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Broadband Access via Satellite

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Abstract

Satellites are well suited for broadband communications. In this paper we consider the special features of satellite systems, some of the broadband applications that are well-suited for satellites and some of the technologies which make possible broadband satellite communications, as well as the research programs that led to their development. We describe how such technologies, and other factors, have contributed to the evolution of broadband satellite systems, and discuss some of the challenges in establishing such systems. We finish by offering some concluding remarks on the role of satellites for broadband access.

Keywords: *Satellite communications; broadband access; multiple access; Internet access; hybrid networks, On Board Processing; Error Control; Ka-Band; V-band.*

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Broadband Access via Satellite

1. Introduction

In recent years the demand for high-speed networking has been growing at an exponential rate. While the expansion of the Internet may be both a cause and an effect of this growth, it is not the only factor that drives the demand for broadband connectivity. As the cost of semiconductor/computer devices continues to fall while the capabilities of such equipment increase, new applications for equipment built with such devices are continually being developed.

In many broadband applications, such as multimedia videoconferencing and software distribution, there is a need to distribute information to many sites that are widely dispersed from each other. Satellites are well suited for carrying such services. Also, a satellite-based infrastructure can in many cases be established to offer widespread service provision with greater ease and simplicity than an infrastructure based on terrestrial broadband links. Thus, the ability to service many users and solving the expensive "last-mile" issue without dedicating to each user cable, fiber, switching equipment ports, etc. makes satellites attractive for broadband communication. Satellites are also attractive for interconnection of geographically distributed high-speed networks. Hence, while much broadband communication today is carried via terrestrial links, satellites will come to play a greater and more important role.

Communication satellites, as a possible way of offering broadband interconnectivity, appear to be a very attractive option because:

- B-ISDN (Broadband Integrated Services for Digital Networks) services can be provided over a large area, without the need of excessive investment in the early phase, especially in areas where the terrestrial network infrastructure is not very well developed.
- Satellite communication systems can be complementary to terrestrial networks, especially for widely dispersed users.
- Common alternative channels can be provided for routes where demand and traffic characteristics are uncertain, so that resources are used at maximum efficiency.
- The broadcast nature of satellites supports efficiently the transmission of the same message to a large number of stations, making satellites the natural choice for point-to-multipoint transmissions.
- A wide range of customer bitrates and circuit provision modes can be supported.
- Satellite networks offer transparency to the type of services carried.
- New users can be accommodated simply by installing new earth stations at customer premises. Thus, network enlargement is not a significant planning problem.

There is no clear definition of what value of data rate demarcates broadband from narrowband communication. The boundary is fuzzy but there is some understanding of what constitutes broadband. Interestingly, this boundary depends somewhat on the transmission medium. While rates around 64 kbps were considered "broadband" a few years ago in Very Small Aperture Terminal (VSAT) networks [1], this is no longer the case today. Not just in satellite systems but in telecommunications in general, new applications are consuming the available bandwidth and are driving the need for increasingly higher rates. In the context of this paper, when we refer to "broadband" we assume rates of 1Mbps or higher. The next generation of satellite systems will have a total capacity in the gigabit-per-second range while the second wave of systems, in the planning stage at the moment, are claiming capacities in the terabit-per-second range. Clearly, satellite systems cannot compete with the capacities, nor with the channel qualities, that can be achieved today in fiber systems. However, the special features and advantages of satellite communications mentioned earlier (and which will be discussed in greater detail in this paper) will guarantee an increasingly important role for satellites as part of a Global Information Infrastructure (GII). There are already several proposed broadband communications systems in various stages of development.). More than 1,300 satellites are slated to be launched in the newly released Ka band alone. Conservative estimates suggest that some 500 broadband satellites will be available in about 10 years, while most Ka-band systems are scheduled to start offering customer service after the year 2002. A lot of this new bandwidth is targeted at business, and there are projections that up to 15 percent of all business bandwidth will eventually come from broadband satellites [1].

A result of the need to accommodate high-rate transmission is to push into increasingly higher frequency bands, namely Ka band (27-40 GHz) and V-band (40-75 GHz). This trend is explained by the relatively large segments of frequency spectrum required for supporting the high data rates planned in newer systems. Such large segments are unavailable at lower frequencies, such as Ku band (12-18 GHz) and C band (4-6 GHz) which were until recently the bands used for Fixed Satellite Service (FSS) communications. Most VSAT and DBS TV systems in operation today use portions of the Ku band [2]. Further, with the proliferation of both terrestrial and satellite-based wireless systems, there is simply not enough spectrum to accommodate all these systems in a single band.

The main problem with the Ka band is significant rain attenuation [3,4,5], as the molecular water vapor absorption resonance frequency is located at the center of the band, at 22.3 GHz. (The term "K band" was originally given to the range 18-27 GHz. After a molecular water vapor absorption resonance was discovered at 22.3 GHz, the terms Ku band (12-18 GHz) and Ka band (27-40 GHz) were introduced to denote "under" and "above" K band; however, the regime 20-30 GHz is now in common use for the "Ka band" designation [2]). As there are different frequency breakdowns from the FCC and the IEEE for satellite band letter designations, to avoid possible confusion we will use in this paper the frequency breakdown adopted by the IEEE.

Continuing demand for additional bandwidth has forced commercial satellite system designers to consider even higher frequency bands, namely the so-called V band (40-75 GHz). Some military satellite systems already operate in this frequency range. These higher frequencies offer additional challenges to the designer such as more severe multipath fading and scattering of transmitted signals.

Some of the key characteristics of a satellite system that are pertinent to their broadband operation should be highlighted. The physical distance of a communications satellite from the source and destination of signals on the earth imposes a significant propagation delay on every transmission. This delay can introduce problems not just in real-time delay-sensitive applications but also adversely affect the performance of certain protocols, such as ATM or TCP/IP. In geostationary earth orbit (GEO) and medium earth orbit (GEO) systems the propagation delay is much higher than in low earth orbit (LEO) systems, but in LEO constellations the need to route a signal through multiple satellites imposes delay, too, and might also increase the variance of the delay.

Satellites are also limited in space, weight and power. A satellite's lifetime is determined by the amount of fuel it can carry for required periodical control of position and pointing angle once in orbit, and by the reliability of all its onboard electronics that face a very harsh radiation environment combined with very sharp temperature changes. Another significant problem in satellite systems is the creation of inter-modulation products by non-linearities in the analog IF/RF components such as amplifiers in earth station equipment and aboard the satellite. Finally, the limited antenna size and limited transmission powers for both the uplink (ground-to-satellite) and downlink (satellite-to-ground) transmissions constrain the achievable transmission rate and raise the cost of the bandwidth.

The structure of this paper is as follows. In the next section we consider some of the broadband applications that are well suited for satellites. We discuss in the following section the historical evolution of satellite communication toward broadband communication in the following section. Next follows a discussion of some of the technical challenges involved in broadband satellite communication. We consider some of the regulatory issues and before finishing with some concluding remarks.

2. Broadband Applications and Satellite Systems

A vast and diverse number of applications could be served better by broadband satellites. Distance education and telemedicine are two important and, for the developing regions of the world, critical services. Direct broadcast digital audio is another service that will be available soon, and companies such as WorldSpace, CD Radio and American Mobile Radio Corporation (AMRC) are planning to launch satellite systems for this purpose. Transmission of financial transactions, videoconferencing [6] and connection of private business intranets will also be among the main services supported by the next generation satellites. We next outline three particular examples of services well suited for broadband satellite systems.

2.1 Asymmetric TCP/IP to Support Internet Applications via Satellite

As the explosive expansion of the Internet continues, the demand for new and faster access to it grows similarly. However, access to the Internet is often either too slow (e.g. dial-up modem/PPP connection) or too expensive (e.g. switched 56 kbps, frame relay) for the home user or for small enterprises. It is however possible to exploit the following three observations to ameliorate this situation: 1) satellites are able to offer high-bandwidth connections to a large geographic area; 2) a receive-only VSAT is cheaper to manufacture and easier to install than one which can also transmit; and 3) computer users, especially those in a home environment, typically wish to consume more data from an external network than they generate. These observations indicate a viable solution, namely breaking the user's TCP/IP connection into two physical channels: a conventional terrestrial dial-up link for carrying data from the user to the Internet, and a higher-speed one-way satellite link for delivering data from the Internet to the user. Now while the provision of access to the Internet in future broadband satellite systems will not be exclusively asymmetric, for reasons more economic than technical such access is likely to be asymmetric for most individual users.

A hybrid network connection as just described is used in the Hughes *DirecPC* system to provide asymmetric access to the Internet. With a goal of supporting bandwidth-intensive Internet applications such as browsing the World Wide Web, this system has been designed to support any personal computer, any commercial TCP/IP package, any unmodified host on the Internet, and any of the routers, etc. within the Internet. In *DirecPC*, To achieve the required routing of a user's inbound information from remote Internet hosts to the *DirecPC* satellite gateway station, IP encapsulation, or tunneling, is used. With tunneling, a user’s outbound IP datagram is encapsulated at his machine within another IP datagram. This IP datagram is routed to the *DirecPC* system, where the encapsulation is removed. The source address of the original IP datagram is then changed to that of the *DirecPC* satellite gateway so that information from the remote Internet host is returned to the gateway instead of to the user via his Internet service provider. When the desired information from the remote host arrives at the gateway, it is sent over the satellite and received by the user with a small satellite antenna dish. With this system, a downlink rate of 400 kbps can be provided to the user. *Figure 1* shows the operation of DirecPC.

The 400 kbps downlink rate just mentioned does not take into account limitations imposed by TCP, which will be described in section 4.4. TCP spoofing, which will be discussed in the same section, has been suggested for improving the operation of *DirecPC* beyond that just described [7].

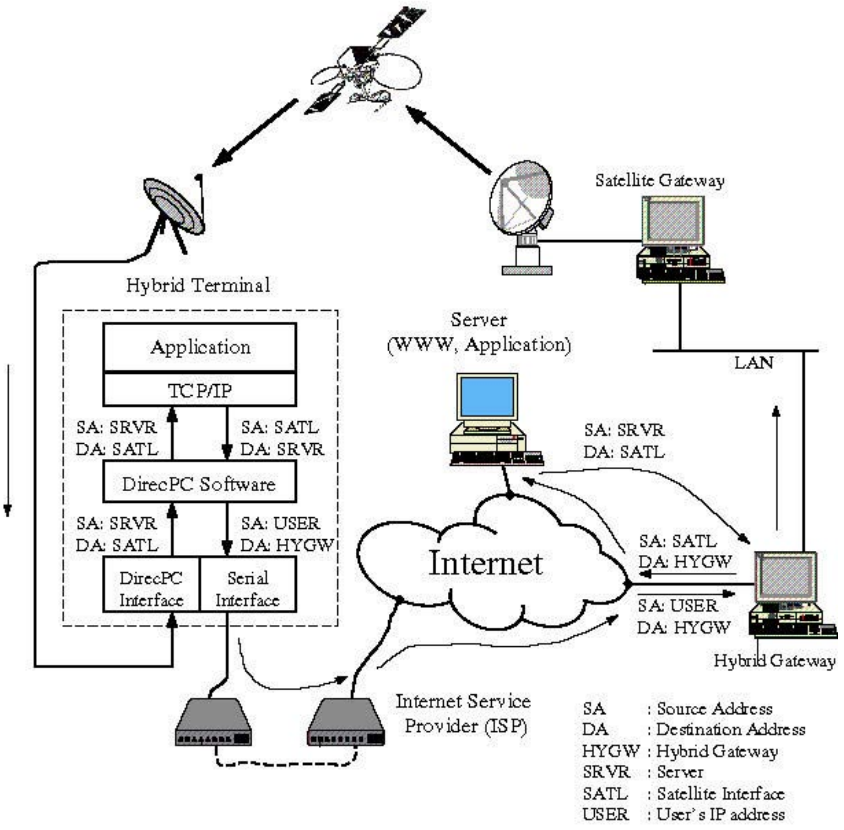

Figure 1. The DirecPC system.

2.2 *Multicast over satellite*

One of the major applications of broadband satellite systems will be the multicasting of information to a large number of dispersed users. Although IP multicast protocols are not yet mature, there is considerable interest and research in this area, and given the obvious potential business interest for multicasting applications and the clear advantage satellite systems can offer we can expect a large demand for services of this type using broadband satellites. Satellite-based videoconferencing could be accomplished by tunneling IP multicast messages through satellite gateways, but this would require establishing multiple tunneled virtual circuits between geographically separate users. This would make group management difficult and use more satellite capacity than would be necessary if satellite onboard switches were to support IP multicast directly [8]. Efficient use of satellite constellations for group applications hence requires satellite onboard switches include support for multicast. However, given the assumption that at least the first generation of broadband systems (Ka band) will probably select technologies that do not rely heavily on sophisticated and risky onboard processing, it appears unlikely that IP multicasting support will be available in commercially proposed schemes in the near future. Leaving implementation of multicast solely to the IP routing ground networks, rather than forcing it on both ground and satellite networks, would appear to make the problem of implementing efficient inter-network multicast with a satellite component more tractable.

It is possible to provide LAN clients without Internet access multicast streams using a DirecPC machine as the LAN’s “multicast server.” The concept is to have a machine within the Internet receive a multicast stream and forward tunneled IP packets to the DirecPC machine. The DirecPC machine will then be responsible for receiving the tunneled packets and distributing them to the LAN as multicast packets. *Figure 2* shows an example of an architecture for multicasting via satellite.

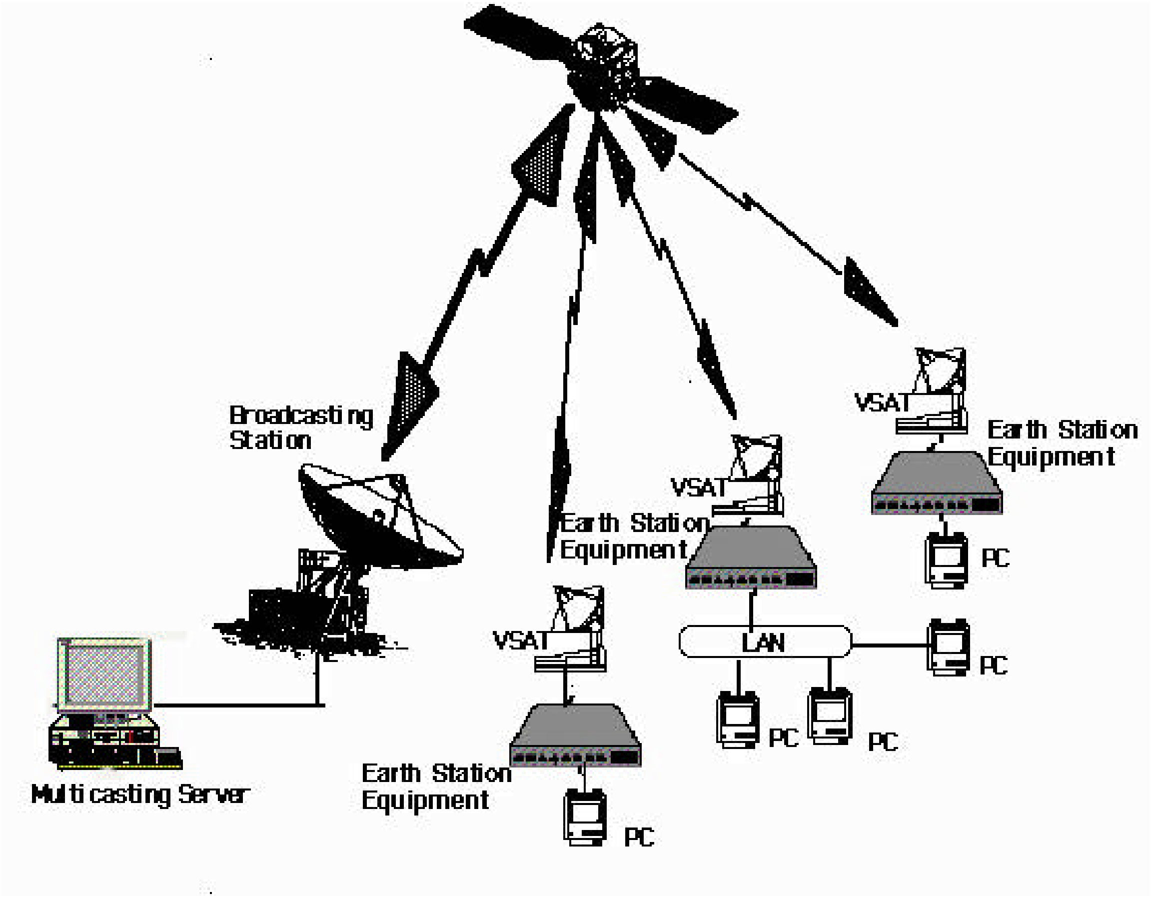

Figure 2. Multicasting using satellites.

2.3 *Web page caching*

There are plans to increase the efficiency of World-Wide Web network connections by carrying the most commonly used data to the Internet Service Providers (ISPs) by satellite. It is possible to use broadband satellites to distribute commonly requested information to local ISPs, where it would be cached for distribution to local customers. Such an arrangement setup would lessen congestion on Internet backbones and cut communications costs for service providers.

This satellite-borne service is a more efficient way to get Internet data to ISPs, because the bulk of Web page requests concern a relatively predictable set of data. Storing that data in caches at the "edge of the Internet" speeds delivery of pages to users and relieves network backbones from the congestion caused by redundant data. To pump the Web’s most popular data into a local cache at the ISP, a satellite dish of one-meter diameter would feed data to a receiver at a rate of 4 Mbps.

3. Evolution of Satellite Communications (Towards Broadband Communication via Satellite)

3.1 *Historical Evolution*

The concept of using artificial satellites to provide telecommunication services is almost 40 years old. The large capacity GEO satellite systems of today and complex constellations of satellites in various orbital locations in the future will offer a wide variety of services to not only fixed users but to mobile users as well.

We can classify the evolution to today's state-of-the-art systems through 5 distinct periods or eras, as follows:

1. SUB-SYNCHRONOUS ERA: The period 1957-63 includes the launch of a number of early experimental satellites following Sputnik that were mainly in lower, non-geosynchronous orbits. There were no commercial services available during this period, but the ability to design, launch and successfully communicate with a spacecraft in orbit around the earth was demonstrated.

2. GLOBAL SYNCHRONOUS ERA: The year 1965 marked the beginning of the commercial era with the formation of INTELSAT and the launch of Early Bird (INTELSAT I), the first geosynchronous satellite offering transcontinental communications. Satellites were mainly used for trunk connections carrying telephone, telex and TV signals, simply complementing submarine cables and interconnecting central national gateways.

3. DOMESTIC & REGIONAL ERA: From 1973 to about 1982 a number of regional (e.g. EUTELSAT, AUSSAT) and domestic (e.g. TELSTAR in US) satellite systems offered various services which were again mainly telephony, TV, and some basic data services. These services were now delivered to a large number of terminals and even in a direct-to-user mode in some cases. INMARSAT was formed during this era, with the main objective of supporting maritime communications. (INMARSAT has since extended its services and its system is the only one currently offering global services to all types of mobile users on land, in air and at sea).

4. SMALL STATION ERA: During the 80's (1982-1990) deregulation of telecommunications in various countries and a number of technological developments enabled the use of satellites for dedicated business networks, offering initially data services, but gradually expanding to include compressed voice and video transmission. These VSAT networks enabled large numbers of users to communicate, usually at low bit rates (≤ 64 kbps). Another area that saw explosive growth was the use of satellites for broadcasting large numbers of television programs to subscribers with small inexpensive receive-only dishes using Direct Broadcast Satellites (DBS).

5. INTELLIGENT SATELLITE ERA: Since 1990 the satellite communication field has entered a major new era, with a large number of global and regional systems in operation, development or design stages. The field has become an area of major activity and there is considerable business interest supporting its development. There are increasing demands for a variety of broadband services to fixed users and for the ability to accommodate global mobility. The advantages of communication satellites allow the service of areas where no other communications infrastructure exists. It is now possible to offer global connectivity to people on the move and to efficiently disseminate information to large numbers of users. Satellites are used not only for niche applications but also as an integral part of the global telecommunications network. The systems are also very diverse, with the introduction of intelligent satellites with onboard processing capabilities and of large constellations of inexpensive satellites in lower orbits (LEO, MEO or hybrid) connected with each other to act as network nodes in the sky. Such new systems contrast

markedly from those of even the recent past, which comprised a few expensive satellites in geosynchronous orbit which served simply as very high altitude repeaters between terrestrial stations [9]. Finally, the constant drive for higher capacity forces these new systems to move to higher frequency bands.

3.2 Technological Evolution

As discussed earlier, until the early 1970's satellites were mainly used for international telephone trunking and TV signal transmission. Most systems were placed in geosynchronous orbits; they used the 6/4 GHz band and large global beams to cover the maximum amount of area under their footprint. They were entirely analog, and a carrier conveyed either a single TV signal or a number of telephone channels using Frequency Division Multiplexing (FDM). Satellites acted as simple bent-pipe repeaters in the sky (INTELSAT I,II,II). Since launching capabilities were limited compared to today and solid state electronics were not available these early satellites were very limited in power, which means they were also limited in capacity.

The constant drive for higher rates led to the development of multibeam satellites (INMARSAT, INTELSAT IV) and the search for methods that would enable frequency re-use. Orthogonal polarization was initially used to effectively double the bandwidth, while spatial separation was later introduced to enable frequency re-use by a much larger factor. Sharing of uplink capacity among stations was resolved at the time via Frequency Division Multiple Access (FDMA).

As the number of low- to medium-capacity users sharing the satellite channel increased, it became necessary to find efficient ways to optimize the utilization of this expensive resource. Single Channel Per Carrier/Frequency Modulation or Phase Shift Keying (SCPC/FM, SCPC PSK) was introduced. Time Division Multiple Access (TDMA) followed, with the introduction of digital techniques such as Digital Speech Interpolation (DSI) that enabled even more efficient use of capacity by taking advantage of the silences in speech. Progress in antenna technology enabled a gradual reduction in size and cost; more precise pointing and tracking enabled the satellite beams to focus on the desired coverage area (e.g. a population center) [10].

These developments improved considerably the link budget, reduced interference and enabled communication at higher speeds. The Ku band (14/12 GHz) became the predominant band used in satellite communications at this stage. The increased number of users led to the development of transponder hopping systems (INTELSAT V, BSB) in order to provide full network connectivity; in addition the large number of spot beams created the need for Satellite Switched TDMA (SS/TDMA) systems and onboard processing techniques [10]. The drive for higher speeds meant that the congested Ku band would not be able to support the next generation systems. As a result, the first experimental satellites with advanced spot beam connectivity operating at the 30/20 GHz (Ka band) were developed, namely ESA's OLYMPUS and NASA's Advanced Communications Technology Satellite (ACTS).

3.3 Research Efforts

After this brief historical account and the review of the technological evolution in satellite communications, we turn our attention to some recent and continuing R&D efforts. We do not present a comprehensive description, but rather attempt to familiarize the reader with some key demonstrations and research projects. We classify the work by geographical area, i.e. North America, Europe and Japan. Since the major driving force for satellite communications is the need for global connectivity, it is important to note that there are also a number of transatlantic and transpacific alliances and international demonstration projects. For example, the G-7 Global Interoperability for Broadband Networks projects concern the establishment of global interconnection of national high-speed test-bed networks, and a number of experimental demonstrations that involve broadband satellite connections have been conducted under this program.

3.3.1 North America

Apart from the developments in the commercial sector and the significant work done at COMSAT Laboratories in recent years, NASA's Advanced Communications Technology Satellite (ACTS) has been a major contribution in enabling the development of next generation broadband satellite systems. ACTS, which was launched in September 1993, has demonstrated with a number of experiments [11,12] the feasibility of using the Ka band for broadband communications and has introduced a number of technological innovations, such as hopping spot beams, onboard processing, and signal regeneration through demodulation/remodulation. These features make possible the use of terminals with very small antennas. In ACTS’s baseband processor (BBP) mode, FEC can be applied as needed to combat fading due to precipitation, a major problem at Ka band as mentioned earlier. The satellite also has a microwave switch matrix (MSM) mode, which can support very high rate Satellite Switched TDMA operation [13]. It is also important to note that a lot of the technological developments that will be implemented in the next generation of broadband satellite systems, such as use of EHF bands, inter-satellite links, onboard processing etc. were originally developed and tested for military satellites through various programs such as The Lincoln Experimental Satellite (LES) series at MIT Lincoln Laboratory.

3.3.2 Europe

The OLYMPUS satellite [ESA/CSA] was one of the first experimental Ka-band satellites. Although it had no onboard processing and was not really broadband, it demonstrated the feasibility of using the Ka band and spot beam technology and allowed a number of experiments mainly in the area of VSAT networks.

In Europe, during the last decade, a lot of research effort in this area was conducted under the auspices of the European Union RACE I & II (1990-94) and Advanced Communications, Technologies and Services (ACTS) (1994-1998) programs. Some projects in the area of broadband satellite communications include:

- The CATALYST project [14], the first demonstration (1992) of transmission of ATM cells via satellite in Europe and which demonstrated the capability of satellite ATM connections to support data, video and multimedia applications.
- VANTAGE (VSAT ATM Network Trials for Application Groups Across Europe), whose aim was to demonstrate user access to ATM networks from small terminals at lower bit rates [15,16].

- NICE (National Host Interconnection Experiments), which is related to the usage of National Hosts for certain demonstrations by means of terrestrial and satellite ATM links.
- SECOMS (Satellite EHF Communications for Mobile Multimedia Services), which investigates a new generation satellite system that will provide broadband services to portable and mobile small size terminals on continental-wide coverage focusing on the 40/50 GHz band [17].
- ISIS (Interactive Satellite multimedia Information System), which aims to demonstrate the technical and economical feasibility of interactive services via satellite in the framework of the future multimedia scenario. Specific emphasis is placed on the critical issues associated with a dual-band satellite link concept, namely Ku band on the forward path and Ka band on the return interactive path. Another joint European effort in this area is sponsored by the European Cooperation in the field of Scientific and Technical research COST Framework: COST Action 226 investigates the integration of Local Area Networks by satellite [18] while COST Action 253 investigates the Service-Efficient Network Interconnection via Satellites [19].

3.3.3 Japan

In Japan, much work has been done recently for the DYANET satellite network. Also, the Gigabit Satellite Project, which plans to offer ATM-based high-speed star or mesh type network services using an onboard ATM switch (155 Mbps to 1.2-1.3 m terminals) and SS-TDMA based point-to-point gigabit connections (1.2-1.5 Gbps to 0.5-1.2 m terminals) using an onboard microwave switch matrix. It will have three scanning and two spot beam antennas, and will operate in the Ku and Ka bands [20,21]. The projected launch for this satellite is 2002.

3.4 Future Commercial Broadband Satellite Systems

3.4.1 Satellite Systems

A reason for the drive to broadband service via satellite is the decision of the major aerospace corporations (which have recently become very large and diverse companies through a series of mergers and acquisitions) to start offering services as well as to build equipment and spacecraft and to thus compete with global telecommunication carriers. A number of international alliances have been formed, aiming to offer direct-to-consumer or direct-to-business services, and this changed the role of the existing satellite service providers such as INTELSAT, INMARSAT, EUTELSAT. These existing satellite service providers are now spawning off commercial divisions and changing their status from international bodies with government signatories to privatized companies with investors. The first big wave toward broadband satellite services was systems offering global mobile phone and low-rate data services (i.e. not broadband services), of which Iridium plans to start offering service in 1998, with Globalstar and ICO following in the near future. The second wave was for systems offering a variety of broadband services such as Internet, data and video on a global or regional basis [22]. Some of these regional systems are already operational and very successful, such as the DBS TV satellites, while others are in the application, planning or design stage. For reasons discussed earlier, the majority of these will operate in the Ka band, and will probably start offering services after 2001. Most of these systems are constellations of a few GEO satellites with some type of onboard processing and intersatellite links [23]. Teledesic is the only one to opt for a LEO constellation of 288 (reduced from an original number of 864) satellites [24]. The third wave, which is currently in the early stages of planning and filing for bandwidth, will consist of more complex constellations operating at even higher frequencies (V-band). Some of these systems will be hybrid LEO/GEO constellations [25], i.e. a large number of satellites in LEO orbits and a GEO ring of satellites. Such constellations will offer real-time, delay-sensitive services using the LEO satellites while the power and capacity of the much bigger GEO satellites will be used for services such as multicasting. Some of these could be extensions of the previous generation systems (the success of the Ka-band systems will in fact influence the nature and number of this next generation). *Tables 1, 2* show a list of planned systems. *Figure 3* shows the Teledesic constellation.

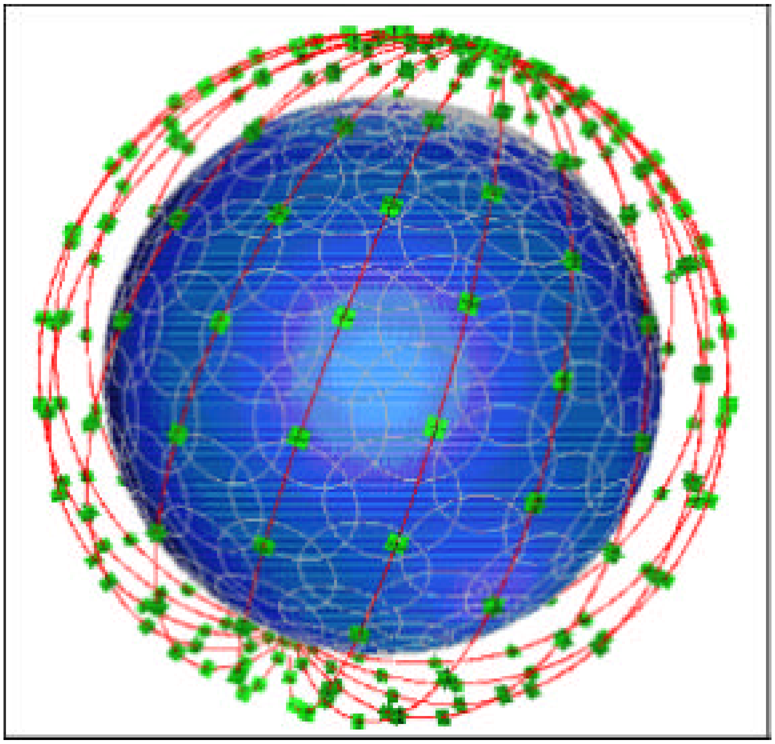

Figure 3. The Teledesic constellation of 288 satellites.

3.4.2 High-Altitude Long-Endurance platforms

Although they cannot be strictly classified as “artificial satellites,” a number of other recent ideas and innovations are targeting the same market with similar services. In particular, a high altitude platform station was defined by the 1997 World Radiocommunication Conference (WRC-97) as, “a station located on an object at an altitude of 20 to 50 km and at a specified, nominal, fixed point relative to the Earth.”

Angel Technologies Corporation and its partners are creating a wireless broadband "super-metropolitan area" network to interconnect tens to hundreds of thousands of subscribers at multi-megabit per second data rates. The HALO Network will offer ubiquitous access and dedicated point-to-point connections throughout a “footprint” 50 to 75 miles in diameter. A piloted, High Altitude Long Operation (HALO) aircraft will provide the “hub” of the network. Operating continuously over each market, the HALO aircraft will create a “Cone of Commerce” in which prospective customers will access broadband services irrespective of their locations. HALO networks will be financed and deployed to select markets, on a city-by-city basis, around the world.

Sky Station’s Stratospheric Telecommunications Service [26] utilizes lighter-than-air platforms which will remain geo-stationary above major metropolitan regions, located in the stratosphere, 22 km above the earth. Sky Station claims its platform will provide high-density, high-capacity, high-speed service with low power requirements and no latency to an entire metropolitan and suburban area extending out into rural areas. Users will access the Sky Station system with common user terminals including modems, laptops, desktops, set-top boxes, screen phones and smartphones. The payload will provide instant T1/E1 access to millions of users in each service area. Advantages of this system include Sky Station platforms not requiring a launch vehicle, while the altitude enables the Sky Station system to provide a higher frequency reuse and thus higher capacity than other wireless systems.

4. Technical Challenges

4.1 Multiple Access and Multiplexing

The satellite, as a shared resource, must be cooperatively used by its users. Thus, to avoid interference in the uplink, there is a need to use appropriate multiple access schemes. Similarly, there may be interference on the downlink from other satellite or terrestrial sources. This interference is usually combated by spatio-temporal signal processing and better antenna pointing. However, the downlink stream may contain a collection of information packages in which each package is intended for a proper subset of the set of users. This situation is common in communications via shared media. Thus there is a need to multiplex information so that when it is sent down from the satellite it can be properly separated by the users. Although multiple access and multiplexing can be considered as two aspects of the general sharing problem, they can often be designed independently. We will focus here on the multiple access aspects with appropriate commentary on multiplexing as needed. The choice of the multiple access scheme has a great impact on the performance of the satellite network. It should match the traffic load of the network and be able to satisfy the users’ quality-of-service (QoS) requirements.

In frequency-division multiple access (FDMA) each user is assigned a different frequency (more accurately, a small band of frequencies) upon which to transmit. With FDMA, many users can simultaneously share the satellite. FDMA has been used for decades in “bent-pipe” satellites for uplinking and downlinking of analog signals such as telephone conversations in INTELSAT systems [27].

In time-division multiple access (TDMA), users are assigned positions in a quickly-repeating schedule for transmitting on a common frequency to the satellite. The abilities of buffering digital data and maintaining tight synchronism have rendered TDMA a practical access technique.

FDMA is attractive for earth stations since an amplifier in an FDMA system operates continuously, while an earth station transmitting with TDMA requires a higher burst power and a correspondingly more expensive amplifier. A drawback of FDMA uplinking is that often the fraction of system channels actually in use is poor, since not every earth station may have something to transmit at all times. This poor "fill factor" represents a short-term excess of capacity that could conceivably be used in a more productive fashion. The inflexibility of FDMA to handle changing system demands has also been cited as a drawback; in a TDMA system, the time slot plan can be changed dynamically to accommodate such varying demands.

However different considerations apply on the satellite. If an FDM downlink is used, then several carriers (corresponding to several signals received by the satellite) must be amplified simultaneously for transmission. Now amplifiers for satellite frequencies are not strictly linear in operation, and the degree of nonlinearity is greatest at maximum power output. The nonlinearity causes input carriers to generate at the amplifier output intermodulation products, which are signals at frequencies other than those inputted to the amplifier. Such products distort the transmitted signal and waste power. The solution is to reduce the power of input signals to correspondingly reduce the power of the undesired products. Of course, this input backoff reduces the power of the desired output signals as well. Thus, for a FDM downlink, a large amplifier must be operated at less than full power. Now if TDM is used, then there is only one input signal to be amplified, which produces no intermodulation products. Further, unlike the case of an earth station transmitting in a TDMA plan, a satellite producing a TDM downlink transmits essentially continuously (whenever there is at least one call/session through the satellite). Hence, FDMA is economically preferable for uplinks to reduce earth station cost while TDM is preferred for downlinks to reduce the satellite cost [27].

TDMA requires synchronization among all earth stations so that their uplink signals all arrive at the satellite at the correct instants. While in practice this has been possible by incorporating timing reference information in TDMA and TDM time slot plans, it remains to be seen how easily this success can be replicated in the broadband systems of the future, which provide for transmission rates orders of magnitude greater than those of the past.

Code-division multiple access (CDMA) is a multiple access technique which is an application of spread-spectrum technology. The essential concept of CDMA is the use of pseudo-noise patterns, or codes, which are used to quickly change the characteristics of the transmitted signal at a rate usually greater than that of the bit stream to be transmitted. In frequency hopping (FH) CDMA, a code is used to rapidly change the carrier frequency of the transmission. Hence FH-CDMA may be thought of as a hybrid of FDMA and TDMA. In direct sequence (DS) CDMA, the user's bit stream modulates a carrier which is modulated again by the code. By assigning to users different orthogonal codes, many users can be simultaneously supported in the same frequency band. Since it is very difficult to intercept a CDMA signal without knowing the code used to generate it, CDMA inherently provides a measure of security which FDMA and TDMA do not. Further, since in both FH-CDMA and DS-CDMA the transmitted signal occupies a bandwidth much larger than otherwise required to send the user information, CDMA provides good protection against fading and interference as well. A significant problem, though, with CDMA is the great bandwidth this technique requires. A signal with information rate of 1Mb/s would be converted to one with actual digital rate of 100Mb/s or higher in a CDMA system. This can severely tax the capabilities of the receiver (especially over poorly performing channels) and might require significant increase in power. This is not necessarily a problem for voice communication; indeed, CDMA is used in some terrestrial cellular and satellite voice systems. But broadband communication requires significantly more spectrum to support the much greater data rates, and so CDMA for such communication exacerbates the spectrum use problem. Accordingly, very few commercial broadband satellite systems under development today employ CDMA.

While FDMA, TDMA, and CDMA are the three "classical" multiple access techniques, two others should be mentioned. Space-division multiple access is one of them; it is based on a simple idea: by using separate beams, a single frequency can be used simultaneously by several users. This frequency reuse is applied well in spot beams, but is limited by how well multiple beams can be separated in space. Polarization-division multiple access is the other; it provides sharing of the satellite by using electromagnetic signals which are spatially oriented specifically to prevent interference between transmissions. There are two versions of polarization which can be employed. In linear polarization, two signals can be accommodated by orienting one in a "vertical" polarization and the other in a "horizontal" polarization. In circular polarization, one signal is oriented in a "left-hand circular polarization" and the other in a "right-hand circular polarization". Of course this method is limited to a maximum two users who share the same frequency at the same time [28].

Uplink access techniques can be classified in various ways according to their characteristics [10]. According to the way they are used to set up connections they could be classified in four types:

1. Random Access or Contention: Techniques such as Aloha and its variations [10] (e.g. Slotted Aloha) have been used for networks of large numbers of users carrying narrowband bursty traffic. Users transmit without checking the channel's status and simultaneous transmissions result in "collisions" and retransmissions. However, contention techniques have reasonable throughputs only at low traffic loads and are not suitable for broadband connection-oriented applications where some type of bandwidth guarantee is required to ensure acceptable Quality of Service.

2. Fixed Assignment: Users are assigned *a priori* a constant number of slots, codes or frequencies. This assignment results in low efficiency if there is no constant traffic flow as slots are wasted when a terminal has no information to send. Static TDMA, FDMA and CDMA belong to this category.

3. Demand Assigned Multiple Access (DAMA):
   (i) Fixed Rate Demand Assignment: Bandwidth is allocated on as-needed basis. In this case a constant bandwidth assignment is made for every new connection. This is more flexible than fixed assignment as just described but might still result in wasted bandwidth.
   (ii) Variable Rate Demand Assignment: This allows dynamic allocation of satellite power and bandwidth based on the changing traffic load of the users [29,30,31]. It is suitable in bursty traffic, where a significant capacity is required but not for the duration of the

connection, and using Single Channel Per Carrier (SCPC) would thus waste valuable bandwidth. Of course using such a scheme implies a system that is more complex and expensive and there are always a number of tradeoffs between improvements in the efficiency of the bandwidth use and the system implementation complexity. By assigning bandwidth to users on a frame-by-frame basis greater efficiency can be achieved, but the drawback is that the significant propagation delay causes the user to have to wait at least 0.25s (double that for non-processing satellites) to receive an allocation for every request. Part of the bandwidth is needed for transmitting the requests to the Network Controller (either aboard the satellite or on the ground).

4. Free Assignment: This concerns the remaining bandwidth not assigned by the fixed- or demand-assignment schemes, and the network controller could freely assign these to active connections in order to increase the throughput and relieve congestion. Criteria such as queue size(s) or priorities can be used to determine the allocation process.

Hybrid versions combining features from the above techniques are also possible.

In conventional TDMA all earth stations transmit and receive on a single frequency, whatever the destination of the bursts. Multi-frequency TDMA (MF-TDMA) was proposed to provide more efficient power use and better performance. MF-TDMA enables the use of smaller antennas (since less power is required) and increases satellite network bandwidth [27]. Designers of a number of future Ka-band systems (such as Teledesic, Cyberstar, Astrolink) are considering variations of MF-TDMA, because it offers a number of attractive features including the possibility of “on-demand” allocation of bandwidth. This could be extremely useful for broadband satellite systems carrying ATM traffic (which also implies “bandwidth on demand”). The MF-TDMA frame can be divided into two areas each containing a set of fixed-size slots on which terminals may transmit: (i) the signaling and synchronization area, for requesting and receive timing information necessary for synchronization, and for sending out signaling information for connection set-up; and (ii) the data area, where ATM cells are framed and transmitted. Within the frame, each terminal granted access may transmit at any one frequency at a given time. A detailed analysis and description of an MF-TDMA satellite system can be found in [32].

4.2 Onboard Processing and Buffering

Onboard processing (OBP) is usually associated with such techniques as demodulation and remodulation, error correction decoding and re-encoding, despreading of spread-spectrum signals and adaptive beamforming. In a system using DAMA with onboard processing, a DAMA resource controller can be placed aboard the satellite, while for multiple-beam satellites, packet switching between beams can be implemented [33,34,35]. Clearly, these types of capabilities increase the required processing and data storage capacities of the satellite [29].

4.2.1 Electronics for OBP

Over the past decade, there have been dramatic improvements in throughputs of general-purpose processors and capacities of solid-state memories, as well as in power consumption, reliability, and costs of both. Radiation-hardened microprocessors with throughputs in the 1 to 4 MIPS range and memory boards with radiation-hard static RAM (random access memory) (SRAM) of 1 to 10 Mbit are readily available. Use of solid-state processors and memories in communications satellites is expected to grow rapidly [36]. Estimated weights and power requirements associated with the processor, memory, and other components of an onboard packet switch can be found in [37]. It is important to note that for the case of Direct Sequence CDMA a signal of high-rate will tax the speeds of the available processors, while processing and RF design is less of a problem in Frequency Hopped CDMA.

Since semiconductors can suffer fatal damage by space radiation the semiconductors used in satellites must be shielded well and specially constructed to resist such effects. Thus radiation hardened semiconductors can be significantly more expensive than their non-hardened counterparts. Also, there are relatively few fabrication facilities for such components and with the expected demand for new satellite systems, the need for radiation-hardened semiconductors is greater than ever and the limited supply may force delays in the deployment of such systems [38].

4.2.2 Onboard Resource Control

Implementing onboard resource control has several merits such as reduced call setup, initiation and teardown times since only two hop delays are required, instead of three. Channel requests need not be downlinked to the ground, and channel assignments and other status information are not uplinked to the satellite since they originate there. In addition, for satellites with multiple beams, setup of calls between users in different beams is simplified [29].

Human control is still required for high-level functions such as beam pointing or congestion management procedures. These can be handled by a ground controller, and a ground controller would in any case always be able to upload new control software or protocol upgrades to the satellite should this be necessary.

4.2.3 Onboard Packet Switching

For using hybrid DAMA with a satellite having a multiple-beam antenna, or having several spot-beam antennas, some type of packet switching is needed to forward packets to the appropriate destinations. This involves selecting the appropriate downlink beam, i.e. the beam whose footprint covers the intended recipient. Although packet switching can be done on the ground, putting both the packet switch and the DAMA resource controller aboard the satellite and integrating them together offer significant benefits. For example, insertion of packets into empty channels can be done more efficiently if downlink channel status information is available to the resource controller without propagation delay.

4.2.4 Onboard Buffering

In a pure DAMA system, there is no need to buffer user transmissions since a fixed transmission rate is allocated to the connection until it is torn down. However, buffering of requests at the resource controller is beneficial because waiting time variability is reduced, and the load on the request channel may also be reduced.

On a multiple-beam satellite that handles packetized data with an onboard packet switch, arrivals of packets destined for users in the footprint of a particular beam will occasionally exceed the available downlink capacity on that beam. Thus, the satellite must be capable of buffering packets, i.e. storing them in memory until they can be transmitted. If the buffer is too small, many packets will be lost because of buffer overflow. In a well-designed system, the probability of packet loss due to buffer overflow should be comparable to or less than the probability of packet loss due to other causes, e.g., noise and interference. For high-rate access, onboard buffering may require substantial amounts of memory. Memories are especially vulnerable to space radiation and thus must be well protected.

For low-altitude satellites not connected by intersatellite links, buffering aboard the satellite permits the delivery of message traffic between users whose geographical separation prevents them from being in each other's view through the same satellite at a given time.

For satellites operating at frequencies around 8 GHz and above, onboard buffering of messages and automatic repeat request (ARQ) can be used to minimize the effects of rain outages [4]. This is particularly advantageous at higher frequencies and at lower elevation angles, both of which significantly increase the excess path loss due to rain.

A common aspect of broadband terrestrial communication is that stations are linked through a routing/switching system. With a single [bidirectional] link to such a system, a single station can communicate with many others without having to break existing "connections" before making new ones. Such a system can be established through a satellite by equipping the satellite with onboard processing to conduct the switching function, directing received packets or ATM cells to the downlink beams for their respective destinations. Such onboard processing also allows for dynamically reconfiguring the network, which is important in data communication since data tends not to be sent continuously but in bursts.

As onboard processing allows for dynamically reconfiguring the network, it also allows for dynamically changing the direction in which the satellite radiates its downlink power. If TDM is used for the downlink, and spot beams are available, the satellite can direct all its power into the beam servicing the station(s) assigned to each slot of the TDM time plan. This hopping spot beam technology, demonstrated on ACTS, helps make possible networks using fairly small antennas, such as VSAT networks.

Onboard processing also allows isolating the uplink and downlink in several ways notable for broadband communication. Onboard processing allows for signal regeneration by demodulating signals upon receipt at the satellite--thereby removing much thermal noise from the uplinks--and then remodulating these signals for downlinking. As broadband satellite communication is particularly susceptible to errors, the signal regeneration providing the equivalent to 2-3 dB of greater transponder power is quite an improvement.

Further, as explained above, FDMA is preferable for uplinks from the earth while TDM is preferable for a downlink from the satellite. Onboard processing makes this conversion possible, and by using recently developed linearization methods multi-carrier systems can operate very close to saturation.

The recently developed theory and methodology of multi-user detection [39], which permits the simultaneous detection of multiple interfering signals, rather than focusing on one and treating all others as noise, is particularly well suited for use on the uplink of satellite systems. The gain in performance in substantial, but at a rather serious complexity cost. However, there are many sub-optimal multi-user detection schemes of reduced complexity and there are algorithms that have been proposed which perform, under certain conditions, optimally but with reduced complexity as well.

Use of multi-user detection is not imminent yet; however, with the extended use of CDMA and the improvements in adaptive antenna arrays (that permit spatio-temporal processing of the received signals), it becomes increasingly possible, if not imperative to resort to this more powerful detection scheme. At high date rates, contending with interfering signals becomes more challenging and if classical non-multi-user detection receivers are to be used, there may be a substantial increase in the value of the required transmission power.

4.3 Error Control

A satellite channel is especially susceptible to errors. While errors in a fiber link may be rare, errors in a satellite link occur frequently, due to moisture-induced attenuation/scattering and due to the effects which are present in all wireless channels (fading, shadowing, etc.). While these effects are tolerable at frequencies much below 10 GHz, they are substantial at higher frequencies. Also, the attenuation effect increases with frequency, indicating transmissions in V- and Q-band systems will suffer more than those at Ka band.

Further, as the transmission bit rate increases, the effective bit duration decreases, and if transmission power stays fixed the “energy per bit” diminishes. As a result the signal-to-noise ratio decreases and hence there is a strong need for error control in broadband satellite communication [40].

One way to combat errors is simply to transmit more power. This solution is not typically employed, though for several reasons. For one, designing a satellite to transmit using more power implies a heavier and larger satellite. Not only does this increase the cost of the satellite, there are limits on satellite size and weight imposed by available launch vehicles. A higher-power ground station also implies a greater size, as well as greater purchase and operating costs.

An alternative to using higher power is to use antennas with higher gain. This does not necessarily mean using a bigger antenna, which is undesirable for both the satellite design and for the user. Rather, a spot beam antenna (array) on the satellite can be used to tightly focus the satellite’s radiated power, and can similarly improve the satellite’s ability to receive a signal from a small part of the earth’s surface. Therefore, making a satellite beam smaller effectively increases the power received by the ground user from the satellite, and that received by the satellite from the ground user.

Aside from the aforementioned schemes, there are two other techniques for error control, both of which entail sending additional bits: forward error correction (FEC) and automatic repeat request (ARQ). FEC techniques have been used in space communication since the time of NASA probes such as Pioneer 9, and are now becoming quite common in satellite communication [41]. For broadband satellite communication, the present trend is to use concatenated coding schemes, typically with a convolutional inner code and a Reed-Solomon outer code. Oftentimes interleaving is used as well to provide additional burst error protection [42,43,44,45,46].

All FEC methods provide coding gain and somewhat improve the link budget. Of course, any error control scheme introduces overhead and hence reduces effective information throughput. More significantly, however, the use of FEC methods has the drawback that if used in a bursty error environment it must either be designed for the worst-case channel profile or offer inadequate error mitigation. This is a common characteristic of all open-loop schemes [41]. Yet, FEC is often preferable for protecting information which has strict delay constraints, such as real-time audio and video broadcasts.

In ARQ, retransmissions are used to correct errors in received information. ARQ works well for protecting information which must be delivered with high fidelity but can withstand some variable delay to achieve this fidelity. In satellite communication, care must be taken in designing an ARQ protocol to operate with propagation delays possibly greatly exceeding those experienced in terrestrial communication, for otherwise the achievable throughput may be limited. This may be mitigated also through the use of a low-bandwidth terrestrial link for retransmissions and control traffic, in which case the propagation delay can be reduced significantly [47].

The advantages of FEC and ARQ can be combined in a scheme called hybrid ARQ. The notion in hybrid ARQ is essentially to improve the channel “seen” by an ARQ protocol by protecting the ARQ packets with FEC. Hence fewer retransmissions are required than in a system without FEC, and the system can use a less powerful FEC code--with less transmitted overhead and/or less sophisticated processing--than would be needed to achieve comparable performance without ARQ. It is also possible to adaptively change the FEC code in hybrid ARQ to achieve improved performance and less overhead [48,49,50].

ARQ protocols (including hybrid ARQ) have also been suggested for satellite multicasting [51,52,53,54]. A notable scheme for reliable multicasting of data without delay constraints in IP networks, including satellite-based IP networks, is Mulitcast File Transfer Protocol (MFTP) [55]. A problem, though, in ARQ multicasting via satellite is that a retransmission is typically required by only a few receivers, so during a retransmission the other stations wait unproductively. As the number of receivers increases, the throughput accordingly diminishes. This may be alleviated by supplementing the satellite multicast link with a system of terrestrial links between the transmitting station and each receiving station. By conducting all retransmissions via the terrestrial links, the flow of new packets on the satellite link need not be interrupted as often and so a high throughput can be maintained. This subtlety about error control over broadcasting media (such as satellite channels) is a strong argument for the use of hybrid (satellite/terrestrial) architectures that may combine the best properties from all link options [56,57].

4.4 TCP

The Transmission Control Protocol (TCP), owing to the popularity of the Internet, is one of the most common and pervasive computer communication protocols in use today. Unfortunately, there are a number of difficulties in using this protocol for broadband satellite communication, and we mention here some of those most commonly discussed in the literature. In a broadband satellite communication system, the high data rate and the large propagation delay cause a large amount of data to be "in flight" between the endpoints of the communication at any given time. Consider as an example a T1-rate (1.544 Mbps) channel through a geostationary satellite, at 22,300 miles altitude. In such a system, the propagation delay from the earth's surface to the satellite exceeds 120 ms. Accordingly, more than 120 x 4=480 ms elapses between the time a byte is sent in this system and the acknowledgment returns via the satellite. Multiplying this "round-trip-time" by the data transmission rate yields a so-called bandwidth-delay product of more than 1544000 x 0.480=741120 bits, or 90.5 kilobytes (kB). The bandwidth-delay product represents the maximum amount of information which can simultaneously be in transit between the endpoints of the communication. However, TCP has a maximum window size of 64 kB (65536 bytes), which limits the throughput achievable in the system to 65536/0.480=136.5333 kB/s, or 1.092 Mb/s, less than three-quarters of the T1 channel rate. This problem of unsuitably small window size is not unique to satellite communication, for it is found in other modern high-speed networks as well; it is simply exacerbated over satellites because of the large propagation delay [58,59,60].

To remedy this problem, a window scaling option has been proposed in RFCs 1072 and 1323. With this option, the window size specified in the communication can be scaled by a power of 2, up to 2^{14}. With this option, a maximum window size of 65536 x 2^{14}=1 GB can be specified [61].

Another problem with TCP for broadband communication is that TCP provides 32 bits for specifying a sequence number for the frame (in TCP parlance, the segment). In a broadband network, the corresponding space of 2^{31} sequence numbers can be exhausted quickly and then reused. This "rollover" or "wrap-around" of the sequence number can lead to ambiguities in acknowledging frames and in providing them in proper order to higher-level applications. A solution to this problem has been proposed in RFC 1323--namely, that each TCP segment should bear a time stamp. With such time-stamping, the ambiguity caused by wrap-around can be eliminated [61].

TCP's error control strategy is based upon an assumption of segment losses being due to congestion. While congestion can indeed cause frame losses, the imperfections of the satellite channel cause errors as well. The go-back-N sort of retransmission scheme used by TCP may be appropriate for congestion-induced losses, but this scheme results in many retransmissions which are unnecessary and which correspondingly reduce the throughput in the case of random losses [62]. Now while TCP's fast retransmit/fast recovery algorithm indeed retransmits a single frame lost randomly, TCP does not provide for the receiving entity to specify multiple randomly lost individual frames. Correspondingly, there is no provision for retransmitting multiple non-contiguous individual frames. A solution to such shortcomings is proposed in RFC 2018 [63], which suggests using selective acknowledgments. With this method, TCP segment numbers are used to specify upper and lower edges of blocks of received bytes. A TCP implementation supporting this option can infer from such information which segments need to be retransmitted.

The window scaling, time-stamping and selective acknowledgements options will be incorporated in Version 6 of the TCP/IP protocol suite [64]. Another technique to improve TCP performance over satellite meriting mention here is that of spoofing. Spoofing may be described as splitting a long physical path of a TCP connection into multiple shorter links, and thereby the intermediate node(s) along the long path fools the TCP implementations at the link endpoints into thinking they are communicating over shorter paths. An analogy for comparing a spoofed TCP connection to a conventional, end-to-end connection might be X.25 vs. frame relay. Frame relay, which conducts end-to-end error control, was developed to replace X.25, which conducts node-by-node error control. In a network with short, error-free links, the end-to-end operation of frame relay is preferred over the node-by-node operation of X.25. However, in a system with long, error-prone links, conventional TCP requires large window sizes (as discussed above) and long periods for error recovery, and splitting the end-to-end connection into a series of two or more connections may be advisable. An important distinction between X.25 and spoofed TCP, and at this point the analogy must be abandoned, is that X.25 allows only one frame to be in the end-to-end connection, while spoofed TCP allows multiple frames in each link/node-by-node connection, and by extension in the end-to-end connection as well. Spoofed TCP is commonly mentioned as a scheme for improving throughput over satellite connections: recovery from a loss in the satellite link can be achieved by the gateway to that link rather than by the host remotely accessed [65,66].

4.5 ATM via Satellite

Asynchronous Transfer Mode (ATM) has been adopted as the main technology for the implementation of the Integrated Broadband Communications Network (IBCN). However, the deployment of a ubiquitous terrestrial infrastructure to support this technology would probably take many years and the traffic demands on such a network are as yet unknown. Satellite networks offering broad geographical coverage and fast deployment appear to be an attractive option for the early deployment of the IBCN and could play a major role in its development, provided a number of difficulties arising from the nature of satellite systems can be overcome. A more detailed discussion of ATM over satellite can be found in [45,67].

In ATM, information flows in fixed-size blocks called cells, each consisting of a header and an information field. Cells are transmitted over Virtual Circuits, and routing is based on the Virtual Circuit Identifier (VCI) contained in the cell header. Slots are allocated to a call on an asynchronous (demand-based) manner and the bandwidth is efficiently used, since no bandwidth is consumed unless information is actually being transmitted. ATM can accommodate Variable Bit Rate (VBR) services and can be used to improve bandwidth efficiency by statistically multiplexing traffic from bursty sources. ATM can also accommodate circuit-oriented and Continuous Bit Rate (CBR) services by allocating bandwidth based on a fixed rate for a connection, given that sufficient resources are available [68].

The higher error rates of satellite channels, however, preset a problem in the integration of satellites with terrestrial B-ISDN [69,70,71]. The ITU-R Recommendations for Satellite Communications specify a BER of 10^{-7} at 95% of the time, while the specifications of performance over a fiber link specify a BER of 10^{-9} at 99.9% of the time. Another complication is the possibility of bursty errors in a satellite system, especially in Ka-band operation. Since the ATM header error check (HEC) is able to correct only single-bit errors, the burst errors in the

ATM header cannot be corrected. Therefore, there might be a significant increase in ATM cell discard probability, which is defined as the ratio of the number of ATM cells that are discarded due to uncorrectable errors to the total number of cells received. The burst error characteristics can also affect the performance of ATM adaptation layer (AAL) protocols [72,73]. AAL1 and AAL3/4 employ 3-bit and 10-bit CRCs, respectively while AAL5 employs a 32-bit CRC which is more powerful in burst error detection. Therefore, AAL5 appears to be more suitable for a satellite environment. However there might still be severe discarding of cells at the physical level, and there is a need to compensate for this by using interleaving mechanisms, error recovery algorithms or efficient coding schemes for error correction.

ATM has two major aspects: the multiplexing aspect (achieved by the segmentation into standard-size cells) and the switch management aspect that ensure that the quality-of-service (QoS) guarantees are met for each of the multiplexed traffic commodities. The multiplexing aspect is easily handled over the satellite channel, provided the appropriate modifications to the cell structure are made (some of these were just outlined above). The QoS aspect, however, is more challenging. If there is to be no switch management aboard the satellite, then that aspect can also be handled (on the ground) by viewing the satellite link just as the traditional, long-propagation bent-pipe link. However, this considerably limits the potential role of the satellite. As mentioned earlier, onboard processing and switching gives new degrees of freedom that provide flexibility and potential performance improvement. However, managing the onboard switch to satisfy QOS guarantees is a daunting task. The packets (or cells) of each multiplexed traffic commodity encounter errors and delays on the uplink that must be taken into account by the switch. Thus a super-intelligent, dynamic switch management process must be developed in order to provide the appropriate priority handling to each cell [74].

A significant role for broadband satellite systems would be the provision of seamless interconnection of LANs/MANs using ATM [9,75]. A number of problems need to be addressed before this can be achieved however. For real-time applications, the significant propagation delay must be accommodated in the protocol implementation, especially in the case of GEO satellites. Suitable conversion protocols and Satellite-ATM Interface Units between various LAN/MAN architectures need to be developed for efficient and seamless interconnection. Efficient flow control mechanisms [76] are needed to minimize the cell losses, taking into account that the satellite channel is a limiting bottleneck in terms of bandwidth and delay. Finally, traffic control mechanisms [45] that take into account the characteristics of the satellite environment need to be developed in order to ensure QoS guarantees can be met. *Figure 4* shows the protocol layer architecture for ATM-over-satellite transmission.

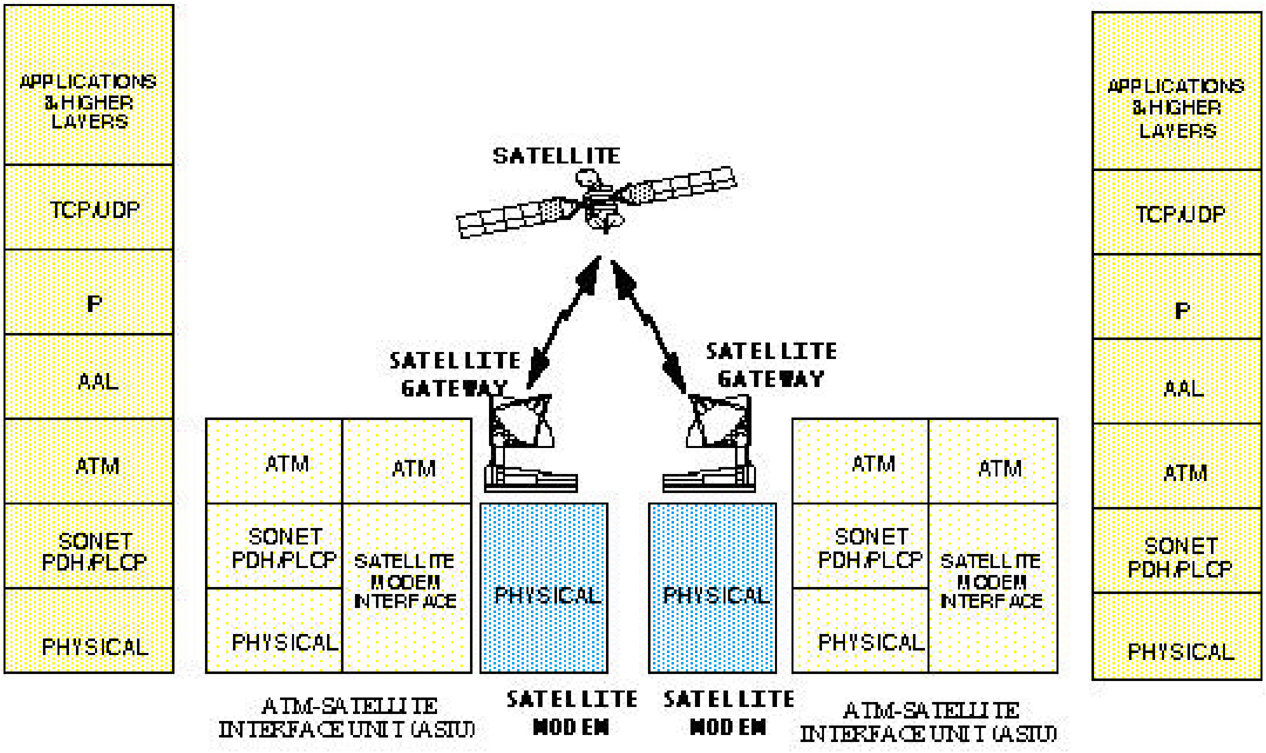

Figure 4. ATM over satellite protocol layers

4.5.1 Onboard ATM Switch

The ATM satellite network configuration is similar to that of conventional terrestrial implementations. We have already discussed the need for multiple focused spot beans that would allow small inexpensive terminals to be used at user sites. However, a multibeam configuration implies some form of switching between beams. For this, baseband switching is used because it offers flexibility and 3 dB of regeneration gain [77]. Note that supporting ATM services does not necessarily require an onboard switch. There are systems that offer a concept of ATM switching by having the “sky-in-the-switch” [78], i.e. no onboard switching fabric but sophisticated gateway equipment, thus essentially transposing the switching functions to the ground. This might have serious performance disadvantages but offers a more flexible system that could be reconfigured later on, i.e. represents a significantly lower risk system.

4.5.2 Primary Access and Scheduling

On the uplink, most systems will use multiple frequency time-division multiple access [27]. Although this is not the only choice [79] it allows for the flexibility and bandwidth efficiency provided by preamble-less TDMA and allows a smaller ground station size due to the reduced burst rate. On the downlink, time-division multiplexing (TDM) will be used. The combination of MF-TDMA and TDM allows for the use of bandwidth-on-demand capacity allocation, thus taking full advantage of the features of ATM.

Scheduling algorithms are used to assign slots. Because of the onboard message regeneration and packet switching, it is possible to disassociate uplink from downlink scheduling and resolve some contention onboard. Wireless medium scheduling, while not a standard feature of ATM switches, can be integrated with the overall access mechanisms [77].

On the uplink, such a multiple access scheme will use fixed assignment for synchronization and out-of-band signaling. Constant and variable rate reservations will be used for priority traffic--with peak cell rate for constant bit rate (CBR) traffic, sustainable cell rate for variable bit rate (VBR) traffic, and minimum cell rate for some available bit rate (ABR) and ATM block transfer (ABT) traffic. Free assignment of remaining time/frequency slots will serve best-effort traffic--ABR, undefined bit rate (UBR), and ABT. Out-of-band signaling will be used for new connection admission. In such a system no slot will be accessed in a random manner, so there are no collisions. The major feature of the scheme is that after initial login, connection admissions can be processed onboard. The combination of out-of-band and in-band signaling creates a powerful means of following the traffic dynamics even when considering the one-way delay from terminal to onboard switch and the very bursty conditions of multimedia traffic. The major drawback is the added delay between initial signaling and allocation of capacity, which prevents highly interactive applications from running over a geostationary satellite. The onboard scheduling will of course add more complexity to the switch hardware [77,80].

4.6 Intersatellite Links/Routing Optimization

An Intersatellite Link (ISL) is a direct connection between two satellites in space. The main goal of using ISLs within a satellite system is the achievement of more versatile connectivity. The satellites are allowed to route long distance traffic not only via the earth stations, but also through neighboring satellites [81,82]. There are currently very few satellites in operation which use intersatellite links. The MILSTAR US military satellite system is one example, while Iridium will probably be the first commercial system that will use these on a large scale. Most future LEO and even some GEO satellite constellations plan to implement some form of “network in the sky” by connecting satellites via ISLs.

One major advantage of using ISLs is that the network can operate with a significantly smaller number of ground gateways, i.e. global coverage can be realized without investing in a large terrestrial network with a large number of gateways. If handled correctly, the ability to route traffic to a particular destination using direct satellite-to-satellite links might improve performance by providing a shorter path [81].

The introduction of ISLs however complicates the operation and performance management of the network. As satellites move in space, the antennas must be re-directed with precision and speed, and the additional hardware components needed for the ISL ports add to the weight of the satellite payload, which makes the launching and control more difficult.

There are generally two-types of ISLs, intra-plane and inter-plane. Intra-plane ISLs connect satellites within the same orbit. Such ISLs are in general permanent links, since satellites in the same orbital plane maintain their relative position to each other. Therefore, intra-plane ISLs can be provided with fixed antennas.

On the other hand, inter-plane ISLs connect satellites belonging to adjacent orbit planes. Since in this case the relative position of the satellites changes with time, careful antenna steering is needed. Inter-plane ISLs are in many cases non-permanent; as the two satellites move away, the distance between them increases. The ISL must be turned off when the line of sight between the two satellites is interrupted by other satellites or by the earth.

ISLs can be either high frequency RF links or optical links. In the case of RF ISLs, more bulky antennas are required, while in the case of optical links higher transmission speeds can be achieved by smaller and lighter equipment. However, the pointing of the very narrow laser beams in the optical case must be very precise [81].

LEO satellite networks possess many unique characteristics and constraints. As satellite nodes move with time, spatial and temporal dynamics are integral to network operation and must be factored into centralized or distributed packet routing algorithms. The network connectivity between any two points is dynamic, and the network topology changes over time. Additionally, packet-dropping and flow control algorithms are limited by buffer capacity aboard the satellite. Network routing algorithms must accommodate possible temporary or permanent satellite failure modes. Furthermore, a key performance requirement of ATM networks is the need for cell sequence integrity for a Virtual Channel Connection (VCC). This presents some challenging design problems given the dynamic nature of the network topology. Since the connectivity is constantly changing, calls with long holding times will be constantly rerouted. Routing algorithms which were originally designed to handle failure scenarios in the terrestrial network will be invoked routinely in a LEO satellite system supporting virtual circuits, and there is a pressing need for the development of strategies and algorithms to control the traffic so that the diverse performance requirements are met.

Congestion control mechanisms within the satellite network must be designed such that they minimize the onboard satellite processing requirements. The inherent burstiness of ATM traffic will pose potential performance problems with the relatively small buffers and limited processing power aboard the satellites unless traffic shaping is performed. The performance impact at a given ISL or gateway uplink can be assessed by approximating the input streams by a Batch Markovian Arrival Process (BMAP) or its discrete analogue. Priority strategies need to be studied for these models.

The network analysis of the satellite nodes will be challenging, since traffic can enter the node from the user terminal uplink, the gateway uplink, or one of the ISLs. The existence of any of these links depends on the position of the satellite, and the temporal dynamics of the connectivity may need to be factored into the analysis.

Maintaining network connectivity, finding the best route across the hybrid terrestrial and satellite network and ensuring that a quality of service is maintained across a connection of several links are all interesting issues for investigation and will play a crucial role in optimizing the performance of these networks. For constellations such as Teledesic that plan to use large numbers of satellites in LEO orbits, ISLs are going to be a critical part of the network architecture. In [82,83,84] an ATM-based concept of the routing of information in LEO and MEO systems with ISLs is discussed. The authors propose a virtual topology by means of virtual path connections (VPC's) connecting all pairs of end nodes in the ISL subnetwork for a complete period in advance, similar to implementing a set of time-dependent routing tables. Clearly, the average number of route changes for an end-to-end connections needs to be minimized in such systems and an optimized routing strategy (given the constellation geometry and ISL connectivity) over specific time intervals of the constellation period is desired. Delay jitter is also a major concern in this environment.

For broadband systems, the main limitation in the use of ISLs is the acceleration of all needed functions, from switching and routing, to link tracking and maintenance.

4.7 Security

Unlike terrestrial broadband systems, which have historically been based on wireline transport media, a satellite-based system inescapably involves the use of wireless links. As such links can be easily and without detection monitored by unknown parties, there is strong possibility for satellite-borne information intended for select users to be improperly intercepted. Accordingly security is an important issue in satellite communication, and a critical one for attracting the business customers that most broadband systems hope to service. Services such as critical financial information, design plans or subscription-based services such as software distribution must be protected to safeguard the information distributed and/or to avoid a loss of the service provider's rightful revenue. Providers will need to demonstrate the ability to protect customer information, but also need to secure their own network resources, such as satellite controls, billing or other vital information [85].

Protection of information through encryption techniques is of course hardly new. However, much broadband communication is intended for real-time consumption. Hence the encryption and decryption implementations, as hardware, software, or a combination, must have the speed to support the high data rates involved.

For obvious reasons, most of the leading prospective broadband satellite companies are unwilling to discuss security, or simply present rudimentary information on their solutions; however they all stress the importance they assign to this issue. Some plan to provide an authentication scheme (e.g. CyberStar) and others promise link encryption (e.g. Teledesic).

Many global next-generation satellite systems switch traffic between nations. Providing security on a national level is a difficult task, but achieving a global security policy will be even more difficult. U.S. restrictions on the export of strong encryption might further complicate the issue, with the possibility of one encryption system available to customers in North America and a different scheme to customers in other regions [85].

Since a lot of the traffic will traverse several national boundaries, and will probably travel across intermediate terrestrial partners, the service provider will need to meet the needs of multiple nations requiring key escrow or recovery, and to resolve situations in which one nation opposes having its national traffic subjected to review by another nation.

Scrambling signals is a simple solution, already used for protecting unauthorized reception of video broadcasts, but here the stakes are higher. Also, the wide availability of relatively inexpensive chips that can decode 40-bit DES (Data Encryption Standard) at speeds close to real-time means that weak encryption is inadequate for sensitive traffic.

Security has been a major issue in the discussions of the IETF and a major concern for the use of TCP spoofing to accommodate the latency of GEO satellites. TCP spoofing isn't expected to work with Standards-based IPSec (IP Security). Spoofing and IPSec are incompatible because once a transmission is encrypted, it becomes impossible for an outside entity, such as a satellite service provider to check the packet content to perform spoofing. On the other hand, if the TCP header were to be left unencrypted, the data stream would become vulnerable to malicious TCP or IP spoofing.

The primary alternative to IPSec is application-layer security, like SSL (Secure Sockets Layer), which secures the user, transaction or application, instead of the node, as IPSec does. Application-layer security is compatible with TCP spoofing. The downside to application security is that it must be implemented individually in each application and intruders can still snoop out certain information, including the destination of transmitted signal.

Another security hurdle for broadband satellite providers lies in their widespread acceptance of ATM infrastructure. While link encryption can be used on ATM, a standard for end-to-end cell-based encryption is still evolving while the cost of ATM-compatible key security systems is currently too high.

5. Regulatory Issues

There are currently more than 1000 satellites orbiting the Earth and that number will significantly increase over the next several years, even if only some of the planned systems described earlier materialize. Portions of the electromagnetic spectrum from just a few hertz up to beyond 300 GHz are designated for specific purposes, and several bands of spectrum have been allocated for satellite systems. As new satellite systems are proposed, agreements at various jurisdictional levels are required.

The international authority for management of the electromagnetic spectrum is the International Telecommunications Union (ITU). The ITU's role is to make sure a proposed system does not interfere with a system that is already in orbit, or with terrestrial systems, and this process requires international coordination. The ITU, an agency of the United Nations, also conducts periodic meetings of delegates from the world's countries to discuss the International Table of Frequency Allocations. These meetings, called World Radiocommunication Conferences (WRCs), are held every two years, and the most recent was WRC-97.

The preparation process before a WRC involves several steps of drafting and discussing documents at national and regional levels. The high volume of material on a WRC agenda often requires that matters scheduled for a WRC be deferred to the next one, and there are currently plans to extend the period between WRCs to two-and-a-half years. This means that a new broadband satellite system must be designed and approved quickly. But, to secure internationally sanctioned positions in the electromagnetic spectrum--and positions in the prized geostationary orbit, too, if required--requires strong effort in the WRC preparation process. This effort must be applied not only to the formal matters, such as participating in WRC preparatory meetings, but also in simply keeping the proposed system in the foreground of the many issues the ITU delegates consider during the WRC preparation process.

The ITU allocates spectrum to a given service, e.g. Fixed Satellite Service (FSS), rather than individual companies. The process starts at the national level; a consortium looking for spectrum allocation for a particular system would first go to their national administration (e.g., the Federal Communications Commission (FCC) in the United States). If certain criteria, which relate to the technical and financial feasibility of the project, and how the proposed system, if approved, will constitute a benefit to the public are met, the national administration would approve the filing and the request would then be passed on to the ITU. The ITU reviews the application, which includes such information as the starting date, orbital specifications, and characteristics of the network. The information is then published and distributed to representatives of countries which are part of the ITU who study the data to see if and how any of the existing systems in their countries will be affected. Members are given four months to respond and then the ITU goes through a process of coordination and notification which may take several years. Services must request permission for spectrum allocation up to nine years before the systems actually get off the ground.

In cases where a large demand for a particular segment of spectrum is expected, a national administration may establish a filing dateline by which all candidate systems must submit their applications. This happened recently with Ka- and V-band filings with the FCC in the United States. The systems are then reviewed to ensure they meet the required criteria. In certain cases where there is significant demand, national administrations could also auction spectrum to the highest bidder.

Not only must a new system conform to international regulation, but it must also be licensed for being built, launched, and operated by the government of the company proposing to develop it. In the United States, for example, a filing for such authority with the FCC includes some technical information about the system and also statements explaining the fiscal viability of developing that system.

Aside from securing approval of a home government, a company developing a satellite system to service stations in other countries must often secure permission in those countries as well. One particular concern is the potential of causing interference to existing terrestrial microwave systems, which are used for telephone trunking and aircraft navigation. Also, it is possible a government may object to some of the content which will potentially be delivered on a proposed broadband satellite system, on the grounds of the content being politically, morally, or religiously offensive. Objections as these are sometimes coupled with a requirement to let residents of the country have access only to government-approved content. Such concerns can have strong implications in the technical design of the system, such as revising satellite antenna radiation patterns.

Recognizing the important role satellites will play in the future GII, the recent WRC-97 took many decisions that will significantly help future satellite communication systems. In particular, WRC-97 took decisions that enabled the broadband non-GEO FSS networks SkyBridge and Teledesic to proceed [86].

6. Conclusion

Satellites are unique components of communication systems that possess singular properties. Some of these properties (breadth of broadcast "reach," ubiquitous access, low-cost global coverage, large capacity etc.) represent significant advantages. Some others (propagation delay, wireless channel quality, exposure to space radiation, etc.) constitute serious shortcomings. Finally, a few others (onboard switching, spot-beam technology) offer opportunities and represent challenges that can transform some of the shortcomings into strengths.

For broadband access in particular, satellites offer substantial bandwidth that can support transmission at Gbps rates. At the same time, significant difficulties arise at these rates that stem mainly from the delay and error characteristics of the satellite channel. In a network environment these characteristics impact adversely some of the broadband network protocols (from ATM to TCP).

It is realized today that satellites have a place in the world's communication infrastructure. It has also been realized recently that they have a place in the delivery of broadband access and services. We hope that this article provides to the reader a view of satellite capabilities (especially from the broadband point of view) and a description of the technology challenges that must be overcome to permit the successful and harmonious integration of satellite and terrestrial resources.

Company	System	Number of Satellites	Estimated Satellite Capacity (Gbps)
Lockheed Martin	Astrolink	9	6.0
Loral	Cyberstar	3 GEO	9.0
Hughes	Spaceway	20 MEO/16 GEO	4.4
G.E. Americom	GE*Star	9 GEO	4.7
Teledesic	Teledesic	288 LEO	10.0

Table 1. Some of the Ka-band broadband filings with the FCC.

Company	System	Number of Satellites
CAI Satellite Communications Inc.	TBD	1 GEO
Denali Telecom LLC	Pentriad	13 HEO
GE American Communications	GE*Starplus	11 GEO
Globalstar L.P.	GS-40	80 LEO
Hughes Communications Inc.	Expressway	14 GEO
Hughes Communications Inc.	Spacecast	6 GEO
Hughes Communications Inc.	Starlynx	4 GEO/20 MEO
Leo One USA Corp	LEO One	48 LEO
Lockheed Martin Corp.	TBD	9 GEO
Loral Space and Communications Ltd.	Cyberpath	4 GEO
Orblink LLC	Orblink	7 ME0
Panamsat Corp.	V-Stream	12 GEO
Spectrum Astro Inc.	Aster	25 GEO
Teledesic Corp.	V-band supplement	72 LE0
TRW Inc.	TBD	15 MEO/4 GEO

Table 2. Some of the V-band broadband filings with the FCC [2].

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