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RADIO WAVE PROPAGATION INTO SANDSTORMS – SYSTEM DESIGN BASED ON TEN-YEARS VISIBILITY DATA IN RIYADH, SAUDI ARABIA

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Reliability analysis for millimetric radio links is presented in this paper. Based on 10-years visibility data for Riyadh City, Saudi Arabia, the expected outage caused by sandstorms is estimated. It is shown that an extended hop length of 10 to 20 km can be achieved with high reliability for dry conditions and small particle size. The present analysis is limited to frequencies up to 40 GHz; since no data are available for the complex dielectric of sand at higher frequencies. It is shown that beside visibility data, knowledge of particle size and moisture content are also needed for the estimation of excess attenuation during a sandstorm.

Link reliability versus fade margin is plotted for various hop lengths and storm conditions. A complete system design must account for outage caused by rain attenuation, multipath fading and sand-storms.

1. INTRODUCTION

Sand and dust-storms occur in many parts of the world, especially in the Middle East and arid parts of Asia for a significant percentage of time. During the storm, sand and dust particles may rise high enough above the earth's surface to lie within the path of microwave or millimetric wave radio links causing a loss of signal

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energy and resulting in a service interruption. The effect of sandstorm on radio propagation is more profound at extremely high frequencies EHF, which is finding more applications in civil and military communication, because of the increasing congestion at lower frequency bands. A field trial by the author is presently underway in Riyadh in which three millimetric wave radio links are being monitored to measure the effect of storms, among other parameters, on the system reliability. However, several years of measurements are needed before the outcome of such a study is known.

This paper presents a method of estimating the effect of sand-storms on radiowave propagation based on ten years visibility data in Riyadh obtained from the Meteorological & Environmental Protection Administration (MEPA) of the Ministry of Defense and Aviations. The aim is to define the optimum hop length and proper tower heights which minimize system cost for a given performance and reliability criteria.

Predicting attenuation and phase shift, caused by sand/dust storms, requires the knowledge of pertinent storm parameters affecting propagation. Such parameters include particle shape, size distribution, refractive index, concentration and composition. Long term meteorological data are not expected to include such detailed information. On the other hand, a record of visibility is kept with sufficient accuracy in most places of the world. Hence, most radio meteorological measurements of sand and duststorms are made in terms of optical visibility. As will be shown in Section 2, visibility can be used to calculate the number density (number of particles/unit volume) and mass concentration (total mass of particles/unit volume). In the next section a method of using visibility data to determine system reliability is presented, together with the study case of Riyadh city. Section 3 is a discussion of the results and limitations of the present analysis. Concluding remarks are outlined in Section 4.

2. EFFECT OF SANDSTORMS ON RADIO PROPAGATION

2.1 Attenuation in sand/dust storms

The visibility, or more accurately the visible range, is defined as the distance at which an isolated object can be just distinguished from background (Middleton 1952). Visibility is affected by wind speed, hygroscopic particles and relative humidity. The presence of sand or dust particles in the atmosphere may cause the visual range to vary from few meters to several kilometers.

The optical visibility V_o and the optical attenuation (α_o) are related by the simple relation (Chu 1979)

$$V_o(\text{Km}) = \frac{15}{\alpha_o(\text{dB/Km})} \qquad (1)$$

and for spherical particles of radius a (meters), it can be shown that the number of particles per (m^3) is given by (Chu 1979)

$$N\ (\text{Number of particles}/m^3) = 0.55\times10^{-3}\left(\frac{1}{V_o\, a^2}\right) \qquad (2)$$

The derivation of the above equation depends on several assumptions which are reasonably applicable to the atmosphere, such as spherical particle and constant optical extinction coefficient along the path (Ansari and Evans 1982). Eq. (2) is used to find the number of equisized sand particles of radius a, causing an optical attenuation of α_o (dB/Km). Unfortunately, there is no direct frequency scaling method that can be applied to relate wave attenuation at any frequency to that at optical frequency. A simple method of estimating the attenuation caused by such particles was presented by (Chu 1979). Using a slab-of-particles model and applying the Rayleigh approximation, the attenuation coefficient is given by

$$\alpha = 12.6\ \alpha_o \frac{a}{\lambda}\ \mathrm{Im}\left\{\frac{\varepsilon-1}{\varepsilon+2}\right\} \qquad \left(\frac{dB}{Km}\right) \qquad (3)$$

where λ is the wave length (m) and ε is the complex relative permitivity of the particles given by

$$\varepsilon = \varepsilon' - j\ \varepsilon'' \qquad (4)$$

Using Eqs. (1)-(4) the attenuation coefficient is expressed in terms of the number density N as:

$$\alpha = 3.43\mathrm{x}10^5\ \frac{a^3 N}{\lambda}\ \frac{3\varepsilon''}{(\varepsilon'+2)^2 + \varepsilon''^2} \qquad (dB/Km) \qquad (5)$$

Or in terms of the optical visibility V_o:

$$\alpha = \frac{0.0189}{V_o}\ \frac{a}{\lambda}\ \frac{3\varepsilon''}{(\varepsilon'+2)^2 + \varepsilon''^2} \qquad (dB/Km) \qquad (6)$$

Eq. (6) will be utilized in the following section to estimate the attenuation at any wavelength λ as a function of visibility V_o. Knowledge of the particle size and dielectric constant is assumed.

2.2 Visibility Data

Table 1 lists all events of sand and duststorms which hit Riyadh during a span of ten years beginnig in 1972. The record was obtained from MEPA and includes dates and durations over which the optical visibility was reduced due to storm events. Although the original record maintained by MEPA includes an exhaustive list of all storms with visibility ranging from 10 Km down to few meters, only severe storms are shown in Table 1.

In order to relate the above data to attenuation in dB/Km at a given frequency, the use of Eq. (5) requires the knowledge of the sand parameters in the storm. If equisized particles are assumed, to simplify the present analysis, the radius a and dielectric constant must be determined. Since the records lack such information we will study two limiting cases of a = .01 mm and a = 0.1 mm. Larger particle sizes were reported (Ghobrial et al 1978) which can increase the predicted attenuation.

Table 1. Dates on which visibility was 500 meters or less.

	Visibility in meters						
DATE	500 m	400 m	300 m	200 m	100 m	5 m	ZERO
1972							
Nov. 5	–	–	–	60	–	–	–
Nov. 5	–	60	–	–	–	–	–
1973							
Jul. 24	–	–	–	60	–	–	–
Aug. 9	–	–	60	–	–	–	–
1974							
Jan. 24	–	60	–	–	–	–	–
Apr. 27	–	–	–	–	–	–	9
May 5	–	–	18	–	–	–	–
1976							
Mar. 6	–	–	–	–	–	–	15
Apr. 19	12	–	–	–	–	–	–
May 2	–	–	–	–	–	–	7
Sept. 15	–	–	18	–	–	–	–
Sept. 15	18	–	–	–	–	–	–
Nov. 13	30	–	–	–	–	–	–
1977							
Mar. 4	–	–	–	–	93	–	–
Mar. 19	–	–	–	–	–	–	9
Mar. 19	21	–	–	–	–	–	–
Apr. 15	–	–	–	–	–	–	60
Apr. 15	–	–	–	–	180	–	–
Apr. 15	–	–	–	60	–	–	–
Apr. 15	–	–	60	–	–	–	–
Oct. 22	–	–	–	35	–	–	–

DURATION IN MINUTES

Table 1. (contd.)

DATE	Visibility in meters							
	500 m	400 m	300 m	200 m	100 m	5 m	ZERO	DURATIN IN MINUTES
1979								
Jan. 9	-	-	-	-	-	81	-	
Mar. 24	15	-	-	-	-	-	-	
May 1	29	-	-	-	-	-	-	
May 27	23	-	-	-	-	-	-	
May 31	-	-	26	-	-	-	-	
Jun. 1	-	-	14	-	-	-	-	
Jun. 11	-	78	-	-	-	-	-	
1978								
Jan. 25	-	-	-	-	-	-	24	
Mar. 17	15	-	-	-	-	-	-	
Mar. 23	-	-	-	-	-	30	-	
Mar. 25	-	-	60	-	-	-	-	
May 14	5	-	-	-	-	-	-	
May 28	-	-	-	-	18	-	-	
Jun. 24	120	-	-	-	-	-	-	
Jul. 18	-	-	-	-	-	-	9	
Jul. 18	-	-	15	-	-	-	-	
Jul. 18	21	-	-	-	-	-	-	
1980								
Jun. 2	-	9	-	-	-	-	-	
Jun. 30	-	-	-	-	-	-	33	
Jun. 30	69	-	-	-	-	-	-	
Jun. 29	-	-	-	-	-	12	-	
1981								
Feb. 10	12	-	-	-	-	-	-	
Mar. 3	78	-	-	-	-	-	-	
Mar. 21	9	-	-	-	-	-	-	
Mar. 26	-	-	-	-	8	-	-	
Apr. 1	-	-	-	-	-	18	-	
Apr. 8	-	-	-	-	-	24	-	
Apr. 18	-	-	120	-	-	-	-	
May 16	300	-	-	-	-	-	-	
May 16	-	60	-	-	-	-	-	
May 16	3	-	-	-	-	-	-	
Nov. 22	24	-	-	-	-	-	-	

However, the field study run by the author will provide particle size distribution, as a function of height, such information is not available presently elsewhere.

The complex dielectric constant ε is a function of sand composition and moisture content. It was reported, however, that ε is almost unaffected by the chemical and mineral composition of soils except where significant amounts of metallic or magnetic minerals are present (Cohlar and Ulaby 1974). Table 2 presents attenuation data for the two limiting sizes of $a = .01$ mm and $a = 0.1$ mm considered in our analysis. Four moisture contents are given and attenuation is calculated for visibilities of 500 to 100 meters at a frequency of 37 GHz, based on Fig. 6 of (Ansari and Evans 1982).

A glance over Table 2 reveals that attenuation increases markedly with moisture content. In duststorms, individual dust grains floating in humid air take on a layer of water molecules and behave more as water drops. Such a case will be more relevant to the coastal areas of the desert. The first column of Table 2 represents the worst case of large particles and high humidity, while the last column to the right takes care of smallest dust grain under dry conditions.

2.3 Reliability analysis

Excess attenuation caused by various storm conditions is plotted in Figs. 1 as a function of hop length. The curves of Figs. (1-a) through (1-e) are based on the five visibility conditions of Table 2. In fact, each of the five figures represents one row of Table 2.

Our aim, now, is to use the available data on storm occurrence, obtained for Riyadh, to estimate the effect of sandstorms on link reliability. An outage event may be regarded as the time duration over which the excess attenuation (other than free space attenuation) exceeds the available fade margin. Reliability and outage are related by:

$$\text{Reliability} = 1\text{-outage}, \qquad (7)$$

Table 2. Attenuation (in decibels/kilometer) for medium of 0.1 mm and 0.01 mm sand/dust particles for different visibility against percentage humidity.

Visibility	0.1 mm sand/dust particles moisture content				0.01 mm sand/dust particles moisture content			
	20%	10%	5%	Dry	20%	10%	5%	Dry
500	3.7	3.1	1.57	0.28	0.37	0.31	0.082	0.015
400	4.1	3.4	2	0.31	0.42	0.35	0.09	0.017
300	4.5	3.8	2.2	0.35	0.46	0.39	0.11	0.019
200	5	4.1	2.38	0.38	0.5	0.42	0.125	0.021
100	5.4	4.4	2.5	0.4	0.54	0.45	0.14	0.024

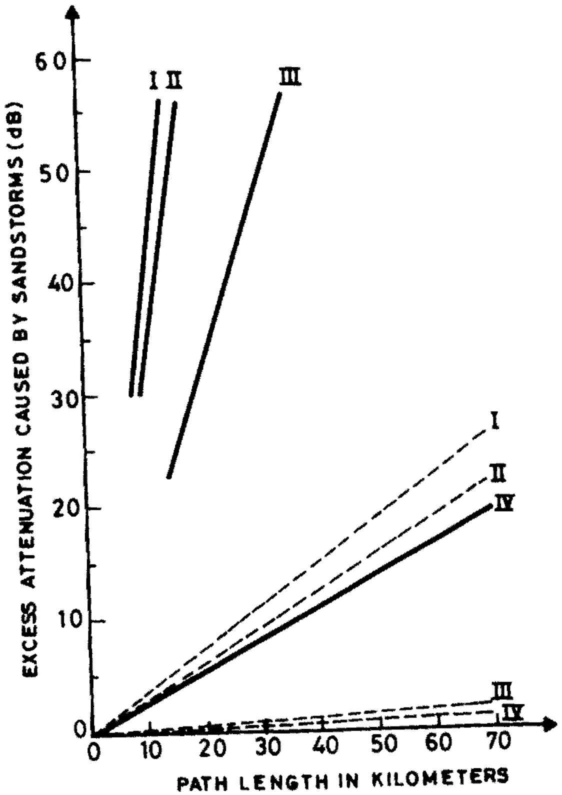

Fig. (1-a) Fade margin in dB vs. path length in kms for loamy fine sand at 37 GHz (Based on visibility 500 m).

—— a = 0.1 mm
---- a = 0.01 mm
I) 20% moisture
II) 10% moisture
III) 5% moisture
IV) dry.

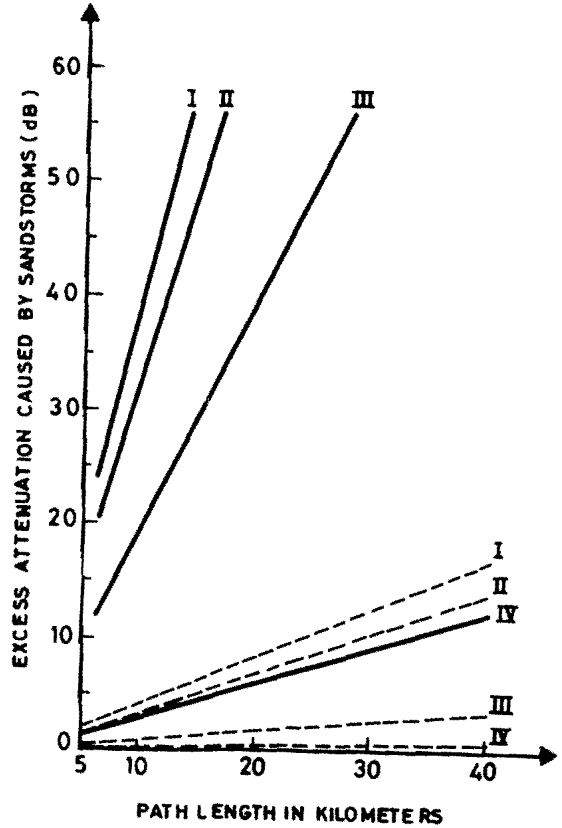

Fig. (1-b) Fade margin in dB vs. path length in kms for loamy fine sand at 37 GHz (Based on visibility 400 m).

—— a = 0.1 mm II) 10% moisture
---- a = 0.01 mm III) 5% moisture
I) 20% moisture IV) dry.

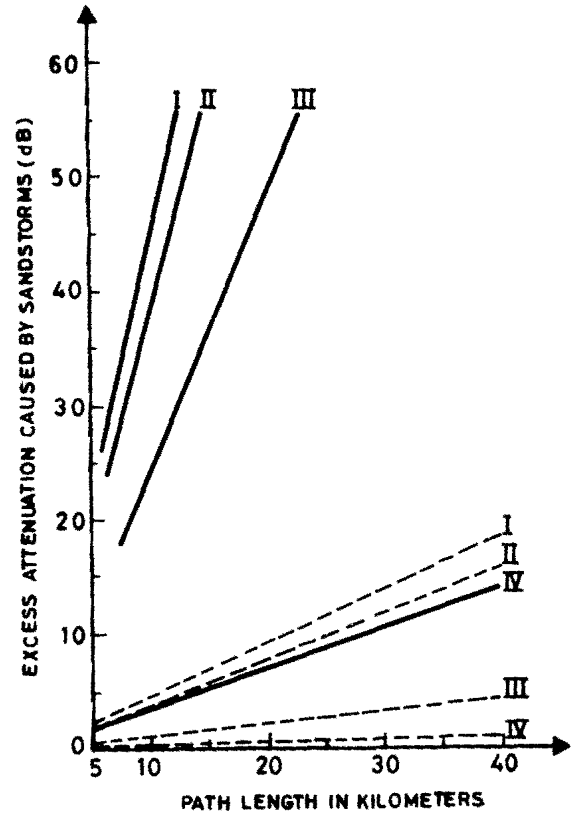

Fig. (1-c) Fade margin in dB vs. path length in kms for loamy fine sand at 37 GHz (Based on visibility 300 m).

—— a = 0.1 mm II) 10% moisture
---- a = 0.01 mm III) 5% moisture
I) 20% moisture IV) dry.

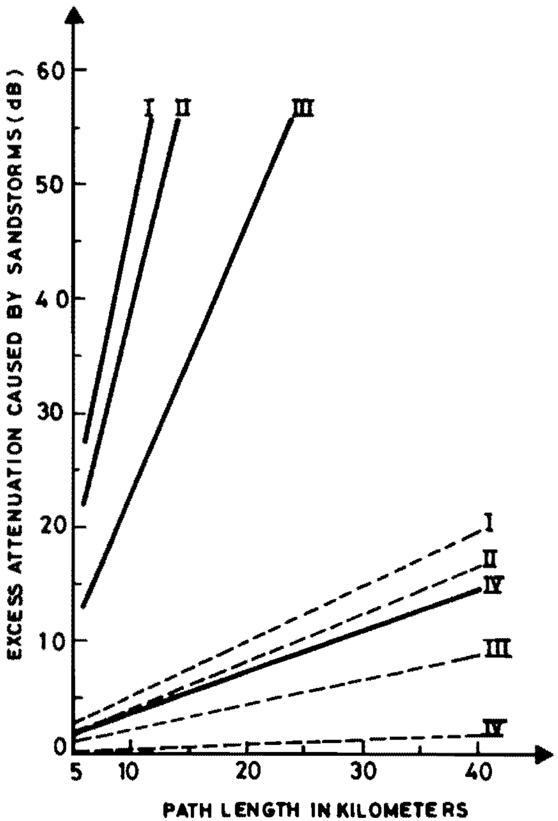

Fig. (1-d) Fade margin in dB vs. path length in kms for loamy fine sand at 37 GHz (Based on visibility 200 m).

—— a = 0.1 mm II) 10% moisture
---- a = 0.01 mm III) 5% moisture
I) 20% moisture IV) dry.

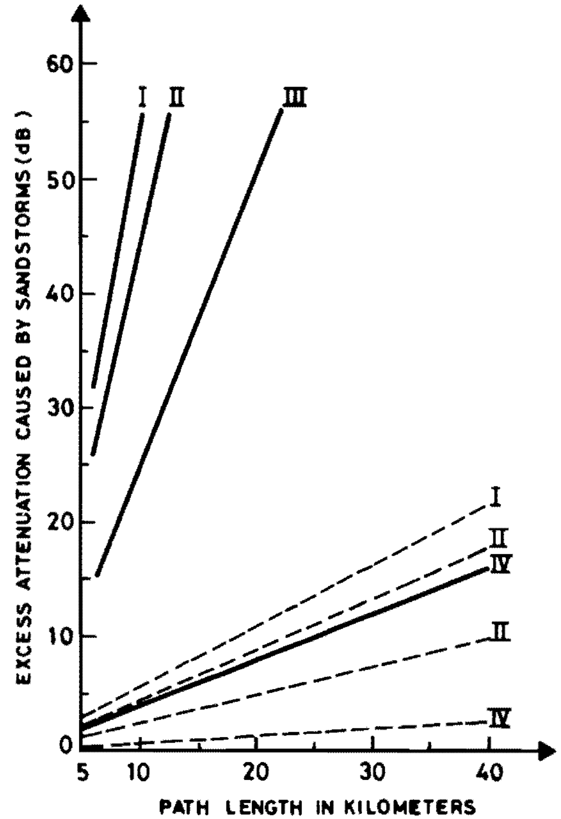

Fig. (1-e) Fade margin in dB vs. path length in kms for loamy fine sand at 37GHz (Based on visibility 100 m).

—— a = 0.1 mm II) 10% moisture
---- a = 0.01 mm III) 5% moisture
I) 20% moisture IV) dry.

Table 3. Relationship between system reliability and outage time.

Reliability %	Outage Time %	Outage time per Year	Month (Avg.)	Day (Avg.)
0	100	8760 hours	720 hours	24 hours
50	50	4380 hours	360 hours	12 hours
80	20	1752 hours	144 hours	4.8 hours
90	10	876 hours	72 hours	2.4 hours
95	5	438 hours	36 hours	1.2 hours
98	2	175 hours	14 hours	29 minutes
99	1	88 hours	7 hours	14.4 minutes
99.9	0.1	8.8 hours	43 minutes	1.44 minutes
99.99	0.01	53 minutes	4.3 minutes	8.6 seconds
99.999	0.001	5.3 minutes	26 seconds	0.86 seconds
99.9999	0.0001	32 seconds	2.6 seconds	0.086 seconds

Table 4. Average time of reduced visibility based on 10 years record for Riyadh city.

Visibility m	Outage Time %	Outage time per Year	Month (Avg.)	Day (Avg.)
500	0.4389	38.45	3.1 hours	6.4 minutes
400	0.28139	24.65	2 "	4.1 "
300	0.2374	20.8	1.7 "	3.5 "
200	0.1607	14.08	1.2 "	2.5 "
100	0.063	11.08	54.6 "	1.9 "

where both the reliability and outage are percentages of time in a year. Table 3 is a list of reliability vs outage which is included for the completion of the subject. The average time, of the ten years record, over which visibility was reduced is shown in Table 4 for various visibilities.

Based on Table 4 and the excess attenuation caused by various storm conditions shown in Figs. 1, we may construct a set of eight figures covering the various combinations of size and humidity conditions in a storm. Figs. (2-a) through (2-h) depict expected link reliability based on ten years visibility measurement in Riyadh. For a given fade margin, the maximum hop length can be determined depending on the knowledge of prevailing storm conditions (particle size and relative moisture content). On the other hand, the curves can be used to determine the required excess system gain (Fade Margin) which provides protection against sandstorms for a given hop length.

3. DISCUSSION AND CONCLUSIONS

The present analysis have assumed several simplifications regarding particle size, particle size distribution and complex dielectric constant. In order to check the validity of such assumptions, a field study is needed. The first field study, known to the author, which is done at millimetric waves for determinig the effect of sandstorms on propagation is now underway in Riyadh. Full description of the experiment is found elsewhere (Ali and Alhaider 1983 & 1984), however, the results of such study will not be known before few years. In order to enable more precise estimates of outage based on visibility data the following points are worthwhile mentioning:

1. A careful literature survey done by the author has revealed that the data available on the dielectric constant of sand and other types of soil is severely limited and conflicting. Besides, such data are only available up to 37 GHz, a fact that proves the need for further studies.

2. Although particle size is known since the work of (Bagnold 1973), particle size distribution during a

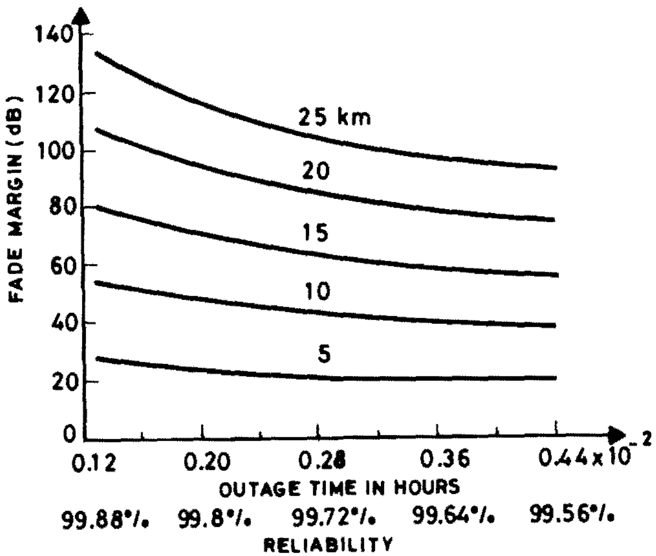

Fig. (2-a) Outage time in hours per year vs. Fade margin for 37 GHz paths of various length, for medium of 0.1 mm sand/dust particles and 20% moisture cont.

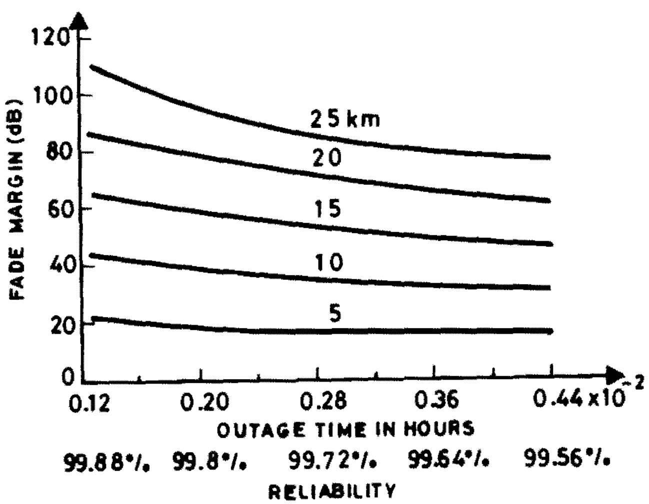

Fig. (2-b) Outage time in hours per year vs. Fade margin for 37 GHz paths of various length, for medium of 0.1 mm sand/dust particles, 10% moisture content.

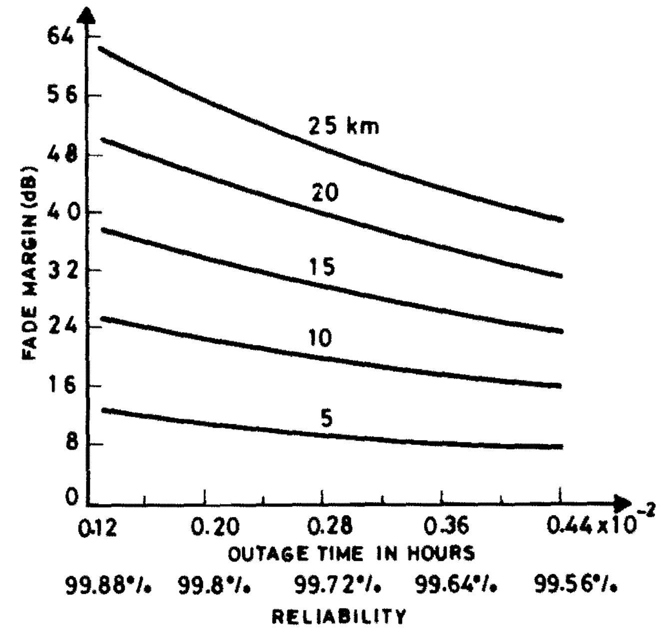

Fig. (2-c) Outage time in hours per year vs. Fade margin for 37 GHz paths of various length, for medium of 0.1 mm sand/dust particles, 5% moisture content.

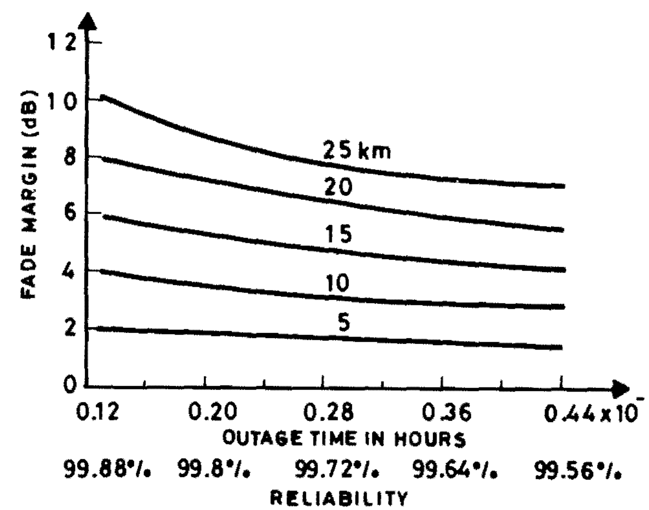

Fig. (2-d) Outage time in hours per year vs. Fade margin for 37 GHz paths of various length, for medium of 0.1 mm sand/dust particles and dry.

storm, is not known. Further, larger grains are not expected to rise as high as smaller particles, hence, size distribution is expected to vary with antenna height.

3. The estimated attenuation is directly proportional to the inverse of visibility, hence, accurate visibility record has to be kept for various places of the country. A standard method of measuring visibility has to be adopted, together with a proper resolution of few meters in stormy conditions.

4. In order to establish a complete system design at millimetric wave length, the excess attenuation caused by precipitation and multipath fading must be accounted for as well. For short hops, multipath fading is unlikely to affect system availability, however, such is not the case for arid land design with longer hops. The effect of rain cannot be completely ignored when transmitting at millimetric wave lengths in desert conditions. Although total rain fall per year is not worth mentioning in arid land, at least when compared to rain climate region 1 or region 2 (CCIR Report 1972), rain data for Riyadh city suggests otherwise (Middleton 1952).

5. From the present analysis, Fig. (2-d) shows that for the dry regions, long hops can be used with reliability objectives of better than 99.8% with moderate fade margins. In particular, Fig. (2-g) shows that with 5% moisture content and small particles of .01 mm, hop length of 25 km can be established with reliability of 99.9% with a 5 dB fade margin.

6. The variation of reliability with the particle size as shown in Figs. (2-a) to (2-g) suggests that the antenna height may be also considered as an important design factor. Lower antenna as subject will be affected by larger particles. On the other hand, higher antennas may enable longer hops. Again, all the above conclusions regarding link reliability assume the outage caused by sandstorms alone. Effect of rain, multiple path fading and equipment failure should be added for a complete system design.

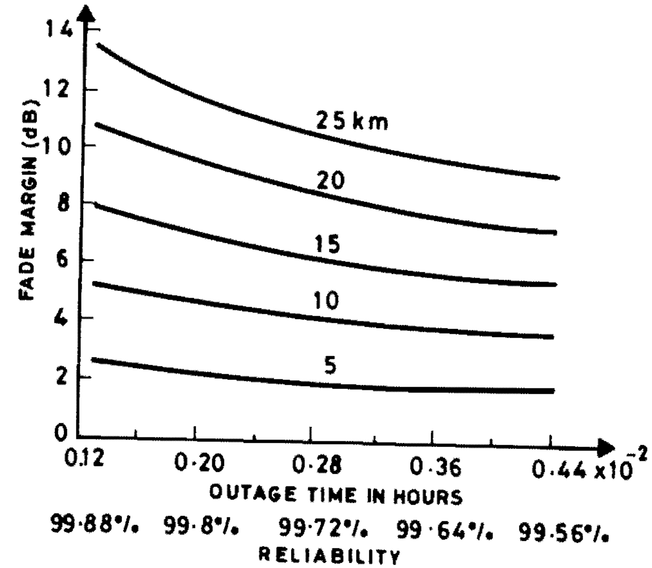

Fig. (2-e) Outage time in hours per year vs. Fade margin for 37 GHz paths of various length, for medium of 0.01 sand/dust particles, 20% moisture content.

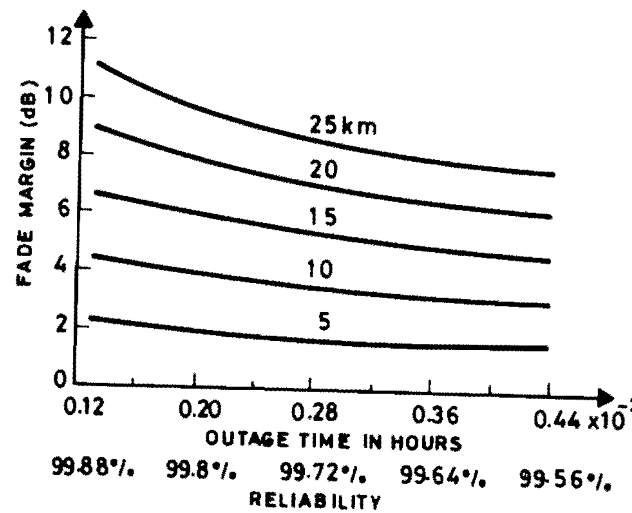

Fig. (2-f) Outage time in hours per year vs. Fade margin for 37 GHz paths of various length, for medium of 0.01 sand/dust particles, 10% moisture content.

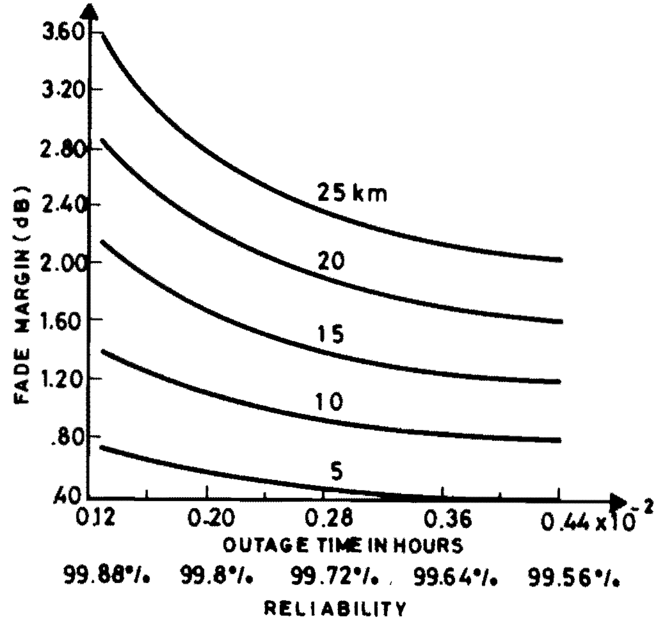

Fig. (2-g) Outage time in hours per year vs. Fade margin for 37 GHz paths of various length, for medium of 0.01 mm sand/dust particles, 5% moisture content.

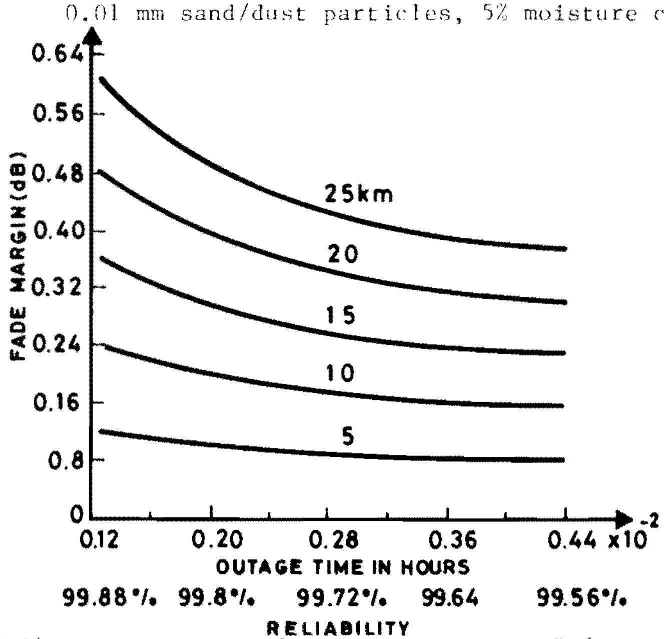

Fig. (2-h) Outage time in hours per year vs. Fade margin for 37 GHz paths of various length, for medium of 0.01 mm sand/dust particles and dry.

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