RECOMMENDATION ITU-R S.1593

Methodology for frequency sharing between certain types of homogeneous highly-elliptical orbit non-geostationary fixed-satellite service systems in the 4/6 GHz and 11/14 GHz frequency bands

(Question ITU-R 231/4)

(2002)

The ITU Radiocommunication Assembly,

considering

a) that many fixed-satellite service (FSS) frequency bands may be used for both geostationary (GSO) and non-GSO satellite networks according to the Radio Regulations;

b) that the technology advances necessary to allow the implementation of non-GSO FSS satellite systems capable of providing regional or worldwide service to small earth stations in a cost-effective manner are becoming available;

c) that some non-GSO FSS systems are not designed to employ the interference mitigation technique of satellite diversity;

d) that studies have shown that without the use of interference mitigation techniques, it will be impracticable for large numbers of non-GSO FSS systems to share the same frequency band when the systems are of significantly varying design;

e) that studies have shown that multiple non-GSO FSS systems using only the mitigation technique of homogeneous design can share with each other in the same frequency bands;

f) that for non-GSO FSS systems using a highly-elliptical orbit (HEO) design, the implementation of satellite diversity comes at a design cost and complexity that may make its use by such systems in sharing with other types of non-GSO FSS systems difficult;

g) that multiple non-GSO FSS systems that operate in the 11/14 GHz and 4/6 GHz bands using an HEO design (e.g. USAKUS2 as described in Recommendation ITU-R S.1328) can employ geometric mitigation techniques to share with each other by several methods of satellite separation, including interleaving of satellites within orbital planes,

recommends

1 that in the 4/6 GHz and 11/14 GHz bands, the methodology presented in Annex 1 be used to perform analysis of frequency sharing between co-frequency, co-directional non-GSO FSS satellite systems of homogeneous sub-geosynchronous HEO design, i.e. the apogees, perigees, and inclinations of the systems are identical.

NOTE 1 – The methodology in Annex 1 may also be applicable to other types of non-GSO FSS systems. To determine whether the sharing prospects are different between multiple homogeneous non-GSO FSS systems of the type considered in Annex 1 and inhomogeneous non-GSO FSS systems, further study is required.

ANNEX 1

Methodology for sharing between certain types of homogeneous HEO non-GSO FSS systems in the 4/6 GHz and 11/14 GHz frequency bands

1 Introduction

The methodology presented in this Annex addresses sharing between certain types of homogeneous non-GSO FSS systems in the 4/6 GHz and 11/14 GHz frequency bands. This approach applies to systems that have homogeneous orbits; i.e. the apogee, perigee, and inclination are identical. The systems must have exactly the same ground tracks for the active portions of their orbits. The difference will come in the phasing of the satellites in the orbital track. The methodology applies to systems that are designed such that the portions of the orbit in which the satellites are either transmitting or receiving (active arcs) do not cross each other. The approach involves the interleaving of satellites within the same orbital ground track when sharing between multiple non-GSO FSS systems. It is applicable generally to non-GSO systems that employ HEO in which the satellites are only transmitting or receiving in a certain portion of the orbit. However, it may be applicable to other non-GSO systems provided that the active portions of the orbit do not cross each other. This approach eliminates in-line interference events since the active arcs do not cross. This means that there will be no need for complicated switching strategies in order to avoid in-line interference events and there will be no need to know the exact locations of the satellites in other constellations as they will be phased in such a way that there will always be a minimum separation between two satellites in adjacent systems. Appendix 1 to this Annex contains an example application of this methodology.

2 Description of methodology

The following Steps comprise this methodology:

Step 1: Select a minimum true anomaly separation angle between satellites in adjacent constellations.

This is the satellite separation angle between adjacent satellites in two constellations near apogee, when the satellites in adjacent constellations will be the closest to each other. At other locations in the active arc (or during any other portion of the orbit), satellites in adjacent systems will be further separated. The approach taken here is to select a minimum true anomaly separation angle between two satellites that are in adjacent constellations around the apogee. Since the apogee point is when the satellites are travelling at the slowest rate of speed, if the satellites in adjacent constellations are placed symmetrically around the apogee, this will be when the satellites would be closest to each other. Thus, the apogee will be chosen as the centre true anomaly and the true anomalies of the satellites in the two constellations will be equal to the true anomaly at apogee plus one-half the minimum true anomaly separation angle and the true anomaly at apogee minus one-half the minimum true anomaly separation angle. The resultant true anomalies (E) for the two satellites are given in equations (1) and (2):

$$E_1 = E(apogee) + \frac{Separation\ angle}{2} \qquad \text{degrees} \qquad (1)$$

$$E_2 = E(apogee) - \frac{Separation\ angle}{2} \qquad \text{degrees} \qquad (2)$$

Step 2: Determine the orbital locations (latitude, longitude and altitude) of the satellites that are located at the minimum true anomaly separation.

From the values for the true anomalies and the other orbital parameters for the system, it is then possible to calculate the eccentric anomaly (E_e), mean anomaly (E_m) and time (t) (relative to the time of the ascending node). From these values, it is possible to calculate the latitude, longitude and orbital altitude of the two satellites. The relevant equations for these calculations are as follows:

$$E_e = 2 \cdot \tan^{-1}\left(\tan\left(\frac{E}{2}\right)\sqrt{\frac{1-e}{1+e}}\right) \qquad \text{degrees} \qquad (3)$$

where e is the eccentricity of the orbit.

$$E_m = E_e - e \sin E_e \qquad \text{degrees*} \qquad (4)$$

$$t = \frac{T}{360} \cdot (E_m - E_{ma}) + t_a \qquad \text{s} \qquad (5)$$

where:

T: period of the orbit

E_{ma}: mean anomaly at the ascending node time, t_a.

$$long = \tan^{-1}(\cos(i) \cdot \tan(\theta_p + E)) + \Lambda - \omega_e \cdot (t - t_a) \qquad \text{degrees} \qquad (6)$$

where:

i: inclination angle of the orbit (degrees)

θ_p: argument of perigee of the orbit (degrees)

Λ: longitude of the ascending node of the orbit (degrees)

ω_e: rotation rate of the Earth (degrees/s)

$$lat_{geocentric} = \sin^{-1}(\sin(i) \cdot \sin(\omega_p + E)) \qquad \text{degrees} \qquad (7)$$

The latitude calculated in equation (7) is the geocentric latitude. The geographical latitude can be derived from the geocentric latitude by using the formula in equation (8).

$$lat_{geographical} = \tan^{-1}\left(\frac{1}{(1-J_\alpha)^2} \cdot \tan(lat_{geocentric})\right) \qquad \text{degrees} \qquad (8)$$

where J_α is the factor for the Earth's oblateness.

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* The solution to this equation has been developed using a trigonometric series developed by Lagrange.

$$Altitude = \alpha\left(1 - e \cdot \cos(E_e)\right) - R_e \qquad \text{km} \qquad (9)$$

where:

α: semi-major axis of the orbit (km)

R_e: radius of the Earth (km).

Step 3: Determine the locations of the other satellite systems that are within the same active arc based on the minimum true anomaly separation and the orbital parameters of the system.

The mean anomaly difference between the two satellites that are nearest to their apogee point allows for the computation of the time intervals between satellite passages over any point in the ground track. For example, if the mean anomaly difference between two satellites is 15° and the orbital period of both satellites is 8 h, then it will take $(E_m / 360) \times T = (15/360) \times 8 = 1/3$ h = 20 min between passages of the two satellites past any point on the orbit. Since the satellites in the different constellations will follow the same ground tracks, this will allow for the calculation of the location of the satellites in the other constellations at the instant that the first two satellites are nearest to their apogee point (separated by the true anomaly separation) by simply adding or subtracting the time interval to the times for the first two satellites. For this example, if one satellite moves forward 20 min in the same orbital ground track, the next satellite (which is in another constellation) will be located at this point in the orbit when the original satellite is located at one-half the true anomaly separation past apogee. Using the time difference between the first two satellites (these times are calculated in Step 1), the time relative to time of the ascending node for each of the other satellites in the other systems may be found by simply adding the time difference to the time of the satellite that is past apogee or subtracting the time difference to the time of the satellite that is before apogee. Given the time (relative to the time of the ascending node) of the satellite in the next system, the mean anomaly, eccentric anomaly, true anomaly, latitude, longitude and altitude of that satellite can be found using the following equations:

From the new time, the mean anomaly can be calculated:

$$E_m = \frac{360}{T} \cdot (t - t_a) + E_{ma} \qquad \text{degrees} \qquad (10)$$

The eccentric anomaly is then found by applying an iterative solution to equation (4). The true anomaly is then calculated as:

$$E = 2 \cdot \tan^{-1}\left(\tan\left(\frac{E_e}{2}\right)\sqrt{\frac{1+e}{1-e}}\right) \qquad \text{degrees} \qquad (11)$$

The latitude, longitude and altitude of the satellite at this time can then be calculated using equations (6) through (9). The time interval is added to or subtracted from each new satellite until the time is reached where the satellite is not in the active arc. This process results in the locations of all of the satellites in the active arc.

Step 4: Determine the number of satellites and, thus, systems that are in the active arc.

This is a simple process of just adding the number of satellites determined in Step 3 to be within the active arc based on the minimum true anomaly separation. In some cases, the satellite entering the active arc and the one leaving the active arc will be of the same system. In these cases, the total number of systems within the active arc will be the total number of satellites minus one.

Step 5: Select one satellite to be in the wanted satellite system and calculate the interference from each of the other satellite systems into the wanted system for both the uplink and the downlink and calculate the aggregate interference from all of the interfering systems into the wanted system.

After selection of the wanted satellite, the earth station location for the wanted system is selected. This selection can be done randomly or a worst-case earth station location can be used. For the uplink, the off-axis angle for the interfering earth station antenna is calculated (this is the angle between the direction toward the satellite this earth station is communicating with and direction to the wanted satellite). For the downlink, the off-axis angle for the wanted earth station antenna is calculated (this is the angle between the direction toward the wanted satellite and the direction toward the satellite in the interfering system). The interference contributions from each of the interfering systems into the wanted system are calculated using equation (12) for the uplink and equation (13) for the downlink.

$$I_{\uparrow} = P_{ES} + G_{ES,t}(\theta_i) - \left(32.45 + 20\log(f_{\uparrow} \cdot d_{\uparrow})\right) + G_{s,r} \qquad \text{dBW} \qquad (12)$$

$$I_{\downarrow} = P_s + G_{s,t} - \left(32.45 + 20\log(f_{\downarrow} \cdot d_{\downarrow})\right) + G_{ES,r}(\theta_w) \qquad \text{dBW} \qquad (13)$$

where:

P_{ES}: transmitted power of the interfering earth station (dBW)

θ_i: interfering earth station off-axis angle (degrees)

$G_{ES,t}(\theta_i)$: gain of the interfering earth station antenna in the direction of the wanted satellite (dBi)

$f_{\uparrow}$: frequency of the uplink (MHz)

$d_{\uparrow}$: distance between the interfering earth station and the wanted satellite (km)

$G_{s,r}$: receiving antenna gain of the wanted satellite (dBi)

P_s: transmitted power of the interfering satellite (dBW)

$G_{s,t}$: transmitting antenna gain of the interfering satellite (dBi)

$f_{\downarrow}$: frequency of the downlink (MHz)

$d\downarrow$: distance between the interfering satellite and the wanted earth station (km)

θ_w: wanted earth station off-axis angle (degrees)

$G_{ES,r}(\theta_w)$: gain of the wanted earth station antenna in the direction of the interfering satellite (dBi).

The aggregate interference is calculated using equation (14).

$$I_{aggregate} = 10 \log \sum_{1}^{n} 10^{\frac{I_n}{10}} \qquad \text{dBW} \qquad (14)$$

where:

n: number of interfering satellite systems

I_n: interference contribution of the n-th system.

Step 6: Calculate the resultant $C/(I+N)$ due to the aggregate interference from these multiple interfering systems for both the uplink and the downlink into the wanted system link budget and calculate the total link $C/(I+N)$. Determine if the system meets its required performance criteria. It is noted that another interference evaluation methodology, such as I/N or $\Delta T/T$ may be used in place of $C/(I+N)$.

The resultant $C/(I+N)$ for the uplink and downlink are calculated using equations (15) and (16).

$$I + N = 10 \log \left(10^{\frac{I_{aggregate}}{10}} + 10^{\frac{N}{10}} \right) \qquad \text{dBW} \qquad (15)$$

$$\frac{C}{I+N} = C - (I+N) \qquad \text{dB} \qquad (16)$$

where:

N: noise power density and is equal to $k\,T\,B$

where:

k: Boltzmann's constant

T: receiver noise temperature of either the wanted satellite or the wanted earth station (K)

B: bandwidth (Hz).

The total $C/(I+N)$ for the entire link is calculated using equation (17).

$$\left(\frac{C}{I+N}\right)_{total} = -10 \log \left(\sum 10^{-\left(\frac{C}{I+N}\right)\uparrow/10} + 10^{-\left(\frac{C}{I+N}\right)\downarrow/10} + 10^{-\left(\frac{C}{I+N}\right)_{other}/10} \right) \quad \text{dB} \qquad (17)$$

where:

$C/(I+N)_{total}$: total link $C/(I+N)$

$C/(I+N)_{other}$: link $C/(I+N)$ due to other sources of interference, such as intermodulation, cross polarization and multi-beam.

Step 7: Repeat Steps 5 and 6 for each satellite as the wanted system.

Step 8: If the link budget performance requirements are not met, select a new minimum separation angle and return to Step 2.

APPENDIX 1

TO ANNEX 1

Example application of the methodology

1 Introduction

This Appendix presents an example application of the methodology described in this Recommendation. This example application will use the USAKU-H2 system.

2 Parameters of the USAKU-H2 system used in the analyses

The USAKU-H2 system proposes to use sub-geosynchronous inclined elliptical orbits in order to ensure a large angular separation of the active satellites from the GSO orbit. The parameters for the system that are used in this analysis are described below and given in Table 1. More detailed information on this system may be found in Recommendation ITU-R S.1328. The satellites in this system are active only in certain portions of their orbits, and this feature results in active satellite separation angles from the GSO arc of at least 40°.

The USAKU-H2 system is comprised of three five-satellite sub-constellations – two for northern hemisphere operation and one for southern hemisphere operation. The active arcs of the USAKU-H2 satellites in each sub-constellation occur only when the sub-satellite points of the satellites are at latitudes above 45° N or below 45° S, respectively. At these locations, the satellites are at high elevations over much of their service areas in the northern and southern hemispheres. The USAKU-H2 system thus achieves a combination of very high elevation angles from the service area to the active satellites, low signal propagation delays compared to geostationary satellites, limited satellite handoffs, and high angular separation from the GSO orbit. It also provides non-uniform distribution of capacity to the northern and southern hemispheres in proportion with demand. Figure 1 shows the sub-satellite ground tracks of the USAKU-H2 system, with the active service arcs indicated by bold lines.

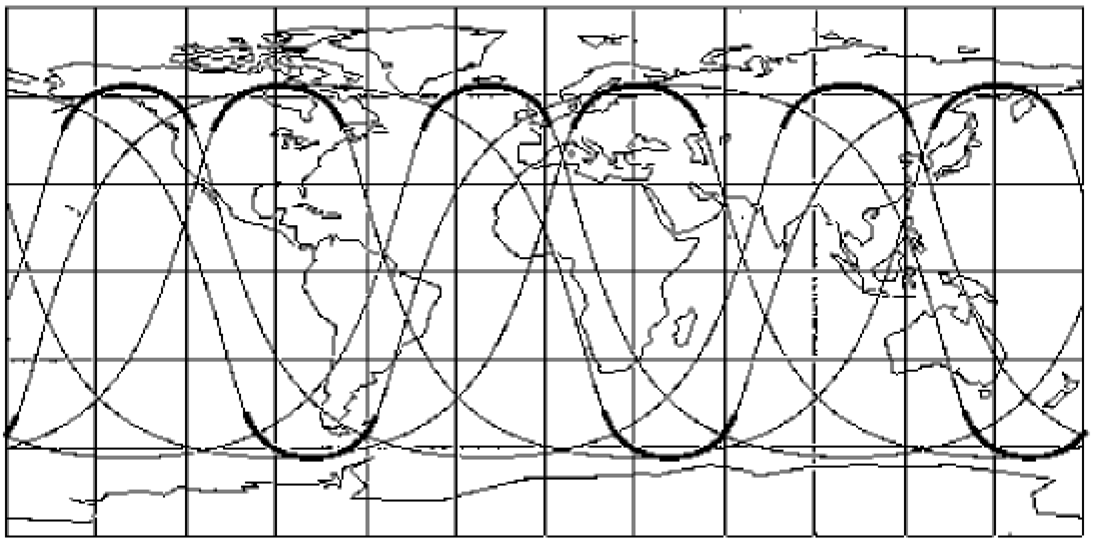
TABLE 1

Parameters of USAKU-H2 system used in the analysis

Number of satellites	15
Number of planes	15
Number of satellites per plane	1
Orbital inclination (degrees)	63.435
Orbit period (min)	480
Altitude of apogee (km)	27 288.3
Altitude of perigee (km)	517.4
Eccentricity	0.66

FIGURE 1

Sub-satellite ground tracks of the USAKU-H2 system



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The USAKU-H2 system will use the 14.0-14.5 GHz frequency band for uplinks from user stations and the 12.75-13.25 GHz, 13.8-14.0 GHz, and 5 925-6 725 GHz frequency bands for uplinks from gateway stations. The system will use the frequency band 11.2-12.7 GHz for downlinks to user stations and the 10.7-11.2 GHz and 3.7-4.2 GHz frequency bands for downlinks to gateway stations.

3 Sharing criterion used in the analysis

Most of the studies in the past have used an I/N or $\Delta T/T$ criterion as the basis for sharing among multiple non-GSO systems. This criterion is adequate when doing studies where there are several unknown parameters for the systems involved. However, when analysing the real potential for interference from other non-GSO FSS systems into the desired non-GSO FSS system, the determining factor is the overall link budget of the desired system. The real measure for determining the capability of multiple non-GSO FSS systems to share is whether each of the systems involved will meet its overall link budget requirements in the presence of interference from other systems.

For this analysis, it is assumed that each of the non-GSO FSS systems has the same orbital characteristics as the USAKU-H2 system except that the satellite phasing within the ground tracks will differ by a certain amount (i.e. homogenous orbits and ground tracks). This will ensure that the satellites of a given system are always at a given minimum orbital separation away from the satellites of the adjacent systems. It is also assumed that the transmission parameters for each of the non-GSO FSS systems will be the same (i.e. link balancing). Thus, this analysis is investigating the combination of two of the mitigation techniques described in Recommendation ITU-R S.1431: homogeneous orbits and link balancing.

The analysis considers the worst-case situation where the antenna beams of all of the satellites are centred at the same location on the Earth and the receiving or transmitting earth stations for each of the systems are located at this point. The analysis assumes that all co-directional operations are co-frequency and co-polarization.

The analysis is based on typical link budgets for the USAKU-H2 system. This system operates links that go up from the user terminal to the satellite and down to a gateway station or up from the gateway station to the satellite and down to the user terminals. The analysis looks at the overall links and determines the amount of aggregate interference that is acceptable from all of the other non-GSO FSS systems. The typical link budgets in clear-sky used in this analysis are given in Tables 2 and 3. These link budgets assume that the gateway earth stations use antennas with a diameter of 5 m and the user terminals use 0.45 m antennas. The link budgets assume that the satellite is located at its maximum distance away from the earth station. This results in the minimum link margins. It should be noted that the system uses power control so that the received signal at either the earth station or the satellite will be the same regardless of the orbital altitude of the satellite. All earth stations used in the analysis are conservatively assumed to have $36 - 25 \log(\theta)$ antenna gain patterns.

TABLE 2

Gateway to user link budgets (gateway uplinks in the 5 925-6 725 MHz and 14.0-14.5 GHz bands, user terminal downlinks in the 11.2-12.7 GHz band)

Parameters	6 GHz uplink	14 GHz uplink
Maximum distance (km)	31 150	31 150
Uplink carrier frequency (MHz)	6 325	14 250
Earth station transmit power to antenna (W)	38.9	12.8
Earth station transmit antenna gain (dBi)	48.2	55.1
Earth station transmit e.i.r.p. (dBW)	64.1	66.2
Atmospheric and other losses (dB)	0.3	0.5
Free space loss (dB)	198.3	205.4
Satellite receive antenna gain (dBi)	33.0	38.0
Received signal power (dBW)	–101.5	–101.7
Satellite receive noise temperature (K)	600	600
Carrier noise bandwidth (kHz)	45 000	45 000
Satellite noise power (dBW)	–124.3	–124.3
Uplink *C*/*N* (dB)	22.7	22.6
Satellite channel gain (dB)	120	120
Satellite transmit power (W)	70.1	67.1
Satellite transmit gain (dBi) – edge of coverage	35.0	35.0
Satellite transmit e.i.r.p. (dBW) – edge of coverage	53.5	53.3
Downlink carrier frequency (MHz)	11 950	11 950
Atmospheric and other losses (dB)	0.5	0.5
Free space loss (dB)	203.9	203.9
Earth station receive antenna gain (dBi)	32.8	32.8
Received signal power (dBW)	–118.1	–118.3
Receive system noise temperature (K)	110	110
Receive system noise power (dBW)	–131.6	–131.6
Downlink *C*/*N* (dB)	13.5	13.4
Information bit rate (kbit/s)	36 000	36 000
C/*I* – intermodulation (dB)	22	22
C/*I* cross polarization (dB)	25	25
C/*I* – multibeam (dB)	18	18
Overall $C/(I+N)$ (dB)	11.2	11.1
Required overall $C/(I+N)$ (dB)	3.0	3.0

TABLE 3

User to gateway link budgets (user uplinks in the 13.8-14 GHz band, gateway downlinks in the 3 700-4 200 MHz and 10.7-11.2 GHz bands)

Parameters	4 GHz downlink	11 GHz downlink
Maximum distance (km)	31 150	31 150
Uplink carrier frequency (MHz)	13 900	13 900
Earth station transmit power to antenna (W)	6.4	6.4
Earth station transmit antenna gain (dBi)	34.3	34.3
Earth station transmit e.i.r.p. (dBW)	42.4	42.4
Atmospheric and other losses (dB)	0.5	0.5
Free space loss (dB)	205.2	205.2
Satellite receive antenna gain (dBi) – edge of coverage	35.0	35.0
Received signal power (dBW)	–128.3	–128.3
Satellite receive noise temperature (K)	600	600
Carrier noise bandwidth (kHz)	2 500	2 500
Satellite noise power (dBW)	–136.8	–136.8
Uplink C/N (dB)	8.5	8.5
Satellite channel gain (dB)	120	120
Satellite transmit power (W)	0.15	0.15
Satellite transmit gain (dBi)	33.0	38.0
Satellite transmit e.i.r.p. (dBW)	24.7	29.7
Downlink carrier frequency (MHz)	3 950	10 950
Atmospheric and other losses (dB)	0.2	0.5
Free space loss (dB)	194.3	203.1
Earth station receive antenna gain (dBi)	44.1	53.7
Received signal power (dBW)	–125.7	–120.2
Receive system noise temperature (K)	80	110
Receive system noise power (dBW)	–145.6	–144.2
Downlink C/N (dB)	19.9	23.9
Information bit rate (kbit/s)	2 000	2 000
C/I – intermodulation (dB)	22	22
C/I cross polarization (dB)	25	25
C/I – multibeam (dB)	18	18
Overall $C/(I + N)$ (dB)	7.5	7.7
Required overall $C/(I + N)$ (dB)	3.0	3.0

4 Application of the methodology

4.1 *Step 1*: Select a minimum true anomaly separation angle between satellites in adjacent constellations

For this analysis, a minimum true anomaly separation angle of 6.7° is selected. As the true anomaly at apogee is 180°, this results in the following true anomalies for the two closest satellites in adjacent constellations: $E_1 = 183.35°$ and $E_2 = 176.65°$.

4.2 *Step 2*: Determine the orbital locations (latitude, longitude and altitude) of the satellites that are located at the minimum true anomaly separation

Using equations (3) to (9), Table 4 gives the values of the eccentric anomaly (E_e), mean anomaly (E_m), time (t), latitude, longitude and altitude of the two satellites that are near apogee.

TABLE 4

Parameters	Satellite No. 1	Satellite No. 2
Eccentric anomaly, E_e (degrees)	187.39	172.61
Mean anomaly, E_m (degrees)	192.26	167.74
Time, t (s)	12 460.4	10 502.5
Longitude (degrees)	344.44	337.71
Latitude (°N)	63.39	63.39
Altitude (km)	27 176.99	27 176.99

4.3 *Step 3*: Determine the locations of the other satellite systems that are within the same active arc based on the minimum true anomaly separation and the orbital parameters of the system

The time interval between satellite passages over any point in the ground track is calculated using the mean anomaly difference given in Table 4. The time interval is: 1 957.9 s. The latitude, longitude and altitude of all satellites within the active arc based on this time interval are calculated using equations (10), (11), and (6) to (9) and are shown in Table 5.

TABLE 5

Satellite No.	Latitude (°N)	Longitude (degrees)	Altitude (km)
3	61.83	331.37	27 177.0
4	61.83	350.79	27 177.0
5	58.60	325.98	26 279.9
6	58.60	356.17	26 279.9
7	53.39	321.66	24 448.7
8	53.39	0.50	24 448.7
9	45.27	317.98	17 593.3
10	45.27	4.18	17 593.3

4.4 *Step 4*: Determine the number of satellites and, thus, systems that are in the active arc

As Table 5 shows, there are ten satellites within the active arc based on this minimum true anomaly separation. For the USAKU-H2 system, the satellite entering the active arc is in the same system as the one leaving the active arc, thus there are nine satellite systems.

4.5 *Step 5*: Select one satellite to be in the wanted satellite system and calculate the interference from each of the other satellite systems into the wanted system for both the uplink and the downlink and calculate the aggregate interference from all of the interfering systems into the wanted system

Satellite No. 1 is selected as the wanted system. For this analysis, the earth stations were located at the same longitude as the wanted satellite and at the latitude minus 30° of the wanted satellite.

4.5.1 Interference on the 6 GHz gateway to user link

4.5.1.1 Interference on the 6 GHz gateway uplink

The USAKU-H2 system is designed to use power control so that the received signal power (in both the uplink and the downlink) remains constant throughout the active arcs of the satellites. Based on the link budgets given in § 3 of this Appendix, the earth station transmit power to achieve the necessary received signal power for the gateway uplink is calculated as follows:

$$P_{ES} = C_{\uparrow} - G_{ES} + L_{\uparrow} + \left[32.45 + 20\log(f_{\uparrow} \cdot d_{\uparrow})\right] - G_s \qquad \text{dBW} \qquad (18)$$

where:

- P_{ES}: transmitted power of the wanted earth station (dBW)
- $C\uparrow$: required received carrier power in the uplink (as given in the link budgets) (dBW)
- G_{ES}: gain of the wanted earth station antenna in the direction of the wanted satellite (dBi)
- $L\uparrow$: free space transmission and other losses, including atmospheric, on the uplink (dB)
- $f\uparrow$: frequency of the uplink (MHz)
- $d\uparrow$: distance between the interfering earth station and the wanted satellite (km)
- G_s: satellite receiving antenna gain of the wanted satellite (dBi).

This calculation results in a P_{ES} for the wanted link equal to 15.08 dBW. All of the systems are homogeneous both in orbit parameters and in transmission parameters, so the transmitted power of each of the interfering earth stations needs to be adjusted so that each uplink meets the required receiving signal power for its gateway uplink. The other transmission parameters for each of the other systems are as given above. The interference contribution from each satellite is calculated using equation (12) and the calculations are shown in Table 6. For this analysis, an earth station antenna gain pattern of 36 – 25 log(θ) is used.

TABLE 6

Satellite No.	P_{ES} (dBW)	θ_i (degrees)	$G_{ES,t}(\theta_i)$ (dBi)	$L\uparrow$ (dB)	$d\uparrow$ (km)	$f\uparrow$ (MHz)	Free space loss (dB)	$G_{s,r}$ (dBi)	$I\uparrow$ (dBW)
2	15.08	3.58	22.14	0.3	28 212.3	6 325	197.5	33	–127.55
3	14.77	3.87	21.29	0.3	28 212.3	6 325	197.5	33	–128.71
4	14.79	7.39	14.28	0.3	28 212.3	6 325	197.5	33	–135.71
5	14.12	8.63	12.61	0.3	28 212.3	6 325	197.5	33	–138.05
6	14.16	12.04	8.99	0.3	28 212.3	6 325	197.5	33	–141.60
7	13.02	15.15	6.49	0.3	28 212.3	6 325	197.5	33	–145.27
8	13.08	18.46	4.34	0.3	28 212.3	6 325	197.5	33	–147.36
9	11.21	25.41	0.88	0.3	28 212.3	6 325	197.5	33	–152.69
10	11.32	28.66	–0.43	0.3	28 212.3	6 325	197.5	33	–153.89

The aggregate interfering signal power received is –124.37 dBW. The satellite noise power (from the link budgets given in § 3 of this Appendix) is –124.3 dBW. The resultant uplink $C/(I+N)$ is 19.83 dB.

4.5.1.2 Interference on the 11 GHz user downlink

Based on the link budgets given in § 3 of this Appendix, the earth station transmit power to achieve the necessary received signal power for the gateway uplink is calculated as follows:

$$P_s = C_\downarrow - G_s + L_\downarrow + [32.45 + 20\log(f_\downarrow \cdot d_\downarrow)] - G_{ES} \quad \text{dBW} \quad (19)$$

where:

- P_s: transmitted power of the wanted satellite (dBW)
- $C\downarrow$: required received carrier power in the downlink (as given in the link budgets) (dBW)
- G_s: transmitting antenna gain of the wanted satellite (dBi)
- $L\downarrow$: free space transmission and other losses, including atmospheric, on the downlink (dB)
- $f\downarrow$: frequency of the downlink (MHz)
- $d\downarrow$: distance between the interfering satellite and the wanted earth station (km)
- G_{ES}: gain of the wanted earth station antenna in the direction of the wanted satellite (dBi).

This calculation results in a P_{ES} for the wanted link equal to 17.61 dBW. All of the systems are homogeneous both in orbit parameters and in transmission parameters, so the transmitted power of each of the interfering earth stations needs to be adjusted so that each uplink meets the required receiving signal power for its gateway uplink. The other transmission parameters for each of the other systems are as given above. The interference contribution from each satellite is calculated using equation (12) and the calculations are shown in Table 7. For this analysis, an earth station antenna gain pattern of 36 – 25 log(θ) is used.

TABLE 7

Satellite No.	P_s (dBW)	$G_{s,t}$ (dBi)	$L\downarrow$ (dB)	$d\downarrow$ (km)	$f\downarrow$ (MHz)	Free space loss (dB)	θ_w (degrees)	$G_{ES,r}(\theta_w)$ (dBi)	$I\downarrow$ (dBW)
2	17.61	35	0.5	28 231.9	11.950	203.0	3.58	22.14	–128.76
3	17.30	35	0.5	27 237.6	11.950	202.7	3.87	21.29	–129.61
4	17.32	35	0.5	27 297.3	11.950	202.7	7.39	14.28	–136.62
5	16.65	35	0.5	25 273.5	11.950	202.1	8.62	12.61	–138.29
6	16.69	35	0.5	25 276.8	11.950	202.1	12.04	8.99	–141.91
7	15.54	35	0.5	22 250.1	11.950	200.9	15.15	6.49	–144.41
8	15.60	35	0.5	22 405.6	11.950	201.0	18.46	4.34	–146.56
9	13.74	35	0.5	18 072.6	11.950	199.1	25.41	0.88	–150.02
10	13.85	35	0.5	18 300.2	11.950	199.2	28.66	–0.43	–151.33

The aggregate interfering signal power received is –125.33 dBW. The satellite noise power (from the link budgets given in § 3 of this Appendix) is –131.6 dBW. The resultant uplink $C/(I + N)$ is 6.31 dB.

4.5.2 Interference on the 14 GHz gateway to user link

The same calculations as in § 4.5.1 are performed for the other four links for Satellite No. 1 as the wanted system. Results are shown in Table 8.

4.5.3 Interference on the user to 4 GHz gateway link

The same calculations as in § 4.5.1 are performed for the other four links for Satellite No. 1 as the wanted system. Results are shown in Table 8.

4.5.4 Interference on the user to 11 GHz gateway link

The same calculations as in § 4.5.1 are performed for the other four links for Satellite No. 1 as the wanted system. Results are shown in Table 8.

4.6 *Step 6*: Calculate the resultant $C/(I+N)$ due to the aggregate interference from these multiple interfering systems for both the uplink and the downlink into the wanted system link budget and calculate the total link $C/(I+N)$. Determine if the system meets its required performance criteria

Using equation (17) and including the C/N contributions due to intermodulation, cross-polarization and multibeam, the overall link $C/(I+N)$ is 5.69 dB. The required link $C/(I+N)$ is 3.0 dB. The overall link margin is, thus, 2.69 dB.

4.7 *Step 7*: Repeat Steps 5 and 6 for each satellite as the wanted system

The results for all of the satellites on all of the links are shown in Table 8.

TABLE 8

Wanted satellite No.	$C/(I+N)$ total on 6 GHz gateway to user link (dB)	Resultant overall link margin on 6 GHz gateway to user link (dB)	$C/(I+N)$ total on 14 GHz gateway to user link (dB)	Resultant overall link margin on 14 GHz gateway to user link (dB)	$C/(I+N)$ total on user to 4 GHz gateway link (dB)	Resultant overall link margin on user to 4 GHz gateway link (dB)	$C/(I+N)$ total on user to 11 GHz gateway link (dB)	Resultant overall link margin on user to 11 GHz gateway link (dB)
1	5.69	2.69	5.72	2.72	4.96	1.96	5.24	2.24
2	5.69	2.69	5.72	2.72	4.96	1.96	5.24	2.24
3	6.47	3.47	6.49	3.49	5.36	2.36	5.62	2.62
4	6.47	3.47	6.49	3.49	5.36	2.36	5.62	2.62
5	7.76	4.76	7.75	4.75	5.97	2.97	6.20	3.20
6	7.76	4.76	7.75	4.75	5.97	2.97	6.20	3.20
7	9.14	6.14	9.10	6.10	6.54	3.54	6.74	3.74
8	9.14	6.14	9.10	6.10	6.54	3.54	6.74	3.74
9	10.29	7.29	10.21	7.21	6.94	3.94	7.12	4.12
10	10.29	7.29	10.21	7.21	6.94	3.94	7.12	4.12

4.8 *Step 8*: If the link budget performance requirements are not met, select a new minimum separation angle and return to Step 2

For the scenario investigate in the above sections, the link budget performance requirements are met.

5 Second application of the methodology

The methodology described in this Recommendation was applied to the USAKU-H2 system using an earth station antenna gain pattern of $32 - 25 \log(\theta)$. The results for each satellite for each link are given in Table 9.

TABLE 9

Interferred with satellite	$C/(I+N)$ total on 6 GHz gateway to user link (dB)	Resultant overall link margin on 6 GHz gateway to user link (dB)	$C/(I+N)$ total on 14 GHz gateway to user link (dB)	Resultant overall link margin on 14 GHz gateway to user link (dB)	$C/(I+N)$ total on user to 4 GHz gateway link (dB)	Resultant overall link margin on user to 4 GHz gateway link (dB)	$C/(I+N)$ total on user to 11 GHz gateway link (dB)	Resultant overall link margin on user to 11 GHz gateway link (dB)
1	5.37	2.37	5.41	2.41	4.72	1.72	5.00	2.00
2	5.37	2.37	5.41	2.41	4.72	1.72	5.00	2.00
3	5.81	2.81	5.84	2.84	4.98	1.98	5.25	2.25
4	5.81	2.81	5.84	2.84	4.98	1.98	5.25	2.25
5	6.60	3.60	6.62	3.62	5.41	2.41	5.67	2.67
6	6.60	3.60	6.62	3.62	5.41	2.41	5.67	2.67
7	7.59	4.59	7.59	4.59	5.91	2.91	6.15	3.15
8	7.59	4.59	7.59	4.59	5.91	2.91	6.15	3.15
9	8.63	5.63	8.60	5.60	6.38	3.38	6.60	3.60
10	8.63	5.63	8.60	5.60	6.38	3.38	6.60	3.60
11	9.57	6.57	9.51	6.51	6.76	3.76	6.96	3.96
12	9.57	6.57	9.51	6.51	6.76	3.76	6.96	3.96
13	10.42	7.42	10.33	7.33	7.05	4.05	7.24	4.24
14	10.42	7.42	10.33	7.33	7.05	4.05	7.24	4.24

6 Summary and conclusions

This Appendix has given an example application of the methodology described in this Recommendation for multiple USAKU-H2 type systems sharing with each other. The results show that at least nine such systems could share assuming an earth station antenna off-axis gain pattern of $36 - 25 \log(\theta)$, and at least 13 such systems could share assuming an earth station off-axis gain pattern of $32 - 25 \log(\theta)$.