A Survey of Future Broadband Multimedia Satellite Systems, Issues and Trends

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ABSTRACT

The demand for advanced information services is growing in terms of both the number of users and the services to be supported. Voice and low-rate data services are insufficient for users in a world where high-speed World Wide Web access is taken granted. The trend is toward global information networks offering flexible multimedia information services to users on demand, anywhere, anytime. Potential services include video on demand, interactive video, fast Internet access, telemedicine, tele-education, and large file transfer. The need to support bandwidth-intensive multimedia services places new and challenging demands on satellite systems and networks. Flexibility, efficiency, mobility, and the ability to guarantee end-to-end quality of service are at a premium.

INTRODUCTION

A survey of future broadband multimedia satellite systems is provided in this article. Consistent with emerging third-generation (3G) communications systems, the focus is on multimedia information services over IP and IP/asynchronous transfer mode (ATM). The implementation of future IP/ATM over satellite communications (SATCOM) networks can be divided into two fundamental cases: the *bent-pipe* satellite relay and the *switch in the sky*. The relative advantages and disadvantages of each architecture will be discussed. Key issues and trends will also be examined.

FUTURE BROADBAND SATCOM SYSTEMS

Future broadband SATCOM systems will offer high-speed Internet access and multimedia information services, such as multicasting and interactive video. Multimedia communication requires guaranteed quality of service (QoS), which differs by service class (e.g., voice and data) and may be complicated by increased errors, delay, and delay jitter over satellite links.

ATM was designed especially for multimedia information services and supports guaranteed QoS by service class. At present, IP supports only one service class, but work is in progress to enhance IP. Few current SATCOM systems employ ATM in a meaningful way; however, several major systems are in the planning stages and others are envisioned. A summary of future broadband satellite systems is provided in Table 1 [1–8]. Most plan to employ either IP, ATM, or a combination of both.

Some systems, such as Teledesic, have constellations with many low earth orbit (LEO) satellites, while others like Cyberstar and iSky (KaStar) plan to operate with as few as two to four satellites in geosynchronous earth orbit (GEO). Broadband satellite architectures may be based on ATM with sophisticated onboard processing (OBP), onboard switching (OBS), and intersatellite links (ISLs), while others employ simple bent-pipe transponder relays. The system design choices depend on factors including coverage, cost, user service, and traffic.

Most of the systems in Table 1 operate at Ka-band. SkyBridge operates at Ku-band. The key reason for the use of Ka-band is the availability of bandwidth to support broadband multimedia communication (i.e., capacity). This is the common denominator. Each of these systems is designed to exploit the emerging market for high-quality multimedia information services on demand, to users with relatively small terminals, over broadband wide area networks.

Astrolink — The Astrolink satellite constellation contains nine GEO satellites [1, 3]. Astrolink is a Ka-band satellite system. The uplink is 28.35–28.8 GHz and 29.25–30.0 GHz. The downlink is 19.7–20.2 GHz. The system is designed to support high-speed multimedia communication. Astrolink employs OBP for increased efficiency and OBS for flexibility. Each satellite is an integral part of the communication network, as opposed to being a bent-pipe relay. Data rates range from as low as 16 kb/s to 9.6

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System	Operation	Satellites	Altitude (km)	Frequency	Access	Network	Capacity	Services
Astrolink	2003	9 GEO	36000	Ka-band	FDMA TDMA	IP/ATM ISDN	6.5 Gb/s	High-speed multimedia
Cyberstar	2001	3 GEO	36000	Ka-Band	FDMA TDMA	IP/ATM Frame relay	9.6 Gb/s	Internet access, VoD broadband services
Spaceway	2002	16 GEO 20 MEO	36000 10352	Ka-Band	FDMA TDMA	IP/ATM ISDN Frame relay	4.4 Gb/s	High-speed Internet BoD, multimedia
SkyBridge	2001	80 LEO (Walker)	1469	Ku-Band	CDMA TDMA FDMA	IP/ATM	> 20 M users	High-bit rate Internet access, interactive multimedia service
Teledesic	2002	28 LEO 12 planes of 24	1375	Ka-Band 60 GHz	MF-TDMA ATDMA	IP/ATM ISDN	10.0 Gb/s	"Internet-in-the-Sky," high quality voice, data, video
iSky (KaStar)	2001	2 GEO	36000	Ka-Band	—	IP/ATM	—	Internet, DBS, PCS, BoD

Table 1. *Next-generation SATCOM systems.*

Mb/s. 384 kb/s are supported to 90 cm dishes, which makes Astrolink potentially suitable for large mobile platforms.

Cyberstar — The Ka-band Cyberstar constellation consists of three GEO satellites [1,4]. Cyberstar is designed to provide IP multicasting services to Internet service providers (ISPs), large and small business organizations, and multimedia content providers. The capacity of the Cyberstar network is 9.6 Gb/s. IP multicasting is implemented based on frame relay and ATM technology.

Spaceway — The Spaceway constellation consists of 16 GEO and 20 medium earth orbit (MEO) satellites [5]. The Ka-band system is designed to support high-speed data, Internet access, and broadband multimedia information services. The Spaceway satellite architecture is based on conventional bent-pipe relay. It offers high QoS (bit error rate, BER < 10^{-10}) to users with terminals as small as 0.66 m, at data rates starting at 16 kb/s up to 6 Mb/s. The Spaceway system is compatible with ATM, integrated services digital network (ISDN), frame relay, and X.25 terrestrial standards.

SkyBridge — The SkyBridge constellation consists of 80 satellites in circular LEO at 1469 km [6]. The orbital inclination is 53°. The system is intended to support advanced information services (e.g., interactive multimedia) at data rates from 16 kb/s to as high as 60 Mb/s. SkyBridge satellite design is based on a bent-pipe relay architecture. Unlike the other systems in Table 1, SkyBridge is a Ku-band system. The uplink operates at 12.75–14.5 GHz, and the downlink is 10.7–12.75 GHz. The choice of Ku-band is due to the availability of Ku-band technology.

SkyBridge gateway stations interface with terrestrial networks via ATM switches. The majority of services are expected to be IP-based. SkyBridge employs a combined code-/time-/frequency-division multiple access (CDMA/TDMA/FDMA) waveform; however, the satellites themselves are transparent (i.e., bent-pipe). Spot beams, with frequency reuse in each beam, are employed to enhance capacity. SkyBridge is designed to accommodate traffic from over 20 million simultaneous users.

Teledesic — The Teledesic constellation consists of 288 satellites in 12 planes of 24 satellites [1, 7]. Teledesic is a Ka-band system with 60 GHz ISLs between adjacent satellites in each orbital plane. The uplink operates at 28.6–29.1 GHz, and the downlink at 18.8–19.3 GHz.

Teledesic employs full OBP and OBS. The system is designed to be an "Internet in the sky." It offers high-quality voice, data, and multimedia information services. QoS performance is designed for a BER < 10^{-10}. Multiple access is a combination of multifrequency TDMA (MF-TDMA) on the uplink and asynchronous TDMA (ATDMA) on the downlink. The capacity of the network is planned to be 10 Gb/s. User connections of 2 Mb/s on the uplink and 64 Mb/s on the downlink are possible. A minimum elevation angle of 40.25 enables the Teledesic system to achieve an availability of 99.9 percent.

iSky (KaStar) — iSky, formerly KaStar, is focused on providing broadband data and Internet services to North America [1, 8]. This Ka-band system is designed to support high-speed two-way Internet access, direct broadcast services (DBS), and future personal communications systems (PCS) to homes and offices via small aperture (e.g., 26 in) antennas. The initial constellation consists of two GEO satellites. The uplink frequency is 19.2–20.0 GHz, and the downlink 29.0–30.0 GHz. Data rates up to 40 Mb/s are envisioned, with typical rates in the range of 1.5–5 Mb/s.

Future Trends and Issues

Ka-band and Higher Frequency

Many future satellite systems will operate at Ka-band. Examples are provided in Table 1. A major reason is the availability of spectrum. Other frequencies may also be of interest, including V-band (40–50 GHz) and millimeter wave (e.g., 60 GHz). As the number of satellite systems and

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users and the bandwidth they demand increase, further pressure to consider higher frequencies is expected, despite the well-known problems associated with rain and atmospheric attenuation at those frequencies. Another reason for interest in Ka-band and higher frequencies is the potential for smaller antennas. However, this must be balanced against other factors, such as increased rain attenuation at these frequencies, which favors the use of larger antennas.

GEO VS. LEO

Coverage is the primary advantage of GEO satellites over LEO systems. The wide-area coverage of GEO satellites makes them ideal for multicasting. However, the higher orbit means that the round-trip delay is much larger than for LEO or MEO systems. Longer delay means that GEO satellites are typically less suitable for applications such as voice or interactive video than LEO systems. Higher altitude also makes GEO satellites more expensive to launch (i.e., than LEOs).

LEO systems require frequent handover between the ground terminal and the satellites, which are in view for a relatively short period of time. Additionally, they also rely on crosslinks between neighboring satellites to increase coverage. This tends to increase the complexity of LEO systems (e.g., OBP in support of routing). It also leads to a problem with delay jitter, which can degrade voice performance. One way to address delay jitter is through buffering. This is the approach employed by Teledesic.

ENHANCED TCP

Research is ongoing into various aspects of TCP implementation and performance of TCP/IP over satellite links [9]. Issues include the slow start algorithm, the ability to accommodate large bandwidth-delay products, congestion control, acknowledgment, and error recovery mechanisms.

The slow start algorithm is especially inefficient for data transfers that are short compared to the delay-bandwidth product. Larger initial window sizes and byte counting are under investigation [9]. Furthermore, when the product of the data rate over the TCP connection and the round-trip delay exceeds the available memory, performance degrades rapidly [10, 11]. This favors the use of LEO satellite systems over, say, GEO systems. There are several potential solutions. One involves "spoofing" TCP. In this case, premature acknowledgments are sent to trick TCP into continuing transmission. Another option is selective repeat acknowledgment (SACK), and a SACK version of TCP is under study by the Internet Engineering Task Force (IETF). SACK-based loss recovery mechanisms can be employed to improve both protocol efficiency and congestion control over long delay links [9].

IP, ATM, AND ENHANCED QOS AWARENESS

IP, ATM, or a combination of the two (e.g., IP/ATM) is expected to form the backbone of efficient future multimedia information networks [9–12]. The trend is toward increasingly flexible, packet-oriented, QoS-aware networks. Multiple service and priority levels are expected, in terms of both quality and speed. Guaranteed QoS is essential to multimedia communication. The ability to allocate exactly the necessary resources per service class is important in terms of efficiency (e.g., optimal use of resources).

ATM was designed to support guaranteed QoS per-service class. By comparison, IP currently supports only a single QoS via best-effort delivery; however, in the future, IP is also expected to support multiple QoS classes (e.g., IETF RFCs 2475 and 2216), and therefore multimedia services.

IP SECURITY OVER SATCOM

As e-commerce increases, the need for reliable Internet security does as well. The potential for interception and corruption may be increased by the wide-area coverage of satellite links. Internet Protocol Security (IPSec) mechanisms must ensure confidentiality, authentication, integrity, access control, and key management [13]. Confidentiality means that only the appropriate users have access to the information. Authentication requires verification of a user's identity and right to access. Integrity means that the information has not been corrupted. Access control ensures that the system cannot be compromised by unauthorized access (e.g., pirating a satellite). Key management is a key issue with respect to IPSec over multicast SATCOM [13]. The problem is to provide an efficient means of dynamically generating and distributing keys. The problem may be further complicated by the routing technique (e.g., encapsulation of headers).

IP ROUTING AND ATM SWITCHING

IP routing is a logical option for networks that carry IP traffic. It is also of interest because it can support multicast transmission via the widely used Internet Group Management Protocol (IGMP) (RFC2236). However, IP routing presents new challenges over satellite networks, perhaps especially with respect to multicast routing in full mesh LEO satellite networks.

The development of routing protocols capable of supporting multicast transmissions over wide areas with dynamic group membership and changing ISLs is simply more complex than for static SATCOM links [9, 12]. Topology information on which terrestrial Internet routing protocols, such as Open Shortest Path (OSPF) and Routing Information Protocol (RIP), rely can rapidly become obsolete.

Routing may be implemented on the ground or onboard the satellite (onboard routing, OBR). In either case, current information concerning the space segment (e.g., satellite ID and ISL interface) and the ground segment (e.g., geographic position, host ID and MAC information, such as the CDMA code, TDMA time slot, or FDMA frequency) is required [12]. Research is ongoing into various IP routing techniques for SATCOM, including tunneling, network address translation (NAT) (RFC2663), Border Gateway Protocol (BGP) (RFC1771), IP/ATM with Multi-Protocol Label Switching (MPLS), as well as proprietary constraint-based routing techniques tailored to the satellite network. In the future, IP routing for satellite networks may be implemented via a combination of tunneling, NAT, border rout-

ing, and MPLS, which appears to be well suited to support IP routing over ATM-SATCOM networks [12].

Most of the proposed broadband commercial satellite systems are expected to be ATM-based. Switching/routing would be accomplished via proprietary protocols in combination with ATM, IP/ATM, encapsulation, and tunneling. For example, Teledesic is expected to employ its own proprietary protocols for both the ISLs and the space–ground links. Spaceway and Astrolink use ATM-based communication for the ISLs and earth-space links, as well as a custom MAC/LLC and custom signaling. SkyBridge employs ATM in the ground segment (i.e., there are no ISLs or OBP, OBS, or OBR). Each of these systems is expected to support IP via tunneling [12].

Bent-Pipe Satellite Relay vs. the Switch in the Sky

In a bent pipe satellite relay, the satellite transponder performs signal amplification and frequency translation (e.g., at 650 MHz). Signal detection, decoding and protocol translation are not performed. The satellite is, essentially, independent of signal format and transparent to the protocol suite. In principle, any user, with the appropriate terminal (i.e., power, bandwidth and out-of-band radiation), could access the satellite. This case will be referred to as the satellite relay ATM (SR-ATM).

Implementation of a "switch-in-the-sky" requires substantial on-board processing (OBP). The case of a satellite with a fully capable on-board satellite switch (SS) will be referred to as satellite switched ATM (SS-ATM). Although rare today, the use of OBP, OBS, and OBR is expected to increase in the future, since they afford potentially superior performance and more sophisticated networking capabilities than the basic transparent pipe relay.

OBP, OBS, and OBR

One of the main goals of processed satellites is to provide single-hop connectivity to small earth stations. Examples of satellites with varying degrees of OBP, OBS and or OBR include the US Milstar, the NASA Advanced Communication Technology Satellite (ACTS), and Italsat 2. There are many forms of OBP, which may be applicable to the implementation of ATM-SATCOM networks. OBP may be divided into three classes [14], which roughly correspond to:

- Class 1: Baseband OBP and OBS/OBR
- Class 2: Intermediate/radio frequency (IF/RF) processing and switching
- Class 3: Support processing

Class 1 is commonly referred to as a *fully processed* satellite. It is exemplified by the case of the satellite "switch in the sky." Class 2 roughly corresponds to that of a *partially processed* satellite. It may include signal regeneration and RF or IF switching, but does not include baseband OBS. Other forms of processing, not directly related to communications, but which support communications functions, are grouped into class 3. Only baseband OBP and OBS are considered in this article.

Baseband Processing

The goal of baseband OBP is to enhance link performance and efficiency. Enhancements may be applied to reduce cost or increase capacity, the latter favored by current trends [14] such as broadband communication. Perhaps most important, the combination of baseband OBP and OBS can enhance overall network efficiency and flexibility. OBS is the essential element satellite switch-in-the-sky concept. In the case of SS-ATM, OBP enables cell-based OBS.

Baseband OBP involves much more than merely signal amplification and frequency translation. Key functions include demodulation, demultiplexing, error detection and correction, and removal of routing and control information. Examples of baseband OBP functions associated with signal regeneration and transmission are switching or routing of data, beam-forming, data buffering, and data multiplexing.

Signal regeneration techniques are usually employed to improve the signal-to-noise ratio (S/N) and reduce the BER. This may be especially important with respect to the operation of ATM over SATCOM, where the ability to achieve and maintain a BER of 10^{-8} or less may be required [10, 11]. A key point with respect to OBP is that the satellite is no longer a transparent repeater. This has implications in terms of interoperability (i.e., the waveform must be compatible in order to communicate).

In addition to signal regeneration and switching, baseband OBP can facilitate a wide range of techniques for optimizing system performance. Beam-forming is a prime example. OBP can facilitate dynamic beam forming as well as nulling an interferer. Similarly, it may be possible to provide dynamic, on-demand allocation of antenna gain and coverage, which enables flexible allocation of satellite effective isotropic radiated power (EIRP).

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Fully Processed Satellites

A conceptual illustration of a fully processed SS-ATM-SATCOM network is provided by Fig. 1, from which it can be seen that the satellite is a node in the ATM network. Dynamic OBS of logical connections is possible at the cell level, as opposed to slower, less dynamic switching at IF or RF, under ground control. All OBP processing is assumed to be performed at baseband in this example.

OBP and Satellite Resource Allocation

In principle, the combination of OBP and OBS enables resource allocation to be performed by the satellite. This is desirable because the satellite has direct first-hand knowledge of the available resources, unlike an injection terminal, and therefore it can, in principle, more effectively perform access control. Ground-based estimates of the available capacity would not be required; as a result, power and delay uncertainty due to propagation over the satellite are removed.

Although the same argument could be made for satellites with non-ATM-based OBP and OBS, the potential benefit of, and sensitivity to, onboard resource allocation are arguably more

Although full OBP and OBS are not common today, it may be in the future, as processing power and networking demands increase. Of the relatively few satellites with OBP today, most, if not all, are ground controlled.

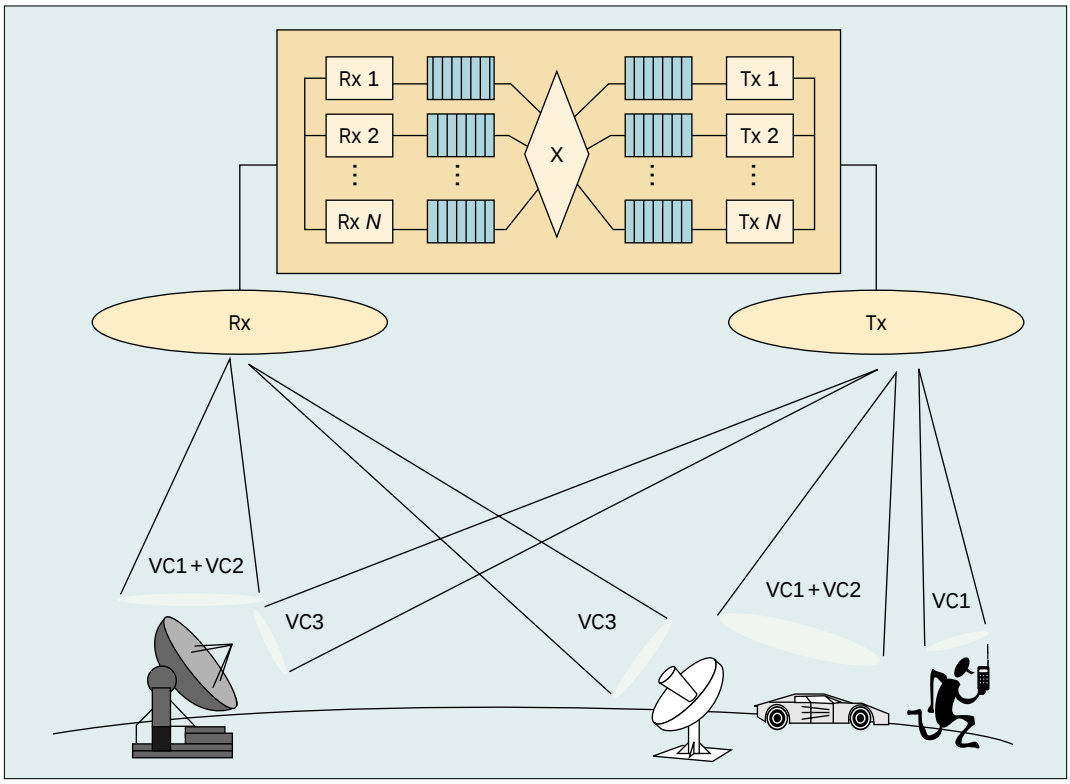


Figure 1. *A fully processed satellite switched ATM-SATCOM network.*

significant with respect to an SS-ATM system, since ATM is uniquely designed to support flexible allocation of any amount of bandwidth, up to the full capacity, on demand, at the appropriate QoS. Not all services are treated alike. Resource allocation is more granular than over a conventional time-division multiplex (TDM)/FDMA link, where capacity is either available or not.

Estimation of Resources

An issue with respect to ATM-SATCOM and resource allocation concerns identification of the available resources. An approximation of the available resources can be obtained using measurements of the queue lengths in the ATM switch, but this is only an estimate of the capacity based on delay. OBP makes it possible to more accurately assess the available capacity at the desired QoS, given direct knowledge of a user's requirements and signal characteristics, as well as all other frequency and power allocations onboard the satellite (i.e., the fully processed satellite controls WAN access and resource allocation).

Adaptive Beam Forming and Resource Allocation

The SS-ATM networking concept illustrated in Fig. 1 also depicts dynamic beam-forming and resource allocation. The use of phased array (PA) or multiple beam antenna (MBA) is envisioned. TDMA is considered in this example, where an association is made between ATM virtual circuits (VCs) and antenna beams in order to match the gain and EIRP as closely as possible to the requirements of user groups, and to facilitate ATM-SATCOM-based multicasting. A proprietary medium access control (MAC) layer tailored to the topology and characteristics of the satellite network is envisioned.

The combination of SS-ATM and the ability to support flexible bandwidth allocation together with adaptive beam-forming and the ability to focus precisely the required gain on the area(s) of interest allow bandwidth, power, and EIRP to be treated as a pool of resources. Ideally, the satellite would be able to allocate exactly the required capacity from this pool to any user or user group on demand, tailored to the service and QoS requirements, and the capability of the terminal. In this way, OBP and ATM can enhance performance, given effective control.

Control may be either autonomous, in which case it is performed onboard the spacecraft, or performed on the ground. Although full OBP and OBS are not common today, they may be in the future as processing power and networking demands increase. Of the relatively few satellites with OBP today, most, if not all, are ground-controlled. The NASA ACTS and Italsat are examples of satellites with ground-controlled baseband OBS [14].

Service-Enabling Platforms

The ability to offer multimedia information services to users with small disadvantaged terminals requires the efficient integration of the service with the terminal (handset) and the network. An important issue in this regard concerns the role of service-enabling platforms, also known as middleware. Service-enabling platforms may be viewed as a layer of functionality between the transport system and the underlying network supporting distributed multimedia information services [15].

Middleware provides the basic mechanisms for

sharing computing and communications resources [15]. It supports adaptability and scalability, and also provides mechanisms to support service management and delivery (e.g., multicast service, security, QoS management, synchronization, and error control). As such, it may affect many aspects of the communication system. In the case of a future system offering Internet services to SATCOM terminals via a processed satellite, the choice of service-enabling platform may ultimately have a role in the way in which the satellite network and communication resources are shared, as well as the integration of the satellite system into distributed multimedia networks.

CONCLUDING REMARKS

Future satellite systems will offer an array of advanced information services. The trend is toward high-speed Internet access and broadband multimedia and IP-based services over IP and/or IP/ATM networks. Services may range from email and voice to broadband multicasting and interactive video.

Satellite architectures may employ OBP, OBS, and/or OBR to augment capacity, or traditional bent-pipe transponders for simplicity and flexibility. Constellations may be LEO, MEO, GEO, or combinations thereof, dependent on the coverage required and the services to be supported. The use of Ka-band and even higher frequencies will be increasingly common as available spectrum becomes more scarce. Higher frequencies also enable the use of smaller terminals and, potentially, greater mobility. Perhaps most significant, the integration of emerging and future satellite systems with terrestrial networks can help bridge the last mile and expand the reach of Internet-based services to business and homes.

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