RECOMMENDATION ITU-R S.1782

Possibilities for global broadband Internet access by fixed-satellite service systems

(Question ITU-R 269/4)

(2007)

Scope

In order to address issues raised both by the Radiocommunication Assembly and by WRC-03, a preliminary study into possibilities for providing access to the Internet at a high data-rate via satellite has been carried out. In one Annex an attempt is made to identify suitable fixed-satellite service (FSS) bands, and 500 MHz bandwidth pairs are selected within the 11/14 GHz, the 20/30 GHz and the 40/50 GHz FSS allocations. On the basis of direct satellite links from user terminals with 30 cm antennas, up and downlink characteristics for each case are developed, and the per-satellite capacities calculated. The total capacities of such systems to serve a 10 000 000 km^2 reference area are estimated. In a second Annex, up and downlink characteristics in the 20/30 GHz and 11/14 GHz bands are developed for a system that would provide direct satellite links for user terminals with 1.2 m antennas, and again per-satellite and total capacities are calculated. In a third Annex the characteristics are developed of an example system based on user access via terrestrial radio links to "community" earth stations and thence via a 20/30 GHz or 11/14 GHz satellite to a single central earth station, and again the corresponding per-satellite and total capacities are calculated.

The ITU Radiocommunication Assembly,

considering

a) that satellite telecommunication technology has the potential to accelerate the availability of high-speed Internet services in developing countries, including the least-developed countries, the land-locked and island countries, and economies in transition;

b) that it is desirable to determine the technical and operational characteristics of fixed-satellite service (FSS) systems that could facilitate the mass-production of simple user terminal equipment at affordable prices;

c) that it is desirable to assess the global capacity that could be provided in FSS frequency allocations by systems having the characteristics determined in *considering* b);

d) that the determinations in *considering* b) should take into account both the possibility of designing systems specifically for Internet access at high data-rates via small user terminals, and also the fact that some existing systems already include broadband Internet access facilities;

e) that a variety of earth station sizes are being employed for broadband Internet access via existing FSS systems designed to cater also for other applications and using several frequency bands;

f) that development of standards for the satellite technology mentioned in *considering* a) for Internet applications facilitates the wider use of satellite for Internet access, *noting*

a) that Recommendation ITU-R S.1783 describes the characteristics of high-density fixed-satellite service (HDFSS) systems;

b) that Recommendation ITU-R S.1709 describes the technical characteristics of air interfaces of global broadband satellite systems,

recognizing

a) that the FSS frequency allocations can be used in the short, medium and long term for the global provision of high-speed Internet services,

recommends

1 that the information in Annexes 1, 2 and 3 provides three possible examples that may be used in order to implement global access to the Internet at high data-rates via the FSS.

Annex 1

Possibilities for global[1] broadband[2] Internet access by FSS systems designed for very small earth station antennas

1 Frequency band considerations

1.1 Suitable bands

"Short term" applies to bands for which satellite technology has already been developed. At the present time this is wholly true of the 4/6 GHz and 11/14 GHz FSS allocations, and partially true of the 20/30 GHz FSS allocations. It may be expected that in the "medium term", say during the next ten years, satellite technology in the 20/30 GHz bands will become fully developed, and there will be some development in the 40/50 GHz bands also although experience suggests that it will be the "long term" before that development can be regarded as full. There are FSS allocations above 50 GHz in Article 5 of the Radio Regulations (RR), but significant development in them seems unlikely to occur before the long term and they are not considered here.

Preliminary studies ruled out the use of the 4/6 GHz bands for the subject application, on the grounds that low-cost terminals imply very small antennas which would be unlikely to have adequate gain at those frequencies to operate to the wide-beam satellites typically involved. Furthermore, the 4/6 GHz bands are already heavily utilized so, even if spot-beam C-band satellites were provided, it would be difficult for very small-dish earth stations with their correspondingly wide beamwidths to share frequencies with the existing services. Therefore the 4/6 GHz bands are not considered further in this Annex.

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[1] In this study the adjective "global" is interpreted to mean anywhere that may be served by geostationary satellite.

[2] In this study, the example of "broadband" used is a user rate of 2 Mbit/s.

The preliminary studies also considered that to some degree the considerations in the previous paragraph apply also to the 11/14 GHz bands. The constraint on earth station antenna size is less severe than at 4/6 GHz because gain is higher and (medium) spot-beam operation is more common but, like 4/6 GHz, the non-planned frequencies at 11/14 GHz have been heavily utilized for many years so frequency-sharing may be a problem.

The 20/30 GHz FSS allocations are believed to be intrinsically the most suitable for broadband Internet access in the near term, because the wavelength is consistent with very small antennas, the technology is reasonably well developed, and utilization is as yet relatively low. Moreover, Internet access by individuals is incompatible with the way in which the great majority of international use of the FSS bands has been regulated up to now, i.e. by coordination of individual earth stations. The likelihood, that the user terminals will be sold by "high street" retailers in large numbers and installed in homes as well as offices, necessitates a regulatory regime such as that which is being developed to accommodate HDFSS. RR No. 5.516B, referenced by WRC-03 in its call for studies on possible global broadband FSS systems for Internet applications, is partially repeated below for convenience:

"The following bands are identified for use by high-density applications in the fixed-satellite service:

17.3-17.7 GHz	(space-to-Earth) in Region 1,
18.3-19.3 GHz	(space-to-Earth) in Region 2,
19.7-20.2 GHz	(space-to-Earth) in all Regions,
39.5-40 GHz	(space-to-Earth) in Region 1,
40-40.5 GHz	(space-to-Earth) in all Regions,
40.5-42 GHz	(space-to-Earth) in Region 2,
47.5-47.9 GHz	(space-to-Earth) in Region 1,
48.2-48.54 GHz	(space-to-Earth) in Region 1,
49.44-50.2 GHz	(space-to-Earth) in Region 1,
and	
27.5-27.82 GHz	(Earth-to-space) in Region 1,
28.35-28.45 GHz	(Earth-to-space) in Region 2,
28.45-28.94 GHz	(Earth-to-space) in all Regions,
28.94-29.1 GHz	(Earth-to-space) in Region 2 and 3,
29.25-29.46 GHz	(Earth-to-space) in Region 2,
29.46-30 GHz	(Earth-to-space) in all Regions,
48.2-50.2 GHz	(Earth-to-space) in Region 2."

It is noteworthy that these designations add up to the following aggregate bandwidths:

20/30 GHz bands	Global	plus	Region 1	Region 2	Region 3
Down	500 MHz		400 MHz	1 000 MHz	–
Up	1 030 MHz		320 MHz	470 MHz	160 MHz
40/50 GHz bands					
Down	500 MHz		2 000 MHz	1 500 MHz	–
Up	–		–	2 000 MHz	–

Thus, assuming that frequencies in the bands designated for global use can be reused in two or three Regions simultaneously, the total spectrum identified for HDFSS in these bands is, Region-by-Region:

Region 1 – 3 400 MHz down, 1 350 MHz up;

Region 2 – 3 500 MHz down, 3 500 MHz up;

Region 3 – 1 000 MHz down, 1 190 MHz up.

These totals suggest that much more downlink than uplink bandwidth may be needed to meet the needs of HDFSS applications in Region 1, but that in the other two Regions the needs may be of the same order in both transmission directions.

Insofar as the 20/30 and 40/50 GHz bands are concerned, the considerations in this Recommendation are confined to the bands identified in RR No. 5.516B for all three Regions, i.e. 19.7-20.2 GHz, 28.45-28.94 GHz, 29.46-30.0 GHz and 40.0-40.5 GHz (see Table 1).

Although the invitations for ITU-R study on the present topic by both WRC-03 and the Radiocommunication Assembly envisage use of FSS bands, the analyses in this Annex for the 11/14 GHz FSS bands would yield similar results if carried out for the adjacent BSS bands (i.e. 11.7-12.5 GHz in Regions 1 and 3, and 12.2-12.7 GHz in Region 2).

1.2 Current FSS use of the bands

In order to assess the extent to which broadband Internet access requirements could be met by future satellites in the bands discussed in § 2.1, it is necessary to determine the degree to which the orbit/spectrum resource of those bands is either already utilized by existing satellite systems, or will soon be in use by systems already under development for other FSS applications. Noting that an indication of the variation in current and planned usage from band to band may be obtained from the Radiocommunication Bureau’s SNS database, Table 1 compares the numbers of applications for spectrum for GSO/FSS networks up to January 2005 in a 500 MHz segment of each of the FSS allocations in the 11/14 GHz, 20/30 GHz and 40/50 GHz ranges. Each of these 500 MHz bands (except the last one) is allocated to the FSS in all three Regions:

TABLE 1

Comparison of applications for spectrum assignments

FSS allocation	Bandwidth	Transmission direction	Main purpose	Number of filings
10.95-11.2 GHz } 11.45-11.7 GHz }	500 MHz	Space-to-Earth	General FSS commercial applications	12 417
14.0-14.5 GHz	500 MHz	Earth-to-space		16 467
19.7-20.2 GHz	500 MHz	Space-to-Earth	Identified for HDFSS	5 245
29.5-30.0 GHz	500 MHz	Earth-to-space		4 830
40.0-40.5 GHz	500 MHz	Space-to-Earth	Identified for HDFSS	1 205
(48.2-48.7 GHz[(1)])	500 MHz	Earth-to-space		(797)

(1) This is part of a band identified by WRC-03 for HDFSS uplinks in Region 2. Although it was not similarly identified in respect of Regions 1 and 3, it is added in order that the Table can cover uplinks to complement the 40 GHz downlinks.

Together with the fact that there are many more 11/14 GHz satellite payloads in operation today than payloads in the higher frequency bands, the information in Table 1 leads to the following deductions:

– The main global FSS allocations at 11/14 GHz are currently much more heavily utilized than those parts of the 20/30 GHz allocations that have been identified for future global HDFSS use.

– FSS use of the 40/50 GHz frequencies identified for future HDFSS has yet to begin.

2 Possible technical characteristics

2.1 Satellite beams

Studies have found that the objective of providing facilities to access the Internet via satellite at high-data-rates to individual user terminals at affordable prices would best be met by systems designed to accommodate ultra-small aperture terminals (USATs) at the user end of the links 30 cm diameter is the example used in this study. The relatively low antenna gain of such terminals, especially at the lower frequencies under consideration, would lead to modest capacity per satellite and hence to relatively high space-sector cost per bit of information, unless each satellite was designed for frequency reuse via multiple spot-beams.

Tables 3, 4 and 5 summarize relevant parameters from the Annexes to Recommendation ITU-R S.1328, that are relevant to this study, and give an indication of the dimensions of spot-beams likely to be available either now or in the near future. In the case of the 11/14 GHz bands the data in Table 3 is augmented by satellite antenna receive gain figures deduced from replies to a Radiocommunication Bureau Questionnaire in 1998. It may be assumed that satellites designed in the immediate future to provide broadband Internet access will incorporate multiple spot-beams toward the narrow (i.e. high gain) end of the ranges in Tables 3, 4 and 5. Accordingly the parameters in Table 2 are selected as bases for the characterization of the user links of suitable satellite systems. It is assumed here that, for operational convenience, the satellite antenna sub-systems will be designed so that each pair of transmit and receive beams have the same beamwidths and their footprints have the same fixed positions on the Earth's surface.

TABLE 2

Satellite spot-beam characteristics selected

FSS frequency range	11/14 GHz	20/30 GHz	40/50 GHz
Gain at beam centre (dBi)	42	50	55
−3 dB beamwidth (degrees)	1.4	0.6	0.3
Number (*n*) of dual-polar transmit/receive beams per satellite	12	32	64

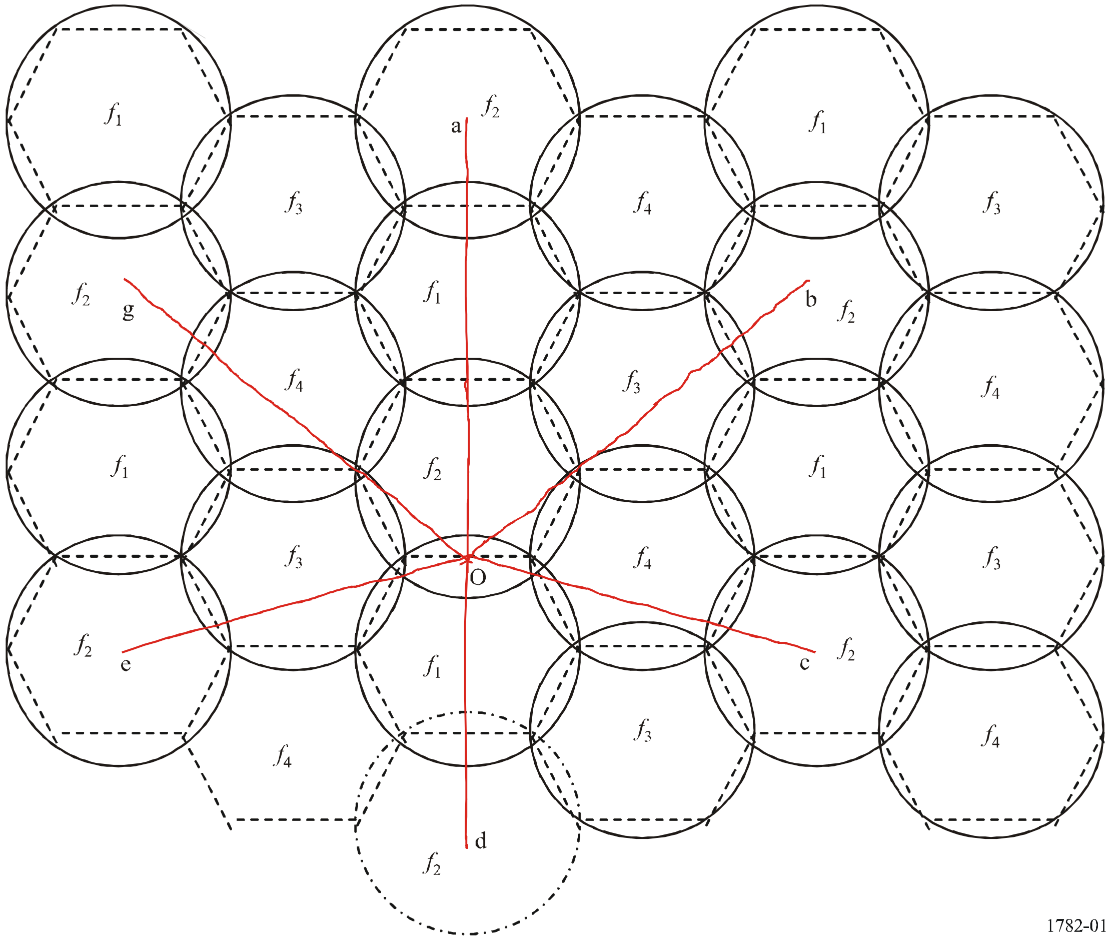
It is important to note here that, as the beamwidth reduces, the pointing accuracy requirement increases, and hence the difficulty and cost of controlling the beam footprints increases.

In the light of spacecraft development in recent years it is reasonable to assume antenna feed arrangements that compensate for the curvature of the Earth's surface to enable all beams generated by a given satellite to have circular footprints of the same diameter regardless of pointing direction. Thus, with the exception of a beam pointing at the sub-satellite point, each beam will have an approximately elliptical cross-section, and its axial ratio and orientation will depend on its pointing direction relative to the direction of the sub-satellite point. The beamwidths of the major (φ_a) and minor (φ_b) axes will be such that $((\varphi_a)\cdot(\varphi_b))^{0.5} = (\varphi_0)$, where ($\varphi_0$) is the −3 dB beamwidth of the (circular) beam pointing to the sub-satellite point.

For continuous coverage via multiple beams with circular footprints a hexagonal pattern of overlaps may be assumed, as in Fig. 1.

FIGURE 1

Hexagonal pattern for footprints of overlapping satellite beams



A one-in-four frequency reuse pattern is shown in Fig. 1, and each beam is assumed to be dual-polarized. Given practicable rates of roll-off and first-sidelobe levels such as those described by the equations in Recommendation ITU-R S.672, the discrimination between the centre of a beam and the nearest edge of the next co-frequency beam should be just about adequate to support this mode of operation. For example, at point "o" at the edge of one of the hexagonal areas served by a frequency f_2 beam, the interference contributions from the nearest six co-frequency beams can be calculated from the off-axis angles oa, ob, oc, od, oe, and og, subtended at the satellite. From the geometry of the diagram:

$$oa = 5(\varphi_0/2) \cdot \cos(30°) = 2.165(\varphi_0)$$

$$ob = og = (\{2(\varphi_0/4) + \varphi_0\}^2 + \{3(\varphi_0/2) \cdot \cos(30°)\}^2)^{0.5} = 1.984(\varphi_0)$$

$$oc = oe = (\{(\varphi_0/2) \cdot \cos(30°)\}^2 + \{2(\varphi_0/4) + \varphi_0\}^2)^{0.5} = 1.561(\varphi_0) \text{ and}$$

$$od = 3(\varphi_0/2) \cdot \cos(30°) = 1.299(\varphi_0)$$

TABLE 3

Spot-beam dimensions of GSO/FSS satellites designed to use 11/14 GHz bands

a) Information extracted from Recommendation ITU-R S.1328

Table in Annexes of Recommendation ITU-R S.1328	Table 2		Table 17	Table 29
Satellite system	GSO-C	GSO-D	GSO-VX	Pan-Af
Peak gain of satellite transmit antenna (dBi)	30	30	33.5	32-38
−3 dB width of satellite transmit beam (degrees)	(5.6)	(5.6)	(3.7)	(4.5-2.2)
Peak gain of satellite receive antenna (dBi)			33.5	
−3 dB width of satellite receive beam (degrees)			(3.7)	
Polarization	Circ	Dual C	Dual C	Linear
Number of service beams per satellite				10

b) Information extracted from replies to a Radiocommunication Bureau Questionnaire

Ninety of the 11/14 GHz links for which data was supplied include satellite receive antenna peak gain values greater than 30 dBi. Thus the corresponding half-power beamwidths are less than 6°, and the beams can be regarded as spot-beams.

These gain values ranged from 30.1 to 45.6 dBi, with an average of 36.5 dBi, corresponding to beamwidths of 5.5° (maximum), 0.93° (minimum) and 2.7° (average) respectively.

TABLE 4

Beam dimensions of GSO/FSS satellites designed to use 20/30 GHz bands; information extracted from Recommendation ITU-R S.1328

Table in Annexes of Recommendation ITU-R S.1328	Table 1		Table 2		Table 3			Table 5		Table 6	Table 12		Table 13
Satellite system	GSO13	GSO20	GSO30	GSOF	GSO11	GSO12	GSO13	System P		Syst Q	GSO Ka-J		EKX
Peak gain of satellite transmit antenna (dBi)	46.5	43.5	55	49	49.5	33	46.5	53.2	46.2	49	41	47	48.4
–3 dB width of satellite transmit beam (degrees)	(0.84)	(1.18)	(0.32)	(0.63)	0.44	(3.97)	1.4	0.3	0.6	0.55	(1.58)	(0.79)	(0.67)
Peak gain of satellite receive antenna (dBi)	46.5	43.5	55	49	~50[(1)]		~47[(1)]	57.2	47.7	49			48.4
–3 dB width of satellite receive beam (degrees)	(0.84)	(1.18)	(0.32)	(0.63)	(~0.56)		0.9	0.3	0.6	0.55			(0.67)
Polarization	Circ	Dual C	Dual C		Dual L	Circ	Dual C			Dual C	Circ	Circ	Dual
Number of service beams per satellite					7 + 7	1	24 + 24						

(1) Deduced from *G*/*T*.

TABLE 5

Beam dimensions of GSO/FSS satellites designed to use 40/50 GHz bands; information extracted from Recommendation ITU-R S.1328

Table in Annexes of Recommendation ITU-R S.1328	Table 17	Table 18	Table 19	Table 21	Table 22	Table 27	Table 28
Satellite system	GSO-VX	GSO-SV	GSO-LV	GSO-VI	GEOSAT-X	GSOV-B1	GSOV-B2
Peak gain of satellite transmit antenna (dBi)	49.0	58.0	52.0	53.0	56.5	51.5	53.1
–3 dB width of satellite transmit beam (degrees)	(0.63)	0.15	0.15	(0.4)	(0.27)	0.3	(0.39)
Peak gain of satellite receive antenna (dBi)	49.0	58.0	52.0	53.0			53.1
–3 dB width of satellite receive beam (degrees)	(0.63)	(0.22)	0.15	(0.4)			(0.39)
Polarization	Dual Circ.	Dual Circ.	Dual Circ.	Dual Circ.	Dual Circ.	Linear	
Number of service beams per satellite		40		24	48	24	80

Notes to Tables 3, 4 and 5:

The non-bracketed figures in these Tables were taken directly from Recommendation ITU-R S.1328. The bracketed beamwidths were derived from the corresponding peak gain figures as follows:

For a dish antenna $G_m = 10 \log((4\pi)/\lambda^2(\pi D^2/4)\eta)$

where:

G_m: peak gain (dBi)

D: diameter (m)

λ: wavelength (m)

η: aperture efficiency, say 0.65.

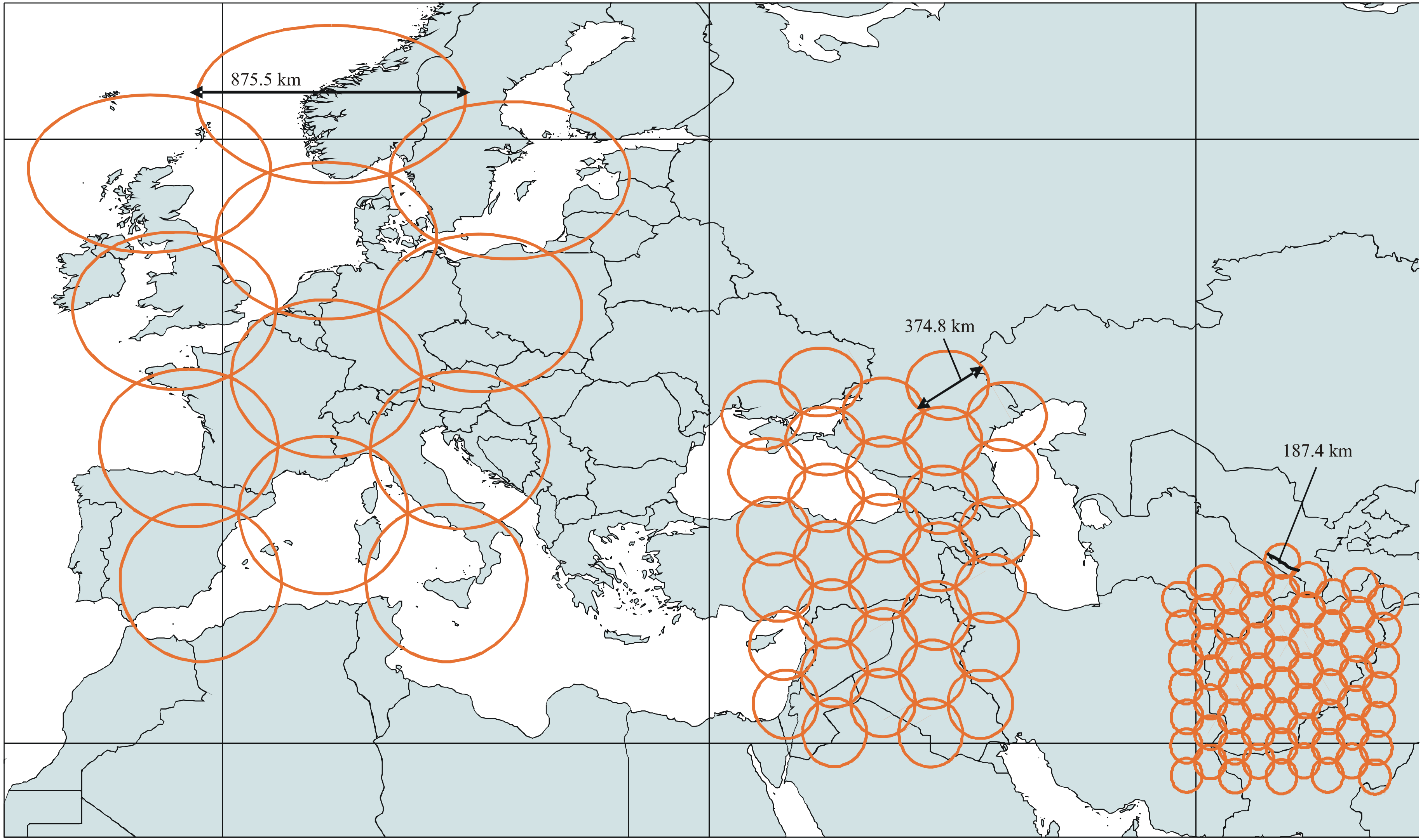
Hence $D/\lambda = (10^{0.05Gm})/(\pi\sqrt{(0.65)})$.

Also, an empirical expression for the half-power beamwidth is $\varphi_{-3} = 70\lambda/D$ degrees, so substituting for D/λ gives: $\varphi_{-3} = (177.3)10^{-0.05Gm}$ degrees.

Blank entries in the tables occur because the relevant data is missing in Recommendation ITU-R S.1328 and cannot be reliably deduced from the available data items.

FIGURE 2

Examples of beam arrangements for FSS satellites that could provide high-speed Internet access



Footprints of 12 beams in 11/14 GHz bands

Footprints of 32 beams in 20/30 GHz bands

Footprints of 64 beams in 40/50 GHz bands

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By reference to Recommendation ITU-R S.672 concerning simple circular and elliptical beams it is seen that, if the first sidelobe gain is 25 dB below peak gain then, assuming the same e.i.r.p. at each beam centre and assuming that the co-to-cross-polar ratio of each beam is also 25 dB, the net carrier-to-frequency reuse interference ratio is given by:

$$(C/I)_{FR} = -10 \log(7\{10^{-(25/10)}\}) = 16.5 \text{ dB}$$

In practice $(C/I)_{FR}$ is likely to be rather higher than this, because not all six contributions are likely to correspond to sidelobe peaks.

Examples of the coverages of geostationary satellites having the beam arrangements summarized in Table 2 are illustrated in Fig. 2. It may be noted that the overall coverage reduces roughly in inverse proportion to frequency.

2.2 Example link parameters

The present study addressed the case where individual users access the satellite directly, via USATs. The alternative option of using earth stations with larger antennas is covered in Annexes 2 and 3.

Calculations producing parameters for user links to a satellite were performed for all three sets of frequency bands described in § 1, using the following assumptions:

– Whilst the user earth stations would be based on USATs, the earth stations to which they would communicate via satellite, and which would interface with the Internet, would contain large antennas and are here termed "base stations". There would be far fewer base stations than user terminals.

– QPSK modulation with rate 3/4 FEC would be used. The availability threshold would occur when the post-demodulator BER falls to 1×10^{-6}, corresponding to $C/N = 8.5$ dB. Allowing for degradations due to the feeder link and the frequency reuse interference in § 2.1 ($C/I = 16.5$ dB), the $(C/N)_\uparrow$ and $(C/N)_\downarrow$ values required at threshold should not be less than 9.85 dB.

  NOTE 1 – Use of rate 1/2 FEC and the addition of coding such as Reed Solomon would reduce the C/N required, and thus reduce the up and downlink e.i.r.p.s and the satellite prime power requirement. Turbo-coding is another possibility with similar objectives. Results based on $(C/N)_\uparrow$ and $(C/N)_\downarrow$ threshold values of 7.0 dB assuming some such stronger coding are added to the results below.

– The systems will support user terminals with antennas of 30 cm diameter, which should help to minimize prices and would facilitate portable terminals. Antenna transmit gain would then be 30.2 dBi at 12.75 GHz, 31.0 dBi at 14 GHz, 37.2 dBi at 28.45 GHz, 41.7 dBi at 48.2 GHz. Antenna receive gain values would be 28.7 dBi at 10.7 GHz, 28.9 dBi at 10.95 GHz, 34.0 dBi at 19.7 GHz, 40.1 dBi at 40 GHz.

– The minimum operating elevation angle would be 10° at 11/14 GHz, 17° at 20/30 GHz and 25° at 40/50 GHz.

– The e.i.r.p. levels would be set to include the following margins to accommodate degradations due to rain fading for at least 99% of the time in most climates:
  – uplinks: 4.5 dB at 14 GHz, 11 dB at 30 GHz, 21 dB at 50 GHz;
  – downlinks: 3.5 dB at 11 GHz, 7 dB at 20 GHz, 20 dB at 40 GHz.

  In the 30 and 50 GHz bands it is likely that uplink power control would be employed, except perhaps in the driest climates, in order to minimize the potential for creating interference. However, the user terminals would still require output stages capable of generating the e.i.r.p. calculated by including the margin, even though the level would be substantially backed-off for most of the time. Uplink power control would conserve battery capacity in portable terminals, but the clear-air e.i.r.p. should be maintained at about 2.5 dB above the availability threshold to ensure a normal BER of at least 1×10^{-9}.

– The minimum values of satellite beam gain used in the calculations were 3 dB below the values given in the second row of Table 2, i.e. beam-edge values.

– The uplink noise temperature, including an allowance for external interference, would be of the order of 800 K in the 14 GHz band, 1 000 K in the 30 GHz band, and 1 200 K at 50 GHz.

– The downlink noise temperature, again allowing for external interference, would be of the order of 200 K in the 11 GHz band, 300 K in the 20 GHz band, and 500 K at 40 GHz.

– Interpreting the terms "broadband" and "high-speed" as applied to Internet access, a user bit rate of 2 Mbit/s is assumed here both for transmissions to and from the satellite. For QPSK modulation with rate 3/4 FEC, and allowing for 50% cosine roll-off filtering, this corresponds to a bandwidth of 1.6 MHz per carrier.

Using these assumptions in the link-budget equations gives the following carrier power levels to be fed to the user terminal antenna under clear-air conditions (the figures in brackets,{}, correspond to the above assumption of additional error-correction coding, and the associated bandwidth per carrier would be about 3 MHz).

14 GHz band: 14.3 dBW (27 W), or with uplink power control 12.3 dBW (17 W);
{11.5 dBW (14 W)} {9.5 dBW (8.8 W)}

30 GHz band: 13.6 dBW (23 W), or with uplink power control 5.1 dBW (3.2 W);
{10.8 dBW (12 W)} {2.3 dBW (1.7 W)}

50 GHz band: 19.2 dBW (83 W), or with uplink power control 0.7 dBW (1.2 W);
{16.4 dBW (43 W) {−2.2 dBW (0.6 W)}

and gives the following carrier power levels to be fed to the satellite transmit antenna:

11 GHz band: 7.3 dBW (5.4 W);
{4.5 dBW (2.8 W)}

20 GHz band: 4.4 dBW (2.8 W);
{1.6 dBW (1.4 W)}

40 GHz band: 14.4 dBW (27.5 W);
{11.6 dBW (14.3 W)}.

It is assumed that power-control would not be implemented on the downlinks and hence, since the rain margins assumed are all substantially greater than 2.5 dB, the BER in clear air would be substantially better than 1×10^{-9} in the hub-to-user terminal direction in all three downlink bands.

Whilst the public health requirements for user equipment is outside the authority of ITU, it is important for system planners to be aware of national and international radiation protection levels and guidelines to ensure compliance, especially in the case of ubiquitous deployment.

2.3 Capacity per satellite (C_S)

NOTE 1 – The results in this section, and also those in § 3, were calculated for QPSK carriers with rate 3/4 coding. Approximate corresponding results based on stronger coding as mentioned in § 2.2 are added at the end of this section, and at the end of § 3.

In many communications satellites the output power capability of a transponder is about 40 W at single-carrier saturation, although satellites with more powerful transponders have been built for specific applications. A number of 14/11 GHz satellites with 90 to 120 W transponder are in orbit. In multicarrier mode it is necessary to operate at an output back-off of about 4 dB in order to keep the impact of intermodulation adequately below the degradation due to frequency reuse, which reduces the usable output power to about 16 W. For the values of satellite transmitter output power per carrier deduced in § 2.2 this would accommodate very few carriers (each of 1.6 MHz bandwidth) per transponder. The consequentially large number of transponders required to fully utilize a 500 MHz band would result in a non-optimum payload, and so it is assumed that higher power transponders would be employed for the present application. A transponder output power of 100 W at saturation, i.e. 40 W at 4 dB output back-off, is assumed here both for the 11/14 GHz and the 20/30 GHz satellites. In the case of the 40/50 GHz satellite a transponder capability of 500 W at saturation, i.e. 200 W when backed-off – is assumed owing to the large downlink fade margin required. It is worth noting that it is possible to combat fading in ways other than simply providing high e.i.r.p. – for example adaptive coding – and further study may reveal a preferable alternative involving lower power transponders, with the objective of limiting both user terminal and satellite power requirements. This would seem to be a priority for the 40/50 GHz case because, whereas 100 W satellite transmitters are currently available at 11 GHz and 20 GHz, 500 W transmitters are not yet practicable at 40 GHz,

In the case of the 20/30 GHz satellite the number of 2 Mbit/s carriers that can be transmitted by a transponder is therefore 40/2.8 = 14. Assuming an inter-carrier guardband of 10%, the transponder bandwidth required is therefore $1.6 \times 1.1 \times 14 = 24.6$ MHz, and this is consistent with a 25 MHz spacing between adjacent transponders. This enables five transponders to be connected to each satellite beam, giving a total bandwidth of 125 MHz per beam, and 500 MHz for four beams. These parameters are consistent with the 1-in-4 frequency reuse pattern of Fig. 1. The total capacity of such a satellite may therefore be calculated as below:

Capacity = (2 Mbit/s per carrier) × (14 carriers per transponder) × (2 polarizations)
× (5 transponders per polarization per beam) × (32 beams) = 8 960 Mbit/s

Similarly the capacity of the 11/14 GHz satellite is calculated to be 3 024 Mbit/s, and for the 40/50 GHz satellite it is 16 128 Mbit/s. The transponder and beam arrangements developed above for a satellite in each of the three bands are illustrated in Figs. 3, 4 and 5.

It is noted that the number of transponders per satellite is high. The 11/14 GHz satellite would have 216 transponders, which may be practicable using solid state output stages, and the prime power requirement would be of the order of 54 kW. For the 20/30 GHz satellite the corresponding numbers would be 320 transponders and 80 kW, and for the 40/50 GHz satellite they would be no less than 1 152 transponders and 1.44 MW. The 11/14 GHz and 20/30 GHz spacecraft would be large and relatively expensive[3], and in each case it is worth considering the possibility of dividing the coverage between two or more nominally co-located satellites, each having proportionally fewer beams and transponders and lower prime power. That option seems inevitable in the 40/50 GHz case, where the coverage would need to be divided between around 20 smaller satellites just to reduce the size and power of each to the order of a single 11/14 GHz or 20/30 GHz satellite.

NOTE 1 – The assumption of stronger error-correction coding may lead to different transponder plans than those in Figs. 3, 4 and 5 owing to the increased bandwidth per carrier, but in comparison with the above the essential parameters would be approximately as follows:

Per-satellite capacity:

11/14 GHz − 1 612 Mbit/s; 20/30 GHz − 4 778 Mbit/s; 40/50 GHz − 8 600 Mbit/s

Satellite prime power:

11/14 GHz − 29 kW; 20/30 GHz − 43 kW; 40/50 GHz − 770 kW

[3] The cost to build and launch a large, physically realizable satellite (in 2006) is several hundred million US dollars.

FIGURE 3

Transponder and beam arrangements for 11/14 GHz FSS satellite suitable for high-speed Internet access

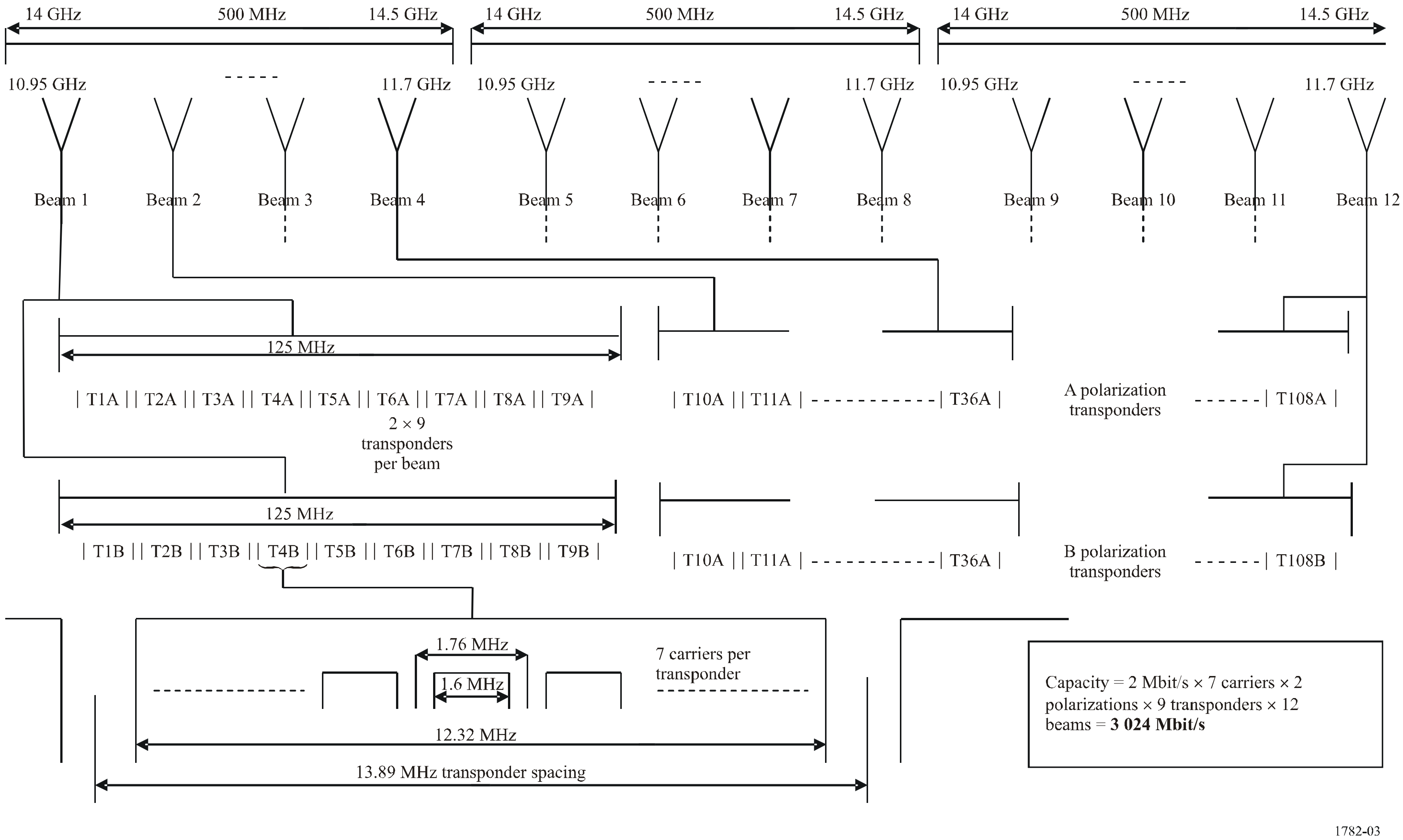

FIGURE 4

Transponder and beam arrangements for 20/30 GHz FSS satellite suitable for high-speed Internet access

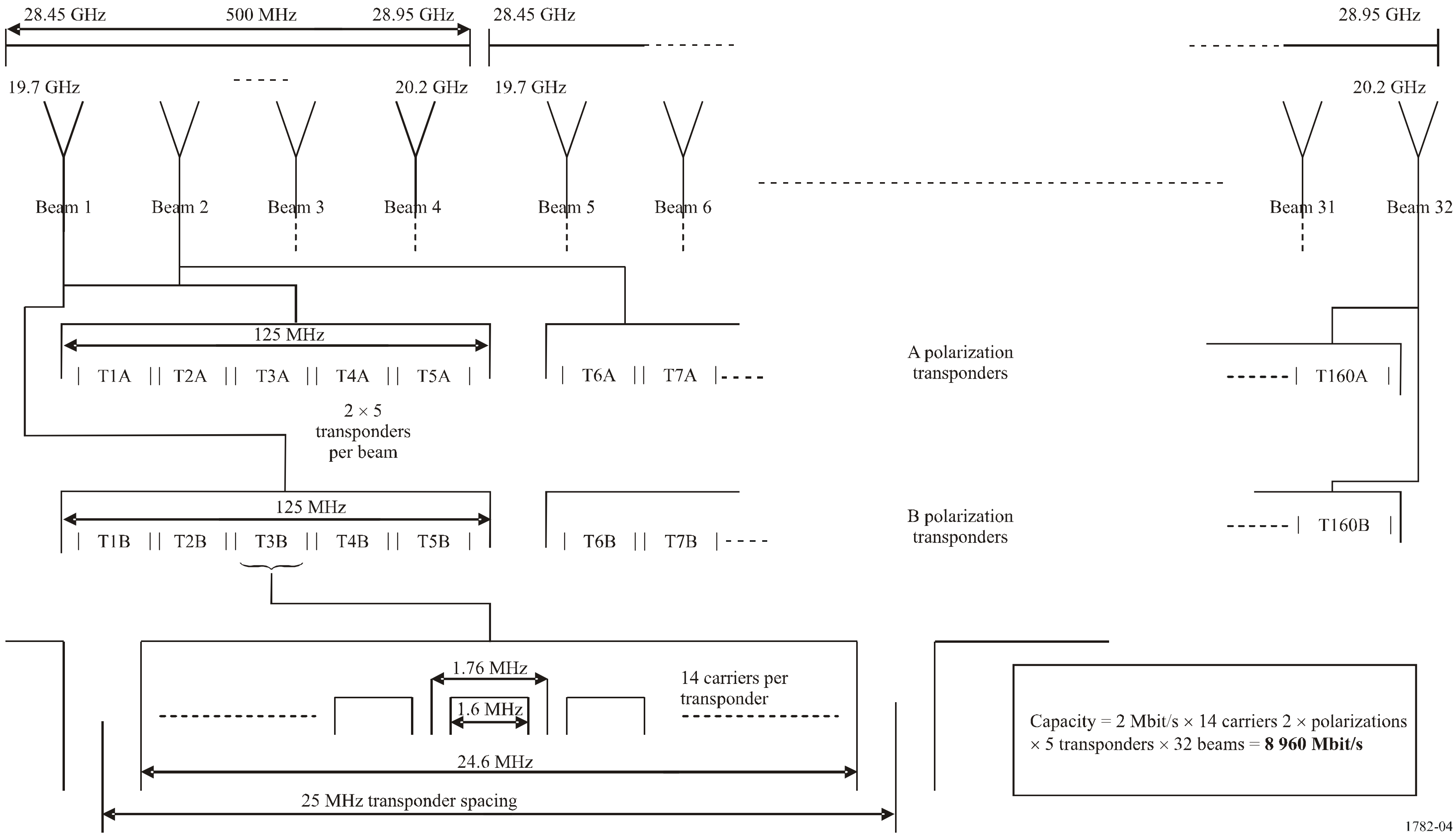

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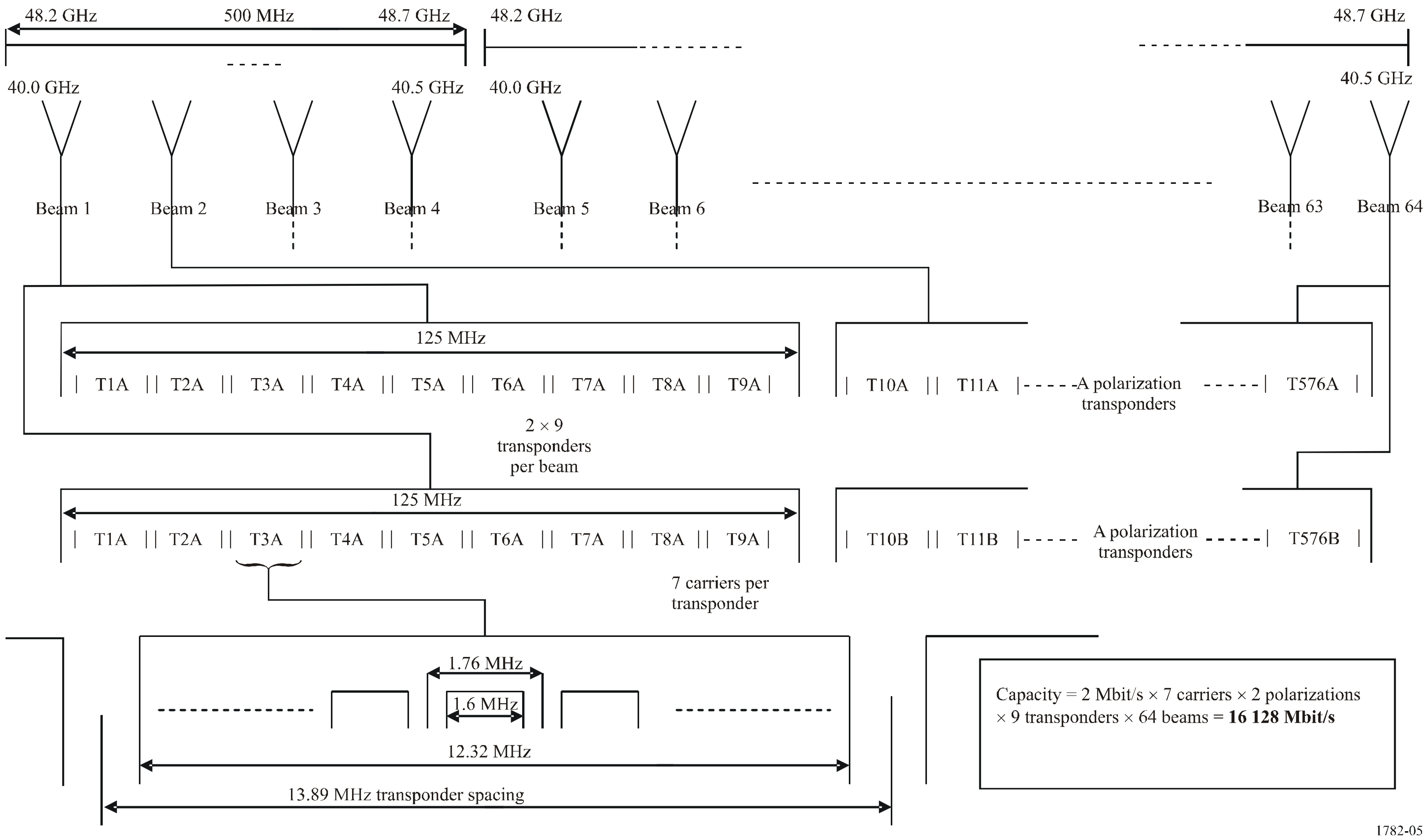
FIGURE 5

Transponder and beam arrangements for 40/50 GHz FSS satellite suitable for high-speed Internet access



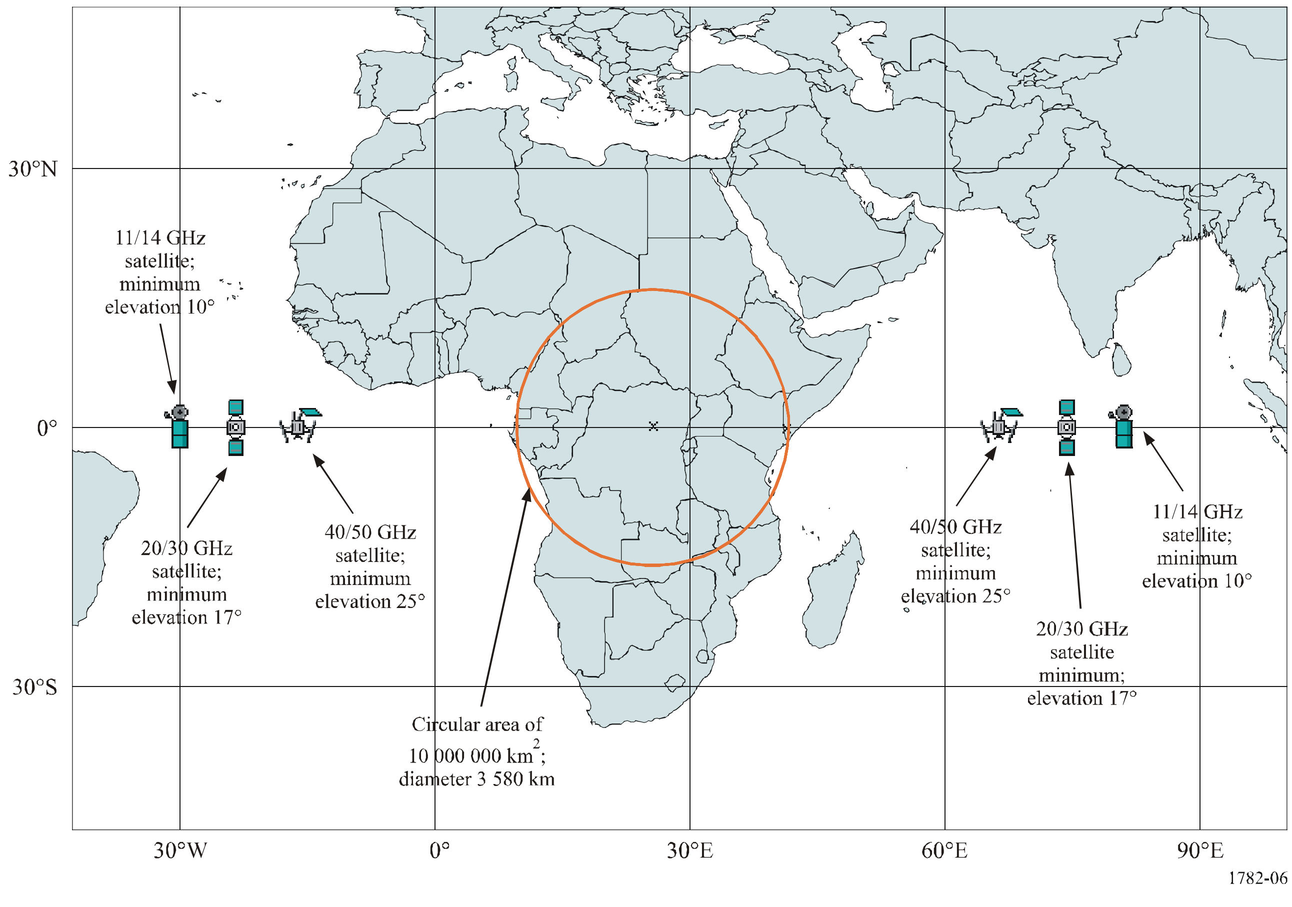
With regard to satellite prime power it is noteworthy that 20 kW is about the maximum for platforms designed to date, so ways of reducing the requirement are of interest here. In this regard it is worth investigating the possibility of retaining FDMA on the uplinks but employing TDMA on the downlinks, since this would obviate the need for transponder back-off and thus potentially reduce the satellite prime power requirement by 4 dB.

3 Potential overall capacity (C_T)

In order to express the overall capacity of FSS satellites in a given band to provide broadband Internet access it is necessary to define the geographical area concerned. Among the possible options are the whole surface of the Earth, the total land area of the Earth's surface, the Earth's surface between given latitudes (e.g. between 60° N and 60° S), the land area between given latitudes, the land area in which the population density is above a specified minimum, and various example areas of given sizes and latitudes. It is suggested that study and debate should be undertaken to determine the most meaningful option. For the purposes of this initial study a circular area of 10 000 000 km^2 centred on the Equator is taken. Figure 6 is an example of such an area located in central Africa, although the results would be the same for any other Equatorial location.

FIGURE 6

Example Equatorial area of 10 million km^2



Owing to the differing minimum elevation angles in the three frequency bands, the longitude ranges over which a geostationary satellite could serve the reference area differ. The ranges are indicated in Fig. 6 and are numerically as follows:

– for 11/14 GHz, from 30.1° W to 81.0° E, a range of 111.1° of longitude;

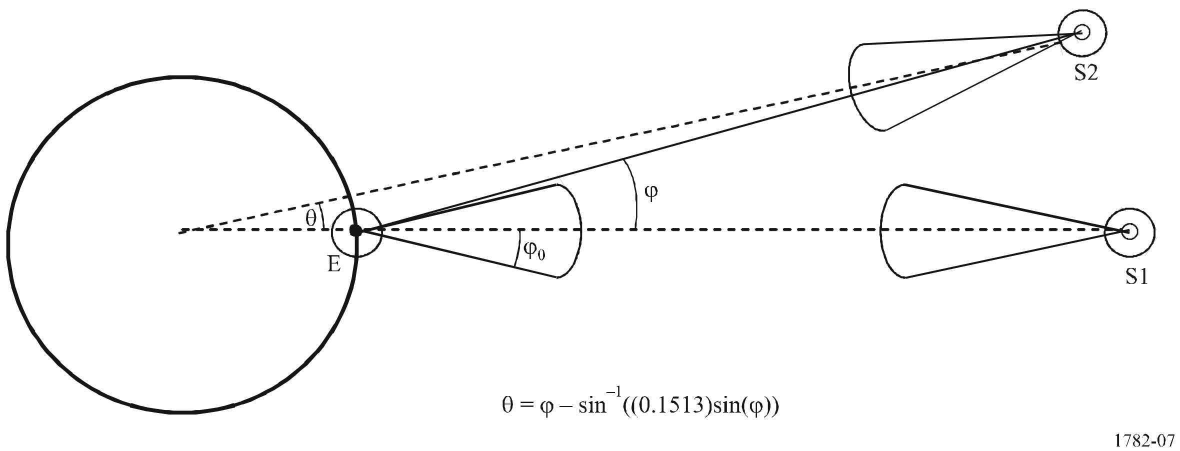
– for 20/30 GHz, from 23.4° W to 74.3° E, a range of 97.7° of longitude; and

– for 40/50 GHz, from 15.8° W to 66.7° E, a range of 82.5° of longitude.

The number of satellites within these ranges that could serve the area using the same frequencies and beam patterns depends on the minimum spacing between adjacent satellites, and this in turn depends on the acceptable level of interference to the uplinks and downlinks of one satellite from its neighbouring satellites. In order not to impact significantly on the overall *C*/*N* ratios calculated in § 3.2, the carrier-to-interference ratio from the two adjacent satellites should be a minimum of about 20 dB, and hence the carrier-to-interference ratio from each of those satellites ($(C/I)_{ADJ}$) should be at least 23 dB. As shown in Fig. 7 the interference level is determined mainly by the discrimination afforded by the user terminal antenna transmit and receive radiation patterns, and their rates of roll-off result in satellites other than the two adjacent spacecraft having negligible impact (assuming equal spacing throughout).

FIGURE 7

Adjacent satellite interference



E represents a user earth station operating to satellite S1, and the path E-S2 is the interference path to and from adjacent satellite S2. Since both satellites S1 and S2 are serving the same area, neither of their antenna patterns affords significant discrimination in the direction of the interference path. The interference from E to S2 occurs at φ° with respect to the axis of the antenna at E, and the interference received by E from S2 also occurs at that off-axis angle. Since this study is based on a single type of carrier, the e.i.r.p.s of "wanted" and "interfering" earth stations are the same, and the e.i.r.p.s of "wanted" and "interfering" satellites are also the same. Therefore in both up and downlink cases:

$$(C/I)_{ADJ} = G_M - G(\varphi)$$

where:

G_M: on-axis gain of the antenna at E

$G(\varphi)$: gain in the interference direction.

Maintaining the earlier assumption of a user antenna diameter of 30 cm, the beamwidths (φ_0) corresponding to the lowest frequency in each of the selected bands are calculated in Table 6.

TABLE 6

Maximum numbers of co-frequency, co-coverage satellites (φ_0 = 70.λ/D)

Frequency (GHz)	10.95	14.0	19.7	28.45	40.0	48.2
Beamwidth (φ_0°)	6.39	5.0	3.55	2.46	1.75	1.45
φ_{min} (degrees)	8.84	6.92	4.91	3.40	2.42	2.01
θ_{min} (degrees)	7.51	5.88	4.17	2.89	2.05	1.71
N	**14**	18	**23**	33	**40**	48

Assuming a square-law main-beam roll-off, $G(\varphi) = G_M - 12(\varphi/\varphi_0)^2$ dBi, and hence the required minimum discrimination occurs when $G_M - (G_M - 12(\varphi/\varphi_0)^2) = 23$ dB, i.e. when $12(\varphi/\varphi_0)^2 = 23$ dB. Rearranging, $\varphi = 1.384\varphi_0$ for minimum satellite separation, and these angles are given as φ_{min} in the third row of Table 6. The corresponding values of θ are shown in the fourth row. Bearing in mind the satellite spacing of 3° (or 2° in Region 2) normally adopted for conventional FSS networks in the 11/14 GHz bands, the values of θ_{min} in Table 6 underline the likely difficulty of sharing with existing systems in these bands. In the 20/30 GHz bands the θ_{min} values are also incompatible with the aim for 3° or 2° spacing, but at least there are few satellites actually in existence at present so the sharing problems are largely hypothetical. Generally the θ_{min} values reflect the fact that the use of small user terminal antennas limits orbit/spectrum efficiency.

Dividing the longitude ranges shown in Fig. 6 by θ_{min} gives the number of co-frequency satellites that can serve the reference area in each of the selected 500 MHz bands, and these numbers are given in the fifth row of the table as "*N*". Since only both-way connections are considered in the present study, the values of *N* relevant here are determined by the downlink frequencies and are highlighted in Table 6.

The hexagonal area, *A*, within the footprint of a single satellite beam may be shown from the geometry of Figs. 1 and 2 to be given by $A = 211\,375\,383(1 - \cos(d/222.63))$ km^2, where *d* is the diameter of the footprint (km) as shown in Fig. 2. The values of *A* to be used here are thus:

A = 497 683.88 km^2 for 11/14 GHz, 91 238.83 km^2 for 20/30 GHz, and 22 810.94 km^2 for 40/50 GHz

By multiplying these footprint areas by the number, *n*, of beams per satellite from Table 5, and then dividing the results into the reference area shown in Fig. 6, the numbers of satellites of the types described in § 3 that may serve the reference area from a single GSO location are obtained. These do not necessarily have to be integer numbers, because those beams whose footprints fall outside the reference area may exist, and they represent fractions of per-satellite capacity not available to users within the reference area. The total capacity, C_T, for the reference area is then given by:

$$C_T = N.C_S.(10\,000\,000)/(A.n) \text{ Mbit/s}$$

where C_S is the capacity per satellite as in § 3.

Hence the values of C_T for two-way connections in the 500 MHz bands selected are approximately:

10.95-11.2 GHz + 11.45-11.7 GHz down with 14.00-14.50 GHz up – **71 {38} Gbit/s**;

19.7-20.2 GHz down with 28.45-28.95 GHz up – **706 {380} Gbit/s**;

40.0-40.5 GHz down with 48.20-48.70 GHz up – **4 400 {2 400} Gbit/s**.

NOTE 1 – The figures in brackets correspond to the assumption of stronger error correction coding.

Noting typical costs of building and launching a large satellite, it is clear that provision of capacities of these orders would be very expensive. However, the potential market for global Internet access at high data-rates is commensurately high.

These capacities are for continuous use and, since the user-rate assumed is 2 Mbit/s, the maximum number of simultaneous two-way connections is half the capacity in each pair of bands. If individual carriers are dynamically allocated on an "on-demand" basis, the number of users will exceed the number of available carriers in inverse proportion to the mean user activity factor.

The capacities per satellite in § 2.3, and hence the overall capacities in this section, were calculated for Internet access via user terminals with 30 cm antennas. If a larger diameter had been assumed then different results would have been obtained, but to calculate them it would be necessary to first decide whether it would be appropriate to change other assumptions in addition to the user antenna diameter. If all other assumptions remained the same, then increasing the antenna diameter to 60 cm, for example, would enable the rate 3/4 FEC coding to be removed and the user bit rate to be increased to about 2 560 kbit/s, which would increase the capacity per satellite by 28% and the overall area capacity would be multiplied by a factor of about 2.5. However, depending on the antenna size assumed, it might be deemed appropriate to sacrifice some or all of the capacity increase in order to reduce the user transmitter power and/or the satellite prime power requirement. Alternatively, some or all of the increase in user antenna gain could be employed to reduce the gain per satellite beam proportionally, thus increasing the width of each satellite beam and enabling the same area to be covered by fewer beams. It is evident that capacity assessment for a larger user antenna should be based on a set of assumptions appropriate to that case.

4 Conclusions

This Annex outlines the key features of a type of FSS system design that would afford global broadband access to the Internet, and gives broad estimates of the overall capacity that could be provided by such systems. Since it is important to allow scope for refinement of the analysis and its adaptation to differing geographical and market circumstances, it is considered that it would be inappropriate to include system characteristics for broadband access to the Internet via satellite in the RR, and that this Recommendation should be reviewed from time to time in the light of developments.

Annex 2

Possibilities for global broadband Internet access by FSS systems designed for larger earth station antennas

1 General

The system architecture in Annex 1 was largely driven by the choice of 30 cm antennas for the user earth stations, which fall within the category sometimes termed "ultra-small aperture terminals", or USATs. If larger user antennas are assumed the requirements of broadband Internet access via satellite (excepting portability of terminals) may be met by a variety of system architectures, and it should be noted that only one is exemplified here.

For broadband Internet access the appropriateness of the various bands allocated to the FSS up to 50 GHz is discussed in § 1 of Annex 1, and it is unnecessary to repeat it here. Based on that discussion the parameters in this Annex are determined only for the 20/30 GHz and 11/14 GHz FSS bands, the same system architecture being assumed in both cases.

Although the size of user antenna is less dominant on system design for terminals other than USATs, it still has significant influence and therefore it is appropriate to select a popular size for the present Annex. In the replies to a Radiocommunication Bureau Questionnaire in 1998, which covered 20/30 GHz earth stations with antennas from 0.3 m to 7.6 m in diameter, the diameter occurring most often was 1.2 m. Replies to the same Questionnaire covered 11/14 GHz earth stations with antennas from 0.4 m to 18.0 m in diameter, and for those also the diameter occurring most frequently was 1.2 m. Thus 1.2 m was chosen for the present example, noting that earth stations using antennas of this size are among those referred to as "very small aperture terminals" (VSATs).

As in Annex 1, the aim is to facilitate a data rate of 2 Mbit/s from and to individual users. The access method assumed here for each satellite transponder is FDMA, and the modulation method is QPSK. The addition of rate 1/2 FEC coding is assumed in order to make reasonably efficient use of transponder output power.

2 System architecture

Again, as in Annex 1, this example is based on a "star" configuration, in which the access for a number of user earth stations is provided via satellite links to a single "hub" earth station connected to the Internet. In order to minimize the impact of the link between the satellite and the hub station on the *C*/*N* performance of outbound and inbound carriers, a large antenna (7.6 m in diameter) is assumed for the hub station. Figure 8 illustrates the link arrangement.

In this example the satellites use 500 MHz of spectrum in both the up and down directions of transmission, and the bands are, as before:

– 20/30 GHz system – 19.7-20.2 GHz space-to-Earth and 28.45-28.95 GHz Earth-to-space;

– 11/14 GHz system – 10.95-11.2 GHz and 11.45-11.7 GHz space-to-Earth, and

– 14.0-14.5 GHz Earth-to-space.

3 Coverage

For QPSK with rate-1/2 FEC a *C*/*N* ratio of about 7.5 dB is required at the input of a typical demodulator/decoder to produce a BER of 1×10^{-6} in the output bit stream, which may be regarded as the availability threshold for the present application. As in Annex 1 it is assumed that this BER should be met for at least 99% of the time in most climates, for which the link between the user and the satellite should be designed to accommodate rain fades of about 11 dB at 30 GHz, 7 dB at 20 GHz, 4.5 dB at 14 GHz, and 3.5 dB at 11 GHz, provided that the minimum elevation angle is 17° for the 20/30 GHz system and 10° for the 11/14 GHz system. Many of today's satellites have transponders which individually produce 40 W of output power at single carrier saturation. Taking these factors together with the user antenna diameter of 1.2 m, and making appropriate allowances for noise and internal and external interference contributions, it was found from link calculations that a satellite beam of about 2° half-power beamwidth would be required. As can be seen in Tables 3 and 4 this is well within the capabilities of current technology.

FIGURE 8

Link arrangement for broadband Internet access via satellite using VSATs

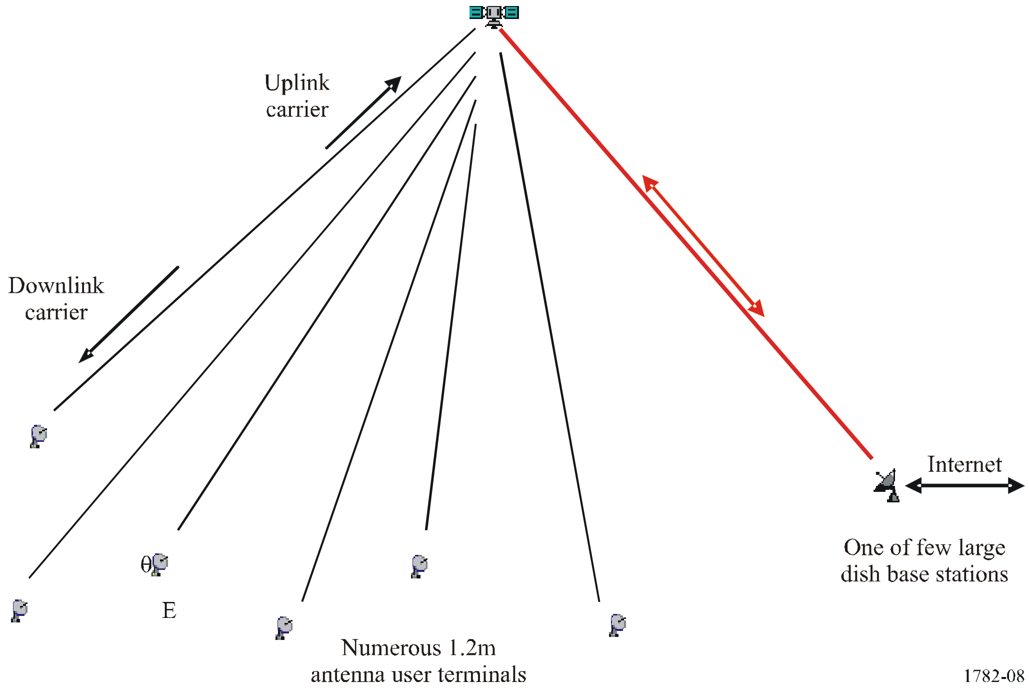


Figure 9 shows that a continuous area approximately equal in size to the circular reference area of 10 000 000 km^2 in Annex 1 (Fig. 6) would be covered by eight circular beams (A to H), each of 2° beamwidth, arranged so that their overlap boundaries form a pattern of interlocking hexagons. It is shown in § 2.1 of Annex 1 that frequency reuse by 1 beam in 4 leads to a minimum *C*/*I* ratio of at least 16.5 dB for multibeam interference.

4 Satellite payload configuration

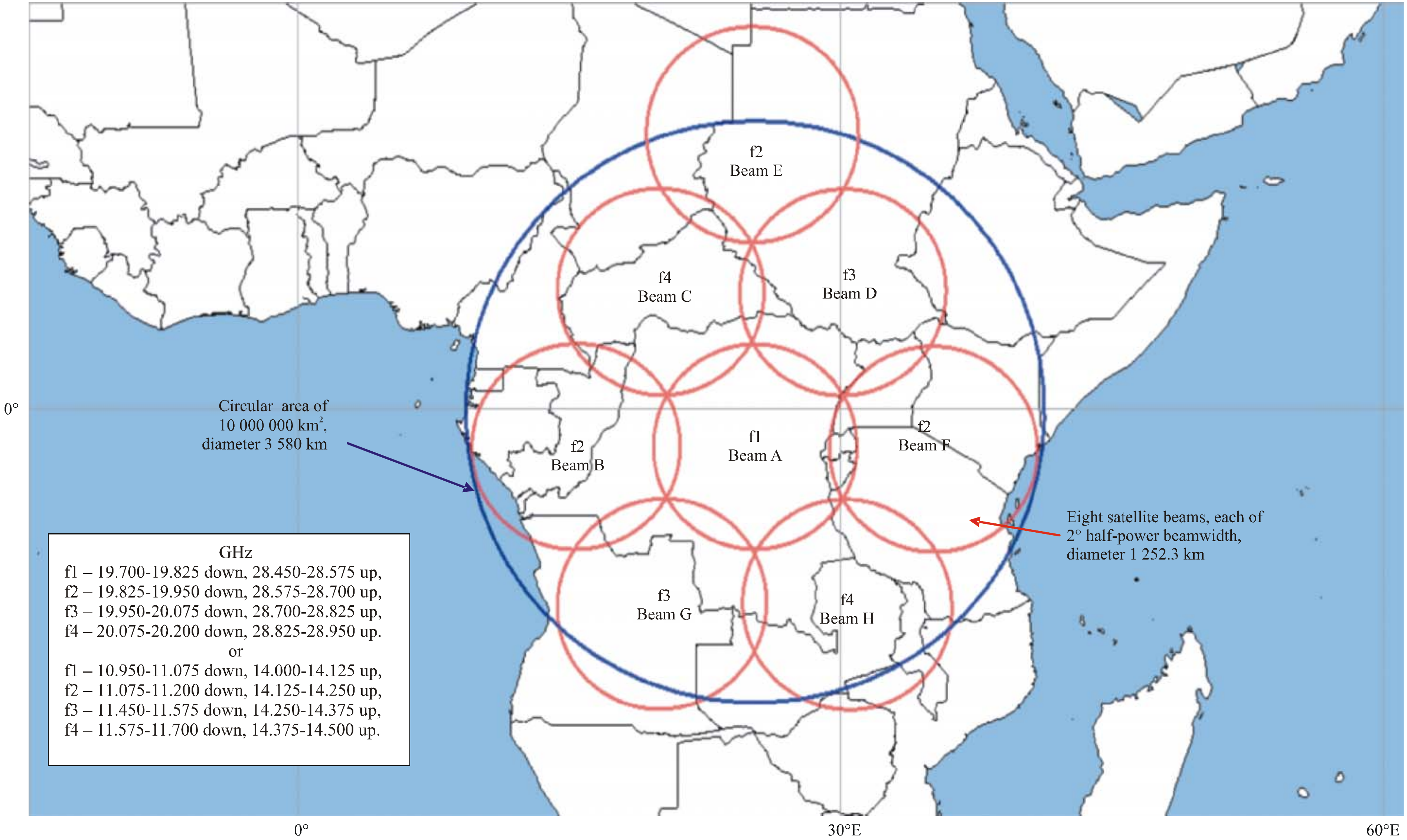
Given the parameters assumed in the foregoing sections of this Annex, a suitable transponder plan to make optimum use of power and bandwidth is shown in Fig. 10. The bandwidth of each carrier is given by:

{2 (Mbit/s data rate)/2 (QPSK)} × 2/1 (rate 1/2 FEC) × 1.2 (spectrum shaping) = 2.4 MHz

Allowing 18% of transponder bandwidth for intercarrier guardbands this corresponds to a carrier spacing of 2.84 MHz. This relatively generous allowance is consistent with the operation of 10 carriers within a transponder bandwidth of 28.4 MHz, and makes optimum use of transponder output power as shown later. A further 10% allowance for inter-transponder guardbands leads to a transponder spacing of 31.25 MHz, which enables four transponders to fit within 125 MHz – a quarter of the satellite bandwidth. Thus each of the eight beams whose half-power footprints are illustrated in Fig. 9 can accommodate four transponders on each of two polarizations (either dual linear or left and right-hand circular). The total number of transponders is therefore 64.

FIGURE 9

Example satellite beam arrangement for broadband Internet access via satellite by user stations with 1.2 m antennas



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5 Link budgets

For an up or downlink between an earth station and a satellite the relationship is:

$$P_T + G_T - 20\log((4\pi df)/(3 \times 10^8)) - F + G_R - 10\log(BT) - (-228.6) = C/N \text{ dB} \quad (1)$$

where:

- P_T: power fed to the transmitting antenna (dBW)
- G_T: gain of the transmitting antenna (dBi)
- d: path length between earth station and satellite (m)
- f: frequency (Hz)
- F: margin (dB) to compensate for fades for the required percentage of time
- G_R: gain of the receiving antenna (dBi)
- B: carrier bandwidth (Hz)
- T: link noise temperature (K)
- C/N (dB): ratio at the receiver to achieve the availability threshold BER.

In order to allow for performance degradation from thermal noise on the satellite-to-hub station link, multibeam frequency reuse, cross-polar interference, intermodulation in the satellite, and interference from external sources, the carrier-to-thermal noise ratio on the uplink and on the downlink between satellite and user terminal should be at least 8.5 dB. It is noted that the C/I ratio for those degradations in combination that would yield an overall $C/(N + I)$ ratio of 7.5 dB (corresponding to the availability threshold) is 14.4 dB, and the combination of frequency reuse and cross-polar interference ($C/I > 16.5$ dB), intermodulation ($C/I > 23$ dBi), base-station link noise ($C/I > 24$ dB), and external interference ($C/I > 23$ dB) is likely to be no worse than that (i.e. > 14.39 dB).

Hence:

Uplink from user earth station in 30 GHz FSS band

As equation (1), where:

- P_T = 11.3 dBW (13.5 W) (and about 3 dBW in clear air with uplink power control (ulpc))
- G_T = 49.19 dBi (1.2 m antenna at 28.45 GHz)
- d ≤ 39 853 746 m (17° minimum elevation)
- f = 28 450 000 000 Hz
- F = 11 dB (< 1% of time fade)
- G_R = 37.7 dBi (half-power edge of 2° satellite beam)
- B = 2 400 000 Hz
- T = 1 000 K, and therefore
- C/N = 8.5 dB.

Uplink from user earth station in 14 GHz FSS band

As equation (1), where:

- P_T = 3.95 dBW (2.5 W) (and about 2 dBW in clear air with ulpc)
- G_T = 43.19 dBi (1.2 m antenna at 14.25 GHz)

d ≤ 40 583 982 m (10° minimum elevation)

f = 14 250 000 000 Hz

F = 4.5 dB (< 1% of time fade)

G_R = 37.7 dBi (half-power edge of 2° satellite beam)

B = 2 400 000 Hz

T = 800 K, and therefore

C/N = 8.5 dB.

Downlink to user earth station in 20 GHz FSS band

As equation (1), where:

P_T = 2.1 dBW (1.62 W)

G_T = 37.7 dBi (edge of 2° satellite beam)

d = 39 853 746 m (17° minimum elevation)

f = 19 700 000 000 Hz

F = 7 dB (< 1% of time fade)

G_R = 46.0 (1.2 m antenna at 19.7 GHz)

B = 2 400 000 Hz

T = 300 K, and therefore

C/N = 8.5 dB.

Downlink to user earth station in 11 GHz FSS band

As equation (1), where:

P_T = 2.1 dBW (1.62 W)

G_T = 37.7 dBi (edge of 2° satellite beam)

d = 40 583 982 m (10° minimum elevation)

f = 10 950 000 000 Hz

F = 3.5 dB (< 1% of time fade)

. G_R = 40.9 (1.2 m antenna at 10.95 GHz)

B = 2 400 000 Hz

T = 200 K, and therefore

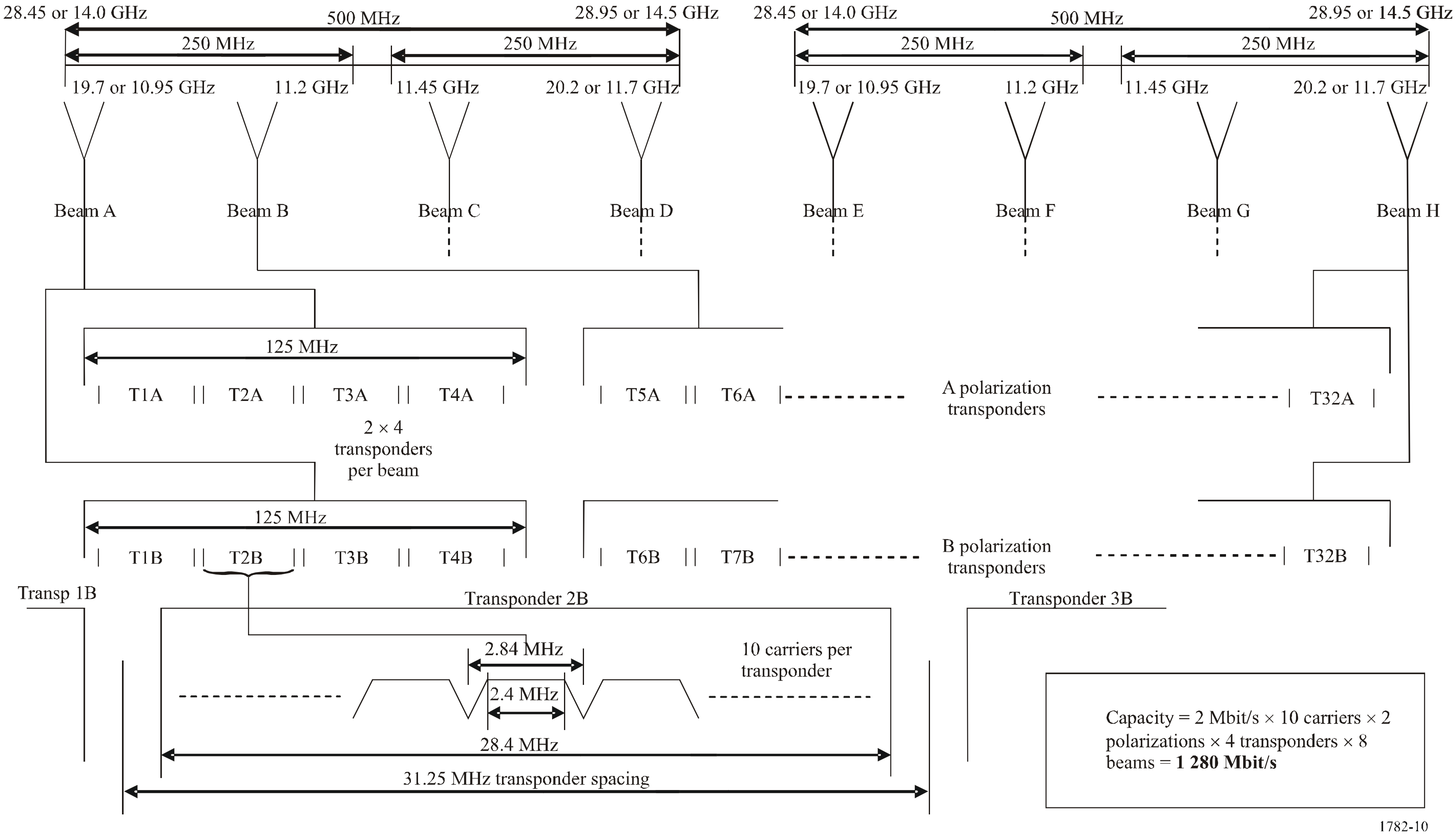
C/N = 13.6 dB.

The most critical of these links is the downlink at 19.7 GHz, for which the satellite output power required per carrier, P_T, is 1.62 W. Since the total multicarrier output power of a transponder capable of 40 W at single-carrier saturation is about 16 W (i.e. with 4 dB output back-off to limit intermodulation), the number of 2 Mbit/s carriers per transponder is **10** (i.e. ≅ 16/1.62) – as indicated in Fig. 10.

In the 11/14 GHz system the lower fade margin results in a generous C/N ratio for 10 carriers per transponder at 1.62 W per carrier, and a more optimum arrangement would be 11 carriers per transponder, with the intercarrier guardbands reduced to about 7.6% and the satellite power per carrier reduced to 16/11 = 1.45 W.

FIGURE 10

Transponder and beam arrangements for 20/30 GHz or 11/14 GHz FSS satellite suitable for high-speed Internet access



6 Capacity per satellite (C_S)

The capacity of a satellite having the payload configuration shown in Fig. 10 would be:

(2 Mbit/s per carrier) × (10 carriers per transponder) × (2 sets of 4 transponders per beam) × (8 beams) = **1 280 Mbit/s**

Assuming a power efficiency of 35% for each transponder and that the payload represents 75% of the satellite's power demand, the total prime power requirement for such a satellite would be about (40 W × 2 × 4 × 8)/(0.35 × 0.75) = 9 752 W, say **10 kW**.

In the 11/14 GHz case, if 11 carriers per transponder were operated the capacity would be 1 408 Mbit/s.

7 Potential overall capacity (C_T)

In § 3 of Annex 1 it is shown that the geostationary orbit can be seen at an elevation angle of 17° or more, from the whole of the 10 000 000 km^2 reference area, over a longitude range of 97.7°. It is also shown that for a minimum elevation angle of 10° the longitude range is 111.1°. Using the method described in that section it is found that, if the user earth stations have 1.2 m antennas, the minimum spacing between satellites could theoretically be less than 2° for both the 20/30 GHz and the 11/14 GHz examples. However, to minimize risk of interference due to such factors as imperfect satellite position control, a minimum spacing of 2° is commonly set by regulation, and therefore it is assumed here. Hence the number of co-frequency satellites of the type described in this Annex that could simultaneously serve the reference area is 48 in the 20/30 GHz case, and 55 in the 11/14 GHz case. Hence the total capacity that could potentially be provided by satellites of the present type for broadband Internet access by users within the reference area is:

– for the 20/30 GHz example – 48 × 1 280 = **61.44 Gbit/s**,

– for the 11/14 GHz example – 55 × 1 408 = **77.44 Gbit/s**.

However, because of the need to share frequencies with existing FSS systems, it is likely that some of this capacity would not be realizable in the foreseeable future, especially in the lower frequency bands.

Annex 3

Example of global broadband Internet access by an FSS system designed for "community" earth station antennas and local terrestrial distribution

1 General

In Annex 1 the objective was to provide direct access to user earth stations with 30 cm antennas and this determined the nature of the space sector, i.e. satellites with multiple spot-beams as narrow as is practicable – and therefore characterized the type of system architecture required. For the present Annex, however, in which user access would be via local radio networks to relatively few sites containing "community" earth stations, the size of antenna used by such earth stations is less critical, and a range of system architectures becomes possible. A variety of possibilities (including a range of frequency bands) exists for the implementation of the local terrestrial radio networks connecting the users to the "community" earth stations. Therefore this Annex provides only one example of a system architecture that would facilitate broadband Internet access via local radio networks centred on community earth stations. This example is based on the use of FDMA for the user-to-local hub terrestrial radio networks, with conventional QPSK modulation and rate 3/4 FEC, in the 4 GHz FS band. This choice has some influence on the design of the satellite links between the local earth stations and the central earth station connected to the Internet, although that influence is not so strong as to restrict possibilities to the example given here.

Although the example in this Annex uses the 4 GHz FS band for local terrestrial distribution, there are a number of other possibilities for providing this part of the access network in terms of the service type, for example FS or MS, and frequency band. The choice of application will depend on a number of factors such as; data rate and power requirements; required service range from the community earth station; frequency sharing and coordination with other services; and regulatory constraints. Since each of the local terrestrial networks linked to the Internet by the same satellite would be self-contained, it would be possible for different areas to use different FS and/or MS frequency allocations; this may be convenient where the satellite's service area covers more than one country for example.

2 Frequency band considerations

With regard to the identification of FSS frequency bands suitable for this application the first paragraph of § 1.1 of Annex 1 applies also here, but in this case the use of the 4/6 GHz and 11/14 GHz FSS bands is not constrained by the need to accommodate earth stations with very small antennas. In principle the community earth stations could incorporate antennas of any size, although it would be uneconomic to employ very large antennas in this role.

A survey of the current use of satellite bands is covered by § 1.2 of Annex 1, which leads to the conclusion that at present the 20/30 GHz FSS allocations are much less heavily used than those at lower frequencies, and that as yet there has been little FSS development in the 40/50 GHz allocations.

In view of the above this Annex presents an example of a community earth station-based system, and gives parameters for its implementation in the 20/30 GHz bands and also for its implementation in the 11/14 GHz bands. However it is noted that for worldwide implementation in the near future it is likely that the higher frequency band would involve fewer frequency-sharing problems than the lower.

3 Possible technical characteristics

3.1 System architecture

The system architecture for this example is illustrated in Fig. 11, where four bidirectional dual-polarized satellite beams would utilize a total of 500 MHz uplink bandwidth plus 500 MHz of downlink bandwidth (i.e. 125 MHz up and 125 MHz down per beam). Each beam would support four local community earth stations on one polarization plus another four on the orthogonal polarization, linking the eight earth stations via satellite to a central earth station for connection to the Internet. Thus the satellite would provide Internet access for 32 local communities.

3.2 Local terrestrial radio systems

Associated with each local earth station would be a terrestrial radio system equipped to serve a number of subscribers within a radius of about 3 km. The number of users that could be supported at any one time would depend upon the bit rates they were using and the activity factors on their connections. For domestic users of the Internet an activity factor of about 30:1 is typical and for business applications about 10:1. The bandwidth employed is extremely variable spanning applications from short text messages up to videoconferencing. The service description "broadband Internet" usually covers speeds starting at 256 kbit/s and runs up to many Mbit/s but the lower limit increases every few months as customer expectations mature. For example, if it was assumed that say 100 simultaneously connected business users were wishing to run at 2 Mbit/s for 10% of the time then this would require 20 Mbit/s to service and the availability of a further 6 Mbit/s could be shared between, say, 30 × 23 (256 kbit/s users in 6 Mbit/s) ≅ 700. Therefore the capacity would be 100 business users plus 700 simultaneous domestic users or, allowing for commercial considerations, say 150 + 1 000. However, if one of the users wished to run very bandwidth intensive applications such as real time TV then that user could capture a substantial proportion of the available capacity unless some sharing procedure were imposed by the network operator. This is a network management issue that is outside the scope of this study.

For the purposes of this Annex the example is taken of 200 subscribers using each local network at an average activity factor of 13%, up to 13 of whom would therefore be able to transmit simultaneously at a data rate of 2 Mbit/s and another 13 would be able to receive simultaneously at 2 Mbit/s data rate, in the 4 GHz FS band. If required, it would be possible to permit some of the subscribers to both transmit and receive simultaneously at 2 Mbit/s, or at higher bit rates, but then the supportable number of simultaneously active subscribers would be commensurately lower than 26. Conversely if some of the subscribers operated at bit rates lower than 2 Mbit/s, the supportable number of simultaneously active subscribers would be commensurately higher than 26.

For this example it is assumed that the subscriber links in the local terrestrial networks (which would be point-to-multipoint networks) would be FDMA links, and that their modulation would be QPSK with rate 3/4 FEC. Within each community terminal (i.e. terrestrial hub plus local earth station) the outgoing signals (e.g. thirteen at 2 Mbit/s) would be digitally multiplexed into a single 26 Mbit/s signal for onward transmission to the satellite, and the incoming signals (e.g. thirteen at 2 Mbit/s) would be de-multiplexed from a 26 Mbit/s signal received from the satellite.

3.3 Satellite links

The uplink and downlink carriers between each community earth station and the satellite have also been assumed to employ QPSK modulation with rate 3/4 FEC, and in the satellite they would be converted to and from 16-QAM carriers for the links between the satellite and the central earth station. Since there would be only one central earth station per beam (or possibly only one per satellite located where the four beams overlap) it would incorporate an antenna large enough to provide the uplink and downlink C/N ratios required by the 16-QAM carriers. In the central earth station the 26 Mbit/s bit streams would be processed into the formats necessary for connection to and from the Internet.

3.4 Coverage

Figure 12 shows that if the four satellite (both-way, dual-polarized) beams were designed to have half-power beamwidths of about 3°, and to be pointed so that their footprints coincided at a single point on the Equator, they would jointly cover a total area similar to the 10 000 000 km^2 area used as a basis for capacity calculations in Annex 1 (see Fig. 6 of that Annex). The frequency ranges to be covered by each of the four beams if the system was implemented in the 20/30 GHz bands, or in the 11/14 GHz bands, are indicated in Fig. 12. As described in Annex 1, the satellite antennas would be designed so that the beam footprints would remain circular, and of the same diameter (1 884.6 km on the Earth's surface), in whatever direction they were pointed to the Earth's surface down to a minimum elevation angle of 17° for 20/30 GHz or 10° for 11/14 GHz.

FIGURE 11

Example architecture for broadband Internet access via local terrestrial radio networks plus satellite

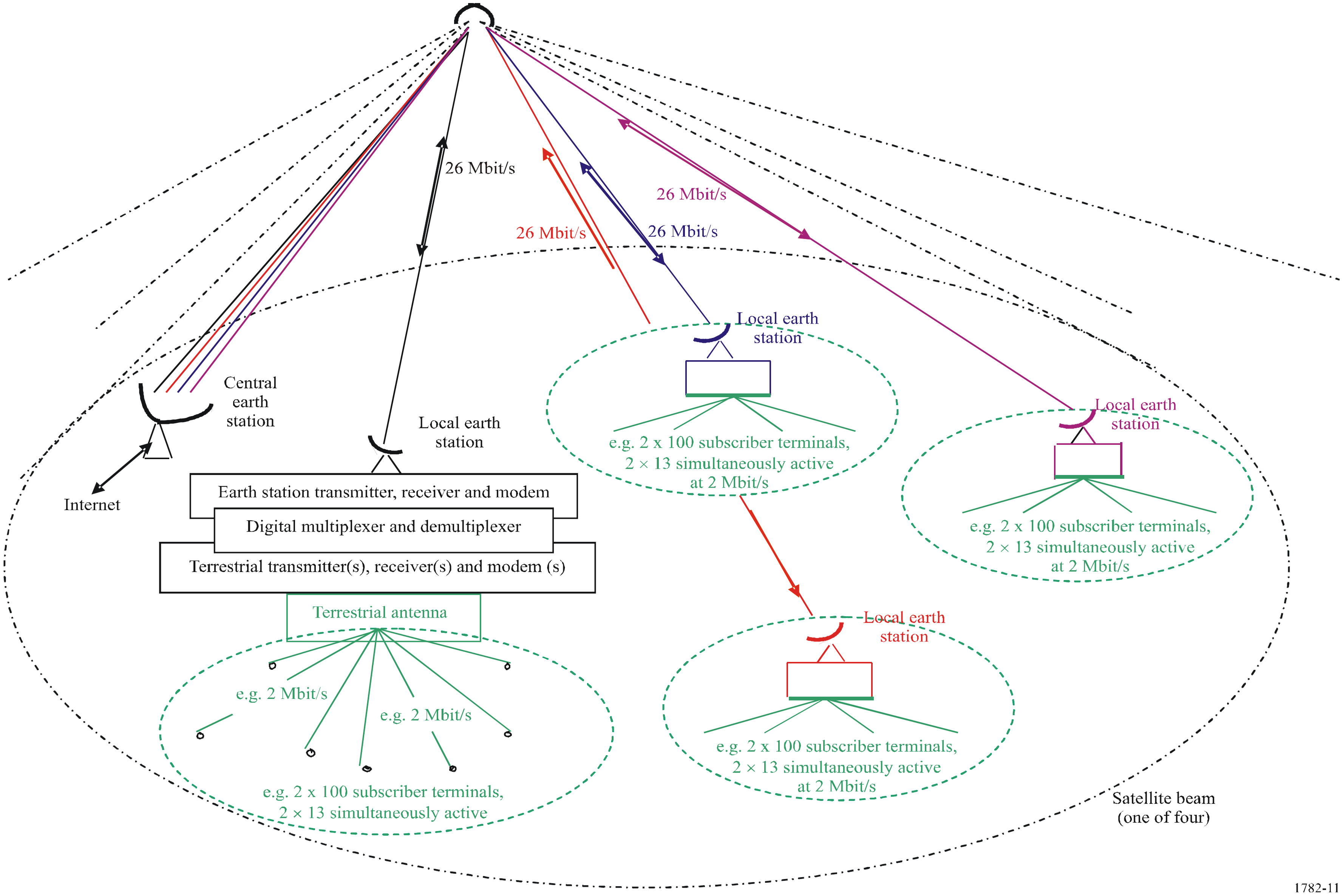
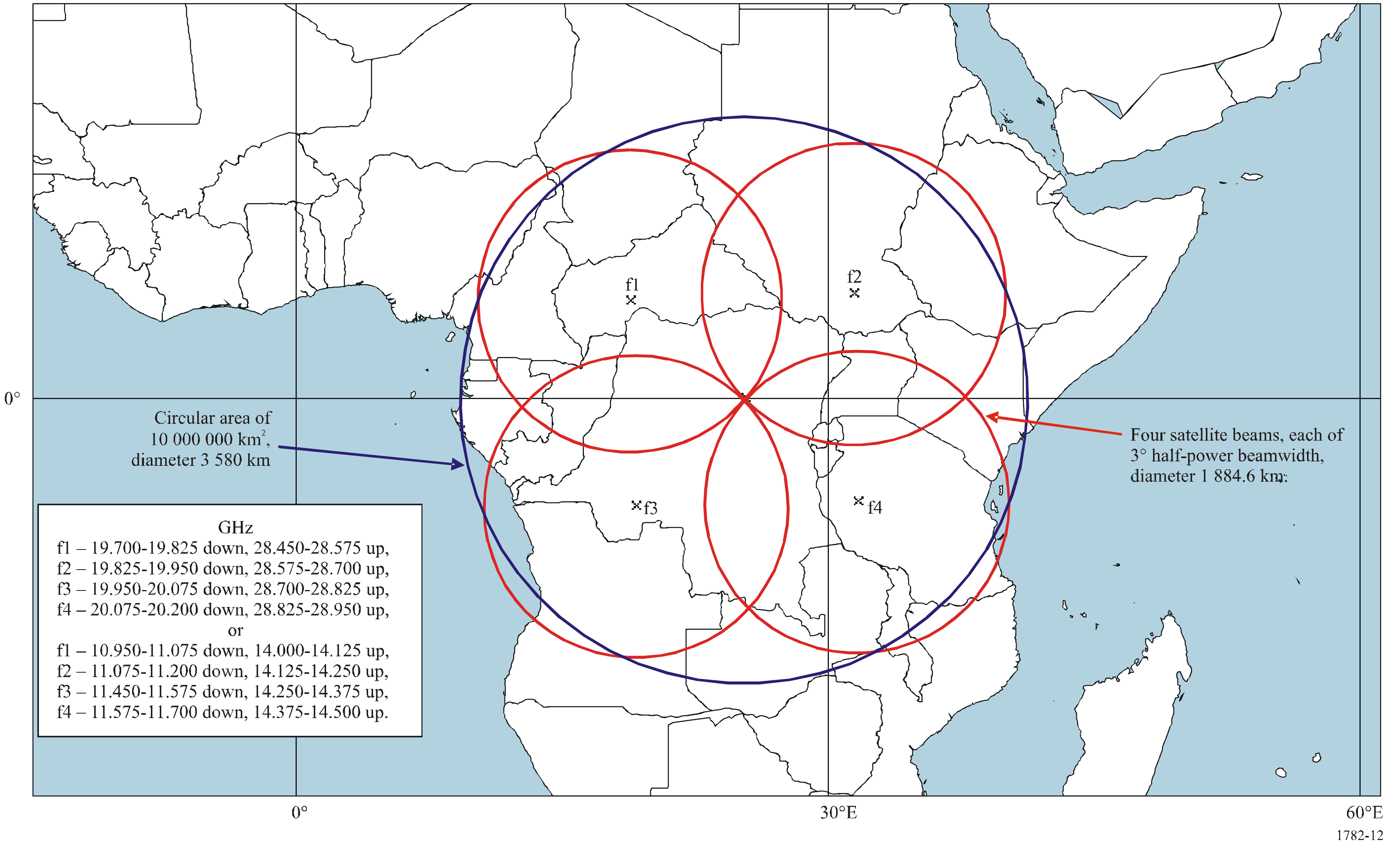


FIGURE 12

Example satellite beam arrangement for broadband Internet access via satellite plus local terrestrial radio network



3.5 Satellite payload arrangement

The satellite payload arrangement envisaged is shown in Fig. 13, from which it may be seen that the number of transponders required to make full use of the 500 MHz uplink and downlink bandwidth, using both polarizations, is 64. It can also be seen that, by the inclusion of equipment to convert the outgoing 26 Mbit/s streams from QPSK to 16-QAM, and vice-versa for the incoming streams, more efficient use of the bandwidth is made than if non-demodulating transponders had been assumed. For QPSK with rate 3/4 FEC the transmission bandwidth of a 2 Mbit/s carrier is about $2 \times 1/2 \times 4/3 \times 1.2 = 1.6$ MHz, and the bandwidth of a 26 Mbit/s carrier is about $26 \times 1/2 \times 4/3 \times 1.2$ MHz = 20.8 MHz. If the availability threshold is defined as the point where the BER reaches 1×10^{-6}, the overall *C*/*N* required for these carriers under faded conditions is around 8.5 dB, so allowing for noise in other parts of the link and external interference it is necessary for each channel to be designed to achieve a faded *C*/*N* of at least 9.5 dB. This applies to the most critical link in a chain, which in the outgoing direction is the link from subscriber terminal to community terminal and in the incoming direction is the downlink from satellite to local earth station. The other links should be designed to meet higher *C*/*N* thresholds in order to limit their impact on the end-to-end performance.

For 16-QAM modulation the bandwidth of a 26 Mbit/s carrier is about $26 \times 1/4 \times 1.2 = 7.8$ MHz. This allows the 125 MHz bandwidth per beam to accommodate, on each polarization, four 20.8 MHz carriers plus four 7.8 MHz carriers with intercarrier guardbands of approximately 8.5%. However, since the modulation of each 7.8 MHz carrier is 16-QAM it must be designed to meet an availability threshold *C*/*N* of about 25 dB (for BER $=1 \times 10^{-6}$) under faded conditions.

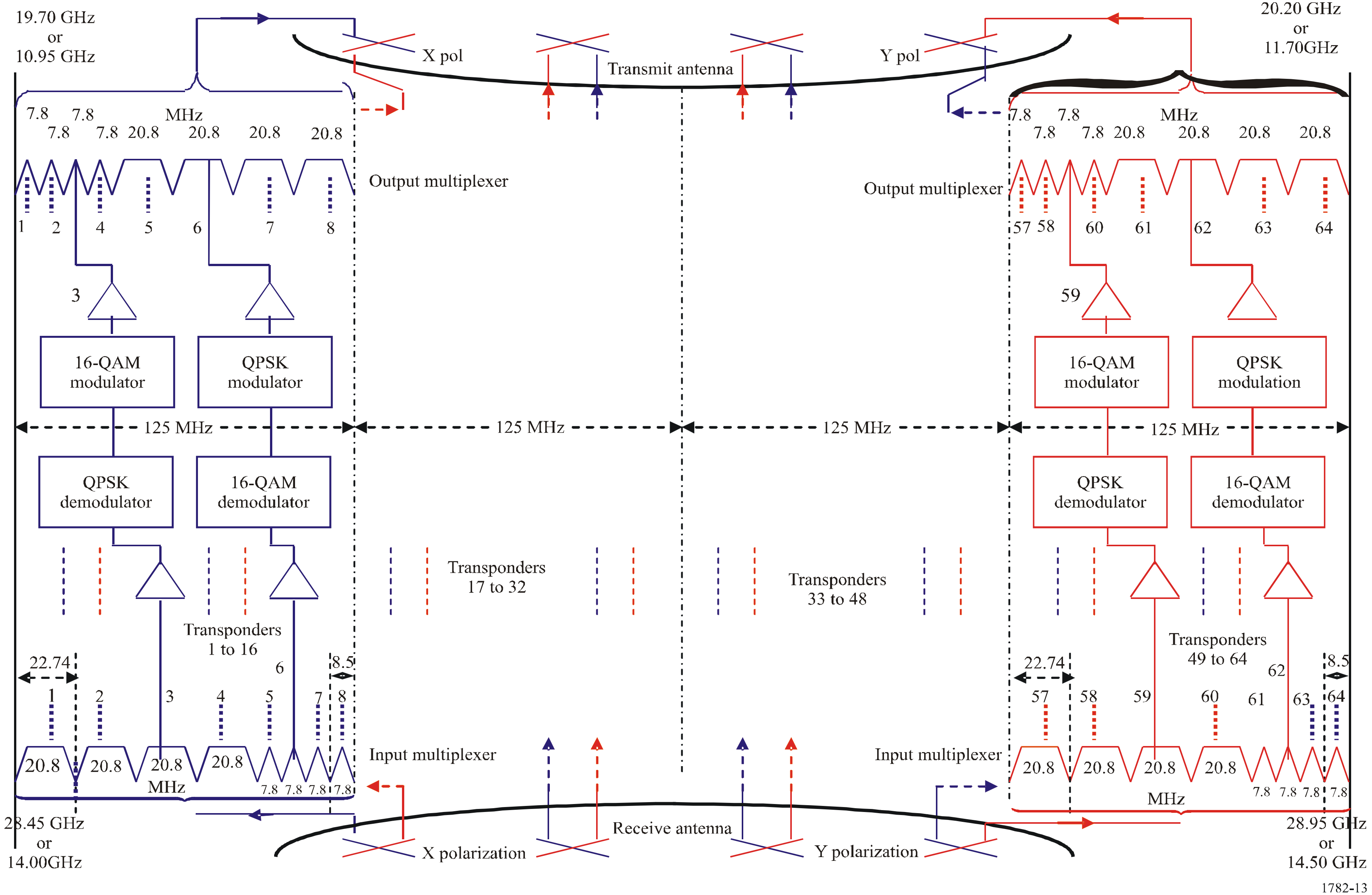
The conversion between QPSK + FEC and 16-QAM in each transponder adds complexity to the satellite payload, but not to the same extent as full on-board processing. A similar payload based on "transparent" ("bent-pipe") transponders would have only about two-thirds of the capacity.

3.6 Link budgets

On the basis of the foregoing paragraphs the essential parameters for the 4 GHz local terrestrial radio links, and also for the satellite links in both the 20/30 GHz and 11/14 GHz options, are given in the following link budgets:

FIGURE 13

Example satellite payload arrangement for broadband Internet access via satellite plus local terrestrial radio network



3.6.1 Local terrestrial links

Subscriber terminal-to-local earth station link in 4 GHz band

$$P_T + G_T - 20\log((4\pi df)/(3 \times 10^8)) - F + G_R - 10\log(BT) - (-228.6) = C/N \text{ dB} \quad (2)$$

where:

P_T = 3 dBW (2 W)
G_T = 0 dBi (low directivity)
d ≤ 3 000 m
f = 4 000 000 000 Hz
F = 20 dB (fading and blockage)
G_R = 10 dBi (all azimuths)
B = 1 600 000 Hz
T = 4 000 K, and therefore
C/N = 9.5 dB.

Local earth station-to-subscriber terminal link in 4 GHz band

As equation (2):

where:

P_T = 5.4 dBW (3.5 W)
G_T = 10 dBi (all azimuths)
d ≤ 3 000 m
f = 3 750 000 000 Hz
F = 20 dB (fading and blockage)
G_R = 0 dBi (low directivity)
B = 1 600 000 Hz
T = 4 000 K, and therefore
C/N = 12.5 dB.

3.6.2 Links between local earth station and satellite

Uplink from local earth station in 30 GHz FSS band

As equation (2):

where:

P_T = 24 dBW (251 W)
G_T = 53.63 dBi (2 m antenna at 28.45 GHz)
d ≤ 39 853 746 m (17° minimum elevation)
f = 28 450 000 000 Hz
F = 11 dB (< 1% of time fade)
G_R = 34 dBi (half-power edge of 3° satellite beam)
B = 20 800 000 Hz
T = 1 000 K, and therefore
C/N = 12.5 dB.

Uplink from local earth station in 14 GHz FSS band

As equation (2):

where:

P_T = 16.7 dBW(47 W)

G_T = 47.63 dBi (2 m antenna at 14.25 GHz)

d ≤ 40 583 982 m (10° minimum elevation)

f = 14 250 000 000 Hz

F = 4.5 dB (< 1% of time fade)

G_R = 34 dBi (half-power edge of 3° satellite beam)

B = 20 800 000 Hz

T = 800 K, and therefore

C/N = 12.5 dB.

Downlink to local earth station in 20 GHz FSS band

As equation (2):

where:

P_T = 13 dBW (20 W)

G_T = 34 dBi (edge of 3° satellite beam)

d = 39 853 746 m (17° minimum elevation)

f = 19 700 000 000 Hz

F = 7 dB (< 1% of time fade)

G_R = 50.44 (2 m antenna at 19.7 GHz)

B = 20 800 000 Hz

T = 300 K, and therefore

C/N = 10.7 dB.

Downlink to local earth station in 11 GHz FSS band

As equation (2):

where:

P_T = 7.8 dBW (6 W)

G_T = 34 dBi (edge of 3° satellite beam)

d = 40 583 982 m (10° minimum elevation)

f = 10 950 000 000 Hz

F = 3.5 dB (< 1% of time fade)

G_R = 45.34 (2 m antenna at 10.95 GHz)

B = 20 800 000 Hz

T = 200 K, and therefore

C/N = 10.7 dB.

3.6.3 Links between central earth station and satellite

Uplink from central earth station to satellite in 30 GHz FSS band

As equation (2):

where:

P_T = 24.7 dBW (295 W)

G_T = 63.88 dBi (6.5 m antenna at 28.45 GHz)

d = 38 377 622 m (32.7° elevation)

f = 28 450 000 000 Hz

F = 16 dB (< 0.1% of time fade)

G_R = 36 dBi (within 1° of satellite beam axis)

B = 7 800 000 Hz

T = 1 000 K, and therefore

C/N = 25.0 dB.

Uplink from central earth station to satellite in 14 GHz FSS band

As equation (2):

where:

P_T = 14.3 dBW (26.9 W)

G_T = 57.86 dBi (6.5 m antenna at 14.25 GHz)

d = 38 656 773 m (29.5° elevation)

f = 14 250 000 000 Hz

F = 6.5 (< 0.1% of time fade)

G_R = 36 dBi (within 1° of satellite beam axis)

B = 7 800 000 Hz

T = 800 K, and therefore

C/N = 25.0 dB.

Downlink to central earth station in 20 GHz FSS band

As equation (2):

where:

P_T = 15.4 dBW (35 W)

G_T = 36 dBi (within 1° of satellite beam axis)

d = 38 377 622 m (32.7° elevation)

f = 19 700 000 000 Hz

F = 12 dB (< 0.1% of time fade)

G_R = 60.68 dBi (6.5 m antenna at 19.7 GHz)

B = 7 800 000 Hz

T = 300 K, and therefore

C/N = 25.0 dB.

Downlink to central earth station in 11 GHz FSS band

As equation (2):

where:

P_T = 9.7 dBW (9.3 W)

G_T = 36 dBi (within 1° of satellite beam axis)

d = 38 656 773 m (29.5° elevation)

f = 10 950 000 000 Hz

F = 8 dB (< 0.1% of time fade)

G_R = 55.58 dBi (6.5 m antenna at 10.95 GHz)

B = 7 800 000 Hz

T = 200 K, and therefore

C/N = 25.0 dB.

4 Capacity per satellite (C_S)

As can be deduced from Figs. 11 and 13, each of the 64 transponders in this example would operate in single carrier mode, and would convey a 26 Mbit/s carrier. The total capacity per satellite would therefore be $C_S = 64 \times 26 = 1\ 664$ Mbit/s.

No back-off is required in single carrier per transponder mode, so from the link budgets above it may be seen that transponders capable of delivering 35 W at saturation would suffice for a 20/30 GHz system, and transponders capable of delivering 9.3 W at saturation would suffice for an 11/14 GHz system. The power requirements of stages prior to the output stage are relatively small, so assuming a power-conversion efficiency of 33% of the total prime power needed to supply the payload would be about (64 × 35)/0.33 = 6.8 kW for a 20/30 GHz satellite, or (64 × 9.3)/0.33 = 1.8 kW for an 11/14 GHz satellite.

The introduction of extensive multiplexing and buffering capabilities at each community earth station site would maximize the number of end users that could be simultaneously supported over such a network.

5 Potential overall capacity (C_T)

As calculated in § 3 of Annex 1, the minimum elevation angles assumed (17° for 20/30 GHz operation and 10° for 11/14 GHz operation) lead to the following ranges of longitude for satellites serving the circular 10 000 000 km^2 reference area shown in Fig. 12:

– for 20/30 GHz, from 23.4°W to 74.3°E, a range of 97.7° of longitude;

– for 11/14 GHz, from 30.1°W to 81.0°E, a range of 111.1° of longitude.

Using the method described in Fig. 7 and the associated text, the minimum longitude spacing between satellites of the type described in this Annex to keep adjacent satellite interference adequately low can be shown to be technically less than a degree in both cases. However, taking other factors such as satellite control practicalities into account, 2° is the minimum spacing typically permitted by licensing authorities for adjacent co-frequency, co-coverage satellites, and thus it is considered the appropriate value to assume here. Hence the total number of 20/30 GHz systems of the type described in this Annex that could serve the reference area simultaneously is calculated to be 48, and the number of 11/14 GHz systems is 55.

Therefore the total capacity that could potentially be provided by systems of the type described here, to a 10 000 000 km^2 equatorial area, using an uplink bandwidth of 500 MHz and a downlink bandwidth of 500 MHz, is calculated to be 48 × 1 664 Mbit/s = 79.872 Gbit/s for the 20/30 GHz example, and 55 × 1 664 Mbit/s = 91.52 Gbit/s for the 11/14 GHz example. However, because of the need to share frequencies with existing FSS systems, it is likely that some of this capacity would not be realizable in the foreseeable future, especially in the lower frequency bands.