms the main focus of this paper. The QoS framework with parameters and objectives are discussed in Section 3, and satellite specific QoS architecture and functional allocation are described in Section 4. The broadband satellite multimedia standardizations by European Telecommunications Standards Institute (ETSI), and IP over satellite by International Telecommunications Union—Radiocommunication (ITU-R) are used as guidelines for development of future applications.

2.2.2. Teleeducation configuration. Teleeducation application is of special relevance because it demonstrates on the one hand, the importance of satellite networks and, on the other hand, emphasizes the need of QoS guarantees to achieve user satisfaction.

The motivation for satellite QoS is explained through an example of teleeducation provided over a satellite Internet. Figure 2 shows a satellite network based on web access providing interactive and non-interactive services for remote sites. The following are the network elements.

Core network: A high-speed satellite network provides full connectivity with main sites (MSs), and is characterized by high interoperability. It uses videoconferencing, teleworking and multimedia tools for data exchange at high speed.

Distribution network: A low cost distribution network either satellite or heterogeneous, using a star topology, consists of several service users (Terminal Users—TUs). These could be residential users, enterprises, public and private institutions such as schools and learning centres. The TU is connected to the core network.

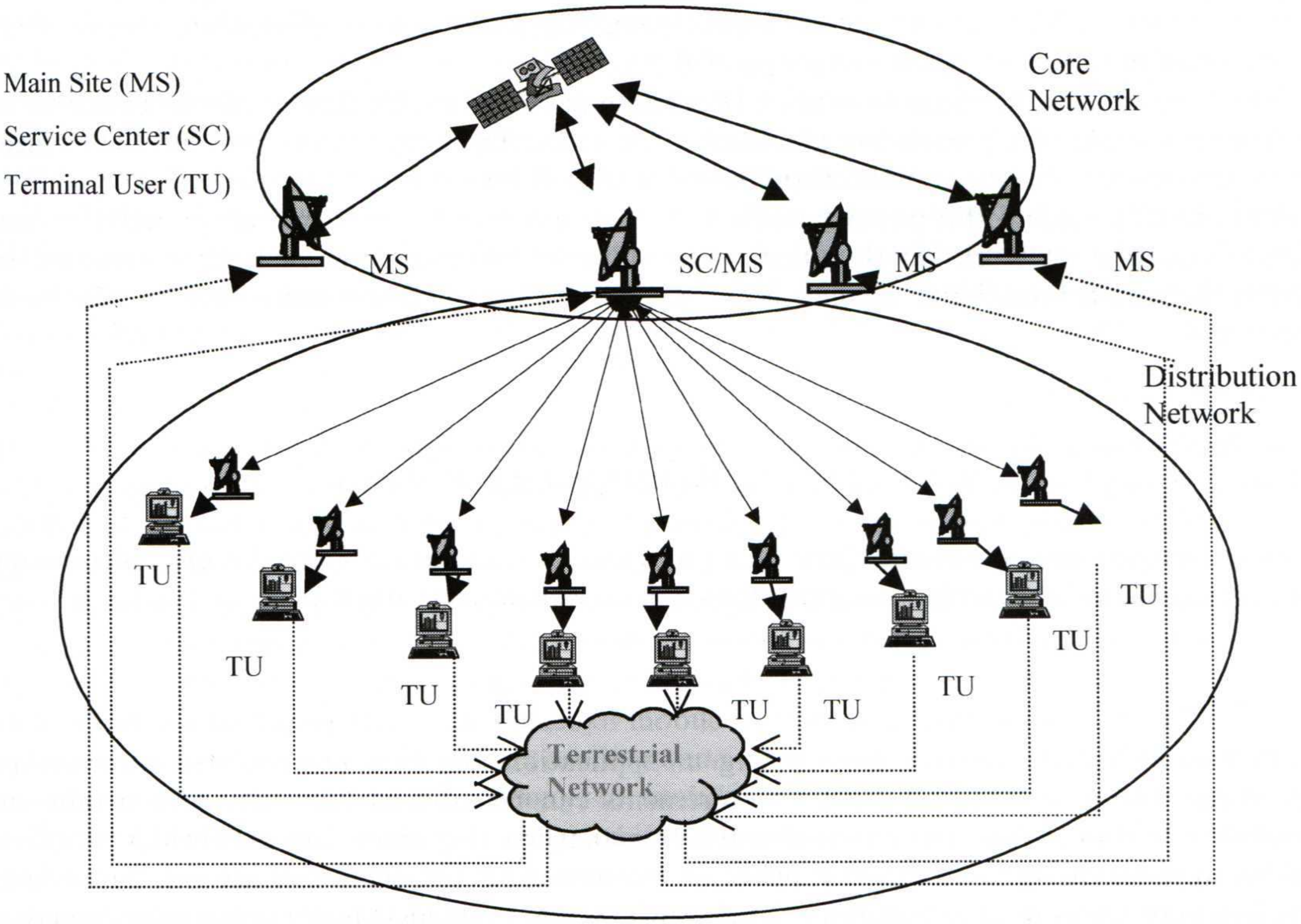


Figure 2. Teleeducation network example.

Service Centre: A Service Centre (SC) is an interconnection node between the two networks and is aimed at storing and distributing the multimedia data and contents flowing from the core network to the distribution network. It could also provide necessary network control and management functions. The network concept has been further explained in a real system example in Section 4.

For example, consider a teleeducation program with four main campus in different locations providing remote teleeducation to remote sites which in turn can serve several other campuses as necessary. The services provided by such a teleeducation network include lectures, interactive discussions between teacher and students, accessing on-line database consisting of question papers, answers, special reports and referenced papers. The contents may be stored in each of the main sites or localized in the service centre. Each main site can collect the information flowing from the other main sites, and exchange the data with other sites as required and also send it to the remote sites. It provides service through a WEB interface both to the main sites and the terminal users. The terminals receive the data via satellite assuming an interactive role through a satellite network, if devices for the satellite transmission are located at the TUs; or a terrestrial network through ISDN, ADSL or other technology.

This network configuration can be extended to other applications such as videoconferencing, telecontrol and access to remote sensors and telemedicine. This concept provides certain critical design issues such as selection of orbital configurations e.g. low Earth orbit (LEO) or medium Earth orbit (MEO) for real-time and geostationary Earth orbit (GEO) for non-real-time on-board processing and switching as needed, intersatellite linking vs ground gateways, Earth coverage vs spot beam antennas and master control network centres. The discussion of these system design issues is outside the scope of this paper.

The teleeducation application over an IP satellite discussed in this section requires bandwidth guarantees, delay, delay variation and packet loss rates. The architectures and models to meet the necessary service requirements form the basis of QoS for satellite IP networks. Some of these issues are discussed in this paper based on the research efforts, standardization activities and some industrial network developments. This type of configuration is further explored in detail through a broadband satellite network architecture suitable for multimedia services in Section 4.

3. QUALITY OF SERVICE FRAMEWORK

This section defines end-to-end QoS, and provides an overview of terrestrial QoS technology background. It also describes satellite IP QoS requirements and objectives.

3.1. What is QoS

QoS is the ability of a network element (e.g. an application, host or router) to have some level of assurance that its traffic and service requirements can be satisfied. QoS manages bandwidth according to application demands and network management settings. The bandwidth allocated to an application in a resource reservation is no longer available for use by 'best-effort' applications. QoS-enabled high-priority applications must not disable the low-priority Internet applications.

According to ISO 8402, QoS is defined as 'the totality of characteristics of an entity that bear on its ability to satisfy stated and implied needs'. ISO 9000 defines quality as the degree to which a set of inherent characteristics fulfils requirements. ITU-T Recommendation E.800 defines QoS as 'the collective effect of service performance which determine the degree of satisfaction of a user of the service' [12]. The end-to-end network performance includes the access network performance and the core network performance. Other ITU-T Recommendations, such as ITU-T I.350 and ITU-T Y.1540 have developed network performance and network interface-network interface QoS. Recently [13], has developed six classes of applications and provided application QoS objectives.

The term QoS is used in many meanings, ranging from the user's perception of the service to a set of connection parameters necessary to achieve particular service quality. A general QoS model, and the approaches are discussed in Reference [14].

According to the ITU/ETSI approach, the different viewpoints of QoS are customer's QoS requirements, QoS offered by service provider, QoS achieved by service provider, and QoS perceived by customer. Based on the customer's QoS requirements, QoS offered and achieved by the service provider will be different from the QoS perceived by the customer. A customer's QoS parameters are focused on user perceived effect, and do not depend on the network design. The parameters might be assured to the user by the service providers through contracts.

QoS offered by the service providers is a statement of the level of quality expected to be offered to the customer by the service provider for planning and service level agreements (SLA). Each service would have its own set of QoS parameters. For example, service providers may state that the availability of basic telephony service is planned to be 99.995% in a year with not more than 1 min break at any one occasion and not more than three breaks over the year.

QoS achieved or delivered by the service provider is a statement of the level of quality actually achieved and delivered to the customer. For example, in the previous quarter, availability was 99.97% with five breaks of service of which one lasted 55 min. QoS perceived by the customer is expressed usually in terms of degrees of satisfaction, through customer surveys. For example, rating of 3 on a 5-point scale indicating excellent service. The service provider may not be in a position to offer customers the level of the required QoS. Ideally all these viewpoints are to be converged for a given service.

3.1.1. Mobile satellite QoS. Mobile communication exists between mobile host-to-fixed host and mobile host-to-mobile host. This communication could arise either in a purely wireless satellite or a hybrid satellite with a terrestrial network. In the terrestrial case the definition of QoS and its parameters are still valid. Whereas, in a mobile satellite environment, the mobile QoS is related to bandwidth variation due to mobile host roaming, link delay and nodal congestion. An essential aspect of QoS for mobile systems in LEO or MEO satellite networks, is the handover QoS [15]. As the mobile host migrates from one satellite coverage to another, a connection can be forced due to the failure of mobile handover. These failures are characterized by handover blocking probability. This results due to (a) inability to provide the desired QoS in the new satellite, (b) failure of a gateway, (c) inability to handover in time and (d) failure of satellite. In a mobile satellite IP network architecture these handover QoS parameters include: handover urgency, probability of handover blocking, probability of new packet blocking, traffic disruption period during handovers, packet loss during handovers and speed of handover operation. The IETF is currently working on defining the mobile IP for terrestrial networks.

However, for a global hybrid satellite/terrestrial networks, not much research is reported and QoS architectures and performance models are yet to be developed.

3.2. QoS parameters

There is more than one level of criteria to satisfy different types of traffic (e.g. time sensitive financial, still images, large data, video). For example, the time delay in transferring large files and high-resolution images may not be adequate for voice communication. QoS has become an extremely important issue to be addressed. The QoS parameters are discussed in the following paragraphs.

Delay is the time for a packet to be transported from the sender to the receiver.

For the TCP protocol, higher orders of delay result in greater amounts of data held 'in transit' in the network. This affects in turn the counters and timers associated with the protocol. TCP is a 'self-clocking' protocol, where the sender's transmission rate is dynamically adjusted to the flow of signal information coming back from the receiver, via the reverse direction acknowledgements. Larger delays between sender and receiver make the feedback loop insensitive, and therefore the protocol becomes more insensitive to short-term dynamic changes in network load. For interactive voice and video applications, larger delays are not acceptable.

Jitter is the variation in end-to-end transit delay.

High levels of jitter cause the TCP protocol to make very conservative estimates of round trip time (RTT), causing the protocol to operate inefficiently when it reverts to timeouts to reestablish a data flow. High levels of jitter in UDP-based applications are unacceptable for real-time applications, such as audio or video. Jitter causes the signal to be distorted, which in turn can only be rectified by increasing the receiver's reassembly playback queue. This increases the delay, which is unattractive for interactive applications.

Bandwidth is the maximal data transfer rate that can be sustained between two end points.

This is limited not only by the physical infrastructure of the traffic path within the transit networks, which provides an upper bound to available bandwidth, but is also limited by the number of other flows which share common components of this selected end-to-end path.

Packet loss is defined as the ratio of the number of undelivered packets to the total number of sent packets. It can occur due to a poorly configured or poorly performing switching system which delivers packets out of order or even drops packets through transient routing loops. Unreliable or error-prone network transit paths can also cause retransmission of the lost packets. For example, TCP cannot distinguish between loss due to the packet corruption and loss due to congestion. Packet loss invokes the same congestion avoidance behaviour response from the sender, which reduces the sender's transmit rate.

Reliability is the percentage of network availability depending upon various environmental parameters such as rain and atmospherics. In a satellite-based network, the availability depends on the frequency band of operation, power levels, antenna size and the traffic for the service provided. Advanced error control techniques are used to provide good link availability.

3.3. QoS requirements

ITU-T G.1010 provides a model for user-centric QoS categories. Eight distinct groupings covering a range of applications have been identified. This recommendation provides end-user QoS in terms of delay and packet loss for different service categories as shown in Figure 3. This model can be used as a guideline irrespective of the transport technology e.g. IP, ATM,

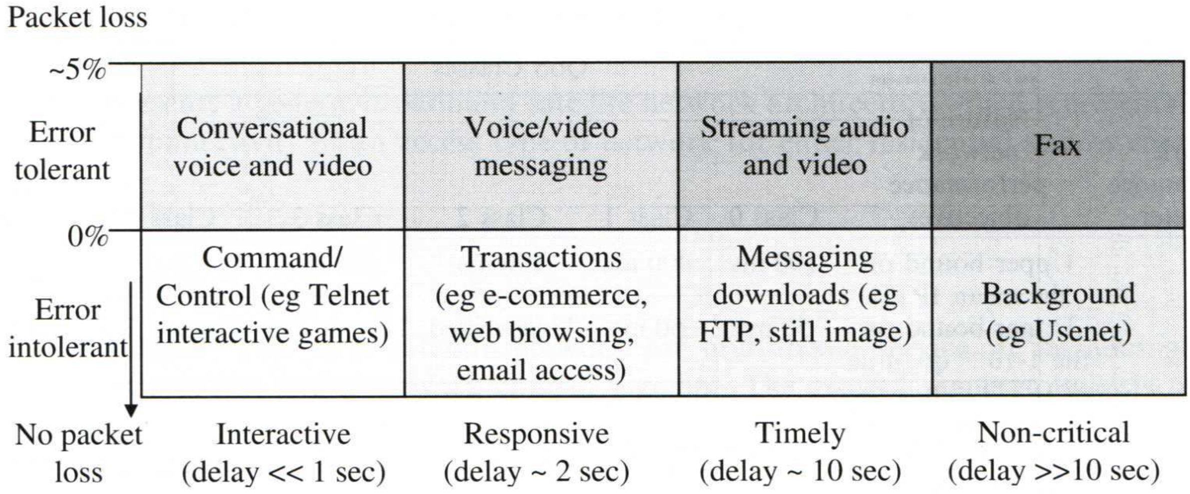


Figure 3. Application QoS requirements (ITU-T G.1010).

terrestrial, wireless. This can be used as the basis for deriving realistic application specific QoS classes for differentiating service performance [16].

3.4. IP QoS objectives

Reference [13] defines six QoS classes which are intended to be the basis of agreement between end users and network service providers and between service providers. These QoS objectives are applicable when access link speeds are at T1 or E1 rate or higher. Table I provides the provisional IP QoS class definitions and network performance objectives. These must be evaluated for satellite transport. The network performance parameters include:

- IP packet transfer delay (IPTD).
- IP packet delay variation (IPDV).
- IP packet loss ratio (IPLR).
- IP packet error ratio (IPER).

3.4.1. Satellite IP QoS objectives. The use of geostationary satellites was considered during the study of the hypothetical reference paths (HRPs). A single geostationary satellite can be used within the HRPs and still achieve end-to-end objectives on the assumption that it replaces significant terrestrial distance, multiple IP nodes, and/or transit network sections. The use of low- and medium-Earth orbit satellites was not considered in connection with these HRPs.

When a path contains a satellite hop, this portion will require an IPTD of 320 ms, to account for low Earth station viewing angle, low rate time division multiple access (TDMA) systems or both. In the case of a satellite on-board processing capabilities, 330 ms of IPTD is needed, to account for on-board processing and packet queuing delays.

It is expected that most HRPs, which include a geostationary satellite, will achieve IPTD below 400 ms. However, in some cases the value of 400 ms may be exceeded. For very long paths to remote areas, network providers may need to make additional bilateral agreements to improve the probability of achieving the 400 ms objective. Reference [13] serves as a guideline but the application QoS mapping needs a detailed study. The issue of the delay requirements for

Table I. Provisional IP QoS class definitions and network performance objectives.

		QoS Classes					
Network performance parameter	Nature of network performance objectives	Class 0	Class 1	Class 2	Class 3	Class 4	Class 5 Unspecified
IPTD	Upper bound on the mean IPTD	100 ms	400 ms	100 ms	400 ms	1 s	Unspecified
IPDV	Upper bound on the 1-10^{-3} quantile of IPTD minus the minimum IPTD	50 ms	50 ms	Unspecified	Unspecified	Unspecified	Unspecified
IPLR	Upper bound on the packet loss probability	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	Unspecified
IPER	Upper bound	1×10^{-4}					

such satellite IP networks covering remote areas and on-board buffering models to meet the specific user applications needs further investigation.

3.5. *End-to-end satellite QoS*

From a user perspective, end-to-end QoS in satellite/terrestrial network depends on the QoS achieved at each layer of the network based on satellite-dependent and -independent functions to be performed at the layer interfaces. QoS requires the co-operation of all network layers from top to bottom, as well as every network element. At each layer, the user performance requirements are achieved by using efficient technologies and counteracting any factors for performance degradation.

For example, at the physical layer, bandwidth efficient modulation and encoding schemes have to be used to improve the bit error rate (BER) and power level performance under weather conditions such as rain. Similarly, a superior QoS is achieved providing guaranteed bandwidth at the link layer using efficient bandwidth on demand multiple access schemes and studying the interaction of mechanisms in the presence of congestion and fading. The provision of a specific bandwidth to be offered by the physical layers to the upper layers implies the existence of a bandwidth allocation scheme that shares the bandwidth available among the different user terminals with different traffic classes. To satisfy the different QoS service level guarantees, service classification, marking, queuing and scheduling functions provide the services according to the SLAs in the case of DiffServ at the network layer. The TCP protocol needs to be optimized for guaranteed throughputs, delay and minimum delay variations over a satellite environment mitigating the link impairments as discussed in Section 8.

To achieve such an end-to-end QoS in both satellite and/or hybrid satellite/terrestrial networks is a non-trivial problem. The recent literature shows good progress in bandwidth allocation schemes and TCP enhancements. However, end-to-end QoS objectives including security need a considerable research. A successful end-to-end QoS depends upon the proper interface design at each subsequent layer—lower to the higher. These ideas are explained through ETSI BSM architecture in Section 4.

4. SATELLITE NETWORK ARCHITECTURE

This section presents a generic broadband satellite network architecture which represents either a user-to-user connectivity or an access type of network for either residential and/or enterprise users.

4.1. Broadband satellite network

Figure 4 illustrates broadband satellite network for multimedia service. It includes ground segment, space segment and a network control segment. The ground segment consists of user terminals, gateways and the network control centre. The various functions of the system elements are as follows.

User terminal: User terminal (UT) is located at user premises e.g. corporation or residence. The users access the services offered by the providers over a satellite network. These users could be connected to the terminal as part of a local area network (LAN) or individually. User terminals include some application PCs which access the satellite via gateways.

Gateways: The gateways provide the interface between the satellite network and the Internet or any service provider. Gateway functions involve in all the protocol layers with specific functions of the satellite link. The gateway performs resource allocation, and end-to-end security depending on the type of implementation. An example of TCP performance enhancement proxies (PEP) gateway is discussed in Section 8.3.

Satellite segment: Satellite segment could consist of one or more GEO satellites. Depending on the system design, either intersatellite links are provided or a ground intersatellite link gateway could be used for establishing end-to-end connectivity. In access networks, a non-regenerative or bent pipe payloads are proposed. To support personal and mobile broadband

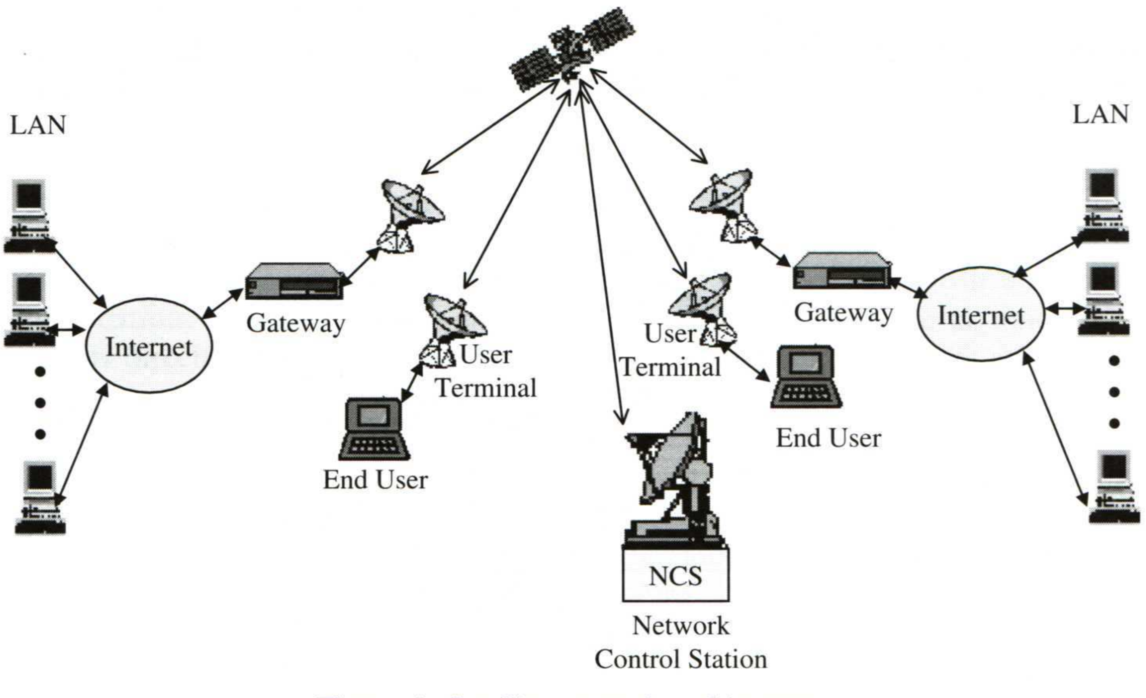


Figure 4. Satellite network architecture.

communications via satellite, new IP-based network infrastructure must be developed. For such future architetures, QoS guarantees is a critical system requirement [17].

Network control station (*NCS*): NCS provides overall control and management of the satellite network. The functions include, resource allocation, congestion control, performance monitoring and reporting.

To illustrate a broadband satellite network meeting the challenge of future applications, the following sections describe ETSI QoS architecture standardization effort.

4.2. Protocol architecture—ETSI

Figure 5 shows protocol architecture for a broadband satellite multimedia (BSM) proposed by ETSI [18]. This figure shows the satellite-dependent and -independent functionality at the different layers shown. A satellite-independent service access point (SI-SAP) is defined for the air interface to separate the satellite-independent upper layers from the satellite-dependent lower layers. It allows transport layer protocols alternative to TCP and UDP and introduces an access point independent of the satellite technology. The services offered by the lower layers provide the necessary QoS mapping at the higher layers. The architecture is not restricted to the current used protocols only. However, a complete end-to-end QoS realization of a broadband network depends upon the specific resource allocation algorithms, link impairments mitigation techniques, congestion control and classification of service mechanisms. These issues are addressed in later sections.

4.3. Satellite IP QoS functions

A functional model for a possible implementation of BSM QoS which consisting of two main functional components is developed in Reference [18]. These components are: (a) control plane functions that establish BSM bearer services in response to user demands which includes BSM bearer service control above the SI-SAP and the related bearer service manager below the SI-SAP, (b) user plane functions that operate on the individual packets which includes packet classification and packet conditioning functions above the SI-SAP and admission control

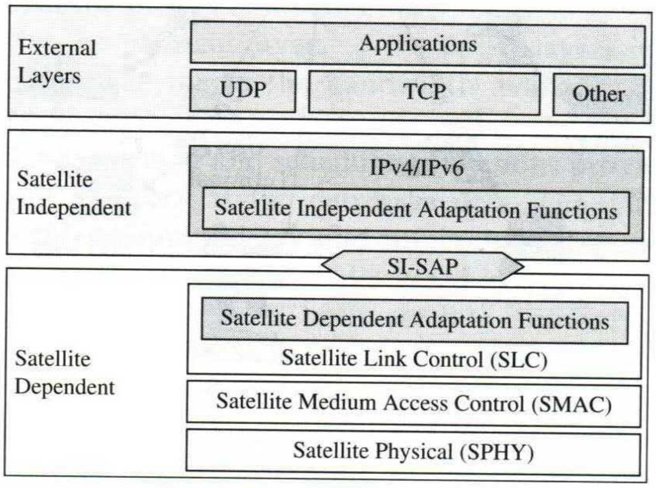


Figure 5. ETSI: BSM protocol architecture.

Table II. QoS functions mapping.

System element	Role	QoS function	QoS parameters
Customer network	IP packet generation and forwarding packet marking	QoS parameters generation	Throughput End-to-end delay
SI-SAP	Segmentation/reassembly queuing bandwidth on demand FEC/modulation/transmission	Packet marking Admission control Congestion control Power control Adaptive coding	Cell/packet delay packet loss BER Throughput symbol rate Power level
Payload bent pipe	Transmission	None	None
Payload OBP	Demodulation/remodulation decoding/encoding Queuing Switching Scheduling Routing	Pre-emption Congestion control Power control Code control	Cell/packet delay packet loss BER Throughput symbol rate Power level
Satellite access	Segmentation/reassembly Queuing Bandwidth on demand FEC/modulation/transmission ATM adaptation (as needed)	Packet classification Packet marking Admission control Congestion control Power control	Cell/packet delay packet loss BER Throughput symbol rate Power level
Network Control centre	Network management performance monitoring	Policy management bandwidth management Security, reporting	Security level bandwidth efficiency

functions below the SI-SAP. The subscription control function provides the authorization for all users transactions, both C-plane and U-plane.

Table II describes the QoS functions of satellite network elements and also the QoS parameters [19]. These functions described do not reflect the layer by layer, but help define QoS classes to be mapped with the IP QoS at the higher layer. The QoS functions are managed through control actions at different elements of the system discussed in the next section. A proper satellite network design with a particular business model and the applications to be serviced dictate the QoS parameter values. The objectives for a satellite IP network for six classes of service are provided in Table I. These need to be reviewed with a specific satellite system, application, simulation and measurements to validate. A substantial amount of work is needed in this direction to provide guidelines to satellite network designers and operators.

4.4. QoS management functions

The QoS management includes the following control functions which are allocated to the terminals, gateways, payload and the network control centre. These functions depend on the specific system designs including on-board processing and switching [20].

- *Admission control* decides if a new connection can enter the network by verifying if the overall resources are sufficient or not to guarantee a fixed level of QoS and if the new call can be accepted or rejected.

- *Traffic control* has the role of shaping the traffic and verifying if it is conformant with the declaration contained in the traffic contract (and the relative expectations of the schedulers).
- *Scheduling* decides the service discipline in the queues and the packets to be transmitted. In particular, scheduling algorithms are required to respect priorities and bandwidth assigned to different traffic classes deserving a specific QoS.
- *Buffer management* sets the buffer sharing policy and rules the volumes of data that can be managed by a single node.
- *Congestion control* rules the amount of data flowing through the network so as to equilibrate the different speed of the nodes in the network. The aim is not to overwhelm a slow node overcoming its management capacity. Congestion control may be applied also at different portions of the network.
- *QoS routing* decides the best route to the destination, verifies if the path has sufficient resources and often optimizes resource distribution through the path. Metrics such as delay and bandwidth heavily depend on the QoS routing strategy.

The QoS functions and parameters discussed in Sections 3 and 4 are elaborated further in the rest of the paper following the end-to-end QoS layer concepts, surveying the issues, research results and the future work needed through examples.

5. PHYSICAL LAYER QOS

Due to the new applications for IP satellite services, there is a great interest among satellite network designers to apply advanced technologies to increase the data handling capacity of the existing and planned satellite transponders. The advanced technologies are essentially characterized by the way they improve either power performance (E_b/N_o) or bandwidth efficiency (bps/Hz) or both. Another important criteria to achieve guaranteed QoS is rain attenuation and fade mitigation techniques. In this section, a brief overview of such mitigation techniques are given for completeness. Further details can be obtained from References [21–24].

An account of modulation and encoding techniques, adaptive coding, power control and diversity is given in the following sections.

5.1. Modulation and coding

5.1.1. Modulation. In a satellite system, data rate, modulation and coding choices drive link availability, required transmitter power and required bandwidth. Modulation choices must also consider transponder linearity and adjacent channel interference. Quadrature phase shift keying (QPSK) is the existing modulation scheme. Higher-order modulation is being studied to increase the achievable bps/Hz compared to the more common QPSK. The two most common higher-order waveforms available in off the shelf products are 8-PSK (phase shift keying) and 16-QAM (quadrature amplitude modulation). 8-QPSK is spectrally more efficient. Depending on the implementation, it may be operated with a non-linear (saturated) power amplifier at the Earth station and/or satellite transponder. Turbo coding compensates for power increase requirements with use of 8-PSK. However, the 16-QAM signal must be used [25] with linear channels—which can significantly reduce the link C/N_o compared to a saturated transponder. It generally is not applicable for small terminal satellite applications.

5.1.2. Coding. Coding choices must consider packet sizes and flush bit overhead. Concatenated convolutional and block coding generally has an acceptable overhead and has flush bits for small IP packets. With turbo coding, significant performance enhancements are possible. Convolutional latency and flush bits must be evaluated for small IP packets. The main advantage of turbo coding is that it reduces the E_b/N_o needed to close a link at a given code rate. Known turbo codes at reasonable block size and the complexity can come quite close to the Shannon channel capacity limit (within about 1–2 dB) [26]. For instance, an $R = \frac{1}{3}$ turbo code can achieve a BER of about 10^{-7} at an $E_b/N_o = 1$ dB with a block size of less than 2000 bits. Reducing the code rate to $R = \frac{1}{4}$ would reduce the E_b/N_o required to about 0.7 dB. The turbo codes are being standardized for digital video broadcasting—return channel via satellite (DVB-RCS) systems.

5.2. Adaptive coding

The use of adaptive coding allows a satellite system to be throughput efficient while at the same time conserving its most valuable resource—satellite electrical power. The principle relies on the fact that powerful modern coding techniques allow constant user data throughput by employing heavy code in a link-by-link basis depending on the link conditions at any point in time. Algorithms can be used which allow automated sensing of degrading and improving link conditions. One way of adapting throughput is to control the coding rate (always less than 1), which is defined as the ratio of the number of input bits to the encoder to the number of output bits. The channel symbol can be a QPSK symbol or a generalized time and/or frequency slice of a waveform [27].

There are other possible adaptation schemes, some involving direct adaptation of the bandwidth. All involve effective changes in coding rate, but clearly other factors can also be varied. The focus is exclusively on those systems which only vary the throughput by adapting the coding rate. Thus, in particular, the duration of a channel symbol is assumed constant, or stated another way, the bandwidth of the transmission is constant.

Efficient adaptive coding systems allocate as little system capacity as possible to link margin. Typically, the most critical link margin is calculated at the edge of beam where, for a fixed size receive Earth station, it is at a minimum. Under the assumption that the GSO satellite effective isotropically radiated power (EIRP) is backed off at higher terminal elevation angles, it may be assumed that the worst-case, edge-of-beam link margin is constant for all beams in the GSO system.

Reference [27] describes that for a 6–8 dB rain attenuation design goal, a 0.9 dB/s fade slope can be accommodated 99.9% of the time. Given this fade slope, a prudent system design with adaptive coding control at a network control centre requires 1 dB of clear-sky margin so that the system BER design goal can be maintained.

In order to protect service availability from rain events, excess down link margin in an adaptive coding system allows each terminal enough time to: (1) determine that a rain event is going to cause, with high probability, performance incompatible with the present coding state, (2) request a new coding state via a centralized protocol and (3) respond to a command from the regional network control centre to change the coding state, given that the terminal's request is granted.

5.3. *Power control*

This section provides an important issue of compensation of rain attenuation through power control for uplink and downlink [28].

5.3.1. Uplink power control. The uplink power control approach for dynamic allocation of additional power to the transmit carrier(s) at an Earth station is used in order to compensate for rain attenuation. Three types of power control techniques can be considered:

- *Open loop*—One station receives its own transmit carrier and must rely on its measurement of beacon fading in the downlink in order to perform uplink power control.
- *Closed loop*—Two Earth stations are in the same beam coverage and an Earth station can receive its own transmit carrier. Uplink power control based on this carrier is erroneous due to changes in input and output backoffs under uplink and downlinks fading. It needs to be on the reception of a distinct carrier transmitted from another station.
- *Feedback loop*—A central control station monitors the levels of all carriers it receives, and commands the affected Earth stations to adjust their uplink powers accordingly. This technique has inherent control delays, and requires more Earth segment and space segment resources.

5.3.2. Downlink power control. This technique allocates additional power to the transmit carrier(s) at the satellite in order to compensate for rain attenuation. As the downlink fading occurs, downlink carrier power degrades and sky noise temperature seen by the Earth station increases. Power control correction of approximately 1.5 times fade is required to maintain carrier to noise ratio. The reader is referred to further details on these in Reference [29].

5.4. *Site diversity*

This technique involves tandem operation of two Earth stations, and exploits the finite size of rain cells (5–10 km). Fading at sites separated by distances exceeding the average rain cell size are expected to be correlated. Diversity gain or the reduction in link margin depends on site separation, frequency, elevation angle and baseline orientation angle [29].

6. LINK LAYER QOS—BANDWIDTH ALLOCATION

At the link layer, medium access control (MAC) schemes should be adapted to provide QoS. Recently, IP-based broadband satellite access systems for interactive multimedia services are being developed using multifrequency-time division multiple access (MF-TDMA). In MF-TDMA systems, the dynamic bandwidth allocations providing QoS for different classes of service is a critical issue. Historically, several experiments were done on SATNET [30, 31] testing the feasibility and extensibility of various multiple access schemes and performance evaluation of packet satellite networks [31]. During the past several years, multiple access, demand assignment multiple access and dynamic bandwidth allocation algorithm have been studied extensively and results were presented in the literature. A number of TDMA-based multiple access schemes have been proposed in References [32, 33] which span from fully random access schemes such as ALOHA to hybrid reservation DAMA schemes at the other end of the spectrum. However, for broadband interactive satellite networks, for global and regional systems, an MAC protocol has to be standardized. Several proprietary versions of MAC protocols exist for satellite systems under development. A comprehensive performance comparison of various MAC protocols is reported in References [32, 34–40]. A comparison of DAMA techniques for circuit and packet switched systems [33] is described.

To successfully provide user guaranteed QoS satisfaction for broadband satellite networks, the following issues need further research.

Bandwidth on demand (BoD) or dynamic bandwidth allocation algorithms: BoD should be developed to handle different classes of service over a satellite IP network similar to QoS definitions developed by traffic management in satellite ATM networks [41, 42]. An example of this using DiffServ over a satellite IP network is described in Section 7.3. The interface offered should be independent of the technology, so that IP, acting at the upper layer, may use the services. The MAC protocols providing guaranteed bandwidth could be addressed either for bent pipe or on-board processing satellite network. References [43, 44] provides an initial set of performance results as discussed in Section 6.2.

Interaction between BoD and transport layer protocols: To provide system flexibility in terms of bandwidth allocation at the MAC layer and supported by the upper layers using TCP protocol should be addressed. Very little research is reported on achieving sufficient TCP throughputs for BoD systems over satellite links. Reference [45] provides performance of BoD in terms of the TCP enhancements for a satellite network as discussed in Section 6.2.2.

Interaction of BoD and network congestion: Even though traditional TCP treats all errors as being due to congestion, several improvements have been performed to take into account link impairments for satellite links. There is a considerable capacity incompatibility in a backbone network and access network. The network infrastructure which results in congestion points at the access portion resulting in performance degradation. This issue needs to be addressed for a proper selection and performance of BoD or bandwidth allocation schemes.

Bandwidth allocation with fading: In multiservice broadband networks, to provide the desired level of performance under varying traffic conditions, proper control mechanisms should be devised. In particular, for satellite systems, dynamically varying fading conditions, caused by adverse atmospheric events (e.g. rain, hail or snow) can heavily affect the transmission quality, especially at Ka band. Reference [46] has addressed the problem of resource allocation with fading at the link layer.

As an alternative to MF-TDMA, a code division multiple access (CDMA)-based spread ALOHA multiple access with single code and its variants for return channel of a broadband satellite network are proposed and developed. The performance is discussed in Section 6.3.

6.1. IP satellite network example

Figure 6 shows an example of broadband satellite network using the digital video broadcasting via satellite (DVB-S) protocol standard for the forward channel and the DVB-RCS standard for the return channel [47, 48]. The *forward* channel refers to the link from the gateway that is received by the user terminal and the *return* channel is the link from the user terminal to the gateway.

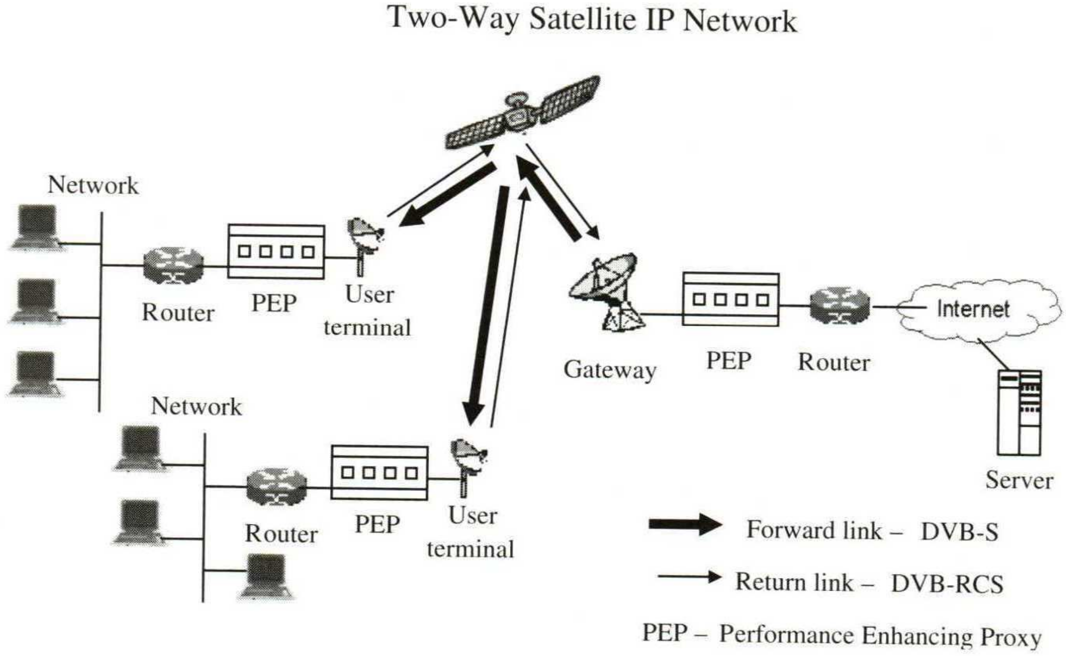


Figure 6. IP satellite network.

The two-way interactive satellite Internet access network also presents a network asymmetry environment. The DVB-S forward link is about 38–45 Mbps and return link using satellite is with around 20:1 or higher asymmetry. To accommodate such network path asymmetry, several mitigation techniques have been proposed [49, 50]. In the DVB network, *a satellite* forward and return links typically use frequency bands in Ku (12–18 GHz) and/or Ka (18–30 GHz). The return links use spot beams and the forward link global beams are used for broadcasting and Ku-band.

The DVB example network elements consist of an Enterprise Model, SLA, and TCP PEP, the gateway and the user terminal. The target applications of the DVB network could be Small and Medium Enterprises and residential users. In business-to-business applications, the user terminal is connected to several user PCs via an LAN and a router. The gateway implements the forward link via a conventional DVB-S chain (similar to digital TV broadcasting) whereby the IP packet is encapsulated into DVB-streams, IP over DVB. The return link is implemented using the DVB-RCS standard 'MF-TDMA Burst Demodulator bank', IP over ATM like. The gateway is connected to the routers of several Internet service provider (ISPs) via a broadband access server. It maps the traffic of all user terminals belonging to each ISP satellite. To allocate the bandwidth to these user terminals in such a network, an efficient dynamic bandwidth allocation algorithm is critical.

6.2. MF-TDMA bandwidth allocation

In the above IP satellite example, the DVB-RCS standard provides the various bandwidth allocation approaches as below. However, these approaches need dynamic allocation algorithms and scheduling mechanisms to provide the user QoS. A brief discussion on the capacity allocation and the current research results on the allocation is discussed.

Continuous rate assignment (*CRA*): Rate capacity (in slots/frame), is provided to the satellite interactive terminal (SIT) in full when needed and reserved for the duration of connection. The bandwidth is negotiated at call set-up between the SIT and the call processing function of the network management system (NMS) and configured in the scheduler. CRA is typically used for real-time applications e.g. voice, video streaming—(CBR, rt-VBR). The features of CRA include fixed guaranteed bit rate, no scheduling latency, minimum delay jitter.

Rate-based dynamic capacity (*RBDC*): In RBDC, requests are made in slots/frame up to a maximum booked value (maxRBDC), and configured into the scheduler by the NMS at connection set-up. The capacity is guaranteed for a number of successive frames, until a new request is made or until a time-out expires. RBDC is used for nrt-VBR, ABR applications. It is tolerant to scheduling delay and suitable for jitter tolerant applications.

Volume-based dynamic capacity (*VBDC*): Requests are made for absolute volume, in number of slots, with no time constraint by the SIT. Bandwidth in VBDC is assigned for a specific period only if both the conditions are met: (a) all CRA capacity has been assigned the SIT population for that frame period (b) the SIT population guaranteed assignment has not been reached or there is unused capacity available. VBDC typically is used for ABR and UBR services which are tolerant for scheduling latency, and delay jitter.

Free capacity assignment (*FCA*): Free capacity represents the capacity left after all requests have been satisfied and there are no signaling requests from SITs. FCA is assigned for a specific period after all CRA and VBDC capacity has been assigned for that frame period and if there is unused capacity available. If available, FCA is assigned at a throughput of 16 kbps for a single frame period. FCA can be used for best-effort users.

These capacity allocations methods should be mapped into different DiffServ per hop behaviours to provide end-to-end application QoS for different applications. This problem has been addressed by Ronga *et al.* [43] and Iuoras *et al.* [44].

6.2.1. Demand assignment multiple access. The issue of bandwidth allocation in response to the user requests on a dynamic basis has been very well addressed in the literature. In particular, dynamic bandwidth allocation using reservation algorithms increases the network throughput. The reservation process can be implicit or explicit. In explicit reservation over a TDMA satellite channel, a reservation slot is assigned to each terminal within the control subframe of every TDMA frame. In implicit reservation, the terminals normally use a random access using slotted ALOHA protocol to request for the reservation slots. Based on this concept, combined free/DAMA (CFDAMA) and its modifications using weighted W_CFDAMA, weighted round-robin R_CFDAMA have been developed [51,52]. A PRedictive DAMA (PRDAMA) to allocate free bandwidth based on an estimate of the positive varying trend of Internet traffic at each terminal has been proposed and analysed [53]. The average delay results of PRDAMA have been compared with other protocols and it has been found that PRDAMA is superior to others providing a lower average delay over a wide range of throughput values. Also, average delay jitter for higher throughput > 0.5, is found to be lower than the other DAMA protocols compared.

6.2.2. Bandwidth on demand with TCP. Another important issue relating to bandwidth allocation is the performance of bandwidth-on-demand (BoD) algorithms, sometimes called as the DAMA algorithms, in the presence of transport layer protocols such as TCP. A BoD system provides a range of QoS classes to support different user applications. The performance achieved by a TCP flow using such a BoD satellite network is highly dependent on the delay and the variation of the delay experienced by TCP. This issue of TCP enhancements for satellite links under BoD requirement in an interactive satellite network has not been fully addressed. However, Reference [45] has described the BoD mechanisms, and their expected impact on TCP behaviour and studied the performance through simulations using an implementation of TCP combined with a model of some simple satellite BoD access schemes to characterize the performance and efficiency of BoD algorithms.

6.2.3. Bandwidth allocation with fading. For satellite systems, dynamically varying fading conditions, caused by adverse atmospheric events can heavily affect the transmission quality, unless adaptive fade countermeasure techniques are adopted. In essence, fade countermeasures address the physical layer requirement of keeping the BER below a given threshold, whatever the channel degradation may be, within a certain operating range, beyond which the station is declared to be in outage conditions. A control architecture for resource allocation in satellite networks is proposed, along with the specification of performance indexes and control strategies. One of the control strategies is based on some knowledge of the fading conditions over the satellite network channels. The master Earth station assigns the available bandwidth among traffic Earth stations depending on traffic. The traffic Earth stations measure their signal fade level continuously which is used by the master station to decide whether the assignment can be made static, based on the a prior knowledge of long-term fading statistics, or dynamic, based on the updated measurements. More details on the performance of resource allocation under fading can be obtained from Reference [46].

6.3. CDMA-based return channel multiple access

A CDMA-based Spread ALOHA single code multiple access scheme for broadband satellite return channel is proposed as an alternative to MF-TDMA DVB-RCS. Also CDMA can be considered as a connection multiple access scheme when the assignment of the available set of codes is made on a per-user basis after an initial set-up process. For voice applications or continuous flow of information this strategy can be efficient. However, it may lack flexibility when dealing with bursty traffic. In this case contention policies also based on CDMA become more suitable. In Reference [54] a performance comparison between slotted ALOHA, CDMA and multiple ALOHA multiple access (MAMA) is presented. Authors conclude that by using error control coding the CDMA packet radio exhibits higher peak throughput, less delay (for low offered load) and much better stability than MAMA [54, 55].

Spread spectrum ALOHA with one single code can be implemented in two ways: spread aloha multiple access (SAMA$^{\text{TM}}$) and code reuse multiple access (CRMA$^{\text{TM}}$). SAMA$^{\text{TM}}$ repeats the code or spread sequence every symbol. Conversely, CRMA$^{\text{TM}}$ uses one single code as long as the packet. For convenience, these are referred to as spread ALOHA once code (SAOC) and spread ALOHA one long code (SAOLC), respectively, [56]. Figures 7 and 8 show the performance for different maximum number of simultaneous users without considering interference effects.

The throughput performance results show that SAOLC throughput increases above SAOC throughput as the maximum number of simultaneous users increases. This demonstrates that SAOLC is limited by interference while SAOC is limited by collisions. SAOLC follows the curve $Y = X$ from low loads up to about 0.5, and up to 12 users. The throughput increases almost to 0.85 for 60 users up to 200 users. These regions present virtually no packet loss. SAOLC degrades rapidly as the load approaches $N_{\max}$ while the interference increases significantly. Thus, SAOC behaves better for higher normalized offered traffic.

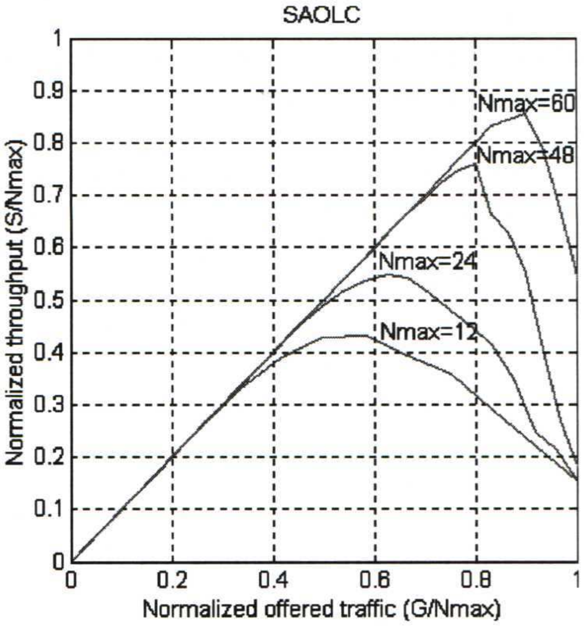


Figure 7. SAOLC normalized throughput for different number of users.

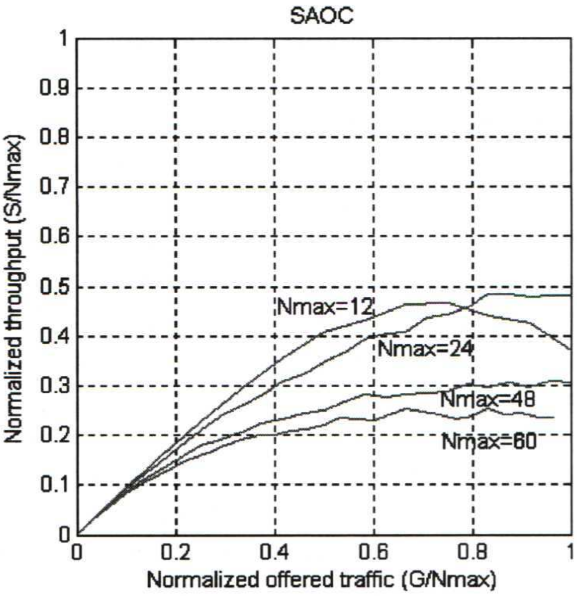


Figure 8. SAOC normalized throughput for different number of users.

Future satellite broadband systems could consider these return channel protocols for high bandwidth return interactive channel since they present good normalized throughput characteristics. However, the implementation complexities and the application suitability for real system needs further study.

7. IP QOS ARCHITECTURES

The current Internet treats all IP packets equally on a best-effort basis. The data applications which are not delay sensitive, might receive satisfactory performance. But the performance for delay sensitive applications such as voice and video over satellite has been poor. To improve the QoS performance for multimedia applications, three different approaches have been proposed [57–59]. A simple and scalable system to verify QoS in a differentiated services domain has been developed using edge-to-edge monitoring approach with measurement agents collecting information about delays, losses and throughput, and reporting to a service level agreement monitor (SLAM). The SLAM detects potential service violations, bandwidth theft, denial of service attacks and flags the need to redimension the network domain or limit its users. This research results could be extended for a satellite network designs also [60]. These IP QoS schemes are proposed for terrestrial access of the Internet only. Many satellite systems are currently supporting Internet applications and many more are planned. However, there are no current QoS provisioning architecture standards for the support of multimedia services over satellite IP [61].

In this section, IntServ and DiffServ mechanisms are described. Some performance results reported recently on UDP (for real time) and TCP (for non-real time) traffic supported for a GEO satellite network with DiffServ are provided. A brief discussion of MPLS traffic engineering applied to such an application is also included.

7.1. IP QoS models

The QoS mechanisms for terrestrial IP networks are briefly discussed below.

7.1.1. Integrated services (IntServ). IntServ is a per-flow-based QoS framework with dynamic resource reservation. A specific flow, defined by the vector 'IP source address, IP destination address, TCP/UDP source port, TCP/UDP destination port', is recognized in the network and may deserve a specific treatment. Integrated services are based on an ATM-like paradigm, where each source–destination flow is distinguished. This implies the use of resource reservation, packet scheduling and buffer management, exactly as in ATM technology. It requires that routers through the path traversed keep information about the status of each flow and that the status is periodically refreshed by a signaling protocol, which is used also to communicate the bandwidth needs among the routers. IntServ uses the resource reservation protocol (RSVP) [62] to signal requests. Two types of traffic services are conceived: guaranteed service [63] and controlled load service [64]. The former guarantees a reliable upper bound on the metric 'end-to-end packet delay' based on worst-case assumption. The bound guarantee implies the use of control mechanisms as access control and traffic policing. The latter is aimed at providing a service similar to the level a non-congested router would provide, does not provide any upper bound but still requires packet scheduling and buffer management on per-flow basis. If the network dimension increases, integrated services may be difficult and expensive to manage, even if they could be provided in a small private network.

7.1.2. Differentiated services (DiffServ). DiffServ [65, 66] has been proposed by IETF with scalability as the main goal. It does not distinguish each traffic flow. DiffServ uses the bits type of service (ToS) of the IPv4 packet format to distinguish the packets that need a different treatment within routers. The packets are marked when they enter the network. DiffServ is aimed at overcoming the scalability problem mentioned for the integrated services and do not require per-flow state and signaling. In practice, traffic is divided into classes that deserve a common service in the network. The advantage stands in the aggregation of many flows into a traffic class, whose packets are forwarded in the same way in a router, but the drawback is that no service per-flow can be guaranteed. So, even if a DiffServ network can be adapted to large size, it does not provide per-flow isolation within a class. As seen above, there are applications claiming stringent requirements, which can be met only operating on per-flow basis.

7.1.3. IntServ/DiffServ. Models using IntServ at the edge and DiffServ at the core of the network are proposed to match the service requirements with the need of having a scalable network [67]. Since the use of integrated services does not introduce huge scalability problems, the lack of per-flow mechanisms in the DiffServ approach is not so dramatic and it can be bypassed by proper traffic engineering techniques that assign a proper dimension to the bandwidth pipe assigned to each traffic class. Based on DiffServ/IntServ approaches, a system implementation can be found in Reference [68].

Table III shows a comparison between the features of IntServ and DiffServ.

7.1.4. Multiprotocol label switching (MPLS). MPLS is a technology convergence between ATM and IP. MPLS attempts to set up paths in a network along which packets that carry appropriate labels can be forwarded very efficiently (i.e. the forwarding engine would not look at the entire packet header, rather only at the label and use that to forward the packet). Not only does this allow packets to be forwarded more quickly, it allows the paths to be set up in a variety of ways: the path could represent the normal destination-based routing path, it could represent a policy-based explicit route, or it could represent a reservation-based flow path. Ingress routers classify incoming packets and wrap them in an MPLS header that carries the appropriate label for forwarding by the interior routers.

In the MPLS model, the labels are distributed by a dynamic label distribution protocol (LDP), which effectively sets up a label switched path (LSP) along the label switched routers (LSR). The LDP could be driven off destination-based routing (e.g. OSPF) or from reservation requests (e.g. RSVP) or some other policy-based explicit route. In some sense, LDP is creating label state in the network, but this is not so different from the normal forwarding tables created by routing protocols. It is important to note that this label state is not per packet or per flow,

Table III. IntServ/DiffServ comparison.

Feature	IntServ	DiffServ
QoS assurance	Per flow	Per aggregate
QoS assurance range	End-to-end (application-to-application)	Domain (edge to edge) or DiffServ region
Resource reservation	Controlled by application	Configured at edge nodes based on service level agreement
Resource management	Distributed	Centralized within DiffServ domain
Signaling	Dedicated protocol (RSVP)	Based on DiffServ code point (DSCP) carried in IP packet header
Scalability	Limited by number of flows	Limited by number of classes of service
Class of service (CoS)	Guaranteed service, controlled load, best effort	Best effort and a set of mechanisms for CoS design
Complexity	High	Low
Availability	Yes	Yes

but usually represents some aggregate (e.g. between some source–destination pair). Therefore, the state produced by MPLS is manageable and scalable [69–72].

7.2. *Queue management*

In the interior routers, differentiated packets have to be handled differently. To do so, the router may employ multiple queues, along with some class-based queuing (CBQ) service discipline or simple priority queuing. Generally, delay-sensitive traffic will be serviced sooner, and loss-sensitive traffic will be given larger buffers. The loss behaviour can also be controlled using various forms of random early detection (RED). These disciplines using probabilistic methods to start dropping packets when certain queue thresholds are crossed, in order to increase the probability that higher-quality packets can be buffered at the expense of more dispensable packets.

RED is a congestion avoidance algorithm that detects congestion and keeps the average queue length in a region of low delay and high throughput. During congestion, when routers drop packets, it is very likely that the dropped packets belong to many different connections. By detecting congestion and notifying only a randomly selected fraction of users, RED avoids congestion and the global synchronization problem. It also avoids bias against bursty connections [73, 74].

7.3. *DiffServ TCP/UDP performance*

This section explores the issue of fair allocation of excess network bandwidth between congestion sensitive and insensitive flows in a DiffServ assured forwarding traffic class. A model with a wide range of simulations, varying several factors to identify the significant ones influencing fair allocation of excess satellite network resources among congestion sensitive e.g. TCP and insensitive e.g. UDP flows is developed for GEO, MEO and LEO satellite networks. In the absence of any mechanism to distinguish between out-of-profile traffic of such flows, congestion sensitive flows will get most of the excess network bandwidth. However, if out-of-profile traffic of these flows are ‘coloured’ differently, network can be configured so as to give better treatment to excess packets of congestion sensitive flows and achieve fair allocation of excess network bandwidth. With a view to clearly distinguish between out-of-profile packets of both flows, three levels of drop precedence are required.

The factors that are studied include (a) number of drop precedences required (one, two or three), (b) percentage of reserved (highest drop precedence) traffic, (c) buffer management (Tail drop or Random Early Drop with different parameters), and (d) traffic types (TCP aggregates, UDP aggregates). An experimental design based on analysis of variation (ANOVA) to study the influence of these parameters over the QoS is included.

Three QoS issues are addressed in this simulation study. (a) Three drop precedence levels represented by green, yellow and red which help clearly distinguish between congestion sensitive and insensitive flows. (b) The reserved bandwidth should not be overbooked, that is, the sum should be less than the bottleneck link capacity. If the network operates close to its capacity, three levels of drop precedence are redundant as there is not much excess bandwidth to be shared. (c) The excess congestion sensitive (TCP) packets should be marked as yellow while the excess congestion insensitive (UDP) packets should be marked red. The RED parameters have significant effect on the performance. The optimal setting of RED parameters is an area for further research.

Buffer management techniques help identify which packets should be dropped when the queues exceed a certain threshold. It is possible to place packets in one queue or multiple queues depending upon their colour or flow type. For the threshold, it is possible to keep a single threshold on packets in all queues or to keep multiple thresholds. Thus, the accounting (queues) could be single or multiple and the threshold could be single or multiple. These choices lead to four classes of buffer management techniques—(a) single accounting, single threshold (SAST), (b) single accounting, multiple threshold (SAMT), (c) multiple accounting, single threshold (MAST) and (d) multiple accounting, multiple threshold (MAMT). This simulation assumed SAMT buffer management scheme.

Figures 9 and 10 show reserved rate utilization by TCP and UDP customers with three levels of drop precedence in GEO satellite networks.

UDP customers receive good reserved rate utilization as opposed to TCP customers which show a wide variation in reserved rates with two and three levels of drop precedence [75, 76]. Also the fairness for two and three colours (precedence levels) was studied and it was concluded that with three colours, there was a wide variation in fairness with the best results being close to 1. Fairness is not good in two colour simulations. This analysis was extended to different satellite system configurations with and without on-board processing and studied the influence of BER. In all cases, the results were the same. Further details on the simulation configuration and results can be found in Reference [75].

7.4. MPLS satellite performance

For applications including real-time interactive traffic (e.g. VoIP), real-time non-interactive traffic (e.g. streaming video), and non-real-time traffic (e.g. web traffic) it is necessary to

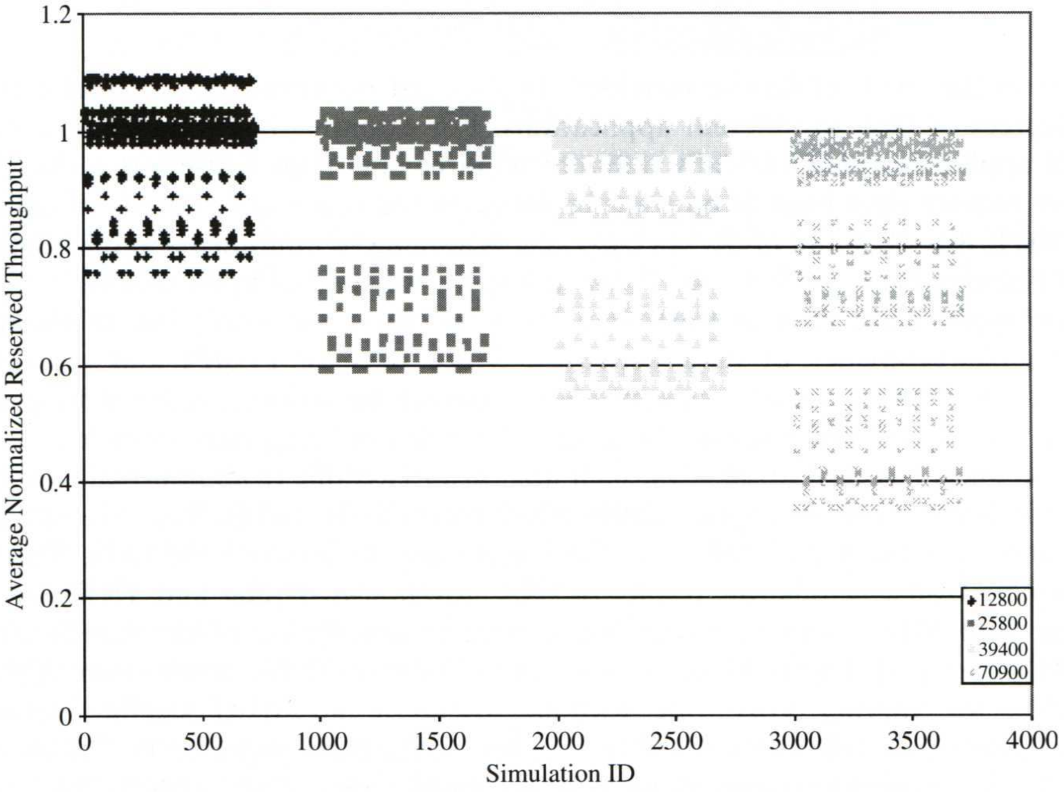


Figure 9. GEO simulation results: reserved rate utilization by TCP customers with three levels drop of precedence.

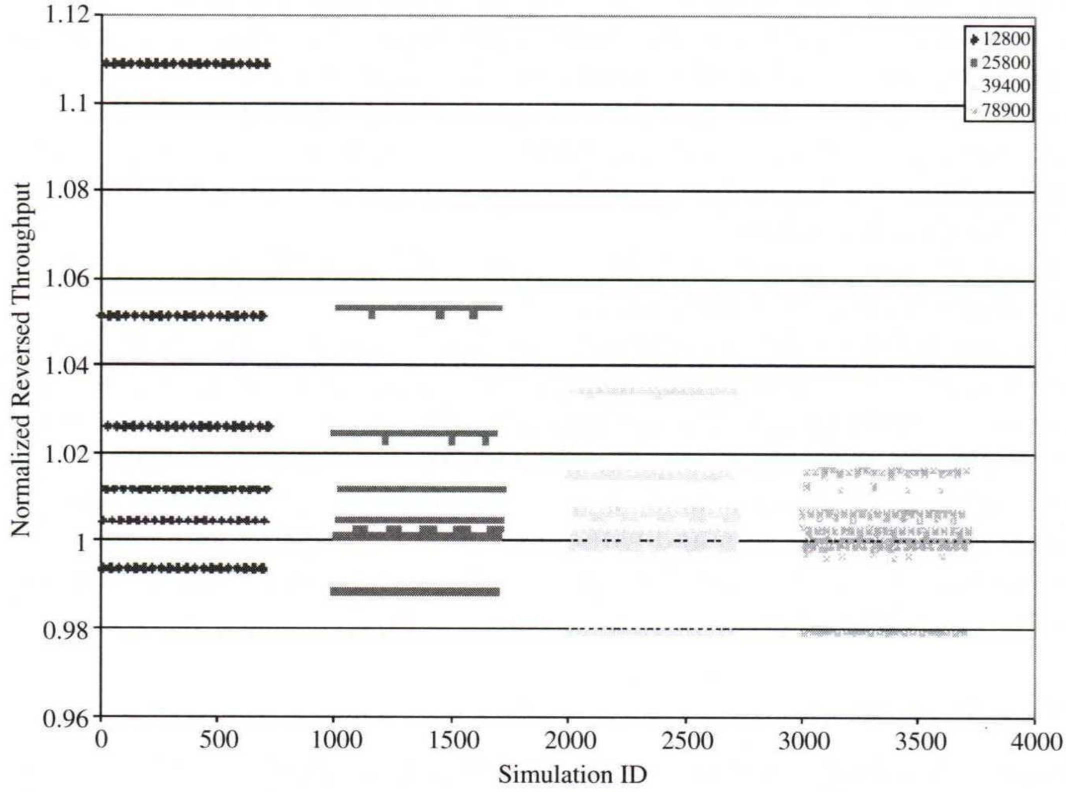


Figure 10. GEO simulation results: reserved rate utilization by UDP customers with three levels drop of precedence.

differentiate in the levels of service provided. High-speed networks should be able to support different degrees of QoS to different applications. For example, real-time traffic generated by multimedia applications has radically different requirements than best-effort traffic. Real-time applications require tight bounds on transfer delay (in the order of hundreds of milliseconds). Secondly, the loss probability of network packets belonging to multimedia applications must be very small (varying from 10^{-12} to 10^{-13} depending on the kind of application).

Real-time applications such as VoIP and streaming video are susceptible to changes in the transmission characteristics of data networks. Voice over IP (VoIP) and real-time traffic (variable bit rate {VBR}) are also susceptible to network behaviours, referred to as delay and jitter, which can degrade the voice application to the point of being unacceptable to the average user. So it becomes essential to separate such high priority traffic from non-real-time traffic e.g. file transfer and route them on explicit paths, which meet the desired QoS requirements. This is a perfect example for the use of MPLS traffic engineering to improve the QoS. The following sections provide some simulation results of TCP for non-real time and UDP for real-time applications with MPLS traffic engineering. Complete description of the simulations can be found in Reference [77]. Figure 11 shows simulations of three traffic flows—two TCPs and one UDP (VoIP), for varying VoIP rate without MPLS in an MEO satellite network. The simulation results show that as the VoIP rate increases, the throughput of TCP flows decreases. In Figure 12, two separate trunks using label switched paths (LSP) with TCP1 routed on a separate LSP while the UDP and TCP2 share another LSP. It can be seen that TCP1 throughput is not affected by the UDP traffic whereas TCP2 is affected.

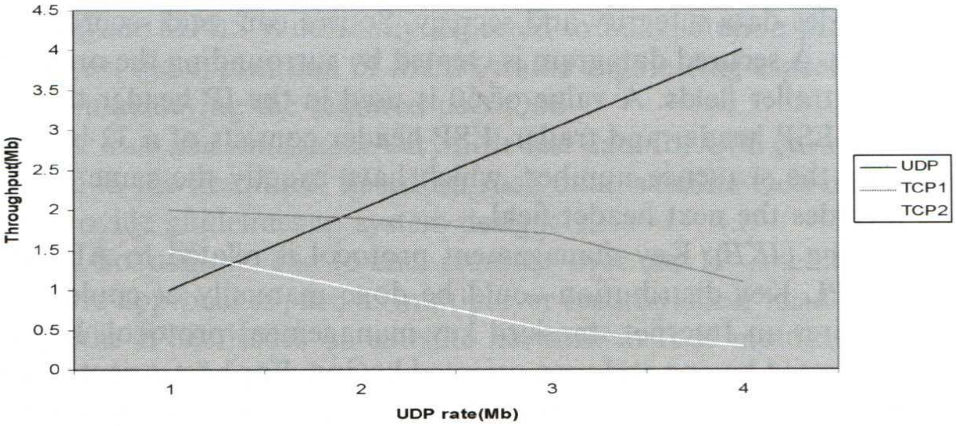


Figure 11. UDP and TCP throughput without the use of MPLS.

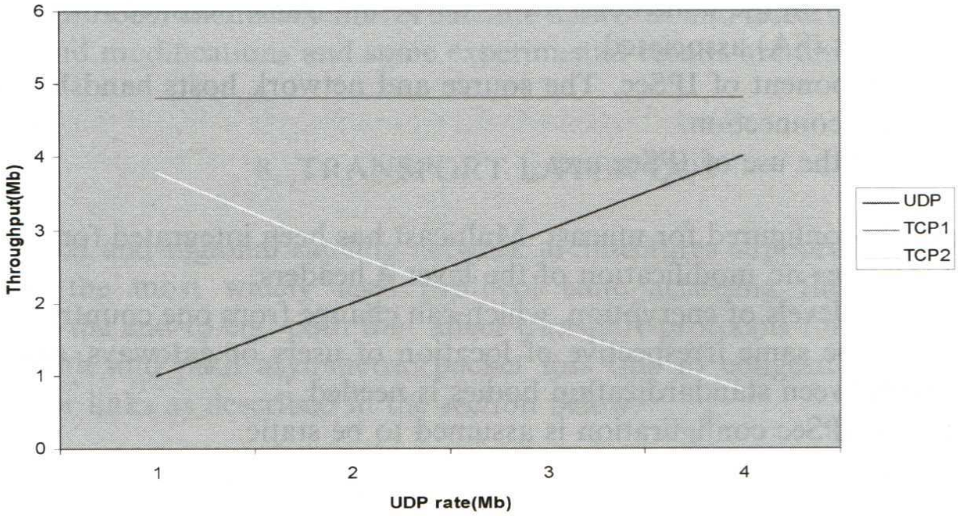


Figure 12. UDP and TCP throughput using of MPLS.

These simple simulation show that traffic engineering of MPLS improves the performance of network throughput for different application traffics. This simulation study should to be extended for larger number of flows and different traffic scenarios in a satellite environment.

7.5. *IP security*

The security standards for the Internet known as IP security (IPSec) [78] is used to provide interoperable cryptographically based security services (i.e. confidentiality, authentication and integrity) at the IP layer. It is composed of an authentication protocol—authentication header (AH) [79], a confidentiality protocol—encapsulated security payload (ESP) [80], and an internet security association establishment and key management protocol (ISAKMP) [81]. These protocols are aimed mainly at unicast transmissions between one sender and one receiver. IP Security is mandatory for IPv6.

AH protocol provides source authentication and data integrity but not secrecy. The source can send secured datagrams, that include the AH header. A value of 51 is used in the IP header to that an AH header has been included. The fields in AH header include next header field, security parameter index (SPI) field, sequence number field and authentication data field.

ESP protocol provides data integrity and secrecy. Source can send secured datagrams, that include the AH header. A secured datagram is created by surrounding the original IP datagram data with header and trailer fields. A value of 50 is used in the IP header to indicate that the datagram includes an ESP header and trailer. ESP header consists of a 32-bit field for the SPI and a 32-bit field for the sequence number, which have exactly the same role as in the AH protocol. Trailer includes the next header field.

Internet key exchange (*IKE*): Key management protocol is related to AH header and ESP header only by the SPI. Key distribution could be done manually or could be automated in which case, keys requires an Internet-standard key management protocol. Keying approaches for IP include host-oriented keying and user-oriented keying. For host-oriented keying, users on one host share the same key on out coming traffic destined for all users on another host. Integrity and confidentiality can be provided when dynamic key management techniques and certain algorithms are in use. For user-oriented keying, one user has one or more keys (not shared with other users on the same host) for its outbound traffic destined for another host with the security agreement (SA) associated.

SA is another component of IPSec. The source and network hosts handshake and create a network layer logical connection.

The constraints on the use of IPSec are:

- It was originally configured for unicast. Multicast has been integrated for IPSec over IPv6.
- IPSec ESP tolerates no modification of the layer 4 headers.
- ESP has different levels of encryption, which can change from one country to another. For security level to be same irrespective of location of users or gateways, agreement on the usage of ESP between standardization bodies is needed.
- In tunnel mode, IPSec configuration is assumed to be static.

7.6. *QoS routing*

Routing and QoS in broadband LEO satellite networks describes mechanisms for supporting QoS strategies for LEO satellite networks and their effects on link handover. Novel routing and resource reservation algorithms as well as connection admission control strategies are proposed to minimize the handover blocking probability while maintaining QoS requirements [82]. Further issues to address include IP mobile network architecture, and QoS provisioning for mobile multimedia applications.

7.7. *IP layer QoS issues*

To successfully provide guaranteed QoS to user satisfaction for broadband satellite networks at IP layer, the following issues need further research.

DiffServ/IntServ satellite QoS: DiffServ and IntServ are proposed by IETF for delivering QoS for terrestrial networks. Development of specific QoS architectural models based on DiffServ and/or IntServ for both global and regional access satellite networks must be developed taking into consideration satellite specific characteristics. This requires efficient queue management and scheduling algorithms. Based on this DiffServ QoS provisioning, a gateway architecture for satellite IP network with dynamic resource management is described in Reference [43].

MPLS satellite QoS: MPLS is currently expected to be a solution providing terrestrial QoS guarantees. However, the application of MPLS traffic engineering aspects must be explored for satellite networks in achieving the required user QoS.

QoS performance tests and validation: Very little test data for QoS parameters for real satellite systems is reported in the literature. Based on such data, satellite QoS objectives require to be standardized to provide guidelines to system designers.

Satellite IPSec: To achieve end-to-end security over an IP satellite network, it is very important to explore approaches such as multiplayer security, clear headers or application layer security. Some of the IPSec issues on satellite network include multicast support, end-to-end encryption rules, overhead optimization for tunnel model, and performance enhancement proxies (PEP) security.

Interconnectivity with wireless IP: Interoperability of satellite IP networks with mobile wireless IP networks providing 3G or 4G services in future must be addressed [2, 83, 84].

The transport protocol enhancements for satellite networks and research on alternative classic TCP protocols and modifications and some experimental results are discussed in Section 8.

8. TRANSPORT LAYER QOS

Most of the global and regional satellite network architectures support Internet applications, and TCP/IP is the most widely used protocol suite accessing the Internet. The main characteristics of the end-to-end path that affect transport protocols for satellite networks are latency, bandwidth and path asymmetric packet loss due to congestion, and losses due to transmission error links as described in the section below.

8.1. Satellite link characteristics affecting TCP

The satellite link characteristics are:

- *Latency*—Among the three components of latency, propagation delay, transmission delay and queuing delay, propagation delay is the dominant part in broadband satellite links. Especially for GEO configurations, large variations of RTT may lead to false timeouts and transmissions.
- *Link impairments*—Satellite systems are subject to various impairments including multipath, interference, fading, rain attenuation and shadowing. TCP cannot distinguish between a segment loss due to congestion and a loss due to bit errors. Consequently, the sender will reduce its transmission rate even when segments are lost because of bit errors not due to congestion.
- *Bandwidth asymmetry*—In broadband satellite access networks bandwidth asymmetry in terms of forward to the return channels exist anywhere in the order of 20:1 or more. Network asymmetry affects the performance of TCP because the protocol relies on feedback in the form of cumulative acknowledgements from the receiver to ensure reliability. TCP uses the arrival rate of ACKs on the reverse time to control the flow of packets in the forward direction. Thus, bottlenecks or congestion in the reverse direction can lead to poor channel utilization in the forward direction.
- *Multiple segment loss*—The bandwidth delay product defines the maximum amount of data that can be in-flight (transmitted but unacknowledged). In connections with a large

bandwidth delay product, such as GEO satellite networks, TCP senders and receivers with limited congestion/receive windows will not be able to take advantage of the bandwidth that is available.

- *RTT fairness*—Because the TCP algorithm is self-clocking, based on received ACKs, several connections sharing the same bottleneck may see their clocks running at different speeds. A long RTT connection will not be able to increase its congestion window as quickly as a short RTT connection and so the short RTT connection will unfairly capture a larger portion of the network bandwidth as a result.

The RTT for GEO satellite is more than 500 ms which is the time it takes for a TCP sender to determine whether or not a packet has been successfully received at the destination. This delay hurts some of TCP congestion control algorithms as described. The TCP protocol specifies the following congestion control algorithm.

- *Slow start*—TCP uses the slow-start mechanism to probe the network at the start of connection. The time required by the slow start to reach a bit rate B is given by the following formula [85]:

$$\text{Slow-start duration} = \text{RTT}\left(1 + \log_2 \frac{B\,\text{RTT}}{l}\right),$$

where l is the average packet length expressed in bits.

If delayed ACK mechanism [86] is implemented then the time required by the slow start to reach the bit rate B is given by the following formula [87]:

$$\text{Slow-start duration} = \text{RTT}\left(1 + \log_{1.5} \frac{B\,\text{RTT}}{l}\right)$$

That means the slow-start duration becomes even longer the previous one. Thus, delayed ACKs are another source of wasted capacity during the slow-start phase.

Many actual TCP flows, like those carrying HTTP, transfer small files. In these cases thus, the entire transfer could occur during slow start, which means that a TCP connection is not able to utilize all available resources in the network. Furthermore, when packets are lost, TCP reenters slow start or congestion avoidance. And the losses could be caused by link errors and not by congestion. When TCP experiences losses early in the slow start, it will set its initial estimate of the available bandwidth far too low. And since the probing becomes linear (congestion avoidance) rather than exponential, after the initial estimate is set, the time to get to full transmission rate can be very long [85].

- *Congestion avoidance* [88]: In congestion avoidance the growth of data rate is a function of the delay-bandwidth product. In fact, during each RTT, the data rate is increased by $1/(B\,\text{RTT})$. So if a TCP connection is in congestion avoidance and some bandwidth becomes available, this connection will not use the bandwidth for a long time. This time will be longer in the presence of transmission losses. Therefore, the congestion avoidance in satellite networks with high RTT performs lower than in a terrestrial network.
- *Fast retransmit and fast recovery* is also affected by long RTTs, typical for satellite connections. These connections are able to inject enough new segments into the network during recovery to trigger multiple fast retransmissions per window of data, which may hurt TCP performance.

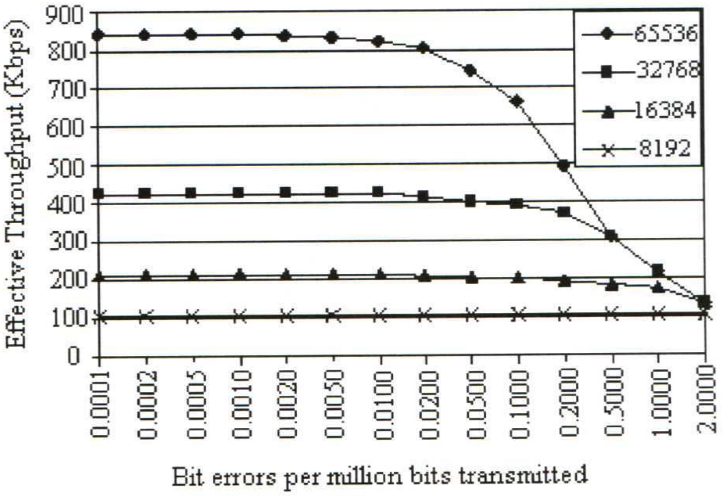


Figure 13. Impact of BER on TCP throughput for large files with window size as parameter. RTT = 590 and $B = 2048$ kbps.

The effect of BER on TCP throughput is another significant factor. As shown in Figure 13 [89] TCP can perform poorly in the presence of errors and is more sensitive to errors for larger window size. In order to reach a larger congestion window, TCP should not experience losses, that means should have lower BER.

8.2. TCP enhancements

Many enhancements have been reported to mitigate the link impairments. Recent survey articles provide excellent discussions on them [50, 90–95]. The different TCP enhancements which are well documented include, initial window [96], delayed acknowledgements [97], byte counting [98], TCP vegas [99], TCP new reno [100], TCP SACK [101–103], TCP FACK [104], window scaling [105], T/TCP [106], and Path MTU directory [107]. Reference [108] provides discussion on TCP slow start, congestion avoidance, fast retransmit and fast recovery algorithms. The explicit congestion notification is reported in Reference [109].

To enhance the TCP throughput performance, for large bandwidth-delay product environment such as satellite link, many solutions have been proposed. The TCP performance enhancement techniques for satellite links are extensively studied in References [5, 110–112]. The IETF has proposed standard mechanisms for studying the TCP enhancement over satellite channels [6]. Other studies for TCP performance over satellite network include Reference [85, 113–115]. The significant issue of delivering QoS over satellite IP has been addressed by a few Reference [116–118].

Research issues for TCP in satellite IP network have been addressed [7]. Solutions for network path asymmetry just like in satellite access networks with ratios of 20:1 or greater for forward to return links are well documented [49, 119]. Extensions of TCP for space communications have been studied [120, 121]. Table IV summarizes the TCP enhancements.

8.3. Performance enhancement proxies (PEP)

TCP extensions can solve some of the limitations of standard TCP over satellite links, but other problems such as long end-to-end latency and asymmetry are not effectively addressed. One way to alleviate the effects of large end-to-end latency is to split the TCP connection into two or

Table IV. TCP enhancements comparison.

TCP over Satellites	RFC	Latency	Large BDP	Impairments and disconnections	Asymmetry
Large initial window (IW)	2414, 2581, 2488	Yes			
Delayed acknowledgement (DACK)		Yes			
Byte counting	2414	Yes			Yes
TCP NewReno	2582	Yes	Yes	Yes	
TCP selective acknowledgement (SACK)	2018, 2883, 2488	Yes	Yes	Yes	
TCP Vegas		Yes	Yes	Yes	
Window scaling	1323	Yes	Yes		
TCP for transactions (T/TCP)	1644	Yes			
Path MTU discovery	1191, 2488	Yes			
Explicit congestion notification (ECN)	2481	Yes	Yes		
Forward error correction (FEC)	2488			Yes	
Multiple connections	2760	Yes	Yes		
TCP pacing	2760	Yes	Yes		
Header compression	2507			Yes	

more parts at the ground stations connecting the satellite network and terrestrial networks. Three approaches to splitting TCP connections over satellite links include [6, 7] TCP spoofing, TCP splitting and web caching.

To mitigate the disadvantages of TCP over long-latency links, researchers have been introducing performance enhancement proxies into networks [122–129]. PEPs can be classified by layer (transport vs application), by implementation distribution (single node vs several nodes e.g. two PEPs in a satellite link), by treatment of connections (splitting) in a satellite link and by degree of transparency. PEP mechanisms include ACK spacing, ACK regeneration (not in the draft yet), local acknowledgements, local transmissions, tunnels to control routing of packets, header compression, payload compression and priority-based multiplexing. PEP implications are (a) end-to-end security, (b) end-to-end fate sharing, (c) end-to-end reliability and (d) end-to-end failure diagnostics.

Use of PEPs and IPSec is generally mutually exclusive unless the PEP is also both capable and trusted to be the end point of an IPSec tunnel. Use of an IPSec tunnel is deemed good enough security for the applicable thread model. User/network administrator must choose between improved performance and network layer security. In some cases, transport of higher layer security can be used in conjunction with a PEP to mitigate the impact of not having network layer security. PEP itself must be protected from attack, represent a network point where the traffic is exposed. This makes it an ideal platform for launching denial of service or man in the middle attack. PEP must be protected (e.g. by a firewall) or must protect itself from improper access by an attacker just like any other device which resides in the network. Considerable work is still needed to attain end-to-end security for satellite IP networks using PEP gateways.

8.3.1. Example of PEP gateway for satellite link. The effectiveness of protocol gateways under various loading conditions, TCP connection rates and error rates for typical satellite link conditions are investigated. In addition to simulating satellite conditions, the effect of Internet congestion on end-to-end throughput with protocol gateway was also examined [130]. The tests conducted include single TCP connection throughput for various link bandwidths and multiple TCP connections with fixed per-connection bandwidth.

TCP with protocol gateway enhancement: Without performance enhancement, the maximum throughputs are 320 kb/s for the terrestrial connection and 91 kb/s for the satellite-terrestrial link. These results demonstrate that without performance enhancement, the maximum single-connection TCP throughput rate will be approximately equal to the window size (8 kbyte × 8 bit)/RTT(e.g. 200 ms) = 320 kb/s, even if the link rate is increased.

Figure 14 shows test results for a round trip delay of 700 ms with TCP enhancement. The performance using the protocol gateway is clearly orders of magnitude better than the theoretical TCP maximum. Even despite a 700 ms delay, the protocol gateway allows the connection to take advantage of the full bandwidth available.

Multiple TCP connections with protocol gateway enhancement: Figure 15 illustrates the effects of adding the protocol gateway to the network for a delay of 700 ms. It allows the connection to

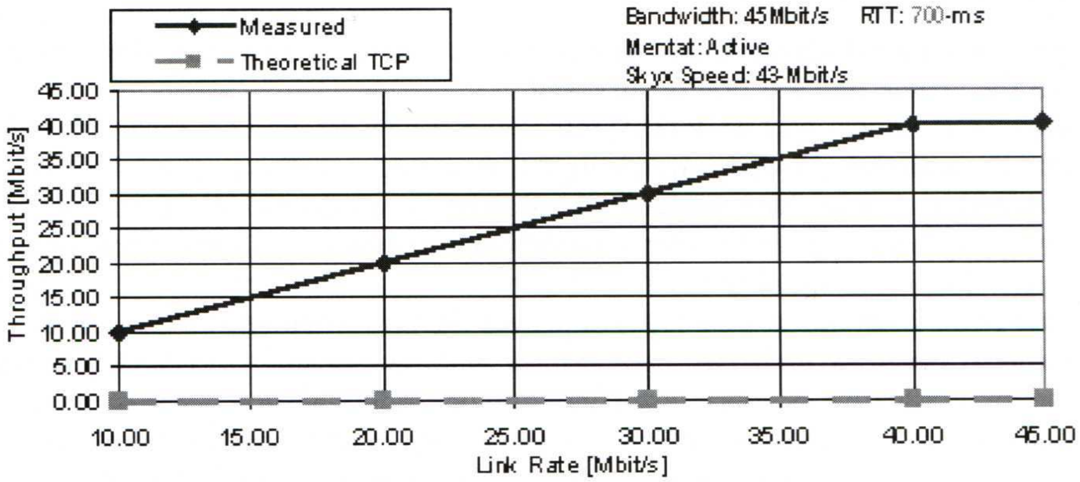


Figure 14. Single TCP connection over satellite link with protocol gateway enhancement.

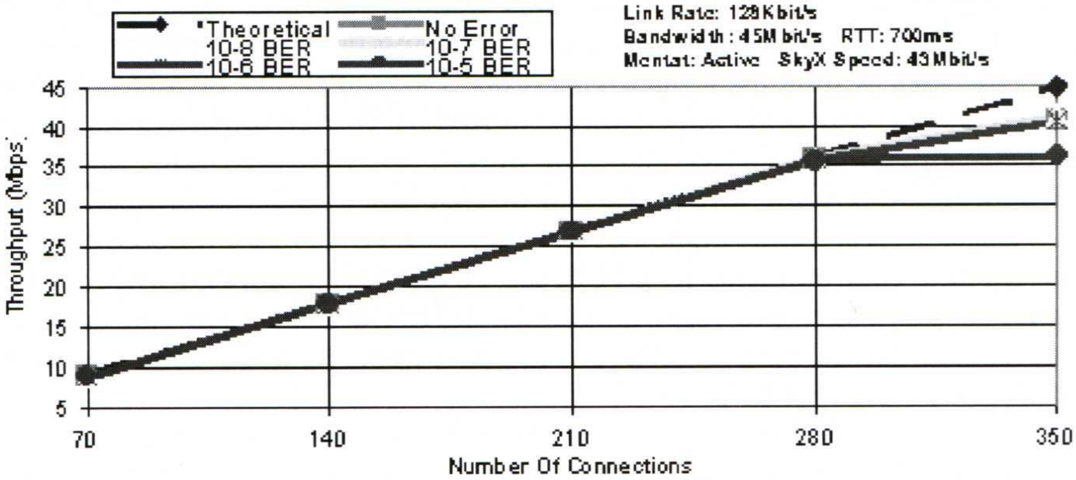


Figure 15. Multiple TCP connections over satellite link with protocol gateway enhancement.

utilize the full bandwidth available. The performance is essentially identical to the theoretical limit for up to 280 connections.

Comparing this graph to the results in Figure 14 for the satellite-based network, the protocol gateway provides a substantial increase in aggregate bandwidth at low BERs and at a packet loss rate of 10%, the aggregate throughput for 350 connections with the gateway is 33 Mb/s compared to only 10 Mb/s for enhanced TCP.

The results show that protocol gateway/connection splitting devices can improve the throughput for carriers with TCP/IP-type traffic on satellite links with up to 700 ms in delay. The tests also show that the TCP/IP throughput is not affected as long as the link BER is better than 1×10^{-7}.

An alternative to the use of PEPs, is to use an alternative end-to-end transport protocol in place of TCP. This approach preserves the end-to-end behaviour of the transport layer while still permitting part of the protocol to be matched to the characteristics of a link or subnetwork on the network path [18].

8.4. Advanced TCP enhancements

In this section, the recent research on various enhancements to TCP and alternative transport protocols to the classic one are briefly surveyed.

Quick-start TCP: Quick-start TCP [131] introduces a new mechanism for transport protocols to determine an optional allowed initial congestion window at the start of data transmission. Quick-start could be required for connections using initial window higher than four segments. It could be especially beneficial for moderate-sized connections in well-provisioned environments including high bandwidth satellite links.

High-speed TCP: High-speed TCP [131] improves the performance of TCP in high bandwidth links where TCP operates with large congestion window. In high-speed TCP the additional increase and multiplicative decrease are functions of the congestion window itself instead of being constant values as in standard TCP. This makes it possible to use high bandwidth links with reasonable error rates and reduces delays to recover from multiple timeouts or to use available bandwidth. It requires changes only to the TCP sender.

TCP peach [132]: TCP Peach is a new TCP congestion control scheme designed for satellite networks and is composed of two new algorithms: Sudden start and rapid recovery, besides the two traditional TCP algorithms, congestion avoidance and fast retransmit. The new algorithms are based on the uses of dummy segments to probe the availability of network sources. Even though this scheme is shown to outperform standard TCP over satellite links, it requires co-ordination between sender and receiver and most importantly requires all routers in the connection path to apply some sort of priority mechanism.

Explicit transport error notification (*ETEN*) [133]: ETEN was proposed for error-prone wireless and satellite environments. In ETEN the TCP sender is notified when packets get lost due to errors, so the sender can react differently. ETEN assumes that sufficient information about the corrupted packet, such as IP addresses, port numbers and TCP sequence numbers is available to intermediate routers or receivers.

TCP Westwood [134]: The key innovation of TCP Westwood (TCPW) is the use of bandwidth estimate to directly drive cwnd and ssthresh. The TCP sender continuously monitors ACKs from the receiver and computes its current eligible rate estimate (ERE). ERE is based on the rate of ACKs and their payload. Upon a packet loss indication (3DUPACKs or a timeout) the sender sets the cwnd and ssthresh based on ERE.

Explicit control protocol (*XCP*): XCP is a generalization of explicit congestion notification (ECN) [135]. Instead of the one bit congestion indication used by ECN, in XCP routers inform the sender about the degree of congestion at the bottleneck. XCP is shown to perform very well in high bandwidth-delay paths, where TCP suffers significantly.

Satellite transport protocol (*STP*): STP [110] is a transport protocol that was designed to perform well over satellite links. The STP sender and receiver use buffer sizes that are of the order of the bandwidth-delay product of the links. Like TCP, STP provides a reliable, byte-oriented streaming data service to applications.

Space communications protocol specifications: Transport protocol (SCPS-TP)—SCPS-TP [120, 136] was developed by Mitre to account for the 'stressed environment' i.e. space environment with delay, and multiple sources of data loss. SCPS-TP uses a congestion control algorithm that does not depend on packet loss as a way to signal congestion in the network.

TCP swift start [137]: A way for TCP to estimate available network capacity and swiftly scale its transmission rate at the start of a TCP connection. While the method does estimate capacity, the limited studies conducted suggest it performs slightly worse than regular TCP over a low-delay modest-bandwidth Internet path.

8.5. Modified transport layer protocol

An example of the basic principle of using an alternative transport protocol in place of TCP is illustrated in Figure 16. The transport layer is divided into two sub-layers: the upper one, which guarantees the end-to-end characteristic, and the lower sub-layer, which is divided into two parts and interfaces the satellite transport layer (STL). The terrestrial side of the lower transport layer may also be represented by TCP. The transport layer is modified even if the interface with the adjacent layers may be the same as in TCP. The upper transport layer will include the TCP and the UDP implementation to allow a full compatibility with a different architecture, as shown in Figure 16, for example, to guarantee a correct working even if a TCP/IP stack is

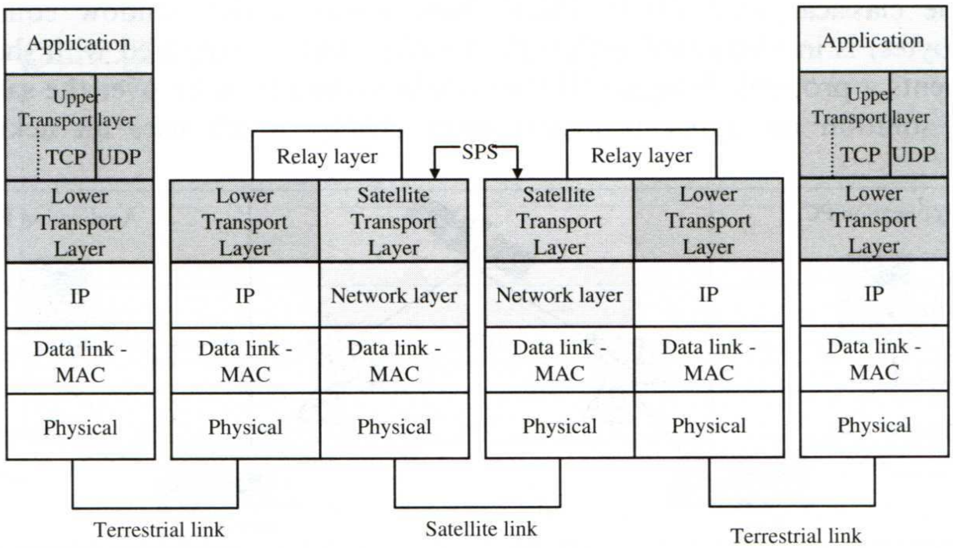


Figure 16. Example of modified transport layer protocol.

present at the destination. TCP/IP stack includes the use of UDP. The transport layer at the destination is properly identified during the set-up.

This approach has implications that include [18]:

- End-to-end behaviour of the protocol should be preserved. In particular, the end-to-end reliability between the communicating end hosts should be guaranteed.
- Both the end hosts should implement the alternative transport layer protocol. In order to maintain full interoperability with a range of different end hosts, this approach must therefore include the ability to revert to using the standard TCP transport protocol if one of the end hosts does not support the alternative protocol.
- Fairness should be provided between flows that share a common part of an Internet path. This implies that any new protocol must adopt a congestion control procedure that is accepted for use within the general Internet.
- Some architectural issues might be introduced including how a host selects the transport protocol if alternative offering exist, etc.

It is important to address the architectural and protocol issues before deploying or modifying transport protocols for the TCP/IP protocol suite. The IETF has not currently recommended a subnetwork-specific transport protocol for use in the general Internet.

Performance results [138] for the modified TCP discussed earlier are presented. The reference test bed is contained in Figure 17. In the scenarios considered, the Internet is a link with a bandwidth of 10 Mbps (scenario 1) and 640 kbps (scenario 2), and the satellite link offers bandwidth of 2 Mbps.

In this case, the performance of the system is evaluated for a transfer of 100 Mbytes and no errors are experienced by the transmission links. The bandwidth bottleneck is represented by the gateway accessing to the satellite link in scenario 1 and by the gateway on the other side of the satellite link in scenario 2. The performance metrics are the global throughput value and the transfer time.

Scenario 1: In scenario 1, the satellite link has an RTT equal to 0.500 s. In this case, an architecture where two routers allow the access to the satellite link (instead of the Gateways) and where the classical TCP (TCP SACK New Reno, initial window equal to 1, TCP buffer = 64 kbytes) is implemented within the terminal PC is compared with the architecture, which implements a properly designed STP to optimize data transfer over the satellite portion. In the latter solution an upper transport layer (UTL) which uses an acknowledgement

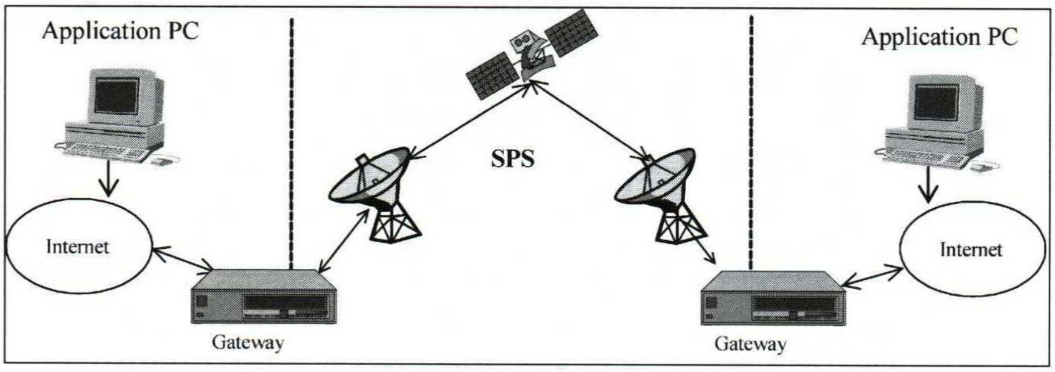


Figure 17. Modified transport layer protocol testbed.

mechanism where data batches are confirmed transmission window is used equal to one batch and to five batches (one batch is composed of 1500 packets of 1500 bytes each), in order to analyse how the system performance changes if different transmission windows are employed at the UTL layer.

As shown in Figure 18, it is clear that the solution based on the UTL approach provide satisfying results. This behaviour is due to the utilization of a proper satellite protocol (STP) on the satellite link and the spoofing mechanism on the gateways, by allowing the speed-up of the transmission. This means that the data transmission is regulated by the arrival of the ACK generated by the relay entity. As a consequence, the sliding of the transmission window is performed without waiting for a complete RTT. On the other hand, when the classical TCP architecture is considered, the results reported are limited, because the use of classical TCP deteriorates the overall performances and the transmission window is regulated by the arrival of acknowledgements, generated by the destination machine, which involves a full RTT.

The new solution presents two different final throughput values, depending on the size of the transmission window. If a bigger transmission window (UTL $W = 5$) is employed, the sender side does not wait the BATCH ACK to send the next batch; furthermore, with a larger window the channel is filled more quickly and then the performances are even more satisfying. The best solution presents a global throughput value of nearby 256 000 bps ($W = 1$ solution provides approximately 240 000 bps) that corresponds to the full saturation of the channel while the TCP-based solution experiences a throughput of only 60 000 bps.

Reference [138] describes scenario 2 in which the bottleneck is positioned on the other side of the satellite link. A satellite network with two hops, a bandwidth of 2 Mbps, and a global RTT of 1 s, is considered in order to evaluate the behaviour of the proposed architecture when very high propagation delays are experienced by the satellite link. In the case of UTL approach, the performances are not deteriorated because the UTL entity hides from the sender the satellite part and speeds up the data transmission independently of the propagation delay experienced by the satellite network. On the other hand, when a classical TCP architecture is applied, the global throughput reported by the analysis is not satisfying because the transmission window

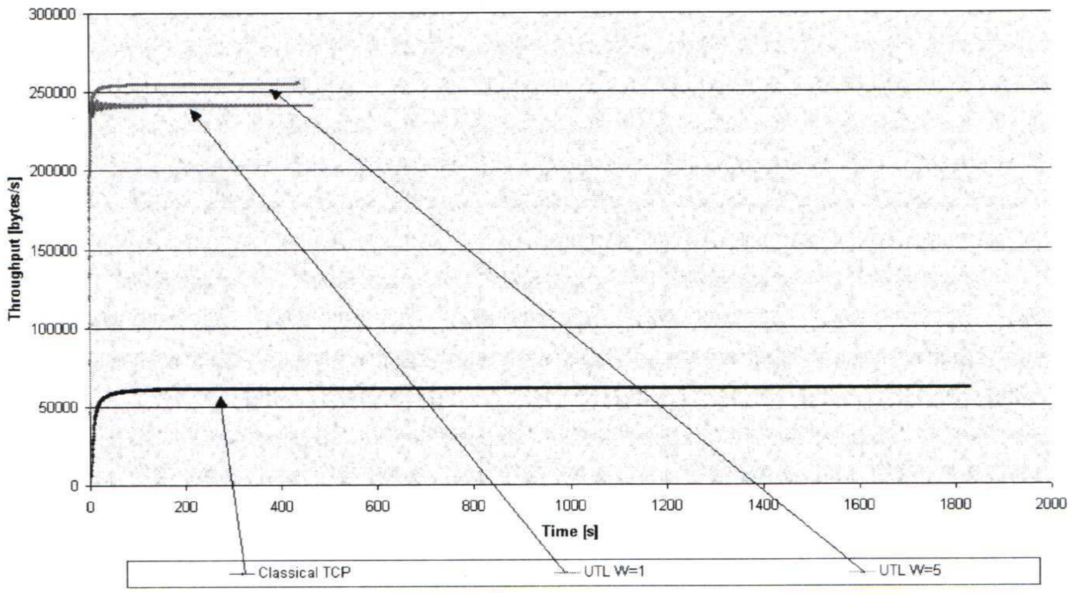


Figure 18. Modified transport layer protocol (RTT = 0.500 s—100 Mbytes file transfer).

calculation is regulated by the acknowledgement arrival that requires at least 1s (i.e. at least the RTT experienced by the satellite network). The performance of the new approach is not deteriorated.

Much research effort has been made to optimize the TCP performance over satellite networks to mitigate the link impairments. Most of the solutions address the non-real-time applications over satellite IP networks. Considerable work needs to be done to enhance TCP performance for multimedia services which require significant QoS guarantees.

9. SATELLITE IP PROJECTS AND PROGRAMS

This section provides a brief overview of some satellite IP programs and projects which are in progress.

European Space Agency (ESA) started a specific program in 1996 dedicated to Multimedia within Advanced Research in Telecommunications System (ARTES). ESA, whose 13% of annual budget is allocated to telecommunications, supports the ARTES program which provides multimedia services. The activities are divided into three lines: applications, development of satellite communication system elements and pioneering novel systems. Many activities are involved with IP development.

ARTES studies are involved in the studies of developing standard Internet transport protocol, TCP, improvements over satellite links and TCP alternative transport protocols preserving end-to-end context, matching resource allocation at the DAMA and QoS mechanisms.

Advanced broadcast architecture for retail Internet services (*ABARIS*): An example project ABARIS [139] is dedicated to establish a satellite multicasting e-commerce IP-based platform, focused initially on the delivery of CD quality audio products. ABARIS offers a simple World Wide Web (WWW) interface to acquire music products and covers also aspects as payment and copyright clearance. The platform is based on the ASTRA-NET satellite service.

SiMPLE: SiMPLE [140] covers the development of on-board processing technology, intelligent antennas, inter-satellite links and communications control technology and low-cost user terminals. Additionally, SiMPLE provides automatic WWW contents delivery via reliable multicast directly to the end users.

Domino 2 (*Alcatel Space Industries*): Domino 2 [141] is a Ka-band GEO satellite system using multibeam offering multimedia services. Various issues addressed in this development include on-board processing, circuit and packet switched payloads, QoS and SLA management and network architecture with resource allocation.

Euroskyway (*Alenia*): Eursoskyway [142] is a satellite network in Europe for the delivery two-way broadband communications to users equipped with simple terminals and small antennas. EuroSkyWay will offer 'bandwidth on demand' to service providers such as telecommunications operators, TV broadcasters and Internet access providers who want to expand their infrastructure and reach new customers. It also provides high-speed Internet connections, video conferencing with the office and even shopping via communications links.

Spaceway [143]: A GEO broadband satellite network developed at Ka-band by Hughes network systems is expected to provide private line, frame relay services, IP virtual private network services, broadband service to small, medium and small office/home office (SOHO), teleworkers and for other 'extranet' applications. They are planning first spacecraft launch in mid-2003, projected in service by Q2, 2004. The second and third spacecrafts are expected to be launched by mid-2004 and in mid-2005, respectively.

Astrolink [144]: Astrolink will provide global bandwidth-on-demand digital communications utilizing a constellation of nine Ka-band GEO satellites deployed in five orbital locations and interconnected by means of inter-satellite links. The Astrolink satellites will employ high-gain spot beams, adaptive coding in response to rain, and on-board packet switching based on ATM. Astrolink will provide both dial-up user access and secure virtual private networks which will allow business, government and individual users to extend their communications—voice, data and video—throughout the world. It improves reliability by complementing terrestrial networks.

Wildblue [145]: Wildblue is a two-way Ka-band system. It consists of two GEO satellites with lifetime of 10–15 years. The satellites have an uplink frequency of 19.2–20.0 GHz and downlink frequency of 29–30 GHz with data rates higher than 1.544 Mbit/s. The services offered are broadband data services and Internet by satellite. Data rates are from 64 kbit/s to 155 Mbit/s, but typically 1.5–5 Mbit/s. The satellites will cover US, Central and South America and parts of Europe and Mexico. It targets broadband data services in North American markets, especially for SOHO customers.

Starband [146]: StarBand is a joint venture founded in January 2000 by Gilat, EchoStar, Microsoft and others. It is a two-way Ku band access satellite, providing always-on, high-speed satellite Internet service to consumer. It also provides bundled PC and direct-to-home TV services on DISH network. The satellite system covers the continental United States, Alaska, Hawaii, Puerto Rico and the U.S. Virgin Islands who have been unable to get broadband Internet service.

10. CONCLUSIONS AND FURTHER RESEARCH

QoS is a critical element for a successful deployment of satellite networks to meet the future bandwidth hungry applications such as content delivery, streaming audio/video, teleeducation and telemedicine. Various contributions to end-to-end QoS at each layer are surveyed. At the physical layer, an overview of bandwidth efficient modulation and coding schemes and adaptive coding is given. At the link layer, media access control techniques dealing with BoD, and bandwidth allocation with fading are surveyed. Further issues such as interaction between BoD and transport layer protocols and network congestion are identified. DiffServ-based simulation results for TCP/UDP handling non-real-time and real-time traffic over satellite IP network for GEO, MEO constellations are described. An MPLS traffic engineering application to such a satellite network is demonstrated through a simple example using separate trunks for TCP and UDP traffic streams. The TCP enhancements for satellite networks are surveyed and a brief account of the advanced TCP and alternative transport protocols are described. Test bed results for a modified TCP are provided showing an improvement at the user terminals and gateways.

To provide QoS guarantees, considerable research is needed in the areas of bandwidth efficient modulation, advanced coding techniques, bandwidth allocation, DAMA, DiffServ, traffic engineering technologies for future applications meeting the service level guarantees. For satellite IP networks, further research on return channel access protocols, application QoS models and interoperability with mobile wireless is needed. Even though extensive research results have been reported for TCP enhancements optimizing TCP for satellite links, more is required to address multimedia applications and end-to-end security in satellite IP networks. In addition to the analytical and simulation results, the actual systems test data should support the QoS parameters for standardization. Co-ordination between ETSI, IETF and ITU for satellite IP networks standardization is emphasized.

APPENDIX: ACRONYMS

ACTS	Advanced Communications Technologies Satellite
ABARIS	Advanced Broadcast Architecture for Retail Internet Services
ADSL	Asynchronous Digital Subscriber Line
AH	Authentication Header
ANOVA	Analysis of Variation
ARTES	Advanced Research in Telecommunications System
ATM	Asynchronous Transfer Mode
AVBDC	Absolute Volume Based Dynamic Capacity
BER	Bit Error Rate
BoD	Bandwidth on Demand
BSM	Broadband Satellite Multimedia
CBQ	Class Based Queuing
CDD	Content Distribution and Delivery
CDMA	Code Division Multiple Access
CFDAMA	Combined Free/DAMA
CoS	Class of Service
CR	Capacity Request
CRA	Continuous Rate Assignment
CRMA	Code Reuse Multiple Access
DACK	Delayed Acknowledgment
DAMA	Demand Assignment Multiple Access
DSCP	Differentiated Services Code Point
DVB-RCS	Digital Video Broadcasting—Return Channel via Satellite
DVB-S	Digital Video Broadcasting via Satellite
ECN	Explicit Congestion Notification
EIRP	Effective Isotropically Radiated Power
ERE	Eligible Rate Estimate
ESA	European Space Agency
ESP	Encapsulated Security Payload
ETEN	Explicit Transport Error Notification
ETSI	European Telecommunications Standards Institute
FCA	Free Capacity Assignment
FEC	Forward Error Correction
GEO	Geostationary Earth Orbit
GSO	Geosynchronous Orbit
HRP	Hypothetical Reference Paths
IETF	Internet Engineering Task Force
IKE	Internet Key Exchange

IP	Internet Protocol
IPDV	IP Packet Delay Variation
IPER	IP Packet Error Ratio
IPLR	IP Packet Loss Ratio
IPSec	IP Security
IPTD	IP Packet Transfer Delay
ISAKMP	Internet Security Association Establishment and Key Management Protocol
ISDN	Integrated Service Digital Network
ISO	International Standards Organization
ISP	Internet Service Provider
ITU-R	International Telecommunications Union—Radiocommunication
ITU-T	International Telecommunications Union—Telecommunication
IW	Initial Window
LAN	Local Area Network
LDP	Label Distribution Protocol
LEO	Low Earth Orbit
LSP	Label Switched Path
LSR	Label Switched Routers
MAC	Medium Access Control
MAMT	Multiple Accounting, Multiple Threshold
MAST	Multiple Accounting, Single Threshold
MEO	Medium Earth Orbit
MF-TDMA	MultiFrequency-Time Division Multiple Access
MPLS	Multiprotocol Label Switching
MS	Main Site
NCS	Network Control Station
NGSO	Non-Geosynchronous Orbit
OSPF	Open Shortest Path First
PEP	Performance Enhancement Proxies
PRDAMA	PRedictive DAMA
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RBDC	Rate Based Dynamic Capacity
RCST	Return Channel Satellite Terminal
RED	Random Early Detection
RSVP	Resource ReSerVation Protocol
RTP	Real-Time Protocol
RTT	Round Trip Time
SA	Security Agreement
SACK	Selective Acknowledgement
SAMA	Spread Aloha Multiple Access
SAOC	Spread ALOHA Once Code
SAOLC	Spread ALOHA One Long Code
SAMT	Single Accounting, Multiple Threshold
SAST	Single Accounting, Single Threshold

SC	Service Center
SCPS-TP	Space Communications Protocol Specifications—Transport Protocol
SCTP	Stream Controlled Transmission Protocol
SI-SAP	Satellite Independent Service Access Point
SIT	Satellite Interactive Terminal
SLA	Service Level Agreement
SLC	Satellite Link Control
SMAC	Satellite Medium Access Control
SOHO	Small Office/Home Office
SPI	Security Parameter Index
STL	Satellite Transport Layer
STP	Satellite Transport Protocol
TCP	Transmission Control Protocol
TCPW	TCP Westwood
TDMA	Time Division Multiple Access
ToS	Type of Service
T/TCP	TCP for Transactions
TU	Terminal User
UDP	User Datagram Protocol
UT	User Terminal
UTL	Upper Transport Layer
VBDC	Volume Based Dynamic Capacity
VBR	Variable Bit Rate
VoIP	Voice over IP
WWW	World Wide Web
XCP	Explicit Control Protocol

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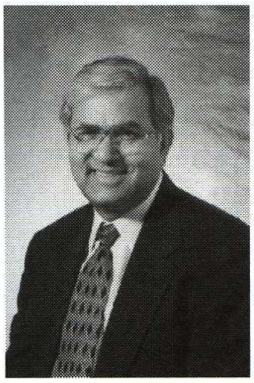

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