RECOMMENDATION ITU-R S.1329*,**

Frequency sharing of the bands 19.7-20.2 GHz and 29.5-30.0 GHz between systems in the mobile-satellite service and systems in the fixed-satellite service

(Question ITU-R 81/4)

(1997)

The ITU Radiocommunication Assembly,

considering

a) that the World Administrative Radio Conference for Dealing with Frequency Allocations in Certain Parts of the Spectrum (Malaga-Torremolinos, 1992) (WARC-92) made allocations, on a primary basis, to the mobile-satellite service (MSS) in the bands 19.7-20.1 GHz and 29.5-29.9 GHz in Region 2 and 20.1-20.2 GHz and 29.9-30.0 GHz in all three Regions;

b) that earlier WARCs allocated these bands to the fixed-satellite service (FSS) on a primary basis;

c) that WARC-92 adopted Recommendation No. 719 which requests the ITU-R "to study as a matter of urgency technical characteristics, including pointing techniques, of multiservice*** -satellite networks using the geostationary-satellite networks encompassing mobile-satellite and fixed-satellite applications, and the sharing criteria necessary for compatibility with the fixed-satellite service in the frequency bands referred to above";

d) that the Radiocommunication Assembly in 1993 approved Question ITU-R 81/4 and accorded it priority;

e) that separately owned and operated networks may include FSS only satellites, MSS only satellites and dual-service (i.e. FSS and MSS) satellites, and that each of these three types of network may have to share the bands with either or both of the other two types;

f) that in 1997 more than 180 20/30 GHz geostationary-satellite orbit (GSO) FSS networks are in coordination;

g) that the technology of some currently planned GSO FSS networks might support 2° spacing of the arc with uplink antenna beam widths equal to or smaller than 1°;

h) that GSO MSS networks as originally studied would require more than 2° spacing from the nearest GSO FSS that is co-frequency co-coverage to provide necessary protection to the MSS,

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* This Recommendation should be brought to the attention of Radiocommunication Study Group 8.

** Radiocommunication Study Group 4 made editorial amendments to this Recommendation in 2001 in accordance with Resolution ITU-R 44 (RA-2000).

*** This term is used here to imply satellites equipped to operate in more than one service category.

recommends

1 that, in the planning and development of FSS, MSS and dual-service systems to utilize the geostationary orbit and to operate in the above frequency bands, the information on the technical characteristics and interference protection criteria of such systems contained in Annex 1 may be taken into consideration;

2 that new planned GSO FSS and MSS networks in the 29.5-30.0 and 19.7-20.2 GHz bands should take into account the technical characteristics of the FSS as described in Annex 2 and the characteristics of the MSS as being studied by Radiocommunication Study Group 8 under Question ITU-R 104/8.

NOTE 1 – Administrations are urged to submit further contributions on the subject matter contained in Annexes 1 and 2, particularly with regard to parameters of planned or future systems intended to operate in the above bands.

ANNEX 1

Frequency sharing between FSS and MSS networks in the 30/20 GHz bands

1 Introduction

WARC-92 produced Recommendation No. 719, which states that studies should be carried out on the technical characteristics of 30/20 GHz multiservice satellite networks and the sharing criteria necessary for their compatibility with the FSS.

A considerable amount of work has been carried out on this subject, with several administrations submitting input papers to the annual WP 4A meetings. At the fourth meeting of WP 4A, in November 1993, a number of contributions were submitted, including papers suggesting that the use of code division multiple access (CDMA), as the multiple access technique, might help alleviate the sharing situation. Some opposition to this suggestion was expressed, on the grounds that the use of CDMA can have certain disadvantages from the point of view of the mobile operator. For example, one particular problem that was highlighted was the effect of power control on CDMA systems and their capacity. The material in this Annex is based on a broad range of contributions and includes some detailed consideration of various aspects of CDMA, power control and other 30/20 GHz system parameters.

2 Some aspects of current MSS technology

This section outlines some key aspects of MSS technology which need to be carefully considered before any reliable analysis of orbit efficiency and sharing potential can be developed. Following a brief treatment of some fundamental theory relating to CDMA systems, some practical aspects are considered, based on available information on some planned future 30/20 GHz band systems. It should be emphasized that this is in no way a full, definitive treatment. However, results are produced which allow useful conclusions to be drawn.

2.1 CDMA satellite systems

Two forms of CDMA exist, frequency hopping CDMA (FH-CDMA) and direct sequence CDMA (DS-CDMA). For economic reasons the use of FH-CDMA is usually limited to military systems hence only DS-CDMA is considered here. CDMA can be transmitted/received using two basic methods (although the boundary between these methods is blurred by the fact that quasi-synchronous CDMA exists). The two basic methods are asynchronous and synchronous CDMA. In an asynchronous CDMA system a user can transmit information with no particular regard to the state of his unique chip sequence. In synchronous CDMA, a master code is transmitted that is received by every station in the system. This master code, amongst other things, allows every transmitting station to synchronize their chip codes and helps receiving stations to acquire the wanted incoming chip codes. Since all transmitting stations are synchronized, the cross-correlation products of their codes are kept to a minimum (especially if low cross-correlation codes are used, e.g. Gold codes), and so system self noise is minimized implying that the system's capacity is maximized. However, in a synchronous system, achieving initial synchronization to the wanted code is harder due to the reduced signal-to-noise ratio which arises because of the lack of synchronizm.

2.1.1 Theoretical maximum number of accesses

Consider a direct sequence CDMA (DS-CDMA) system, with m received carriers all of equal power C. The useful carrier power at the receiver input is therefore C and if E_b is the energy per information bit and R_b is the information bit rate:

$$C = E_b R_b \tag{1}$$

The total noise power at the receiver input (in receiver bandwidth B) is given by the sum of the system self-noise power generated by $(m - 1)$ users, the thermal noise power and any other interfering noise power:

$$N_0 B = (m - 1) \; C + N_{0TH} B + I \tag{2}$$

So, using these two equations:

$$\begin{aligned} C/I &= \frac{E_b R_b}{N_0 B - (m - 1) C - N_{0TH} B} \\ &= \frac{1}{\left(\frac{N_0 B}{E_b R_b}\right) - (m - 1) - \left(\frac{N_{0TH} B}{C}\right)} \end{aligned} \tag{3}$$

Now, for a carrier of bit rate R_c, the modulation spectral efficiency is given by:

$$\Gamma = \frac{R_c}{B} \tag{4}$$

The processing gain of a CDMA system is defined as:

$$F \, \Delta \, \frac{R_c}{R_b} \tag{5}$$

Combining these three equations, and rearranging, gives:

$$m = 1 + \frac{F}{\Gamma\ (E_b/N_0)} - \frac{1}{(C/I)} - \frac{1}{(C/N_{TH})} \tag{6}$$

This equation shows how an increase in external interference can be readily accommodated in a CDMA system by reducing system capacity. For a given required E_b/N_0 and assuming C/I and C/N_{TH} are negligible compared with self-noise, the maximum number of simultaneous accesses is:

$$m_{max} = 1 + \frac{F}{\Gamma\ (E_b/N_0)} \tag{7}$$

It should be noted that this limit is almost inversely proportional to E_b/N_0. CDMA is unique amongst the three access methods in that a drop in system performance can accommodate an increase in capacity without changing any other system parameters (see § 2.1.2 a)) and *vice versa*.

In deriving equation (7) a number of assumptions have been made:

– the noise contributions from both thermal noise and any external interference noise are neglected, as stated above;

– all the carrier powers, at the receiver input, are equal, also as stated above;

– the receiver is locked onto, and tracks perfectly, the incoming signal frequency;

– the receiver is perfectly synchronized to the incoming chips.

Note that in power limited digital systems the capacity is proportional to power and a typical system allows noise plus external interference to reduce the capacity by about 10% from the theoretical maximum. Of this, about 2.5% is due to the aggregate external interference. It is assumed here therefore that *the baseline reduction in a CDMA system's theoretical capacity*, to allow for external interference and thermal noise, *is 10% (7.5% thermal noise allowance and 2.5% external interference allowance)*.

2.1.2 Some advantages of using CDMA in particular applications

Many texts show that CDMA has a poor throughput compared with frequency division multiple access (FDMA) and, especially, time division multiple access (TDMA). Despite this, CDMA may have mitigating advantages relative to both FDMA and TDMA in some particular applications. Some of the common reasons given for advocating the use of CDMA, even with the reduced capacity that CDMA offers, are summarized below:

a) Under overload conditions, CDMA system quality degrades gracefully, i.e. allowing a temporary increase in bit error ratio (BER) makes more capacity temporarily available. Conversely if the system load, at any time, is actually lower than the peak load then link quality improves (in terms of BER) compared with a fully loaded system.

b) Voice activation can easily be applied to systems using CDMA as their multiple access method. Voice activated CDMA provides simultaneous demand assignment multiple access (DAMA) of both a transponder's bandwidth and its power.

c) CDMA reduces each individual terminal's transmitted power spectral density (PSD) so reducing its interference potential into narrower bandwidth carriers. A DS-CDMA system spreads the terminal's baseband spectrum over a large bandwidth, reducing its PSD by an amount equal to the processing gain of the CDMA system. This is a very useful property when a CDMA system is sharing with terrestrial systems, particularly if the CDMA system has mobile terminals with wide beamwidth, small diameter antennas.

d) A CDMA signal, because of its lack of a sharp threshold, will perform better in a fading/shadowing environment due to the simultaneous shadowing of both the wanted and the interfering signals (compared with FDMA) and due to its lower sensitivity to multipath. Multipath signals will either add constructively or destructively to the wanted signal. If they add destructively they appear simply as more system noise which is correlated out of the wanted signal in the receiver.

2.1.3 Acquisition and synchronization

One of CDMA's advantages in frequency tracking is its relative immunity to Doppler shift. However, three fundamental problems for a CDMA system are the initial acquisition, synchronization and tracking of both the wanted chip code and the transmission frequency. These problems have been well studied and can be now fully overcome using digital signal processing.

2.1.4 The effect of imperfect power control

A further problem that must be addressed when considering the use of CDMA, at 30/20 GHz frequencies, is the effect of power control. In an ideal CDMA system, every transmitted signal will have the same carrier power at the receiver input. Indeed this was one of the basic assumptions that was made when the CDMA capacity equation was developed earlier. From this equation it can be seen that system capacity is approximately inversely proportional to E_b/N_0, which can be effectively related to received carrier power. So qualitatively, from this equation, as the required E_b/N_0 increases the system's maximum capacity falls. In a real system there are a number of factors that can act either alone, or combine together, giving rise to differences in received signal carrier powers. These factors include:

– transmitter power control;

– rain fading;

– geographical effects due to satellite antenna discrimination and different free space path attenuations;

– shadowing and blockage (for mobile terminals);

– antenna mispointing (this is not particularly important when wide beamwidth mobile antennas are considered, but is a problem for narrow beamwidth vehicle mounted antennas);

– satellite movement (this is not too much of a problem with geostationary satellites).

To overcome these factors and to equalize, as far as possible, all signal carrier powers at the receiver, some form of up-path power control at each transmitter must be implemented. This implies that every earth terminal, in a CDMA system, requires:

– some method(s) of monitoring its power flux-density (pfd) at the satellite;

– a transmitter with adjustable output power over some pre-determined range.

Note that however good the earth terminal power control system, there will always be errors resulting in different received signal strengths if only due to the time delays inherent when using geostationary satellites and differences in up-path and down-path propagation fades. The term "imperfect power control" is used to describe these errors. There have been many studies into the effect of imperfect power control (sometimes called the "near-far effect") in cellular terrestrial systems. However, due to the fundamental differences between the channel characteristics of terrestrial and satellite systems (including different time delays and different propagation environments), these studies provide limited insight into the effects of imperfect power control on satellite CDMA systems. The derivation given below examines the effects of imperfect power control on a satellite CDMA system's capacity.

Consider a single user, referred to as user 1, in an *asynchronous* DS-CDMA system (which is a worst case assumption). The total system self-noise interference power spectral density, I_{0SN}, as seen by user 1 is:

$$\begin{aligned} I_{0SN} &= \frac{I_{SN}}{B} \\ &= \frac{I_{SN}}{R_c / \Gamma} \\ &= \frac{I_{SN}\,\Gamma}{R_b\,F} \end{aligned} \tag{8}$$

where:

$$I_{SN} = \sum_{i=2}^{m} C_i \tag{9}$$

Now, the total noise PSD, N_0, is given by the sum of the system self-noise interference PSD, I_{0SN}, the thermal noise PSD, N_{0TH}, and any other external interference PSD, I_0. So the E_b/N_0 of user 1's signal is:

$$\begin{aligned} \frac{E_{bI}}{N_0} &= \frac{E_{b1}}{I_{0SN} + N_{0TH} + I_0} \\ &= \frac{E_{bI}}{\left(\dfrac{I_{SN}\,\Gamma}{R_b\,F}\right) + N_{0TH} + I_0} \end{aligned} \tag{10}$$

For user 1 to maintain a required BER, a certain E_b/N_0 is required (dependent upon the coding scheme used). This value of $(E_b/N_0)_{req}$ therefore must occur when the self-noise of the system is at a maximum:

$$(E_b/N_0)_{req} = \frac{E_{b1}}{\left(\frac{I_{SN_{max}}\,\Gamma}{R_b\,F}\right) + N_{0TH} + I_0} \tag{11}$$

By rearranging this equation, and using $C_1 = E_{b1}\,R_b$, the maximum tolerable system self-noise can be calculated:

$$I_{SN_{max}} = \frac{C_1\,F}{\Gamma}\left(\frac{1}{(E_b/N_0)_{req}} - \frac{1}{(E_{b1}/N_{0TH})} - \frac{1}{(E_{b1}/I_0)}\right) \tag{12}$$

Now the average power of all the other DS-CDMA signals, excluding user 1, is given by:

$$\overline{C} = \frac{I_{SN_{max}}}{m - 1} \tag{13}$$

Now assume that user 1 is the user with the weakest signal (i.e. the worst case scenario for user 1), and define the signal dynamic factor, D, at the receiver input by:

$$\overline{C} = DC_1 \tag{14}$$

Note that D is a measure of how well the power control works and, by this definition, $D \geq 1$. So combining the above three equations and rearranging gives:

$$m = 1 + \frac{F}{D\Gamma}\left(\frac{1}{(E_b/N_0)_{req}} - \frac{1}{(E_{b1}/N_{0TH})} - \frac{1}{(E_{b1}/I_0)}\right) \tag{15}$$

Assuming that the system design parameters are kept constant, equation (15) can be expressed in the form (where A is a constant):

$$m = 1 + \frac{A}{D} \tag{16}$$

From either of these two equations it can be seen that:

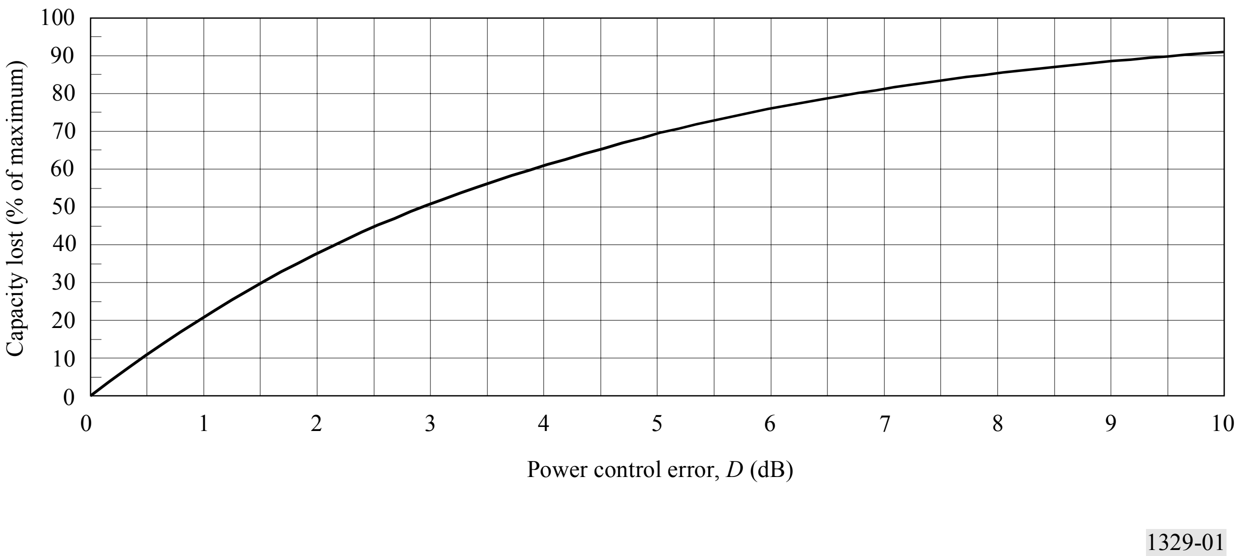
– to maximize the system capacity the optimum value is $D = 1$. This simply implies that all the signals are at the same level at the receiver input, i.e. all power levels are being perfectly controlled;

– as expected, minimizing the power control error maximizes the system capacity.

Using equation (16), if the maximum system capacity is known (assuming the power is perfectly controlled), the system capacity at any level of power control can be found by calculating the constant A and assuming that the system parameters do not change. If the maximum system capacity is relatively large, equation (16) can be approximated by $m \approx A/D$. This approximation can be used to plot a graph (see Fig. 1) of power control versus percentage of capacity lost for a large number of carriers. From this graph, for example, if $D = 1.25$ ($\approx$ 1 dB) then 20% of the maximum capacity is lost.

FIGURE 1

Percentage of CDMA capacity lost (for a large maximum capacity) versus power control error, *D*



It is very important to note that these equations have been developed assuming fully asynchronous CDMA. This represents a worst case assumption since a fully synchronous CDMA system will be less affected by the magnitude of the imperfect power control (particularly if low cross-correlation code sequences are used, e.g. Gold codes). This is the case because the maximum system capacity will be increased, compared with that achieved with asynchronous CDMA, since each transmitter's chip sequence will be synchronized carefully minimizing all cross-correlation products and hence the system self-noise interference. However, the use of fully synchronous CDMA in mobile systems may not be viable for economic reasons.

Despite the problem of imperfect power control, CDMA possesses certain features which may make it an attractive multiple access technique for systems using mobile terminals. Frequency sharing can be eased by the ability to readily accommodate interference by a reduction in system capacity. Many texts state that CDMA throughput is low; this implies that CDMA spectral efficiency is also low. Now, although the single satellite efficiency is low, the efficiency around the orbit arc might be larger than with other access techniques due to the closer satellite spacings. This implies that when considering the efficiency of a proposed system, some measure related to the minimum achievable orbital spacing should be included; for example the modulation spectral efficiency per satellite spacing degree of orbital arc.

2.1.5 The effect of power control on BER

Signals in 30/20 GHz bands suffer large fades due to rain, in addition to any attenuation due to atmospheric absorption. At lower frequencies rain fades are also a problem but are small enough to be countered by fixed rain margins in the link budget. The performance of a link is based on the magnitude of this fixed rain margin and a prediction of what percentage of time this margin is exceeded for. These performance criteria are typically specified with figures like 99.9% or 99.99% of the time. At 30/20 GHz the fades exceeding such criteria are too large to be directly countered by fixed margins and so, if these high percentages are required, other methods must be used, or else poorer performance must be endured. 30/20 GHz rain fades can occur at speeds of up to 3 or 4 dB per second. Possible methods of countering rain fades include space diversity, adaptive forward error correction (FEC), up-path power control, adaptive transmission rate and adaptive TDMA or CDMA.

Equation (16) was used in § 2.1.4 to calculate the effect of imperfect power control on system capacity. In the derivation leading up to this equation, user 1's $(E_b/N_0)_{req}$ was kept constant. However, in a practical system, short-term degradations in BER (and so in E_b/N_0) might be acceptable. The possibility of allowing such degradations would depend on the normal system operating conditions. For example, a system normally operating at a BER of 1×10^{-7} may be able to accept short-term falls in C/N resulting in BER of 1×10^{-3} for a time aggregating to say 0.01% of a year. In contrast a PCN system normally operating at a BER of 1×10^{-3} may not be able to accept a reduction in C/N of similar magnitude. Equation (16) can be rearranged to find out what power control errors such degradations would accommodate. The magnitude of the power control errors, that could be handled by allowing a short-term BER degradation, depends directly on the FEC scheme used in the link. A simple worked example is presented here to demonstrate the possibilities of allowing short-term degradations.

Consider carrier number 15 from the carrier Table 1. This carrier is used in a CDMA FSS hub to VSAT system. The system works at an E_b/N_0 of 5.3 dB with ½ rate, constraint length 7, soft decision Viterbi decoded, convolutional FEC. This provides a BER of 1×10^{-6}. QPSK modulation is used (which has a spectral efficiency of $\Gamma = 2$ bit/s/Hz ideally) and a CDMA system processing gain of $F = 1\,000$ is used. Throughout this example external interference and thermally generated noise are assumed to be negligible, for ease of calculation. Using equation (16), if the power control is perfect, the maximum system capacity is given by:

$$\begin{aligned} m &= 1 + \frac{F}{D\Gamma\,(E_b/N_0)} \\ &= 1 + \frac{1\,000}{1 \times 2 \times 10^{0.53}} \\ &= 148.56 \end{aligned} \tag{17}$$

So, with perfect power control (i.e. $D = 1$), the maximum system capacity is 148 simultaneous carriers. Assume for this system that the BER is required to exceed 1×10^{-6} for a time aggregated to 99.9% of the year. Figure 2 shows p% (percentage of the year that a maximum fade depth is likely to occur) versus 30/20 GHz bands rain fade depth in England. Examining this graph shows that for a 99.9% threshold (i.e. $p = 0.1$%) a maximum fade depth of 8.5 dB will not occur at a frequency of 30 GHz (which is the worst case frequency). So, to ensure that 148 carriers can operate for 99.9% of the year, a perfect power control system with a range of 8.5 dB is needed. Assume that such a system is possible and now let the BER fall to 1×10^{-3} whilst keeping the same number of simultaneous accesses. With the coding scheme described, a BER of 1×10^{-3} results in an E_b/N_0 of 3.4 dB. The maximum power control error that can be accommodated by allowing such a fall in BER can be calculated from equation (16):

$$m = 1 + \frac{F}{D\Gamma(E_b/N_0)}$$

i.e.:

$$148.56 = 1 + \frac{1000}{D \times 2 \times 10^{0.34}} \tag{18}$$

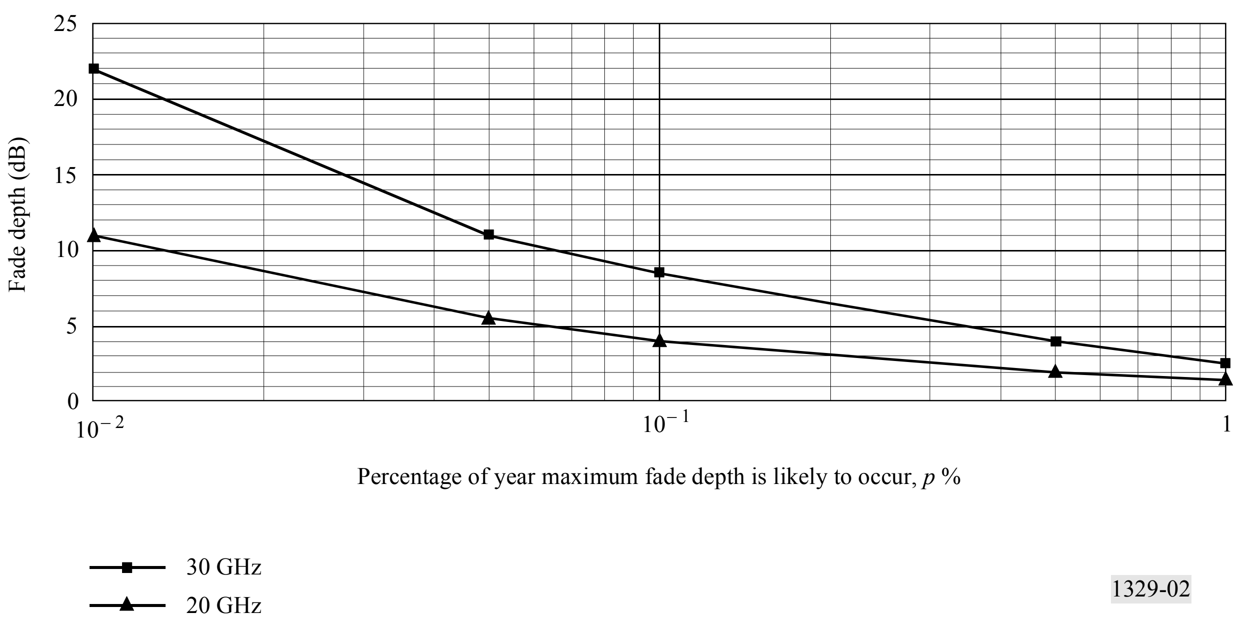
from which

$$D = 1.55 \text{ or } 1.9 \text{ dB}$$

So for a tolerable BER of 1×10^{-3}, with 8.5 dB of maximum perfect power control range, a fade of depth 10.4 dB can be accommodated. From Fig. 2 the percentage of the year that this fade depth is exceeded is $p = 0.06$% at a frequency of 30 GHz. From the above, if the system has perfect power control over a range of 8.5 dB, 148 simultaneous carriers are available at a BER of 1×10^{-6} for all year except a time aggregating to 8 h 45 min (i.e. $p = 0.1$%). If the system can suffer a BER fall to 1×10^{-3} for a time aggregating to 3 h 30 min (i.e. 0.1% minus 0.06% of a year) then a system with 148 carriers is possible all year except for a time aggregating to 5 h 15 min (i.e. $p = 0.06$%).

FIGURE 2

30/20 GHz rain fades over England



Note that this example assumed negligible external interference and thermal noise and also assumed perfect power control over a range of 8.5 dB. It is relatively simple to extend this example, with techniques described in this Recommendation, to accommodate external interference, thermal noise and imperfect power control.

2.1.6 Power control and its accuracy

There are many methods (for example variable rate coding and variable transmission rate) that could be used in order to maintain a constant BER on a fading satellite link. These solutions however would still result in an overall loss in system capacity due to the variation of carrier power levels at the receiver input. The only way to tackle this problem, and so keep the link BER constant and the capacity at its design limits, is to have up-path power control at the transmitter.

The accuracy with which the up-path power is controlled is of great importance in a CDMA system, as described in § 2.1.4. This accuracy depends on the accuracy with which the power control error can be measured and the accuracy with which the transmitter power can be controlled. The following are two methods of power control error measurement, for use with an up-path power control system:

– *Fast open loop*: Here a beacon signal from the satellite is monitored and the transmitter power control is set according to the variations in this beacon. This beacon may be on board the satellite or may be a signal that is transmitted by the hub station, in its transmissions, at a higher level (e.g. 6 dB) than the actual information signals. This signal can then not only be used for power control but also, for example in a CDMA system, to acquire and track the wanted signal's frequency and code i.e. provide synchronous CDMA. The single hop propagation delay means that this method is relatively fast. Note that this method works well for effects where both the uplink and downlink frequencies are affected (for example, shadowing effects due to buildings and trees) but will obviously not be so effective where the effects are frequency selective (for example, rain fading which is often de-correlated on the transmit and receive frequencies). Due to the problem of frequency selective effects, this method of power control is sometimes referred to as "coarse" since there is often a considerable error remaining in the signal power at the receiver.

– *Slow closed loop*: Here, some measure of the link performance (for example the link C/N or BER) is taken at the receiving earth terminal and then power control information is sent back to the transmitting earth terminal using the return link (for example, in the return link associated control channel). In order that uplink power control errors are the ones measured, and not errors on the downlink due to fades, etc., all incoming signals at the receiving earth terminal need to be monitored. If one signal level drops compared with the others then that signal is suffering an uplink fade and power control information needs to be sent out; if every signal level drops then a downlink fade is occurring and no power control information needs to be sent out. Measuring the link BER is often slow (of the order of a few seconds), particularly if the link is a low bit rate link, since a fair number of errors must be counted (e.g. 50-100 errors) before the measured BER becomes valid. Coupled with the requirement of a two hop propagation delay when using closed loop control it is easy to see why this method is called slow! However the power control information that is sent back is relatively accurate, even if it is old information by the time it is received, and so it is often used in a predictive system where the old information is processed to give an estimate of the current situation.

These two methods can be used alone, but both have failings and so often they are used together in some predetermined manner (for example, the open loop control adjusts the power unless it is overridden by the closed loop control).

Due to the shortcomings of these measurement systems, and any inaccuracies in the setting of the required transmitter power, there will always be some residual power control error. The effect of this error, on the capacity of a CDMA system, can be gauged from equation (15). Unfortunately it has not been possible to fully resolve this effect, during the course of this study, since no published results have been located on how well power control systems can perform. The lack of published results based on practical measurements is not just a 30/20 GHz bands problem, but a problem at all frequencies and also a problem for all terrestrial cellular CDMA systems (which are in a more advanced state of development than mobile satellite CDMA systems).

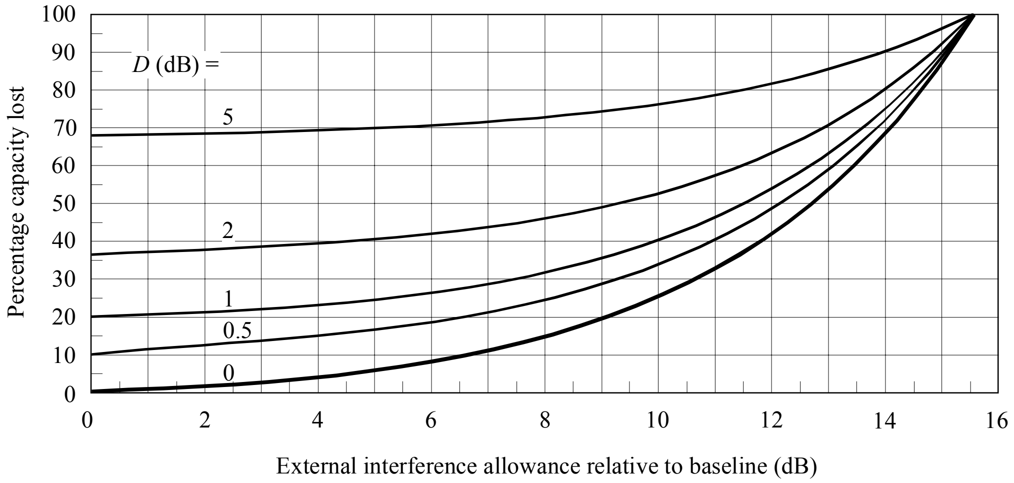
2.1.7 CDMA capacity versus interference allowance trade-off

Equation (6) shows that an increase in external interference can be readily traded off for a reduction of capacity in a CDMA system whilst still operating at the required link quality and without changing the modulation or access parameters. *CDMA is unique amongst the three major access techniques in this respect*. Note that by reducing a CDMA system’s capacity, its interfering potential is also reduced as the aggregate e.i.r.p. of the CDMA block is reduced. Also note that the required protection ratio for the CDMA block is reduced, so reducing its susceptibility to interference, as the capacity is reduced (see § 3.4 for further discussion on CDMA protection ratios). The external interference versus capacity trade-off, including the effects of power control error, is shown in Fig. 3 for a system that uses carrier 15 from the carrier Table 1. Note that, in plotting this graph, the baseline value of thermal noise reduces the theoretical maximum capacity by 7.5% (and this percentage remains constant), whilst the baseline value of external interference reduces the theoretical maximum capacity by 2.5% (and it is this percentage that is increased). See § 2.1.1 for further discussion of these baseline values.

So, for example, allowing an increase in external interference allowance of 7 dB above baseline reduces capacity (relative to the baseline maximum) by 10% with perfect power control, by 20% with 0.5 dB power control error (i.e. $D = 0.5$ dB), by 30% with 1 dB power control error, by 44% with 2 dB power control error and by 73% with 5 dB power control error. Losses in capacity may be acceptable if they allow coordination and the alternative is complete inability to coordinate.

FIGURE 3

Percentage of CDMA capacity lost versus external interference allowance including the effect of power control error, *D*



Note 1 – The carrier 15 was used to plot this graph.

1329-03

2.2 The effect of spot beams

In the context of this study, an assumption of low interbeam interference, in a carefully designed satellite spot beam system, can be made in order to reduce the adjacent satellite spacings. If beams utilizing the same frequencies, from adjacent satellites, are spaced well apart or even interleaved, large satellite antenna discriminations can occur between the wanted and interfering signals. Considering such non co-coverage cases can radically reduce satellite spacings as interference levels become reduced by an amount equal to the additional discrimination. However if two administrations wish to cover the same area and:

– one wants to use spot beams whilst the other wants a broad beam; or

– both wish to use spot beams but they are unable to agree on a suitable beam/frequency interleaving plan,

then problems will arise. Generally the use of interleaved satellite spot beams, as a means of achieving efficient orbital and spectrum usage, may be practicable only in cases where the same operator controls all the frequency sharing networks.

Both spot beams and broad beams, with their differing parameters, can be considered in a sharing study but co-coverage operation is often a necessity to ensure equitable access to the GSO.

2.3 The effect of using regenerative OBP

On board processing (OBP) is required for satellite systems utilizing multiple spot beams to ensure full and efficient connectivity between beams. Regenerative OBP implies that an incoming signal is demodulated, decoded, switched to the correct output beam, recoded and remodulated. This process essentially decouples the uplink and downlink noise and allows for the option of using different modulation and multiple access schemes on the uplink and downlink. If the BER on the uplink is BER_u and the BER on the downlink is BER_d then, with regenerative OBP and if the BERs are small, the total link BER, BER_t, is approximated by:

$$BER_t \approx BER_u + BER_d \tag{19}$$

For a given E_b/N_0, the BER will be smaller than that for a transparent transponder satellite system. When considering a transparent transponder, the total link C/N gives the link E_b/N_0 which can be related to a BER. To achieve the same BER with a regenerative OBP satellite, a maximum reduction in C/N of 3 dB is possible if, and only if, 50% of the noise occurs on the uplink and 50% on the downlink. A reduction of 3 dB in the C/N implies a 3 dB reduction in that carrier's protection ratio, which can be translated into a 32% decrease in satellite spacings (assuming the antenna side lobes fall off at 25 $\log_{10}\varphi$). Although a balanced distribution of noise on the uplinks and downlinks is likely to be common for networks employing direct mobile-to-mobile links it is not likely to be the case for many other applications. As the noise distribution becomes more unbalanced, what is a reasonable reduction falls off quite rapidly towards zero; for example, if 10% of the noise occurs on the uplink and 90% on the downlink then a reduction of 0.4 dB in the C/N occurs implying a 4% decrease in satellite spacings. Whatever the actual magnitude of the decrease, regenerative OBP does indeed decrease satellite spacings but entails the use of complex technology which is not yet mature.

3 Analysis

3.1 Carrier parameters

The carriers, and their associated parameters, that were used in the present analysis can be found in Table 1. All these carriers are digital since analogue carriers were studied by Radiocommunication WP 4A in 1992. Note that the column headed "No. of simultaneous carriers" has a value "1" for any access method other than CDMA, and for CDMA has a value calculated from equation (8) assuming the baseline values of thermal noise allowance and external interference allowance (together producing a 10% reduction in maximum capacity). It should also be noted that, for CDMA carriers, the e.i.r.p.s provided in the table are aggregate e.i.r.p.s calculated by multiplying the single carrier e.i.r.p. by the number of CDMA block carriers (the figure in the column "No. of simultaneous carriers"). This allows the CDMA block to be treated like a single large PSK carrier in any calculations.

Carriers numbered 8 to 33 were taken from a 1993 WP 4A input from the United Kingdom. These represent a selection of the most and least interfering and the most and least susceptible to interference. The system parameters for these carriers were frequency scaled from 1.6/1.5 GHz band and 30/20 GHz band. The validity of the frequency scaling was verified by subsequent comparison of similar frequency scaled parameters and planned network parameters.

Carriers numbered 40 to 43 are 30/20 GHz carriers that are used in current or planned networks. Note that, in order to account for variations in climatic zone, geographical location, etc., 3 dB was added to the satellite and earth terminal e.i.r.p.s to give maximum values and 3 dB has been subtracted to give minimum values.

Carriers numbered 50 to 62 are all the carriers presented in an INTELSAT input paper to the WP 4A 1993 meeting. Note that again 3 dB was added/subtracted from satellite and earth terminal e.i.r.p.s to give maximum/minimum values.

Carriers numbered 80 to 86 are carriers developed from the parameters given in a Canadian contribution to the 1993 WP 4A meeting. Each link uses a multi-user multimedia (MUMM) terminal as a hub station. Transparent transponder link budgets were calculated, in each case, to provide the same overall link BER as regenerative transponders (using equation (19) to calculate the overall BER in a regenerative transponder link). On forward links 10% of the noise was assumed to occur on the uplink and 90% on the downlink. On reverse links 10% of the noise was assumed to occur on the downlink and 90% on the uplink. Using this, the required satellite and earth terminal e.i.r.p. values could be found. Note that again 3 dB was added/subtracted from satellite and earth terminal e.i.r.p.s to give maximum/minimum values.

3.2 Fixed and mobile antenna patterns

Co-coverage is the worst case scenario for satellite spacing calculations. When considering co-coverage it is only the antenna off-axis discriminations of the wanted and interfering earth terminals that decide the minimum satellite spacings. Therefore the roll-off characteristics of any earth terminal antenna that may be used must be known before spacing calculations can be performed.

Carrier Table 1 shows which antenna patterns were used with each carrier's transmitting and receiving earth terminal. Every carrier was used with its respective antenna pattern; for example the hypothetical "INTELSAT" mobile terminal to hub link uses the mobile earth terminal transmitting pattern postulated in the Intelsat paper and the United Kingdom fixed earth terminal receiving pattern. Appendix 1 to Annex 1, § 1 gives the equations of all antenna patterns used. It should be noted that:

– the United Kingdom fixed earth terminal pattern is from Radio Regulations (RR) Appendix S8;

– the United Kingdom mobile earth terminal pattern was based on an INMARSAT model, adjusted for frequency;

– both of the Canadian patterns have maximum gain from 0° off boresight to 100 $\lambda/D°$. In a Canadian input paper, if spacing could not be achieved with 0° but could be achieved with a spacing angle less than 100 $\lambda/D°$ then the spacing value was increased to 110 $\lambda/D°$. The pattern shown in Appendix 1 to Annex 1, § 3 performs this process automatically;

– the Canadian fixed earth terminal pattern was given –10 dBi far side lobes, as in RR Appendix S8, because no value was provided in the input paper;

– the Canadian mobile earth terminal pattern was given far side lobes constant at the level reached at 48° since no value was provided in the input paper;

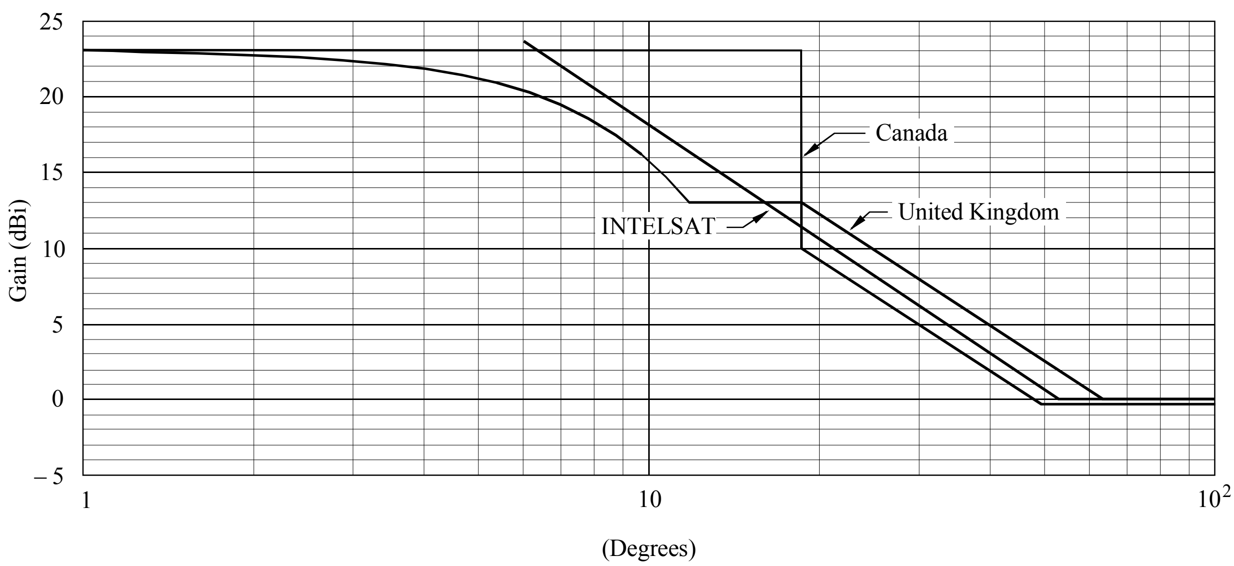
– the United Kingdom fixed earth terminal pattern was used for INTELSAT fixed earth terminals, since no equations were given except that their patterns were characterized by $29 - 25 \log_{10} \varphi$ as is the United Kingdom fixed earth terminal pattern;

– the hypothetical "INTELSAT" mobile earth terminal patterns were given 0 dBi far side lobes, as there were no values provided and this was the value achieved at the limit of the equations provided.

A comparison of the United Kingdom, Canadian and "INTELSAT" receiving mobile earth terminal patterns is shown in Fig. 4. In this Figure all three antennas have the same maximum gain. Figure 5 shows a comparison of the United Kingdom, Canadian and "INTELSAT" transmitting mobile earth terminal patterns. Again, in this Figure, all three antennas have the same maximum gain.

FIGURE 4

Receive mobile antenna pattern comparison

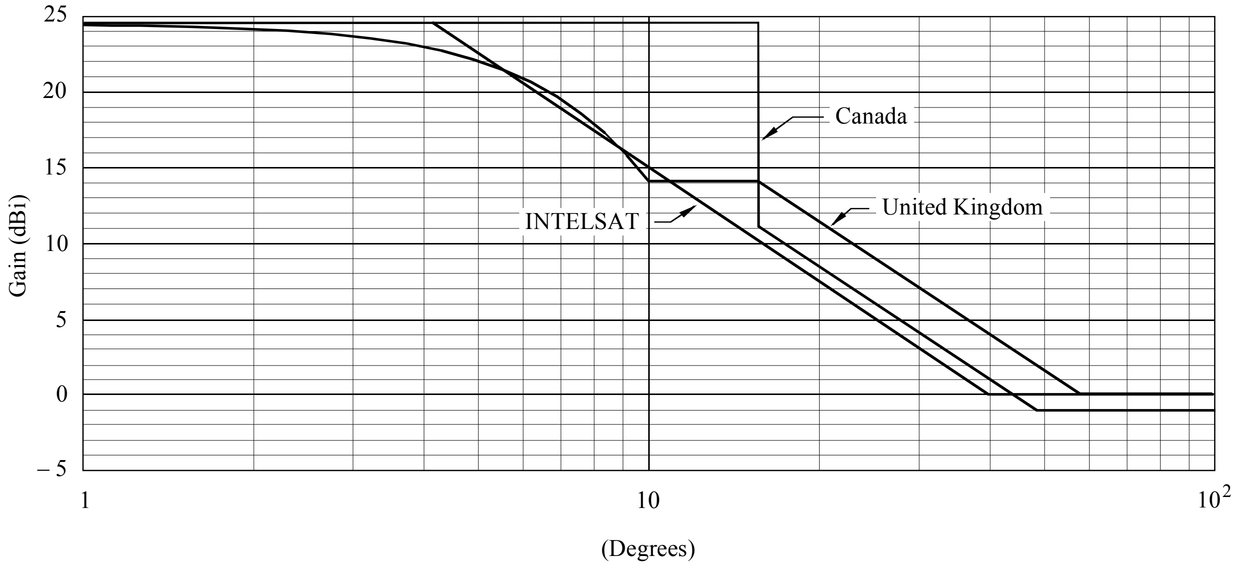


Note 1 – All antennas have same on-axis gain.

1329-04

FIGURE 5

Transmit mobile antenna pattern comparison



Note 1 – All antennas have same on-axis gain.

1329-05

No values for the pointing accuracy of any of these antennas were provided. The loss of gain due to mispointing could be very important in a CDMA system (see § 2.1.4) so some values were needed. The antennas were assumed to have systems which can keep the pointing accuracy within 1° for the phased array (which has a maximum gain of 24.5 dBi) and 0.1° for the VSAT (which has a maximum gain of 23.5 dBi). The loss due to a mispointing of $\theta_p°$ can be approximated by:

$$Loss\ (\text{dB}) = 12\left(\frac{\theta_p D}{68\,\lambda}\right)^2 \tag{20}$$

So the losses due to mispointing are approximately 0.1 dB for the phased array and 0.9×10^{-3} dB for the VSAT. These values of loss are relatively small compared with those due to rain fades at 30/20 GHz and therefore have been ignored in the present analysis. The validity of the 0.1 dB figure for mobile terminals may, however, need to be reviewed in the future.

3.3 Satellite interference equations

When considering co-coverage the worst case assumptions are that:

– the wanted earth terminal is at the edge of coverage of the wanted satellite and at the beam centre of the interfering satellite;

– the interfering earth terminal is at the beam centre of the wanted satellite and at the edge of coverage of the interfering satellite.

Using these assumptions the equations for calculating link *C*/*I* ratios are straightforward. The uplink *C*/*I* equation is given by:

$$(C/I)_U = (e.i.r.p._{ESw} - 3) - (e.i.r.p._{ESi} - G_{ESi} + G_{ESi}(\varphi)) \quad (21)$$

where:

$e.i.r.p._{ESw}$: wanted earth terminal's e.i.r.p.

$e.i.r.p._{ESi}$: interfering earth terminal's e.i.r.p.

G_{ESi}: interfering earth terminal's maximum antenna gain

$G_{ESi}(\varphi)$: interfering earth terminal's antenna gain at φ°.

Likewise the downlink *C*/*I* equation is given by:

$$(C/I)_D = (e.i.r.p._{SATw} - 3 + G_{ESw}) - (e.i.r.p._{SATi} + G_{ESw}(\varphi)) \quad (22)$$

where:

$e.i.r.p._{SATw}$: wanted satellite's e.i.r.p.

$e.i.r.p._{SATi}$: interfering satellite's e.i.r.p.

G_{ESw}: wanted earth terminal's maximum antenna gain

$G_{ESw}(\varphi)$: wanted earth terminal's antenna gain at φ°.

If the same carriers are considered on uplink and downlink then, for regenerative transponders, these two equations are all that are needed. For transparent transponders the *C*/*I* ratio for the entire link is required. This is given by:

$$(C/I)_{tot}^{-1} = (C/I)_U^{-1} + (C/I)_D^{-1} \quad (23)$$

3.4 Protection ratios

The protection ratios used in the analysis for each combination of wanted and interfering carriers are given in Table 2. The software model embodied a relatively simple set of rules to give an estimate of the minimum acceptable single entry *C*/*I* which would cause a signal impairment no worse than that regarded as acceptable to each particular wanted carrier. This depends on a number of factors:

– the target *C*/*N* ratio for the wanted carrier;

– the allowable baseband single entry interference for the wanted carrier;

– the occupied bandwidths of the wanted and interfering carriers;

– the modulated spectra of the wanted and interfering carriers.

Note it was assumed in § 2.1.1 that the baseline reduction in a CDMA system's theoretical capacity, to allow for external interference and thermal noise, is 10% (7.5% thermal noise allowance and 2.5% external interference allowance). So the protection ratio, for a wanted CDMA carrier, can be calculated by treating the whole CDMA block as a single PSK carrier if 4.8 dB (i.e. $10 \log_{10}(7.5\%/2.5\%)$) is added to the overall *C*/*N* and a bandwidth factor included.

3.5 Calculating satellite spacing angles

A computer program was written to evaluate the minimum satellite spacings required between the various combinations of carriers given in Table 1. For every combination of wanted and interfering carriers the protection ratio was calculated. The required spacing angle, φ, was then calculated. If sufficient protection could not be given to the wanted carrier then the extra discrimination required to achieve a spacing was calculated. The output data was then given:

– the wanted and interfering carrier numbers (for identification);

– the required protection ratio;

– either the required satellite spacing, φ, or the extra discrimination needed to achieve spacing;

– the spectral efficiency per degree of spacing on the orbital arc. This is calculated by multiplying the number of simultaneous users of the bandwidth by the channel bit rate and dividing the result by the channel bandwidth and the required orbital spacing.

Note that in calculating the spectral efficiency per degree of spacing on the orbital arc it is assumed that the system is bandwidth and not power limited.

Note that the angle φ is in fact a topocentric angle i.e. the angle between adjacent satellites as seen from an earth terminal at a point on the Earth's surface. The actual required satellite spacing angle is, of course, given by the geocentric angle, θ, and when considering geostationary satellites, it can be shown that for a given topocentric angle, φ, the geocentric angle varies from:

$$\theta = \varphi - 2\sin^{-1}\left[0.1512\sin(\varphi/2)\right] \qquad \text{at the equator} \qquad (24)$$

to $\theta \approx \varphi$ (at high latitudes).

However the quasi-worst case is $\theta = \varphi$, which is the case that is considered here.

Also note that in areas where the topocentric angle is smallest, giving the minimum earth terminal antenna discrimination, the interference path length is the longest, so that the two effects tend to cancel out. This implies that, to a good approximation, the fact that all terminals in a system are not in the same place may be ignored.

4 Results

In Table 1, carriers 21 to 26 inclusive, carriers 55 to 58 inclusive and carriers 80 to 85 inclusive are FDMA MSS carriers. Carriers 30 to 33 inclusive and carriers 59 to 62 inclusive are CDMA blocks of spread spectrum MSS carriers. All the other carriers in this table, with the exception of carriers 15 to 18 inclusive which are CDMA blocks of spread spectrum FSS carriers, are FDMA FSS carriers.

Table 2 shows the protection ratios (dB) required for wanted and interfering carrier combinations. Table 3 shows the co-coverage satellite spacings (degrees) required to ensure that the respective protection ratios, of wanted and interfering carrier combinations, are achieved. A number in brackets indicates that it is impossible to achieve the required protection ratio with any spacing. The number in brackets itself is the additional discrimination (dB) required in order that the relevant protection ratio can be achieved. Table 4 shows the wanted carrier's modulation spectral efficiency per degree of spacing orbital arc (bit/s/Hz/degrees) achieved at the relevant wanted and interfering carrier combination spacing. This value is calculated by dividing the wanted carrier's modulation spectral efficiency (calculated by dividing its channel bit rate by its channel bandwidth) by the spacing achieved for the relevant wanted and interfering carrier combination and then multiplying this by the maximum number of simultaneous accesses for the wanted carrier's channel bandwidth (which is 1 for all access methods except CDMA, and for CDMA can be calculated from equation (15) assuming the baseline interference and thermal noise allowances). A "0" in brackets indicates that the relevant protection ratio was not achieved and so no value of satellite spacing exists. A "–1" in brackets indicates that 0° spacing was achieved (resulting in an infinite modulation spectral efficiency per degree of orbital arc).

For example, if a wanted satellite carrying a 5 MHz MSS CDMA block of carriers (carrier 30) is covering the same area as an interfering satellite carrying a 64 kbit/s VSAT to VSAT link (carrier 40) then:

– a protection ratio of 26.8 dB is required;

– a 2.2° satellite spacing is required to achieve this protection ratio;

– a modulation spectral efficiency per degree of orbital arc of 0.197 bit/s/Hz/degree results for the wanted carrier at this spacing.

Perusal of Tables 3 and 4 provides the following:

a) The satellite spacings for FDMA FSS to FDMA FSS combinations are not too large; the majority of the spacings are well below 10° and are of a magnitude suggesting, if coordination techniques are applied (for example, carrier interleaving or spectrum segmentation), spacings of 3° should be achievable. The satellite spacings for FSS combinations when one or both of the carriers considered uses CDMA are also relatively modest and result in generally similar spectral efficiencies per degree of orbital arc to those produced by wholly FSS FDMA combinations.

b) The satellite spacings for FSS carriers interfering with MSS carriers are of the same magnitude, or slightly larger than those in a) implying that coordination could probably reduce them to usable levels. Note that the satellite spacings are generally smaller if the MSS carriers use CDMA rather than FDMA. As expected, the spectral efficiencies per degree of orbital arc are less than those achieved in a). However, using either FDMA MSS or CDMA MSS carriers produces similar values.

c) For MSS carriers interfering with FSS carriers the satellite spacings are generally quite large and coordination would appear to be quite difficult. The use of CDMA, rather than FDMA, for the MSS carriers generally helps to reduce these spacings but they are still quite large. However it might be viable to trade some CDMA block capacity for a reduction in these spacings. The use of CDMA by both the MSS and FSS carriers helps reduce spacings to levels where usable solutions may be produced by the coordination process. As expected the spectral efficiencies per degree of orbital arc are smaller than those achieved in a). However CDMA MSS carriers (particularly those numbered 30 to 33 inclusive) have generally larger spectral efficiencies per degree of orbital arc than those using FDMA.

d) For MSS to MSS carrier combinations generally either the satellite spacings are large or extra discrimination is needed to achieve the required protection ratio. Coordination exercises probably could not produce satisfactory outcomes. However it is worth noting that the use of CDMA generally helps reduce spacing (particularly if CDMA is used for both wanted and interfering MSS carriers). Also it may be viable to trade capacity for reduced spacings, when using CDMA, in order to achieve an acceptable outcome to coordination. It is also worth noting that when CDMA is used the spectral efficiencies per degree of orbital arc are often larger than those achieved with FDMA. This demonstrates the usefulness of CDMA in a sharing environment, particularly when the ease of trading capacity for a reduction in spacings (without changing any system parameters) is also considered.

NOTE 1 – The use of CDMA reduces the spectral efficiency (bit/s/Hz) of a link compared with that achieved when using FDMA or TDMA. However, where CDMA is used for either the wanted carrier or the interfering carrier or (particularly) both carriers the modulation spectral efficiency per degree of orbital arc (bits/s/Hz/degrees) is generally as good as, and often better than, that achieved when FDMA or TDMA is used.

5 Conclusions

In the 30/20 GHz bands, the minimum geocentric separation angles, for satisfactory sharing, between two FSS satellites are generally much smaller than between two MSS satellites. The sharing angle between an FSS satellite and an MSS satellite is usually determined by the protection required for the MSS carriers.

Co-coverage, co-frequency sharing between FSS networks, at satellite spacings of the order of 3°, is practicable if traditional coordination techniques are applied. Co-coverage, co-frequency sharing between FSS and MSS satellites, and particularly between MSS satellites alone, creates larger separation angles, or lower than traditional link qualities, or smaller than traditional carrier capacities.

If co-coverage, frequency sharing with MSS carriers is required, some method is needed in order to reduce the satellite spacings. Methods such as the use of CDMA or spectrum segregation or geographical isolation via spot beams can be considered.

Use of spectrum segregation is undesirable, as is the use of geographical isolation. The use of interleaved spot beams can be considered but will probably lead to complex sharing scenarios.

A CDMA system's capacity can be traded-off relatively easily, with no changes in network parameters, in order to accept more external interference. As capacity is traded-off in a CDMA system, it also becomes less interfering. In this study, CDMA systems generally were found to have higher spectral efficiencies per degree of orbital arc than similar FDMA systems, even though the capacity per satellite was higher in the FDMA case. However the capacity of a CDMA system is heavily dependant on the power control error at the receiver input. Whether or not a CDMA system, used for communication by portable transceivers, is economically viable will therefore depend on the accuracy and cost of its power control system, as these two are inextricably linked.

APPENDIX 1

TO ANNEX 1

1 Antenna patterns

To calculate a value for D/λ the following equation can be used (assuming a 70% antenna efficiency):

$$\frac{D}{\lambda} = \frac{1}{\pi}\sqrt{\frac{10^{0.1G_{max}}}{0.7}} \tag{25}$$

2 United Kingdom antenna patterns

Fixed earth terminal antenna pattern (from RR Appendix S8):

$$G(\varphi) = \begin{cases} G_{max} - 2.5 \times 10^{-3}\left(\frac{D}{\lambda}\varphi\right)^2 & \text{for} \quad 0 < \varphi < \varphi_m \\ 2 + 15\log_{10}\left(\frac{D}{\lambda}\right) & \text{for} \quad \varphi_m \le \varphi < \varphi_r \\ 29 - 25\log_{10}\varphi & \text{for} \quad \varphi_r \le \varphi < 48° \\ -10 & \text{for} \quad 48° \le \varphi \le 180° \end{cases} \tag{26}$$

Mobile earth terminal antenna pattern:

$$G(\varphi) = \begin{cases} G_{max} - 2{,}5 \times 10^{-3}\left(\frac{D}{\lambda}\varphi\right)^2 & \text{for} \quad 0 < \varphi < \varphi_m \\ 2 + 15\log_{10}\left(\frac{D}{\lambda}\right) & \text{for} \quad \varphi_m \le \varphi < 100\frac{\lambda}{D} \\ 52 - 10\log_{10}\left(\frac{D}{\lambda}\right) - 25\log_{10}\varphi & \text{for} \quad 100\frac{\lambda}{D} \le \varphi < \varphi_1 \\ 0 & \text{for} \quad \varphi_1 \le \varphi \le 180° \end{cases} \tag{27}$$

where:

$$\begin{aligned} \varphi_m &= \frac{20\lambda}{D}\sqrt{G_{max} - 2 - 15\log_{10}\left(\frac{D}{\lambda}\right)} \\ \varphi_r &= 15.85\left(\frac{D}{\lambda}\right)^{-0.6} \\ \varphi_1 &= 120\left(\frac{D}{\lambda}\right)^{-0.4} \end{aligned} \tag{28}$$

3 Canadian antenna patterns

Fixed earth terminal antenna pattern:

$$G(\varphi) = \begin{cases} G_{max} & \text{for} \quad 0 < \varphi < 100\dfrac{\lambda}{D} \\ 29 - 25\log_{10}\varphi & \text{for} \quad 100\dfrac{\lambda}{D} \le \varphi < 48^\circ \\ -10 & \text{for} \quad 48^\circ \le \varphi \le 180^\circ \end{cases} \tag{29}$$

Mobile earth terminal antenna pattern:

$$G(\varphi) = \begin{cases} G_{max} & \text{for} \quad 0 < \varphi < 100\dfrac{\lambda}{D} \\ 49 - 10\log_{10}\left(\dfrac{D}{\lambda}\right) - 25\log_{10}\varphi & \text{for} \quad 100\dfrac{\lambda}{D} \le \varphi < 48^\circ \\ 7 - 10\log_{10}\left(\dfrac{D}{\lambda}\right) & \text{for} \quad 48^\circ \le \varphi \le 180^\circ \end{cases} \tag{30}$$

4 "INTELSAT" antenna patterns

Fixed earth terminal antenna pattern:

– the United Kingdom fixed antenna pattern was used.

Transmit mobile earth terminal antenna pattern:

$$G(\varphi) = \begin{cases} 24.5 & \text{for} \quad 0 < \varphi < 4.17^\circ \\ 40 - 25\log_{10}\varphi & \text{for} \quad 4.17^\circ \le \varphi < 39.8^\circ \\ 0 & \text{for} \quad 39.8^\circ \le \varphi \le 180^\circ \end{cases} \tag{31}$$

Receive mobile earth terminal antenna pattern:

$$G(\varphi) = \begin{cases} 23.0 & \text{for} \quad 0 < \varphi < 6.03^\circ \\ 43 - 25\log_{10}\varphi & \text{for} \quad 6.03^\circ \le \varphi < 52.5^\circ \\ 0 & \text{for} \quad 52.5^\circ \le \varphi \le 180^\circ \end{cases} \tag{32}$$

5 Table of results

TABLE 1

30/20 GHz bands carrier parameters

Carrier No.	No. of simul-taneous carriers	Single carrier channel bit rate (kbit/s)	Noise band-width (kHz)	Channel band-width (kHz)	*C/N* (dB)	Satellite		Earth station						Carrier description
						maximum e.i.r.p. (dBW)	minimum e.i.r.p. (dBW)	maximum e.i.r.p. (dBW)	minimum e.i.r.p. (dBW)	Tx gain (dBi)	Tx antenna pattern	Rx gain (dBi)	Rx antenna pattern	
8	1	120 000	66 000	72 000	13.2	64.6	62.3	87.4	84.4	62.3	UK Fix	60.2	UK Fix	UK FSS 120 Mbit/s TDMA QPSK
9	1	128	85	112.5	6.8	31.7	19.6	54.5	37.3	57.2	UK Fix	55.1	UK Fix	UK FSS 64 kbit/s + 1/2 FEC FDMA QPSK
10	1	4 096	2 700	3 173	6.8	46.8	34.6	69.6	52.4	57.2	UK Fix	55.1	UK Fix	UK FSS 2 048 kbit/s + 1/2 FEC FDMA QPSK
15	134	10	5 000	5 500	7.7	53.8	43.8	69	59	60	UK Fix	41.3	UK Fix	UK FSS (H->V) 5 kbit/s + 1/2 FEC CDMA QPSK
16	134	10	5 000	5 500	7.7	43.8	33.8	59.5	49.5	43.4	UK Fix	57.8	UK Fix	UK FSS (V->H) 5 kbit/s + 1/2 FEC CDMA QPSK
17	134	100	50 000	55 000	7.7	63.8	53.8	79	69	60	UK Fix	41.3	UK Fix	UK FSS (H->V) 50 kbit/s + 1/2 FEC CDMA QPSK
18	134	100	50 000	55 000	7.7	53.8	43.8	69.5	59.5	43.4	UK Fix	57.8	UK Fix	UK FSS (V->H) 50 kbit/s + 1/2 FEC CDMA QPSK
21	1	24	14.4	20	4.3	40.6	32.1	76.9	68.3	54	UK Fix	28	UK Mob	UK FSS->MSS Inm-B 24 kbit/s Glob FDMA
22	1	24	14.4	20	3.6	28.4	15.5	30.2	24.2	31.5	UK Mob	50.5	UK Fix	UK MSS->FSS Inm-B 24 kbit/s Spot FDMA
25	1	8	4.8	10	4.2	39.6	31.1	79.9	71.3	54	UK Fix	23	UK Mob	UK FSS->MSS Inm-M 8 kbit/s Glob FDMA
26	1	8	4.8	10	3.4	26.3	9.5	25.1	20.1	27.5	UK Mob	50.5	UK Fix	UK MSS->FSS Inm-M 8 kbit/s Spot FDMA
30	226	9.6	4 800	5 000	7.9	71.1	65.1	52.3	46.3	53.5	UK Fix	19	UK Mob	UK FSS->MSS 4.8 kbit/s + 1/2 FEC CDMA QPSK
31	226	9.6	4 800	5 000	7.9	42.2	36.2	43.2	37.2	23	UK Mob	50	UK Fix	UK MSS->FSS 4.8 kbit/s + 1/2 FEC CDMA QPSK
32	226	96	48 000	50 000	7.9	68.5	62.5	62.3	56.3	53.5	UK Fix	29	UK Mob	UK FSS->MSS 48 kbit/s + 1/2 FEC CDMA QPSK
33	226	96	48 000	50 000	7.9	52.2	46.2	51.2	45.2	32.5	UK Mob	50	UK Fix	UK MSS->FSS 48 kbit/s + 1/2 FEC CDMA QPSK
40	1	128	153.6	179.2	5.1	27.5	21.5	40.5	34.5	45.5	UK Fix	42.1	UK Fix	CODE (V->V) 64 kbit/s + 1/2 FEC FDMA BPSK
41	1	4 096	2 460	3 240	10.8	42.5	36.5	74.9	68.9	53.8	UK Fix	42.1	UK Fix	CODE (H->V) 2 048 kbit/s + 1/2 FEC FDMA QPSK
42	1	128	153.6	179.2	6	27.5	21.5	41.5	35.5	45.5	UK Fix	50.9	UK Fix	CODE (V->H) 64 kbit/s + 1/2 FEC FDMA BPSK
43	1	3 000	2 180	2 520	11.7	34.6	28.6	66.5	60.5	53.5	UK Fix	50	UK Fix	ACTS (V->V) 1.5 Mbit/s + 1/2 FEC FDMA QPSK

TABLE 1 (*continued*)

Carrier No.	No. of simul-taneous carriers	Single carrier channel bit rate (kbit/s)	Noise band-width (kHz)	Channel band-width (kHz)	*C/N* (dB)	Satellite maximum e.i.r.p. (dBW)	Satellite minimum e.i.r.p. (dBW)	Earth station maximum e.i.r.p. (dBW)	Earth station minimum e.i.r.p. (dBW)	Tx gain (dBi)	Tx antenna pattern	Rx gain (dBi)	Rx antenna pattern	Carrier description
50	1	128	76.8	89.6	10	23.9	17.9	50.8	44.8	63	UK Fix	59.7	UK Fix	INTELSAT M3QL (K3->K3) 64 kbit/s + 1/2 FEC FDMA QPSK
51	1	128	76.8	89.6	13.4	29.9	23.9	56.8	50.8	56	UK Fix	51.7	UK Fix	INTELSAT M2QL (K2->K2) 64 kbit/s + 1/2 FEC FDMA QPSK
52	1	128	153.6	179.2	11.9	35.6	29.6	62.5	56.5	50	UK Fix	46.5	UK Fix	INTELSAT M1BL (K1->K1) 64 kbit/s + 1/2 FEC FDMA BPSK
53	1	128	153.6	179.2	16.2	35.6	29.6	62.5	56.5	63	UK Fix	51.7	UK Fix	INTELSAT S32BH (K3->K2) 64 kbit/s + 1/2 FEC FDMA BPSK
54	1	128	153.6	179.2	17.9	41.5	35.5	68.4	62.4	50	UK Fix	46.5	UK Fix	INTELSAT M1BH (K1->K1) 64 kbit/s + 1/2 FEC FDMA BPSK
55	1	9.6	11.5	13.4	4.4	11.7	5.7	23.6	17.6	24.5	Intelsat Mob	59.7	UK Fix	INTELSAT F3I (MT->K3) 4.8 kbit/s + 1/2 FEC FDMA BPSK
56	1	9.6	11.5	13.4	4.4	13.6	7.6	25.5	19.5	24.5	Intelsat Mob	51.7	UK Fix	INTELSAT F2I (MT->K2) 4.8 kbit/s + 1/2 FEC FDMA BPSK
57	1	9.6	11.5	13.4	4.4	40	34	66.9	60.9	63	UK Fix	23	Intelsat Mob	INTELSAT F3O (K3->MT) 4.8 kbit/s + 1/2 FEC FDMA BPSK
58	1	9.6	11.5	13.4	4.4	40	34	66.9	60.9	56	UK Fix	23	Intelsat Mob	INTELSAT F2O (K2->MT) 4.8 kbit/s + 1/2 FEC FDMA BPSK
59	652	9.6	7 617	8 064	4.4	42.7	36.7	54.6	48.6	24.5	Intelsat Mob	59.7	UK Fix	INTELSAT C3I (MT->K3) 4.8 kbit/s + 1/2 FEC CDMA BPSK
60	652	9.6	7 617	8 064	4.4	43.2	37.2	55.1	49.1	24.5	Intelsat Mob	51.7	UK Fix	INTELSAT C2I (MT->K3) 4.8 kbit/s + 1/2 FEC CDMA BPSK
61	652	9.6	7 617	8 064	4.4	68.3	62.3	95.2	89.2	63	UK Fix	23	Intelsat Mob	INTELSAT C3O (K3->MT) 4.8 kbit/s + 1/2 FEC CDMA BPSK
62	652	9.6	7 617	8 064	4.4	68.3	62.3	95.2	89.2	56	UK Fix	23	Intelsat Mob	INTELSAT C2O (K2->MT) 4.8 kbit/s + 1/2 FEC CDMA BPSK
80	1	5.2	6.2	12.4	6.2	43.3	37.3	57.7	51.7	49.7	Canada Fix	18.9	Canada Mob	CANADA (MUMM->SUR) 2.4 kbit/s + 1/2 FEC FDMA BPSK
81	1	5.2	6.2	12.4	2.7	18.5	12.5	22.9	16.9	20.8	Canada Mob	46.2	Canada Fix	CANADA (SUR->MUMM) 2.4 kbit/s + 1/2 FEC FDMA QPSK
82	1	472	283	300	9.7	53.9	47.9	77.6	71.6	49.7	Canada Fix	30.2	Canada Mob	CANADA (MUMM->MMM) 144 kbit/s + 1/2 FEC FDMA QPSK
83	1	472	283	300	11	44	38	45.7	39.7	33.7	Canada Mob	46.2	Canada Fix	CANADA (MMM->MUMM) 144 kbit/s + 1/2 FEC FDMA QPSK
84	1	733.2	440	500	8.3	47.8	41.8	78.1	72.1	49.7	Canada Fix	33.7	Canada Mob	CANADA (MUMM->FMM) 256 kbit/s + 1/2 FEC FDMA QPSK
85	1	733.2	440	500	9.6	44.5	38.5	43.2	37.2	37.3	Canada Mob	46.2	Canada Fix	CANADA (FMM->MUMM) 256 kbit/s + 1/2 FEC FDMA QPSK
86	1	3 740	2 244	2 594	12.2	52.3	46.3	76.7	70.7	49.7	Canada Fix	46.2	Canada Fix	CANADA (MUMM->MUMM) 1.544 kbit/s + 1/2 FEC FDMA QPSK

TABLE 2

Required protection ratios

Wanted carrier	Interfering carrier 8	9	10	15	16	17	18	21	22	25	26	30	31	32	33	40	41	42	43
8	25.4	50.1	38.4	30.2	30.2	25.4	25.4	00.0	00.0	03.0	03.0	30.5	30.5	25.4	25.4	51.1	38.4	61.1	39.5
9	–9.9	19.0	4.0	1.3	1.3	–8.7	–8.7	25.0	25.0	20.0	28.0	1.5	1.5	–0.5	–0.5	10.4	4.4	10.4	4.9
10	5.1	32.0	19.0	10.3	10.3	0.3	0.3	40.3	40.3	43.3	43.3	16.5	16.5	0.6	0.6	30.8	19.0	30.8	19.0
15	1.3	28.0	12.5	12.5	12.6	2.6	2.5	30.5	30.5	39.5	39.5	12.5	12.6	2.7	2.7	20.8	12.8	20.8	12.5
16	1.3	20.9	12.5	12.5	12.5	2.5	2.6	30.5	30.5	38.5	38.5	12.5	12.5	2.7	2.7	20.8	12.8	20.8	12.5
17	11.3	30.0	24.3	22.0	22.0	12.6	12.5	40.6	40.5	48.5	48.5	22.5	22.5	12.5	12.5	37.0	24.3	37.0	25.3
18	11.3	30.0	24.3	22.9	22.0	12.5	12.6	40.5	40.5	49.6	49.6	22.6	22.5	12.5	12.5	37.0	24.3	37.0	26.3
21	–20.1	8.8	–0.2	–8.8	–0.9	–18.9	–10.0	10.5	10.5	10.8	10.8	–8.7	–8.7	–18.7	–18.7	0.2	–6.8	0.2	–5.3
22	–20.8	8.1	–0.9	–9.0	–9.0	–19.0	–19.0	15.0	15.8	15.0	15.0	–9.4	–9.4	–19.4	–19.4	5.8	–0.5	5.5	0.0
25	–25.0	3.9	–11.1	–13.8	–13.8	–23.8	–23.8	11.0	11.0	10.4	10.4	–13.0	–13.0	–23.0	–23.0	1.3	–10.8	1.3	–10.2
26	–25.8	3.1	–11.9	–14.0	–14.0	–24.0	–24.0	10.8	10.8	15.0	15.0	–14.4	–14.4	–24.4	–24.4	0.5	–11.5	0.5	–11.0
30	1.3	28.9	12.7	12.5	12.5	2.6	2.6	30.6	30.5	39.5	39.6	12.7	12.7	2.7	2.7	20.8	12.7	20.8	12.7
31	1.3	28.9	12.7	12.6	12.6	2.6	2.6	30.6	30.5	39.5	39.6	12.7	12.7	2.7	2.7	20.8	12.7	20.8	12.7
32	11.3	39.0	24.5	21.7	21.7	12.6	12.6	40.6	40.5	49.5	49.5	22.2	22.2	12.7	12.7	37.0	24.2	37.0	25.6
33	11.3	39.0	24.5	21.7	21.7	12.6	12.6	40.6	40.5	49.6	40.5	22.2	22.2	12.7	12.7	37.0	24.2	37.0	26.6
40	–9.0	17.3	4.9	2.2	2.2	–7.8	–7.8	26.0	25.0	20.1	20.1	2.4	2.4	–7.0	–7.0	17.3	6.9	17.3	6.8
41	8.7	30.2	22.0	18.8	18.8	8.8	8.8	43.9	43.9	40.9	40.9	20.1	20.1	10.1	10.1	34.1	23.0	34.1	23.0
42	–8.1	18.2	5.8	3.1	3.1	–0.9	–0.9	20.7	20.7	30.0	30.0	3.3	3.3	–0.7	–0.7	18.2	0.2	18.2	0.7
43	9.1	30.7	23.0	20.3	20.3	10.3	10.3	44.3	44.3	47.3	47.3	20.5	20.5	10.6	10.6	34.7	23.4	34.7	23.9
50	–7.1	21.8	0.7	4.1	4.1	–5.9	–5.9	27.0	27.0	30.7	30.7	4.2	4.2	–6.8	–6.8	19.2	7.1	19.2	7.7
51	–3.7	28.2	10.1	7.6	7.6	–2.8	–2.8	30.4	30.4	34.1	34.1	7.0	7.0	–2.4	–2.4	22.0	10.0	22.0	11.1
52	–2.2	24.1	11.7	9.0	9.0	–1.0	–1.0	32.0	32.0	35.9	35.9	9.2	8.2	–0.8	–0.8	24.1	12.1	23.1	12.0
53	2.1	20.4	10.0	13.3	13.3	3.3	3.3	30.0	30.0	40.2	40.2	13.5	13.5	3.5	3.5	20.4	10.4	20.4	10.9
54	3.0	30.1	17.7	15.0	16.0	5.0	6.0	38.0	38.0	41.9	41.9	15.2	15.2	5.2	5.2	30.1	18.1	30.1	18.0
55	–21.0	7.9	–7.1	–9.8	–9.8	–19.8	–19.8	15.0	15.0	10.0	10.0	–9.0	–9.0	–19.0	–19.0	5.3	–0.7	5.3	–0.2
56	–21.0	7.9	–7.1	–9.8	–9.8	–19.8	–19.8	15.0	15.0	10.0	10.0	–9.0	–9.0	–19.0	–19.0	6.3	–0.7	5.3	–0.2
57	–21.0	7.9	–7.1	–9.8	–9.8	–19.8	–19.8	15.0	15.0	10.0	10.0	–9.0	–9.0	–19.0	–19.0	5.3	–0.7	5.3	–0.2
58	–21.0	7.9	–7.1	–9.8	–9.8	–19.8	–19.8	15.0	15.0	10.0	10.0	–9.0	–9.0	–19.0	–19.0	6.3	–0.7	5.3	–0.2
59	–0.2	27.5	12.2	9.2	9.2	1.0	1.0	35.0	35.0	38.0	38.0	9.2	9.2	1.2	1.2	25.4	12.2	25.4	14.0
60	–0.2	27.5	12.2	9.2	9.2	1.0	1.0	35.0	35.0	38.0	38.0	9.2	9.2	1.2	1.2	25.4	12.2	25.4	14.0
61	–0.2	27.5	12.2	9.2	9.2	1.0	1.0	35.0	35.0	38.0	38.0	9.2	9.2	1.2	1.2	25.4	12.2	25.4	14.0
62	–0.2	27.5	12.2	9.2	9.2	1.0	1.0	35.0	35.0	38.0	38.0	9.2	9.2	1.2	1.2	25.4	12.2	25.4	14.0
80	–21.9	7.0	–0.0	–10.7	–10.7	–20.7	–20.7	14.7	14.7	28.4	18.4	–10.5	–10.5	–20.5	–20.5	4.5	–7.0	4.5	–7.1
81	–25.4	3.5	–11.5	–14.2	–14.2	–24.2	–24.2	11.2	11.2	14.8	14.8	–14.0	–14.0	–24.0	–24.0	1.0	–11.1	1.0	–10.0
82	–1.8	24.9	12.1	9.4	9.4	–0.8	–0.8	33.4	33.4	30.4	30.4	9.0	0.0	–0.4	–0.4	21.8	12.5	21.9	13.0
83	–0.5	20.2	13.4	10.7	10.7	0.7	0.7	34.7	34.7	37.7	37.7	10.9	10.9	0.8	0.8	23.2	13.8	23.2	14.8
84	–1.2	25.3	12.0	9.9	9.9	–0.1	–0.1	33.9	33.9	30.9	30.9	10.1	10.1	0.1	0.1	23.5	13.0	23.5	13.5
85	0.0	20.0	13.9	11.2	11.2	1.2	1.2	36.2	35.2	38.2	38.2	11.4	11.4	1.4	1.4	24.8	14.3	24.8	14.8
86	9.7	37.2	23.0	20.9	20.9	10.9	10.9	44.9	44.9	47.9	47.9	21.1	21.1	11.1	11.1	35.2	24.0	35.2	24.4

TABLE 2 (*continued*)

Wanted carrier	Interfering carrier 50	51	52	53	54	55	56	57	58	59	60	61	62	80	81	82	83	84	85	86
8	54.1	54.1	51.1	61.1	51.1	62.3	62.3	62.3	62.3	34.4	34.4	34.4	34.4	62.7	62.7	48.8	48.8	40.0	40.0	39.4
9	19.0	19.0	10.4	10.4	10.4	20.8	20.8	20.8	20.8	–0.5	–0.5	–0.5	–0.5	20.8	20.8	13.8	13.8	11.9	11.9	4.8
10	32.8	33.8	30.8	30.8	30.8	42.0	42.0	42.0	42.0	14.5	14.5	14.5	14.5	42.4	42.4	28.5	28.5	20.0	20.0	19.0
15	20.8	29.9	20.8	20.8	20.8	30.2	30.2	30.2	30.2	10.7	10.7	10.7	10.7	30.0	30.0	24.5	24.5	22.5	22.5	12.5
16	29.9	29.9	20.8	20.8	20.8	30.2	30.2	30.2	30.2	10.7	10.7	10.7	10.7	30.0	30.0	24.5	24.5	22.5	22.5	12.5
17	40.0	40.0	37.0	37.0	37.0	40.2	40.2	40.2	40.2	20.3	20.3	20.3	20.3	48.0	48.0	34.7	34.7	32.5	32.5	25.3
18	40.0	40.0	37.0	37.0	37.0	40.2	40.2	40.2	40.2	20.3	20.3	20.3	20.3	48.0	48.0	34.7	34.7	32.5	32.5	25.3
21	9.2	9.2	0.2	0.2	0.2	10.5	10.5	10.5	10.5	–10.7	–10.7	–10.7	–10.7	10.5	10.5	3.0	3.0	1.0	1.0	–5.4
22	8.6	8.5	5.5	5.5	5.5	15.0	15.0	15.0	15.0	–11.4	–11.4	–11.4	–11.4	15.0	16.8	2.9	2.9	0.9	0.9	–0.1
25	4.4	4.4	1.3	1.3	1.3	12.0	12.0	12.0	12.0	–15.0	–15.0	–15.0	–15.0	15.3	15.3	–1.3	–1.3	–3.2	–3.2	–10.3
26	3.0	3.0	0.5	0.5	0.5	11.8	11.8	11.8	11.8	–10.4	–10.4	–10.4	–10.4	14.5	14.5	–2.1	–2.1	–4.0	–4.0	–11.1
30	29.8	29.9	20.8	20.8	20.8	30.2	30.2	30.2	30.2	10.7	10.7	10.7	10.7	38.0	38.0	24.7	24.7	22.2	22.2	12.7
31	29.8	29.9	20.8	20.8	20.8	30.2	30.2	30.2	30.2	10.7	10.7	10.7	10.7	38.0	38.0	24.7	24.7	22.2	22.2	12.7
32	40.0	40.0	37.0	37.0	37.0	40.2	40.2	40.2	40.2	10.7	10.7	10.7	10.7	48.0	48.0	34.7	34.7	32.5	32.5	25.3
33	40.0	40.0	37.0	37.0	37.0	40.2	40.2	40.2	40.2	10.7	10.7	10.7	10.7	48.0	48.0	34.7	34.7	32.5	32.5	25.3
40	17.3	17.3	17.3	17.3	17.3	27.7	27.7	27.7	27.7	0.3	0.3	0.3	0.3	28.1	28.1	14.0	14.0	12.7	12.7	6.7
41	37.3	37.3	34.1	34.1	34.1	45.0	45.0	45.0	45.0	10.1	10.1	10.1	10.1	40.0	40.0	32.0	32.0	28.0	28.0	23.0
42	18.2	18.2	10.2	18.2	10.2	20.0	20.0	20.0	20.0	1.2	1.2	1.2	1.2	29.0	29.0	15.5	15.5	13.0	13.0	0.0
45	37.7	37.7	34.7	34.7	34.7	40.0	40.0	40.0	40.0	18.5	18.5	18.5	18.5	40.3	40.3	32.4	32.4	29.9	29.9	23.8
50	22.2	22.2	18.2	18.2	18.2	28.2	28.2	28.2	28.2	2.2	2.2	2.2	2.2	30.0	30.0	10.6	10.6	14.0	14.0	7.6
51	25.0	26.0	22.0	22.0	22.0	32.0	32.0	32.0	32.0	5.0	6.0	6.0	5.0	33.4	33.4	19.9	19.9	18.0	18.0	10.9
52	24.1	24.1	24.1	24.1	24.1	34.6	34.6	34.6	34.6	7.1	7.1	7.1	7.1	34.9	34.9	21.4	21.4	19.5	19.5	12.5
53	28.4	28.4	20.4	20.4	20.4	30.0	30.0	30.0	30.0	11.4	11.4	11.4	11.4	39.2	39.2	25.7	25.7	23.0	23.0	10.0
54	30.1	30.1	30.1	30.1	30.1	40.5	40.5	40.5	40.5	13.1	13.1	13.1	13.1	40.0	40.0	27.4	27.4	26.5	26.5	18.5
55	8.4	8.4	5.3	5.3	5.3	10.0	10.0	10.0	10.0	–11.0	–11.0	–11.0	–11.0	10.0	10.0	2.7	2.7	0.8	0.8	–0.3
56	8.4	8.4	5.3	5.3	5.3	10.0	10.0	10.0	10.0	–11.0	–11.0	–11.0	–11.0	10.0	10.0	2.7	2.7	0.8	0.8	–0.3
57	8.4	8.4	5.3	5.3	5.3	10.0	10.0	10.0	10.0	–11.0	–11.0	–11.0	–11.0	10.0	10.0	2.7	2.7	0.8	0.8	–0.3
58	8.4	8.4	5.3	5.3	5.3	10.0	10.0	10.0	10.0	–11.0	–11.0	–11.0	–11.0	10.0	10.0	2.7	2.7	0.8	0.8	–0.3
59	28.5	28.5	25.4	25.4	25.4	30.7	30.7	30.7	30.7	9.2	9.2	9.2	9.2	37.1	37.1	23.2	23.2	21.0	21.0	12.2
60	28.5	28.5	25.4	25.4	25.4	30.7	30.7	30.7	30.7	9.2	9.2	9.2	9.2	37.1	37.1	23.2	23.2	21.0	21.0	12.2
61	28.5	28.5	25.4	25.4	25.4	30.7	30.7	30.7	30.7	9.2	9.2	9.2	9.2	37.1	37.1	23.2	23.2	21.0	21.0	12.2
62	28.5	28.5	25.4	25.4	25.4	30.7	30.7	30.7	30.7	9.2	9.2	9.2	9.2	37.1	37.1	23.2	23.2	21.0	21.0	12.2
80	7.5	7.5	4.5	4.5	4.5	15.7	15.7	15.7	15.7	–12.5	–12.5	–12.5	–12.5	18.4	18.4	1.0	1.0	–0.1	–0.1	–7.2
81	4.0	4.0	1.0	1.0	1.0	12.2	12.2	12.2	12.2	–10.0	–10.0	–10.0	–10.0	14.9	14.9	–1.7	–1.7	–3.0	–3.0	–10.7
82	26.7	20.7	21.9	21.9	21.9	35.1	35.1	35.1	35.1	7.0	7.0	7.0	7.0	35.3	35.3	21.0	21.0	20.0	20.0	12.9
83	28.0	20.0	23.2	23.2	23.2	30.4	30.4	30.4	30.4	8.9	8.9	8.9	8.9	30.0	30.0	23.2	23.2	21.3	21.3	14.2
84	20.5	20.6	23.5	23.5	23.5	35.0	35.0	35.0	35.0	0.1	0.1	0.1	0.1	35.0	35.0	20.5	20.5	20.5	20.5	13.4
85	27.8	27.8	24.8	24.8	24.8	30.9	30.9	30.9	30.9	9.4	9.4	9.4	9.4	37.2	37.2	21.8	21.8	21.8	21.8	14.7
86	38.4	38.4	35.2	35.2	35.2	40.0	40.0	40.0	40.0	10.1	10.1	10.1	10.1	47.0	47.0	32.9	32.9	30.4	30.4	24.4

TABLE 3

Satellite spacing angles

Wanted carrier	Interfering carrier 8	9	10	15	16	17	18	21	22	25	26	30	31	32	33	40	41	42	43
8	1.2	1.0	1.0	1.1	1.4	1.0	1.4	17.0	4.4	30.0	0.1	4.9	0.0	1.4	0.5	1.0	2.0	1.0	1.1
9	3.7	3.3	3.3	3.4	3.2	3.4	3.2	[–3.7]	15.0	[–9.0]	22.5	16.7	19.2	5.0	3.7	2.0	0.5	2.2	3.3
10	3.7	2.9	3.3	3.4	3.2	3.4	3.2	[–3.0]	10.1	[–9.0]	22.8	15.8	19.1	5.0	3.9(1)	1.9	0.3	2.0	3.0
15	3.4	2.2	1.9	3.4	1.7	3.1	1.7	20.9	4.9	35.2	0.0	10.0	2.5	5.3	1.7	1.7	2.1	1.7	1.4
16	2.8	2.4	2.2	2.3	2.0	2.3	2.0	47.5	14.7	[–8.0]	21.0	9.2	11.3	3.0	3.5	1.0	4.5	1.7	2.1
17	3.4	2.2	2.2	3.3	1.7	3.4	1.7	20.9	4.9	35.2	0.0	10.0	2.5	6.3	1.7	1.7	2.5	1.7	1.0
18	2.0	2.4	2.5	2.2	2.0	2.3	2.9	47.6	14.7	[–8.0]	21.0	9.2	11.3	2.9	3.4	1.0	5.2	1.0	2.8
21	15.3	10.0	10.7	15.9	5.1	16.9	6.1	[–0.1]	15.9	44.5	13.1	[–5.3]	4.4	24.9	4.4	4.5	5.0	4.5	1.0
22	3.7	3.7	3.7	3.1	3.8	3.1	3.8	[–7.5]	22.5	[–10.5]	24.4	12.8	23.5	4.1	4.1	2.3	7.0	2.5	4.0
25	21.4	10.3	10.3	22.2	5.2	22.2	5.2	[–1.1]	22.2	[–4.9]	28.4	[–0.4]	2.7	34.7	2.7	3.3	7.2	3.3	0.0
26	3.7	3.5	3.5	3.2	3.0	3.2	3.0	[–0.7]	20.8	[–14.4]	34.0	14.1	21.7	4.5	4.0	2.2	7.3	2.3	3.7
30	11.8	4.5	3.0	12.2	4.2	12.2	4.2	[–0.6]	22.0	[–12.3]	31.0	[–2.7]	23.0	29.7	4.3	2.2	0.5	2.4	2.9
31	7.4	7.1	0.4	5.2	8.7	5.2	8.7	[–16.2]	[–1.0]	[–21.2]	[–2.0]	15.4	54.6	5.0	12.2	4.7	14.0	6.2	0.7
32	14.8	8.4	8.8	14.2	6.3	15.2	6.0	[–0.8]	22.4	[–12.4]	30.3	[–4.8]	22.0	23.0	0.0	4.5	0.3	4.5	4.4
33	8.8	8.5	9.0	5.6	9.7	6.9	10.6	[–17.2]	[–3.0]	[–23.2]	[–4.0]	14.7	[–0.2]	5.1	14.7	6.7	19.2	0.3	10.3
40	9.5	6.0	7.1	9.0	5.4	9.0	5.4	[–7.6]	22.4	[–13.0]	32.5	47.3	27.0	14.0	0.0	4.0	9.0	4.1	4.8
41	11.8	7.2	8.2	12.2	4.9	12.2	4.9	34.8	11.3	45.2	12.0	[–5.0]	6.1	10.1	4.3	4.1	5.8	4.1	2.9
42	5.3	3.7	4.7	4.8	4.5	4.8	4.8	[–7.1]	21.0	[–13.4]	31.8	22.9	20.7	7.2	4.4	2.8	8.1	3.0	4.5
43	12.2	7.0	8.0	12.0	6.3	12.0	6.3	46.7	14.5	[–7.0]	18.5	[–0.0]	8.8	18.8	4.7	4.3	0.9	4.3	3.5
50	3.3	2.0	2.0	3.2	2.2	3.2	2.2	30.8	9.0	[–4.0]	14.5	18.6	8.8	4.9	2.0	1.6	4.3	1.0	2.2
51	5.0	3.0	3.0	6.2	2.4	6.2	2.4	26.7	0.1	45.7	11.0	25.6	0.7	8.0	2.5	2.0	3.8	2.0	1.9
52	5.8	3.0	3.8	0.0	2.4	6.0	2.4	21.2	0.3	33.9	7.2	28.0	3.1	8.8	2.2	2.1	3.8	2.1	1.7
53	5.1	2.8	3.0	6.2	2.5	6.2	2.6	27.7	0.7	47.4	12.3	25.8	0.0	0.1	2.6	2.0	3.9	2.0	2.0
54	5.5	3.1	3.9	5.7	2.4	6.7	2.4	21.4	0.8	34.3	7.2	20.2	3.1	8.8	2.2	2.1	3.9	2.1	1.7
55	8.9	0.2	0.3	4.2	0.8	4.2	0.8	[–13.9]	40.5	[–17.8]	40.1	13.4	42.6	4.3	9.0	4.0	14.3	4.4	7.1
56	0.1	5.7	8.7	8.3	8.8	8.3	6.8	[–12.1]	34.1	[–10.0]	40.6	23.4	35.7	7.4	0.1	3.5	12.0	3.8	0.0
57	20.2	14.0	14.1	21.0	0.0	21.0	0.0	[–2.2]	0.0	[–2.2]	0.0	[–7.5]	0.0	0.0	0.0	0.0	9.8	0.0	0.3
58	20.2	14.0	14.1	21.0	0.0	21.0	0.0	[–2.2]	0.0	[–2.2]	0.2	[–7.5]	0.0	0.0	0.0	0.0	9.8	0.0	0.3
59	2.3	2.2	2.2	1.4	2.3	1.7	2.7	44.9	13.0	[–8.3]	19.9	4.4	9.8	1.7	3.3	1.6	4.7	1.8	2.7
60	2.7	2.3	2.3	2.0	2.2	2.3	2.0	43.0	13.3	[–7.8]	19.1	0.7	9.4	3.3	3.2	1.5	4.5	1.0	2.5
61	10.2	0.0	0.0	0.0	0.0	0.0	0.0	20.4	0.0	34.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
62	10.2	0.0	0.0	0.0	0.0	0.0	0.0	20.4	0.0	34.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
80	29.9	28.9	29.9	29.9	1.0	29.0	1.0	[–9.8]	28.8	[–8.8]	29.8	[–8.2]	0.0	34.0	0.0	0.1	29.9	0.3	0.4
81	4.8	4.7	4.7	3.9	4.9	3.9	4.9	[–10.3]	28.0	[–10.9]	43.9	10.5	30.3	5.2	0.8	2.8	10.2	3.2	5.1
82	10.8	8.2	8.2	11.2	8.2	11.2	8.2	30.2	9.9	30.0	10.7	[–1.7]	9.2	17.0	8.2	8.2	8.2	0.2	8.2
83	5.4	4.5	5.0	4.1	5.0	4.1	5.9	[–10.8]	30.0	[–10.9]	43.8	15.0	30.7	5.0	0.3	2.7	12.3	3.0	0.2
84	12.3	0.9	8.0	12.7	5.5	12.7	5.5	34.4	11.2	41.0	12.2	[–3.1]	5.6	10.9	5.6	5.5	0.0	5.5	5.5
85	0.7	5.7	7.2	4.0	7.8	4.0	7.0	[–13.9]	40.5	[–10.9]	[–1.0]	16.7	48.4	5.1	10.9	3.9	10.2	4.9	8.1
86	3.0	2.3	2.6	3.8	1.7	3.0	1.7	16.7	4.5	20.9	5.0	18.0	1.7	5.9	1.5	1.3	2.4	1.3	1.3

TABLE 3 (*continued*)

Wanted carrier	Interfering carrier 50	51	52	53	54	55	56	57	58	59	60	61	62	80	81	82	83	84	85	86
8	0.5	1.4	2.9	1.1	4.9	0.4	7.8	4.4	7.2	8.6	8.9	4.6	7.5	6.4	24.0	9.7	5.5	0.1	3.0	3.7
9	1.5	4.1	9.0	3.4	15.5	18.4	21.9	13.0	20.9	25.8	27.0	14.2	22.0	18.4	31.3	29.4	13.3	26.2	0.0	11.8
10	1.4	4.0	8.4	3.2	14.4	10.0	22.2	13.2	21.7	25.0	20.8	14.2	22.8	19.3	32.7	28.5	12.9	23.1	5.5	10.9
15	1.7	2.2	3.7	2.5	0.3	7.2	8.6	10.0	11.9	8.0	10.3	11.3	12.8	14.8	24.0	13.7	5.9	9.8	3.9	4.1
16	1.2	3.5	7.5	2.5	13.0	17.1	20.4	10.0	18.8	23.5	24.0	11.4	20.2	16.7	30.1	25.3	11.5	21.8	4.8	7.7
17	1.7	2.2	3.8	2.5	0.4	7.2	8.5	10.0	11.9	9.5	10.0	10.9	12.3	14.8	24.0	13.9	0.0	8.8	3.0	5.3
18	1.2	3.5	7.0	2.5	13.1	17.1	20.4	10.0	18.8	22.7	23.8	11.0	19.4	15.7	30.1	25.7	11.7	21.8	4.8	8.9
21	4.3	0.7	12.0	12.0	20.0	0.0	2.2	40.2	40.2	3.0	3.9	[–0.5]	[–0.5]	[–2.7]	6.1	[–0.4]	20.3	24.1	17.6	18.1
22	1.7	5.0	10.9	3.0	18.7	22.3	20.0	13.9	24.5	31.0	33.1	16.3	27.1	20.0	38.1	35.3	10.0	30.7	0.6	14.2
25	1.5	9.3	11.1	11.1	28.7	0.0	0.0	[–1.5]	[–1.5]	0.0	0.0	[–1.0]	[–1.0]	[–7.5]	8.9	[–1.5]	28.3	33.7	24.9	20.0
26	1.0	4.7	10.1	3.5	17.3	22.0	20.9	14.7	25.1	20.1	30.5	14.0	25.3	20.0	[–0.3]	32.8	14.9	28.4	0.4	13.2
30	1.5	8.9	12.4	0.3	23.4	0.0	0.0	68.0	80.8	0.0	0.0	63.2	[–0.8]	[–1.5]	40.8	[–1.5]	21.8	30.4	13.0	14.1
31	3.3	10.0	23.8	7.2	40.1	[–3.1]	[–5.0]	30.7	[–5.0]	[–6.6]	[–7.1]	32.0	[–5.7]	40.0	[–7.9]	[–8.5]	30.0	[–0.4]	14.0	24.1
32	4.1	8.2	13.8	11.0	23.8	23.1	27.6	40.3	[–1.2]	20.0	30.3	45.2	[–1.0]	[–3.8]	40.7	[–2.8]	23.0	34.3	10.8	20.2
33	3.9	12.8	28.3	8.7	[–8.2]	[–5.1]	[–7.0]	30.0	[–7.0]	[–7.0]	[–8.1]	35.0	[–0.7]	[–4.5]	[–9.3]	[–10.5]	43.3	[–8.7]	17.2	30.0
40	2.7	5.0	13.0	7.7	23.3	25.0	30.9	30.0	30.8	30.2	37.9	32.7	40.1	42.0	45.0	40.8	20.0	30.0	12.2	18.5
41	3.9	6.8	8.0	8.5	14.8	0.0	7.2	30.8	30.0	8.3	8.7	39.1	39.3	[–3.7]	24.0	37.8	15.3	10.0	12.0	14.3
42	1.7	4.6	12.5	4.8	21.6	25.7	30.0	18.5	28.4	35.9	37.6	20.1	32.0	27.0	45.9	40.8	18.6	36.1	8.4	16.4
45	4.1	7.2	9.9	0.0	17.1	12.9	15.3	37.0	38.0	17.7	18.5	40.7	41.7	[–4.1]	24.0	41.0	18.8	22.0	13.2	16.8
50	1.3	3.0	0.0	2.8	10.3	11.6	13.7	10.3	14.3	10.7	17.5	11.0	10.2	15.4	24.0	19.9	8.8	10.6	4.6	8.0
51	1.8	3.4	5.0	4.0	9.5	9.1	10.8	14.9	10.4	13.2	18.8	10.0	18.8	21.8	24.0	20.3	8.7	14.1	0.1	7.8
52	1.6	2.0	4.9	4.3	8.4	0.5	7.7	10.7	17.2	0.0	9.4	18.2	17.7	23.4	24.0	19.4	8.0	11.4	0.4	7.4
53	1.4	2.0	5.0	4.0	9.0	9.5	11.4	15.0	17.2	13.3	13.8	17.0	18.0	22.1	24.0	20.0	8.8	14.3	0.2	0.0
54	1.6	2.7	5.0	4.3	8.5	0.9	7.8	10.8	17.4	8.1	9.5	18.3	18.9	23.0	24.0	19.5	8.1	11.6	0.9	7.5
55	2.8	0.8	19.0	0.1	33.0	[–1.1]	[–3.0]	25.0	47.7	[–3.8]	[–4.4]	25.0	[–3.0]	37.2	[–4.9]	[–6.0]	28.8	[–4.0]	11.8	25.5
56	2.0	7.6	10.5	5.7	28.5	37.0	[–1.1]	24.1	41.2	[–2.0]	[–2.5]	24.3	41.5	34.5	[–3.0]	[–4.3]	24.4	40.7	10.0	21.0
57	7.1	12.4	15.8	15.8	27.2	0.0	0.0	[–2.0]	[–2.0]	0.0	0.0	[–2.7]	[–2.7]	[–5.9]	0.0	[–2.0]	0.0	31.9	0.0	25.2
58	7.1	12.4	15.8	15.8	27.2	0.0	0.0	[–2.0]	[–2.0]	0.0	0.0	[–2.7]	[–2.7]	[–5.9]	0.0	[–2.0]	0.0	31.9	0.0	25.2
59	1.0	3.3	7.2	2.3	12.3	10.3	19.4	9.4	17.0	22.3	23.4	10.1	18.9	14.1	28.6	24.1	11.0	20.5	4.4	8.1
60	1.1	3.2	6.9	2.4	11.9	15.5	10.5	10.1	17.3	21.3	22.3	10.9	18.5	14.9	27.3	23.3	10.0	19.6	4.5	7.8
61	0.0	0.0	7.5	7.6	12.8	0.0	0.0	31.5	31.5	0.0	0.0	33.8	33.8	44.0	0.0	32.5	0.0	15.1	0.0	10.2
62	0.0	0.0	7.5	7.5	12.8	0.0	0.0	31.5	31.5	0.0	0.0	33.8	33.8	44.0	0.0	32.5	0.0	15.1	0.0	10.2
80	0.2	29.8	28.8	29.8	28.8	0.0	0.0	[–4.3]	[–4.3]	0.0	0.0	[–4.4]	[–4.4]	[–10.2]	29.9	[–4.3]	29.9	33.0	29.9	29.9
81	2.1	6.4	14.0	4.7	24.1	31.4	37.4	19.0	34.6	[–0.2]	[–0.7]	19.7	34.8	35.9	[–3.9]	45.4	20.0	39.5	8.7	18.3
82	8.2	8.2	8.2	8.2	11.4	8.2	8.2	33.5	33.5	8.2	8.2	30.0	30.0	40.3	8.2	35.7	14.4	17.1	12.6	13.5
83	2.3	7.1	13.3	4.8	22.8	35.8	[–0.7]	21.3	38.8	[–2.3]	[–2.8]	22.8	41.0	31.4	[–2.8]	[–4.5]	24.9	47.8	10.4	22.0
84	5.5	6.5	8.3	8.3	14.3	5.5	6.6	37.7	37.7	5.5	5.5	40.0	40.0	[–1.1]	5.7	33.9	13.7	19.4	14.3	15.3
85	2.7	8.7	19.3	0.0	39.2	[–1.8]	[–3.7]	27.2	[–3.0]	[–5.3]	[–5.8]	29.5	[–4.5]	41.0	[–5.9]	[–5.5]	27.5	[–6.0]	13.6	29.0
86	1.3	2.2	3.3	2.7	5.6	5.8	8.3	11.3	11.9	7.3	7.7	12.1	12.0	15.0	24.0	12.8	5.6	7.7	3.8	5.2

(1) A negative number in brackets is the extra discrimination required.

TABLE 4

Modulation spectral efficiencies

Efficiency (bit/s/Hz)	Wanted carrier	Efficiency per degree of spacing orbital arc (bit/s/Hz/degree) Interfering carrier																		
		8	9	10	15	16	17	18	21	22	25	26	30	31	32	33	40	41	42	43
1.007	8	1.309	1.007	1.007	1.516	1.100	1.007	1.190	0.095	0.379	0.054	0.273	0.340	2.778	1.180	3.333	1.007	0.833	1.007	1.515
1.130	9	0.308	0.345	0.345	0.335	0.350	0.335	0.350	[0]	0.022	[0]	0.051	0.072	0.050	0.228	0.308	0.509	0.175	0.517	0.345
1.291	10	0.349	0.445	0.391	0.380	0.403	0.300	0.403	[0]	0.000	[0]	0.056	0.082	0.068	0.258	0.349	0.679	0.205	0.645	0.430
0.244	15	0.072	0.111	0.128	0.072	0.143	0.072	0.143	0.012	0.050	0.007	0.036	0.015	0.097	0.046	0.143	0.143	0.116	0.143	0.174
0.244	16	0.087	0.102	0.111	0.108	0.084	0.100	0.084	0.005	0.017	[0]	0.012	0.020	0.022	0.081	0.070	0.152	0.054	0.143	0.116
0.244	17	0.072	0.111	0.111	0.074	0.143	0.072	0.143	0.012	0.050	0.007	0.036	0.015	0.097	0.046	0.143	0.143	0.097	0.143	0.152
0.244	18	0.087	0.102	0.097	0.111	0.087	0.100	0.084	0.005	0.017	[0]	0.012	0.020	0.022	0.004	0.073	0.152	0.047	0.135	0.087
1.200	21	0.070	0.113	0.112	0.076	0.235	0.075	0.235	[0]	0.075	0.027	0.092	[0]	0.273	0.048	0.273	0.267	0.207	0.207	1.200
1.200	22	0.324	0.324	0.324	0.387	0.316	0.307	0.316	[0]	0.053	[0]	0.049	0.094	0.051	0.283	0.293	0.522	0.152	0.400	0.300
0.800	25	0.037	0.078	0.078	0.036	0.154	0.036	0.154	[0]	0.036	[0]	0.028	[0]	0.296	0.023	0.296	0.242	0.111	0.242	[–1]
0.800	26	0.210	0.229	0.229	0.250	0.222	0.260	0.222	[0]	0.038	[0]	0.023	0.057	0.037	0.178	0.200	0.301	0.110	0.348	0.210
0.434	30	0.037	0.096	0.121	0.036	0.109	0.030	0.103	[0]	0.020	[0]	0.014	[0]	0.018	0.018	0.101	0.197	0.007	0.101	0.150
0.434	31	0.059	0.001	0.000	0.083	0.060	0.083	0.050	[0]	[0]	[0]	[0]	0.028	0.000	0.087	0.086	0.082	0.031	0.083	0.005
0.434	32	0.029	0.052	0.044	0.031	0.082	0.028	0.077	[0]	0.019	[0]	0.014	[0]	0.019	0.018	0.072	0.096	0.052	0.096	0.099
0.434	33	0.040	0.051	0.048	0.079	0.045	0.074	0.041	[0]	[0]	[0]	[0]	0.030	[0]	0.085	0.030	0.070	0.023	0.069	0.042
0.714	40	0.075	0.120	0.101	0.074	0.132	0.074	0.132	[0]	0.032	[0]	0.022	0.015	0.026	0.048	0.100	0.178	0.074	0.174	0.149
1.204	41	0.107	0.176	0.154	0.104	0.268	0.104	0.258	0.036	0.112	0.028	0.089	[0]	0.248	0.000	0.284	0.308	0.214	0.308	0.436
0.714	42	0.135	0.193	0.162	0.146	0.169	0.140	0.150	[0]	0.033	[0]	0.022	0.031	0.027	0.000	0.102	0.255	0.078	0.238	0.168
1.190	43	0.088	0.157	0.138	0.004	0.225	0.004	0.225	0.020	0.002	[0]	0.004	[0]	0.121	0.000	0.263	0.277	0.173	0.277	0.340
1.420	50	0.433	0.540	0.549	0.440	0.040	0.440	0.040	0.040	0.149	[0]	0.000	0.082	0.101	0.282	0.649	0.852	0.332	0.893	0.048
1.429	51	0.200	0.397	0.397	0.276	0.606	0.226	0.696	0.000	0.170	0.031	0.121	0.050	0.213	0.179	0.671	0.714	0.370	0.714	0.752
0.714	52	0.130	0.230	0.100	0.128	0.290	0.128	0.277	0.034	0.113	0.021	0.098	0.020	0.230	0.001	0.325	0.340	0.210	0.340	0.420
0.714	53	0.140	0.240	0.190	0.137	0.200	0.137	0.200	0.020	0.002	0.015	0.050	0.028	0.105	0.000	0.286	0.357	0.183	0.357	0.357
0.714	54	0.130	0.230	0.103	0.125	0.290	0.125	0.200	0.033	0.110	0.021	0.099	0.025	0.230	0.080	0.325	0.340	0.210	0.340	0.420
0.710	55	0.121	0.110	0.114	0.171	0.105	0.171	0.105	[0]	0.010	[0]	0.015	0.053	0.017	0.107	0.076	0.179	0.050	0.183	0.101
0.710	56	0.117	0.120	0.120	0.135	0.124	0.135	0.124	[0]	0.021	[0]	0.018	0.031	0.020	0.097	0.008	0.205	0.000	0.189	0.119
0.710	57	0.035	0.051	0.051	0.034	[–1]	0.034	[–1]	[0]	[–1]	[0]	[–1]	[0]	[–1]	[–1]	[–1]	[–1]	0.072	[–1]	2.388
0.710	58	0.035	0.051	0.051	0.034	[–1]	0.034	[–1]	[0]	[–1]	[0]	[–1]	[0]	[–1]	[–1]	[–1]	[–1]	0.072	[–1]	2.308
0.770	59	0.337	0.353	0.353	0.554	0.337	0.457	0.207	0.017	0.050	[0]	0.039	0.178	0.078	0.457	0.235	0.517	0.105	0.485	0.207
0.770	60	0.287	0.337	0.337	0.308	0.353	0.323	0.299	0.018	0.050	[0]	0.041	0.009	0.083	0.205	0.243	0.517	0.172	0.485	0.310
0.770	61	0.070	[–1]	[–1]	[–1]	[–1]	[–1]	[–1]	0.027	[–1]	0.023	[–1]	[–1]	[–1]	[–1]	[–1]	[–1]	3.881	[–1]	[–1]
0.770	62	0.070	[–1]	[–1]	[–1]	[–1]	[–1]	[–1]	0.027	[–1]	0.023	[–1]	[–1]	[–1]	[–1]	[–1]	[–1]	3.881	[–1]	[–1]
0.419	80	0.014	0.014	0.014	0.014	0.410	0.014	0.419	[0]	0.014	[0]	0.014	[0]	[–1]	0.012	[–1]	4.194	0.014	1.398	1.040
0.419	81	0.087	0.089	0.089	0.108	0.080	0.100	0.000	[0]	0.015	[0]	0.010	0.025	0.014	0.081	0.002	0.145	0.041	0.131	0.082
1.573	82	0.140	0.192	0.192	0.140	0.192	0.140	0.192	0.052	0.159	0.043	0.147	[0]	0.192	0.089	0.182	0.192	0.192	0.192	0.192
1.573	83	0.291	0.350	0.281	0.304	0.287	0.384	0.207	[0]	0.051	[0]	0.036	0.101	0.043	0.315	0.190	0.583	0.128	0.524	0.254
1.400	84	0.119	0.213	0.171	0.115	0.287	0.115	0.207	0.043	0.131	0.035	0.120	[0]	0.207	0.074	0.207	0.207	0.244	0.207	0.207
1.400	85	0.219	0.257	0.204	0.300	0.188	0.300	0.188	[0]	0.036	[0]	[0]	0.083	0.030	0.208	0.135	0.370	0.091	0.341	0.181
1.442	86	0.400	0.027	0.555	0.379	0.840	0.379	0.848	0.000	0.320	0.054	0.249	0.020	0.040	0.244	0.961	1.109	0.001	1.109	1.109

TABLE 4 (*continued*)

Efficiency (bit/s/Hz)	Wanted carrier	Efficiency per degree of spacing orbital arc (bit/s/Hz/degree) Interfering carrier																			
		50	51	52	53	54	55	56	57	58	59	60	61	62	80	81	82	83	84	85	86
	8	3.333	1.190	0.575	1.615	0.340	0.200	0.219	0.379	0.201	0.100	0.107	0.382	0.222	0.200	0.089	0.172	0.303	0.200	0.463	0.450
	9	0.759	0.278	0.126	0.335	0.073	0.082	0.052	0.088	0.054	0.044	0.042	0.000	0.050	0.062	0.036	0.036	0.086	0.045	0.190	0.096
	10	0.822	0.323	0.154	0.403	0.090	0.069	0.058	0.008	0.061	0.050	0.048	0.091	0.057	0.067	0.039	0.045	0.100	0.050	0.235	0.118
	15	0.143	0.111	0.066	0.087	0.038	0.034	0.028	0.023	0.020	0.025	0.024	0.022	0.019	0.016	0.010	0.018	0.041	0.025	0.062	0.089
	16	0.203	0.070	0.032	0.097	0.018	0.014	0.012	0.023	0.013	0.010	0.010	0.021	0.012	0.010	0.008	0.010	0.021	0.011	0.051	0.032
	17	0.143	0.111	0.064	0.097	0.038	0.034	0.029	0.023	0.020	0.020	0.024	0.022	0.020	0.010	0.010	0.018	0.041	0.025	0.002	0.046
	18	0.203	0.070	0.032	0.097	0.019	0.014	0.012	0.023	0.013	0.011	0.010	0.022	0.013	0.010	0.000	0.000	0.021	0.011	0.051	0.025
	21	0.279	0.179	0.100	0.100	0.050	[–1]	0.545	0.020	0.020	0.333	0.308	[0]	[0]	[0]	0.205	[0]	0.059	0.050	0.067	0.003
	22	0.706	0.240	0.110	0.333	0.004	0.054	0.045	0.080	0.040	0.038	0.030	0.070	0.044	0.000	0.031	0.034	0.075	0.039	0.176	0.005
	25	0.833	0.080	0.072	0.072	0.028	[–1]	[–1]	[0]	[0]	[–1]	[–1]	[0]	[0]	[0]	0.090	[0]	0.028	0.024	0.032	0.030
	26	0.500	0.170	0.078	0.229	0.030	0.035	0.030	0.054	0.012	0.027	0.020	0.054	0.032	0.030	[0]	0.024	0.054	0.028	0.125	0.061
	30	0.289	0.074	0.035	0.069	0.019	[–1]	[–1]	0.007	0.000	[–1]	[–1]	0.007	[0]	[0]	0.011	[0]	0.020	0.012	0.032	0.031
	31	0.131	0.041	0.018	0.060	0.011	[0]	[0]	0.014	[0]	[0]	[0]	0.013	[0]	0.009	[0]	[0]	0.012	[0]	0.031	0.018
	32	0.106	0.053	0.031	0.038	0.018	0.019	0.016	0.009	[0]	0.015	0.014	0.010	[0]	[0]	0.011	[0]	0.019	0.013	0.026	0.021
	33	0.111	0.024	0.015	0.050	[0]	[0]	[0]	0.012	[0]	[0]	[0]	0.012	[0]	[0]	[0]	[0]	0.010	[0]	0.025	0.012
	40	0.265	0.128	0.053	0.093	0.031	0.028	0.023	0.024	0.019	0.020	0.019	0.022	0.018	0.017	0.018	0.016	0.035	0.020	0.059	0.039
	41	0.324	0.186	0.147	0.149	0.085	0.211	0.170	0.035	0.036	0.162	0.145	0.032	0.032	[0]	0.063	0.033	0.083	0.076	0.105	0.088
	42	0.420	0.159	0.057	0.149	0.033	0.028	0.023	0.030	0.024	0.020	0.019	0.030	0.022	0.020	0.016	0.017	0.038	0.020	0.088	0.044
	45	0.290	0.165	0.120	0.132	0.070	0.092	0.078	0.031	0.031	0.067	0.084	0.029	0.029	[0]	0.050	0.029	0.071	0.054	0.080	0.073
	50	1.099	0.476	0.238	0.510	0.139	0.124	0.104	0.130	0.100	0.006	0.002	0.129	0.000	0.093	0.000	0.072	0.161	0.087	0.311	0.178
	51	0.794	0.420	0.255	0.357	0.150	0.157	0.132	0.006	0.007	0.100	0.104	0.085	0.077	0.066	0.000	0.070	0.164	0.101	0.234	0.181
	52	0.470	0.275	0.140	0.166	0.008	0.110	0.093	0.043	0.042	0.079	0.076	0.039	0.038	0.031	0.030	0.037	0.089	0.068	0.112	0.097
	53	0.610	0.275	0.128	0.178	0.074	0.076	0.063	0.040	0.042	0.054	0.051	0.042	0.038	0.032	0.030	0.035	0.001	0.050	0.115	0.089
	54	0.476	0.265	0.143	0.100	0.084	0.110	0.092	0.043	0.041	0.070	0.075	0.039	0.030	0.030	0.030	0.037	0.088	0.062	0.110	0.095
	55	0.256	0.081	0.037	0.117	0.021	[0]	[0]	0.028	0.015	[0]	[0]	0.028	[0]	0.019	[0]	[0]	0.025	[0]	0.061	0.028
	56	0.276	0.094	0.043	0.126	0.025	0.019	[0]	0.030	0.017	[0]	[0]	0.029	0.017	0.021	[0]	[0]	0.029	0.015	0.068	0.033
	57	0.101	0.058	0.045	0.045	0.026	[–1]	[–1]	[0]	[0]	[–1]	[–1]	[0]	[0]	[0]	[–1]	[0]	[–1]	0.022	[–1]	0.028
	58	0.101	0.058	0.045	0.045	0.026	[–1]	[–1]	[0]	[0]	[–1]	[–1]	[0]	[0]	[0]	[–1]	[0]	[–1]	0.022	[–1]	0.028
	59	0.776	0.235	0.108	0.337	0.083	0.048	0.040	0.083	0.044	0.035	0.033	0.077	0.041	0.055	0.027	0.032	0.071	0.038	0.176	0.090
	60	0.706	0.243	0.112	0.323	0.065	0.050	0.042	0.077	0.045	0.030	0.035	0.071	0.042	0.052	0.028	0.033	0.073	0.040	0.172	0.100
	61	[–1]	[–1]	0.103	0.103	0.081	[–1]	[–1]	0.025	0.025	[–1]	[–1]	0.023	0.023	0.018	[–1]	0.024	[–1]	0.051	[–1]	0.076
	62	[–1]	[–1]	0.103	0.103	0.081	[–1]	[–1]	0.025	0.025	[–1]	[–1]	0.023	0.023	0.018	[–1]	0.024	[–1]	0.051	[–1]	0.076
	80	2.097	0.014	0.014	0.014	0.014	[–1]	[–1]	[0]	[0]	[–1]	[–1]	[0]	[0]	[0]	0.014	[0]	0.014	0.012	0.014	0.014
	81	0.200	0.066	0.030	0.089	0.017	0.013	0.011	0.021	0.012	[0]	[0]	0.021	0.012	0.012	[0]	0.000	0.020	0.011	0.040	0.014
	82	0.192	0.192	0.192	0.192	0.130	0.192	0.192	0.047	0.047	0.192	0.192	0.044	0.044	0.034	0.192	0.044	0.108	0.092	0.125	0.117
	83	0.604	0.222	0.116	0.366	0.069	0.044	[0]	0.074	0.040	[0]	[0]	0.069	0.038	0.050	[0]	[0]	0.063	0.033	0.151	0.072
	84	0.267	0.226	0.177	0.177	0.103	0.267	0.267	0.038	0.038	0.267	0.267	0.030	0.030	[0]	0.257	0.043	0.107	0.076	0.103	0.096
	85	0.543	0.169	0.076	0.244	0.044	[0]	[0]	0.054	[0]	[0]	[0]	0.050	[0]	0.038	[0]	[0]	0.089	[0]	0.108	0.051
	86	1.109	0.655	0.437	0.534	0.257	0.272	0.228	0.128	0.121	0.198	0.187	0.119	0.113	0.091	0.060	0.113	0.262	0.187	0.370	0.277

[–1] indicates that 0° spacing is achieved.

[0] indicates that extra discrimination is required.

NOTE 1 – The carriers are assumed to be bandwidth limited.

ANNEX 2

Technical characteristics of FSS networks at 20/30 GHz

1 VSAT 20/30 GHz technical characteristics

The system characteristics of ten GSO VSAT networks were contributed to Radiocommunication Working Party 4A in March 1996. A composite was made using the parameters which agreed with a majority of the systems and tested in § 2 for sharing with each other. This composite is shown in Table 5. Some parameters such as antenna masks were deduced from the contribution to Radiocommunication Working Party 4A and verified in the sharing analysis as being necessary.

TABLE 5

Generic 20/30 GHz VSAT technical characteristics

Parameter	Uplink	Downlink
Transponder	Remodulation	Remodulation
Modulation	QPSK	QPSK
Coding	No	Yes
Access	SCPC	TDM/TDMA
Minimum link $E_b/(N_0 + I_0)$	8.0	6.0
Typ/data rate (Mbit/s)	0.384	100
Satellite antenna peak gain (dBi)	45	45
Satellite antenna mask	Rec. ITU-R S.672	Rec. ITU-R S.672
E/S antenna (dBi)	45	42
E/S antenna mask	Rec. ITU-R S.672	Rec. ITU-R S.672
Noise temperature (K)	600	250
Tx power (dBW)	0 maximum –10 minimum	13 maximum 13 nominal
Adaptive power control	Yes	No
Link margin (dB)	5-10(1)	3-5(1)
Up/down E/S antenna discrimination at 2° (dB)	23	20
Frequency reuse	(2)	(2)

(1) Depends on the location of E/S station relative to peak of beam.

(2) Not obvious, but generally about 4:1-6:1 through multiple spot beams and not through polarization.

2 Sharing among VSATS

As can be seen from Table 5, the VSAT networks rely on multiple co-frequency spot beams for frequency reuse but not all beams can carry the same frequency and polarization as excessive adjacent beam interference would occur. Therefore, the intrabeam interference was estimated assuming at least a cross polarization discrimination factor between adjacent beams. The goal of this analysis is to determine whether it is feasible to share with similar VSAT systems with spacing as low as 2°.

Some simplifying assumptions were required in order to achieve this first order approximation of the feasible of sharing with 2° spacing. The link margins were carefully balanced to consider that uplink power control was feasible and practical with single channel per carrier (SCPC) operation while the downlink power and margins were fixed due to TDM operation. The 10 dB rain fade on the uplink was selected as a maximum to ensure that an adjacent satellite would not suffer excessive interference during occasional severe fades. A 5 dB fixed fade margin was selected on the downlink as the approximate margin to achieve a given availability consistent with 10 dB on the uplink and FEC coding was consider necessary to achieve the downlink margin.

The 18 dB E_b/I_0 adjacent beam interference was based on some published estimates for a particular system design. Sharing at 2° spacing with 0.7 m antennas would be nearly impossible without the intra-network interference being about the same as from adjacent satellites. Therefore, it was assumed that high performance satellite antennas as described in Recommendation ITU-R S.672 would be necessary.

The static link margins were budgeted such that the uplink was robust enough to absorb an occasional maximum increase in uplink power from an adjacent network. It is reasonable to assume the downlink would not be fully faded at the same time as an adjacent satellite and therefore the static fade margin of 5 dB would achieve the necessary protection from adjacent satellite interference. Coding on the downlink was necessary to increase these link margins as antenna isolation is not as great at 20 GHz for a fixed size earth terminal aperture.

To a first approximation the topocentric angles were conservatively estimated to be equal to the geocentric angle. And finally interference contributions from adjacent satellites at 4° spacing would require more detailed study of high performance apertures at KaBand. It is reasonable to assume somewhere between 3 and 8 dB additional isolation would be realized. Similarly, the links would require additional analysis if 100% frequency reuse was considered within a beam via automatic compensation for atmospheric depolarization. Polarization isolation between different networks is extremely difficult to estimate at these frequencies.

With these assumptions, the VSAT links are examined as shown in Table 6.

TABLE 6

VSAT link calculations for 2° spacing

	Downlink			Uplink		
	Rain	Clear	Clear	Rain	Clear	Clear
Transmitter	Beam peak	Beam peak	Adjacent satellite	Beam peak	Beam peak	Adjacent satellite
Frequency (GHz)	19.9	19.9	19.9	29.7	29.7	29.7
Power (dBW)	13.0	13.0	13.0	0.0	–10.0	–10.0
Antenna gain (dB)	45.0	45.0	45.0	45.0	45.0	22.0
Circuit loss (dB)	0.0	0.0	0.0	0.0	0.0	0.0
Pointing loss (dB)	0.0	0.0	0.0	0.0	0.0	0.0
e.i.r.p. (dBWi)	58.0	58.0	58.0	45.0	35.0	12.0
e.i.r.p. density (dB(W/Hz))	–22.0	–22.0	–22.0	–10.8	–20.8	–43.8
System losses						
Slant range (km)	37 000.0	37 000.0	37 000.0	37 000.0	37 000.0	37 000.0
Margin (dB)	0.0	0.0	0.0	0.0	0.0	0.0
Space (dB)	–209.8	–209.8	–209.8	–213.3	–213.3	–213.3
Atmosphere (dB)	–0.5	–0.5	–0.5	–1.0	–1.0	–1.0
Rain (dB)	–5.0	0.0	0.0	–10.0	0.0	0.0
Total (dB)	–215.3	–210.3	–210.3	–224.3	–214.3	–214.3
Receiver						
Received signal (dBWi)	–157.3	–152.3	–152.3	–179.3	–179.3	–202.3
Pointing/polarization (dB)	–0.4	–0.4	–0.4	–0.9	–0.9	–0.9
Antenna gain (dB)	42.0	42.0	23.0	45.0	45.0	45.0
Rx input (dBW)	–115.7	–110.7	–129.7	–135.2	–135.2	–158.2
Temperature (K)	250.0	250.0		575.0	575.0	
Noise density (dB(W/Hz))	–204.6	–204.6		–201.0	–201.0	
Bandwidth (dB(Hz))	80.0	80.0		55.8	55.8	
Noise power (dBW)	–124.6	–124.6		–145.2	–145.2	
Link E_b/N_0 (dB)	8.9	13.9		10.0	10.0	
Adjacent beams E_b/I_0 (dB)	18.0	18.0		18.0	18.0	
Adjacent satellites E_b/I (dB)	17.0	22.0		26.0	26.0	
Net $E_b/(N_0 + I)$ (dB)	7.9	12.0		9.3	9.3	
Required E_b/N_0 (dB)	6.0	6.0		8.0	8.0	
Static margin (dB)	1.9	6.0		1.3	1.3	
Other						
Recommended pfd (dB(W/m^2))	–124.4	–124.4		–113.2	–123.2	
G/T (dBi(K^{-1}))	18.0	18.0		17.4	17.4	
Tx power density (dB(W/Hz))	–67.0	–67.0		–55.8	–65.8	
e.i.r.p. density (dB(W/Hz))	–22.0	–22.0		–10.8	–20.8	
Bit rate (Mbit/s)	100.0	100.0		0.384	0.384	
2° antenna discrimination (dB)	19.0	19.0		23.0	23.0	

As can be seen, the 2° spacing is feasible if the earth terminal antenna size is equal to or greater than about 0.7 m so that high discrimination can be achieved at 2° spacing. However, the systems also must be moderately homogenous in link margins.

3 Sharing between VSATs and larger terminals

It would be anticipated that 30/20 GHz bands would be useful for long haul high data rate traffic as satellite link costs are relatively distance insensitive and in fact several GSO systems are already operational and designed for that kind of traffic. Tables 7 and 8 give typical characteristics of such a terminal taken from information available to Radiocommunication Working Party 4A, and from published RR AP 3 notifications.

TABLE 7

Generic 20/30 GHz large terminal technical characteristics

Parameter	Uplink	Downlink
Transponder	Bent pipe	Bent pipe
Modulation	QPSK	QPSK
Access	SCPC/TDMA	SCPC/TDMA
Minimum link $E_b/(N_0 + I_0)$ (dB)	20	10
Typ/data rate (Mbit/s)	120	120
Satellite antenna peak gain (dBi)	51	47
E/S antenna peak gain (dBi)	60.5	57.2
E/S antenna mask	Rec. ITU-R S.465	Rec. ITU-R S.465
Noise temperature (K)	900	325
Tx power (dBW)	22 maximum	11 saturated
Adaptive power control	No	No
Link margin (dB)	15(1)	10(1)
Up/down E/S antenna discrimination at 2° (dBi)	21.5	25.5
Adaptive power control	No	No

(1) It is assumed that the up and downlinks for the transparent transponder would rarely suffer deep fades at the same time due to the large geographic separation.

Using the characteristics from Table 7, sample links were developed and summarized in Table 8.

TABLE 8

Sharing between large KaBand terminals at 2° spacing

	Downlink			Uplink		
	Rain	Clear	Clear	Rain	Clear	Clear
Transmitter	Beam peak	Beam peak	Adjacent satellite	Beam peak	Beam peak	Adjacent satellite
Frequency (GHz)	19.9	19.9	19.9	29.7	29.7	29.7
Power (dBW)	11.0	11.0	11.0	22.0	22.0	22.0
Antenna gain (dB)	47.0	47.0	47.0	60.5	60.5	21.5
Circuit loss (dB)	0.0	0.0	0.0	0.0	0.0	0.0
Pointing loss (dB)	0.0	0.0	0.0	0.0	0.0	0.0
e.i.r.p. (dBWi)	58.0	58.0	58.0	82.5	82.5	43.5
e.i.r.p. density (dB(W/Hz))	–22.8	–22.8	–22.8	1.7	1.7	–37.3
System losses						
Slant range (km)	37 000.0	37 000.0	37 000.0	37 000.0	37 000.0	37 000.0
Margin (dB)	0.0	0.0	0.0	0.0	0.0	0.0
Space (dB)	–209.8	–209.8	–209.8	–213.3	–213.3	–213.3
Atmosphere (dB)	–0.5	–0.5	–0.5	–1.0	–1.0	–1.0
Rain (dB)	–10.0	0.0	0.0	–15.0	0.0	0.0
Total (dB)	–220.3	–210.3	–210.3	–229.3	–214.3	–214.3
Receiver						
Received signal (dBWi)	–162.3	–152.3	–152.3	–146.8	–131.8	–170.8
Pointing/polarization (dB)	–0.4	–0.4	–0.4	–0.9	–0.9	–0.9
Antenna gain (dB)	57.2	57.2	21.5	51.0	51.0	51.0
Receiver input (dBW)	–105.5	–95.5	–131.2	–96.7	–81.7	–120.7
Temperature (K)	325.0	325.0		900.0	900.0	
Noise density (dB(W/Hz))	–203.5	–203.5		–199.1	–199.1	
Bandwidth (120 MHz) (dB(Hz))	80.8	80.8		80.8	80.8	
Noise power (dBW)	–122.7	–122.7		–118.3	–118.3	
Link E_b/N_0 (dB)	17.2	27.2		21.6	36.6	
Adjacent beams E_b/I_0 (dB)	30.0	30.0		30.0	30.0	
Adjacent satellites E_b/I (dB)	28.7	38.7		27.0	42.0	
Link $E_b/(N_0 + I)$ (dB)	16.7	25.2		20.0	28.9	
Net receiver $E_b/(N_0 + I)$ (dB)	16.1	23.6				
Required E_b/N_0 (dB)	10.0	10.0		20.0	20.0	
Static margin (dB)	6.1	15.2		0.0	8.9	
Other						
Recommended pfd/MHz (dB(W/m^2))	–125.2	–125.2		–100.7	–100.7	
G/T (dBi(K^{-1}))	32.1	32.1		21.5	21.5	
Tx power density (dB(W/Hz))	–69.8	–69.8		–58.8	–58.8	
e.i.r.p. density (dB(W/Hz))	–22.8	–22.8		1.7	1.7	
Bit rate (Mbit/s)	120.0	120.0		120.0	120.0	
2° antenna discrimination (dB)	35.7	35.7		39.0	39.0	

As can be seen from Table 8 the E_b/I_0 from adjacent satellite is from 27 to 42 dB depending on whether the channel is faded or not. Clearly, 20/30 GHz GSO networks with earth terminal antennas on the order of 3 m carrying high data rate traffic from point to point can feasibly be deployed every 2° along the arc.

With regard to a mixture of VSATS and large terminals, consider the comparison in Table 9. The table compares the e.i.r.p. density in the off axis direction of 2°. Clearly the downlink interference levels are comparable but the uplink differs by 6.5 dB. This is a natural consequence of the bent pipe satellite carrying fixed uplink margins and the VSAT employing adaptive power control. Some more balancing of the fixed margins would be necessary to accommodate a mixture of networks with both fixed uplink margins and adaptive uplink power control.

This indicates that it is feasible for VSATs to share the arc with larger trunking networks and maintain the 2° spacing. Because there are likely to be few large trunking earth terminals relative to VSATs, some additional isolation could be achieved through geographic separation of co-frequency earth terminals.

TABLE 9

Comparison of off axis e.i.r.p.s

	Downlink e.i.r.p. density (dB(W/Hz))	Uplink e.i.r.p. density (dB(W/Hz))
3.0 m E/S	–22.8	–37.3
0.7 m E/S (VSAT)	–22.0	–43.8

ANNEX 3

1 Glossaries

1.1 Glossary of abbreviations

BER: Bit Error Rate

BPSK: Binary Phase Shift Keying

CDMA: Code Division Multiple Access

DAMA: Demand Assignment Multiple Access

DS-CDMA: Direct Sequence CDMA

e.i.r.p.: effective isotropic radiated power (W)

EOC: Edge Of satellite Coverage

FDMA: Frequency Division Multiple Access

FEC: Forward Error Correction

FH-CDMA: Frequency Hopping CDMA

FSS: Fixed-Satellite Service

GSO: Geostationary Orbit

MSS: Mobile-Satellite Service

OBP: On Board Processing
PCN: Personal Communications Network
PFD: Power Flux-Density (Wm^{-2})
PSD: Power Spectral Density
PSTN: Public Switched Telephone Network
QPSK: Quadrature Phase Shift Keying
TDMA: Time Division Multiple Access
VSAT: Very Small Aperture Terminal
WARC: World Administrative Radio Conference (now WRC)
WP 4A: Working Party 4A (of the Radiocommunication)
WRC: World Radio Conference (formerly WARC)

1.2 Glossary of notation

B: system noise bandwidth (Hz)
C: carrier power (W)
C/I: carrier power to interference power ratio
$(C/I)_D$: downlink carrier power to interference power ratio
$(C/I)_{tot}$: link total carrier power to interference power ratio
$(C/I)_U$: uplink carrier power to interference power ratio
C/N: carrier power to noise power ratio
D: antenna diameter (m)
also signal dynamic factor (distance a signal has deviated from its mean)
E_b: energy per information bit
F: CDMA system processing gain
I: interference power (W)
I_0: interference PSD (W/Hz)
I_{0SN}: CDMA system self-noise interference power (W)
I_{SN}: CDMA system self-noise interference PSD (W/Hz)
m: number of carriers/simultaneous accesses
m_{max}: maximum number of carriers/simultaneous accesses to a system
N_0: Noise PSD (W/Hz)
N_{0TH}: thermal (Gaussian) noise power spectral density (W/Hz)
p: percentage of year that a given fade depth is exceeded
R_b: information bit rate (bit/s)
R_c: channel bit rate (bit/s)
Γ: digital modulation spectral efficiency (bit/s/Hz)
θ: geocentric satellite spacing angle (degrees)
λ: wavelength (m)
φ: angle off antenna boresight (degrees)
also topocentric satellite spacing angle (degrees)