Broadband satellite system technologies for effective use of the 12–30 GHz radio spectrum

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Broadband satellite systems are an integral part of communications technology, aiming to provide a wide range of services to a society that increasingly expects ubiquitous access to broadband telecommunication services. Key drivers behind the development of these systems include rapid growth in the use of the Internet, PC- and TV-based e-commerce and interactive broadcasting services. In the UK, broadband satellite service trials are currently being conducted by BT, amongst others, with a primary objective of providing services to areas where asymmetric digital subscriber line (ADSL) technology has not been deployed. Two key factors for the success of broadband satellite technology lie in the area of overcoming constraints associated with frequency spectrum and orbital resources. This paper provides a review of technologies employed in geostationary (GSO) and nongeostationary (NGSO) satellite networks designed for the provision of broadband services to fixed and portable ground terminals within the 12 to 30 GHz frequency range. After reviewing the system design parameters related to the use of the radio frequency spectrum, consideration is given to the issues involved in sharing spectrum between GSO and NGSO satellite networks.

1 Introduction

The continued growth in demand for fast Internet access and multimedia services provides a basis for the development of broadband satellite systems despite the recent global economic decline. Direct-to-home broadband satellite services are already on offer by the key European players—Eutelsat and Astra. Using a fixed satellite dish and a PC card, it is possible to establish a direct home-to-satellite link in order to benefit from a range of services including TV on PC, fast Internet access, multicasting (where multimedia content (news, music, video, scientific data) is distributed to dedicated user groups) and interactive teletraining.

The provision of broadband satellite services critically depends on the availability of radio spectrum and orbital resources. Geostationary orbit slots have been filled up by C-band (6/4 GHz) and Ku-band (14/12 GHz) satellite systems. Therefore, in recent years, attempts have been made to make use of the high-capacity offered by the Ka-band (30/20 GHz). After a number of successful technology demonstration satellite missions, Ka-band system applications involving hundreds of GSO and NGSO satellites were filed with the International Telecommunications Union (ITU)[1–3].

In parallel to developments in GSO satellite system technology, deregulation of telecommunications services led to structural changes in the satellite communications industry that, coupled with the existing congestion of orbital and spectral resources, drove the exploitation of new frequency bands and orbital configurations, for example the use of non-geostationary orbits to establish broadband satellite networks. Many of the NGSO systems that have been proposed for operation at Ku- and Ka-band frequencies are still at the planning and fund-raising stage[4,5]. The best known proposals under development with an increased likelihood of deployment are the Skybridge, a Ku-band low earth orbit (LEO) constellation comprising 80 satellites, and Teledesic, a Ka-band constellation proposing to use 288 LEO satellites*.

As a consequence of an ever increasing demand, the regulation and management of spectrum and orbital resources are becoming increasingly important. Access to radio spectrum is based on the Table of Frequency

*At the time this paper was being finalised Teledesic announced a new constellation design based on 30 medium-earth-orbit satellites.

Fig. 1 **Multibeam satellite downlink coverage**

Allocations of the ITU Radio Regulations where the frequency bands in different parts of the spectrum are allocated for different radio services. Due to scarcity of the radio spectrum, many frequency bands are allocated to more than one radio service and are, therefore, shared.

The plans for spectrum sharing among GSO and NGSO broadband satellite systems at Ku- and Ka-band frequencies have sparked lively debates at an international level. There has been an enormous interest at international meetings, where investigations on the operational compatibility of GSO/NGSO systems have been discussed. This paper describes some GSO and NGSO satellite system design issues related to the efficient use of the radio spectrum at these frequencies. This is followed by detailed discussions concerning spectrum sharing between GSO and NGSO satellite networks.

2 GSO system characteristics

GSO satellites designed for Ku-band operation are equipped with multiple (typically between 12 and 52) high-power transponders, each comprising transmitter and receiver equipment with typical bandwidths in the range 24–72 MHz[6–9]. A transponder's available power and bandwidth are shared among a number of different carriers by employing conventional multiple access techniques, which may also be used in combination to increase the efficient use of the available radio spectrum[10,11]. It is worth noting that most GSO networks employ transparent transponders; the first commercial satellite—*Hot Bird 4*—with an on-board processing transponder operating in Ku-band was launched by Eutelsat in February 1998.

In a typical Ku-band GSO application, a satellite is located at a single orbital position on the GSO arc to provide fixed multiple widebeam coverage over a very large geographical area. Fig. 1 illustrates the Eutelsat *Atlantic Bird 1* satellite (planned to be launched this year) multibeam downlink coverage map[6].

In addition to multiple fixed widebeam transmit and receive coverage, a steerable beam coverage may also be employed to establish single-satellite hop links between different geographical areas. The satellite payload equipment, therefore, includes fixed and steerable antennas with diameters, typically, within the range 1–3 m. To maximise the system capacity, transponders may support orthogonal polarised carriers.

As far as a GSO system ground segment is concerned, earth stations may be connected to the end-user directly, as for example with very small aperture terminals (VSATs), or via terrestrial networks. Depending on the type of applications to be supported, Ku-band earth station antenna diameters may be as large as 10 m.

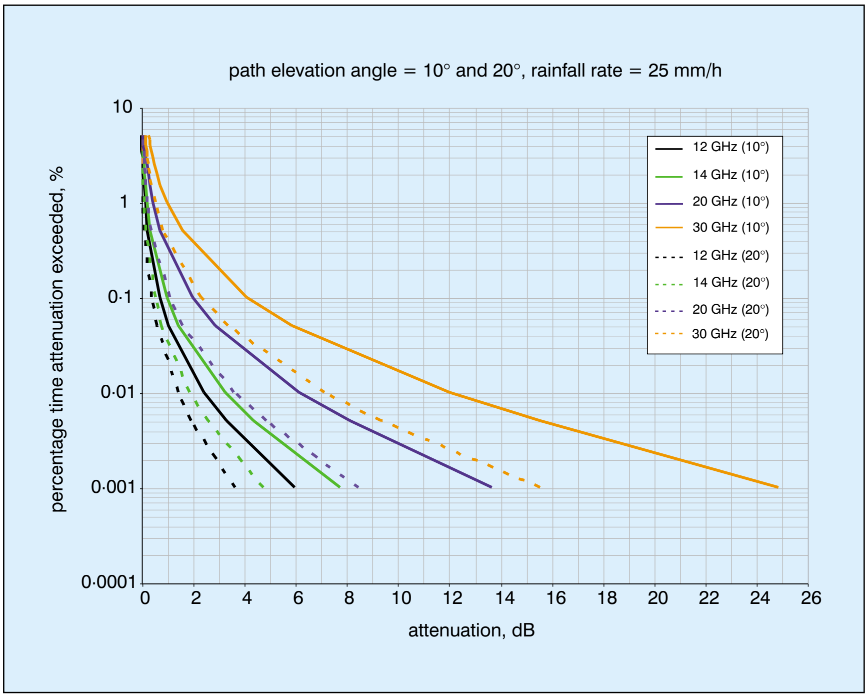


Fig. 2 **ITU-R Rec. P.618 rain attenuation statistics**

Currently, GSO satellite networks are being developed to support both Ku- and Ka-band carriers. The Astra-1H satellite launched in June 1999 was the first commercial satellite employing transparent Ka-band transponders to provide broadband interactive multimedia services[12].

Primary concern in both Ku- and, especially, Ka-band satellite system design is that of overcoming rain attenuation. The operating frequency, geographic location (i.e. longitude and latitude) and path elevation angle are the key parameters determining the impact of rain on satellite links. The impact of rain increases at low elevation angles as the path length through the rain region becomes greater. Therefore, satellite networks operating in these bands can only provide services to ground terminals that have elevation angles greater than, for example, 10° to limit the adverse rain effects.

In general, the statistical rain attenuation model defined in International Telecommunications Union Radiocommunications Section Recommendation P.618 (ITU-R Rec. P.618)[13] is used for estimating the link rain fading when designing satellite links. This model is empirical and based on long-term rain fading measurements stored in the ITU-R data bank. The rain statistics obtained from the ITU-R Rec. P.618 are in the form of a cumulative distribution of rain attenuation exceeded for a given percentage time. The statistical model is valid up to 55 GHz for percentage times in the range 0·001% to 5%.

The rain attenuation cumulative distribution functions for Ku- and Ka-band frequencies are illustrated in Fig. 2 for path elevation angles of 10° and 20°. It is assumed that the links are operating at 0° longitude and 50° latitude and that the rainfall rate is 25 mm/h.

The ITU-R Rec. P.618 rain statistics indicate that, for frequencies between 12 GHz and 30 GHz, the rain attenuation values exceeded for 0·01% of the time vary in the range 2·5–12·5 dB at 10° elevation and 1·5–7 dB at 20° elevation. To overcome the rain attenuation, satellite systems are designed to employ high effective isotropically radiated powers (EIRPs) on board the satellites in order to provide high link margins. In Ka-band applications many GSO constellations therefore plan to employ regenerative satellites[14–19].

In addition, rain effects can be minimised by selecting satellite orbit locations on the geostationary arc that ensure that high elevation angles are maintained from the GSO earth stations. This, in turn, implies that at least one GSO satellite should be viewable at sufficiently high elevation angles from a large proportion of the land areas of the earth.

In general, Ka-band GSO networks employ inter-satellite links, digital beam-forming networks producing multiple spot beams, and digital processors for switching traffic among beams. Intersatellite links provide global interconnectivity by enabling long-range communication between GSO satellites and are usually designed to operate in the 60 GHz band. They have lower end-to-end transmission delays than multi-satellite-hop connections involving terrestrial links. Establishing intersatellite links with nearby satellites (within a few degrees of longitude) of other compatible networks has also been proposed in order to increase the interconnectivity further[15].

Ka-band offers relatively larger bandwidths but requires higher satellite EIRPs to compensate for higher link fading. These features, in turn, require satellite antennas capable of radiating a large number of narrow spot beams so that power and bandwidth resources can be focused on the service areas[3]. Ka-band GSO system proposals may include multiple satellite antennas (~1 m in diameter), each having an offset reflector fed by an array of feed elements, which are used to generate up to 100 high-power, shaped, multiple spot beams per satellite. An alternative proposed antenna technology uses direct-radiating phased-array antennas in which all the radiating elements contribute to each of the spot beams.

Spot beams are generally positioned on a regular matrix and overlap at a crossover point close to their nominal half power beamwidth to afford contiguous coverage of the service area. The beamwidths of the spot beams are typically less than one degree and the beams employ orthogonal polarisations to increase the system capacity. It is worth noting that dual polarisation may affect the unavailability of the links in comparison to single polarisation due to depolarisation-induced interference resulting from adverse propagation effects.

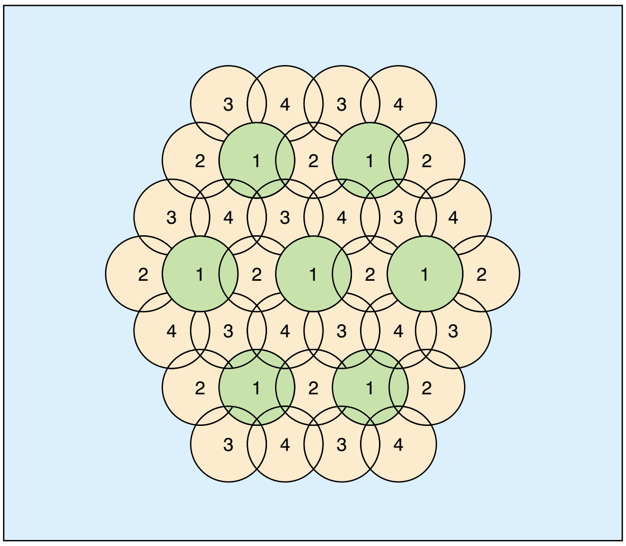


Fig. 3 Four-cell frequency reuse pattern

The use of very small spot beams also allows a high level of frequency reuse. For example, a proposed four-cell frequency reuse pattern ensures that no adjacent beams have the same frequencies allocated to them, and that every beam is isolated from a co-frequency beam by at least one beam spacing as illustrated in Fig. 3[15].

The Ka-band system proposals indicate that these networks will employ low-order modulation techniques (for example, QPSK). Higher order modulation schemes (for example, 64-QAM) require relatively higher carrier-to-noise ratios. In Ka band, this is difficult to achieve due to limitations of the satellite and earth station power amplifiers and the relatively higher rain attenuation.

The ground segment of Ka-band GSO networks comprises user terminals and gateway stations. A range of user terminals is used depending on the capacity requirement, location within the service area, elevation angle to the satellite and required service quality. User terminal antenna diameters typically range from 50 cm to 2 m[14–18]. The primary reasons for deploying larger antennas are to overcome transmitter power limitations, to provide higher link availability for critical applications and to improve system availability in high-rainfall regions and high-latitude areas. To maximise the spectrum efficiency, Ka-band GSO satellite networks facilitate user terminal uplink power control, whereby each terminal adjusts its transmitter operating power according to the strength of the received signal from the satellite.

Gateway earth stations are used to provide interconnection between the satellite network and terrestrial communication networks. Typically, each satellite

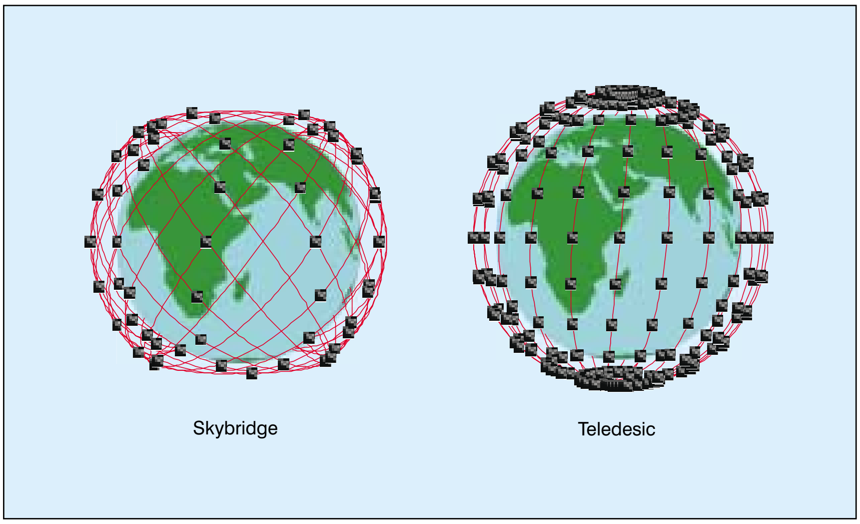


Fig. 4 (*a*) Skybridge and (*b*) Teledesic constellations

coverage area includes at least one gateway having a relatively large antenna (~2·5–5 m in diameter) and employing a transmitter power level of the order of tens of watts[14–18].

3 NGSO system characteristics

Key NGSO constellation design parameters include the number of orbital planes, orbit altitude and inclination, number of satellites in each orbit, orbit spacing and the relative phasing between satellites in adjacent orbital planes. These parameters together with operational system characteristics determine the geographical area over which continuous system coverage is provided.

One of the key objectives of NGSO system design is to provide sufficient coverage using the minimum number of satellites. For example, Skybridge[20], which is a constellation of 80 Ku-band LEO satellites in 20 circular planes each at 1469 km altitude and inclined at 53°, has been designed to provide continuous coverage over the ± 68° latitude band; Teledesic[21], which comprises 288 Ka-band LEO satellites in 12 slightly elliptical near-polar orbital planes each at a nominal altitude of 1380 km and inclined at 84·7°, has been planned to provide continuous coverage over the ± 72° latitude band. Fig. 4 illustrates both constellations.

The use of multibeam satellites orbiting in inclined multiple planes is a common approach taken by NGSO systems. It enables the networks to use their limited power resources efficiently in providing a sufficient degree of service quality. Typically, there are tens of spot beams per satellite in both uplink and downlink directions. These beams are generally produced by direct radiating arrays (i.e. phased arrays). Each spot beam is dynamically assigned to illuminate a service area having a radius of typically a few hundred kilometres. Therefore, NGSO networks are capable of reusing the allocated frequencies over sufficiently separated service areas.

Note that if small service areas were swept by nadir-pointing fixed beams from a LEO satellite, the ground terminals would be served for only a fraction of the satellite orbital period before traffic would need to be handed over to other satellites. Frequent traffic handover limits the system capacity and implies increased processing costs. Therefore, NGSO systems employ an earth-fixed service area design in which spot beams are continuously steered over the service areas in order to remain fixed with respect to the ground. The ground terminals within each service area track the serving satellite as it moves across. This approach is illustrated in Fig. 5[20].

In a slightly different system design approach, satellites are designed to create a fixed contiguous beam pattern over the areas covered by their footprints. In these constellations, a fixed pattern is locked onto a service area and steered to remain fixed as the satellite orbits in its orbital plane, as shown in Fig. 6[22].

Traffic handover between satellites is required for a number of reasons. These include geometry (for example, there is a satellite with a better elevation angle), propagation (for example, local clutter obstructs the link) and interference mitigation (for example, there is a satellite not causing harmful interference into other networks). High rain attenuation, terrain blocking and other existing terrestrial networks make reliable communication between satellites and ground terminals operating at low elevation angles very difficult. Therefore, NGSO systems employ a minimum operational ground terminal elevation angle, typically between 10° and 40°[20–23].

Depending on the type of transponder used in the constellation, the handover process is implemented by gateway earth stations and/or by on-board processing satellites. Constellations are designed to ensure that there will always be at least one satellite available (not only visible) to which traffic can be switched at any time a given satellite becomes unavailable. NGSO networks employ multiple, mechanically steered or active phased-array ground terminal antennas to facilitate the satellite handover.

The service areas covered by spot beams are populated with fixed and transportable user terminals of different sizes and gateway earth stations. The locations of the latter are selected to provide an unobstructed view towards the satellites. They provide connections to system control and monitoring centres and enable the NGSO system to interface with other networks. User terminals are primarily installed on rooftops to minimise the effects of obstacles on line-of-sight paths to satellite positions. Both gateways and user terminals employ directional antennas and this reduces the potential multipath problem caused by the reflection of signals from local clutter.

Since NGSO terminals require lower EIRP levels than GSO terminals due to their relatively short communication links, solid-state power amplifier modules are used as high-power amplifiers. Although these amplifiers have a lower maximum output power than travelling-wave tube amplifiers, they exhibit greater linearity and higher reliability. In addition, solid-state power amplifiers that have smaller volume and mass can be built which, in turn, reduces the weight of the satellite[24].

As far as the antenna size and transmitter power requirements are concerned, parameters including the operating frequency, amount of traffic to be supported, terminal locations within the satellite footprint, availability objectives and orbit type need to be taken into account. For example, the Spaceway NGSO constellation[23] (Ka-band medium earth orbit system proposal) employs 32 cm user antennas with 4 W solid-state power amplifiers (SSPAs) to support data rates up to 2 Mbit/s, 52 cm antennas with 6 W SSPAs for data rates up to 10 Mbit/s and 2 m antennas with 25 W SSPAs for data rates up to 155 Mbit/s. This system supports four phased-array antennas on each satellite, two for transmit with 1·2 m apertures and two for receive with 0·8 m apertures.

NGSO systems are generally designed so that the satellite power level and transmitter antenna gain can be varied to ensure that a constant power flux density over each service area within the satellite's footprint is achieved (i.e. the increased path loss that occurs when serving areas located near the edge of the satellite's footprint is compensated). For example, in the Skybridge constellation[20], the maximum satellite transmitter antenna gain for a service area located at the nadir of a satellite is 15 dBi. The gain is increased to 22·8 dBi for a service area located at the edge of a satellite's footprint. Similarly, the satellite transmit power level is increased from 1·5 to 4·5 W for a 45 MHz carrier used in service links supporting user terminals located in service areas around the nadir and edge of the satellite's footprint, respectively.

To minimise the carrier power, automatic transmitter power control (ATPC) is employed at the ground terminals, and also at the satellites in some proposed NGSO systems. When fading events occur (for example, under rain conditions) transmitter power is increased to compensate for the additional loss. The use of ATPC minimises power consumption under clear-sky conditions and therefore eases problem of sharing spectrum with other networks by reducing the potential interference.

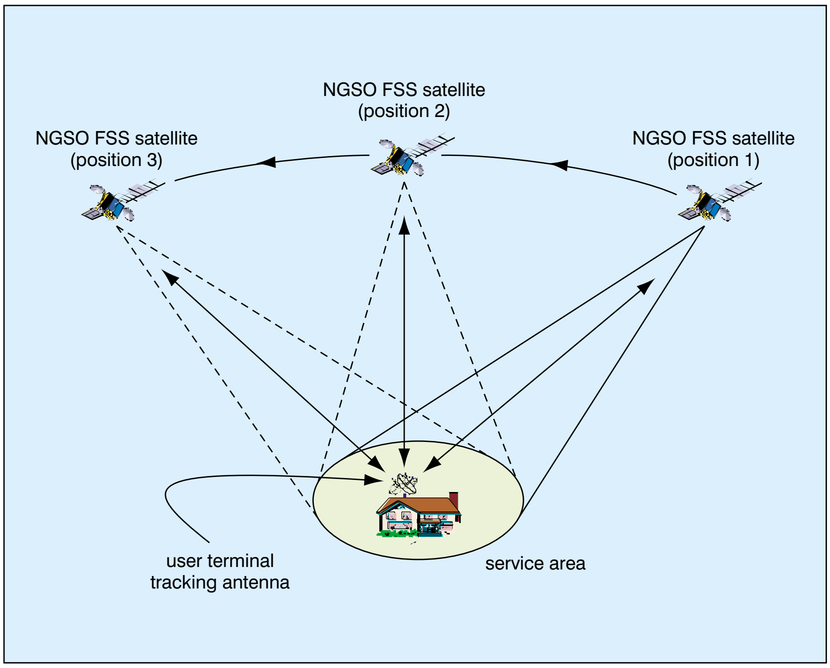


Fig. 5 Spot-beam steering

4 Spectrum sharing

Spectrum sharing enables different categories of radio application to co-exist in the same frequency band and, therefore, ensures that radio frequencies are used as efficiently as possible[25]. The ITU Radio Regulations have recently been updated to allow NGSO systems to share parts of the Ku- and Ka-band spectrums with GSO satellite networks. Extensive studies into the technical and operational compatibility between these systems have been carried out. These studies suggest that NGSO power flux density limits, interference mitigation techniques, GSO earth station reference antenna radiation patterns, co-existence of multiple NGSO systems, cumulative interference from multiple NGSO networks and NGSO

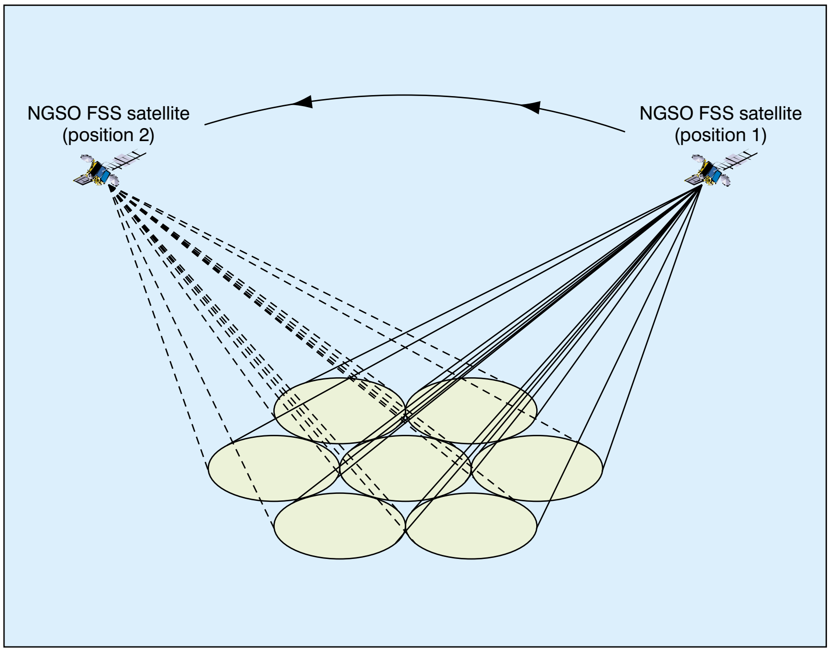
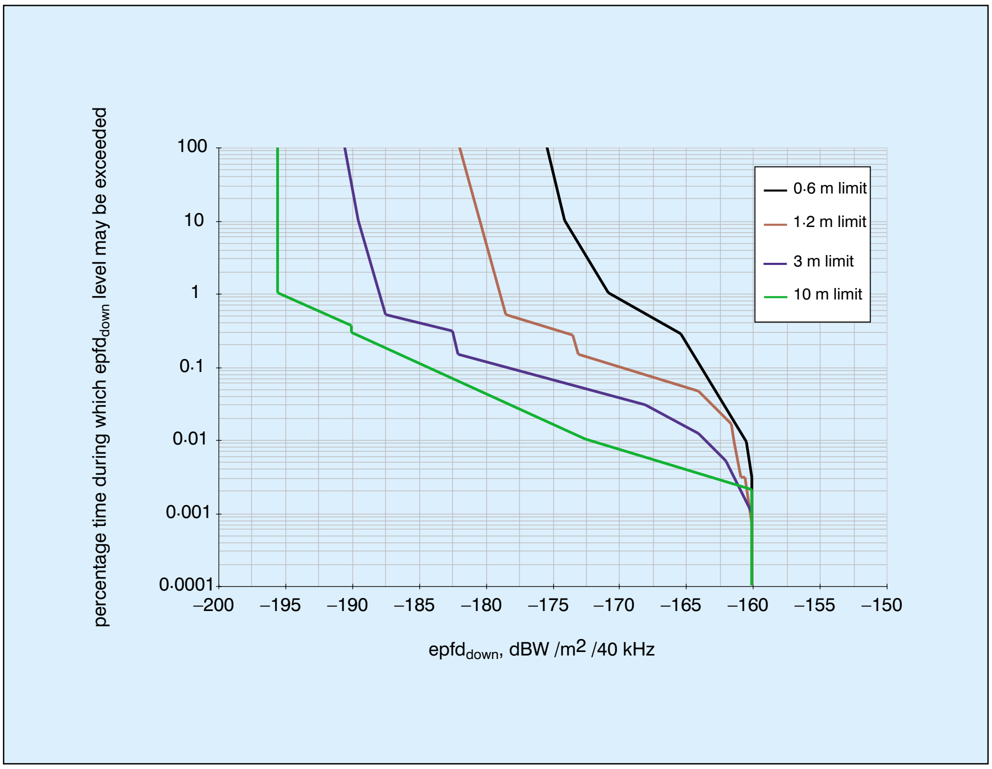


Fig. 6 Fixed-beam pattern

Fig. 7 Revised Ku-band $epfd_{down}$ limits to protect 60 cm, 1·2 m, 3 m and 10 m GSO ground terminal receivers in the band 10·7–12·75 GHz



satellite interference peaks are some of the key topics that need to be considered in the context of NGSO and GSO system co-existence.

NGSO power flux density limits

Traditionally, power flux density (pfd) limits are used to restrict GSO satellite transmit powers in order to protect terrestrial radio stations. These limits relate to the pfd that would be obtained under assumed free-space propagation conditions. They are specified for a single satellite as a function of interference path elevation angle as seen from a point on the earth's surface[26]. Typically, sharing methodologies applied to assess the implications of the pfd limits are based on the calculation of interference from GSO satellite transmissions (represented by pfd masks) at a given terrestrial radio station by employing analytical calculations or static simulation analyses (i.e. simulation scenarios comprising fixed transmitter and receiver stations).

However, interference scenarios involving NGSO and GSO systems require a different approach because the sharing environment is no longer static. Therefore, the concept of equivalent power flux density (epfd) has been introduced to reflect the dynamic nature of the sharing environment. The epfd takes account of both NGSO transmitter and receiver antenna pointings that are time-varying parameters. It is defined as the sum of the power flux-densities produced at a receive station on the earth's surface or in the geostationary orbit by all the transmit stations within an NGSO satellite system, taking the off-axis discrimination of a reference receiving antenna into account[27]. In order to distinguish between uplink epfd (i.e. the epfd at a receive station located in the geostationary orbit) and downlink epfd (i.e. the epfd at a receive station located on the earth's surface), the terms $epfd_{up}$ and $epfd_{down}$, respectively, have been adopted[28].

The epfd masks imposed on NGSO systems were initially incorporated into the ITU Radio Regulations in the form of 'provisional limits' at the World Radio Conference (WRC) in 1997. Since then, a significant amount of work has been undertaken relating to the revision of the provisional epfd limits, and the results of these investigations were considered at the last WRC, held in Istanbul in August 2000. The main outcome of the discussions was that the conference agreed on the revised epfd limits, clearing the way for possible deployment of the new broadband NGSO satellite systems at Ku- and Ka-band frequencies.

Fig. 7 illustrates the revised $epfd_{down}$ limits adopted to limit space-to-earth transmissions from NGSO systems in Ku-band. Note that the epfd limits are defined for an entire NGSO constellation. The primary objective of these limits is to provide interference protection for as many existing and planned GSO links as possible without imposing an excessive burden on the NGSO networks. Fig. 7 indicates that the epfd curves correspond to a number of GSO ground terminal receive antenna diameters. Further studies have been undertaken to define interpolation algorithms to derive epfd limits for antenna diameters not included in the Radio Regulations.

Interference mitigation techniques

NGSO satellite system descriptions include several proposed mitigation techniques for reducing the potential interference into the GSO links. These techniques have a considerable impact on NGSO system design complexity, cost and capacity.

The use of satellite diversity techniques has been proposed to avoid main beam to main beam interference couplings[29]. These techniques are based on either the

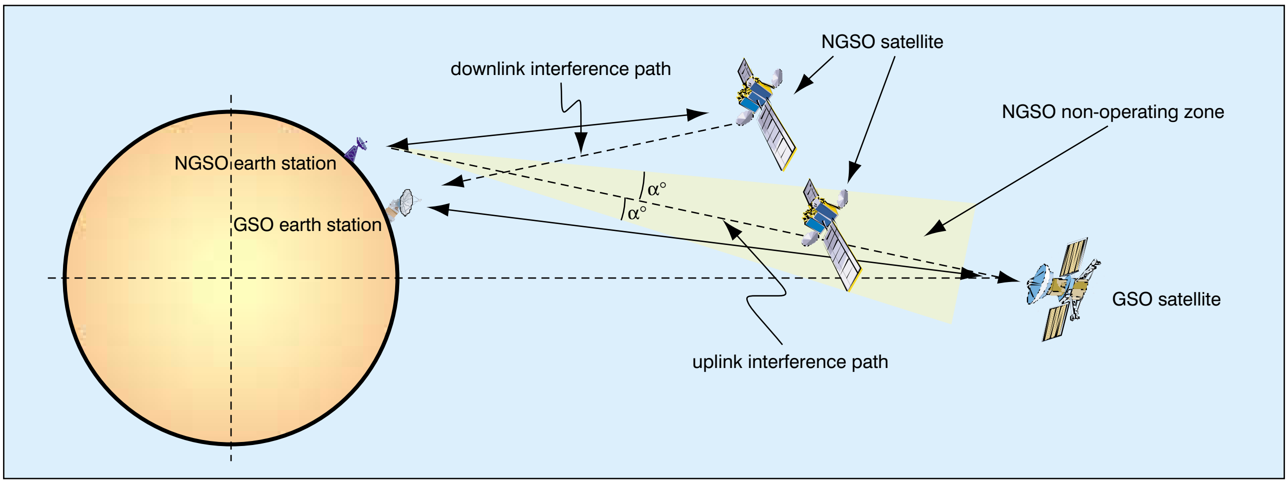


Fig. 8 GSO arc avoidance

selection of another visible NGSO satellite in view or the cessation of transmissions whenever such in-line coupling instances occur. In the former case, it is necessary that the NGSO system be designed to provide a multiple satellite coverage when serving a given ground terminal location. In the latter case, the system should be capable of accepting the loss of coverage and the interruption of links whenever an in-line event occurs.

One proposed diversity technique is based on an NGSO non-operating zone, which is defined to be $\alpha°$ on either side of the geostationary arc as seen by an NGSO earth station, see Fig. 8.

The other proposed technique to avoid main beam interference alignments requires that neither NGSO satellites nor associated NGSO earth stations transmit when NGSO satellites are within the volume defined by $\pm\,\theta°$ in latitude, as illustrated in Fig. 9.

In the implementation of the above techniques, a number of satellite selection procedures are defined. These procedures suggest that a new satellite to which the traffic is switched may be selected either randomly or by applying a selection criterion, for example the highest elevation angle or the largest separation angle away from the GSO arc[30].

The use of high-performance NGSO satellite antennas is also suggested to be an efficient mitigation technique to reduce the impact of downlink interference into GSO earth stations. Satellite antennas with low sidelobe radiation patterns reduce the long-term interference and, therefore, increase the spectrum efficiency.

GSO earth station reference antenna radiation patterns

GSO earth station reference antenna patterns used in spectrum sharing studies represent an envelope of 90% of the actual measured sidelobe peaks. Historically, these patterns were developed to model the worst case interference configurations (i.e. alignments resulting in interference peaks) between the GSO earth stations and the fixed terrestrial radio stations.

As mentioned previously, in the context of spectrum sharing between GSO and NGSO systems, interference events do not correspond to static geometry. This, in turn, suggests that the use of peak envelope antenna reference patterns (based on the worst case static GSO earth station and fixed terrestrial radio station interference alignments) in examining the implications of interference

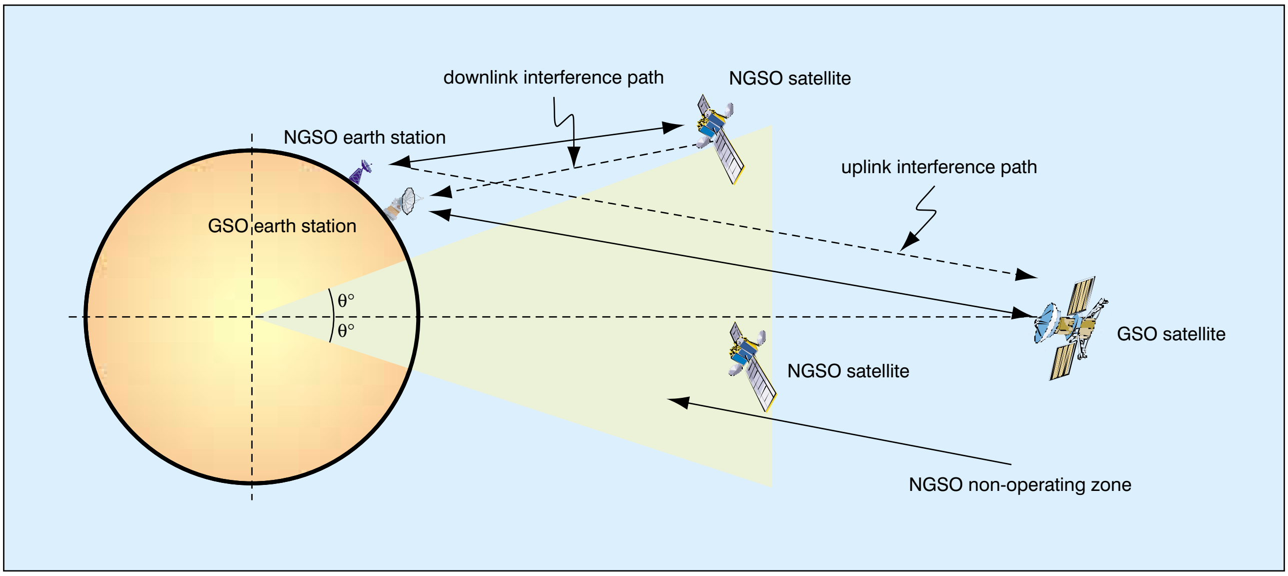
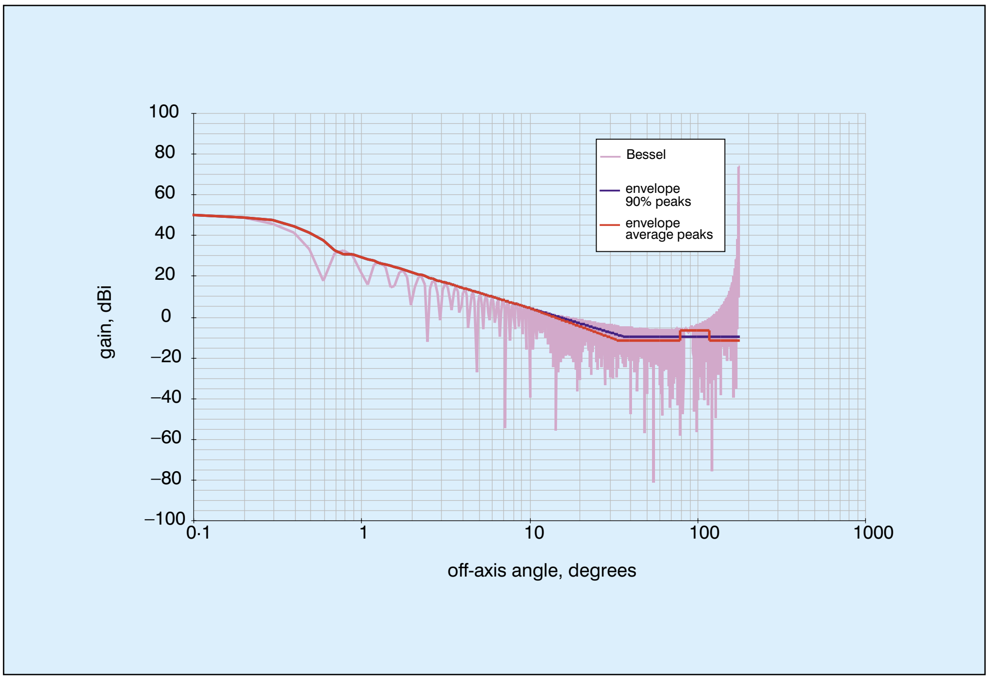


Fig. 9 Latitude avoidance

Fig. 10 Reference antenna radiation patterns



from NGSO satellites (i.e. dynamic, multiple interference sources) may not reflect the actual operating environment.

In a typical GSO and NGSO sharing scenario, NGSO satellites move in and out of the peaks and troughs of an actual GSO earth station antenna radiation pattern and, therefore, interference will vary substantially with time. Two different approaches have been suggested to characterise the GSO earth station reference antenna patterns more accurately in this type of scenario: the use of theoretical Bessel-function-based antenna radiation patterns and the derivation of an average gain envelope based on actual measurements taking both peaks and troughs into account.

Fig. 10 illustrates the reference patterns based on the Bessel function approach[31], the envelope of the 90% sidelobe peaks[32] and the envelope of the average sidelobe peaks[33] for a GSO earth station antenna diameter of 3 m. It can be seen that the Bessel function approach produces slightly reduced near sidelobe peaks and very high gain values near the rearlobe in comparison with the envelope-based patterns. Comparison of the average envelope pattern with the peak envelope pattern suggests that the former reduces the far sidelobe envelope by 2 dB except between 80° and 120°, where the spillover lobe causes a 3 dB higher gain.

From a spectrum-sharing point of view, it is likely that there will be variations in the GSO receiver long-term interference statistics due to the differences in the far sidelobes while the short-term interference is likely to remain at similar levels as the main lobe patterns do not differ significantly.

Co-existence of multiple NGSO systems

As well as avoiding interference into the GSO networks, the NGSO systems need to achieve satisfactory sharing conditions among themselves. Several techniques have been studied for the co-existence of multiple NGSO networks in the same frequency band.

One technique is based on employing NGSO systems in homogeneous orbits. Investigations have suggested that the number of NGSO systems sharing a given frequency band may be increased by using nearly identical orbital parameters, including height and inclination. Plane or satellite interleaving using the same altitude and inclination removes the possibility of an in-line interference alignment where one NGSO satellite is directly between an earth station and another NGSO satellite. However, this degree of similarity between different NGSO networks is unlikely to occur.

The avoidance of in-line interference alignments plays a significant role in facilitating sharing among inhomogeneous constellations. As with the techniques for sharing spectrum between GSO and NGSO systems, mainbeam-to-mainbeam interference couplings between different NGSO networks can be avoided either by switching to another satellite whenever a satellite becomes closer to an in-line interference alignment with a satellite operating in another NGSO network or by simply ceasing transmission and accepting the outage. The complexity of satellite avoidance increases if the number of NGSO systems becomes larger.

The use of satellite diversity implies that NGSO networks filed more recently with the ITU-R require more satellites than those filed (or operational) earlier as the NGSO co-ordination procedures defined in the Radio Regulations place the obligation for implementing interference mitigation techniques on systems filed later. The relatively larger constellation requirement, in turn, brings economic viability into question.

The use of various satellite selection strategies, improved satellite and ground terminal antenna patterns, frequency channelisation and alternate polarisation have been suggested as alternative interference mitigation techniques. A new ITU-R Recommendation S.1431 has been produced comprising key conclusions of the studies concerned with interference among the NGSO systems[34].

Cumulative interference from multiple NGSO systems

As mentioned previously, the epfd limits defined to minimise the impact of interference from NGSO systems into GSO networks are attributed to a single NGSO system (i.e. single entry interference limits represent multiple interference entries from a single constellation). The reason for this approach is that if aggregate epfd limits were to be incorporated into the Radio Regulations this could lead to situations where the first comer would take all of the acceptable allowance for itself, thus preventing other NGSO systems from accessing the frequency band.

In sharing studies, compliance with the epfd limits is checked by comparing the aggregate epfd statistics derived from interference scenarios where single or multiple NGSO systems interfere with a GSO receiver against the single entry epfd limits defined in the Radio Regulations. This raises the question: 'Is there a possibility of defining a conversion method to be used in deriving single-entry epfd statistics from those corresponding to interference from several NGSO systems so that the comparison against the single-entry limits given in the regulations is meaningful?'

Probably the most significant factor involved in relating the single entry epfd to the aggregate epfd is the assumption that the NGSO systems each lead to a similar level of single-entry epfd at a GSO receiver. It is generally agreed that the aggregate interference power from N actual NGSO systems ($N_{physical}$) is likely to be different from the interference power caused by one system multiplied by a factor of N since the various NGSO networks will not have identical impacts. Therefore, the concept of 'number of effective NGSO systems ($N_{effective}$)' has been introduced. On the basis of the findings of sharing studies, it is recommended that the value of $N_{effective}$ should be assumed to be 3·5 when converting the epfd statistics from the aggregate to the single entry[33].

Furthermore, investigations have shown that the mechanisms by which interference from several NGSO networks aggregate need to be considered in the conversion process. In this context, identification of the aggregate epfd boundaries at which interference aggregates on a power and a time basis plays a significant role. Taking the number of effective NGSO systems and the power/time aggregation boundaries into account, it is possible to implement the aggregate-to-single entry epfd conversion[35].

Effects of NGSO satellite interference peaks

It is recognised that very short-term interference peaks from NGSO satellites may cause a loss of synchronisation in the GSO earth station's receive modem. Although an interference event may be of very small duration, the time taken to resynchronise after a loss of synchronisation effectively magnifies (in time) the interference event, and this, in turn, increases the unavailability of the GSO link.

Table 1: Synchronisation loss criterion for various modulation and coding techniques

Modulation and coding	$C/(N+I)$, dB
QPSK rate 7/8	6·0
QPSK rate 3/4	5·3
QPSK rate 1/2	3·5
8-PSK	8·1
16-QAM	11·0

Most of the studies[36–38] on this issue have investigated the level of interference that would cause a loss of synchronisation, the amount of time required to resynchronise and the frequency of synchronisation loss events. Measurements on actual modems operating in the presence of simulated interference peaks have shown that the point at which a GSO earth station receiver loses synchronisation depends largely on the type of modulation and coding employed in the GSO link.

NGSO interference peaks result in two distinct modes of GSO receive modem behaviour. Less severe interference events cause a loss of synchronisation. In such cases, the recovery time is in the order of a few seconds. For more severe interference events, a carrier is lost and search mechanisms are applied for carrier recovery. In these instances, the reacquisition times may be significant.

Table 1 illustrates $C/(N + I)$ ratios below which GSO link synchronisation loss is expected to occur for various types of modulation and coding techniques for data rates less than 34 Mbit/s[35].

In-line interference events that are likely to occur over a portion of the earth's surface are significantly affected by the technical and operational characteristics of the NGSO system. If multiple NGSO systems having different orbital parameters share the same band, the locations of interference peaks from each system may be different. This, in turn, implies that the proportion of the earth's surface subject to NGSO interference peaks is likely to increase.

5 Conclusion

This paper has presented a general overview of GSO and NGSO system technologies to be used in the provision of broadband services within the 12 to 30 GHz frequency range. Important system design characteristics include system coverage requirements, satellite beam characteristics, antenna characteristics, transponder technologies, frequency reuse, propagation impairments and operational characteristics (i.e. minimum elevation angle, power control, beam steering, multisatellite coverage, traffic handover and EIRP requirements). Where GSO and NGSO networks share spectrum consideration must be given to NGSO power flux density limits, interference mitigation techniques, the radiation patterns of GSO earth station reference antennas, the co-existence of multiple NGSO systems, cumulative interference from multiple NGSO networks, and NGSO satellite interference peaks.

References

1 WILLIAMSON, M.: ‘Settling new territory’, *Satell. Today J.*, Philips Business Information Publications, March 1999
2 ROSE, J. L.: ‘Broadband satellites: solutions looking for problems’. IEE Colloquium on Broadband satellite: the critical success factors, technology, services and markets, October 2000, *IEE Colloq. Digest No. 2000/067*, pp.2/1–2/5
3 EVANS, J. V.: ‘Ka-band network design considerations’, *Satell. Commun. J.* (Intertec/Primedia Publications), November 1999, pp.44–50
4 VENKATARAMAN, R., EVANS, A. L., and ROSE, J.: ‘The future of satellite communications’, *Communicate* (Dmg World Media Publications), May 1999, pp.34–37
5 WILLIAMSON, M.: ‘Can satellites unblock the Internet?’, *IEE Rev.*, May 1999, pp.107–111
6 Eutelsat Satellites, see http://www.eutelsat.com
7 Astra Satellites, see http://www.ses-astra.com
8 Intelsat Satellites, see http://www.intelsat.com
9 Panamsat Satellites, see http://www.panamsat.com
10 EVANS, B. G.: ‘Satellite communication systems’ (Peter Peregrinus, 1991)
11 MARAL, G., and BOUSQUET, M.: ‘Satellite communications systems’ (John Wiley, 1993)
12 BULLOCH, C.: ‘For high flying satellite systems’, *Telecommunications* (*Int. Ed.*) (Horizon House Publications), June 1999, **33,** (6), pp.27–31
13 ITU-R Recommendation P.618, ‘Propagation data and prediction methods required for the design of earth–space telecommunication systems’, 1999
14 SARRAF, J.: ‘The Spaceway EXP system’. IEE Colloquium on Broadband satellite: the critical success factors, technology, services and markets, October 2000, *IEE Colloq. Digest No. 2000/067*, pp.15/1–15/6
15 ‘Astrolink-Phase II satellite communication system’. FCC filing, December 1997
16 ‘KaStar satellite communication system’. See http://www.wildblue.com
17 LOSQUADO, G., and MARZIALE, V.: ‘The Euroskyway network with on board processing to support fast Internet and interactive TV services for residential users’. IEE Colloquium on Broadband satellite: the critical success factors, technology, services and markets, October 2000, *IEE Colloq. Digest No. 2000/067*, pp.8/1–8/7
18 ‘Wideband European Satellite Telecommunications (WEST) satellite system’. See http://www.matra-marconi-space.com
19 LOTHIAN, J., and ASHFORD, E.: ‘Critical success factors for the introduction of broadband multimedia in Europe’. IEE Colloquium on Broadband satellite: the critical success factors, technology, services and markets, October 2000, *IEE Colloq. Digest No. 2000/067*, pp.20/1–20/8
20 ‘Skybridge satellite communication system’. FCC filing, February 1997
21 ‘Teledesic satellite communication system’. FCC filing, March 1994
22 ‘@Contact satellite communication system’. FCC filing, December 1997
23 ‘Spaceway NGSO satellite communication system’. FCC filing, December 1997
24 AGHVAMI, A. H., and ROBERTSON, I.: ‘Power limitation and high-power amplifier nonlinearities in on-board satellite communications systems’, *Electron. Commun. Eng. J.*, April 1993, **5,** (2), pp.65–70
25 MCGANN, J.: ‘Caring and sharing’, *Telecommunications (Int. Ed.)*, December 1999, **33,** (12), pp.58–62

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26 ITU Radio Regulations, Articles, ‘Terrestrial and space services sharing frequency bands above 1 GHz (Article S.21)’, Geneva 1998
27 ITU Radio Regulations, Articles, ‘Space services (Article S.22)’, Geneva 1998
28 Modifications to ITU Radio Regulations Articles, ‘Space services (Article S22)’, Istanbul 2000
29 ‘Methods for NGSO FSS systems to enhance sharing with GSO fixed satellite service systems in the frequency bands between 10 and 30 GHz’. ITU-R Working Party 4A, Document 327, April 1999
30 Report of the Meeting of ITU-R Working Party 4A, May 1999
31 ‘Possible use of Bessel functions for representation of reference antenna radiation patterns’. ITU-R Working Party 4A, Document 112, September 1998
32 ITU-R Recommendation S.1323, ‘Maximum permissible levels of interference in a satellite network for a hypothetical reference digital path in the fixed satellite service caused by other codirectional networks below 30 GHz’, Geneva, 2000
33 ITU-R Recommendation S.1428, ‘Reference fixed satellite service earth station radiation patterns for use in interference assessment involving NGSO satellites in frequency bands between 10·7 GHz and 30 GHz’, Geneva, 2000
34 ITU-R Recommendation S.1431, ‘Methods to enhance sharing between NGSO fixed satellite service systems in the frequency bands between 10–30 GHz’, Geneva, 2000
35 Report of the Fourth Meeting of ITU-R Joint Task Group 4-9-11, June 1999
36 ‘Measurement results on the synchronisation losses caused by short term interference into GSO earth station demodulators’. ITU Joint Task Group 4-9-11, Document 248, January 1999
37 ‘Results of further measurements of worst case NGSO interference peaks on demodulators used for high data rate carriers in typical large dish GSO earth station receivers’. ITU Joint Task Group 4-9-11, Document 315, January 1999
38 ‘Analysis by simulation and measurement of the short term interference effects from NGSO satellites into GSO earth stations’. ITU Joint Task Group 4-9-11, Document 359, January 1999

First received 18th June 2001 and in final form 13th February 2002.