Chapter 2

SATELLITE CONSTELLATION NETWORKS

The path from orbital geometry through network topology to autonomous systems

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Abstract: Satellite constellations are introduced. The effects of their orbital geometry on network topology and the resulting effects of path delay and handover on network traffic are described. The design of the resulting satellite network as an autonomous system is then discussed.

Key words: satellite constellation, network, autonomous system (AS), intersatellite link (ISL), path delay and latency, orbit geometry, Walker, Ballard, star, rosette, *Iridium*, *Teledesic*, *Globalstar*, *ICO*, *Spaceway*, NGSO non-geostationary orbit, LEO low earth orbit, MEO medium earth orbit.

1. INTRODUCTION

A single satellite can only cover a part of the world with its communication services; a satellite in geostationary orbit above the Equator cannot see more than 30% of the Earth's surface [Clarke, 1945]. For more complete coverage you need a number of satellites – a satellite constellation. We can describe a satellite constellation as a number of similar satellites, of a similar type and function, designed to be in similar, complementary, orbits for a shared purpose, under shared control. Satellite constellations have been proposed and implemented for use in communications, including networking. Constellations have also been used for geodesy and navigation (the Global Positioning System [Kruesi, 1996] and *Glonass* [Börjesson, et al., 1999]), for remote sensing, and for other scientific applications.

The 1990s were perhaps the public heyday of satellite constellations. In that decade several commercial satellite constellation networks were constructed and came into operation, while a large number of other schemes were proposed commercially to use available frequency bands, then loudly hyped and later quietly scaled back or dropped.

1998 saw the long-awaited launch of commercial services using the 66-active-satellite LEO (low-earth-orbiting) *Iridium* system constructed by Motorola [Leopold and Miller, 1993]. *Iridium* demonstrated the feasibility of Ka-band radio intersatellite links (ISLs) directly interconnecting satellites for wide-scale intersatellite networking. However, *Iridium*'s commercial feasibility was not demonstrated before its operating company had filed for bankruptcy protection. The widespread adoption of mobile telephony and roaming between cellular networks worldwide, largely due to the European GSM standard, had usurped much of *Iridium*'s expected target 'business traveller' market for voice telephony to satellite handsets during the Iridium system's decade-long design and construction period. *Iridium*'s services were later relaunched by a second company, which did not suffer from the original company's need to repay crippling construction debts

The 48-active-satellite LEO *Globalstar* system [Wiedeman and Viterbi, 1993], relying heavily on CDMA-based frequency-sharing technology from Qualcomm, followed *Iridium*, and found the market for a voice telephony service just as difficult. Its operating company filed for bankruptcy protection in early 2002. As the mass market for satellite telephony did not materialise, the focus of *Iridium* and *Globalstar* services was shifted to target niche industrial applications, such as remote mining, construction operations, or maritime and aeronautical use, and low-bit-rate data services (2400bps or 9600bps) were made operational.

Many other proposals looked beyond voice to broadband networking. In 1994 the largest “paper constellation” ever seen was announced; 840 active satellites and 84 in-orbit spares in LEO orbits at 700km altitude for broadband networking to fixed terminals in Ka-band [Tuck et al., 1994]. That proposal was later scaled back by *Teledesic* to a Boeing design of 288 active satellites, which, with its scale and proposed use of intersatellite links, was still more ambitious than the nearest competitor: Alcatel's *Skybridge* proposal for 80 satellites at the same altitude of 1400km [Fraise et al., 2000]. In 2000, *Teledesic*'s parent company took over management of Inmarsat's spinoff *ICO* (for 'intermediate circular orbit'), which had aimed its services at the traditional voice telephony market that *Iridium* and *Globalstar* were designed for, and which had entered bankruptcy protection before even launching [Ghedia et al., 1999].

ICO's mere ten active MEO (medium-earth orbit) repeater satellites without intersatellite links, of which one had been successfully launched and tested by the start of 2002, made for a more realistic, if less exciting, engineering and commercial goal, while *ICO*'s late entry allowed for redesign and increased reuse of popular terrestrial protocol designs, particularly GSM.

2. BENEFITS OF GOING TO LEO

The primary advantage that a LEO constellation has over less complex, higher-altitude systems with fewer satellites is that the limited available frequencies that are useful for communicating through the atmosphere can be reused across the Earth's surface in an increased number of separated areas, or spotbeams, within each satellite's coverage footprint. This reuse leads to far higher simultaneous transmission and thus system capacities.

High system capacity was a desirable goal when commercial expectations for the sale of services using those capacities were also high, even though movement of LEO and MEO satellites relative to the Earth's surface means that a number of satellites have to be launched and made operational before continuous coverage of, and commercial service to, an area become possible. (High-altitude balloons and shifts of endlessly-circling aeroplanes carrying transponders have been proposed as a way of increasing frequency reuse while providing lower-cost targeted or incremental deployment.)

As well as being able to provide truly global coverage, LEO and MEO satellite constellations can have significantly decreased end-to-end path delays compared to geostationary satellites, although this is a secondary consideration for many applications. Though free-space loss is decreased by the lower altitude of the satellites, channel, signal and resulting link characteristics are all considerably complicated by rapid satellite movement, the widely varying atmospheric slant path loss as the satellite's elevation changes with respect to the ground terminals that it is communicating with, and by Doppler shift.

Much of the commercial activity in LEO and MEO satellite constellations resulted from a desire to make as much reuse of limited available allocated frequency bands as possible. Frequency allocation is decided globally by the World Radio Congress (WRC), which meets once every two years, and which eventually accepted the legal concept of a non-geostationary satellite service in addition to the already well-established geostationary services.

The United States' Federal Communications Commission (FCC) held a number of targeted frequency allocation auctions in available bands – all the way from L and S up to V-band. This coincided with a flurry of activity in the US aerospace industry and led to a large number of applications for use of those frequencies [Evans, 2000]. The FCC has been the prime mover at the WRC; far fewer commercial constellation proposals have come from outside the US.

Receiving a license for a satellite constellation requires the licensee to commit to launching the described service and using the allocated frequencies by a specified date. If these terms are not met, the license is revoked. Applications have been made for permission to reuse the allocated frequencies terrestrially, demanding changes in the terms of the licenses in order to make it easier to meet and keep them..

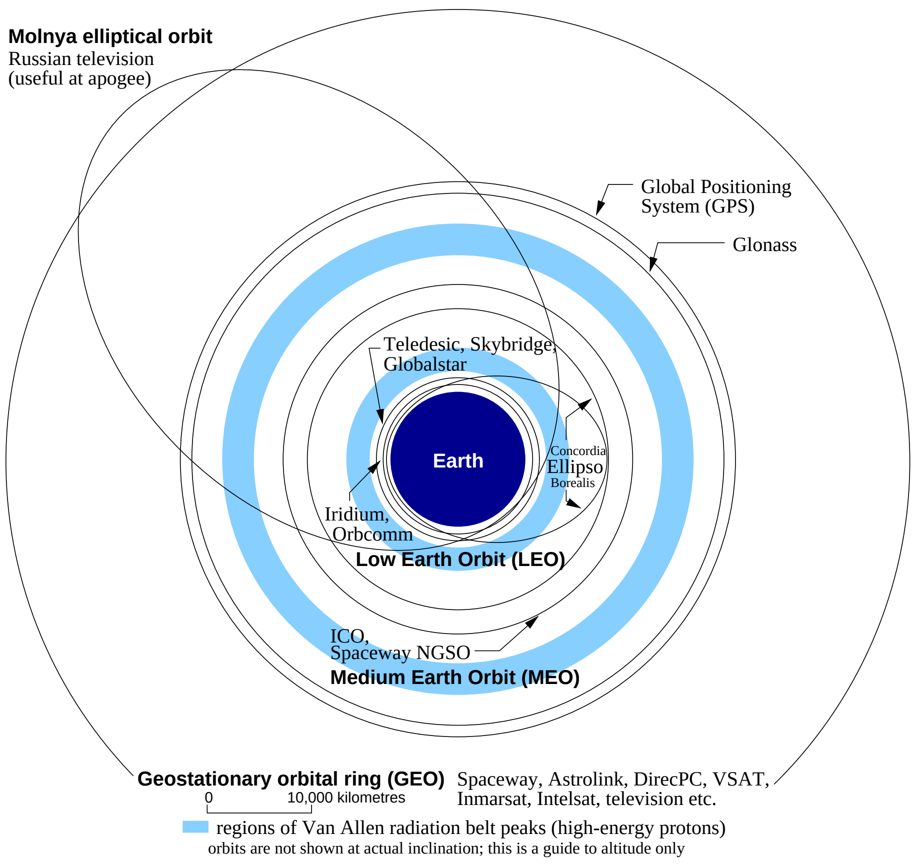


Figure 2-1. Orbit altitudes for satellite constellations and proposals

3. DESCRIBING THE SYSTEMS

We can categorise satellite constellation networks in a number of simple ways:

– by orbital altitude; LEO, MEO, GEO (geostationary) or HEO (highly elliptical orbits). A brief depiction of existing and proposed satellite constellations is given in *Figure 2-1*.
– by constellation geometry, which is based around satellite positioning and orbit type. This, together with intended service and the limitations of the link budget, determines coverage, which can be regional, targeted or global.
– by frequency bands used for services, from C and L up to Ka and V band, and how this affects the resulting payloads, physical channel and link characteristics.
– by intended service provided by terrestrial user terminals, such as voice telephony, broadband data, navigation or messaging.
– by terminal type. We can group terrestrial user terminals into fixed or mobile terminals. A fixed terminal can be placed and oriented with a permanent view of the sky. A mobile terminal raises roaming issues and increased handover challenges; unlike a carefully-sited fixed terminal, a personal handset can suffer link shadowing and multipath effects that must be considered in the design of the satellite constellation. The power output of a personal handset can also be constrained by radiation limits that are acceptable for nearby humans, and this also affects the overall link budget.
– by the approach taken to implementing networking. Approaches that can be taken to implementing networking range from the simple to the complex. The simpler approaches have separate heterogenous ground networks using passing satellites to complete their radio links. A more complex homogenous autonomous system, built from a space-based network using intersatellite links and smart switching satellites, may peer with terrestrial autonomous systems. This is the fundamental difference in satellite network design approaches between the ground-based *Globalstar* satellite networks and the interconnected *Iridium* satellites, or between the *Skybridge* and *Teledesic* proposals, and is shown using classical network layering in *Figure 2-2* and *Figure 2-3*.

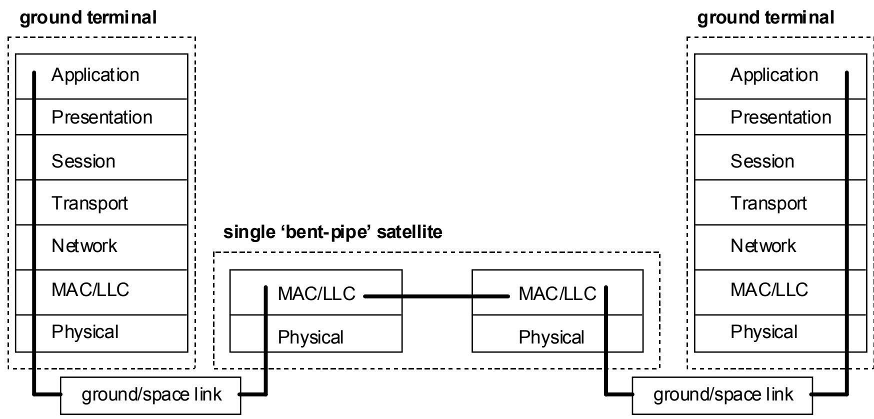


Figure 2-2. Repeating satellite approach, e.g. *Globalstar, Skybridge*

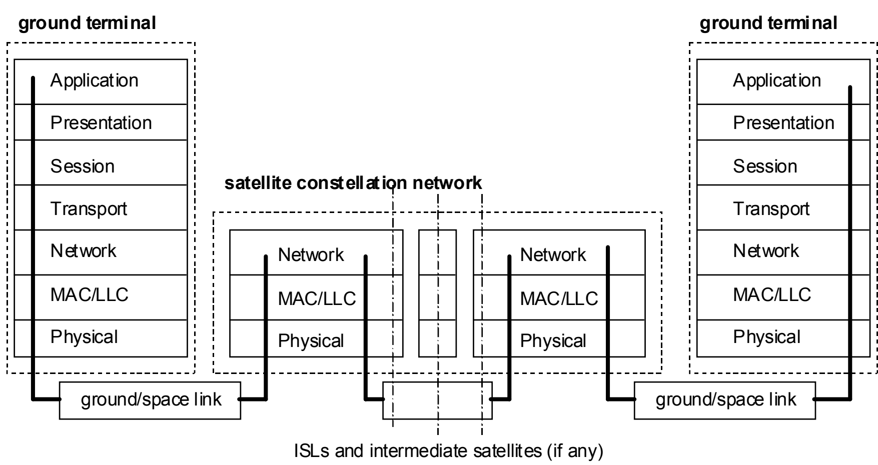


Figure 2-3. Full networking and routing approach, e.g. *Iridium*, *Teledesic*

4. GEOMETRY, TOPOLOGY AND DELAY

Orbital mechanics and the resulting satellite geometry have considerable influence over the design of a satellite constellation network. These affect satellite coverage and visibility of satellites available for use by ground terminals, physical propagation considerations such as power constraints and link budgets, and – particularly important from a networking viewpoint – shape the resulting dynamic network topology and the latency of paths across the satellite network. Path latency affects network performance and delay as seen by applications. It is therefore worthwhile to examine the effects of satellite geometry on network topology.

There are a large number of possible useful orbits for satellite constellations. However, preference is given to regular constellations, where all satellites share the same altitude and orbital inclination to the equator, to minimise the effects of precession and simplify control of ground coverage.

Interconnecting a number of geostationary satellites produces a simple ring network around the Equator; an example of this is the geostationary *Spaceway* proposal from Hughes [Fitzpatrick, 1995]. *Spaceway* was later complemented by an additional MEO proposal with intersatellite links, imaginatively named *Spaceway NGSO*, for nongeostationary [Taormina et al., 1997].

At MEO and LEO, the useful types of regular constellation for satellites at the same altitude are generally divided into the categories of 'Walker delta' or 'rosette' [Ballard, 1980] and the 'Walker star' or 'polar' constellations [Walker, 1984]. These are named for the view of orbits seen from above a pole. With intersatellite links, these form variants of toroidal or 'Manhattan' networks [Wood et al., 2001a].

The rosette constellation, where the coverage of satellites in different orbital planes overlaps, provides its best coverage with visibility of multiple satellites from a single ground terminal at the mid-latitudes where most human population lies, but does not cover the poles from LEO. This multiple visibility and availability of multiple physical channels is known as 'diversity'. *Globalstar* uses CDMA recombination of the multiple signal paths between handset and ground station, provided by the overlapping coverage of 'repeater' satellites, to enable diversity to combat shadowing.

At MEO altitudes, *Spaceway NGSO*'s satellites would be sufficiently high to achieve global coverage. The topology of the *Spaceway NGSO* proposal at a moment in time is shown in *Figure 2-4*, where network connectivity between satellites is indicated with straight lines representing intersatellite links. The lighter lines are links between satellites in neighbouring orbital planes. The flowering 'rosette' shape can be easily seen.

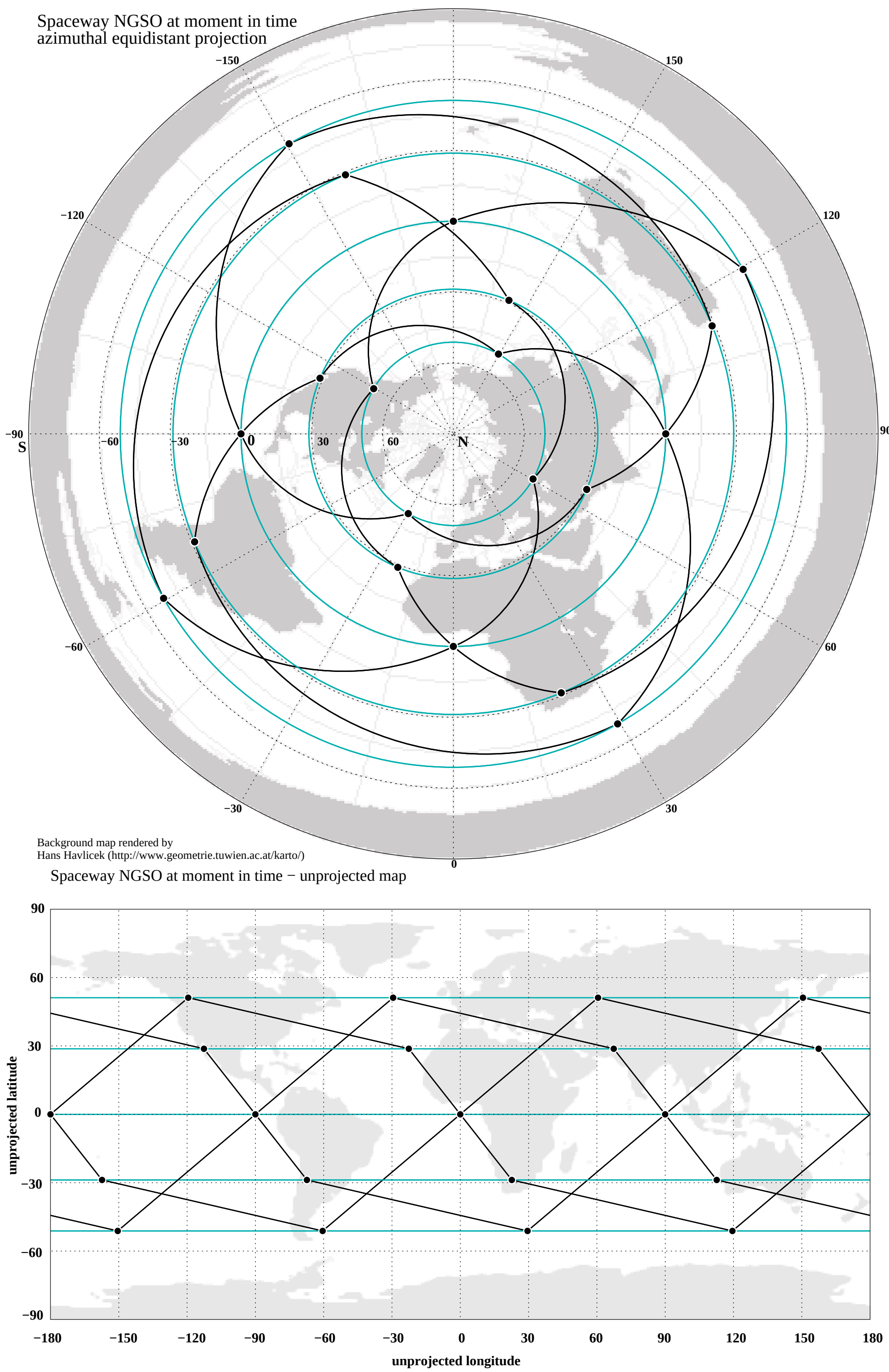


Figure 2-4. A rosette constellation: the 20-active-satellite *Spaceway NGSO* proposal

In contrast, the star constellation provides overlapping coverage at the unpopulated poles even at LEO, which is a side-effect of its near-complete global coverage. *Iridium* and the original and Boeing *Teledesic* proposals are based on Walker star geometries. As satellites pass from view they hand over their communication with ground terminals to satellites following them in the same orbital plane, which provides a 'street of coverage' between the similar streets of coverage of neighbouring planes of satellites orbiting in the same direction [Lüders, 1961]. The Earth slowly rotates beneath and across these planes, so that eventually one plane must hand over its terminals to its neighbour to the east. As a result of the Earth's rotation, the 'orbital seam', between the last plane of 'ascending' satellites (travelling north) and the counter-rotating (or 'descending') satellites of the plane almost 180° away, will be encountered by ground terminals. This seam can have a disruptive effect on path delays between terminals and handover between satellites.

Whether the orbital seam between these counter-rotating planes can be spanned by cross-seam intersatellite links that are rapidly handed off between satellites moving at high speeds in opposite directions has been the subject of some debate. With its four intersatellite link terminals per satellite (one fore and one aft to nearby satellites in the same orbital plane, and two to satellites at either side in each co-rotating neighbouring plane) *Iridium* has shown that ISLs work, but its design did not attempt cross-seam communication. The eight intersatellite link terminals per satellite of *Teledesic*'s proposed 'geodesic' mesh would have permitted each satellite at the edge of the seam to maintain one cross-seam link, while the free terminal attempted to establish the next viable link [Henderson, 1999].

Tracking requirements for intersatellite links in LEO star and rosette and MEO constellations and the range of slewing angles required are discussed in [Werner et al., 1995; Werner et al., 1999].

Figure 2-5 shows the topology of a simulated *Teledesic* proposal at a point in time. The eight-way geodesic mesh of intersatellite links is visible everywhere except at the orbital seam, which has fewer links crossing it. The orbital planes make a 'star' configuration, centred around the pole.

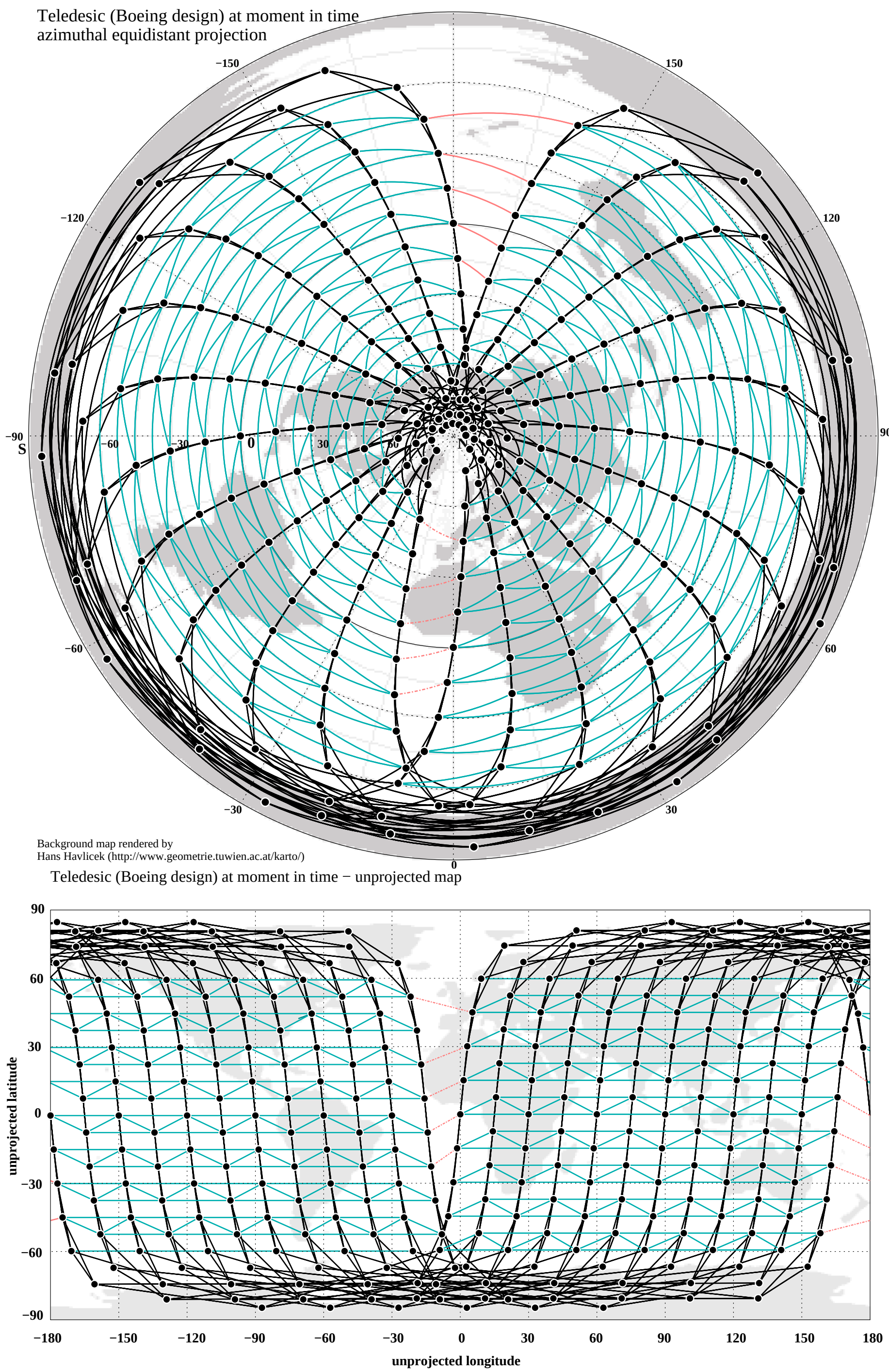


Figure 2-5. A star constellation: The 288-active-satellite Boeing *Teledesic* proposal

Constellations have also been proposed using elliptical orbits, where the satellites are only useful while moving slowly at high apogee, and communication link budgets are dimensioned for that distance.

Many useful elliptical orbits are inclined at 63.4° to the Equator, so that orbital motion near apogee matches the angular rotation of the Earth and appears to be stationary with respect to the Earth's surface. Use of *Molnya* (or *Molniya*) and the larger *Tundra* elliptical orbits is now well established for providing broadcast satellite television services targeted to the high-latitude states of the former Soviet Republic; the delay is constant and exceeds the delay to geostationary orbit.

Draim has explored elliptical constellation geometries extensively, and his work was used in the design of the proposed *Ellipso* constellation for voice telephony [Draim et al., 2000].

5. DELAY

If a path across a network includes a satellite link, then the delay and error characteristics of that link can have a significant effect on the performance of applications whose traffic uses that path. Tweaking the design of transport protocols to improve their performance when used across the extreme delay and error conditions presented by a link via a geostationary satellite has been a popular field over the years [Postel, 1972; Seo et al., 1988; Partridge and Shepard, 1997; Allman et al., 1999; Allman et al., 2000].

It would be difficult to discuss the error characteristics of the satellite links in a proposed constellation in detail based solely on the constellation topology, since these characteristics are subject to a large number of interrelated engineering design choices at various protocol layers, including antenna design, degree of margin in the link budget, error-control coding choices, and link-layer retransmit strategies for each link. The link and error conditions can also vary over time, as the signal from a ground terminal to a non-geostationary satellite low on the horizon will encounter considerable loss due to the long slant path through the atmosphere. This loss decreases with the shortening of the slant path and increase in signal strength as the satellite rises to its local zenith.

However, the delay incurred by using satellite links is easier to consider and to simulate. For a single geostationary satellite, the coordinates of the ground terminals and the longitude of the satellite are enough to calculate the path propagation delay. For more complex constellations, a first-order approximation can be given by knowing how the constellation geometry and network topology are affected over time by orbital mechanics, and simply calculating the speed-of-light propagation delay between ground terminals at the endpoints of a path. This can be refined by considering the amount of time taken to serialise a frame at a given speed onto the channel at each link. Any jitter due to variations in queuing or switching, or added latency due to contention and link capacity management, will vary considerably according to the specific system design and implementation of the links, and can be considered later.

An example of this propagation delay is given in *Figure 2-6*, for traffic sent from a ground terminal in London, England, to another in Quito, Ecuador, over the course of a day as the Earth completes one whole rotation beneath the planes of a number of different satellite constellations.

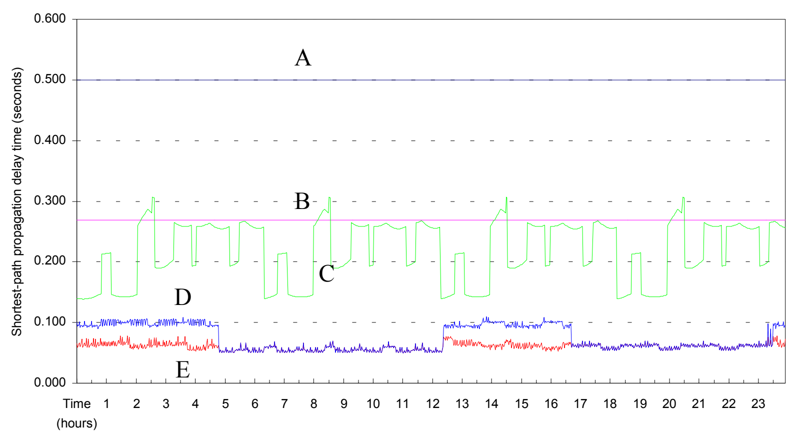
The shortest-delay path across each complex mesh network has been selected by routing decisions. As satellite movement is predictable and on a computationally slow timescale, it is possible to predict network topology and handover and to automate updates of routing tables to a considerable degree. Updates can be computed centrally and terrestrially, and then distributed to all the satellites in the constellation by broadcast command. However, handling unexpected link failures gracefully, or engineering traffic flows for quality of service to meet specific application requirements, still requires robust routing algorithms, and has been a popular research area [Mohorčič, et al., 2000; Ekici et al., 2000].

The smallest path delay between two ground terminals is achieved with a LEO constellation, as is shown by the two delay traces for variants on the Boeing-design *Teledesic* proposal. The effect that the orbital seam between counter-rotating planes has on the traffic from one terminal to another is shown by the difference between the two traces. Traffic between the terminals will be rerouted for the several hours that the seam spends passing through the shortest distance on the Earth's surface between the terminals. If there are no cross-seam intersatellite links, the traffic must be rerouted along an orbital plane over the highest latitudes, incurring added delay.

The larger MEO delay, across a simulation of the proposed *Spaceway NGSO* constellation, clearly shows the gradual slow changes in delay due to the cumulative effect of satellite passes from horizon to local zenith and back slowly varying the distances between satellites and terminals, as well as abrupt changes in delay due to handovers between terminals and satellites leading to path rerouting. *Spaceway NGSO* has four orbital planes of five satellites per plane, and these four planes can clearly be seen in the way that the pattern of the delay trace repeats four times over the course of a simulated day, or full rotation of the Earth. As the rosette does not have streets of coverage, we see large alterations in the path delay, where a terminal has handed over communication from an ascending satellite to a descending satellite in a counter-rotating plane, or vice versa. A rosette constellation with large amounts of overlapping coverage can minimise the incidence of such large changes in path delay [Wood et al., 2001c].

With the streets-of-coverage approach taken by *Teledesic* and other 'star' constellations, we only see such alterations in path delay as the orbital seam between ascending and descending satellites intersects the path traffic takes between the ground terminals. Those changes are minimised by the use of cross-seam intersatellite links.

Finally, the two straight lines show the constant propagation delays incurred by using geostationary links. The shorter delay is via a single geostationary satellite at 0°W, while the longer delay is from the London terminal to that satellite, which then uses an intersatellite link to communicate with a second geostationary satellite at 120°W, used by Quito, as part of a three-satellite Clarke constellation [Clarke, 1945]. In practice, allocation of link capacity between multiple terminals using variants on slotted Aloha or other capacity management techniques will lead to longer, more variable delays for network traffic [Maral, 1995].



(key to figure: A - hop via two geostationary satellites with an intersatellite link
B - hop via a single geostationary satellite
C - *Spaceway NGSO* proposal
D - Boeing *Teledesic* proposal without cross-seam intersatellite links
E - Boeing *Teledesic* proposal with cross-seam intersatellite links)

Figure 2-6. One-way delay between Quito and London via constellations at different altitudes

6. HANDOVER

Movement of MEO or LEO satellites, which hand over coverage of ground terminals to other satellites or between multiple neighbouring spotbeams, means that the path taken by traffic between terminals will change over time. When there is a change in path, we can expect changes in path delay.

The path taken will be altered for any packets already in transit whenever terminal handover occurs at the packets' destination. These 'in flight' packets will travel a slightly different path to reach their destination than previous or subsequent packets. This can lead to packet reordering for high-rate traffic, where a number of packets are in flight as handover occurs, resulting in spikes in path delay as handover occurs. The larger distances and propagation delays in the constellation network increase the chances of this affecting in-flight traffic, making the effect greater than in terrestrial wireless networks. This process is shown in *Figure 2-7*.

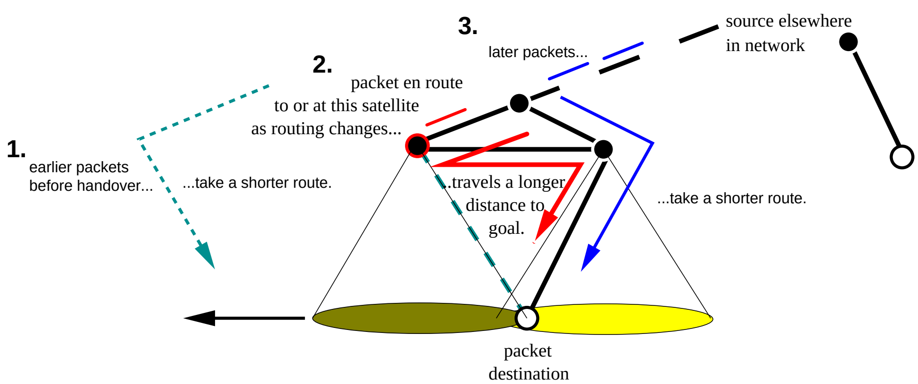


Figure 2-7. How handover can affect traffic in flight

Although low-rate traffic is less likely to experience these transient effects during handover, applications sending high-rate and extremely jitter-sensitive traffic can be affected, and the impact of handover on network traffic must be carefully considered in the system design.

If the satellites along the path knew that a handover was about to take place at the destination terminal, it might be possible for them to buffer packets destined to the terminal along the path to prevent those packets from reaching the last hop before downlink until after handover has been completed. However, that would impose a lot of per-flow state on the satellite network, and is not practical for the high-rate traffic that is most likely to experience these transients. Handovers cannot always be easily predicted, particularly for mobile terminals experiencing shadowing.

To illustrate the possibility of transient delay spikes, high-rate traffic was simulated between neighbouring ground terminals. The time between successive packets was less than half of any link propagation delay experienced by the packets. This allowed us to capture and view transient delay spikes due to terminal handover affecting traffic in flight on intersatellite links. These delay spikes would be seen rarely, if at all, by traffic at lower rates.

Figure 2-8 shows these transients for packets between two terminals communicating using a variant on the *Teledesic* design. The terminals were located on the Equator so that time between plane-to-plane handover was at a maximum, and in similar positions relative to their streets of coverage so that the cumulative effect of satellite passes would be more clearly visible. The steps visible in the curves are due to the resolution of 0.1ms for recorded time within the simulator.

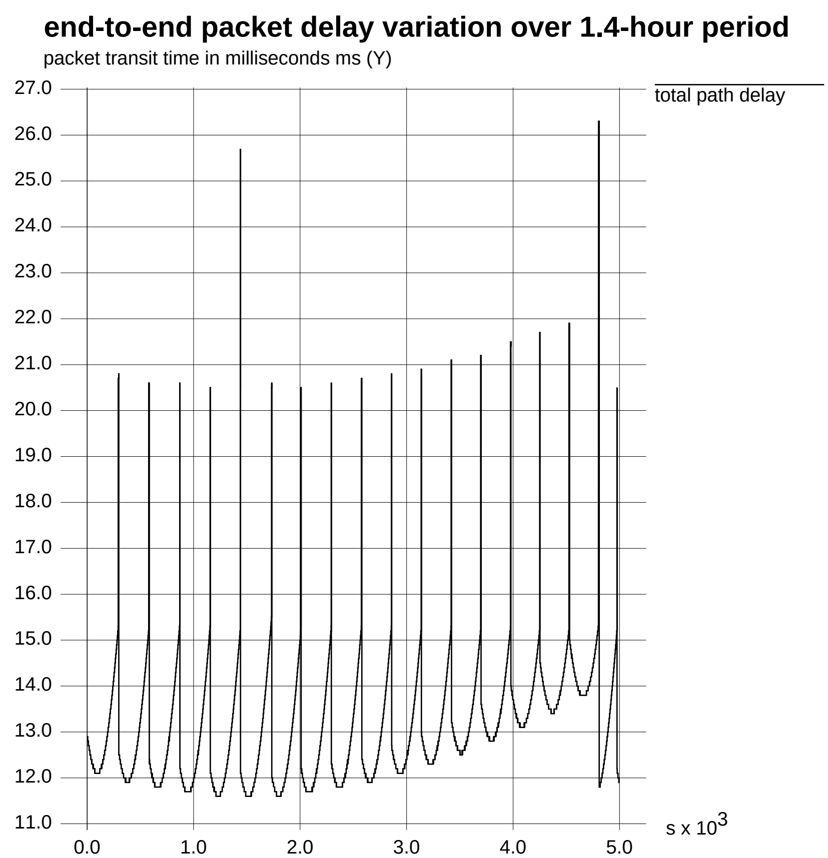


Figure 2-8. Path delay for high-rate traffic over a small timescale

Satellite passes, showing a smooth decrease or increase in path delay for packets as satellites approach or leave the terminals' local zeniths, can be clearly seen. Larger path delays for packets in flight during handover between passes are also visible.

These in-flight packets are in the last intersatellite link of their path in the network before the downlink to their destination, or at the satellite the destination terminal is leaving, as that terminal undergoes handover from satellite to satellite. After reaching the satellite previously used by the destination terminal before terminal handover took place, these packets must then be routed onward to the current satellite the terminal is now using. This adds delay before those packets are received. Later packets bypass the former satellite entirely, and the path delay returns to near its previous value.

The overall rotation of the Earth under the planes of satellites, and movement of the terminals across the planes' streets of coverage, showing a gradual decrease and increase in the minimum delays needed to reach local satellite zenith, are also visible in *Figure 2-8* as a great curve that can be drawn tangentially to all satellite pass curves, encompassing the individual passes. These gradual movements under each plane are separated by larger step changes when terminal handover to another plane, and to another street of coverage, takes place. In-flight packets briefly travel two extra intersatellite links to cross the plane, rather than one, before the path changes again as the other terminal hands over as well.

(The large transient spike near 14,000s occurs between the two passes where the uplink and downlink satellites come nearest their terminals' zeniths. The satellites are held onto for the longest period of time before handover occurs at each ground terminal, and the resulting handover is more dramatic as the satellite network has moved the most in its orbits and relative to the surface of the Earth. Since *Teledesic* is a redundantly-connected 'geodesic' mesh, packets can traverse both long and short intersatellite links, of different delays. Here, packets use a long intersatellite link.)

Encountering these transient delay changes by sending a packet just before a handover event occurs could lead to packet reordering, which can adversely impact applications reliant on an ordered flow of packets. The impact of packet reordering on Internet traffic is discussed further in [Wood et al., 2001b].

7. NETWORKING DESIGN

How is a satellite constellation designed as a network, and how will it perform? Much existing literature has focused on simulating the performance of a constellation network carrying traditional Poisson telephony traffic [Werner et al., 1997b]. However, doing so involves making assumptions about the nature of the traffic – for example, that the amount of traffic would be large enough for a 'worldwide busy hour' to ensue, where variation in the amount of traffic over the course of a day is insignificant compared to the amount of traffic passing across the constellation network. Such assumptions have not been validated by *Iridium* or *Globalstar*, which have had large amounts of unused capacity.

The rise in popularity of the Internet Protocol (IP) has led to a shift in research focus in the literature from simulating voice telephony traffic to simulating IP data traffic. Simulation of adaptive network traffic, such as that of the Transmission Control Protocol (TCP), part of the Internet Protocol suite, is more complex. TCP's congestion-avoiding slow-start and loss recovery algorithms are affected by the long path delay of geostationary links. However, the movement of LEO and MEO satellites is on a slow timescale, where gradual changes in path delay are often beneath the threshold of notice set by the granularity of TCP timers (typically multiples of 100ms). Simplifying the simulation so that the network path across the constellation is chosen and fixed for a point in time is often sufficient for short simulations of a few TCP flows around that point in time [Wood et al., 2001b].

The adaptive nature of many types of network traffic, when experiencing packet loss due to congestion or to link frame corruption, makes realistic and meaningful large-scale simulation of the network performance of an entire constellation and its traffic difficult. Presuming that the on-board satellite switches are operating as IP routers, with similar functionality and features, also presents a number of problems.

First, IP was originally designed for fixed ground networks, where each network is allocated a fixed address space. Those address spaces, or 'blocks', are then aggregated in routing table entries to allow routers to send traffic to and from each network. Internet routing protocols rely on sensible aggregation of a well-design hierarchy of address blocks to be scalable. However, in a satellite constellation, the topology is dynamic with handover as terminals move between spotbeams and satellites, making it difficult to define and use a stable addressing hierarchy for the terminals. Additions to the IP protocol suite have added needed flexibility to IP addressing – for example, the Dynamic Host Configuration Protocol (DHCP) allows a host to learn of and use an available address that is useful within the local subnet [Droms, 1997]. Mobile IP allows a degree of roaming from a 'home' network for a nomadic IP host moving through other fixed IP networks, using IP-in-IP tunnelling, in order to support remote use of applications which policy has configured for use only on local networks [Perkins, 1998]. However, such additions to the IP protocol suite to allow useful flexible on-demand logical IP addressing for single hosts cannot be used effectively to form the basis of a satellite constellation network, where entire isolated terrestrial networks using a ground terminal for connectivity would need to be fully renumbered with every satellite or spotbeam handover. Mobile IP may handle roaming at the IP addressing level, but without careful integration with lower layers it cannot be considered suitable for rapid handoff on wireless links [Solomon, 1996]. Though a satellite constellation network can be expected to carry significant amounts of both IPv4 and IPv6 traffic across it, it is likely that this traffic will pass through gateways or tunnels on the ground, while the satellites will know how to send encapsulated traffic between ground terminals and nothing more [Wood et al., 2001a].

Second, a dedicated MAC layer is needed to send traffic to individual terminals as they hand over to and from each satellite or satellite spotbeam. The variable size of IP packets does not make a good match with MAC-layer protocols that are most efficient when using fixed frame sizes. Much work has been done on designing wireless ATM for the 'air interface' between ground terminal and satellite, where two ATM cells are wrapped together in a satellite-specific MAC layer frame design complete with error coding checks. A number of proposed constellation designs (including *Skybridge* and *Spaceway*) planned to use an ATM-based MAC frame design. ATM-based routing has been suggested for the constellation network [Werner et al., 1997a], although ATM routing has similar fixed-network assumptions to most IP-based routing.

The satellite constellation network is likely to carry non-IP traffic, including circuit-oriented traffic with strict requirements, and is likely to need traffic engineering to enable smooth handling of path rerouting of ordered flows of traffic due to handovers. The predictive nature of orbital geometry, the need for capacity management of shared spotbeams, and intersatellite and intrasatellite interspotbeam handover for active terminals also mean that engineering optimisations are possible that ad-hoc IP networking cannot consider. The likeliest design outcome is the use of a generic satellite network architecture that is tailored to the physical constellation design and that is able to handle a variety of terrestrial protocols and data types.

The constellation network as an autonomous system will communicate with other autonomous systems. From the outside, the constellation network will appear to be a terrestrial IP network to other terrestrial IP networks, or perhaps an ATM network to other ATM networks. As an IP network it will exchange Border Gateway Protocol (BGP) information with peer IP networks it connects to about the reachability of other IP networks [Rekhter and Li, 1995]. Given the range of terrestrial IP networks that this autonomous system will connect to and know about, and its possible use as a reliable fallback when terrestrial connectivity fails, there is scope for increasing the range of information shared using BGP [Ekici, 2001].

Although the constellation network will carry IP or ATM traffic, that does not make its satellites the equivalent of terrestrial IP routers or ATM switches. Even complex switching satellites within the constellation network are likely to know only how to route traffic between terrestrial terminals and gateways using dedicated interior protocols, and, in the interests of minimising onboard state and complexity, are unlikely to know anything about the world beyond those points. With separation of interior and exterior routing, we can also expect separation of interior and exterior design and network protocol choices that allow a flexible network design to be developed that meets the specific needs of the constellation and supports a variety of traffic types, rather than targeting a single expected traffic type, market and service.

8. SIMULATORS

Simulation is an essential tool to gain a solid understanding of the effects of orbital motion on satellite constellations, and how it influences network topology, path delay, and the resulting performance of carried traffic. Some available simulation tools useful for studying satellite constellation networks in a research context are introduced briefly here.

SaVi is free satellite visualization software, originally written at the Geometry Center at the University of Minnesota with cooperation from NASA's Jet Propulsion Laboratory [Worfolk and Thurman, 1997]. *SaVi* is useful for showing satellite and coverage movement in two and three dimensions. Although *SaVi*'s source could be extended further to generate handover statistics or compute path delays, its current focus is on showing what would be physically there in a number of well-known proposed constellations. This makes *SaVi* a useful introduction to the effect of orbital mechanics on basic constellation properties, as well as a convenient way of verifying satellite movement in other simulators.

AVM Dynamics has produced the commercial Symmetrical Constellations package, which has a similar focus to *SaVi*, but with generation of relevant delay graphs and statistics. STK produces a commercial package named *The Satellite Toolkit*, whose various modules contain a wide variety of satellite simulation features aimed at industrial use.

ns, the network simulator, is free software originally developed within the University of California at Berkeley and now maintained at the Information Sciences Institute (ISI) [Fall and Varadhan, 2002]. *ns* began as a tool to research modifications to TCP algorithms. *ns* still focuses on simulation of changes to TCP/IP, but has now been extended to include types of wireless network. Extensions to simulate satellite movement and the changing link delays of circular orbits were added to *ns* [Henderson and Katz, 2000] and were used for the simulations presented in this chapter. The focus on TCP/IP has traditionally meant far less detail at lower networking layers, although hooks are available that allow specific satellite MAC, LLC and channel layers to be added.

MIL3 has produced the commercial *Opnet* network simulation package, which is also capable of simulating satellite networks, TCP/IP and other existing protocols in detail.

9. SUMMARY

Satellite constellation networking can take a space-based or a ground-based approach, with or without the use of complex switching satellites and intersatellite links.

Satellite constellations introduce changes in path delays for network traffic due to satellite movement and handover. These changes can be significant, particularly when traffic is routed across large distances using intersatellite links, and can be modelled in simulation. Regular path changes and handovers form a fundamental part of LEO and MEO satellite constellation networks, and distinguish them from terrestrial networks. Handovers offer particular challenges for high-rate traffic; traffic engineering may be required to keep disruption to traffic to a minimum.

The satellite constellation network will carry IP traffic, but its satellites are unlikely to simply be IP routers; the network design is likely to be tailored to the specific engineering needs of the constellation.

The use of satellite constellations for networking has not yet met the expectations that were raised in the boom years of the mid-nineties. This would seem to make the field more suitable for long-term rather than near-term research, although there has been a decrease in enthusiasm for funding research in this area, just as there has been a decrease in commercial enthusiasm for the satellite industry in general.

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