Chapter 4

FPLMTS Space Segment

4.1. FPLMTS Time Scale

Figure 14 illustrates the availability of the different mobile systems over the past fifteen years and the point at which convergence to FPLMTS recommendations is expected.

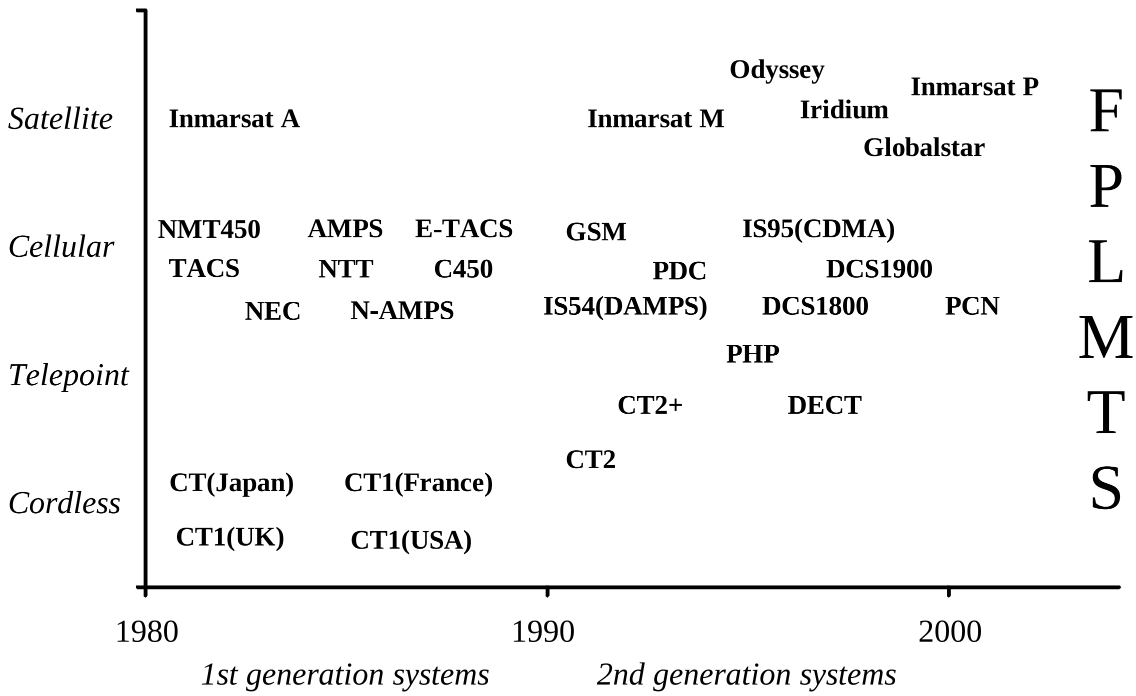


Figure 14 Mobile communications systems

Satellite systems have been characterised by lead times of around 8 years from proposals to launch of service. This means that the proposals already being considered in 1995 for hand-held mobile satellite service are all in the time-frame for the initial roll-out of FPLMTS. Most of these proposals will not be using the 2GHz FPLMTS frequency allocation and do not have to comply with any FPLMTS recommendations. However it will be these proposals that could deliver some of the benefits described in chapter 3 if they can be made compatible with FPLMTS at the level of interconnection with the core network. The work described in this thesis has pursued this goal by keeping the details of implementation of these systems distinct from the functions of network entities. Nevertheless, to enable any of the systems proposed so far to act as a FPLMTS radio access network and interconnect with the FPLMTS core network, the capabilities of the proposed networks and of future developments need to be understood.

Some of the commercial proposals already licensed by the FCC for satellite systems to carry mobile personal communications traffic, including voice, in the late 1990s are [BTTJ, FOLEY, ETR093, FT, WISLOFF, KPMG]:

- Inmarsat-P [ICO], due into service 2001,
- Iridium [IRIDIUM], due into service 1998,
- Globalstar [GLOBLSTR], due into service 1999,
- Odyssey[ODYSSEY], due into service 1999,
- Teledesic[TELEDESIC], due into service 2001,
- AMSC (American Mobile Satellite Corporation), in service since 1995.

Before discussing the network architecture for UMTS, a very brief tour of the engineering capabilities and considerations for these systems is useful.

4.2. Satellite Coverage

The type of coverage required determines the orbit type, the number of satellites required, the possible need for inter-satellite links (ISLs) and the link margin budgeted for.

4.2.1. Breadth of Coverage

Satellite networks could be required for:

- Regional coverage - for example continental USA, Europe, China, Far and Middle East, Africa or Australia. In these cases the GEO minimises the need for multiple satellites and the need to manage satellite motion with respect to the Earth. However, for regions at high latitudes such as Europe, HEOs (highly elliptical orbits) offer increased elevation angles, at the expense of requiring more satellites and management of satellites' motion. Systems such as AMSC and the regional Asian systems all plan a GEO space segment.

- Global coverage. The intention is usually to cover a selection of major markets around the world. This is what systems such as Inmarsat-P, Odyssey, Iridium, Teledesic and Globalstar plan. Medium to low Earth orbits (MEO/LEO) are well suited to global coverage and can be optimized to provide maximum capacity over their biggest markets. By their non-geostationary nature they will cover more of the Earth's surface than just the areas for which the constellation is optimised. This extra coverage can be made fully functional, providing either complete global service or coverage that is as ubiquitous as most travellers would require. Some small, time-varying gaps in coverage could be accepted, where extra satellites would not be justified by the little extra traffic they would cover. As with HEOs, the use of

MEOs or LEOs requires more satellites than a GEO system and requires the management of satellite motion (see section 4.3).

This outlines the capabilities of the various orbit types but does not take into account the difficulty of reaching regulatory agreement to provide service on a global or even regional scale. This is a huge challenge beyond the scope of this thesis, except to note the possible need to prevent satellites from transmitting so as to bar FPLMTS access over certain geographic regions.

4.2.2. Depth of Coverage

"Depth" describes the depth of in-building coverage, that is the system's resilience to shadowing by buildings and so on. Recognizing that in some areas of the world FPLMTS pico-cells will not be available in many rural buildings any more than macro-cellular coverage will be, the performance of satellite terminals inside buildings is important. As satellite power is limited (see section 2.5.3), it is expensive to provide any more than direct line-of-sight radio-communications from a hand-held terminal to the satellite. This minimal coverage would require customer participation in setting up a call, where customers may need to move their position to ensure line-of-sight communications. In clear rural areas this may be easy to do but in urban areas it can become impracticable. There are two approaches to increasing the depth of coverage, as briefly mentioned in section 2.5.5:

1. Increase the link margin in the power budget to allow communications through heavily attenuated and reflected waves. Iridium has been designed this way because its LEO constellation does not usually provide diverse coverage from multiple satellites. In other systems, this has been considered for paging channels to ensure that customers are reliably alerted of incoming calls, even if they may need to move to a better location for radio reception to connect the call.

2. Use macro-diversity, allowing use of multiple satellites visible above the horizon for communications. This increases the probability of having good reception from a satellite at any instant. With higher altitude LEO and MEO constellations multiple satellite coverage is more easily provided, so Inmarsat-P and Globalstar rely on macro-diversity to improve link availability. Even for relatively slow (40ms) switching of a receiver between satellites for the best TDMA frames, a 2dB increase in mean received power can be expected. For CDMA and TDMA systems employing Rake receivers, the power gain will be higher as the signals from different satellites can be equalized and added together.

4.3. Orbits

The altitude of a satellite orbit determines:

- The length of the radio path and therefore the power loss and time delay in the radio path.
- The area of the Earth's surface which the satellite can see.

- The speed at which the satellite moves over the Earth's surface. This determines the rate at which mobile terminals and FESs have to switch satellites and the magnitude of Doppler effects.
- The orbital period. If the orbit can be made to repeat its track every 24 hours then calculation of satellite positions and coverage patterns at the FES is simplified.

4.3.1. LEOs

The most complex networks are those with satellites in the lowest orbits, LEOs. The complexity of some of these systems should not be under-estimated as the management of large numbers of satellites moving very fast requires deft manipulation of radio links and stable orbits to support them. The life expectancy of individual satellites in these constellations is only 5 to 7½ years as a consequence, with network operators operating a continuous programme of satellite replenishment. Control of the constellation of satellites needs to be distributed, making management systems expensive. When this study began in 1991, the lowest LEO that had been proposed was Motorola's Iridium, orbiting at 769km altitude. This altitude has been used as a representative LEO orbit throughout the studies reported in this thesis. Iridium's design specification has since changed to orbit at 780km altitude. Also in the LEO class of orbit are Globalstar, orbiting at 1,414km and Teledesic, orbiting at about 700km.

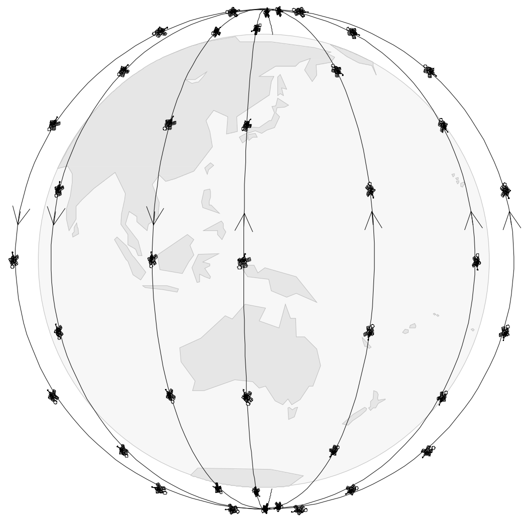


Figure 15 The 66 satellite Iridium constellation

The area of the Earth's surface visible to a satellite (its "footprint") determines the number of satellites required to complete a constellation where a satellite is always visible from all points in the region to be covered. The Iridium constellation (shown in figure 15) has 66 satellites, Globalstar has 48 and Teledesic will require 840 operational satellites. Additional in-orbit spare satellites will also be required. The footprint area becomes particularly important when service is required over ocean regions and yet there is no land visible to the satellite on which to build an FES to carry the backhaul links. The minimum number of FESs required to maintain these backhaul links for global coverage also rises to unacceptable numbers for orbits such as Teledesic, as shown[1] in figure 16. The solution to these difficulties is to use neighbouring satellites to

[1]Figure 16 is analytically derived assuming ideal placement of FESs in a hexagonal mesh across the Earth's surface. Geographic, regulatory and political considerations will mean that the real number of

relay backhaul links to a small number of satellites that are in contact with FESs, using inter-satellite links (ISLs). Teledesic and Iridium both use ISLs but Globalstar satellites are high enough for each satellite to always include land within its coverage footprint and communicate directly with an FES.

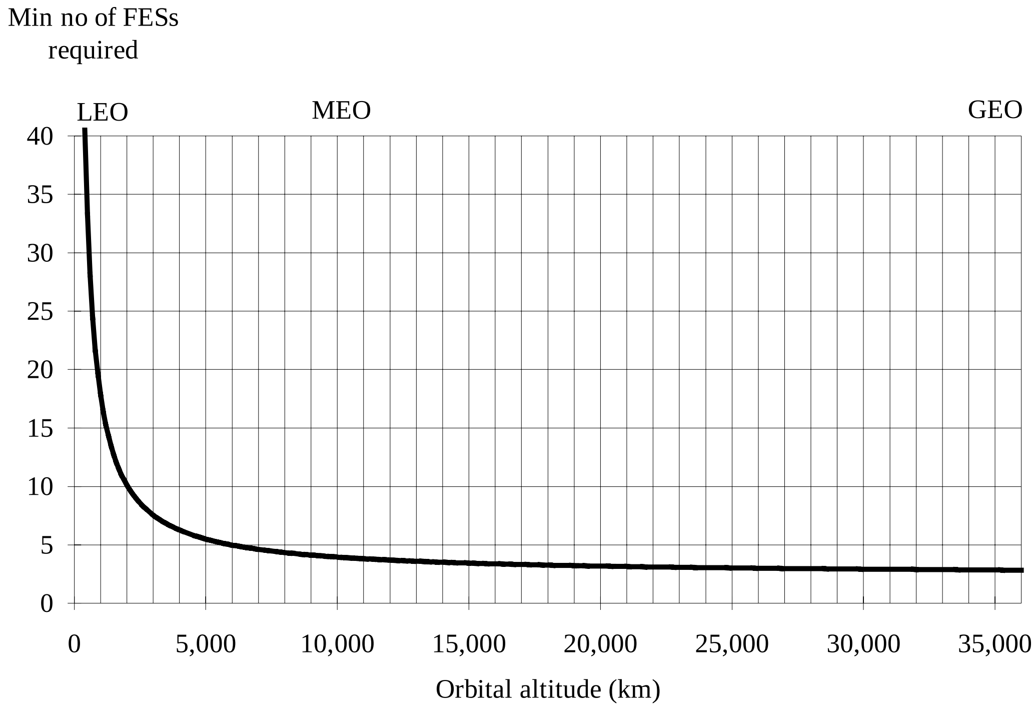
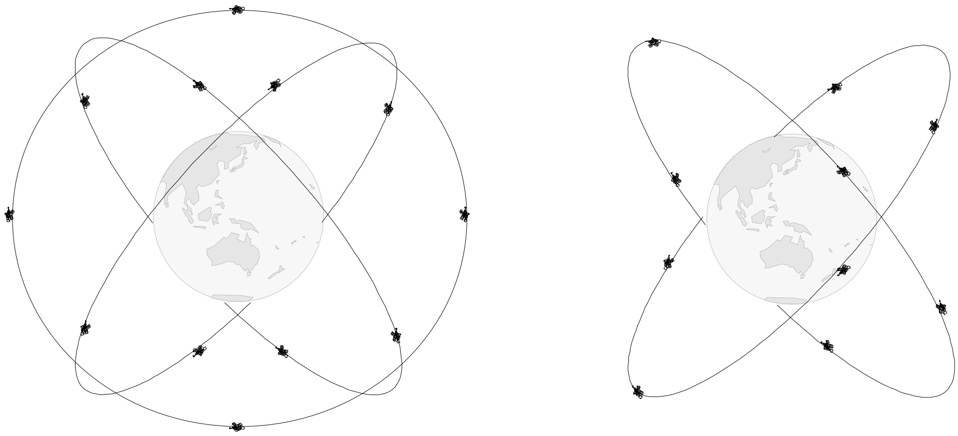


Figure 16 Minimum numbers of FESs required for global coverage assuming ideal placement and no ISLs

4.3.2. MEOs

Two MEO systems are currently proposed, Odyssey and Inmarsat-P, both orbiting at 10,354km. At MEO altitudes we can see that the requirement for FESs is dramatically reduced and the frequency with which communications paths must be handed over from one satellite to the next is also more easily managed. This allows the satellite network to be simplified, reducing the total cost of the networks. The number of satellites required reduces to 12 for Odyssey and 10 for Inmarsat-P as each satellite can see more of the Earth from its higher vantage point. These constellations are shown in figure 17. Path delays are increased to a significant 80ms to satellite and back (compared to under 10ms for LEO). This delay is not enough to be a problem on its own but contributes to the total delay already inherent in error correction, interleaving and source compression and can become a noticeable annoyance to customers.

FESs will be larger than this, at least doubling the number of FESs . This subject will be revisited later in the thesis in chapter 6.



Odyssey *Inmarsat-P*

Figure 17 The 12 satellite Odyssey constellation (left) and the 10 satellite Inmarsat-P constellation (right)

4.3.3. GEOs

GEOs will be with us for some time to come, even in FPLMTS, because they are an economical way to provide regional coverage up to approximately ±80° latitude. Their big advantage is that they remain stationary with respect to the Earth and so there is no need for management of satellite motion. This also means that one or two satellites are sufficient for most regional needs. The simple station keeping requirements enable them to be built with a life span of 10-13 years which makes them very economical propositions. AMSC is already providing a cellular in-fill in the USA using dual-mode D-AMPS and AMSC terminals [SKYCELL]. As noted in sections 2.5.2 and 4.4, with a sufficiently large antenna a GEO satellite is as capable of providing service to a hand held terminal as a LEO or MEO satellite. The disadvantage of GEO is the delay for a radio signal to get to the 35,786km altitude satellite and back - up to 270ms. This is noticeable in interactive applications where forward error correction, interleaving and source compression delays increase the total delay further. The ITU [G.114] recommends limiting the total end-to-end delay for voice telephony to below 400ms. GEOs are more suitable for less interactive data applications where delays are less apparent to customers as long as the transmission protocols have been specially adapted to work with a delay this long. Finally, a problem for mobile systems is that for high latitudes, the satellite is at a low elevation in the sky which limits reception in urban areas.

4.3.4. HEOs

Highly elliptical orbits, inclined at 63.4°, can be used to achieve regional coverage at higher elevation angles than GEO satellites at latitudes of Europe, Canada and the poles without the need for more than three satellites. There is satellite motion with respect to the Earth and handover between satellites. Satellites are rarely eclipsed from the sun, facilitating power generation and high transmit powers. The real drawback with HEOs is the same as that for GEOs - the propagation delay. HEO satellites are only active at the highest part of their orbit, when altitudes are higher than those of GEO for some orbits. So far, no commercial HEO systems have been proposed.

4.4. Spot Beams

The footprint of a satellite is the maximum area it can cover at one time. It is also the maximum area over which its radio transmissions can interfere with others, so preventing radio resource re-use. Given satellites with a single beam, a LEO satellite system would provide greater capacity than a GEO system due to the increased number of satellites and opportunity to re-use radio resources on each satellite.

In common with any cellular system, radio resource re-use can be increased by limiting the propagation of radio signals to as small an area as possible. In a satellite system this is achieved by narrowing the radio beam from the whole footprint to focus on a part of the footprint. An effect of this increased directivity of the signals is to increase the signal power reaching the Earth's surface, so improving the link power budget. This is why it is becoming common practice to split the satellite's coverage into spot beams by using multiple, narrow beam width antennas. In principle, it is possible to develop a GEO system that would have an equivalent capacity to a LEO system by using a very large aperture antenna on a satellite of sufficient size to support such a structure. This represents an increase in complexity over current technology since a large antenna and very complex inter-beam connectivity would be required. Although this has yet to be demonstrated in practice, system capacity can be seen to be not totally dependent on the choice of orbit but on the area of each spot beam on the ground.

With GEO satellites, the spot beam pattern is fixed on the Earth so there is the possibility of directing the smallest spot beams to the densest traffic areas to optimize capacity. In the non-GEO systems, satellites move across the Earth's surface and the spot beam pattern can be used to minimize some of the effects of this motion on the radio link. It is possible to steer beams on non-GEO satellites to track traffic on the Earth's surface, requiring a sophisticated dynamic beam forming network on board the satellite.

The size and shape of the spot beams on LEO and MEO satellites are determined by the satellite antenna radiation patterns and can be tailored to meet the specific requirements, such as maximizing frequency re-use, minimizing Doppler spread across the spot beam or minimizing the frequency of handovers between spot beams.

Because a non-GEO satellite is moving extremely rapidly over its mobile terminals, the motion of the mobiles can safely be ignored and we consider only the motion of the beam pattern over the mobile terminals. To maximize frequency re-use, spot beams are made as small as possible, normally by using circular beams (figure 18(a)). To minimize Doppler spread the beams should be as narrow as possible perpendicular to the direction of satellite motion (figure 18(b)). Conversely, to minimize handovers the beams should be as large as possible parallel to the direction of satellite motion (figure 18(c)).

The simplest beam shape to form is a circular one and this shape of beam generally gives the smallest beams for a given antenna mass. To "squash" the beam shape requires an antenna that is proportionally larger in one dimension than it is the other to reduce the beam width in the appropriate direction. Depending on the design of the satellite bus there may be scope to provide this extra antenna area for little additional cost in satellite mass.

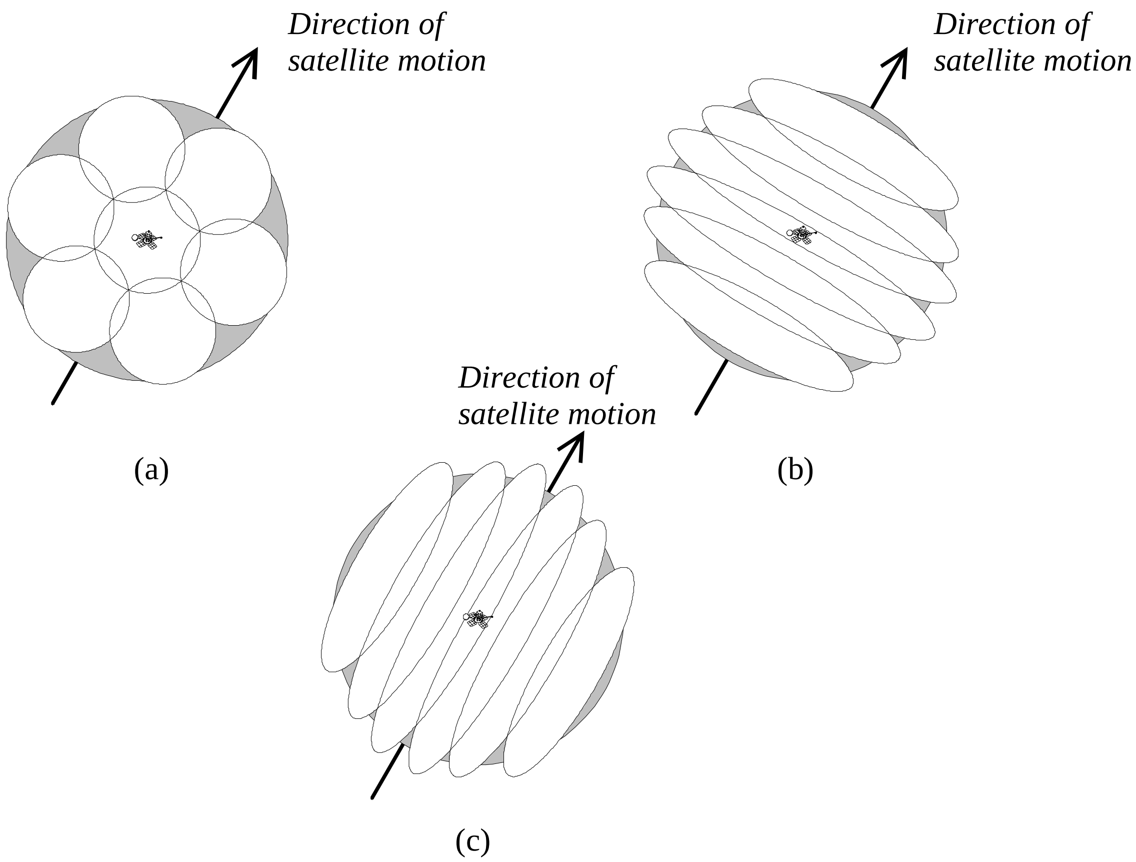


Figure 18 Satellite beam patterns (a) in regular hexagonal pattern, (b) optimized to minimize spread of Doppler shift and (c) optimized to minimize handovers between beams

The beam pattern in 16(c) minimizes handovers between spot beams but does not change the frequency of handovers between neighbouring satellites. Drawing analogy with mobile users moving from one sector to another within a terrestrial cell, movement between spot beams is a very similar operation: the path length in the new spot beam is identical, as are all the channel's characteristics. Intra-satellite handover is the relatively trivial matter of moving the communications from one beam to another. This could be made as simple as moving the existing carrier from one beam to another if the carrier is not being used in the adjacent spot beam or its neighbours.

With spot beams and satellite footprints overlapping, no multiple access system can allow the same radio resource to be used in adjacent cells without interference occurring. However, there are likely to be mobiles in the spot beams next to the mobile's new spot beam that are using the old carrier, which would cause unsatisfactory interference if the carrier were not changed. It is therefore often still necessary to change carrier frequency or time-slot at each spot beam crossing to achieve handover between spot beams. Chapter 7 on satellite channel allocation describes ways to simplify this process. If both spot beams are controlled by the same FES (chapter 6 shows why this might not always be the case) then there is no change to the routing of the call (except the final satellite beam, which originates from the same satellite, destined for the same mobile terminal), there are only minimal synchronization problems. Thus intra-satellite handover is relatively simple to implement (see section 6.5.2).

In view of the simplicity of intra-satellite handover, it is possible to accept frequent intra-satellite handovers if some efficiency advantage can be gained by doing so. Altering beam patterns cannot effect inter-satellite handovers, which is where the handover complexities manifest themselves. Only the orbital altitude effects inter-satellite handover frequency.

Beam patterns like those shown in figure 18(a) and (b) can therefore be considered as optimum patterns for TDMA or FDMA schemes as they can be shown to improve spectral efficiency by reducing the need for frequency guard bands (see section 7.4.3). For the baseline 769km altitude LEO used in this thesis, by using spot beam widths of 20° across their smallest axis the satellite coverage footprint can be split into six spot beams across the footprint diameter in the direction of motion. Proposals for mobile satellite systems in section 4.3 indicate current antenna technology can support six or more spot beams across the diameter of a LEO satellite coverage footprint. For example, Iridium originally proposed seven. Globalstar originally proposed six but CDMA counters its Doppler problems, so they were arranged as in figure 18(c). Odyssey originally proposed only five but in MEO Doppler effect will be less. All three have now increased the number of beams on their satellites but for this thesis the worst original LEO case, six spot beams, is used as a baseline.

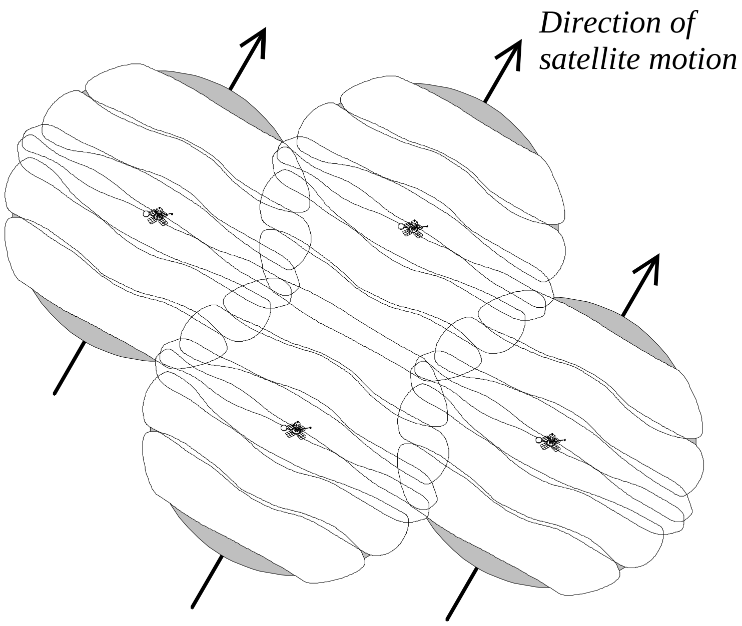


Figure 19 Beam patterns projected onto the equator from four satellites in the 769km baseline LEO

The smallest axis of each beam is parallel to the satellite's motion to give a minimum change in Doppler shift as each spot beam passes over the mobile. Since the rate of change of Doppler frequency shift is largest whilst the satellite is overhead (and changes as a sinusoidal function with time) the beams can be made narrowest at the centre of the satellite footprint and wider at the periphery. Because of the "projection" of the beams onto the spherical Earth's surface, this will tend to happen anyway. Ideally, beams of equal area (and therefore equal traffic demand) are also desirable which is another reason to use long, narrow beams at the centre and shorter, wider beams at the periphery of the footprint. The antenna gain pattern can be shaped to provide roughly equal power flux density at all points on the Earth's surface within the satellite footprint using a so-called "isoflux" antenna. Figure 19 shows beams like this projected over the equator from 4 satellites in the baseline 769km. Further reduction of the beam size, in any direction, would increase frequency re-use as each satellite footprint could be split into more spot beams.

4.5. Distribution of Switching and Control

Before defining the UMTS network architecture it is useful see how the choices of spot beams, orbits and inter-satellite linkage effect the technology required on board the satellites.

The next chapter shows that the FES has very similar functions to the base station and CSS (cell site switch) in the UMTS network architecture. It becomes apparent that the intelligent functions are notionally performed at the FES and the satellite link itself is transparent. This is indeed a satisfactory solution for GEO, HEO and MEO constellations and describes the first class of satellite system to be used in FPLMTS, the bent-pipe transponder class.

ISLs are essential for lower altitude LEO constellations, as noted in section 4.3.1. These potentially complicate the analogy with terrestrial cellular if functions associated with cell-site switching are performed by the satellites themselves. For the UMTS network architecture, it is sufficient to define where network functional entities reside, either within the FES or moved aboard the satellites. Thus two more classes of satellite are defined, those with call handling intelligence on board and those where the satellites' role is limited to a cross-connect between satellites and the ground. Iridium certainly falls into the cross-connect category and it would appear that Teledesic might, too. However, the fully switching satellite class is included because it is only a short step away from the current proposals.

In summary, three distinct classes of satellite systems have been identified:

1. *Bent pipe satellites* with transparent repeaters between mobile terminal and FES (e.g. AMSC, Inmarsat-P, Odyssey, Globalstar)
2. *Cross-connect satellites* with ISLs (typically LEO, e.g. Iridium and Teledesic) but switching functions limited to a cross-connect facility which is programmed by call-control intelligence in the FES [WERNER]
3. *Switching satellites* with inter-satellite links and full call-control and switching on board the satellites (a futuristic LEO scenario).

4.6. Capacities, Services and Costs

Table 4 shows the range of capabilities of the systems licensed by WARC '92, WRC '95 and the FCC and how much they will cost to build. The total in-orbit costs of the constellations are the latest estimates and include the satellites and FESs. Costs of customer's mobile terminals are not shown because their complexity is similar for all the systems and the real cost will depend largely on the size of a system's market. Initially dual-mode terminals are likely to cost the same as AMSC Skycell terminals cost now, US$2000 or more. In a more mature market this cost will drop to about a tenth of this and the cost of terminals might be subsidised by the call revenues of operators. Call charges are tabulated but should be compared with caution. Some are wholesale to service providers, others are cost to the final customer. Some exclude charges in the terrestrial core network, others are all-inclusive rates.

	Teledesic	**Iridium**	**Globalstar**	**Odyssey**	**Inmarsat-P**	**AMSC**
Constellation						
Total system cost	$9bn	$3.8bn	$2.6bn	$2.3bn	$2.6bn	$0.6bn
Manufacturer		Lockheed	Loral	TRW	Hughes	Spar/Hughes
No of satellites	840	66	48	12	10	2
Orbital altitude	695~705km	780km	1,414km	10,354km	10,355km	35,786km
Orbital inclination	98°	86°	52°	55°	45°	0°
No of orbital planes	21	6	8	3	2	1
Minimum satellite elevation	40°	8°	0° (with diversity)	21°	0° (with diversity)	0°
Coverage	Global	Global	Global (to ±80° latitude)	Global	Global	North and Central America
Frequencies (GHz)						
Mobile uplinks	26.6~29.0	1.62~1.63	1.61~1.63	1.61~1.63	1.98~2.01	1.64
Mobile downlinks	18.8~19.2	1.62~1.63	2.48~2.50	2.48~2.50	2.17~2.20	1.54
FES uplinks	27.8~28.4	19.4~19.6	5.09~5.25	29.1~29.4	6.5	
FES downlinks	17.8~18.6	29.1~29.3	6.70~7.08	19.3~19.6	3.6	
Inter-satellite links	59.5~63.5	23.2~23.4	None	None	None	None
Multiple access						
Scheme	TDMA	TDMA	CDMA	CDMA	TDMA	TDMA
Beams per satellite	64	48	16	37	163	6
Spot beam area	2,800km^2	350,000km^2	2,900,000km^2	2,300,000km^2	950,000km^2	11,000,000km^2
Channels per beam	1,563	23	175	62	28	
Channels per million km^2	558,214	66	61	27	29	
Services	Briefcase	Hand held	Hand held	Hand held	Hand held	Briefcase
Voice telephony	16kbit/s	4.8kbit/s	4.8kbit/s	4.8kbit/s	4.8kbit/s	Yes
Transparent data (BER≤ 10^{-3})	16kbit/s	2.4kbit/s	7.2kbit/s	9.6kbit/s	2.4kbit/s	Yes
Call charge, US$ per minute		$3 flat rate	$0.65 + terrestrial charges	$1 + terrestrial charges	$1~$2	$1.50 + $65/month service charge
Lead investors						
Service providers	Bill Gates Craig McCaw AT&T McCaw Kinship Partners	US Sprint Hutchison Vebacom KMT DDI STET	AirTouch Vodafone US West Dacom France Telecom	Teleglobe	Inmarsat Comsat KDD MCN VSNL T-Mobil CPRM	Singapore Telecom AT&T McCaw MTel Bell Canada Teleglobe
Manufacturers		Motorola Lockheed Sony Mitsubishi	Loral Qualcomm Alcatel Alenia Deutsche Aerospace Hyundai	TRW	Hughes NEC	Hughes

Table 4 Current mobile satellite proposals