THE TELEDESIC SATELLITE SYSTEM: OVERVIEW AND DESIGN TRADES

Mark A. Sturza

Teledesic Corporation
2300 Carillon Point
Kirkland, Washington 98033

(818) 907-1302 fax (818) 907-1357

ABSTRACT

There is a significant worldwide demand for broadband communications capacity. Teledesic plans to meet this demand using a constellation of 924 low-Earth orbit (LEO) satellites operating in Ka-band (30/20 GHz). The Teledesic network will provide "fiber-like" service quality, including low transmission delay, high data rates, and low bit error rates, to almost 100% of the world's population starting in 2001.

I. INTRODUCTION

Teledesic was founded in June 1990. Its principle shareholders are Craig McCaw, founder of McCaw Cellular Communications, the world's largest wireless communications company, and Bill Gates, founder of Microsoft, the world's largest computer software company.

"Teledesic seeks to organize a broad, cooperative effort to bring affordable access to advanced information services to rural and remote parts of the world that would not be economic to serve thorough traditional wireline means." [1]

The economics of wireline access are such that rural and remote areas may never get wireline access to broadband networks. As advanced information services become increasingly essential to economic development, education, health care, and public services, the gap between urban and rural areas will widen.

The solution is a satellite-based broadband network whose service cost in rural, remote areas is comparable to that of wireline networks in advanced urban areas. Such a network can provide a variety of services including multimedia conferencing, video conferencing, videotelephony, distance learning, and voice. It will allow people to live and work in areas based on family, community, and quality of life.

The global scope of the Teledesic network embraces a wide range of service needs. Local partners will determine products and prices and provide sales and service in host countries. Teledesic will not market service directly to users. Rather, it will provide an open network for service provides in host countries. Teledesic will not manufacture satellites or terminals. Its goal is to provide the highest quality communications services at the lowest cost.

Wireline broadband (fiber) networks in advanced urban areas will drive demand for global access to broadband applications. Advanced information services are increasingly essential to education, health care, government, and economic development. Continued decrease in the price/performance ratio of microprocessors and computer memory will increase the demand for transmission of information. Video and high-resolution graphics require high data rates.

Most of the worlds population will never get access to advanced digital applications through terrestrial means. The majority of the world does not even have access to basic voice service. Most areas that are not now wired never will be wired. Increasingly, wireless cellular will be the access technology of first choice in rural and remote areas. Cellular is limited to narrowband applications and most existing wireline networks will not support advanced digital applications.

Teledesic will provide seamless compatibility with terrestrial broadband (fiber) networks. Future broadband applications and data protocols will not be designed to accommodate the delays of geostationary satellites. Users will want one network for all applications.

The Teledesic network will be complementary to terrestrial wireless networks. It will be a broadband overlay for narrowband cellular systems, backbone infrastructure for cell site interconnect, and backhaul for long distance and international connections. The aggregation of voice channels requires low-delay broadband capability.

Teledesic will provide a global wide-area network, a seamless, advanced, digital broadband network. It will fill in missing and problematic links everywhere, facilitating economic and social development in rural and remote areas.

Teledesic will supply instant infrastructure, providing rapid availability of advanced “fiber-like” services to almost 100% of the world’s population. System capacity is not rigidly dedicated to particular end users or locations.

The cost of the Teledesic network will be $9 billion. This is a fraction of what will be spent on installing fiber in just the United States. It is less then the $15 billion that will be spent just to lay fiber for interactive TV in California [2]. Teledesic plans to initiate service in 2001.

II. DESIGN CONSIDERATIONS

Some of the key design drivers of the Teledesic Network are:

- High data rate (broadband) service
- Continuous global coverage
- Fiber-like delay
- Bit error rates less than 10^{-10}
- Mitigate effects of rain attenuation and blockage
- Rapid network repair
- Geodesic (mesh) network interconnect

The broadband service requirement drives Ka-band operation. No lower frequency bands are available to support a broadband satellite-based network. The Teledesic satellite uplinks operate in the 30 GHz band and the downlinks operate in the 20 GHz band.

Fiber-like delay requires a low-Earth orbit (LEO) constellation. Geostationary (GEO) satellites introduce a minimum 500 msec round-trip transmission delay. Medium-Earth orbit (MEO) constellations introduce a minimum 133 msec round-trip transmission delay. The round trip transmission delay for a LEO constellation is typically less than 20 msec.

The practical altitude range for LEO constellations is 500 km to 1400 km. Below 500 km, atmospheric drag significantly shortens the satellites lifetime in orbit. Above 1400 km, the Van Allen radiation belt makes radiation hardening of the satellite prohibitively expensive.

Continuous global coverage requires a constellation with a near-polar inclination angle. Rapid network repair requires that the satellites in each orbital plane are decoupled from those in other orbital planes. This allows for the inclusion of active spare satellites in each plane. When a satellite fails, the remaining satellites in the plane spread out to close the resulting gap.

Ka-band communications links are subject to severe rain fading (Fig. 1). This effect is reduced as the Earth terminal to satellite elevation angle is increased. The Teledesic constellation is designed to operate with an Earth terminal elevation mask angle of 40° to provide rain availability of 99.9% over most of the United States.

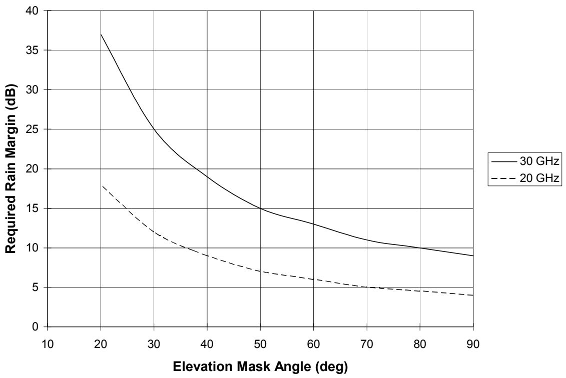

Fig. 1. Required Rain Margin (Region D2, 99.9% Availability)

The Teledesic constellation [3] is organized into 21 circular orbit planes that are staggered in altitude between 695 and 705 km. Each plane contains a minimum of 40 operational satellites plus up to four on-orbit spares spaced evenly around the orbit. The orbit planes are at a sun-synchronous inclination (approximately 98.16°), which keeps them at a constant angle relative to the sun. The ascending nodes of adjacent orbit planes are spaced at 9.5° around the Equator (Fig. 2).

Satellites in adjacent planes travel in the same direction except at the constellation “seams”, where ascending and descending portions of the orbits overlap. The orbital parameters are shown in Table 1.

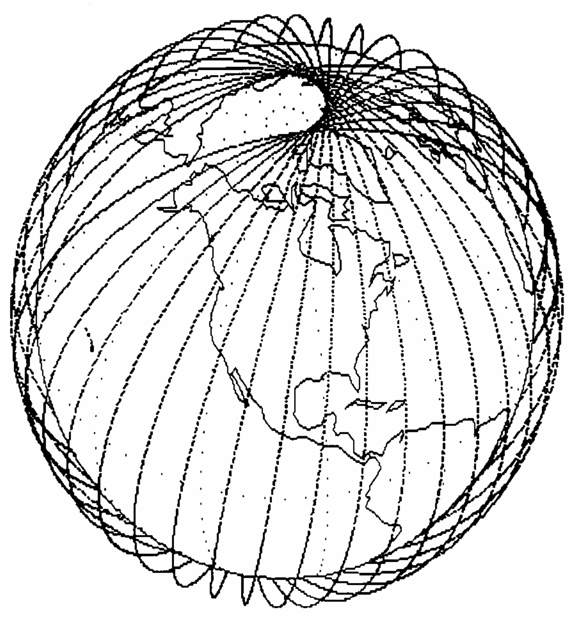

Fig. 2. Teledesic Orbits

Table 1. Constellation Parameters

Total Number of Satellites	840
Number of Planes	21
Number of Satellites Per Plane	40
Satellite Altitude	695 to 705 km
Eccentricity	0.00118
Inclination Angle	98.142° to 98.182°
Inter-Plane Spacing	9.5°
Intra-Plane Satellite Spacing	9°
Inter-Plane Satellite Phasing	Random
Earth Terminal Elevation Mask Angle	40°

III. SYSTEM DESIGN

The system design is described in Teledesic's FCC application [2]. The network (Fig. 3) uses fast packet switching technology based on Asynchronous Transfer Mode (ATM) developments. Each satellite in the constellation is a node in the fast packet switch network, and has intersatellite communication links with eight neighboring satellites. This interconnection arrangement forms a non-hierarchical geodesic network that is tolerant to faults and local congestion.

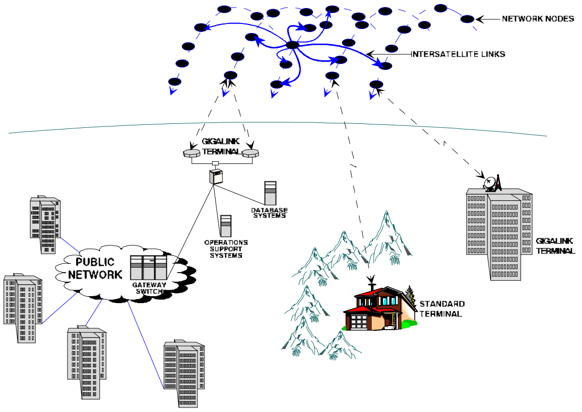

Fig. 3. The Teledesic Network

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 that carries the digitally-encoded video, voice, or data. Conversion to and from the packet format takes place in the terminals. Fast packet switching technology is ideally suited for the dynamic nature of a LEO network.

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 that currently offers the least expected delay to its destination, see Fig. 4. The required packets are buffered, and if necessary resequenced, at the destination terminal to eliminate the effect of timing variations. Teledesic has performed extensive and detailed simulation of the network and adaptive routing algorithm to verify that they meet Teledesic's network delay and delay variability requirements.

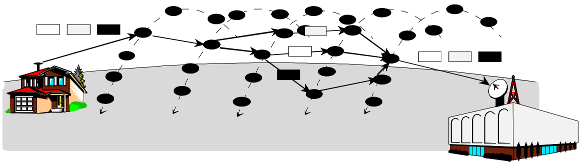

Fig. 4. Distributed Adaptive Routing Algorithm

A. Earth Fixed Cells

The Teledesic Network uses an Earth-fixed cell design to minimize hand-offs. The Earth's surface is mapped into a fixed grid of approximately 20,000 "supercells". Each supercell is a square 160 Km on each side and is divided into 9 cells as shown in Figure 5.

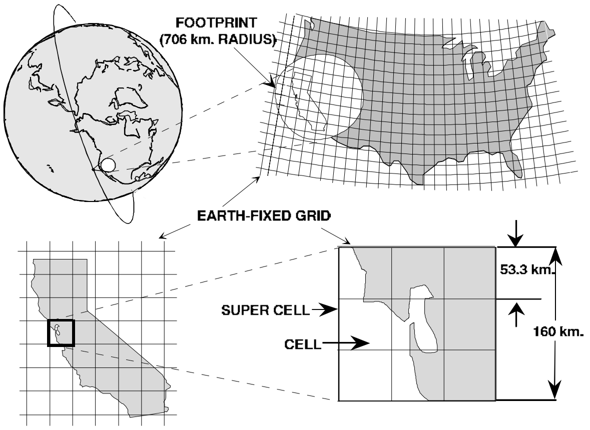

Fig. 5. Earth-Fixed Cells

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 with increasing latitude. Since the number of supercells per band is not constant, the "north-south" supercell borders in adjacent bands are not aligned.

A satellite footprint encompasses a maximum of 64 supercells, or 576 cells. The actual number of cells for which a satellite is responsible varies by satellite with its orbital position and its distance from adjacent satellites. In general, the satellite closest to the center of a supercell has coverage responsibility. 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. This concept is illustrated in Fig. 6.

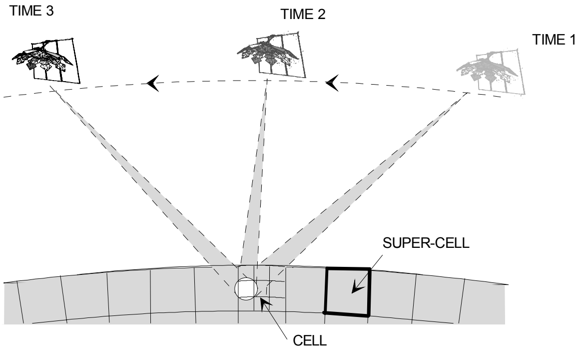

Fig. 6. Beam Steering

Channel resources (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 same Earth-fixed 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 of the frequency management and hand-off overhead.

A database contained in each satellite defines the type of service allowed within each Earth-fixed cell. Small fixed cells allow Teledesic to avoid interference to or from specific geographic areas and to contour service areas to national boundaries. This would be difficult to accomplish with large cells or cells that move with the satellite.

B. Multiple Access

Teledesic uses a combination of space, time, and frequency division multiple access to ensure efficient spectrum utilization (Fig. 7). At any instant of time each fixed supercell is served by one of 64 transmit and one of 64 receive beams on one of the Teledesic satellites. The scanning beam scans the 9 cells within the supercell with a 23.111 msec scan cycle. Each scanning beam supports 1440 16-Kbps channels. FDMA is used for the uplinks and asynchronous TDMA (ATDMA) for the downlinks.

Satellite transmissions are timed to ensure that all supercells receives transmissions at the same time. Terminal transmissions are also timed to ensure that transmissions from the same numbered cell in all supercells in its coverage area reach that satellite at the same time. Physical separation and a checkerboard pattern of left and right circular polarization eliminate interference between cells scanned at the same time in adjacent supercells. Guard time intervals eliminate overlap between signals received from time-consecutive cells.

On the uplink, each active terminal is assigned one or more frequency slots for the call's duration and 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 Standard Terminal's 16 Kbps basic channel with its associated 2 Kbps signaling and control channel. A total of 1440 slots per cell scan interval are available for Standard Terminals.

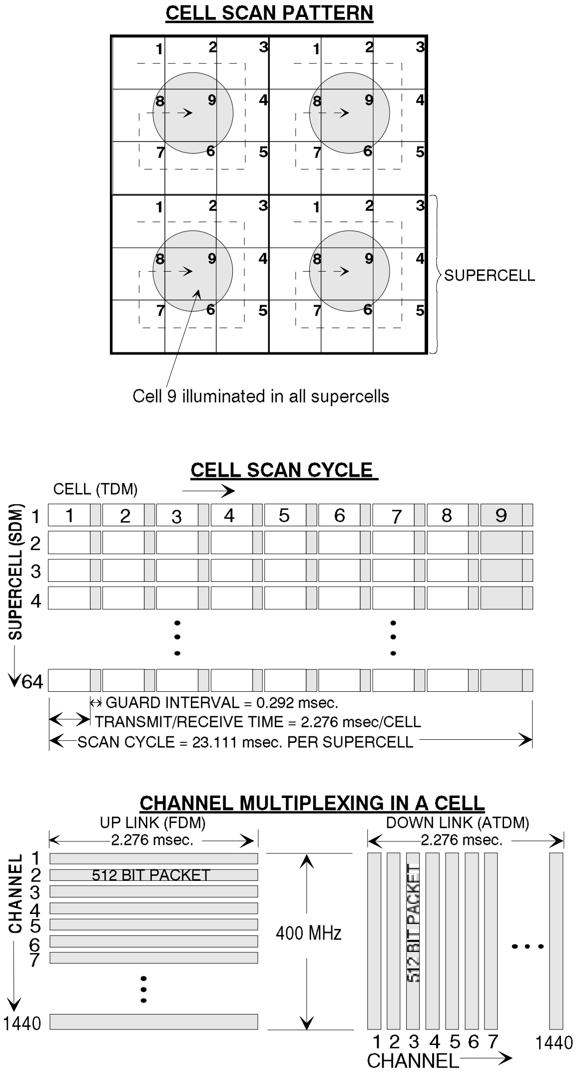

Fig. 7. Standard Terminal Multiple Access

The terminal downlink uses the packet's header rather than a fixed assignment of time slots to address terminals. During each cell's 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. A Standard Terminal operating at 16 Kbps requires one packet per scan interval. The downlink capacity is 1440 packets per cell per scan interval. The satellite transmits only as long as it takes to send the packets queued for a cell.

The combination of Earth-fixed cells and multiple access methods results in very efficient use of spectrum. The Teledesic system will reuse its spectrum over 350 times in the continental U.S. and 20,000 times across the Earth's surface.

IV. COMMUNICATIONS LINKS AND TERMINALS

All of the Teledesic communications links transport data, video, and voice as fixed-length 512 bit packets. The links are encrypted to guard against eavesdropping. Terminals perform the encryption/decryption and conversion to and from the packet format.

The uplinks use dynamic power control of the RF transmitters so that the minimum amount of power is used to carry out the desired communication. Minimum transmit power is used for clear sky conditions; transmit power is increased to compensate for rain.

The Teledesic Network supports a family of subscriber terminals providing on-demand data rates from 16 Kbps up to 2.048 Mbps (E1), and for special applications from 155.52 Mbps (OC-3) up to 1.24416 Gbps (OC-24). This allows a flexible, efficient match between system resources and subscriber requirements.

Standard Terminals include both fixed-site and transportable configurations that operate at multiples of the 16 Kbps basic channel payload rate up to 2.048 Mbps (the equivalent of 128 basic channels). These terminals use antennas with diameters from 16 cm to 1.8 m as determined by the terminal's maximum transmit channel rate, climatic region, and availability requirements. Their average transmit power varies from less than 0.01 W to 4.7 W depending on antenna diameter, transmit channel rate, and climatic conditions. All data rates, up to the full 2.048 Mbps, can be supported with an average transmit power of 0.3 W by suitable choice of antenna size.

Within its service area each satellite can support a combination of terminals with a total throughput equivalent to over 100,000 simultaneous basic channels.

The Network also supports a smaller number of fixed-site GigaLink Terminals that operate at the OC-3 rate (155.52 Mbps) and multiples of that rate up to OC-24 (1.24416 Gbps). Antennas for these terminals range in size from 28 cm to 1.6 m as determined by the terminal's maximum channel rate, climatic region and availability requirements. Transmit power varies from 1 W to 49 W depending on antenna diameter, data rate, and climatic conditions. Antenna site-diversity can be used to reduce the probability of rain outage in situations where this is a problem.

GigaLink Terminals provide gateway connections to public networks and to Teledesic support and data base systems, as well as to privately owned networks and high-rate terminals. Each satellite can support up to sixteen GigaLink terminals within its service area.

Intersatellite Links (ISLs) operate in the 60 GHz band. They interconnect each satellite with its eight neighbor satellites. Each ISL operates at the OC-3 rate, and multiples of that rate up to OC-24 depending upon the instantaneous capacity requirement.

V. SATELLITES

The Teledesic satellites are specifically designed to take advantage of the economies that result from high volume production and launch. All satellites are identical and use technologies and components that allow a high degree of automation for both production and test. To minimize launch cost and the deployment interval, the satellites are designed to be compatible with over twenty existing international launch systems, and to be stacked so that multiple satellites can be launched on a single vehicle. Individual satellites, the constellation as a whole is designed to operate with a high degree of autonomy.

The on-orbit configuration of the Teledesic satellite, Fig. 8, resembles a flower with eight "petals" and a large boom-mounted square solar array. The deployed satellite is 12 m in diameter and the solar array is 12 m on each side. Each petal consists of three large panels containing the phase-array antennas. The octagonal baseplate also supports eight pairs of intersatellite link antennas, the two satellite bus structures that house the engineering subsystem components, and propulsion thrusters. A third satellite bus structure, containing power equipment and additional propulsion thrusters, is mounted at the end of the solar array boom. The solar array is articulated to point to the sun. A functional block diagram of the satellite is shown in Fig. 9.

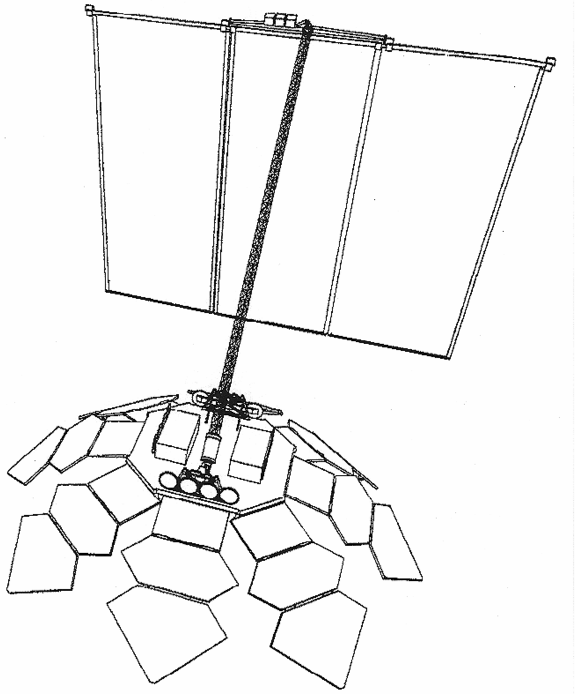

Fig. 8. Teledesic Satellite

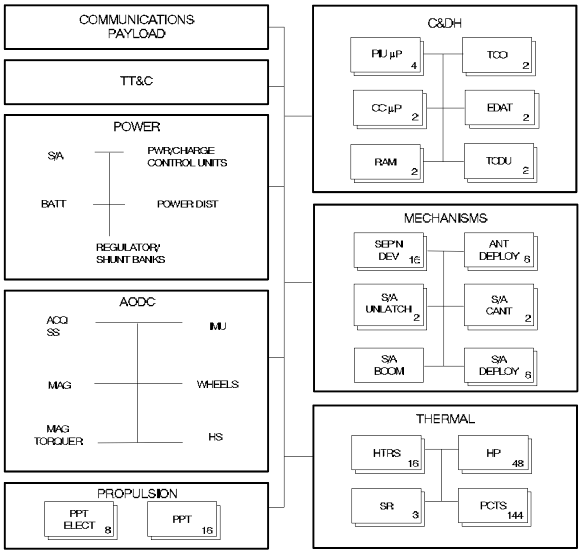

Fig. 9. Satellite Block Diagram

VI. COMMUNICATIONS PAYLOAD

A functional block diagram of the communications payload is shown in Fig. 10. The heart of the payload is the fast packet switch (FPS). It routes packets to and from the Scanning Beam (SB), GSL, and ISL transmitters and receivers. The FPS is essentially nonblocking with very low packet delay, and a throughput in excess of 5 Gbps.

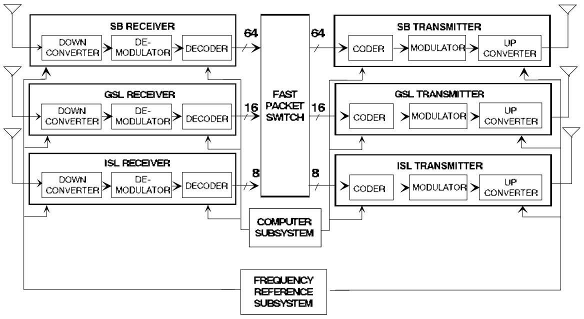

Fig 10. Communications Payload

The frequency reference subsystem provides stable frequency and time references to the SB, GSL, and ISL transmitters and receivers. The computer subsystem provides control information to the FPS and the SB, GSL, and ISL transmitters and receivers.

The SB subsystem consists of 64 transmit channels and 64 independent receive channels plus spares. Each transmit channel accepts digital data packets from the FPS. The packets are encoded and modulated to form an IF signal. The IF signal is upconverted and applied to an active-element phased-array antenna incorporating GaAs MMIC power amplifiers. The antenna converts the RF signal to a free-space propagated waveform with the proper polarization for the Earth-fixed cell that it is serving. The signal frequency is pre-compensated to eliminate the apparent Doppler shift at the center of the Earth-fixed cell.

Each SB receive channel uses an active-element phased-array antenna incorporating GaAs MMIC low-noise amplifiers (LNAs) to convert free space propagated waveforms into a RF signal. The antenna selects the signal polarization corresponding to the Earth-fixed cell that it is serving. The RF signal is downconverted to an IF signal, demodulated, and decoded. The decoded data packets are sent to the FPS.

The SB antenna arrays are located on panels that are oriented at angles to the Earth's surface that reduce the beam steering requirements of each array to a few degrees. The antenna arrays on the inclined panels are elliptical in shape and produce elliptical patterns that compensate for the distortion from circular encountered at antenna grazing angles less than 90° with the Earth's surface.

The GSL subsystem consists of 16 transmit channels and 16 independent receive channels plus spares. Each transmit channel accepts digital data packets from the FPS. The packets are encoded and modulated to form an IF signal. The IF signal is upconverted and applied to an active-element phased-array antenna incorporating GaAs MMIC power amplifiers. The antenna converts the RF signal to a free-space propagated waveform with the proper polarization for the GigaLink Terminal it is serving. The signal frequency is pre-compensated to eliminate the apparent Doppler shift at the GigaLink Terminal.

Each GSL receive channel uses an active-element phased-array antenna incorporating GaAs MMIC LNAs to convert free-space propagated waveforms into a RF signal. The phased-array antenna selects the signal polarization corresponding to the GigaLink Terminal it is serving. The RF signal is downconverted to an IF signal, demodulated, and decoded. The decoded data packets are sent to the FPS.

The ISL subsystem consists of eight transmit channels and eight independent receive channels plus spares. Each transmit channel accepts digital data packets from the FPS. The packets are encoded and modulated to form an IF signal. The IF signal is upconverted and applied to an active-element phased-array antenna incorporating GaAs MMIC power amplifiers. The antenna converts the RF signal to a free-space propagated waveform with the proper polarization for the satellite with which it is communicating. The signal frequency is pre-compensated to eliminate the apparent Doppler shift at the receiving satellite.

Each ISL receive channel uses an active-element phased-array antenna incorporating GaAs MMIC LNAs to convert free space propagated waveforms into a RF signal. The antenna selects the signal polarization corresponding to the satellite it is serving. The RF signal is downconverted to an IF signal, demodulated, and decoded. The decoded data packets are sent to the FPS.

The Teledesic constellation incorporates over 100,000 active-element phased-array antennas. Teledesic will be one of the major consumers of Ka-band GaAs MMICs in the late 1990's [4].

VII. ACKNOWLEDGMENTS

The author wishes to thank David Patterson, Dr. James Stuart, Russ Daggatt, Tren Griffin, David Montanaro, and the other members of the Teledesic team for their contributions to this paper.

VIII. REFERENCES

[1] *Teledesic Company Overview*

[2] George Gilder, “TELECOSM: Ethersphere”, Forbes ASAP, 10 October 1994, pp. 133-148.

[3] *Application of Teledesic Corporation for a Low Earth Orbit (“LEO”) Satellite System in the Fixed Satellite Service (“FSS”)*, 21 March 1994.

[4] M. A. Sturza, “The Teledesic Satellite System”, IEEE National Telesystems Conference, June 1994, pp. 123-126.