

# Wireless via Satellite: Systems for Personal/Mobile Communication and Computation

**“It is dangerous to put limits on wireless.”**

**— Guglielmo Marconi (1932)**

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By the year 2000, more than half of all telecommunications traffic in North America will be wireless, experts say. The wire in the wall no longer will dictate where we must be to use the telephone, send a fax, check our e-mail, or run an application program in this new world of personal communications and mobile computing. Calls will go to people, not to places. In the future, when all interfaces between different systems work smoothly, everyone will need only one number. We will be able to reach anyone by telephone, at any time. This is the motivation for the emerging and fast-growing “wireless personal communications/mobile computing” market.

The wireless landscape consists of many applications and products feeding into huge business and consumer markets, catering to constantly changing work methods and personal lifestyles. There is also the push for increased productivity. Technology is improving at a dramatic rate. Potent new combinations of hardware and software, smaller computers, smaller radios, smaller antennas, better networks and better internetworking are fueling this expansion.

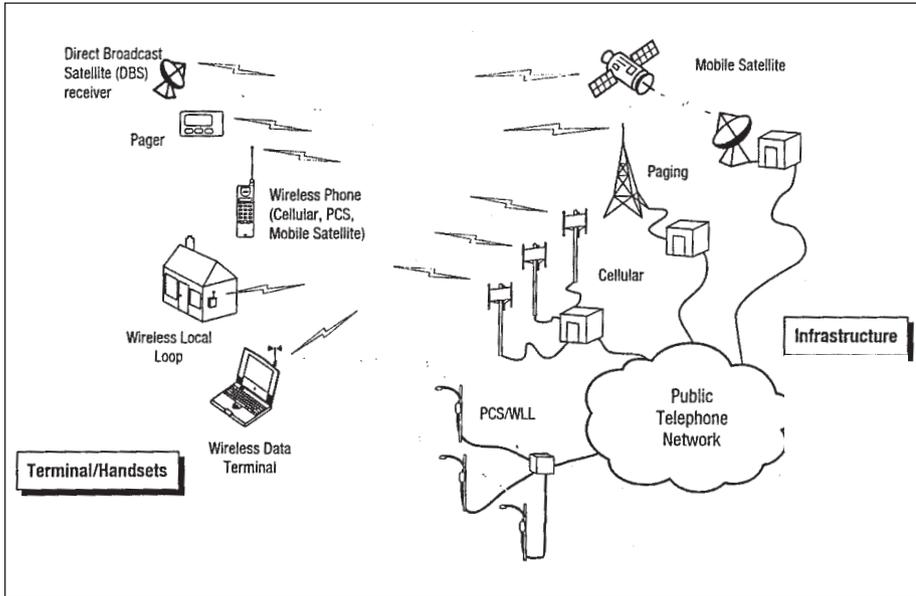
Satellites offer multiple ways of providing wireless interactive digital data services, mobile communications services, broadcast video services and broadband services. Two important trends, increased demand for mobile communications and for Internet access, are pushing satellites toward two-way communications.

Satellites carry calls over the oceans and to areas where the infrastructure lacks terrestrial links. Others broadcast pictures (sound and video) to millions of viewers. Satellites also can provide direct satellite links to personal computers, freeing them from the constraints that affect telephony, cable television and other wire-

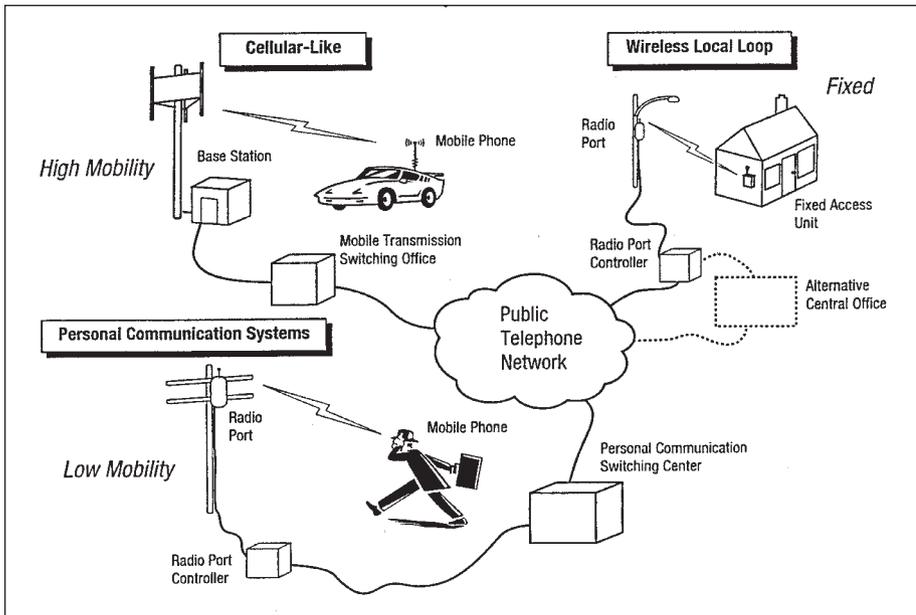
less transmission, and offer two-way interactive service capability.

While the mobile satellite systems envisioned provide wireless access to places without the “wired” infrastructure and promise to provide the most flexibility in the realm of user connectivity, user mobility and multicast services for interactive two-way services for data and voice, this technology raises issues that need further study and new solutions. In the area of satellite technology, these include the development and fielding of digital satellite subsystems (rad hard and otherwise), flexible/steerable antennas, and of course, reliable launch vehicles and operations. In the area of communications and networks, the ongoing issues are the interoperability of multiple standards, complexity of providing roaming capability and latency issues in using the transmission control protocol/Internet protocol (TCP/IP), upon which the transmission of Internet messages is based. The latencies issue, which involves transmitting and propagating messages up and down satellite links, with or without multiple hops, may limit the growth of high bandwidth satellite access to the Internet with the current TCP/IP protocol. This is due largely to the natural signal propagation/transmission latencies in the satellite link, combined with the acknowledgment (connection) oriented nature of TCP/IP protocol. There is research going on in various centers including NASA and various universities to develop alternative protocols and at least to minimize the latency and resulting loss in information transmission speeds.

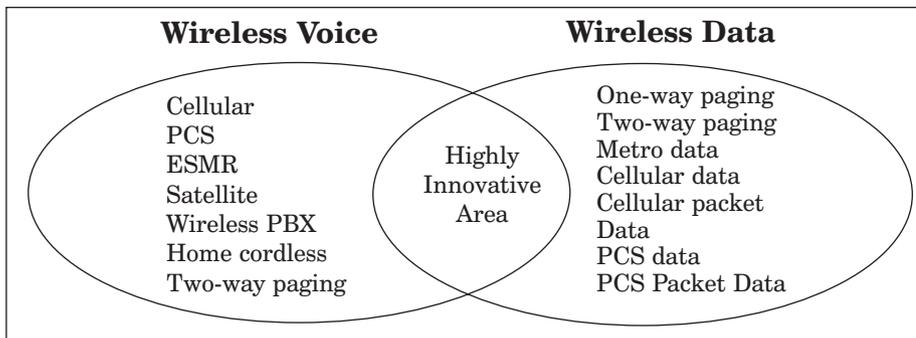
In this paper, we review the requirements and spectrum of wireless applications for mobile/personal communications and computation, and systems currently being developed for global personal communications. The paper also



■ Figure 1. Wireless services include many different applications and products.



■ Figure 2. Personal communications users require applications ranging from fixed to high mobility.



■ Figure 3. Some personal communications technologies are better suited to voice and others to data.

discusses the interface between satellite and cellular communications, technical and market drivers. A comparison of proposed and licensed LEO/MEO satellite systems for mobile personal communications is included.

**Review of personal communications applications**

Many different applications and products on the wireless landscape are creating huge business and consumer markets [24] (Figure 1), catering to constantly changing work methods and personal lifestyles and the push for increased productivity. Contributing to this expansion are potent new combinations of hardware and software, smaller computers, smaller radios, better networks, better internet-working and technology that is improving at a dramatic rate.

Supporting the user at fixed, low mobility and high mobility applications are personal communication applications. At some level they all interface to the public telephone network, whether it is delivered through terrestrial or satellite/wireless intermediary networks, as illustrated in Figure 2.

Fixed applications basically are delivered to home or business through the wireless local loop via radio ports. They are cellular-like, and for high mobility applications they require a base station which connects to the public network by means of a switching office.

Low mobility personal communications systems connect to a public telephone network via radio port and some personal communication switching center.

The type of information transmitted includes wireless voice or wireless data. Figure 3 shows that the type of communications dictates which technologies work best. The area where data and voice can be sent over distance using one type of technology is the most promising and requires innovative technology.

**Wireless data networks**

The type of wireless technology appropriate for different types of data and voice transmission varies

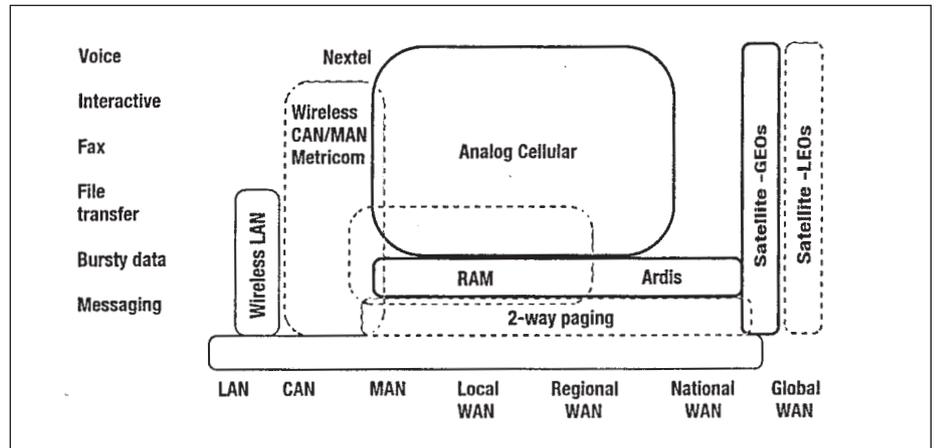
with the nature of data and distance transmitted. In Figure 4, wireless data networks for various type of information are depicted for local through global coverage. Figure 5 summarizes options for wireless data operations by capabilities, interactivity, coverage and availability, indicating a representative system for each category. Among all the options, satellite networks offer the greatest capability for providing direct satellite links to personal computers, freeing them from the constraints that affect telephony, cable television and other forms of wireless transmission.

Satellites also carry calls over the oceans including areas where the infrastructure lacks terrestrial links. Others broadcast television programs to millions of viewers.

### Mobile satellite services

Superior economics and performance of transoceanic fiber optic cable, in particular its low delay, have sidelined satellites for international and mobile voice telephony since around 1988. However, terrestrial networks never will achieve the coverage or roaming capabilities of a satellite-based system.

Satellites in geosynchronous orbit (GEO) offer broad communications coverage. However, in some cases, latency may be a limiting factor for high-quality two-way interactive voice communication (see Figure 8). A single satellite's footprint, or coverage area, can be as much as a third of the earth's area (see the AMSC entry in Table 1). Unlike wired telephony service, the cost of satellite service is not affected by distance. Satellites are well suited to the distribute video to cable head ends and broadcast stations, to transmit TV directly to homes and to relay data between hubs and remote sites of private business networks. They are uniquely able to provide mobile telephone service for ships, aircraft, trucks and individual hand-held phones. For countries with inadequate or old infrastructure, satellites provide an ideal way of acquiring modern communications capability. In addition, when a natural disaster strikes, (remember the dev-



■ Figure 4. Wireless data networks cover a wide spectrum in distance and cover-

	2-way	Voice Capabilities	Interactive Session Capable	Available	U.S. Population Coverage
Analog cellular	X	X	X	Now	98%
Paging	X			1-way now 2-way starting	95%
Cellular digital packet data	X			Now	33%
RAM mobile data	X			Now	Urban
ARDIS	X			Now	Urban
Enhanced mobile radio					
Nextel	X	X	X	Now	Minimal
Geostationary earth orbit satellite	X			Now	100%
Low earth orbit satellite	X	X	X	1998	100%
Iridium, Glbstr.					
Campus and metropolitan area networks	X		X	Now	San Francisco Bay Area
Metricom					

■ Figure 5. Comparison of wireless data operations for different technologies.

astation of Hurricane Hugo) satellites can and do quickly reestablish communications.

The growing role of communications satellites is evident from the rising demand for satellite services. The increased demand reflects both increased applications and improved service efficiency.

Increasing interest in two-way communication and Internet access

adds to the demand for satellites. Satellites offer a number of ways to provide wireless interactive digital data services, mobile communications services, broadcast video services and broadband services.

In the area of wireless interactive data services, data are delivered downlink from a satellite to a site replacing phone delivery of on-line video and data. For the time being

Program	Altitude, km	Altitude, mi	Range, km	Area, km <sup>2</sup>	Fraction
IRIDIUM	755	469	2,273	12,911,471.56	2.52
Constellation	1,000	621	2,763	18,021,088.91	3.53
Globalstar	1,390	864	3,463	24,951,001.69	5.08
Earth Radius	6,378.39	3,963.34	9,995	93,031,683.77	18.2
Odyssey	10,370	6,444	14,418	120,060,298.53	23.48
8 Hour	13,892	8,632	18,165	135,409,968.78	26.49
AMSC	35,859	22,282	40,660	1,742,90624.75	34.09

**■ Table 1. Comparison of constellation coverage for various satellite communications systems.**

the return link, however, is still through telephone lines and is much slower than the downlink rates. But in an interactive environment most of the information is downlinked from the provider to the user. Only a fraction of the information goes the other way. Therefore, for certain applications this lower rate of return may be acceptable.

Another service, expected to be available by the year 2000, is the delivery of wideband data without access to high-rate phone infrastructure using “bandwidth on demand” (BOD) concept. The key to bandwidth on demand is a powerful space borne processor. It can manage, for example, the transmission of video for projection on screens at multiple locations during a video conference. It also carries the accompanying audio. BOD avoids having to dedicate specific channels to specific users. This service can be used for such applications as telemedicine, interactive distance learning, computer networking and access to digital on-line services. The terminal also could receive direct broadcast of TV programs via a small (18-26 inch

diameter) Ultra Small Aperture Terminal (USAT).

Satellite communication capabilities can be used for mobile communications in trucks, automobiles, aircraft and ships, as well as for maritime communications. It is estimated that more than 13 million users throughout the world will be able to afford satellite telecommunications using hand-held, pocket-sized telephones in a decade. These telephones are expected to have multiple interfaces to cellular type communication networks now in place.

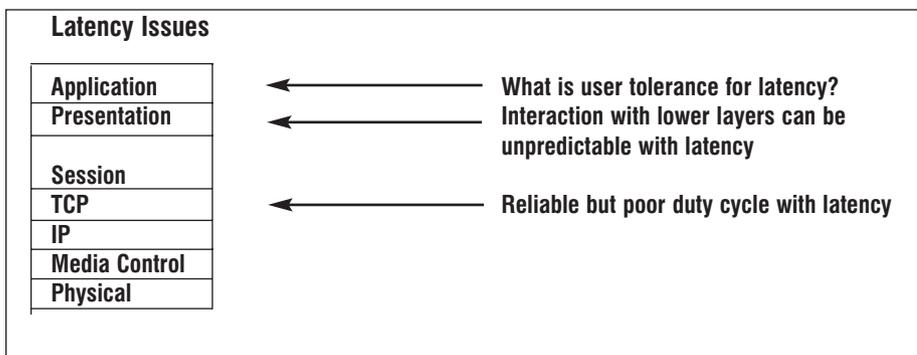
**Satellite access to the Internet**

Satellites can be used to provide connectivity for users (high bandwidth downlink and low bandwidth back channel by way of telephone/terrestrial links), offering uplinks for servers and content providers (many high bandwidth uplink sites for servers and a few high bandwidth downlink sites). It can be used to provide Internet access to mobile users with multicast services that currently are being provided by the multicast service nodes on the Internet.

In all cases, satellite options must be studied to assure that the latencies due to natural transmission time of signals and to the protocols used for specific communication network are within the acceptable limits of the application. Transmission time is an important parameter for any application whose overall performance depends on user or terminal interactivity. Voice, voice-band data, digital data, video telephony and interactive games applications may involve user tasks or terminal equipment characteristics that vary substantially in their sensitivity to transmission delay. Because network and service providers cannot alter the transmission time characteristics nor the transmission media between two networks, some highly interactive tasks may experience degradation at delays on the order of 100 ms [ITU-T Recommendation G.114]. It is assumed that one-way transmission time of 150 ms to 400 ms is acceptable for most applications. It also is known that for verbal interaction, delays greater than 300 ms disrupt communications, create confusion and increase time to complete problem solving tasks. While longer delays are unacceptable for network planning purposes, it also is known that when multihops are required between satellites (satellite-to-satellite or satellite-to-ground), delays above 400 ms may result, both with LEOs (such as Teledesic or IRIDIUM) and GEOs (such as Hughes Spaceway, etc).

For Internet access, in addition to the transmission latency issues, satellite latency introduces problems at three layers of the ISO protocol stack (Figure 6).

At the TCP layer, latency can result in inefficient use of the available bandwidth. This is because the TCP layer is a connection-oriented protocol and requires acknowledgement signals from the receiving computers to confirm that messages are being received correctly. When latency delays these acknowledgments, data transmission speeds come down to a rate that degrades the performance of the underlying terrestrial network and therefore overall network performance is



**■ Figure 6. Latency may limit high bandwidth satellite access to TCP/IP networks.**

Band	Uplink (GHz)	Downlink (GHz)
C	5.9-6.4	3.7-4.2
Ku	14-14.5	11.7-12.2
Ka	30	20
C-band -Immune to atmosphere disturbance -Operates in same range as domestic terrestrial microwave Ku-band -Minimal terrestrial interference from microwaves -Used exclusively for communications between satellites and earth -Signals more susceptible to atmospheric disturbances than C-band signals Ka-band -Newest band opened for satellite communications.		

■ Table 2. Frequency bands for satellite communications.

affected significantly. In recent NASA experiments with GEO satellites, 155 megabits per second fiber optic land lines were slowed to 10

megabits per second when NASA used satellite communications network. LEOs such as Teledesic also may be adversely affected. More

Company/systems	Orbit slots, deg.	No. of slots	Constellation Buildup	Coverage
AT&T VoiceSpan	103, 93, 92, 54 1W, 42, 116E	12	2000 to 2002	No. America, So. America U.S. Africa, Europe, Asia/ India, Asia/Australia
EchoStar Echostar Ka	119, 85W	2		US
GE Americom GE Star	106, 82, 16 W 38,108 E	9		No., So., Central America Caribbean, Europe Asia, West Pacific
HCI Galaxy- SpaceWay	25, 36, 41, 54, 101, 110, 125 149, 164, 173 E 101, 99, 67, 49W	20	1998 to 2004	World
Lockheed- Martin Astrolink	96W, 37, 115, 29W, 168 E	9	1999 to 2002	Americas, Europe/Afr. East Asia/Australia, Atlantic, Oceania
Loral Aerospace CyberStar	110W, 29.5E, 105.5E	3	1999 to 2002	Europe, Asia, CONUS
Morning Star Co. Morning Star	107.4E, 65.5W 30E,148W	4		U.S., Southeast Asia, Europe, India, Carrib., So. Africa, Mexico
Motorola Millennium	105, 103, 88, 86W	4	1998 to 2001	CONUS, Caribbean, No., So., Cen. America
Netsat 28 DBXSAT	103W	1		
Orion	37.5, 47, 12, 127, 83, 58, 79W 126, 78E	8	1999 to 2000	Atlantic Interconnect
PAS PAS 10/11	58N, 79W	2	1995 to 2000	Inter-regional. U.S., Latin America, Europe, W. Africa.
TRW	MEO	12	1991 to	World (feeder link only)
Odyssey				
Teledesic Vision Star	LEO 105W	840 1		World CONUS
Ka Star	93W &/or 119W	1-2		US

■ Table 3. Satellite systems planned and under development for Ka band communications.

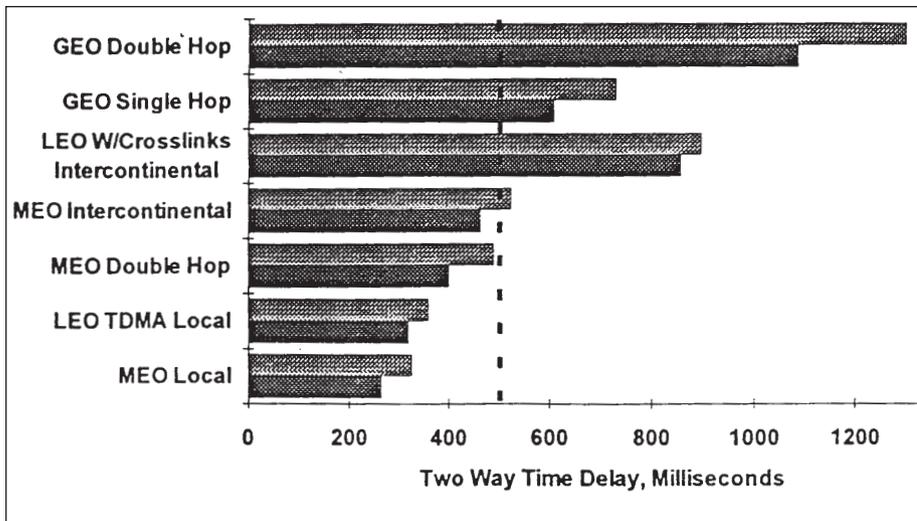
research is needed before the promises of satellite technology can be realized in extending the reach of computer networks to remote locations in the Internet domain.

Presentation and session layers provide the link between the application and the TCP layer. Latencies at this level can cause problems when switching from one application to another, and can make it unreliable. At the application layer, latency causes unacceptable performance for the users, especially for interactive applications.

**Satellite communication systems**

The benefits of satellite communication should be extended to users in all parts of the world in the 1990's through the use of smaller, inexpensive and less sophisticated earth stations for two-way (voice and data) and one-way (video, data) use. While earlier satellite systems have been designed and implemented using C and S band communications with satellites in geostationary orbits (GEO), K-band communications using VSATs (Very Small Aperture Terminals) have enabled the telecommunications across areas of the United States and world where extensive telecommunications networks did not exist and/or were not affordable. [1,2,8,9].

The construction of several systems has been proposed to provide for the global communication of the mobile users using clusters of smaller, less complex satellites in low-earth orbit (LEO) and medium-earth orbit (MEO). [4,5,7,10,12,19-23]. Basic features and uplink downlink frequencies for satellite bands are outlined in Table 2. Table 3 lists all planned Ka-band communications satellite systems currently proposed or under development. Over the last decade, several companies have been trying to extend the phone service in space. Globalstar, Odyssey, IRIDIUM and ICO, plan to launch satellites to provide global telephony and related services. These are individual and two-way. However, they do not provide broadband services. They give each little bandwidth (2400 bps is typical) to carry lots of calls. In contrast, broad-



■ Figure 7. Voice interaction time for satellite systems.

cast satellites like those used for digital television have plenty of bandwidth, but at the cost of individual channels and two-way communications. They simply beam one massive data stream over a large area of earth.

The space industry is developing commercial space systems for providing mobile communications to personal terminals (telephones). Provision of land-mobile satellite service is fundamentally different from the fixed-satellite service provided by geostationary satellites. In fixed service, the earth-based antennas can depend on a clear path from user to satellite. Mobile users in a terrestrial environment commonly encounter blockage due to vegetation, terrain or buildings.

Over the years, communications satellites have become larger and more complex, permitting ground antennas to become smaller and less costly. Until recently, satellite communications services have required heavy and expensive terminals. The cost and size of these terminals have limited access to satellite-based communications. Very Small Aperture Terminals (VSATs) have enabled the development of hybrid systems with terrestrial networks for business, communications, inventory tracking, teleconferencing and disaster contingency planning. [1,2,8,9]. For personal communications, however, further developments in hand-held terminals, communications proto-

cols and compatible standards for continuous coverage is necessary. In addition, cost is a significant factor in the development and acceptance of satellite-based personal communications systems.

The extraordinary improvements in microelectronics RF technology for antennas and electronics components and lower-cost, high-performance spacecraft have made the mass access to satellite-based communications possible. Small personal communications satellite stations can be packaged in the size of a hand-held telephone. These terminals can be manufactured for as little as \$300 and sold for \$500. Mass availability also causes the rates to drop, to rates approximating those charged for cellular service.

**Consumer needs and criteria**

Mass communications systems needs to meet the following criteria to be successful:

- Low cost for service rates and personal terminals (telephone)
- Convenience of hand-held telephones and good availability
- Reliability with low dropout probability and a high probability of connections
- High quality of communications with an acceptable time delay and acceptable voice quality

**Cost**

Service demand rises as the service rate drops. Studies suggest

that to be acceptable, service rates for satellite-based communication services should be comparable or not much higher than the cellular rates. New entries in the satellite-based personal communications system must cost less than existing systems. If the service rate is too high, the systems will not attract enough customer base to succeed. To be competitive, the investment cost per subscriber for future PCS must compare to the investment cost per subscriber for future terrestrial cellular network systems. Cellular telephones now cost between \$100 and \$1,000, with service operators subsidizing the low end units.

**Time delay**

A significant factor for satellite based communications systems is the time delay. If the delays exceed 300 ms, (interaction time for two communicators would be about 600 ms), talk overlap and confusion results. Time delay is comprised of propagation delay and delay due to other factors such as vocoder compression/decompression, processing and terrestrial network transmission delay. For satellites in LEO propagation, delay is on the order of 10 ms. In MEO, the delay is on the order of 80 ms, and in GEO orbits, it is 250-270 ms. Other delays due to processing and transmission are on the order of 80-100 ms for regional calls and 140-180 ms for international calls. When all delays are considered, GEO satellite-based communications may be marginal for quality due to time delays.

We must also consider the nature of the communication networks for the transmission of the signals. Signals may pass through the satellite network once (single hop), or twice (double-hop). Each of the delay elements then adds to up the final time delay introduced into the communication between subscribers. Figure 7 compares various configurations for transmission delay.

**Current and proposed satellite communication systems**

Three types of satellite-based communications systems currently

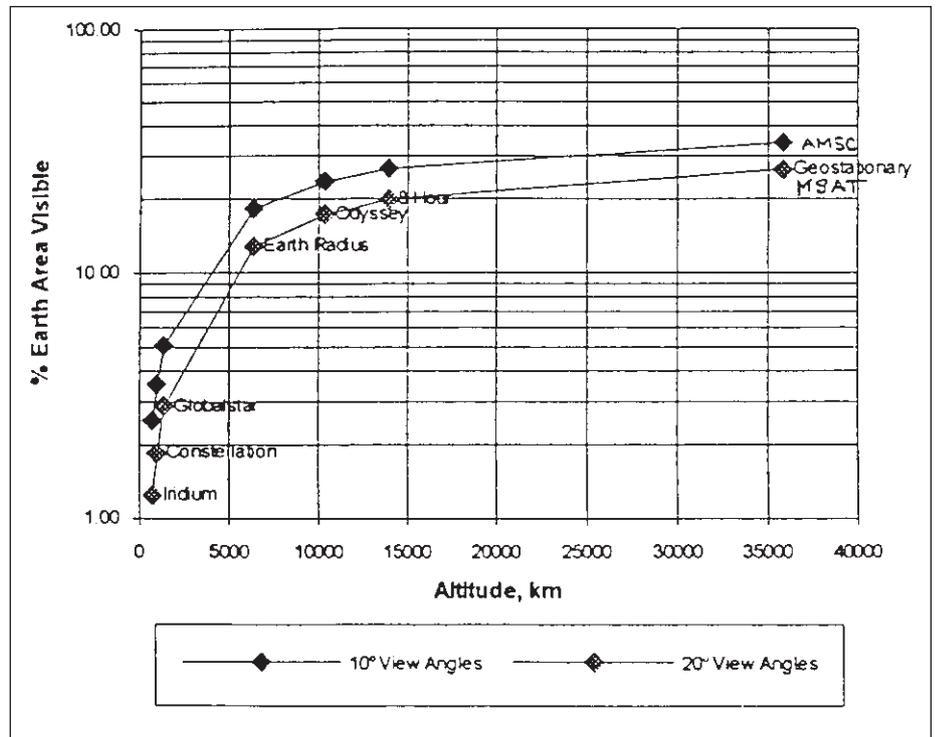
are being proposed. The fundamental difference between them lies in the altitude at which the satellites orbit the earth. (Table 1).

GEO — *Geostationary* satellite systems have few satellites covering earth. Satellites orbit at an altitude of about 36,000 km and as few as three may be enough to provide global coverage. Satellite systems fielded or imminent utilize satellites in GEO orbits.

For years, communication satellites have been maintained in GEO so that the ground antennas could point to a fixed location requiring only three or four satellites to cover the world. To make up for the loss of power over sparsely populated regions due to a fixed footprint, earth stations are rather complex and expensive. Distance also causes long propagation delays and may cause echo, degrading quality of the signal.

MEO — *Medium-earth orbit* systems is a compromise between LEO and GEO systems. The altitude of the orbit is about 10,000 km for these systems and requires fewer and less complex satellites than the LEO systems. Signal propagation delays are more acceptable than a GEO system and delays due to crosslinks and onboard processing do not exist.

LEO — *Low-earth orbit* systems, as the name implies, have the closest proximity orbit to earth. Typically, satellites orbit the earth at about 900 km. Since they do not have a high view angle, to offer adequate global coverage these systems require a large number of satellites (24 to 66 have been proposed). These satellites then must be served by a large number of earth stations, 200 or more. Another option would be to use satellite crosslinks which require complex onboard processing. However, the multiple crosslinks of LEO systems result in additional processing time delays at each satellite, causing lag in communication to the subscriber. Low altitude also may increase the risk of “shadowing” of the signal by vegetation, terrain and buildings. As with cellular service, this may cause interruptions in transmission.



■ Figure 8. AMSC MSAT conceptual system architecture.

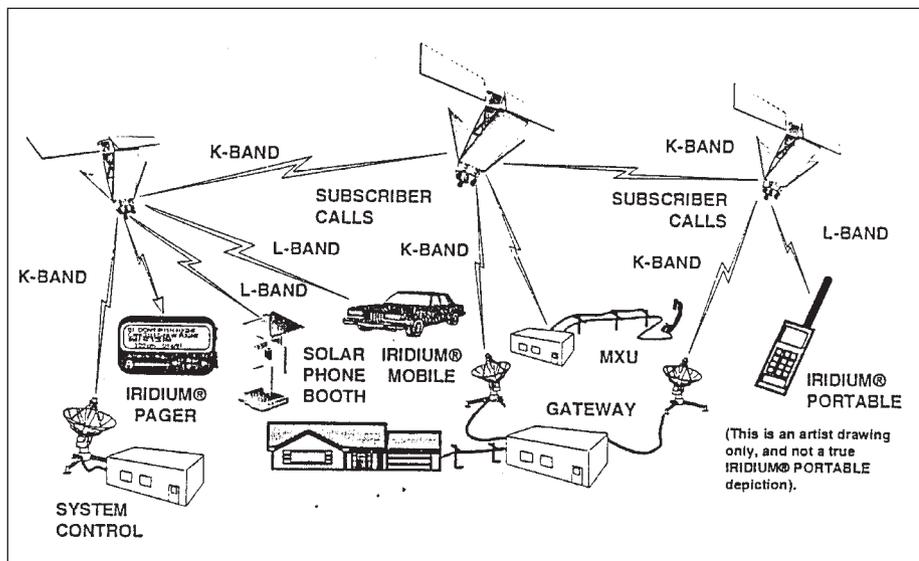
Figure 7 shows the delay times for various configuration satellite systems. Studies indicate that a maximum two-way time delay to avoid is about 600 ms.

An emerging wireless technology that could transmit at up to 2 Mb/s uses low-earth-orbit (LEO) satellites. These so called Little LEOs, clusters of low-earth-orbit satellites using frequencies below 1 GHz, will be used for commercial purposes primarily to provide electronic mail and paging to portable and mobile devices. Little LEO carriers are limited to handling brief digital messages; their systems are not intended to carry voice calls. Satellite voice telephone services will be the domain of the Big LEOs — large complex mobile satellite systems operating above 1 GHz. The most aggressive of the Little LEOs is the one proposed by Teledesic (a joint venture between McCaw Communications and Microsoft). In what Teledesic terms a “global Internet,” the satellites would relay data packets to one another at rates as high as 1.244 Gb/s. Teledesic plans to use a network of LEO satellites where each satellite will be like a cell in a cellphone network, except cells and

callers can both move. Each satellite can devote all its capacity to the relatively few users beneath it. Cells will be 53 km across, small enough to keep the number of users manageable. The network aims to provide 18 simultaneous 1.5 Mbps Internet links in each cell and 20,000 world wide. Because the satellites are in LEO, they avoid the half-second delays of the GEO satellites. Teledesic plans to put the satellites into orbit by the year 2002. This would mean launching 840 satellites in two years.

On the data collection end, digital spread spectrum radio communication technology is used. These devices operate in the 900 MHz. band and can send data at rates up to 10 Mb/s. Unlike the broad band and narrow band spectrum operations, they do not require FCC site licensing.

Low-earth-orbiting satellites for mobile voice telephony, dubbed Big LEO systems, operate above 1 GHz. Motorola’s IRIDIUM, Constellation’s Aries, Qualcomm/Loral’s Globalstar and Mobile Comm’s Elliypso are the major Big LEO systems for mobile personal communications. TRW’s Odyssey system,



■ Figure 9. IRIDIUM conceptual system architecture.

while being a MEO satellite network, shares characteristics of Big LEO systems in the 1 GHz transmission. The satellites in these clusters ultimately will cover the world continuously.

Competing with these systems is the Inmarsat, the International Maritime Satellite Organization and its new entry into satellite communications market (ICO). The ICO satellites provide the mobile satellite service around the world. ICO is an outgrowth of Inmarsat maritime communications satellite network. It will consist of ten satellites plus two spares in MEO orbit. Calls from mobile users are uplinked to an ICO satellite, processed and downlinked at C-band to a satellite access node (SAN). Twelve of these ground stations located around the world are linked together through gateways to the public telephone network for connection to the appropriate party. As a spacecraft passes out of the view of the user, the SANs will hand off communications from one satellite to the other. Telemetry, tracking and command stations are collocated with SANs.

ICO satellites also are supposed to carry a GPS (Global Positioning System) payload to allow ground, air, or sea-based users determine their position, velocity and time, by measuring distance from any four or more GPS satellites in view. The FAA has endorsed GPS as the future

civil standard for air navigation and instrumented approaches and landings by civil aircraft.

Two other GEO systems are lined up to offer more complete and comprehensive services. Spaceway by GM Hughes will offer all digital voice, data and video services directly to U.S. residents beginning in 1997. Through its 48-beam geostationary satellites subscribers would receive telecommuting, telemedicine, digital libraries and other higher bandwidth services at data rates ranging from 16 kb/s to 1.544 Mb/s. Leasing only one channel in America, Hughes has just 12 Mbps of bandwidth to serve the entire country — as much as cable TV networks plan to distribute between 300 homes. Hughes limits each subscriber connection to 400 kb/s. Even so, it can handle only a few hundred users simultaneously (only a fraction of its 2,000 subscribers use the service at any one time). More channels can be leased. However, broadcasting data over entire country for the sake of one user is not the most efficient way of handling this communication.

Broadcast satellites like those used for digital television have plenty of bandwidth, but at the cost of individual channels and two-way communications. They beam one massive data stream over a large area of earth, sometimes the size of a continent. Hughes Network Sys-

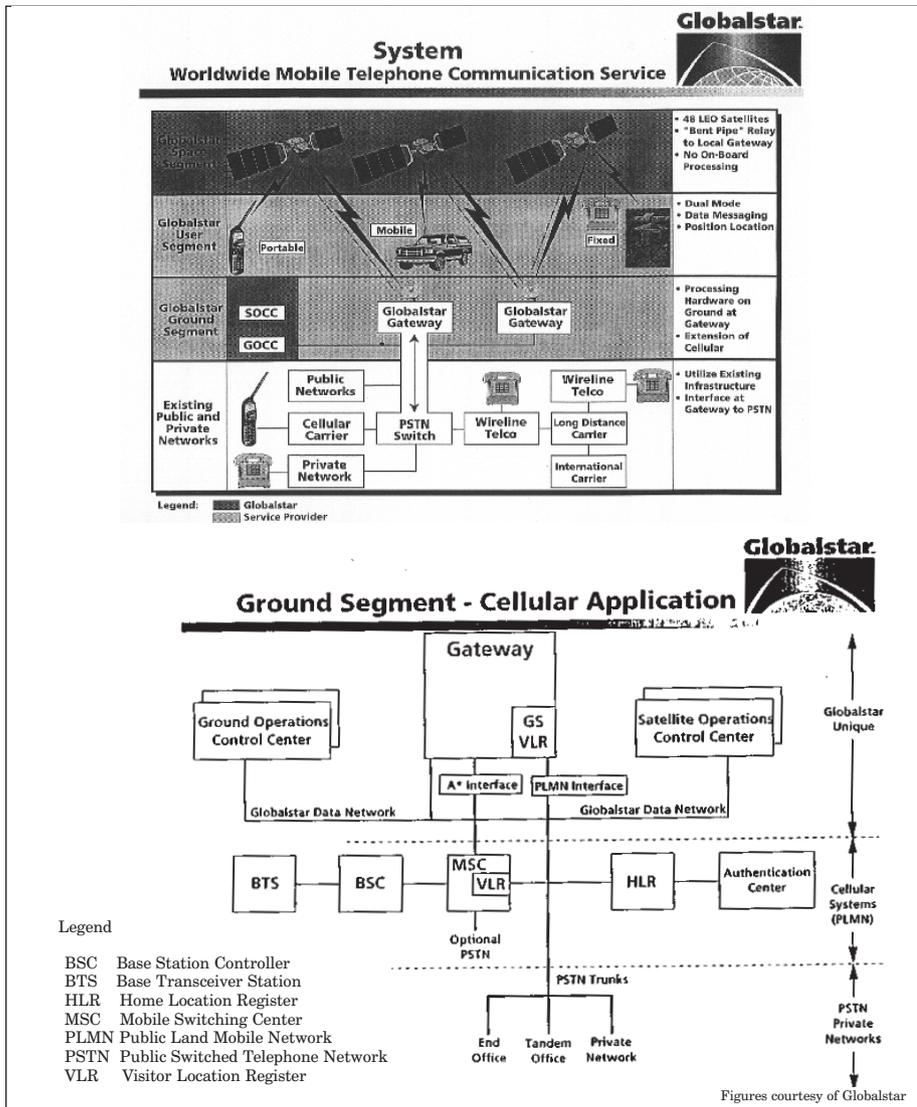
tems uses a few tricks to make this one-way flood imitate a two-way Internet connection with their direct PC, its Internet service. Subscribers send data requests over their regular telephone lines. Hughes routes the responses to its control center, which codes them so that the subscriber's PC can recognize them as their own, and then sends them up to a satellite for broadcasting.

American Mobile Satellite Company's (AMSC), GEO satellite system is also a contender for the more complex and comprehensive services to the North American continent, the United States and Canada. See Figure 8.

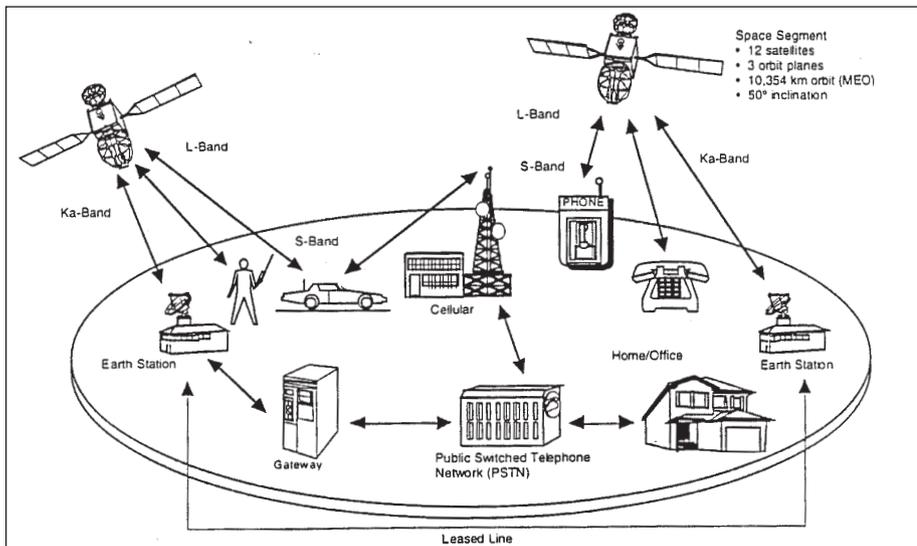
AMSC's first satellite dedicated to providing land mobile services began operations last year in North America. American Mobile Satellite Corp.'s satellites offer voice, data, facsimile, messaging and other services to travelers in trucks, autos, boats and aircraft across the continent. The hand-held units offer multiple modes depending on the type of communication desired. These include dual-mode satellite/cellular, satellite only, transportable and fixed-site terminals. The dual-mode satellite terminals permit users to communicate via satellite or as part of a cellular network. When the vehicle passes beyond the cellular network, calls automatically are routed via satellite. Other units such as one briefcase-sized battery-operated phone terminal by Mitsubishi Electric has facsimile and data ports for connection to a PC.

In the rest of the paper we will consider three of the most promising mobile satellite communications systems for global personal communications in the near future. These are Globalstar, IRIDIUM and Odyssey. In terms of offering a full range of mobile services including voice and data in the 1-3 GHz spectrum, all three systems are in the Big Leo category. In terms of the satellite orbits, however, IRIDIUM and Globalstar (Figures 9, 10) are LEOs while Odyssey (Figure 11) is a MEO system.

Each of these systems are designed to interface with the Public Switched Telephone Network



■ Figure 10. Globalstar system architecture and ground segment.



■ Figure 11. Odyssey conceptual system architecture.

(PSTN) as well as the Public Land Mobile Network (PLMN) to provide ubiquitous service to the public by complementing existing systems, not competing with them. This requires hand-held telephone terminals that are compatible with cellular service as well with other systems such as Europe's GSM system protocol and transmission standards.

**System architecture**

The primary features of the system architectures are shown in Table 4a. and 4b.

The Globalstar system includes 48 LEO satellites at an altitude of 1,400 km, equally divided into eight orbital planes. The orbits are circular with an inclination angle of 52 degrees. The IRIDIUM system includes 66 LEO satellites at an altitude of 785 km and equally divided into six orbital planes. Finally, the Odyssey system includes 12 MEO satellites at an altitude of 10,354 km and equally divided into three orbital planes. Since the satellite altitude is significantly higher than the others, Odyssey requires far fewer satellites to provide global coverage. The mobile user frequency plan is the same for Globalstar and Odyssey with 1.610-1.625 GHz for the uplink, and 2.4835-2.5 GHz downlink range.

IRIDIUM is unique in two ways. First, the same range will be used for both uplink and downlink transmission, using time division duplexing to avoid interference of the time division multiple access signals (TDMA). Second, a truncated range is used in the 1.616-1.6265 GHz frequency band resulting in a 10.5 MHz bandwidth.

The IRIDIUM satellite has the highest planned capacity at 3,840 full duplex circuits/satellite followed by 2,800 circuits/satellite for Globalstar and 2,400 circuits/satellite for Odyssey. Note that the "per satellite" capacity is not additive due to self-interference and beam overlap considerations.

The average satellite connection time for a user is similar for Globalstar and IRIDIUM, due to the similarity of orbital altitudes, and is

	Globalstar	Iridium	Odyssey
# Satellites	48	66	12
Orbit/ inclination	Circle 52°	Circle 86.4°	Circle 55°
# planes	8	6	3
altitude km Mobile user	1401	785	10,354
Uplink-GHz	1.610	1.616	1.610-
Downlink	16.265- 2.4835- 2.500	-1.6265 1.616- 1.6265	1.6265 2.4835- 2.500
Gateway Terminal			
Uplink	C-band	27.5-30.0	29.5-30.0
Downlink	C-band	18.8-20.2	19.7-20.2
FDX cir- cuits/set	2800	3840	2300
Ave. sat. connect time	10-12 min.	9 min.	2 hrs.
Min. eleva- tion angle	10°	8.2°	22°

■ Table 4a. Comparison of system architecture.

	Globalstar	Iridium	Odyssey
Stabilization	3-axis	3-axis	3-axis
Transponder	bent pipe	process- ing	bent pipe
Mission Life (years)	7-5	5	15
Dry Mass (pounds)	704	1100	2703
Mobile User Segment Antenna Design	16-beam phased array	3 16- beam phased array antennas	rigidly mounted 37(up) 32 down beam sta- ing ant.
Crosslinks	No	Yes, 4 crosslinks at 25 Mbps 22.55- 22.53 GHz	No

■ Table 4b. Comparison of systems discussed.

in 10 minute range. based on the MEO orbit, Odyssey has a two-hour connection time. However, due to the fact that seamless connection from satellite-based to terrestrial (cellular) mode is claimed for all systems, this is not considered a major parameter. Last, the higher minimum elevation angle of the Odyssey system may provide a more uniform performance especially in metropolitan and mountainous regions.

**Multi-access scheme**

Tradeoffs between multiple-

access techniques for the mobile satellite systems are actively pursued for the satellite systems and are considered with approaches incorporating some form or combination of code division multiple access (CDMA) [6,14,15].

The multiple access scheme for Globalstar includes a CDMA signal spread across the 16.5 MHz of available bandwidth. It is claimed that this scheme will support a total capacity per satellite of about 2,800 full duplex voice circuits assuming a 4.8 kbps transmission rate and a BER of 10<sup>-3</sup>. This design is the same as now in use in QUALCOMM for cellular/terrestrial applications.

The Odyssey multiple access scheme is a combination of CDMA and FDMA (frequency division multiple access). The 16.5 MHz user bandwidth is divided into three 4.83 MHz channels that utilize CDMA to support multiple users per channel. One CDMA channel is assigned to each of the 16 antenna beams resulting in an aggregate capacity of about 2,300 full duplex voice circuits at 4.8 kbps with an achievable BER of 10<sup>-3</sup>. No two adjacent spot beams occupy the same frequency band.

The IRIDIUM multi-access scheme combines the features of both TDMA and FDMA. It uses FDMA in the sense that a 12-frequency reuse scheme is used over the 10.5 MHz bandwidth. One of the 12 frequencies is assigned to each of the 48 antenna cells/satellite. IRIDIUM is also TDMA using a 90 ms TDMA frame to accommodate four 50 kbps user access per frame. The nominal global throughput is about 172,000 channels assuming 2,150 cells and 80 channels/cells as Motorola claims in its literature.

The scheme proposed by Motorola for IRIDIUM is the most complicated in that it will require: a) coordinated cell utilization, and b) accurate time synchronization signals with complicated algorithms to make it work correctly.

**Handsets**

Several of the key user handset design features are noted in Figure 12. All three systems employ quadrature phase frequency shift keying

(QPFSSK) modulation. Each of the systems employ forward error correction coding (FECC) in the form of convolutional encoding with Viterbi decoding. [13,14,15]. The projected BER for voice is at worst 10<sup>-3</sup> for Globalstar and Odyssey and 10<sup>-2</sup> for IRIDIUM.

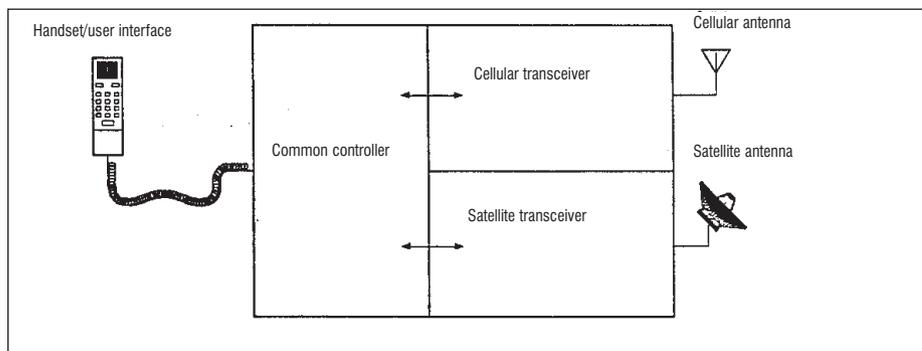
All three systems claim handsets will be similar in weight and dimensions to current hand-held terrestrial/cellular handsets. In fact, they all claim to support a handset design that will be a dual-mode, integrated service hand terminal for “seamless” continuous service for the user as user shifts from terrestrial to satellite-based service regions.

Finally, the estimated initial prices for the handsets vary considerably from Odyssey estimates of \$500 to Globalstar at \$750 and IRIDIUM at \$2,000. The cost of producing dual-mode hand-held terminals is projected to be only slightly higher than the terrestrial hand-held terminals.

**Discussion and conclusions**

The progress made over the last ten years in digital voice processing, satellite technology, antenna design and technology and component miniaturization has resulted in the viability of wide access to satellite-based communications and especially personal mobile communications systems. While mobile satellite systems envisioned provide wireless access to places without the “wired” infrastructure, and promise to provide the most flexibility in the realm of user connectivity, user mobility and multicast services for interactive two-way services for both data and voice, there are many technical issues that need further study and new solutions.

In the area of satellite technology, these include the development and actual fielding of digital satellite subsystems (rad hard and otherwise), flexible/steerable antennas, and reliable launch vehicles and operations. In the area of communications and networks, key issues are the interoperability of multiple standards, complexity of providing roaming capability and latency issues in using the transmission control pro-



	<b>Globalstar</b>	<b>IRIDIUM</b>	<b>Odyssey</b>
Modulation	QFPSK	QPSK	QPSK
FECC	Convolutional Xmit (r=1/3;K=9) Rcv (r=1/2, K=9)	Convolutional (r=3/4; K=7)	Convolutional (r=1/3, K=7)
BER	1E-3 (voice) 1E-5 (data)	1E-2 (voice) 1E-5 (data)	1E-3 (voice) 1E-5 (data)
Supportable data rate (Kbps)	1.2-9.6 (voice & data)	4.8 (voice) 2.4 (data)	4.8 (voice) 1.2-9.6 (data)
Weight (lbs.) Dimensions (in.)	Similar to current terrestrial cellular handsets	Similar to current terrestrial cellular handsets	Similar to current terrestrial cellular handsets
Battery life time	24 hrs standby, 8 hrs @ 5% duty cycle	24 hrs; 1 hr. talk 23 hours standby	30 minutes talk time, 45 hrs standby
Proposed price	\$750.	\$2,000-\$3,000	>\$500

■ **Figure 12. Hand-held unit features.**

tol (TCP/IP), upon which the Internet transmission of messages is based. The issue of latencies involved in transmitting/ propagating messages up and down satellite links, with or without multiple hops, may limit the growth of high bandwidth satellite access to the Internet with the current TCP/IP protocol. This is due largely to the natural signal propagation/transmission latencies involved in sending information up and down a satellite link. It is also due to the acknowledgement (connection) oriented nature of TCP/IP protocol. There is research going on in centers, including NASA and various universities to develop alternatives to protocol issues and at least to minimize the latency and resulting loss in information transmission speeds.

To field these systems within the estimated cost structures and schedules each proposer faces difficult challenges. One challenge is deploying the satellites at the required numbers and time intervals. In full

production, Globalstar and IRIDIUM, for example, require production of one satellite per week. This will cost more and take longer than originally anticipated. Teledesic will have to put 840 satellites in orbit in just two years.

One area that seems to be less planned and developed in all systems described is the earth station technology and the management and organization of the ground segment interfaces. The magnitude of managing these constellations, as well as operating the service, has not been completely addressed by any of the vendors publicly, even though there have been private studies, [7,11,16-19, 20-23]. Estimates of cost and time required for this area run the risk of being lower than required by the actual fully operating system as proposed.

On the regulatory side, while WARC 92 has granted worldwide primary allocation in the 1-3 GHz band for LEO and mobile satellite services, only experimental licenses

have been granted to the proposers mentioned above. In addition, there is disagreement among the proposer organizations on the use and sharing of the spectrum.

To obtain international approval to operate a Big LEO system worldwide, each proposer has partners outside the US that will facilitate regulatory approval abroad on a country-by-country basis. There is currently no straightforward mechanism in place by which a worldwide spectrum allocation can be made. Currently, for the satellite based wireless personal communications systems, more cost and regulatory issues need to be resolved than technical feasibility for these systems to be operational within the next five to seven year time frame as planned by the developers. ■

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