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THE CALLING℠ NETWORK: A GLOBAL TELEPHONE UTILITY

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ABSTRACT: There is a very large demand for basic telephone service in developing nations, and remote parts of industrialized nations, which cannot be met by conventional wireline and cellular systems. This is the world's largest unserved market. We describe a system which uses recent advances in active phased arrays, fast-packet switching technology, adaptive routing, and light spacecraft technology, in part based on the work of the Jet Propulsion Laboratory and on recently-declassified work done on the Strategic Defense Initiative, to make it possible to address this market with a global telephone network based on a large low-Earth-orbit constellation of identical satellites. A telephone utility can use such a network to provide the same modern basic and enhanced telephone services offered by telephone utilities in the urban centers of fully-industrialized nations. Economies of scale permit capital and operating costs per subscriber low enough to provide service to all subscribers, regardless of location, at prices comparable to the same services in urban areas of industrialized nations, while generating operating profits great enough to attract the capital needed for its construction. The bandwidth needed to support the capacity needed to gain those economies of scale require that the system use Ka-band frequencies. This choice of frequencies places unusual constraints on the network design, and in particular forces the use of a large number of satellites. Global demand for basic and enhanced telephone service is great enough to support at least three networks of the size described herein. The volume of advanced components, and services such as launch services, required to construct and replace these networks is sufficient to propel certain industries to market leadership positions in the early 21st Century.

The Global Need for Telecommunications

Developing Nations

Half of the world's population lives more than two hours from a telephone[1]. 527,000 villages in India do not have telephone service[2]. There are over 40 million applicants around the world on waiting lists[3]. Much of this demand, and the larger hidden demand of people who have not joined waiting lists because they have no reasonable hope of getting service, is in provincial areas of developing countries (areas far from the nation's one or two major cities). Many developing countries do not have the skills, technology, and funding to expand their telephone networks rapidly; yet, demand for telephone service continues to mount as economic growth increases their emerging middle class' ability to pay for such service.

For example, the richest 10% of Indonesian households represent a larger market than all households in Portugal; these Indonesians have the same average income as Portugal and comprise more households[4]. Yet, Portugal has 2.7 million access lines and the whole of Indonesia has only 1.3 million[5]. Unserved people in developing countries require low cost access to basic

1. _____, "Phones into Orbit," The Economist, March 28, 1992, pp 14-15
2. N Ravi, "Telecommunications in India," *IEEE Communications Magazine*, March 1992
3. International Telecommunication Union, *Yearbook of Common Carrier Telecommunications Statistics*
4. Calculated from World Bank data and also stated in ______, "Asian Adventures," *The Economist*, May 30, 1992, p 17.
5. International Telecommunication Union, op. cit., p 1

telephone services, such as voice, facsimile, and low-rate data. These are basic services that could be supported by a standard analog telephone line if those lines existed; however, the capital cost of installing physical telephone lines to a significant number of people in a reasonable time is far beyond the resources of most developing nations.

Industrialized Nations

The convergence of computer, telecommunications, and entertainment industries has created a list of new, enhanced telephone services that require more bandwidth than can be supported by standard analog telephone lines. Today's demand for these services, such as interactive multimedia, is mainly in high-income countries. While these services are easy to provide in cities, existing wireline and cellular networks cannot distribute enhanced services to rural areas at reasonable cost. But people in rural areas have the same needs as people in cities: rural areas of high-income countries require high quality, high capacity channels that offer cost-effective bandwidth on demand.

Services to be Provided

To satisfy this demand, the capital cost per subscriber of a new telephone network must be indifferent to its subscribers' location, while the network provides the same services offered by telephone companies and government Administrations in urban areas of high-income nations. It must address the needs of businesses, individuals, and social agencies; and because it is a public utility, it must through its operation bring significant social and economic benefits to the nations it serves.

Business subscribers need flexible access to a wide range of integrated services that modern companies use to conduct their daily business: high quality voice, high rate data, facsimile, full-motion compressed video, interactive imaging, enterprise-wide networks, and interactive high-resolution graphics.

Individuals and social agencies need basic telephone service, distance learning, tele-health, video programming, disaster recovery, and tele-monitoring.

Socioeconomic Benefits

Universal telephone service closes the opportunity gap between urban and rural areas and between the information-rich and information-poor. Equal access to telephone service throughout a country is an enormous economic stimulant. It opens domestic and international markets, allows the disabled to work from home, and lets industries locate near raw materials and pools of labor. Equal access to telephone service allows social services such as health care and education to be delivered to remote and isolated areas that do not have an adequate number of doctors, nurses, and teachers. This provides a dramatic improvement in the quality of life in rural, remote, and underserved areas of all nations, both rich and poor.

Universal telephone service improves the free flow of goods, services, and information within and between remote locations, thereby increasing economic, commercial, and administrative efficiency. It provides direct access to world mercantile and financial markets for manufacturing and intellectual service companies in provincial areas, while supporting the information flow that reduces the operating costs and increases the efficiency, quality, and productivity of rural companies, such as those in agricultural, extractive, and tourist industries.

Since surface disasters such as hurricanes, earthquakes, and floods do not affect satellite network operation, such networks can save many lives when used for emergency relief and disaster recovery.

Reliability of Service

When people have good telephone service, they entrust the safety of their lives and property to the integrity of that service. Reliability of the service and its supporting network is thus of overriding importance. It has been shown[6] that the most robust telephone network is a non-hierarchical structure whose topology resembles a geodesic dome. Such a network is not achievable in practice, but is most closely approximated by a large constellation of low-Earth-orbit satellites of equal rank.

Economic Considerations

Price of Service

Telephone service will not be accepted if its users can't afford it. The acceptable price of telephone service in each nation has already been determined by prices charged by the nation's telephone companies or Administration in urban areas with wired service. As a first approximation, then, any company proposing to provide telephone service throughout a nation must be able to do so at prices comparable to those already charged for the same service elsewhere in the same nation. In many nations, acceptable prices are comparable with those charged for urban service in high-income nations.

Clear, dependable telephone service is a powerful facilitator of economic growth. It works by giving remote businesses and industries in remote and developing areas the same immediate access to world markets for goods, money, and information as their competitors in the world's industrial centers. Telephone service cannot provide this level playing field unless it is delivered at prices similar to standard urban telephone service.

Economic Constraints on the Serving Company

To provide universal service at prevailing prices, the serving telephone company must be large enough to obtain the necessary economies of scale. Our studies show that a global supplier of such services must be about the size of an American Regional Bell Operating Company to be able to supply a full range of telephone and data services at current world prices. Such a company is able to serve about 20 million typical business lines[7] or a correspondingly greater number of residential and village telephone lines.

It is clear that a twenty-million-subscriber company, like its exemplar, the Regional Bell Operating company, must be highly profitable in order to raise the large amount of capital it needs for construction and growth, and to replace its constellation of satellites as it reaches the end of its life. The sheer size of the company and its continuing capital needs demand that it be profitable *in its own right* as a telephone company. It cannot rely on served-nation subsidies or the sale of terminals to supplement its revenue; its served nations deserve the revenue they can derive by manufacturing terminals locally for their own use and for export to their richer neighbors; and a nation that cannot afford to install its own telephone system certainly cannot afford to pay a foreign company to install one for it.

Spectrum Requirements

To provide such a large number of subscribers with high-quality wireless service requires substantial bandwidth, of the order of 200 MHz in both transmit and receive directions. The lowest available frequency bands of this size are in the 20 to 30 GHz range (Ka band). In this

6. Huber, Peter W., *The Geodesic Network, 1987 Report on Competition in the Telephone Industry*, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 1987

7. A typical business line is in use for 10% of the busy hour. This is defined as 0.1 Erlang (or 3.6 CCS).

range, 4.7 GHz is already allocated for use by fixed and mobile satellite systems for wireless connections between user terminals and satellites.

Since radio spectrum is a valuable natural resource owned and shared by all mankind, any system proposing to use such a large amount of spectrum must go to extraordinary lengths to be sure that it uses that spectrum in a highly efficient way. The system we here describe re-uses its frequencies 20,000 times on a global basis.

Complementarity to Proposed LEO Systems

A large system that provides basic and enhanced telephone service must expect that most of its subscribers will be in residences and businesses, and will thus use fixed terminals; such a network is therefore complementary to known proposals for low-Earth-orbit satellite systems. Since active people now expect mobile and personal portable telephone service to be a part of a complete telephone service offering, any large network must support mobile, portable, and handheld service; and in fact, a 20-million subscriber network should expect that a significant number of its terminals will not be in fixed locations. Even though it does not penetrate buildings and dense foliage well, a Ka-band network can supply useful mobile, portable, and handheld service, especially to users who require bandwidths higher than those needed for basic two-way voice communication.

Provision of Service

All nations regulate telecommunications service, and many nations provide it through a government monopoly. The laws of orbital mechanics demand that a low-Earth-orbit network that provides global service have some of its satellites over the territory of every nation, whether that nation permits it to deliver service or not. It follows that those satellites that are over nations which do not permit their use are wasted assets. To help gain access to all nations, a global telephone company must deliver its services through a local service provider in each nation, which may be the government-monopoly "PTT," the already-franchised telephone company, or some other locally-owned and -managed entity. The service must be provided transparently, in the name of the local service provider.

Environmental Considerations

Any enterprise that provides service to the people of the Earth on a large scale must be impeccable in its use of the air, the Earth, and the space that surrounds us. It must use exquisite care not to harm, and if possible must improve, the wholesomeness of the planet we share.

The Design of a Global Telephone Network

We here describe the Calling^{SM} Network, a low-Earth-orbit ("LEO") satellite network capable of seamless distribution of telecommunications capacity, on demand, to support low cost, high quality, flexible, and integrated access to any medium, anytime, anyplace. It is intended to extend basic service to provincial and rural areas of developing countries and to deliver both basic and enhanced services to rural areas of high-income countries. The design achieves economies of scale through volume manufacture and achieves economies of scope (using one network for a variety of services) by offering a wide range of integrated services at a low capital cost per subscriber.

Network Objectives

Calling Communications Corporation intends to build a high-capacity network to offer its subscribers, regardless of their location, a wide range of high-quality modern telecommunication services at prices equivalent to those charged for similar services provided by existing terrestrial systems. The primary market is subscribers in areas that are not served economically by terrestrial systems (e.g., areas of low user density), as well as subscribers needing access to services not available from their conventional telecommunications provider. The network service area encompasses nearly one hundred percent of the Earth's population. The Calling℠ LEO satellite system is designed to provide service to fixed-site terminals, and is also capable of providing ancillary services such as mobile services.

The network provides switched digital connections at multiples of its 16 Kbps basic channel, up to 2 Mbps. The basic channel rate provides network quality voice as well as a variety of data, facsimile, and other services. Higher rate channels support the wide range of services available with an ISDN connection and a multi-rate ISDN connection. The network also provides wideband channels up to DS-3 rates or OC-1 rates (about 44 Mbps) between its gateways for domestic and international toll and private service.

The network accommodates a peak load of more than 2,000,000 simultaneous full-duplex connections, corresponding to over 20,000,000 subscribers at typical "wireline" business usage levels. These capacity estimates assume actual, not uniform, distribution of subscribers within the service area. The system handles a peak channel density of over 100 times the average. The peak density of a cell is 0.5 simultaneous basic-rate channels per square kilometer averaged over a cell. For the system's 53.3 km-square cell, this corresponds to 1440 channels, which will serve over 14,000 typical business subscribers or a larger number of residential and village telephone subscribers.

System Description

Design Summary

Some key elements of the system design are discussed in the following sections. The following is a brief overview of the design (see Figure 1): The network resides in a LEO constellation of 840 satellites plus 84 spares. Each satellite is a switch node in the network and is linked with up to eight adjacent nodes to form a robust mesh topology. Subscriber terminals communicate directly with the satellite network, which connects them with other network subscriber terminals or, through a gateway interface, with the public switched network. Fast packet switching technology combined with a proprietary packet routing algorithm are used to adapt to the continually changing topology of the LEO-based network.

Communication links between Earth terminals and satellites use the 30/20 gigahertz (GHz) frequency band, the lowest band with sufficient spectrum to meet the requirements imposed by Calling's quality and capacity objectives. A combination of a high mask angle (the lowest vertical angle from a terminal at which communication is attempted), high-gain satellite antennas, and small cell size compensate for the rain attenuation and terrain blocking characteristics of these frequencies and minimize interference to and from terrestrial systems.

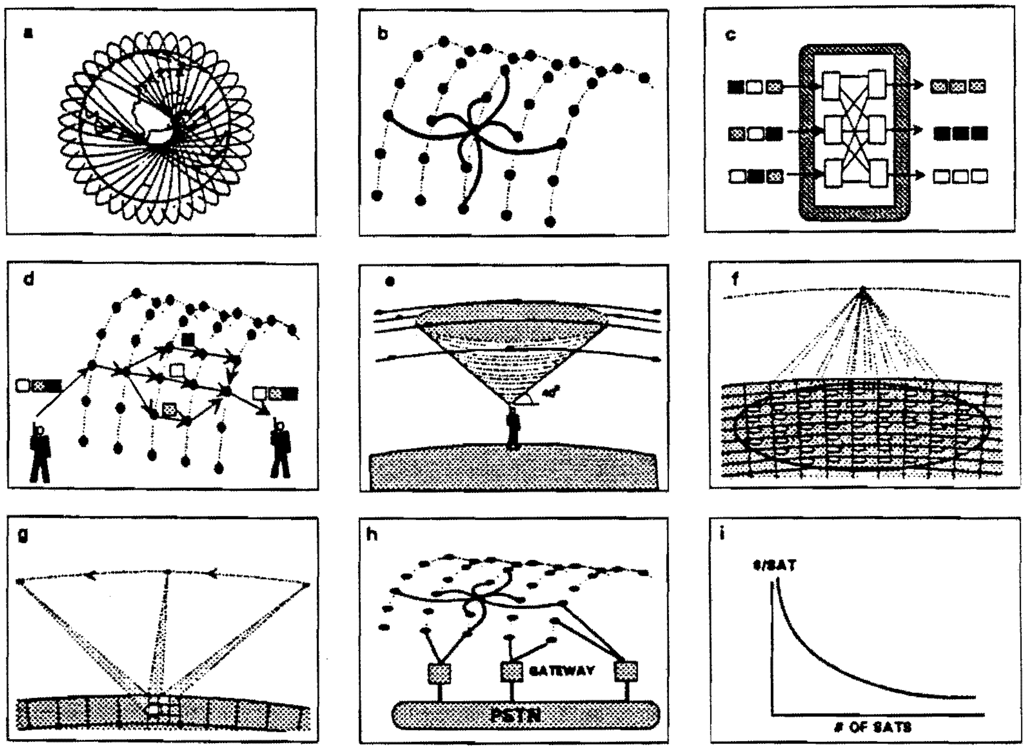

Figure 1 - Calling's distinguishing concepts. a, LEO constellation; b, Geodesic network; c, Fast packet switching; d, Adaptive routing; e, 30/20 GHz links at 40° mask angle; f, Multiple access; g, Earth-fixed cells; h, Standard interfaces; i, Economy of scale.

A unique Earth-fixed-cell technology minimizes the "hand-off" and frequency coordination problems associated with LEO networks. Instead of moving with the satellite footprint, the system's cells are arranged in a fixed grid on the Earth to which the satellites electronically steer their antennas as they pass. This permits a terminal to keep the same channel assignment for the duration of a call, regardless of the number of satellites involved. Hand-offs become the exception rather than the rule. This Earth-fixed-cell technology enables the use of small cells, resulting in high spectral efficiency.

The combination of low Earth orbit and high mask angle results in small satellite footprints. This in turn forces the constellation to contain a large number of satellites to cover the Earth. While a large constellation is expensive, it offers a number of significant advantages to a communications network with high quality, reliability, and capacity objectives. The apparent disadvantages -- the cost and complexity of building, launching, and managing a large constellation -- are not insurmountable. They are subject to economies of scale, as discussed below.

All satellites are identical and designed to take full advantage of the economies of scale of high volume manufacturing and multiple launch. Once launched, each satellite and the constellation as a whole are essentially autonomous. On-board systems maintain the satellites' altitude and position in orbit, monitor and analyze subsystem status, and periodically report the

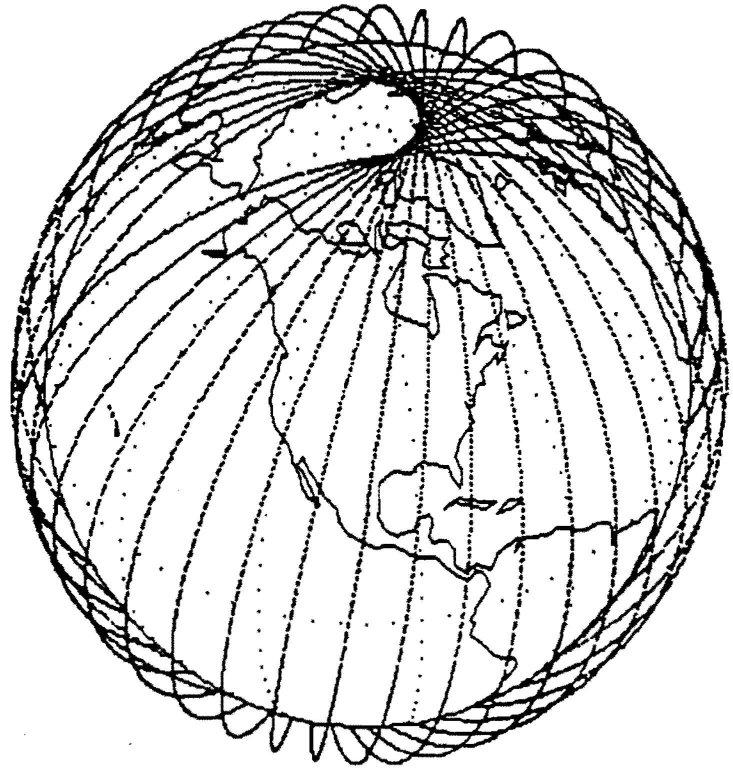

Figure 2 - Calling's 21 orbits spaced 9.5° apart.

results, including a projection of remaining useful life. Control from the ground is required only to handle exceptional cases.

The Calling℠ system demonstrates the important commercial benefits of using technology developed for other purposes by U.S. National Laboratories such as Jet Propulsion Laboratory (JPL) and Lawrence Livermore National Laboratory (LLNL). Many of the subsystems, components, materials, and processes developed for space exploration and national defense can be used directly or indirectly in Calling's network.

The Constellation

The network is embodied in a constellation of LEO satellites orbiting the Earth at an altitude of 700 km. There are 21 orbital planes inclined at 98.2° to the equator, with adjacent ascending nodes spaced at 9.5°. At this inclination, each satellite presents the same face to the sun at all seasons. This sun-synchronous orbit allows significant savings in solar power arrays and allows parts of the satellite's electronics to be cooled by radiation, as explained in more detail below.

Each orbital plane contains 40 active satellites spaced evenly around the orbit, along with up to four operational spares, resulting in a total constellation of 840 to 924 satellites. Figure 2 shows the entire set of orbits. The constellation is designed so that a subscriber's terminal can "see" two or more satellites most of the time. This allows load sharing among satellites, and also provides redundant coverage in the event of satellite failure.

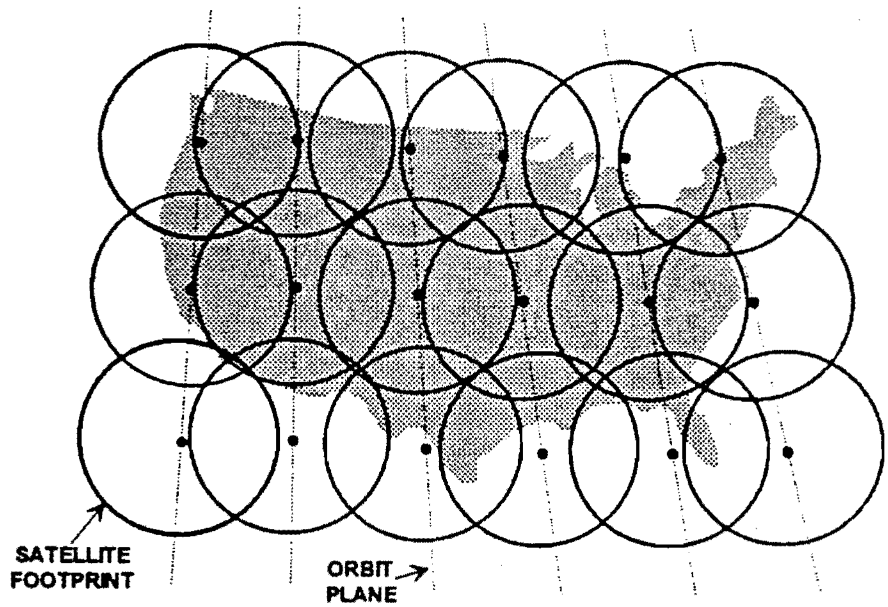

Figure 3 - Overlapping satellite footprint coverage over the United States allows a subscriber's terminal to "see" two or more satellites most of the time.

Figure 3 illustrates the coverage redundancy over the United States. The footprint and coverage diagrams are based on a system design feature which insures that there is at least one satellite no lower than 40° above the horizon. This high "mask angle" minimizes blockage from structures and terrain, minimizes interference with terrestrial microwave links, and limits the effects of rain attenuation and multi-path reflections.

When the constellation is deployed, each launch vehicle carries a number of satellites that depends on the lifting capacity of the vehicle. These satellites are released in their proper orbital plane; each satellite then adjusts its position within the plane. On-board thrusters and an autonomous navigation system continuously monitor and adjust the satellite's altitude, attitude, and position. A number of active spare satellites are placed in orbit along with the first launch of satellites; additional multiple launches are made from time to time to replenish orbiting active spares.

The satellite bus and payload are designed to have a lifetime of ten years. The lifetime is limited by batteries, solar cells, electronic component failure rates, and on-board consumables. Some thirty percent of the satellites are expected to fail at random before the end of the ten years. When an active satellite fails, all satellites in its orbit reposition themselves to fill the gap. This high degree of coverage redundancy minimizes or eliminates service disruption. Service continues during the repositioning process, which is complete in less than two hours. A loosely-coupled coverage pattern allows the satellites in one plane to be repositioned without opening gaps between its adjacent planes. No debris is left behind in orbit: launch vehicles retain enough fuel to deorbit themselves, and satellites at the end of their useful life are deorbited and disintegrate harmlessly in the atmosphere.

The Network

Figure 4 provides an overview of the network architecture. The network uses fast packet switching technology similar to the Asynchronous Transfer Mode ("ATM") technology now being

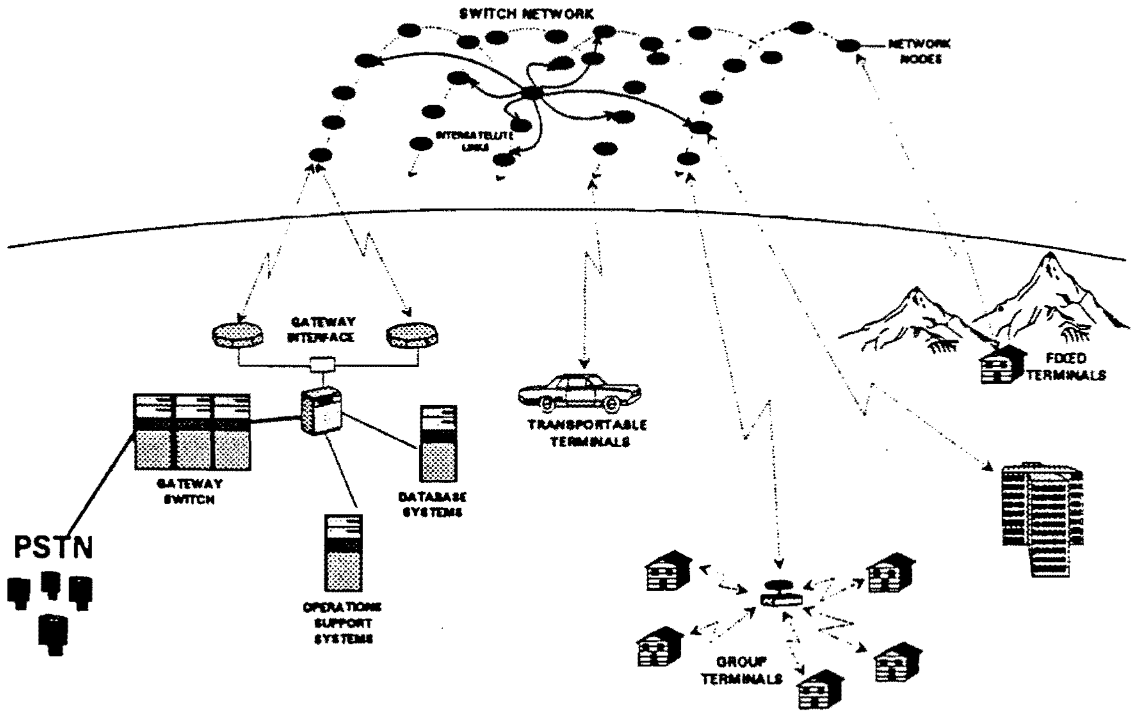

Figure 4 - Calling's LEO network provides low delay digital connections between terminals and, through regional gateway switches, to the Public Switched Network. Distributed administrative and control systems connect to the network through the gateway interface.

developed for LAN, WAN and Broadband ISDN ("B-ISDN") networks. All communication is treated identically within the network as streams of short fixed-length packets. Each packet contains a header that includes address and sequence information, an error-control section used to verify the integrity of the header, and a payload section which carries the digitally-encoded voice or data. Conversion to and from the packet format takes place in terminals and gateway interfaces. The fast packet switch network combines the advantages of a circuit-switched network (low delay "digital pipes"), and a packet-switched network (efficient handling of multi-rate and bursty data). The technology is ideally suited for the dynamic nature of a LEO network.

Each satellite in the constellation is a node in the fast packet switch network, and has intersatellite communication links with up to eight other satellites in the same and adjacent orbital planes, as shown in Figure 5. Each satellite is normally linked with four satellites within the same plane (two in front and two behind), and with one in each of the two adjacent planes on both sides. This interconnection arrangement forms a non-hierarchical "geodesic," or mesh, network and provides a robust network configuration that is tolerant to faults and local congestion.

The satellites communicate directly with fixed, transportable, and mobile terminals and to gateways. Gateways connect Calling traffic, inbound and outbound, to the other networks in the destination country. The gateway interface also provides the network access to various operations support, control, and database systems.

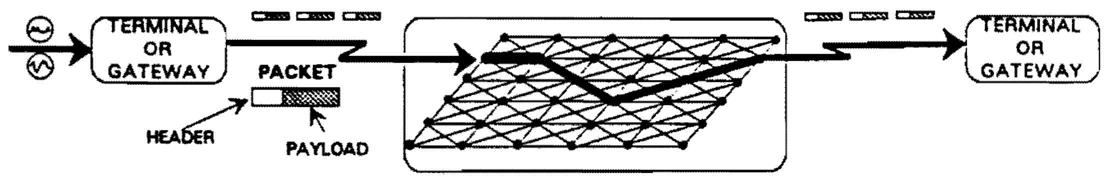

Figure 5 - Terminals and gateway interfaces convert all communication to streams of fixed length packets. Each satellite in the constellation is a switch node in the fast packet switch network. Intersatellite links interconnect the nodes in a robust mesh or "geodesic" topology.

Fast Packet Switch

Figure 6 illustrates the architecture of the satellites' fast packet switch subsystem. The switch node is essentially non-blocking with very low packet delay, and a throughput in excess of five gigabits per second. Packets are received via an input port from an adjacent satellite, or from a gateway or terminal within the satellite footprint. An input packet processor examines the header to determine the packet's destination and the corresponding switch output port. The input processor adds a routing tag to the packet which the self-routing section uses to direct the packet to the selected output port. The output port may be an intersatellite link leading to a distant destination, or it may lead to a local transmitter, a gateway or to a cell currently served by this satellite. A proprietary adaptive routing algorithm adapts the packet routing decisions to the current network configuration and mapping between satellite scanning beams and Earth-fixed cells.

Adaptive Routing

The network topology of a LEO-based network is dynamic. Each satellite keeps the same position relative to other satellites in the same orbital plane, but its position and propagation delay relative to ground terminals and to satellites in other planes changes constantly. Communications links between satellites are connected and disconnected as orbits intersect and as satellites move in and out of communication range. The changes are continuous, but predictable. The system uses a proprietary autonomous orbit determination system to provide the precise position of each satellite to all satellites in the constellation. The information is used for precise beam steering between satellites and to Earth terminals, to calculate propagation delays, and to determine current geographical coverage areas. This position information is derived at a very low cost directly from the geometry of the constellation, without the aid of outside navigation signals.

In addition to the network's changing topology, as traffic flows through the network, queues of packets build up in the satellites, changing the waiting time before transmission to the next satellite. All of these factors affect the routing choice made by the fast packet switch. These

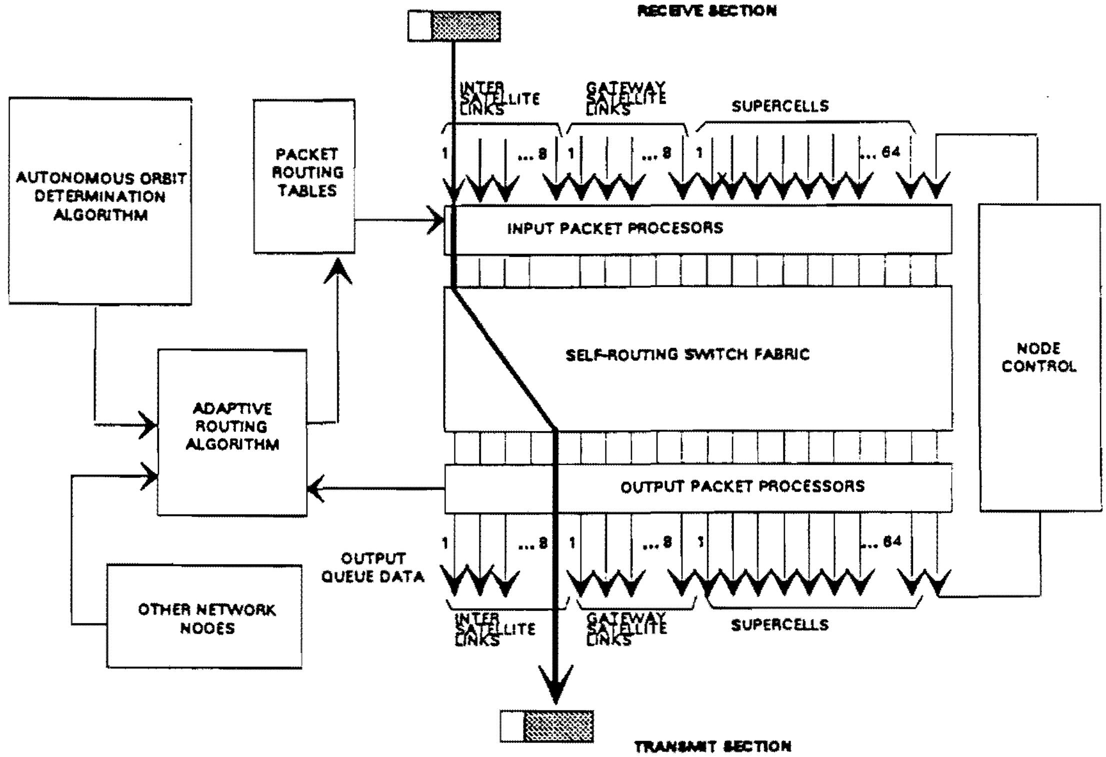

Figure 6 - Calling's fast packet switch node uses the destination address in the incoming packet's header and tables generated by the adaptive routing algorithm to select the output link. A self-routing switch fabric switches the packet to this link.

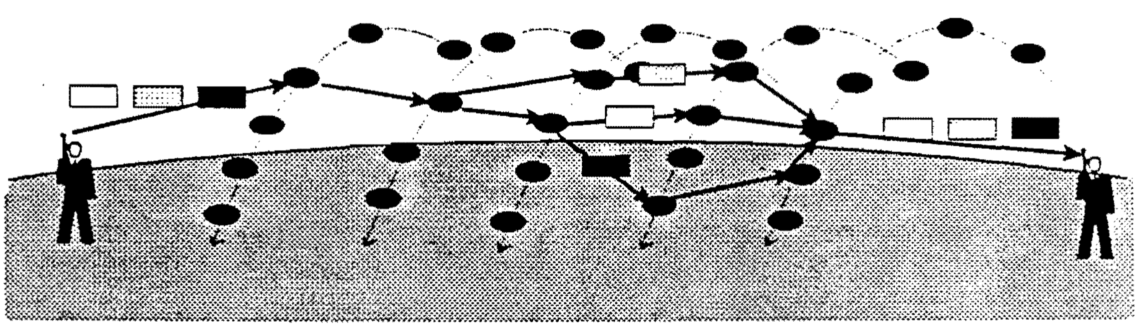

Figure 7 - Calling's distributed adaptive routing algorithm directs each packet along the "least delay" path to its destination. Packets of the same connection may follow different paths through the network. The algorithm communicates with other nodes to "learn" the network status and adapt to changes.

decisions are made continuously within each node, using a proprietary distributed adaptive routing algorithm. This algorithm uses information broadcast throughout the network by each satellite to "learn" the current network status in order to select the least delay path to a packet's destination. The algorithm also controls the connection and disconnection of network links.

The network uses a "connectionless" protocol: packets of the same connection may follow different paths through the network. Each node independently routes the packet along the path which currently offers the least expected delay to its destination (refer to Figure 7). The terminal or gateway interface at the destination buffers, and if necessary reorders, the received packets to eliminate the effect of timing variations. Extensive and detailed simulation of the network and routing algorithm has verified that for a long path the overall end-to-end delay is often less than that of a terrestrial fiber optics system connecting the same points. In addition, the deviation from the average packet delay for a connection is extremely low--typically a few milliseconds.

The Terminals

The system will support a wide variety of channel bandwidth and terminals that fall into two general categories: fixed and mobile.

Fixed Terminals

Fixed terminals can take any form, since there are no stringent constraints on power or antenna size. One possible configuration is shown in Figure 8. Fixed terminals operate at the basic channel rate -- 16 Kbps "payload" with an additional 2 Kbps channel for signaling and control -- and at multiples of the basic rate up to 2 Mbps. The basic rate supports low-delay "network quality" speech coding that is generally indistinguishable from today's 64 Kbps digital landline circuits. It also supports 4.8 Kbps voice-band modems, 16 Kbps digital data, and high-speed

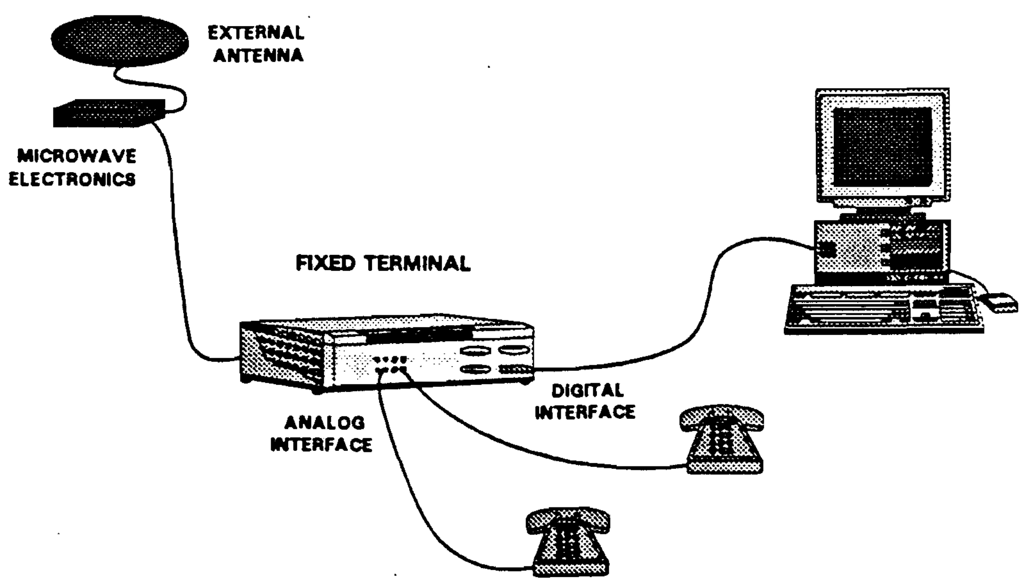

Figure 8 - A fixed terminal configuration at the basic rate supports low delay "network quality" speech coding, voice-band modems, digital data and high speed facsimile. Higher rates support multiple individual channels and combined high-rate channels.

facsimile. The higher channel rates support multiple individual channels and combined high-rate channels, which offer the full range of switched N x 64 and multi-rate ISDN services.

Fixed terminals use a proprietary antenna approximately ten inches in diameter, normally mounted in a fixed position with an unobstructed path above 40°. We expect that most fixed terminals will be units with connections for standard telephones, ISDN sets, private branch exchanges, and/or data equipment. A group terminal option (see Figure 4) provides shared access to a small village or community of subscribers using inexpensive wireless phones.

Mobile Terminals

Mobile terminals are small and lightweight, similar to today's vehicle-mounted cellular terminals. They operate at low power levels and use a low-profile 7.5 cm diameter antenna. The mobile terminal provides a single basic-rate channel (16 Kbps payload plus 2 Kbps signaling and control) which supports network-quality speech, 4.8 Kbps voice-band modems, 16 Kbps digital-data, and high-speed facsimile. To compensate for its smaller antenna size, a mobile terminal requires a higher energy per bit than a fixed terminal.

Gateways

Gateway interfaces are the network access nodes for inbound and outbound traffic to the destination region, and for connections to the system's network administration and control systems. Traffic sources include public or private gateway switches and full-term point-to-point transmission facilities at T-1 and higher rates.

The gateway interface performs the conversion between the network's internal network transmission and signaling formats and the international standards of the connecting systems. The gateway switch interface is based on ISDN standards for compatibility with current digital switches. In this way telephone companies and service providers can use equipment from suppliers with whom they have established relationships, and equipment with which their maintenance craftspeople are familiar.

Network Operational and Control Centers owned and operated by Calling include subscriber and network databases, feature processors, network management, and billing systems. Service providers have remote access to some of these systems for monitoring, testing, and administering terminals within their region.

For reliability and to deal with rain attenuation at the gateways' uplink and downlink frequencies, the gateway interface uses two or more sets of radio and antenna assemblies separated by thirty to fifty kilometers (30 - 50 km) connected by standard commercial fiber-optic or microwave links.

Operations Control Centers

Gateway interfaces provide the interconnection points for the network's Constellation Operations and Control Centers ("COCC"), Network Operations Control Centers ("NOCC") and Service Provider Administration Centers ("SPAC"). COCCs coordinate the satellites' initial deployment, replenishment of spares, fault diagnosis, repair, and deorbiting. The NOCCs include a variety of distributed network administration and control functions including network databases, feature processors, network management and billing systems. SPACs give local service providers control over the administration, billing, and testing of terminals in their region.

Communication Links

As discussed above, the network is based on fast packet technology, and all communications links transport voice and data as fixed-length packets. All links are also encrypted to guard against eavesdropping. Terminals and gateway interfaces perform the encryption/decryption and conversion to and from the packet format. The network has three categories of communications links:

Intersatellite links (ISLs) interconnect a satellite switch node with up to eight other nodes in the same or adjacent orbital planes. Each ISL can use from one to eight 138 Mbps channels, depending on the capacity required at any time.

Gateway-satellite links (GSLs) connect the satellite network through a gateway interface to the public network and to ground-based control, support, and database systems. Each satellite can support eight GSLs, each with a capacity of up to eight 138 Mbps channels.

Terminal-satellite links (TSLs) are direct connections between terminals and the satellite-based network. There are two types of TSLs: Fixed Terminal Satellite Links (FTSLs), which support larger, higher gain terminals (normally fixed-site), and Mobile Terminal-Satellite Links (MTSLs), which support small, moderate gain terminals (normally mobile). The basic channel rate is 16 Kbps for the payload plus 2 Kbps for signaling and control. Fixed terminals support multiples of the basic rate up to a 2 Mbps payload rate.

Frequency Selection

Spectrum requirements are determined by quality, capacity, and channel density objectives. For example, FTSL uplinks and downlinks each require approximately 200 MHz to support 1440 simultaneous full-duplex channels within a 2841 km^2 cell. Table 1 provides details of the bandwidth requirements and modulation parameters for each link.

Table 1 - Bandwidth Requirements and Modulation Parameters

Link Type	Modulation Format	Spectrum Requirement (MHz)
UPLINK		
Fixed Terminals (FTSL)	Rate 2/3 8-PSK TCM	198
Mobile Terminal (MTSL)	Rate 2/3 8-PSK TCM	12.4
Gateway (GSL)	Rate 3/4 16-PSK TCM	544
DOWNLINKS		
Fixed Terminals (FTSL)	Rate 2/3 8-PSK TCM	198
Mobile Terminals (MTSL)	Rate 2/3 8-PSK TCM	12.4
Gateway (GSL)	Rate 3/4 16-PSK TCM	544
INTERSATELLITE (60 GHz)	Rate 3/4 16-PSK TCM	1088

The lowest frequency band with enough bandwidth available to support Calling's TSL and GSL requirements is at 30/20 GHz (Ka-band), which has international allocations for fixed and mobile satellite service. To deal with terrain blocking and high rain attenuation at these frequencies, the system uses a combination of a high mask angle, high-gain antennas, transmitter power control, and (for GSLs) space diversity. The 40° mask angle avoids most terrain interference, minimizes interference with terrestrial systems, limits the user-to-satellite distance to 1022 km, and limits the path length subject to rain attenuation to a few thousand meters (see Figure 9). These techniques result in high link availability in most climate areas. Figure 10 provides a plot of expected link availability for various climatic regions.

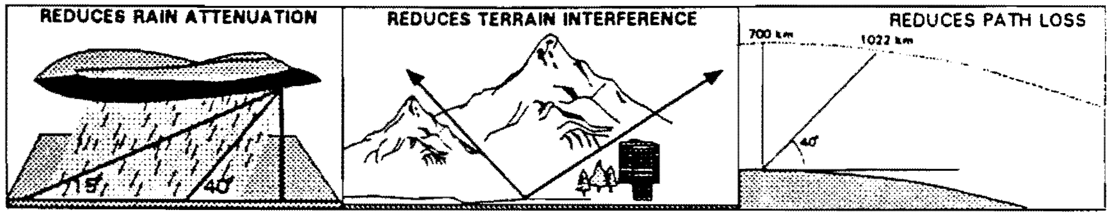

Figure 9 - A 40° mask angle limits the portion of the path exposed to rain to a few thousand meters, eliminates most terrain blocking, and limits the overall terminal-to-satellite path length.

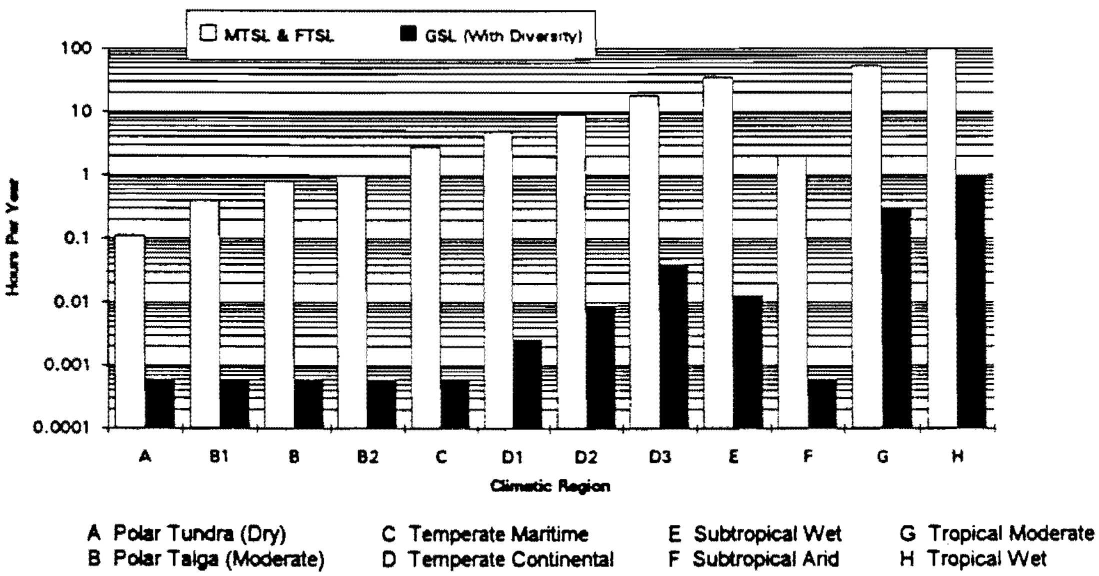

Figure 10 - 30/20 GHz links are subject to high rain attenuation and terrain blocking. Calling's variety of compensation techniques result in very low link outages in most climatic regions. Space diversity on gateway links eliminates most rain outages.

The combination of 40° mask angle and 700 km altitude also defines the satellite's footprint radius (approximately 706 km), which in turn determines the minimum number of satellites in the constellation (see Figure 11).

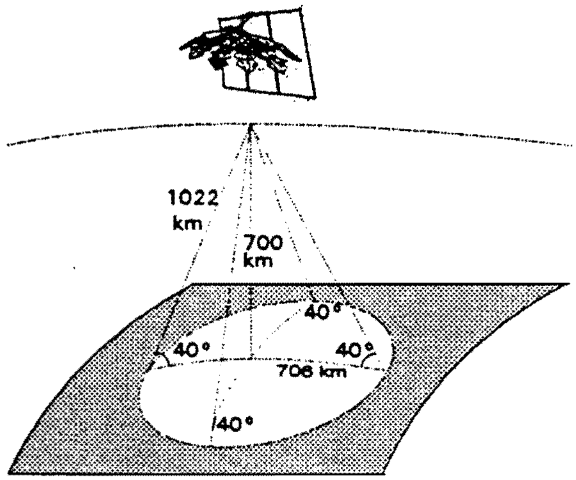

Figure 11 - The combination of a 700 km orbit and a 40° mask angle defines the satellite footprint. The small footprint results in a large number of satellites for global coverage.

Earth-Fixed-Cells

The satellite footprint is composed of contiguous cells, analogous to a terrestrial cellular system. Each cell supports a number of communications channels. Terminals within each cell share these channels using a combination of multiple-access methods. Cells are arranged in a pattern that allows frequencies and time slots to be reused many times within a footprint without interference between adjacent cells. High gain satellite antennas produce small cells (53.3 km square) which efficiently use spectrum, provide high channel density, and requires low transmitter power.

The footprint of a LEO satellite sweeps over the Earth's surface at approximately 25,000 km/hr. If Calling's pattern of small cells moved with the satellite footprint, a terminal would remain in one cell for only a few seconds before a channel reassignment or "hand-off" to the next cell would be required. As is the case with terrestrial cellular systems, frequent hand-offs result in inefficient channel utilization, high processing costs, and lower system capacity. In this constellation, the hand-off problem is minimized with proprietary Earth-fixed-cell technology.

The network maps the Earth's surface into a fixed grid of approximately 20,000 "supercells", each consisting of 9 cells (see Figure 12). Each supercell is a square 160 km on a side, and supercells are arranged in bands parallel to the Equator. There are approximately 250 supercells in the band at the Equator, and the number per band decreases in proportion to the cosine of the latitude. Because the number of supercells per band is not constant, the "north-south" supercell borders in adjacent bands are not aligned.

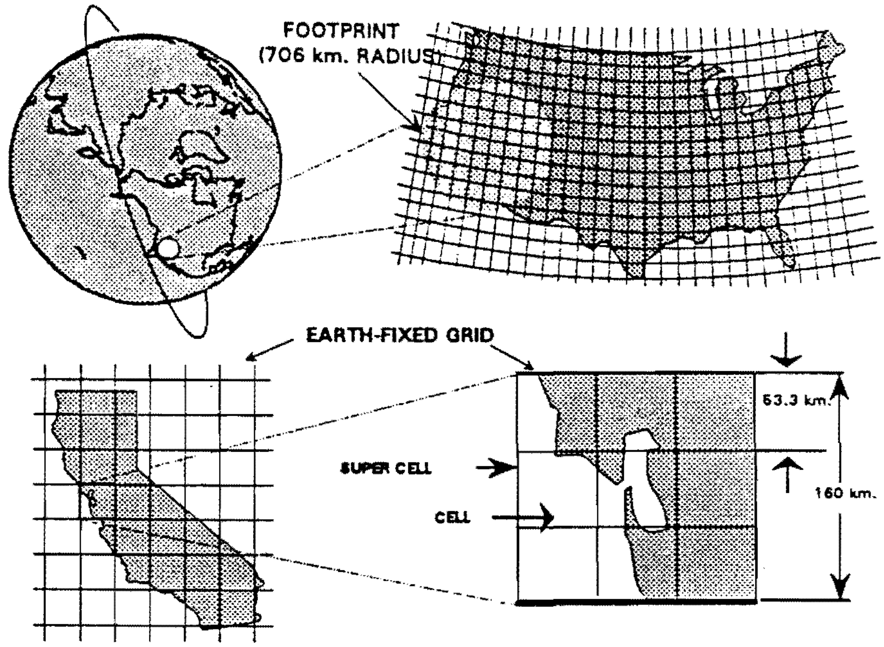

Figure 12 - Calling's small cell (53.3 x 53.3 km) permits high frequency reuse, low transmitter power and high system capacity. This architecture minimizes the "hand-off" problems associated with LEO networks by arranging the cells in an Earth-fixed grid.

There is a fixed relation between supercell coordinates and latitude-longitude coordinates. The time of day defines which orbital plane has primary coverage responsibility for each supercell. Each satellite's orbital position is then used to determine its assigned geographical coverage area. This fixed relationship makes it possible to determine at any time, based on a terminal's location, which satellite has primary coverage responsibility for that terminal.

The satellite footprint encompasses a maximum of 64 supercells, or 576 cells. The actual number of cells for which a satellite is responsible is a variable that depends on satellite location and spacing between satellites. As a satellite passes over, it steers its antenna beams to the fixed cell locations within its footprint. This beam steering compensates for the satellite's motion as well as the Earth's rotation. (An analogy is the tread of a bulldozer that remains in contact with the same point while the bulldozer passes over). This concept is shown in Figure 13. Frequencies and time slots are associated with each cell and are managed by the current "serving" satellite. As long as a terminal remains within the cell, it maintains the same channel assignment for the duration of a call, regardless of how many satellites and beams are involved. Channel reassignments become the exception rather than the normal case, thus eliminating much frequency coordination and hand-off overhead.

Small fixed cells also allow the system to contour service areas to national boundaries, an impossible feat with large cells or cells that move with the satellite. A cell database contained in each satellite defines the type of service allowed within each cell, and can be used to turn off service on a country-by-country basis, or to avoid interference with radio astronomy or other specific sites.

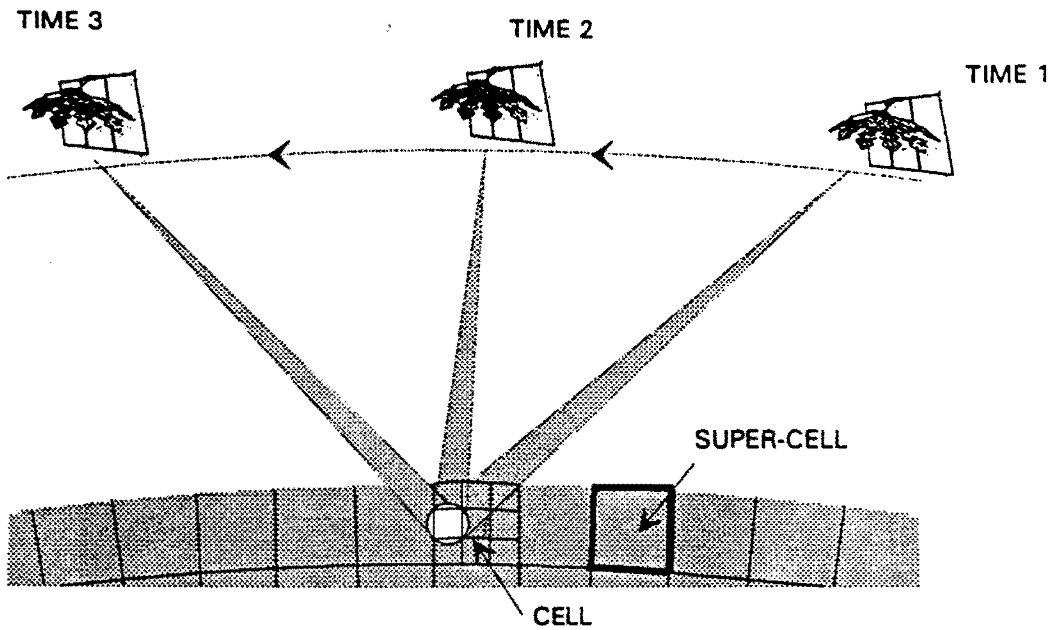

Figure 13 - Calling satellites use electronically-steered phased-array antennas to direct beams to the Earth-fixed cells.

Earth-fixed-cell technology relies on accurate knowledge of the satellites' position and attitude, timing information, and precision beam steering. The enabling technologies for Earth-fixed cells include: autonomous orbit position determination system, active phased array antennas, multiple access method, fast packet switching, and adaptive routing.

Multiple Access Method

A multiple access method is the means by which multiple terminals share a common set of communications resources. The Calling^{SM} system uses a combination of multiple access methods to insure efficient use of these resources (refer to Figure 14). Each cell within a supercell is assigned to one of nine equal time slots during which all communication takes place between the satellite and the terminals in that cell. The full frequency allocation is available within each cell time slot. The cells are scanned in a regular cycle by the satellite's transmit and receive beams, resulting in time division multiple access ("TDMA") among the cells in a supercell. Since propagation delay varies with path length, satellite transmissions are timed to insure that cell N (N=1, 2, 3,...9) of all supercells receive transmissions at the same time. Terminal transmissions to a satellite are also timed to insure that transmissions from cell N of all supercells arrive at the same time. Physical separation (space division multiple access, or "SDMA") eliminates interference between cells scanned at the same time in adjacent supercells. Guard intervals eliminate overlap between signals received from time-consecutive cells.

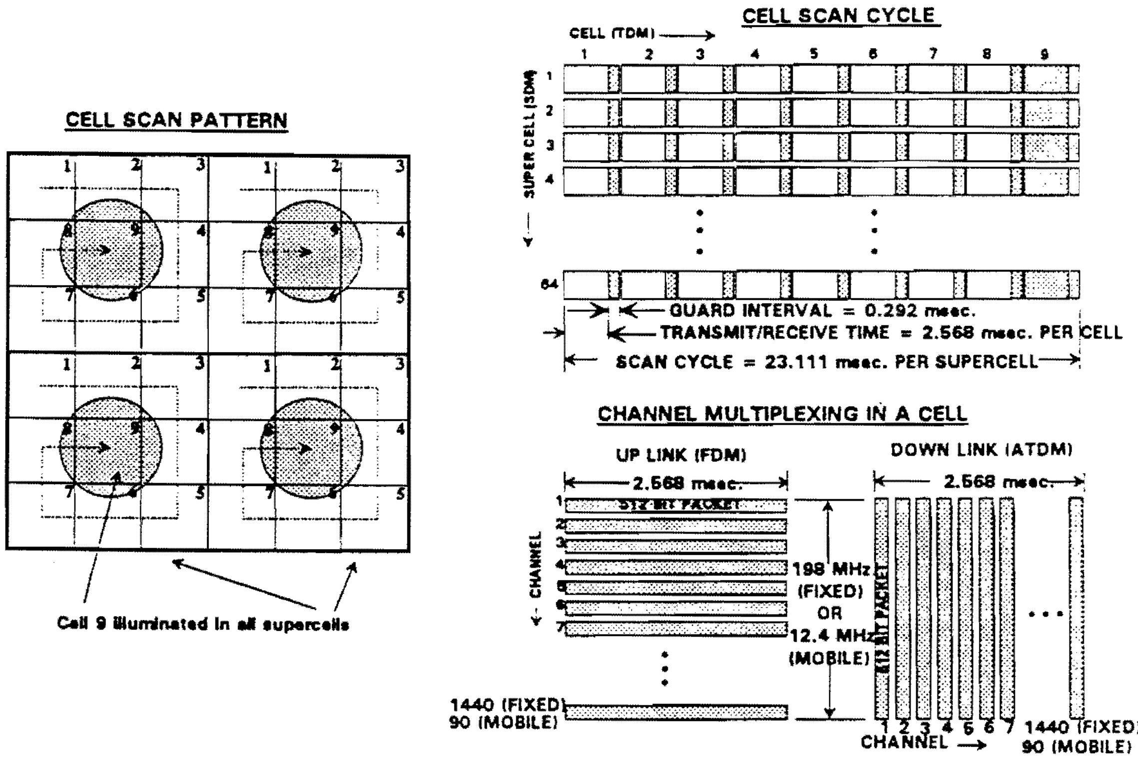

Figure 14 - Calling's multiple access method uses space division between supercells, time division among the 9 cells in a supercell, and a combination of frequency division and asynchronous time division multiplexing for channels within a cell. All communication uses fixed-length packets.

Within each cell time slot, terminals use Frequency Division Multiple Access ("FDMA") on the uplink and Asynchronous Time Division Multiple Access ("ATDMA") on the downlink. On the FDMA uplink, each active terminal is assigned one or more frequency slots for the call duration, and it can send one packet per slot each scan period (23.111 msec). The number of slots assigned to a terminal determines its maximum available transmission rate. One slot corresponds to a fixed terminal 16 Kbps basic channel with its 2 Kbps signaling and control channel. A 64 Kbps channel with a 8 Kbps control channel requires four frequency slots. A total of 1440 slots per cell are available for fixed terminals, and 90 are available for mobile terminals.

The ATDMA downlink does not use a fixed assignment of time slots to terminals. During each cell scan interval, the satellite transmits a series of packets addressed to terminals within that cell. Packets are delimited by a unique bit pattern, and a terminal selects those addressed to it by examining each packet's address field. To compensate for a mobile terminal's lower-gain antenna, the bit duration of packets sent to a mobile terminal is 16 times that for a fixed terminal. The downlink to a cell has 1440 time slots, which support 1440 fixed terminal packets per scan period, 90 mobile terminal packets or a combination of the two. The satellite transmits only as long as it takes to send the packets buffered for the cell. ATDMA takes advantage of the bursty nature of most communications. Since packets are not transmitted during "silent" intervals, satellite power is conserved. In addition, it minimizes packet delay because a terminal is not limited to a single packet per time slot per scan.

The combination of Earth-fixed-cells and multiple access methods results in high spectral efficiency. The same channel resources are reused in each supercell over 350 times in the continental U.S. and 20,000 times across the Earth's surface.

System Control

There are many categories and levels of system control, including call control, network control (overload, reconfiguration, etc.), billing, administration, and satellite constellation control. Although each is critical to the system's operation, we will not attempt to cover them all in this paper.

The network control hierarchy is distributed among the network elements and modeled using the Intelligent Network prototype. Terminals and other network elements use a packet-based protocol for signaling and control messages (similar to the ISDN D-channel and CCITT No. 7 signaling). The network handles these packets as normal traffic.

The highest levels of network control reside in distributed, ground-based systems that are connected via gateway interfaces to the satellite network. Database systems provide terminal/user feature and service profiles, authentication and encryption keys, mobile user location, call routing data, and other administrative data. Administrative systems, from "network-level" to local "in-country" systems provide secure access to various levels of the database and billing data systems. In-country systems provide the local Service Provider with control of terminals in its area, while network and constellation control are restricted to the network-level administrative systems.

High-level call control functions reside in gateway switches and feature processors. The feature processor is a pure control element (no switching), which controls terminal-to-terminal calls as well as the initial set-up of calls involving a gateway. Only control and signaling packets are passed to the feature processor; the "speech path" is a direct network connection between the terminals. The gateway switch controls the calls connected through it.

The satellite-based switch node includes some mid-level call control functions in addition to its packet routing function. It manages the assignment, supervision, and release of all channels in its footprint, and the "hand-off" of channels to other satellites. It also monitors channel signal quality and initiates link power control when required.

Terminals have control of some low-level call control functions similar to those controlled by a cellular or ISDN functional signaling terminal. This includes user authentication, location registration, link encryption, monitoring and reporting of channel quality, channel assignments and hand-offs, and D-channel signaling.

The Satellites

The Calling℠ satellite bus is a lightweight, high-performance, high-power system based on modern components available from existing aerospace suppliers. Figure 15 is an illustration of the satellite's multiple launch configuration and Figure 16 is an artist's rendering of the satellite's fully deployed configuration in orbit over the Earth.

All satellites are identical, with design features tailored specifically for a large constellation, including high-volume production by multiple producers, stacked launch by multiple launchers, and autonomous on-orbit constellation control. Robust design margins and on-orbit spares result in a highly reliable constellation with an extremely low mean time to repair.

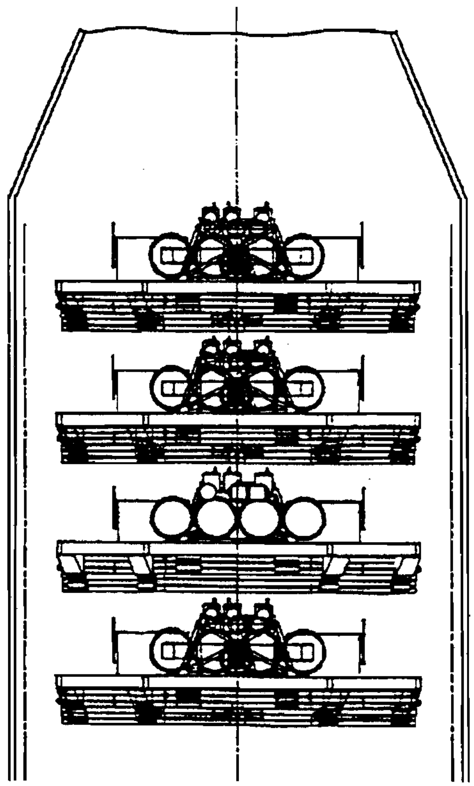

Figure 15 - Satellite multiple launch configuration.

The satellite is designed for a service life of ten years, with propellant for 12 years. The satellite's position is disturbed both by gravitational variations arising from the Earth's irregular shape and by atmospheric drag, which is greatest at the solar maximum when sunspot activity is at the peak of its eleven year cycle. Each satellite carries enough propellant to hold its position within its plane for the satellite's entire lifetime, to reposition itself when required, to overcome atmospheric drag for its design lifetime (including one solar maximum), and for a final deorbit maneuver. Several measures have been taken to avoid creating space debris: launch vehicles and satellites that have reached the end of their useful life are deorbited and disintegrate harmlessly on re-entry. The constellation orbits have been selected to avoid much of the existing debris, and are slightly staggered so that the probability of collision between satellites in the constellation is infinitesimally small. To further reduce this probability, the satellites use active collision avoidance when the separation between two satellites is projected to be less than acceptable limits.

The satellites' structures use light-weight, high-strength materials and techniques which have become available only recently, partly as a result of U.S. Government-sponsored technology development and demonstration programs at JPL and LLNL.

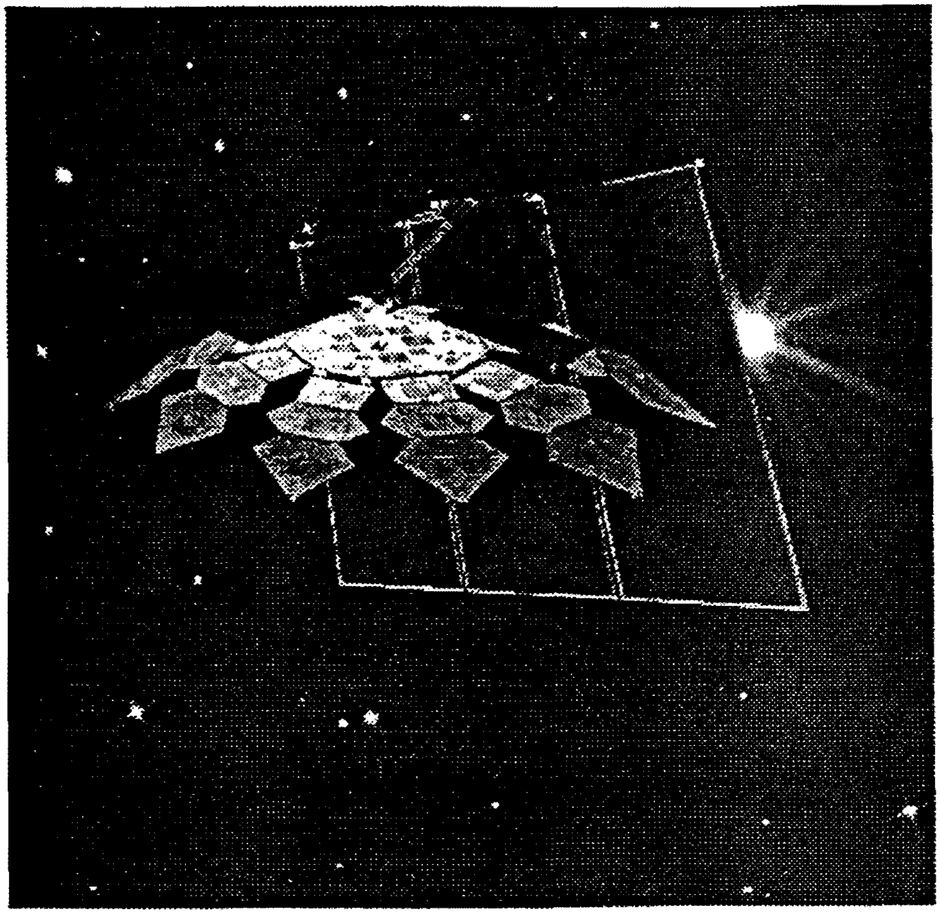

Figure 16 - Artist rendering of Calling satellite in space.

The satellites' electrical energy requirements are generated from extremely thin and light solar arrays made of amorphous silicon. The solar array is also used to shade the satellite electronics from the sun. This allows the electronics package to operate at very low temperatures, thereby significantly increasing electronic efficiency and greatly enhancing the life and reliability of the electronics and antennas.

Although all satellites are identical, their solar panels are adjustable and are maintained at the optimal angle for energy collection and solar shading in the satellite's intended orbit. Because the orbits are sun-synchronous, the satellite's orientation with respect to the sun is constant. The power system is designed to handle wide variations in the communications payload requirements including peak loads of over 100 times the average load.

Individual satellites operate autonomously, and the constellation is managed as a "herd" rather than as individual units. The on-board orbit-determination and navigation systems continuously and autonomously track and maintain each satellite's position within the constellation. Each satellite monitors its status, reports exception conditions immediately, and periodically sends reports on its vital functions to the COCC. These reports, as well as other control information for the spacecraft and its systems, are handled by the network as normal packet traffic. Figure 17 is a satellite block diagram.

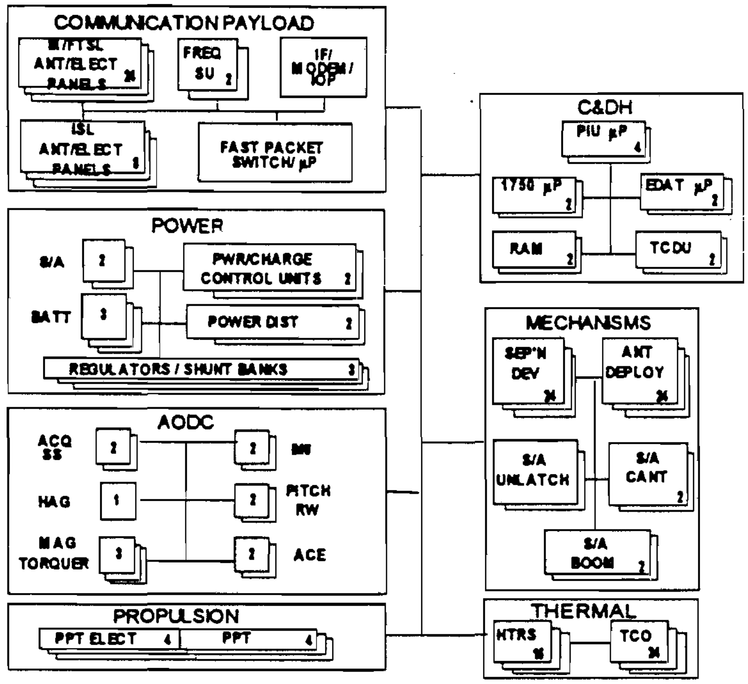

Figure 17 - A block diagram of the satellite subsystems.

Communications Payload

Antennas and radio subsystems comprise the largest and most complex part of the satellite. The satellite uses a multi-panel antenna system with multiple active phased-array antenna facets on each panel. Each antenna facet is dedicated to a transmit or receive function for the TSL or GSL subsystems. Antenna panels integrate advanced composites and a thermal control system into an ultra-light-weight rigid structure.

Several innovations included in the thermal control system contribute to creating an isothermal environment at a low temperature optimum for highly reliable operation of the key electronic components in the communications payload. These include using the solar array as a large sun shade to continuously shield the satellite from solar radiation, passive thermal radiators oriented towards deep space to sustain a cold channel for active GaAs microwave/superconducting millimeter wave subsystems, and phase-change thermal capacitors to absorb thermal transients arising from major changes in the communications payload duty cycle. The active components for the microwave arrays are distributed across the array faces. Solar radiators and thermal capacitors are located on the backs of the array panels in close proximity to active heat loads to minimize thermal transport.

The antenna panels are deployed at angles to the Earth's surface which reduce the beam steering requirements to a few degrees. The antenna arrays on the inclined panels are elliptical in shape and produce elliptical patterns which compensate for the distortion from circular encountered at antenna grazing angles less than 90° with the Earth's surface. All of the satellite antennas are advanced active-element phased-array systems using GaAs MMIC amplifiers and beam steering circuits. These proprietary components and techniques provide dynamic control of gain, beam shape, and power level. This feature allows the satellite to maintain a scanning spot beam of constant shape and flux density on the Earth's surface as the satellite passes overhead.

Additionally, the individual beams can scan and operate in unison with a separation of only two cells. As noted above, the precision beam steering supports the Earth-fixed-cell and multiple access technologies.

Figure 18 shows the antenna panels in a deployed mode from the Earth facing view. The antenna gains and element count are noted in tabular form.

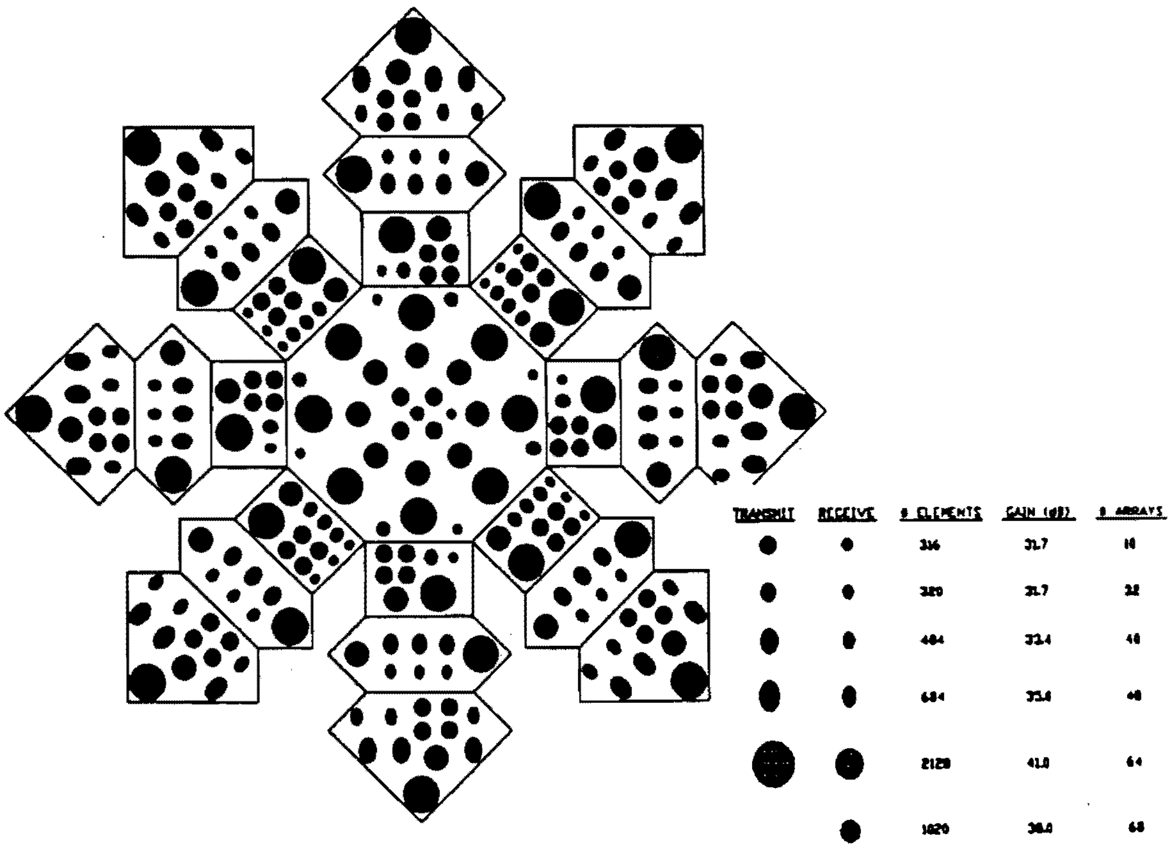

Figure 18 - View of Antenna Panels as seen from Earth.

Satellite Production and Launch

A significant portion of the system cost will be the production, launch, and replenishment of the satellite constellation. It would be impossible to meet system cost objectives using today's satellite production and individual launch methods; satellites are therefore designed to take advantage of the cost benefits of high-volume production and multiple launch. All satellites are identical, there are large numbers of identical components and subsystems within each satellite, and the satellite and Earth terminal antennas use similar technology and components. The feasibility of producing and launching a large constellation of similar satellites at low cost has been shown by recently declassified work done in connection with the Strategic Defense Initiative program and by extensive manufacturing engineering and analysis performed by Calling engineers.

A unique deployment technique satisfies the seemingly conflicting goals of high packing density within the rocket shroud and a large surface area for antenna and solar arrays. The satellites are designed to be stacked, and one or more stacks can be launched in one vehicle. These stacks are compatible with over 20 launchers currently in operation, and with over

10 additional launchers in funded development. This diverse set of international launchers avoids interruptions caused by launch failures, delays, or production problems. The policy of launch independence insures a stable supply of launch vehicles, and the cost benefits of volume launches and competitive bidding.

Conclusion

There is a very large demand for basic and enhanced telephone service in developing nations and in remote parts of industrialized nations which cannot be met by conventional wireline and cellular systems. This demand constitutes the world's largest unserved market.

Advances in active phased-array antennas, fast-packet switching technology, adaptive routing, and light spacecraft technology have converged to make it possible to address this market by designing and building a global telephone network based on a large low-Earth-orbit constellation of identical satellites. A telephone utility using such a network can provide modern basic and enhanced telephone services which are indistinguishable from services offered by telephone utilities in the urban centers of fully-industrialized nations. If the network is sufficiently large, the capital and operating costs per subscriber are low enough to provide these services to all subscribers, regardless of location, at prices comparable to the same services in urban areas of industrialized nations, while generating operating profits great enough to attract the capital needed for its construction.

Global demand for such service is great enough to support at least three networks of the size described herein. The volume of advanced components, such as gallium arsenide integrated circuits, and services, such as launch services, required to construct these networks is sufficient to propel certain industries to market leadership positions in the early 21st Century.