Interference Effects of Deep Space Network Transmitters on IMT-2000/UMTS Receivers at S-Band

C. Ho,[1] M. Sue,[1] T. Peng,[2] P. Kinman,[3] and H. Tan[1]

International Mobile Telecommunications (IMT)-2000 and its European member, Universal Mobile Telecommunications System (UMTS), are planning to deploy mobile radio services in the S-band (around 2 GHz) in the next few years. NASA's Deep Space Network (DSN) has been operating powerful S-band transmitters at three worldwide sites. The DSN's uplink frequency (2110–2120 MHz) is part of the spectrum to be used by the UMTS terrestrial system for the forward links (2110–2170 MHz). It is necessary to determine if the DSN transmitters would interfere with nearby IMT-2000/UMTS receivers through transhorizontal propagation. Under normal conditions, interference causes three types of losses that will reduce the power level as received by a victim receiver: free-space loss, diffraction loss over the spherical Earth, and diffraction loss over mountain peaks. In this article, simplified topographic mountain-peak profiles along the radial direction are used to calculate the losses for all three DSN sites. In addition, there are unusual propagation modes under which the interference can have favorable propagation channels to reach areas beyond the line of sight. They are, respectively, the ducting mode (one-dimensional loss) and rain scattering (rain as a reflector). These two modes are strongly time-percent dependent. The propagation loss for these special modes also is calculated. All losses are combined to estimate the minimum "coordination distance" beyond which the interference will be attenuated below the threshold level of the IMT-2000/UMTS receiver. We find that for 85 percent of the time this distance is about 70 km from the DSN site. The radial distance can be reduced to as small as 30 km in the direction of a large mountain shadow. For 15 percent of the time, ducting and rain scattering can greatly increase the distance to several hundreds of kilometers.

[1] Communications Systems and Research Section.

[2] TMOD Plans and Commitments Office.

[3] Case Western Reserve University, Cleveland, Ohio.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

I. Introduction

A. Background

International Mobile Telecommunications (IMT)-2000 (formerly known as Future Public Land Mobile Telecommunication Systems), also known as third-generation wireless, is intended to provide future public telecommunications capable of broadband and multimedia applications [1–8]. Even though the terrestrial component of IMT-2000 will be implemented on a national basis, seamless global roaming and a high degree of commonality of design and compatibility of services are considered essential attributes of IMT-2000 systems. The Universal Mobile Telecommunications System (UMTS) is the proposed European member of the IMT-2000 family [9,10]. As a concept, it will move mobile communications forward from second-generation systems into the information society and deliver voice, data, pictures, graphics, and other wideband information directly to the user [1,7,8,11]. To achieve these objectives, the World Radiocommunication Conference (WRC)-95 made resolution 212, which allows the frequency spectrum for both terrestrial and satellite communications systems of IMT-2000/UMTS to move up to S-band (around 2 GHz) [1,12,13]. These systems will transmit and receive wideband signals around 2.0 GHz [9,12]. The IMT-2000 community has asked the International Telecommunication Union (ITU) to issue a new spectrum regulation to clean up existing users in this frequency band before it can be used for the above-specified purpose [13]. NASA's Deep Space Network (DSN) has been operating transmitters and receivers with strong transmitted powers in this frequency band at three worldwide sites. Thus, there is an urgency to evaluate the potential interference effects between the DSN and IMT-2000 communications systems. It is informative to study the spectrum-sharing issues between IMT-2000 and the DSN using UMTS as an example.

B. Frequency Spectrum

The structure of the core frequency band for the planned IMT-2000/UMTS is shown in Fig. 1 [9]. At S-band, the frequency bands from 1900 to 1980 MHz, 2010 to 2025 MHz, and 2110 to 2170 MHz are designated for terrestrial UMTS applications. The UMTS satellite (SAT) component applications are

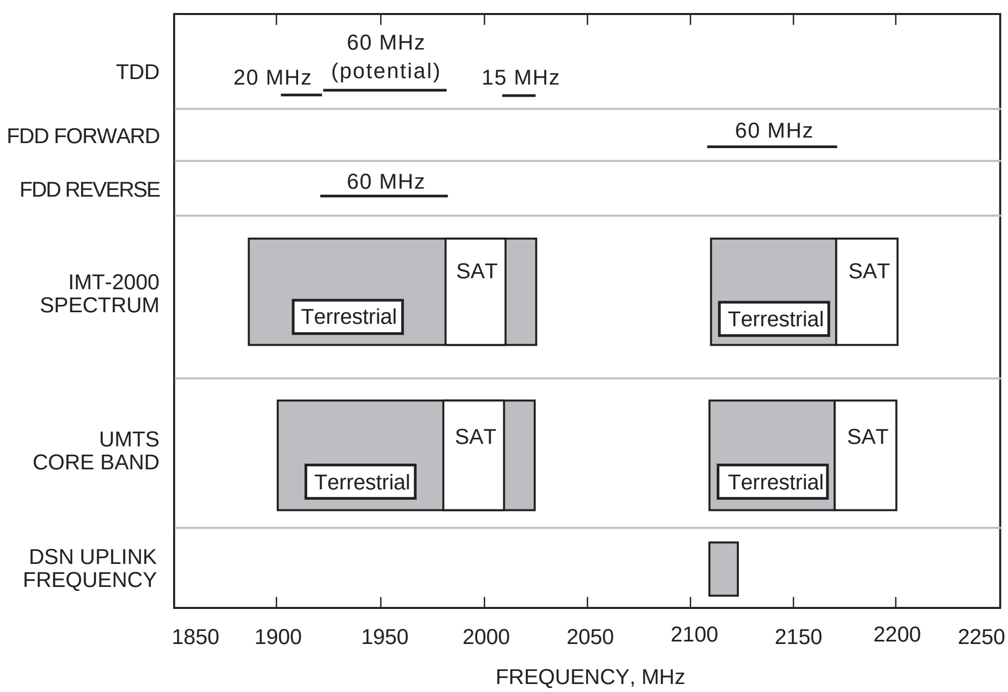


Fig. 1. The planned frequency spectrum and core band for IMT-2000/UMTS.

accommodated within the bands from 1980 to 2010 MHz and 2170 to 2200 MHz [14]. The frequency band from 1920 to 1980 MHz is paired with that from 2110 to 2170 MHz for frequency division duplex (FDD) operation [9]. The duplex direction for FDD carriers in these bands is mobile transmit (reverse link) within the lower band and base transmit (forward link) within the upper band [12]. Thus, mobile personal stations receive signals in the frequency band from 2110 to 2170 MHz. The frequency bands from 1900 to 1920 MHz and 2010 to 2025 MHz are unpaired bands for time division duplex (TDD) operation. The frequency band from 1920 to 1980 MHz also may be used for TDD operation. Carrier spacing for both FDD and TDD has a minimum of 5.0 MHz [9]. The European Radiocommunication Committee (ERC) has requested that the full 155 MHz for terrestrial services and the full 60 MHz for satellite service be available in the year 2005. A 185-MHz frequency-band extension is being requested for the year 2010 [9].

Figure 2 shows the allocations of the IMT-2000 frequencies in both the European and U.S. regions [13,15]. We can see that, in the United States, there is a different frequency deployment for IMT-2000 from the European UMTS. Around 2110 MHz, there is a 40-MHz frequency band for future auction. Thus, the link and duplex direction in this band still has many uncertainties. This study is mainly based on the UMTS spectrum, which is used by both the Spain and Australia DSN sites. We will assume that a future U.S. personal communication system (PCS) has a similar spectrum structure around 2110 MHz.

DSN equipment operating at S-band has an uplink frequency from 2110 to 2120 MHz and a downlink frequency from 2290 to 2300 MHz. The transmitters at three worldwide sites (Madrid, Spain; Goldstone, U.S.A.; and Canberra, Australia) have both 34-m and 70-m antennas. It is obvious that the DSN uplink frequency (2110 to 2120 MHz) overlaps with the frequency band planned by the IMT-2000/UMTS terrestrial system (2110 to 2170 MHz). The uplink frequency used by the DSN transmitters is shown in Fig. 1.

C. IMT-2000/UMTS Terrestrial Systems

There are varieties of complicated infrastructures of second-generation systems such as the Global System for Mobile communication (GSM). By adding third-generation capabilities and upgrading analog networks to digital systems [3,6], GSM can evolve into IMT-2000/UMTS [11]. The ITU has issued the guidelines for evaluation of radio transmission technologies [4–6,8]. A design objective of IMT-2000 is that the number of radio interfaces should be minimal and, if more than one interface is required, there

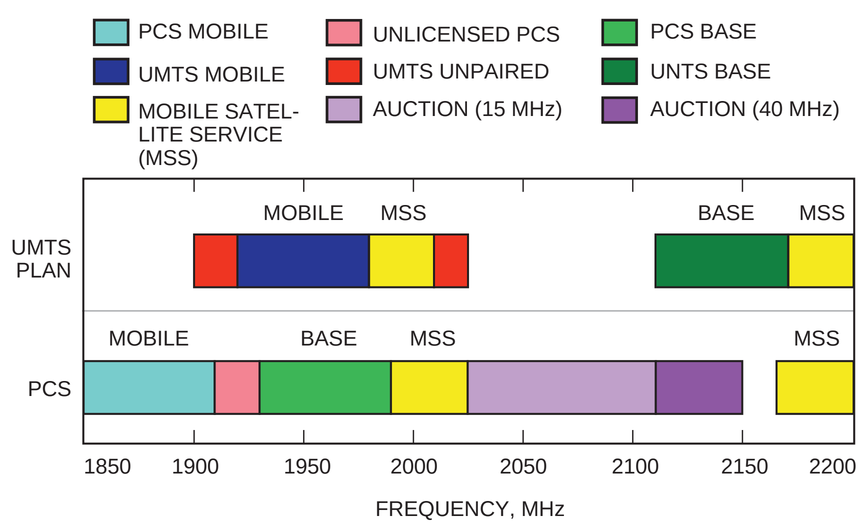


Fig. 2. A comparison of frequency spectra used by European (UMTS) and U.S. (PCS) regions [16].

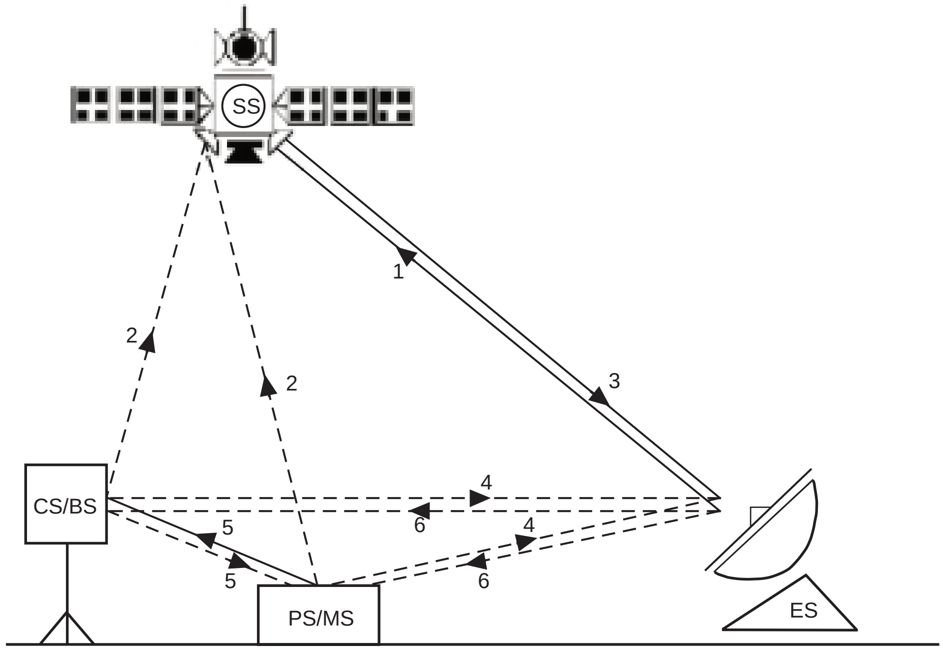
should be a high degree of commonality between them [4,16]. The ITU is unifying the many diverse systems existing today into a seamless radio infrastructure capable of offering a wide range of services [8]. Even though currently there are many different types of mobile communication systems, a terrestrial system generally includes the following radio components: a mobile station (MS), a mobile base station (BS), a personal station (PS), a cell site (CS) personal base station, a mobile Earth station (MES), and a personal Earth station (PES). IMT-2000 also will incorporate FDD and TDD operation schemes, with multiple access methods that can meet the many different mobile operational environments around the world [7,17]. These methods include code-division multiple access (CDMA), time-division multiple access (TDMA), and the newly developed space-division multiple access (SDMA) [7,17]. Table 1 lists some parameters used for the terrestrial component link budget templates [1,6]. In a base station, transmitter antenna gain is about 10 to 13 dBi. The interference threshold level for a personal station (cellular phone) is about −117 dBm (−147 dBW) [1,6].

Table 1. IMT-2000/UMTS terrestrial system parameters [1,6,12].

Parameter	Value
Base station transmitter and receiver antenna gain, dBi	13 (vehicular) 10 (pedestrian) 2 (indoor)
Personal station antenna gain, dBi	0
Receiver noise figure	5 dB
Thermal noise density	−174 dBm/Hz
Average mobile transmit power (3.0-km cell radius)	1950 MHz: 20.7 dBm 2140 MHz: 21.1 dBm
Effective isotropic radiated power (EIRP)	10 W (base); 1 W (mobile); 3 mW (personal indoor); 20 mW (personal outdoor)
Estimated power flux density (PFD)	38 μW/km^2/Hz (base and mobile) 1.5 μW/km^2/Hz (personal)
Permissible interference level	−117 to −119 dBm (personal) [1,12] or −147 to −149 dBW

II. Interference Propagation Models

Because the same frequency band is used by the DSN transmitters and IMT-2000/UMTS, the interference signals potentially will cause a problem if there is not enough geographic separation [1]. Figure 3 shows all possible desired and interference signal links between the two systems. At 2110 to 2120 MHz, there are two desired signal paths (represented by solid lines): link 1 (the uplink signal from the DSN transmitter) and link 5 between the IMT-2000/UMTS terrestrial system base station and personal stations (forward or reverse links). The dashed lines represent undesired interference signals. Link 6 is the interference signals from the DSN transmitter to the IMT-2000/UMTS terrestrial system base station and personal stations (to be assessed in this study). Since the desired downlink signals (link 3) received by the DSN have a different frequency (2290 to 2300 MHz), which is well above the UMTS spectrum, interference signals (link 4) generated by IMT-2000/UMTS will not cause any problem on the DSN receiver. IMT-2000/UMTS may generate some interference signals through link 2 on a spacecraft that has an uplink connection with the DSN transmitter. However, the interference effect will be too small to be considered in this study. Thus, this task has been simplified into solving the problem of one-way transhorizon propagation interference (link-6-only) effects from DSN powerful transmitters on IMT-2000/UMTS terrestrial system personal stations. Mobile personal stations are victims because they are so sensitive



BS = MOBILE BASE STATION
MS = MOBILE STATION
PS = PERSONAL STATION
CS = CELL SITE PERSONAL BASE STATION
ES = EARTH STATION
SS = SPACECRAFT STATION

DESIRED AND INTERFERENCE SIGNAL LINKS

FREQUENCY, MHz	DESIRED SIGNAL (SOLID LINES)	INTERFERENCE (DASHED LINES)
2110–2120	1	6
	5	4

Fig. 3. All possible desired and interference signal links between the IMT-2000/UMTS terrestrial systems and the DSN at S-band.

and are receiving forward link signals from base stations in the frequency band also transmitted by the DSN. Applicable ranges of all interference propagation modes are listed in Table 2. Beyond the line of sight, there are three types of interference mechanisms, as shown in Fig. 4. They are diffraction over the spherical Earth and mountain tops, ducting, and rain scattering. While diffraction and ducting propagation require wave signals to have a nearly horizontal incident angle (which generally corresponds to the side lobe of a DSN transmitter), rain scattering may occur through a transmitter's main-lobe coupling.

Table 2. Minimum and maximum ranges for various propagation modes [19].

Propagation mode	Minimum–maximum applicable range, km
Line of sight	0–50
Diffraction	0–250
Ducting	20–1000
Rain scattering	0–400

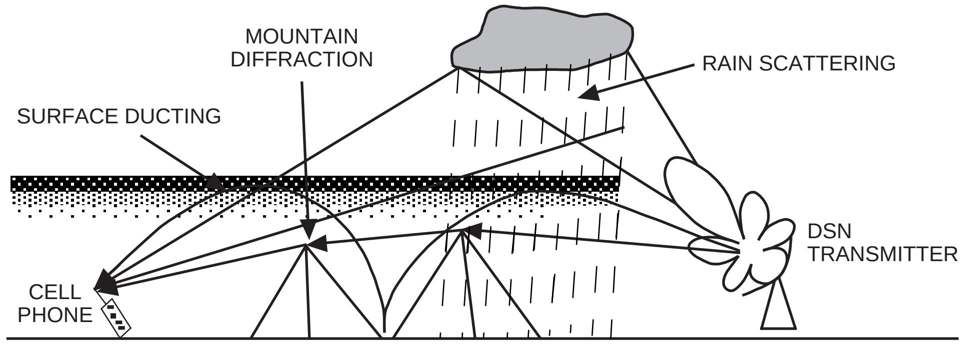


Fig. 4. Three interference mechanisms between a DSN transmitter and IMT-2000 customers beyond the line of sight. There always are some interference signals coming through the mountain diffraction (or Earth spherical surface diffaction). Occasionally, ducting propagation through a surface or elevated duct and rain scattering by a common viewed rain region also can cause serious interference problems.

A. Propagation Losses Under Normal Conditions

Normal propagation loss is the loss that occurs at all times and that dominates most of the time. Thus, it is independent of probability of time percentage. The loss includes three parts: free-space loss, diffraction around the spherical Earth, and diffraction over knife-edge mountains [18–20]. Under normal conditions, the total loss of the interference signals during propagation is a combination of the three types of losses. Gaseous attenuation along a horizontal path [21] at S-band (2.11 GHz) is very small (less than 1.2 dB for a 200-km propagation distance). We have neglected this loss in the following calculation. We also have neglected the tropospherical scatter loss in this article.

1. Line-of-Sight (Free-Space) Loss. Free-space loss, L_{fs}, is a two-dimensional spread loss along the line of sight of propagation:

$$L_{fs} = \left(\frac{4\pi df}{c}\right)^2 \tag{1}$$

where f is the frequency of the transmitted signal, d is the distance between the receiver and the transmitter, and c is the speed of light. Using gigahertz (GHz) as the units of frequency and kilometers (km) as the units of distance in this article (unless otherwise stated specifically), we have

$$L_{fs} = 92.45 + 20 \log f + 20 \log d \tag{2}$$

expressed in decibels (dB).

2. Diffraction Over the Spherical Earth [22]. Microwave rays never can be bent around the Earth, unless a diffraction occurs. There is an additional transmission loss due to the diffraction over the spherical Earth, assuming a smooth surface or slow varying terrain. Diffraction loss, L_{ds}, relative to the free-space signal at the same distance is defined as

$$L_{ds} = F(X) - (G_1 + G_2) \tag{3}$$

where

$$X = 22 f^{1/3} a_e^{-2/3} d \tag{4}$$

and

$G_1 =$ the transmitter antenna height gain, dB

$G_2 =$ the receiver antenna gain, dB

$d =$ the path length, km

$a_e =$ the equivalent Earth's radius, in km (where we use 8500 km)

$f =$ the frequency, GHz

The distance term is given by

$$F(X) = 17.6X - 10\log(X) - 11 \tag{5}$$

The height gain terms are given by Eqs. (11) and (11a) in [22]. When $f = 2.11$ GHz, the transmitter antenna height above the ground is 37 m (for a DSN 70-m antenna), and the receiver antenna height is 2 m, $X = 0.068d$, $G_1 = 14.8$ dB, and $G_2 = -15.8$ dB. As a comparison, free-space loss and diffraction loss over the spherical Earth are shown in Fig. 5.

3. Diffraction Over Knife-Edge Types of Mountain Peaks [22]. Diffraction loss, L_{dp}, over a single knife-edge type of mountain peak is defined as

$$J(\nu) = 6.9 + 20\log\left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1\right) \tag{6}$$

where

$$\nu = h\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1} + \frac{1}{d_2}\right)} = \sqrt{\frac{2d}{\lambda}\alpha_1\alpha_2} \tag{7}$$

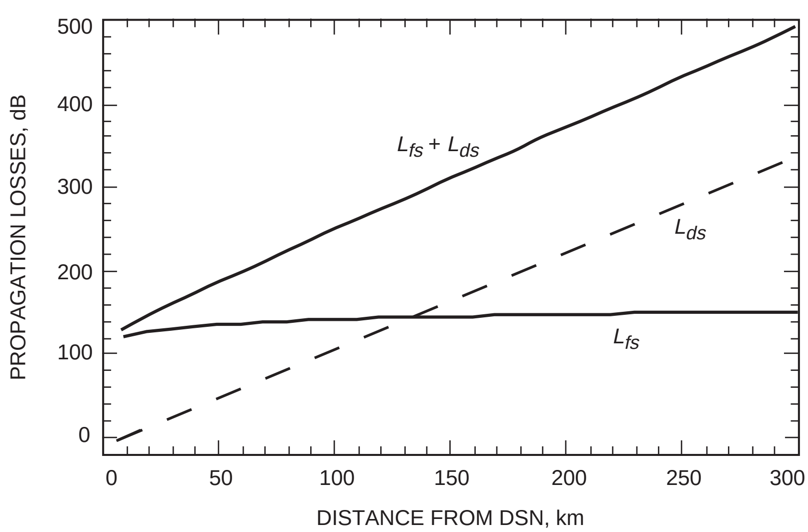


Fig. 5. Free-space loss, L_{fs}, and diffraction loss over the spherical Earth, L_{ds}. L_{fs} increases slowly with increasing distance. At a 140-km distance, the diffraction loss becomes larger than free-space loss.

because $h \approx d_1\alpha_1 \approx d_2\alpha_2$, where h is the height of the top of the mountain above the straight line linking the two ends of the path in a flat plane; d_1 and d_2 are the distances of the two ends of the path from the top of the mountain; d is the length of the path; and α_1 and α_2 (in radiance) are angles between the top of the mountain and one end as seen from the other end, as shown in Fig. 6. To calculate the diffraction loss for multiple knife-edges of obstacles, we have used the method and procedure described in Sections 4.4 and 4.5 of [22].

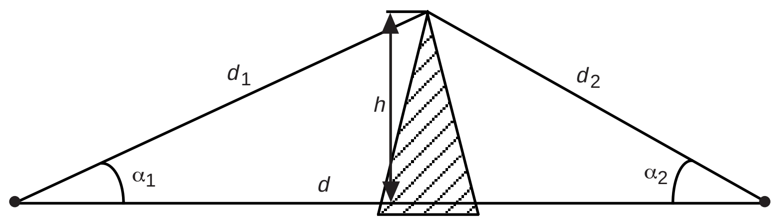


Fig. 6. The way a microwave ray is diffracted at a knife-edge type of mountain peak. All geometric elements also are shown [22].

B. Propagation Losses Under Special Conditions

Under certain conditions, some special paths with much less propagation loss become available. For example, when the atmosphere has strong vertical gradients, slightly upward propagating waves can be reflected at a certain height and propagate forward within the duct between the ground and a reflected atmospheric layer or within an elevated ducting layer. Following these ducts, waves can propagate a thousand kilometers with less attenuation than free-space loss. Rain scattering is another mode that makes it possible for waves to propagate into an area beyond the line of sight. Rain droplets can reflect and scatter the waves as a mirror between a transmitter and a transhorizon receiver. Both types of propagation loss are strongly probability dependent (the percentage of time of existing strong vertical gradients and rain storms) and are almost independent of terrain structures surrounding the transmitter. In the following calculations, we also have neglected the gaseous attenuation term.

1. Transhorizon Ducting (Mode 1) [18–20,23,24]. For a transhorizon ducting propagation along the great circle of the Earth, the transmission loss L_1 is a function of p, the percentage of time of a weather condition:

$$L_1(p) = 120 + 20 \log f + \gamma(p) d_1 + A_h \tag{8}$$

in dB.

Different from two-dimensional free space, ducting propagation has a one-dimensional loss due to tropospheric layer entrapment. In Eq. (8), $A_h = 7.5$ dB is the loss for ducting coupling and obstacles, and $\gamma_(p)$ is ducting attenuation, a function of percentage of time, where

$$\gamma(p) = 0.01 + C_1 + C_2 \log f + C_3 p^{C_4} \tag{9}$$

C_1, C_2, C_3 and C_4 are four parameters; their values depend on the climatic zones one is in. Corresponding to a smaller p, there is a smaller loss, L_1, or stronger interference. Duct thickness is usually several hundreds of meters.

2. Rain Scattering (Mode 2) [18–20,25–27]. For the rain-scattering transmission loss, L_2, a definition different from that for ducting loss is used. The received interference power, P_r, is independent of its antenna gain:

$$L_2(p) = \frac{P_t}{P_r} \tag{10}$$

From the radar equation, we have

$$P_r = \frac{P_t G_t \eta V A_r}{(4\pi)^2 (R_1)^2 (R_2)^2} \tag{11}$$

where η is the cross-section/unit volume, A_r is the effective receiver antenna area, V is the scattering volume, and R_1 and R_2 are the distances (in km) from rain cells to the transmitter and the receiver, respectively. Transmission loss due to the rain scattering is [19]

$$L_2(p) = 168 + 20\log d_2 - 20\log f - 13.2\log R - G_t + \Gamma \tag{12}$$

in dB, where R is the rain rate, a function of percentage of time of the weather condition; G_t is the transmitter antenna gain; and Γ is

$$\Gamma = \frac{631kR^{\alpha}}{\sqrt{R}} 10^{-(R+1)^{0.19}} \tag{13}$$

in dB, where k and α are two coefficients related to the wave frequency.

Figure 7 shows both losses L_1 and L_2 as a function of distance for various time percentages, p. To calculate these losses, an A_2 radioclimatic region consisting entirely of land for ducting propagation and an H rainfall climatic region (defined by the ITU) for rain scattering have been used. The losses increase with increasing distance and percentage of time. Through this comparison, we find that losses for ducting propagation increase linearly with distances. Loss change is much flatter for rain scattering than for ducting for a fixed time percentage. Losses for rain scattering increase very quickly above $p = 1$ percent. This is because rainfall has a very small chance at a larger time percentage. Table 3 lists these values for both propagation modes.

III. Approach and Results

A. Transmitter and Receiver Parameters

There are many different types of antennas for the DSN transmitters, including the standard, high-efficiency (HEF), beam-waveguide (BWG), and high-speed beam-waveguide antennas. For the sake of simplification, we consider only the standard antenna with a pattern described by [28]. The DSN transmitter with a 70-m antenna has 20-kW (43-dBW) transmission power. The antenna gain at the boresight is 62 dB, while its back lobe is −10 dB. Outside the main lobe, antenna gain quickly decreases to −10 dB. We assume that the DSN antenna points above a 10-deg elevation angle all of the time and will not transmit below a 15-deg elevation angle.

Because only the signals with very a small elevation angle (less than 2 deg) can propagate forward through the duct transhorizontally, these signals should come mainly from the side lobe of the transmitter

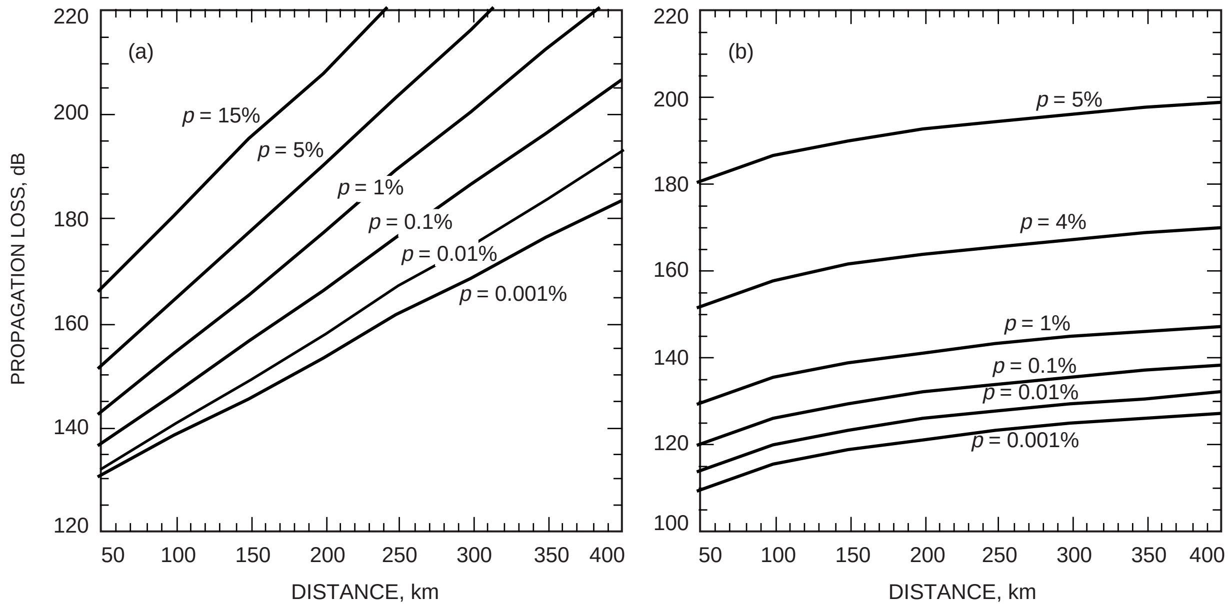


Fig. 7. Propagation loss as a function of distance for various time percentages, *p*: (a) ducting loss for an A_2 inland climatic region at least 50-km away from the sea and (b) rain scattering loss in an H climatic region. Both regions fit the Madrid, Spain, site.

Table 3. Propagation losses in dB for a DSN transmitter at the 2110-MHz band.

Propagation mode (region)	p, percent	Loss, dB							
		50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
Line of sight	—	133	—	—	—	—	—	—	—
Ducting (A_2)	5	151	164	177	190	203	216	229	242
	1	142	154	165	177	189	200	212	223
	0.1	136	146	156	166	176	186	196	206
	0.01	132	141	149	158	167	175	184	193
	0.001	130	138	145	153	161	168	176	183
Rain scattering (H)	5	180	186	190	192	194	196	197	198
	1	129	135	138	141	143	144	146	147
	0.1	120	126	129	132	134	135	137	138
	0.01	113	119	123	125	127	129	130	131
	0.001	109	115	118	121	123	124	126	127

antenna. Diffraction over the spherical Earth also requires a nearly horizontally propagated wave, as shown in Fig. 4. The signals emitted from a DSN antenna main lobe cannot be trapped by the duct. Thus, in this article, we have used a transmitter antenna gain of $G_t = -10$ dB for calculations of ducting and diffraction losses. However, for rain scattering, the interference signals may come through a main-lobe coupling, as shown in Fig. 4. In this coupling, the rain and clouds play the role of reflector between the DSN transmitter and IMT-2000 users. Rainfall can have an extent of 4 km in height. In the worst situation, signals coming from the transmitter main lobe with the maximum gain (62 dB) can be scattered by rain to a region beyond the line of sight. DSN transmitter and IMT-2000 users are linked through a common viewed-rainfall region. In this article, we have used the main-lobe transmitter antenna gain of $G_t = 62$ dB for the calculation of rain-scattering loss in Eq. (12).

In this section, an analysis has been performed to estimate potential interference to UMTS personal stations due to an uplink from a DSN 70-m antenna. The interference potential has been analyzed using the propagation models mentioned in Section II under both normal and special conditions. The transmitting power for a DSN antenna is $P_t = 20$ kW $= 43$ dBW. For an IMT-2000/UMTS personal station, we assume that its receiving antenna is omnidirectional and has a gain of $G_r = 0$ dBi. The equations used to estimate the interference power at a UMTS receiver, P_r, are

$$P_r = P_t - L_2 \tag{14a}$$

in dBW for rain scattering, and

$$P_r = P_t + G_t - L_b + G_r \tag{14b}$$

in dBW for all modes except rain scattering, where L_b is the basic propagation loss. Thus, applying the above parameters, we have $P_r = 33 - L_b$ for all losses except rain scattering, and $P_r = 43 - L_2$ for rain scattering.

B. Coordination Distances Under Normal Conditions

To avoid interference when sharing a frequency band, a geographic separation between the transmitter and the receiver is necessary [19,20]. Coordination needs to be undertaken within an area surrounding the transmitter and extending to distances beyond which the possibility of interference may be considered to be negligible. This area usually is called a “coordination area,” while this distance is a “coordination distance.” For all azimuths, the coordination distance should define a contour or area around the transmitter. Outside this contour, the transmission loss would be expected to exceed a specific value. Thus, the minimum coordination distance at a specific percentage of the time is determined by equalizing the transmission loss, based on an interference propagation model, to a required minimum permissible loss, which corresponds to a permissible interference level (or threshold level) of an IMT-2000/UMTS personal station receiver [19,20].

Under normal conditions, only free-space loss along the line of sight and diffraction losses over the spherical Earth and over the mountain peaks play dominant roles. The first two losses are only radial-distance dependent from the DSN center, as shown in Fig. 5, while the mountain-peak diffraction loss is much more complicated and is dependent on geomorphologic structures around each DSN site. To calculate the third loss, we have used simplified topographic profiles based on *The Times Atlas of the World* [29] along the radial direction from each DSN center. We make these profiles only when there are major mountain peaks in that direction. For those directions without large mountains, we just use a smoothed flat profile to approximate. After we have these topographic profiles with mountain peaks, as shown as in Fig. 6 in a flat plane, we can use Eqs. (6) and (7) to calculate diffraction loss over each knife-edge type of mountain peak. This diffraction loss then is combined with diffraction loss over the spherical Earth and free-space loss. Because of the simplified model we used, the calculated loss due to mountain-peak diffraction is only a rough estimate. It is difficult and almost impossible to perform an accurate calculation by using a real profile.

Total propagation losses through free space and over the spherical Earth and the mountain tops are calculated and are shown in Figs. 8(a) through 8(c) for the three DSN sites. Each map shows a 400-km-by-400-km area centered on each DSN site. The white loop around each DSN site shows the minimum coordination distance, beyond which interference signals are below the threshold of personal

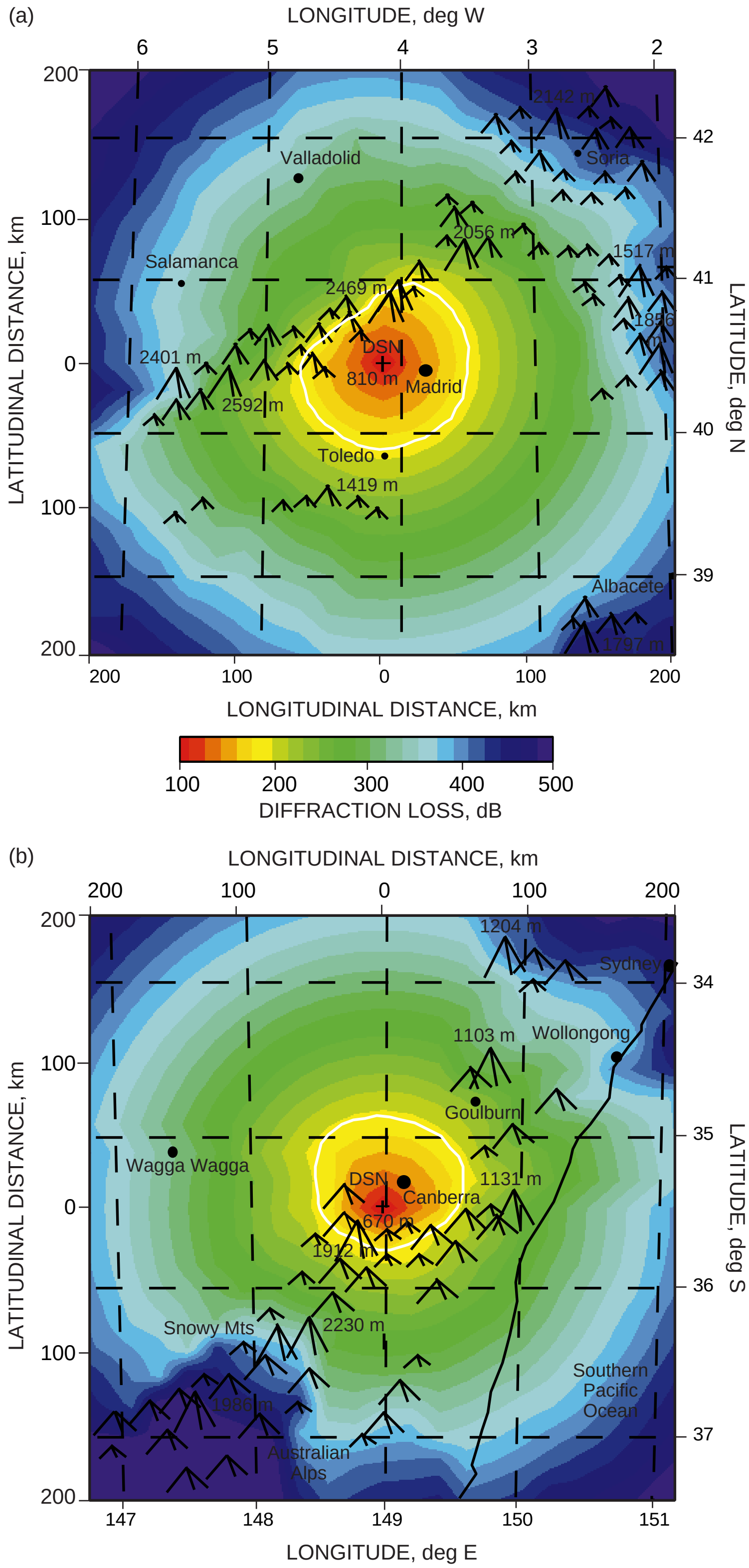


Fig. 8. Total propagation loss under normal condition around three DSN sites: (a) Madrid, Spain, (b) Canberra, Australia, and (c) Goldstone, California.

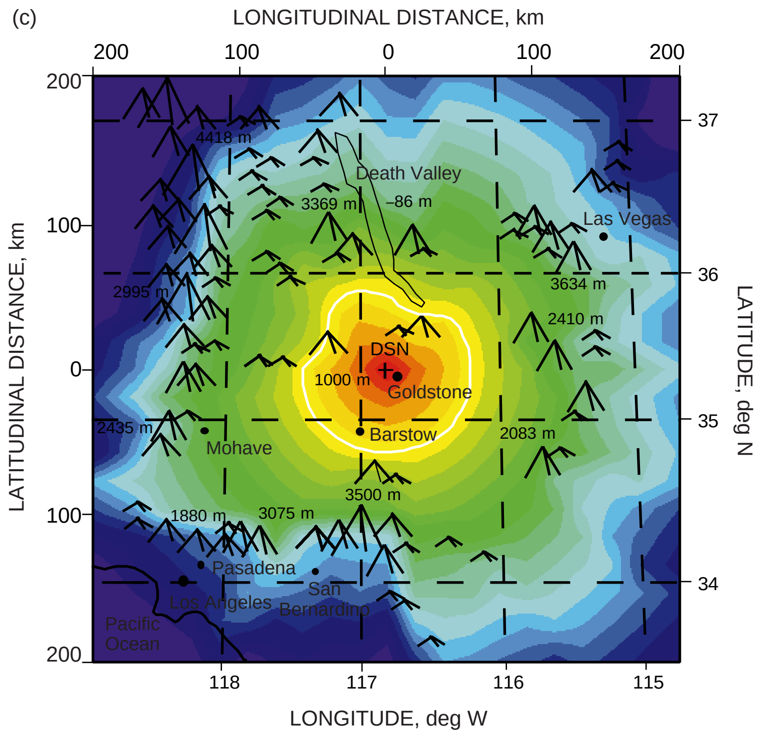


Fig. 8 (cont'd).

mobile stations most of the time. Mountain-peak numbers and locations also are marked in each plot (only major mountains are drawn). For example, the Madrid site (800 m in elevation) has large mountains on its northwest side, while the Canberra site (660 m in elevation) is on the north side of the Australian Alps Mountains. The Goldstone site (1000 m in elevation) has very complicated topographic structures around it. The western side of the Sierra Nevada Mountains, the southwest San Gabriel Mountains, and the southern San Bernardino Mountains all have large peaks. Note that the mountain peak numbers are much reduced as compared with a detailed geographic map.

Using the fundamental relation of Eq. (14), we can calculate the interference margin of an IMT-2000 personal receiver station and determine the minimum coordination distance. The margins are defined as the difference between the threshold level and the received power, P_r. The permissible interference level, P_{th}, for a UMTS personal station is taken to be 10 percent of the receiver noise floor of -98.9 dBm (approximately -99 dBm) [30]. In other words, the permissible interference level is -109 dBm (-139 dBW) and is before despreading. This value is 8-dB larger than the threshold (-147 dBW) listed in Table 1. The interference margin is

$$P_{th} - P_r = L_b - 172 \tag{15a}$$

in dBW for ducting and diffraction, and

$$P_{th} - P_r = L_2 - 182 \tag{15b}$$

in dBW for rain scattering. When the margin is set to zero, we can obtain the location where the loss makes interference signals below the threshold of an IMT-2000/UMTS personal station.

If there is only the free-space loss (assuming a flat plane), the coordination distance to reach a 172-dB loss is about 4300 km. Because of the Earth's curvature, it is impossible for such a large distance to be within the line of sight. For an antenna with a 37-m height (a 70-m antenna) above the ground, the line-of-sight distance is only about 50 km. As shown in Fig. 5, we can see that free-space loss slowly increases with increasing distance. The wave diffraction loss over the spherical Earth exceeds the free-space loss at about a 135-km distance. Adding both losses together, the coordination distance is reduced to about 70 km. Both losses are azimuth independent, with a perfect circle around the DSN transmitter. In Fig. 8, we have used a white loop around each DSN site to represent the minimum coordination distance with a roughly 172-dB loss.

Mountain-peak diffraction loss is an additional individual loss and is greatly dependent on geomorphological profiles around each site. After including this loss, the white loop, which shows the minimum coordination distance, significantly departs from a circle. Thus, the minimum coordination distance becomes azimuthal dependent and asymmetrical. In the direction with large mountain peaks, interference signals are severely blocked and coordination distance becomes much less. Each large knife-type mountain peak contributes at least 10 to 30 dB of additional loss, depending on how high the peak is relative to the ground in a flat plane and how far from the peak the view point is. In the radial direction, where there is no mountain, the loss consists only of free-space loss and spherical diffraction. At the Madrid and Canberra sites, because the large mountains in some directions are very close by, the coordination distances are as close as only 30 km from the DSN site in these directions. Beyond this white loop, the interference level should drop to below the threshold of an IMT-2000/UMTS personal station at most times. It will be shown later that the personal station can be used outside the white loop up to 85 percent of the time. Near the Goldstone site, a medium-sized city, Barstow, is inside of the circle. Thus, there will be some problems for cellular phone users there.

C. Coordination Distances Under Special Conditions

Because ducting and rain-scattering losses are geomorphologically independent and depend only on radial distance, we do not need to show the loss distribution in a three-dimensional plot as we did for diffraction loss. For a ducting-mode calculation, an A_2 radioclimatic region that contains only land and is at least 50 km away from the sea (this region is applicable to all three DSN sites) is selected [19,20]. Thus, the three DSN sites have the same loss as shown in Fig. 7(a) and Table 3. These losses are also a function of the percentage of time of a weather condition, p. For a very small time percentage, an extremely small propagation loss can occur.

For ducting propagation, IMT-2000 receiver margins (in dB) relative to the interference from a DSN transmitter are shown in Fig. 9 and Table 4. A negative margin indicates that the protection-level criterion is exceeded. We expect that, at a smaller p, the ducting mode has a small loss, so that the coordination distance is larger than that for diffraction. Thus, the question is at what percentage of time the ducting loss becomes less than the normal diffraction loss (or the coordination distance exceeds 70 km). In Fig. 9, the interference margin for the ducting mode is shown for various percentages of time (from 0.001 to 15 percent) as a function of distance. We see that, corresponding to 15 percent of the time, the ducting-mode margin starts to become negative at about 70 km (which is the coordination distance made by the normal loss). The minimum coordination distance increases with decreasing time percentage. The interference margin becomes more negative at a lower percentage of time and at a smaller distance, as shown in Fig. 9. At $p = 0.001$ percent (5.2 min), the coordination distance becomes 320 km.

For the rain-scattering mode, the margin is $(P_{th} - P_r) = L_b - 182$ dB through a transmitter main-lobe coupling. The loss is below 182 dB when the percentage of time is under 5, as shown in Fig. 7(b) and Table 3. The corresponding negative margin suggests a much larger coordination distance. When $p = 5$ percent, the loss becomes less than 182 dB at a distance of 70 km. This means that, at a time percentage of ≤ 5, rain scattering will have a coordination distance greater than 70 km. The interference scattering effects depend mainly on the rainfall rates of the areas where the DSN site is located. The losses

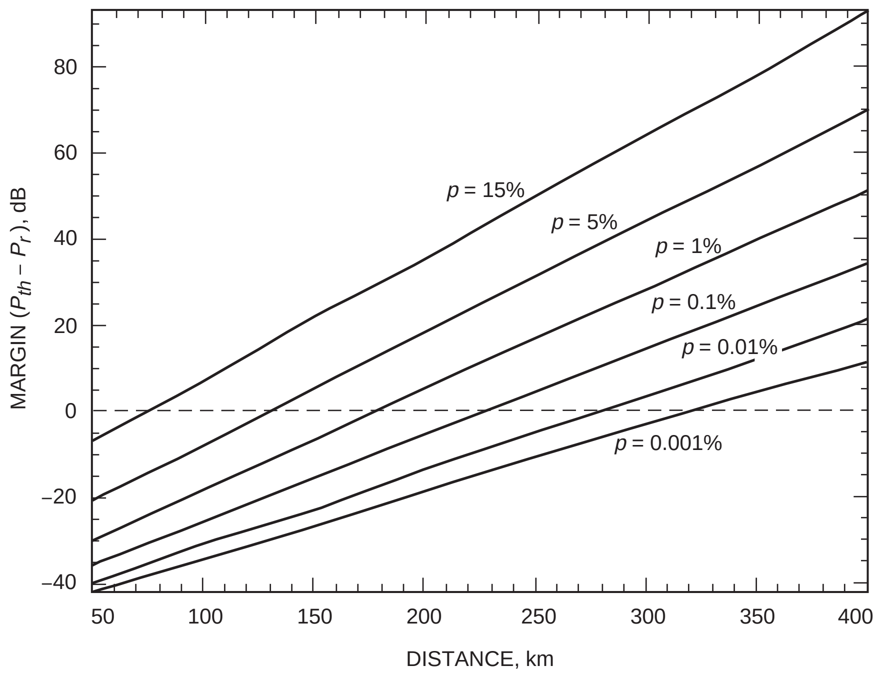


Fig. 9. Ducting propagation can significantly increase the minimum coordination distance at a relatively small percentage of time (approximately 10 percent). For example, at 0.01 percent (52 min), the minimum coordination distance is 282 km.

Table 4. Interference margin in dB for a UMTS personal station.

Propagation mode (region)	p, percent	Interference margin, dB							
		50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
Line of sight	—	−47	—	—	—	—	—	—	—
Ducting (A_2)	5	−21	−8	5	18	31	44	57	70
	1	−30	−18	−7	5	17	28	40	51
	0.1	−36	−26	−16	−6	4	14	24	34
	0.01	−40	−31	−23	−14	−5	3	12	21
	0.001	−42	−35	−27	−19	−11	−3	4	11
Rain scattering (H)	5	−2	4	8	10	12	14	15	16
	1	−53	−47	−43	−41	−39	−37	−36	−35
	0.1	−62	−56	−52	−50	−48	−46	−45	−44
	0.01	−68	−62	−59	−56	−55	−53	−51	−50
	0.001	−74	−67	−64	−61	−59	−58	−56	−55

and coordination distances have only slight differences for the three DSN sites, even though the sites are located in different rainfall regions. The interference margins for the three sites are shown in Figs. 10(a) through 10(c). The rainfall rates for the three DSN sites are different, with Canberra (M region) having the highest rate, followed by Madrid (H region) and Goldstone (E region). A higher rainfall rate will cause relatively intense interference scattering effects. The margins become negative at

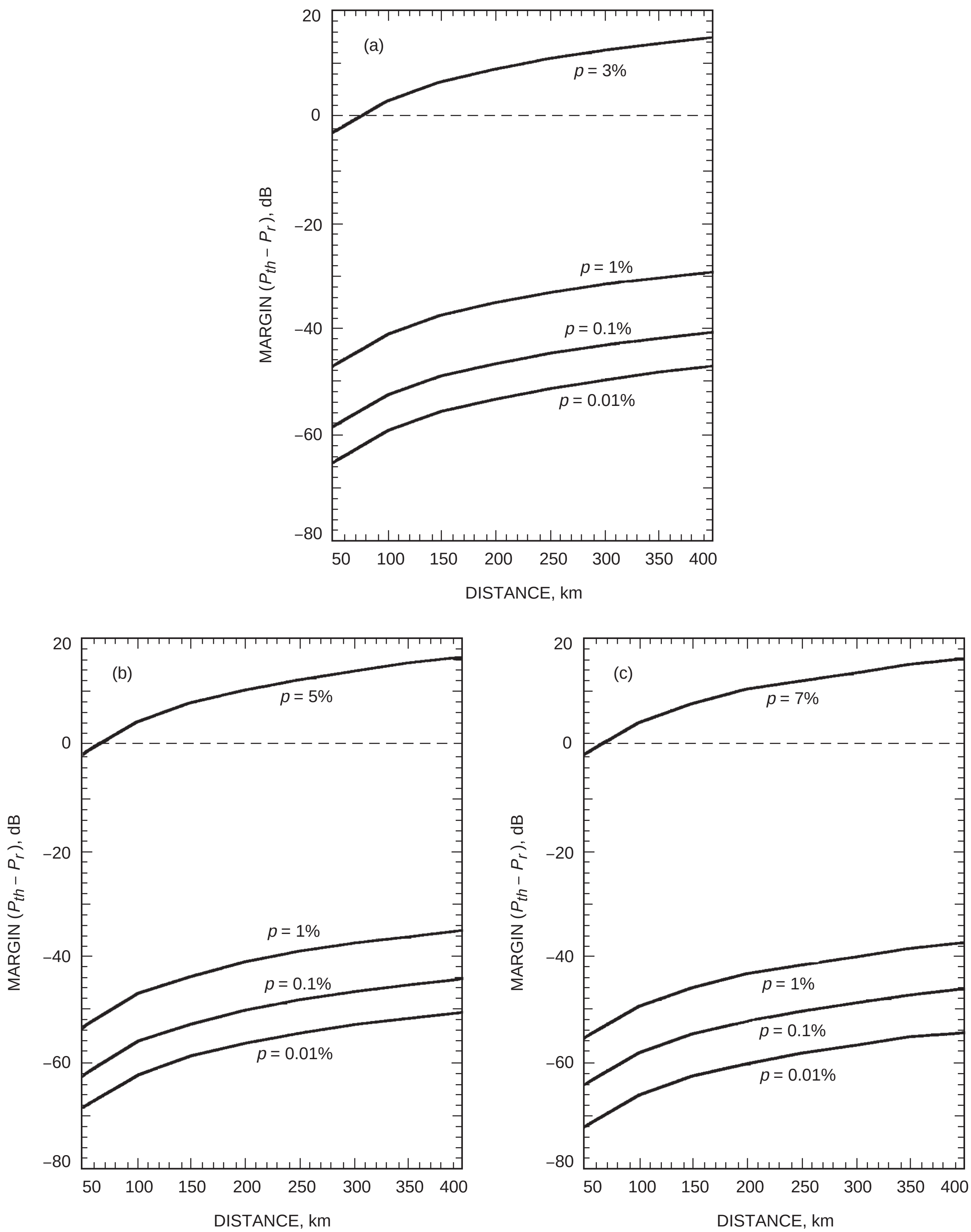


Fig. 10. Rain-scattering margin as a function of distance at three DSN regions for various percentages of time. From the lowest to the highest rainfall rate, the regions are (a) Goldstone, California, region E; (b) Madrid, Spain, region H; and (c) Canberra, Australia, region M.

$d = \sim 70$ km from 3 to 7 percent. Below these time percentages, rain scattering will generate small loses. Thus, there will be large coordination distances, but generally less than the 400-km limit. This suggests that rain scattering plays a role only for time percentages of less than approximately 5.

Keep in mind that the minimum coordination distance due to diffraction and free-space losses is less than 70 km. For the Goldstone site (lowest rain rate), the margin for rain-scattering loss for a time percentage of approximately 3 becomes negative at a distance of 70 km. For Madrid, the margin for 5 percent of the time becomes negative at this distance. For Canberra (the highest rainfall rate), the margin becomes negative at a time percentage of approximately 7. Thus, a lower rain-rate region corresponds to a lower percentage of time during which the 70-km coordination distance, as determined by diffraction and free-space losses, is exceeded. Because the losses due to rain scattering increase slowly with increasing distance, a slight reduction from the above-mentioned percentage of time at each region will increase the coordination distance significantly. For example, in the H region, for a time percentage of 5, the distance is 70 km. For a 4.3 time percentage, the distance reaches 400 km. However, we have an upper limit of 400 km for the coordination distance generated by rain scattering at all regions. At larger percentages of time (greater than 5 percent), because the rainfall becomes much less, the propagation loss significantly increases. The margin always will be positive. Interference due to rain scattering will be overwhelmed by diffraction effects.

As a summary, we have shown in Fig. 11 the minimum coordination distances resulting from all propagation modes. In the top 5 percent of the time, rain-scattering interference can extend the minimum coordination distance to as much as 400 km. Beyond 400 km, rain scattering is not applicable because rain clouds have a limited height. In the top 15 percent of the time, the ducting mode plays a dominant role in interference propagation. During this time range, the minimum distance will extend from 70 km to approximately 300 km. For the other 85 percent of the time, interference signals propagate only through the diffraction over the spherical Earth and mountain tops, as given in Table 5. In the radial direction without mountains, the coordination distance is about 70 km, while the distance can be reduced to as little as 30 km in the direction with large shielding mountains.

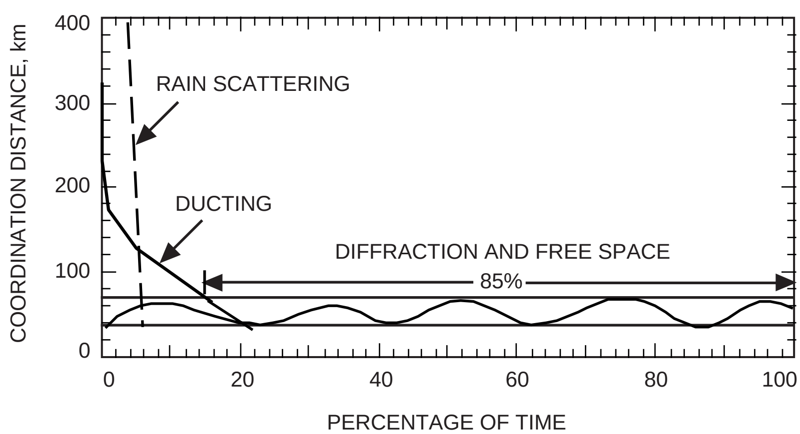


Fig. 11. Minimum coordination distance as a function of percentage of time for the ducting propagation mode. For a very small percentage of time, the distance can be expanded to as much as 300 km.

IV. Summary

After IMT-2000 and its European member, UMTS, move their terrestrial mobile communication systems into S-band, transhorizon interference from DSN transmitters will cause serious problems to IMT-2000/UMTS systems. An analysis has been performed to estimate potential interference to IMT-2000/UMTS personal stations under two different situations.

Table 5. Minimum coordination distances for ducting-mode propagation.

Mode (region)	Coordination distance, km					
	15%	5%	1%	0.1%	0.01%	0.001%
Ducting	70	133	178	232	282	320
Rain scattering (H)	—	70	400	400	400	400

Under normal conditions, interference propagation suffers only three types of loss: free-space loss, diffraction loss over the spherical Earth, and diffraction loss over mountain peaks. The third one has strong dependence on geomorphologic structures and terrain distributions in surrounding areas. All three types of losses always exist and will dominate the propagation up to 85 percent of the time. Other propagation effects will be overwhelmed by the diffraction interference effects. For each DSN site, some simplified topographic mountain-peak profiles along the radial direction are used for the loss calculation. Total propagation losses through free space and over the spherical Earth and the mountain tops are calculated. To perform this calculation, we have assumed that interference comes from a 20-kW DSN transmitter and that the antenna has a side-lobe gain (-10 dB). The latest available IMT-2000 terrestrial system parameters have been used in this article. Results indicate that the minimum coordination distance can be as small as 30 km in the directions of large mountain shadows. Without mountain shielding, beyond a circle with a 70-km radius, the interference will drop to below the threshold level of the victim receiver.

At the top 15 percent of time, ducting loss will become much smaller than the normal diffraction loss. Ducting can significantly increase the coordination distance at a very small time percentage. The distance can change from 70 km at 15 percent of the time to 320 km at 0.001 percent of time. Ducting loss is independent of the topographic profiles and azimuth angles around DSN sites.

At the top 5 percent of time, rain-scattering effects will dominate interference propagation. The interference can propagate through the transmitter main-lobe coupling and be scattered into a region beyond the line of sight. During this small time period, the coordination distance will exceed the 70 km determined by diffraction losses, but with an upper limit of 400 km. This main-lobe coupling is not likely to happen for the line-of-sight and ducting modes because the transmitting DSN antenna pointing angle normally is above 10 deg.

It is concluded that there will be a serious interference problem for IMT-2000/UMTS systems that are inside a 70-km circular area around a DSN site when there is no mountain shielding between the DSN transmitter and the IMT-2000 receivers. Mountain shadow can make the distance smaller. Occasionally, the ducting and rain-scattering modes can significantly increase the coordination distance. For ducting propagation, the circle around a DSN site can be expanded with a 282-km radius for the top 0.01 percent of the time, while rain scattering has an upper limit of 400 km.

Acknowledgments

We would like to thank Dr. Anil V. Kantak for reviewing this article and Dr. Nasser Golshan for his suggestions.

References

[1] International Telecommunication Union, Radiocommunication Sector, "International Mobile Telecommunications-2000 (IMT-2000)," Recommendation ITU-R M.687, 1997.

[2] International Telecommunication Union, Radiocommunication Sector, "Framework for Services Supported on International Mobile Telecommunications-2000 (IMT-2000)," Recommendation ITU-R M.816, 1997.

[3] International Telecommunication Union, Radiocommunication Sector, "International Mobile Telecommunications-2000 (IMT-2000): Network Architectures," Recommendation ITU-R M.817, 1992.

[4] International Telecommunication Union, Radiocommunication Sector, "Framework for the Radio Interfaces and Radio Sub-system Functionality for International Mobile Telecommunications-2000 (IMT-2000)," Recommendation ITU-R M.1035, 1994.

[5] International Telecommunication Union, Radiocommunication Sector, "Requirements for the Radio Interfaces for International Mobile Telecommunications-2000 (IMT-2000)," Recommendation ITU-R M.1034, 1997.

[6] International Telecommunication Union, Radiocommunication Sector, "Guidelines for Evaluation of Radio Transmission Technologies for IMT-2000," Recommendation ITU-R M.1225, 1997.

[7] "ITU Finds Way Forward for 3G Mobile Systems," *ITU News*, pp. 18–19, April 1999.

[8] F. Leite, R. Engelman, S. Kodama, H. Mennenga, and S. Towaij, "Regulatory Considerations Relating to IMT-2000," *IEEE Personal Communications*, pp. 14–19, August 1997.

[9] "European Radiocommunications Committee Decision on the Harmonised Utilisation of Spectrum for Terrestrial Universal Mobile Telecommunications System (UMTS) Operating Within the Bands 1900–1980 MHz, 2010–2025 MHz and 2110–2170 MHz," ERC/DEC/(99)HH, ERC 25th meeting, Helsinki, Finland, March 10–12, 1999.

[10] International Telecommunication Union, "UMTS Forum Report on UMTS/IMT-2000 Spectrum Requirements," ITU-R, Document 8-1/INFO/1-E, United Kingdom, November 19, 1997.

[11] International Telecommunication Union, Radiocommunication Sector, "Evolution of Land Mobile Systems Toward IMT-2000," Recommendation ITU-R M.1308, 1997.

[12] International Telecommunication Union, Radiocommunication Sector, "Spectrum Considerations for Implementation of International Mobile Telecommunications-2000 (IMT-2000) in the Band 1885–2025 MHz and 2110–2200 MHz," Recommendation ITU-R M.1036, 1999.

[13] T. Ojanpera and R. Prasad, "An Overview of Third-Generation Wireless Personal Communications: A European Perspective," *IEEE Personal Communications*, pp. 59–65, December 1998.

[14] International Telecommunication Union, Radiocommunication Sector, "Satellite Operation Within International Mobile Telecommunications-2000 (IMT-2000)," Recommendation ITU-R M.818, 1994.

[15] R. B. Engelman, "Third Generation Mobile Systems: Around the World With IMT-2000, FCC/OET Tutorial," Web material and handout, May 12, 1998.

[16] International Telecommunication Union, Radiocommunication Sector, "Framework for the Satellite Component of International Mobile Telecommunications-2000 (IMT-2000)," Recommendation ITU-R M.1167, 1995.

[17] E. Dahlman, B. Gudmundson, M. Nilsson, and J. Skold, "UMTS/IMT-2000 Based on Wideband CDMA," *IEEE Communications Magazine*, pp. 70–80, September 1998.

[18] International Telecommunication Union, Radiocommunication Sector, "Prediction Procedure for the Evaluation of Microwave Interference Between Stations on the Surface of the Earth at Frequencies Above About 0.7 GHz," Recommendation ITU-R P.452-8, 1997.

[19] International Telecommunication Union, Radiocommunication Sector, "Determination of the Coordination Area of an Earth Station Operating With a Geostationary Space Station and Using the Same Frequency Band as a System in a Terrestrial Service," Recommendation ITU-R IS.847-1, 1993.

[20] International Telecommunication Union, Radiocommunication Sector, "Propagation Data Required for the Evaluation of Coordination Distances in the Frequency Range 0.85-60 GHz," Recommendation ITU-R P.620-3, 1997.

[21] International Telecommunication Union, International Radio Consultative Committee (CCIR), "Attenuation by Atmospheric Gases," Report 719-2, *Propagation in Non-ionized Media, Recommendations and Reports of the CCIR*, vol. V, Geneva, Switzerland, 1986.

[22] International Telecommunication Union, Radiocommunication Sector, "Propagation by Diffraction," Recommendation ITU-R P.526-5, 1997.

[23] International Telecommunication Union, International Radio Consultative Committee (CCIR), "Radiometeorological Data," Report 563-3, *Propagation in Non-ionized Media, Recommendations and Reports of the CCIR*, vol. V, Geneva, Switzerland, 1986.

[24] International Telecommunication Union, International Radio Consultative Committee (CCIR), "Effects of Tropospheric Refraction on Radiowave Propagation," Report 718-2, *Propagation in Non-ionized Media, Recommendations and Reports of the CCIR*, vol. V, Geneva, Switzerland, 1986.

[25] R. K. Crane, "Bistatic Scatter From Rain," *IEEE Trans. Ant. Prop.*, vol. AP-22, pp. 312–320, 1974.

[26] J. Awaka, K. Nakamura, and H. Inomata, "Bistatic Rain-Scatter Experiment at 34.8 GHz," *IEEE Trans. Ant. Prop.*, vol. AP-31, pp. 693–698, 1983.

[27] International Telecommunication Union, International Radio Consultative Committee (CCIR), "Scattering by Precipitation," Report 882-1, *Propagation in Non-ionized Media, Recommendations and Reports of the CCIR*, vol. V, Geneva, Switzerland, 1986.

[28] International Telecommunication Union, Radiocommunication Sector, "Reference Radiation Patterns for Line-of-Sight Radio-Relay System Antennas for Use in Coordination Studies and Interference Assessment in the Frequency Range From 1 to About 40 GHz," Recommendation ITU-R F.699-4, 1997.

[29] *The Times Atlas of the World*, 7th Comprehensive Edition, Times Books, 1985.

[30] European Radiocommunications Committee, *Adjacent Band Compatibility Between UMTS and Other Services in the 2 GHz Band*, ERC Report 65, Annex A, May 1999.