SATELLITE COMMUNICATIONS
- CURRENT FEATURES AND FUTURE TRENDS -*

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ABSTRACT

This paper addresses satellite systems whose primary mission is communications. The focus is on how the design of communications satellite systems has been evolving over the past two decades. The driving features of recently proposed satellite communications system architectures will be presented along with a discussion of the significant trends that might be expected in the near future. Key system characteristics will be identified and discussed.

I. INTRODUCTION

The purpose of this paper is to provide a general overview of current and future space communications systems. Satellites are used for a variety of purposes including sensor and data collection (e.g., Landsat, ARGOS, Defense Satellite Program), weather (e.g., GOES, Defense Meteorological Satellite program), navigation and timing (e.g., GPS), weapons (e.g., “Star Wars” concepts), reconnaissance, and communications (e.g., INTELSAT, INMARSAT, Galaxy, GStar). While every satellite system employs some form of communications to accomplish its mission, this paper will address those satellite systems whose primary mission is communications. The focus will be on how the design of communications satellite system architectures has been evolving over the past two decades. The driving features of recently proposed satellite communications system architectures will be presented along with a discussion of the significant trends that might be expected in the near future. Key system characteristics will be identified and discussed from a radio frequency (RF) perspective. It will be shown in this paper that the movement in space communications architectures envisioned for the next 20 years is toward more satellites/system, lower altitude orbits, increased complexity placed onboard the satellite platforms, and increased support to personal communications services (PCS) users.

II. DISCUSSION

GENERAL SYSTEM CHARACTERISTICS

The overall system characteristics of current and future communications satellite systems are compared in table 1. Current systems have primarily been designed to support a small number of high data rate users. The current systems are typically comprised of one to several large/heavy satellites per constellation deployed in a geostationary orbit, and capable of supporting high data rate transmissions (i.e., in the Mbps range). A geostationary orbit has an altitude of 19,322 nm corresponding to a period of one sidereal day (23 h, 56 m, 4 s), and an inclination of zero degrees which places it on the Equator. Thus, the satellite appears “stationary” from the surface of the Earth, thereby providing continuous communications services over a given area. Depending upon the antenna design, a single satellite in geostationary orbit can illuminate a spot beam that covers approximately 34% of the Earth’s surface assuming a minimum ground antenna elevation angle of 10°.

There are no satellite-to-satellite crosslinks in the commercial satellite inventory. The Tracking and Data Relay Satellite System (TDRSS), which is a civil satellite system (versus commercial), was designed and developed by NASA and does employ crosslinks to support the space shuttle, the Hubble telescope, and other NASA programs. However, the TDRSS is the exception rather than the rule. The mindset over the past thirty years of satellite system development has been to keep the complexity on the ground in order to minimize catastrophic system failures on board the satellite. For example, TDRSS satellites employ a phased array antenna system to support a multi-access service. The antenna element beam weights and phasing angles are computed on the ground and then transmitted to the satellite as opposed to performing the calculations on-board the satellite. The decision to perform the calculations on

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the ground was made to reduce on-board weight as well as to decrease the level of on-board complexity.

From a protocol layer standpoint, current satellite systems only address OSI layers 1 and 2. The space segment can basically be viewed as a repeater that translates the uplink frequency of the received waveform and re-amplifies it via a transponder.

The advent of personal communications services (PCS) has given rise to a desire for lower data rate systems capable of supporting many users. As a result of this, the trend in future communications satellite systems appears to be toward smaller, lighter weight satellites. The deployment philosophy is changing from one to several satellites in geostationary orbit to 10s, and even 100s of satellites in highly inclined low earth orbits (up to ~1000 nm) and medium earth orbits (up to ~10,000 nm). The corresponding satellite periods range from approximately 90 minutes to ~10 hours. Because of the high inclination angles and the rotation of the Earth, the satellites typically only appear overhead twice/day which drives the requirement for more satellites/constellation in order to achieve continuous coverage; albeit with multiple satellite handovers.

Along with the philosophy of increasing the number of satellites/constellation comes an economy of scale that reduces the operational impact of loosing a single satellite. This has resulted in a move toward increasing the complexity on-board the satellite in the form of on-board processing. The term on-board processing means that the received waveform is not only frequency translated and re-amplified prior to re-transmission, but it is processed down to baseband (i.e., to the bit level) via on-board decoding, de-interleaving, demodulation, etc. As a result of this, the satellite can now take on increasing functionality in the protocol arena by supporting a variety of packet-oriented services including routing, flow control, packet error detection/correction, etc. Consequently, the trend in future satellite systems design has been to increase the application of higher layer protocols on-board the satellite. On-board processing also supports satellite-satellite crosslinking in packetized systems which is attractive as the number of satellites/constellation increases and the corresponding user/satellite contact time diminishes.

With the above discussion as a backdrop, the next section discusses the RF systems of current and future systems by going through several case examples. The INTELSAT system is used to describe current, large, high data rate geostationary communications satellite systems; INMARSAT is used as an example of an evolving system that currently uses geostationary satellites to support mobile (primarily maritime) communications and is considering a move to a medium earth orbit (MEO) satellite design to support mobile personal communications services (PCS) users; IRIDIUM, Odyssey, and Globalstar are used to exemplify proposed systems that will cater to low data rate PCS (i.e., <9600 bps) and voice users; ORBCOMM which is designed to support very low data rate (~300 bps) message oriented store-and-forward users; and Teledesic which represents the limit of forward thinking in space based communications.

RF PERSPECTIVE

INTELSAT [refs 1-7]: In August 1964, INTELSAT was formed as an international organization with the goals of production, ownership, management, and use of a global communications satellite system. INTELSAT is comprised of over 130 member nations , with the Communications Satellite Corporation (COMSAT)) acting as the US signatory. The INTELSAT system currently employs a network of 22 geostationary satellites located in orbital positions over the Atlantic, Indian, and Pacific Oceans. INTELSAT supports direct communications links among 200 countries, territories, and dependencies using more than 1,300 antennas at over 800 earth stations.

INTELSAT provides a wide range of international services including telephone, data transfer, facsimile, television broadcasting, and teleconferencing at data rates in the Mbps range. Access to the INTELSAT satellites is through a wide array of terminal types and designs with antenna sizes ranging from .5 m to 30 m and operating frequencies in both the C-band (6 GHz up/4 GHz down; nominal) and Ku-band (14 GHz up/11 or 12 GHz down; nominal). INTELSAT leases space segment capacity in increments of 9, 18, 36, 54, or 72 MHz.

INTELSAT I (or Early Bird) was the first of a long series of satellite designs developed by INTELSAT. A single INTELSAT I satellite was launched into geostationary orbit on 6 April 1965. The INTELSAT I satellite was spin-stabilized, weighed 85 lbs in orbit (at beginning of life [BOL]), and was 28 inches in

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diameter with a height of 23 in. The total capacity was only 240 two-way voice circuits or one television (TV) circuit. The operational frequency was at C-band with a transmit power of 6 watts (W). The orbit was nominally geostationary, which is true for all of the subsequent INTELSAT satellite designs as well.

The current INTELSAT constellation represent four generations of spacecraft including INTELSAT V/V-A, VI, VII/VII-A, and VIII. Because of an ever increasing traffic projection and utilization for INTELSAT resources, every generation of INTELSAT satellites through INTELSAT VI had been designed to accommodate growth resulting in larger satellites that provided increasing levels of throughput capacity. Table 2 summarizes the frequency, power, weight and capacity characteristics for the current INTELSAT constellation compared with INTELSAT I. The trend of increasing capacity and size changed with the design of INTELSAT VII. The in orbit weight of INTELSAT VII is ~4,200 lbs and the orbit is geostationary. INTELSAT VII continues to support both C-band and Ku-band. A number of transmit powers are available with a maximum output transmit power of 50W. The total capacity is 18,000 two-way voice circuits plus 3 TV circuits.

As of April 1995, INTELSAT had 6 INTELSAT VIII series spacecraft on order from Martin Marietta Astro Space, the prime contractor. The first launch is scheduled for October 1996. The INTELSAT VIII satellites are being designed with improved C-band coverage and service and will include the highest C-band power level ever for an INTELSAT satellite.

In summary, the history of INTELSAT is representative of the communications satellite industry up to the present time in that it employs a limited number of large satellites in geostationary orbit that provide high data rate services to a select group of users. The services are relatively expensive (i.e., not designed for personal use), require directional antennas up to 18 m in diameter, and support point-to-point communications (i.e., bent-pipe with no on-board processing). The satellites, while providing a complicated suite of services in the way of transponders and antennas, are based upon proven technology devoid of the satellite complexity that accompanies the implementation of on-board processing techniques and satellite crosslinks.

INMARSAT [refs 1, 6, 8-10]: In 1972, the Intergovernmental Maritime Organization (IMO) began to study the development of an international maritime satellite system. In April 1975, the IMO convened an international conference to begin establishing the system with 48 nations represented. It was unanimously agreed that such a system was necessary and that a new organization, INMARSAT, should be formed to operate the system. In 1976, the INMARSAT Convention and Operating Agreements were developed and were entered into force in July 1979. INMARSAT began operations in 1982 and is headquartered in London.

The initial membership of INMARSAT included 26 nations, increasing to 67 by December 1992. The INMARSAT system currently employs a network of 11 satellites in geostationary orbit located over the Atlantic, Indian, and Pacific Oceans. Approximately 25,000 mobile earth stations (MES) access these satellites, permitting worldwide communications with ships at sea, offshore oil rigs and drilling platforms through approximately 30 shore stations.

The purpose of INMARSAT, as stated in the original INMARSAT Convention, was to provide maritime satellite communications. However, in October 1989 the Convention was amended to permit the provision of aeronautical satellite communications. Furthermore, in January 1989 INMARSAT's Assembly of Nations authorized expansion of the organization's charter to include land-mobile satellite services.

INMARSAT services include telephone (point-to-point, conference, and group calls), record services (data transfer up to 9.6 kbps), a high speed 56 kbps ship-to-shore data service, and private line voice and data services. Land-mobile services were also introduced in 1989. This capability was primarily developed to support long-service trucking companies, but the service is not limited in this respect and is expected to support a wider range of users in the future. Finally, INMARSAT is also actively working on its INMARSAT-P initiative in which it hopes to provide a world-wide pocket-sized telephone service by the end of the decade.

Having secured an adequate initial operating capability via the use of leased satellites, INMARSAT was then prepared to sponsor the development of their own satellite design designated INMARSAT II. A contract was awarded to British Aerospace in 1985 to design and develop 3 INMARSAT II satellites with options to purchase up to 6 additional satellites. One of these options was converted into a firm order in 1988 making the total acquisition 4 INMARSAT II satellites. All 4 of these INMARSAT II satellites have been deployed and are currently the primary user support satellites in the INMARSAT space segment.

The INMARSAT II satellite body is rectangular with a deployed solar array span of ~50 ft. The in orbit weight is ~1,500 lbs at BOL. The frequency plan is unusual in that the communications payload has 1 channel for shore-to-ship transmissions and 4 channels for ship-to-shore transmissions. Since the INMARSAT satellite uses L-band (1.5-1.6 GHz - nominal) for communications with ships and C-band for communications with shore stations, the result is a single uplink C-band channel (for use by the shore-to-ship communications) and 4 L-band channels for ship-to-shore communications. The downlink is just the opposite with a single L-band channel to communicate from shore-to-ship and 4 C-band channels to communicate from ship-to-shore.

The INMARSAT II satellite transmit power is 30W and the antenna system includes a 61-element array along with two 7-element arrays; all 3 providing earth coverage. The design life for the INMARSAT II satellite is 10 years and the capacity is 250 two-way voice channels. The first 2 launches occurred on 30 October 1990 and 8 March 1991, respectively, followed by the third and fourth launches in 1992.

The INMARSAT III series will address the need for increased capacity and power. Since the spectrum for mobile satellite communications is limited, the capacity increase will come from the use of five spot beams having increased gain relative to INMARSAT II. The result will be an effective radiated spot beam power approximately twenty times greater than that of the INMARSAT II global beam. The INMARSAT III capacity will be 2,000 two-way voice circuits.

In summary, INMARSAT is a system that supports maritime voice and low data rate (i.e., 600 bps) mobile satellite communications users via a constellation of relatively large geostationary satellites using intermediate sized earth terminals with minimum dimensions on the order of a suitcase. While, relative to INTELSAT, INMARSAT took a significant step forward in supporting PCS-like services, it still cannot support user connectivity using inexpensive (i.e., < $1000), handheld terminals which is considered by many to be a must if satellite based PCS systems are going to become viable in the future marketplace.

The past several years has seen a widespread move away from the traditional geostationary orbits to low Earth orbit (LEO) satellite constellation designs. Before discussing several of these systems, it is beneficial to consider the primary drivers for such a paradigm shift.

Why The Move To LEO Orbits?: As stated earlier, the altitude of a geostationary satellite is 19,322 nm resulting in a minimum one-way, single hop time delay of approximately a quarter of a second accounting only for the speed of light transmission delay. Signal processing delays further add to the overall delay. These delays are unattractive from a voice communications standpoint. Furthermore, the communications propagation loss increases as a function of distance squared in accordance with the following equation:

$$L_{fs} = \left[\frac{4pzf}{c}\right]^2 \qquad (1)$$

where L_{fs} is the free space propagation loss, z is the source (or user) to destination (or satellite) distance, f is the operating frequency, and c is the speed of light. Equation (1) is plotted in figure 1 at an operating frequency of 2 GHz which is in the frequency range allocated to mobile satellite services. As shown, the free space loss is significantly higher for satellites in geostationary altitudes as compared with low earth orbit (LEO) satellites in the <1000 nm range.

Also plotted in figure 1 is the maximum achievable data rate as a function of satellite altitude for a nominal communications link assuming an operating frequency of 2 GHz, a receive satellite antenna diameter of .33 m, a receive satellite antenna noise temperature of 750 K, a transmit power of 1 W, other link losses of 6 dB (i.e., due to multi-path fading, rain, atmospheric absorption, etc.), a required received signal-to-noise ratio (SNR) of 10 dB, and a link margin of 3 dB. The maximum achievable data rate was calculated for three difference transmit antennas types including an omni antenna (i.e., similar to a cellular type antenna), and 1 and 3 meter parabolic dish antennas. The following observations can be made:

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1. The maximum achievable data rate increases with increasing transmit antenna (in fact it increases proportionally to the increase in transmit antenna gain), and
2. The maximum achievable data rate decreases with increasing satellite altitude (due to the corresponding increase in free space propagation loss).

The minimum data rate required to support toll quality voice is expected to be on the order of 2400 bps within the next several years. If we assume this to be the case and that the only choice for the transmit antenna is an omni antenna to support handheld mobile communications, it is clear from figure 1 that the choice of satellite altitude had to move into the LEO range since geostationary satellites would require prohibitively large satellite antennas to compensate for the excessive propagation loss at the higher altitude. The four systems discussed below have been designed with this in mind and represent the trend in future satellite communications systems toward more satellites/system, lower altitude orbits, and increased support to PCS users.

IRIDIUM and Globalstar [11-13]: The IRIDIUM and Globalstar systems represent the primary LEO contenders in providing mobile telephony in the next 2-3 years. In the parlance of the regulatory community, these systems are referred to as Big LEOs since they would provide the full range of mobile satellite services (MSS) including voice and data and operate in the 1 to 3 GHz band[1].

Some of the key architecture characteristics of the Globalstar and IRIDIUM systems are shown in table 3. Globalstar includes 48 LEO satellites at an altitude of 1401 km and equally divided into 8 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 6 orbital planes.

The IRIDIUM satellite enjoys the largest capacity at 3840 full duplex (FDX) circuits/satellite followed by Globalstar with 2800 circuits/satellite. It should be noted that the “per satellite” capacity is not cumulative due to self interference and beam overlap considerations.

Each satellite is 3-axis stabilized with a mission life of between 5 and 7.5 years. The Globalstar system includes traditional bent-pipe transponders whereas the IRIDIUM satellite will employ on-board processing techniques. This is a major design feature of the IRIDIUM system and is essential to support the satellite-to-satellite crosslinks which will circumvent the need to downlink voice and data traffic to intervening hub stations. Four crosslinks would exist on each satellite; one forward within a plane, one backward within a plane, and two cross-plane links. The satellite crosslinks will operate at 25 Mbps in the 22.55 GHz to 23.55 GHz frequency range. The onboard processing feature, together with the satellite crosslink capability, provide increased flexibility in message routing at the expense of system design complexity. Motorola is aiming to be the first vendor to utilize these techniques in a commercial satellite system.

The dry masses of the satellites are currently estimated to be 704 lbs for Globalstar and 1100 lbs for IRIDIUM. The IRIDIUM satellite is heavier than Globalstar primarily due to the additional crosslink communications payload together with the on-board processing equipment.

Both IRIDIUM and Globalstar were awarded an operational license by the Federal Communication Commission (FCC) in January 1995. IRIDIUM’s first launch is scheduled for September 1996 while Globalstar is planning a first launch in July 1996. The IRIDIUM system will employ a time division multiple access (TDMA) scheme to support the user traffic whereas Globalstar will employ a code division multiple access (CDMA) scheme. The schemes are incompatible with each other resulting in a unique spectrum sharing solution generated by the FCC.

ORBCOMM: Recent technological advancements in the areas of antenna design, signal reception in fading channels, and unit miniaturization have resulted in the feasibility and manufacture of mobile communications systems supporting transmission in the 100 to 300 bps range. One such system is ORBCOMM. ORBCOMM is designed to provide full-time global two-way digital communications services capable of supporting messaging, emergency alert functions, position determination, and remote data collection. The space segment will be comprised of 36 satellites

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[1] In contrast, Little LEOs are systems that provide non voice, store-and-forward mobile satellite services and operate at a frequency below 1 GHz. An example is the ORBCOMM system.

with 4 satellites in near-polar orbit and the remaining 32 satellites at a 45° inclination[2]. The ORBCOMM satellites will be launched on the Pegasus launch vehicle developed by OSC.

The satellite design life is 4 years and the weight is ~85 lbs. Space/ground communications is at VHF with 148-150.05 MHz used for the uplink and 137-138 MHz used for the downlink. The user segment is comprised of a handheld unit operating at a transmission rate of 2400 bps to the satellite and receiving data at a rate of 4800 bps from the satellite. The effective throughput will be in the 300 bps range.

ORBCOMM can basically be viewed as a store-and-forward mail box in the sky. The source user messages will be sent via the ORBCOMM space segment to gateway earth stations that will then either forward the message directly to the destination users via leased lines or will act as a central repository to be accessed by external users upon demand. The satellite design is very simple, small, and easily deployed. The throughput is low (i.e., ~300 bps); however, the services being provided are global and are in demand from a variety of users. The first two satellites were launched in April 95. Limited services are currently being offered.

Teledesic [ref 14]: The newest contender for a piece of the future satellite communications pie is Teledesic. Teledesic in under development by the Teledesic Corporation; principal shareholders include the Chief Executive Officer (CEO) of McCaw Cellular Communications Inc. (Mr. McCaw) and the CEO of Microsoft Corporation (Mr. Gates). The services to be provided include domestic and international fixed satellite service. The most interesting feature of Teledesic is that it is not catering to the mobile user market but, rather, it is posturing itself in the same way as AT&T was configured before the breakup. That is, Teledesic will be a wholesaler of communications capacity and offer bulk network capability to retail telecommunications providers such as U.S. West, NYNEX, etc.

The current Teledesic architecture is shown in figure 2. The space segment will be comprised of 840 satellites employing onboard processing techniques and supporting packet switched asynchronous transfer mode (ATM) communications. The altitude is ~700 km and the orbit is sun-synchronous. Each satellite will have 8 crosslinks supporting a nominal data rate of 155.2 Mbps with a maximum supportable data rate of 1.244 Gbps. The crosslink frequency band is 59-64 GHz.

Connectivity with the ground is via Ka-band with 30 GHz (nominal) used for the uplink and 20 GHz (nominal) used for the downlink. The maximum achievable data rate supported by Teledesic is 1.244 Gbps to both user ground terminals and Teledesic gateways or “GigaLink” terminals. Only limited data is available in the public domain concerning the details of the ground segment except that it will be compatible with ATM/SONET technology and protocols under development and it will have the capability to interface with existing public and private networks.

Within the context of this paper, Teledesic is the greatest example of showing where future satellite communications appears to be going. Other than IRIDIUM, each of the other future systems identified in this paper are examples of systems that are applying proven technology to new applications (i.e., mobile voice and data communications and messaging).

III. SUMMARY AND CONCLUSIONS

The communications satellite systems in existence today have primarily been designed to support a small number of high data rate users. They typically comprise one to several large/heavy satellites per constellation deployed in geostationary orbits. The technological advancements supporting the types of personal communications services envisioned for the next 15-20 years, along with the growing acceptance and demand for these services, has driven the designs of communications satellite systems toward more satellites/system, lower altitude orbits, increased complexity placed onboard the satellite platforms, and lower data rates with services provided directly to the user. Most of the emerging system designs are implementing these changes within the context of applying proven/existing technology to new applications; however, IRIDIUM and Teledesic are certainly examples of systems that are pushing the envelope in terms of making substantial inroads toward integrating higher layer protocols into the developing systems.

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[2] The final constellation architecture is still under development and may include 26 satellites versus 36 satellites.

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Table 1: Comparison of Current and Future System Characteristics for Satellite Communications Systems

System Characteristic	Current	Future
Platform size	Large/Heavy	Smaller/Light Weight
Orbit	Geostationary	Low Earth Orbit (LEO) and Medium Earth Orbit (MEO)
Constellation	One to Several Satellites	10s to 100s of Satellites
Sat/Sat Connectivity	None (except for TDRSS); Bent-Pipe Operations	Cross Links; On-Board Processing
Complexity	Primarily on Ground	Primarily on Satellite
Protocol layers	Only Layers 1 and 2	All 7 Layers

Table 2: INTELSAT System Satellite Characteristics

INTELSAT	Frequency	Power (W)	Weight (lbs)	Capacity (2-way voice channels)
I	C Band	6	85	240
V	C and Ku Bands	Up to 8.5	2260	12,000
VI	C and Ku Bands	Up to 40	4600	24,000
VII	C and Ku Bands	Up to 50	4200	18,000
VIII	C and Ku Bands	Up to ~44	3370	22,500

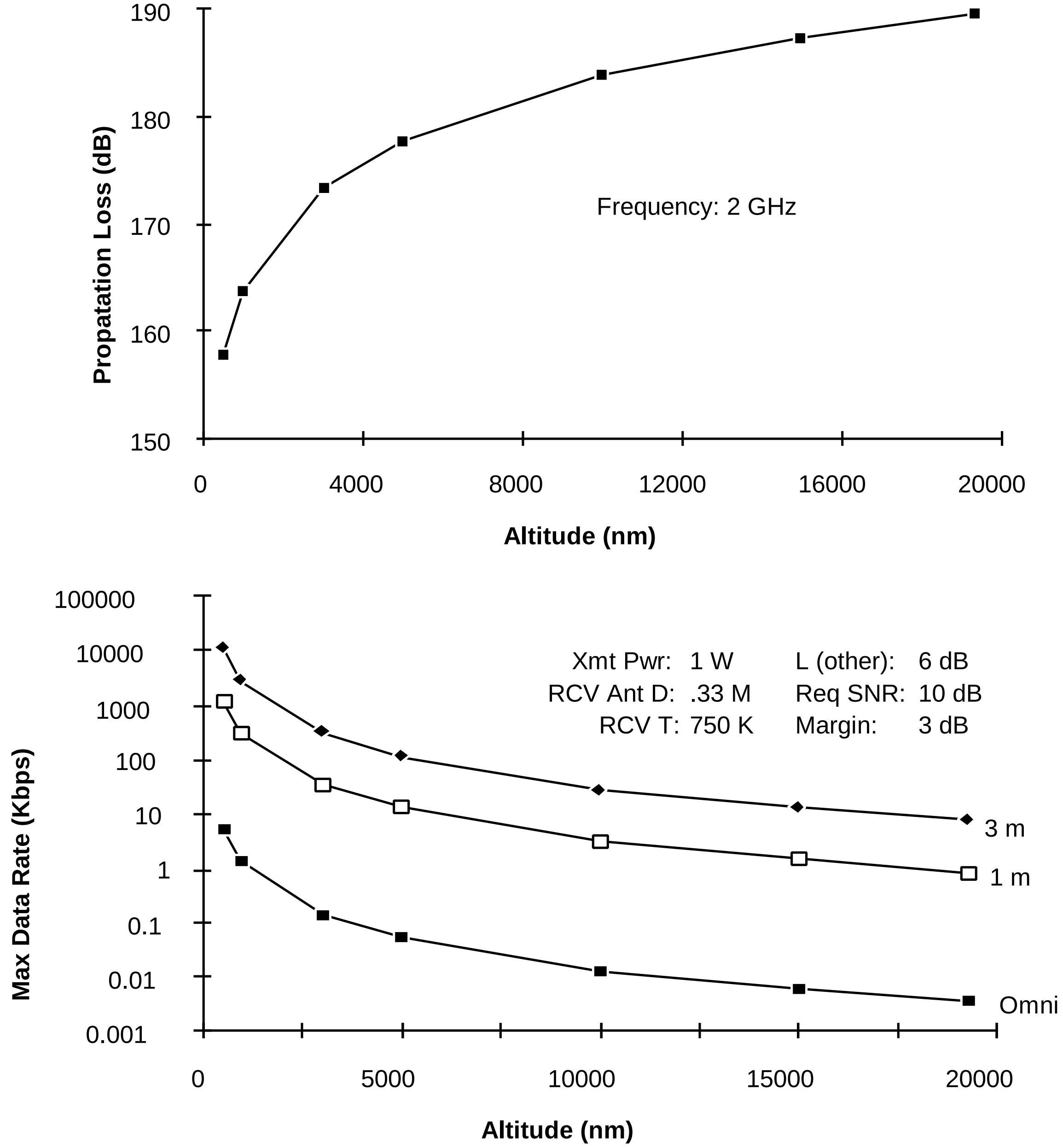

Figure 1: **Free Space Propagation Loss and Maximum Achievable Data Rate as a Function of Satellite Altitude at 2 GHz**

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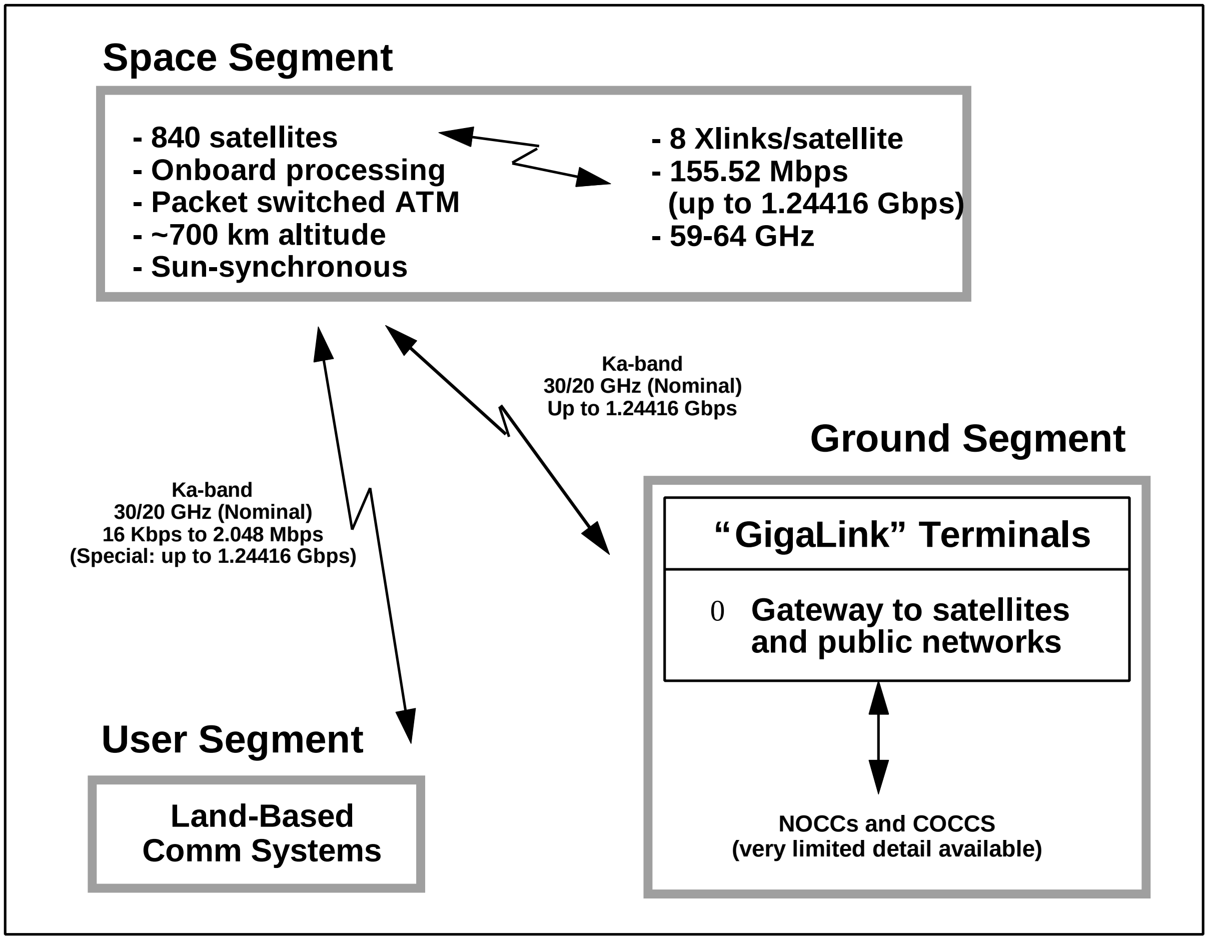

Figure 2: Proposed Teledesic Architecture

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Table 3: Comparison of System Characteristics for the Globalstar, IRIDIUM, Orbcomm, and Teled

		Globalstar	IRIDIUM	ORBCOMM	
Services Provided		Mobile Telephony & Low Rate Data (9.6 Kbps)	Mobile Telephony & Low Rate Data (2.4 Kbps)	Store-n-Forward Messaging (up to 300 bps thruput)	Hi Sa (up
Constellation	# Satellites	48	66	36	
	Inclination (°)	52	86.4	45	Su
	Altitude (Km)	1401	785	775	
Satellite	Transponder	Bent Pipe	Processing	Bent Pipe	
	Mission Life	7.5 Yrs	5 Yrs	4 yrs	
	Dry Mass (lbs)	704	1100	85	
	Crosslinks	No	Yes; 4 crosslinks @ 25 Mbps; 22.55 to 23.55 GHz	No	Ye @ 5

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