Effect of multipath fading on millimetre wave propagation: a field study

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Abstract: Analysis of clear air fading encountered on millimetric wave and infrared radio links are presented. The analysis is based on data obtained during a four-year field study in the city of Riyadh, Saudi Arabia. The region can be considered as a typical arid climate where the rate of evaporation is higher than the rate of precipitation. Maximum rain rate is of the order of 30 mm/h for 0.001% of the year. A brief description of the experimental setup is presented, together with the results of measuring clear air fading experienced by the radio links. Statistical characterisation of fading is given for both the millimetric wave links operating near 40 GHz and the infrared radio link at a wavelength of 0.88 μm. It is shown that fading is dominated by multipath, having a Rayleigh amplitude distribution and an occurrence factor similar to the microwave band. Fades were highly correlated for the two links sharing the same path and separated in frequency by 1%. Multipath fading was also measured on the infrared link. Even at the short hop length at 0.75 km, the occurrence factor was about 1%. Time duration of fades are also analysed, and fade durations were essentially exponentially distributed. Small fades, however, have normal duration distribution.

1 Introduction

The increasing demand for new services, coupled with the crowding of lower microwave bands, has promoted the research for new bands to meet such demand. The new frontier is the millimetric waveband which provides a potential for more services than all the lower radiobands put together. Unfortunately, shorter wavelengths are more attenuated by absorption and scattering from rain. Hence short hops of 3 to 5 km may be considered for climatic regions dominated by rain.

Saudi Arabia can be considered as a typical arid climate where the rate of evaporation is higher than the rate of precipitation. For most of the year rainfall is very little [1] and hence rain attenuation may not be the dominant propagation factor. Much longer hops may be feasible in arid climate, resulting in a lower cost and higher reliability. For longer hops, however, multipath and other clear air fading phenomenon may play a dominant role in link reliability. Together with rain attenuation and clear air fading, sand and dust storms result in a significant attenuation, especially when coupled with high humidity [2–4]. The results of measuring attenuation due to rain- and sandstorms are reported elsewhere [5–7]. In this paper we present results of measuring the effect of multipath fading on wave propagation at 40 GHz and near infrared.

2 Experimental system description

2.1 Path parameters

The geographical arrangement of the experimental links is shown in Fig. 1. The receivers are situated at the

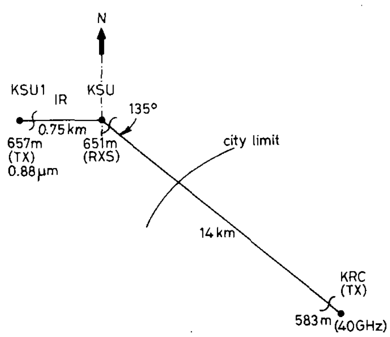

Fig. 1 *Geographical arrangement of experimental links*

College of Engineering, King Saud University (KSU). The transmitters are located at Khazan Residential Centre (KRC) 14 km distant at azimuth 135°, and at the maintenance building (KSU1) 0.750 km distant at azimuth 270°.

Path profiles along the links are shown in Fig. 2. The elevation angles are 0.029°, 0.3° for the KRC, and KSU1 paths, respectively. The KRC path is partly over open arid area and partly over an urban area of Riyadh city. The KSU1 path is over the KSU compound which is an

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open arid area. Path clearances are much larger than the first Fresnel zone at all frequencies, and everywhere.

2.2 Links and meteorological instrumentation

A block diagram of the experimental system is shown in Fig. 3. The system comprises: (i) a set of three transmission links, two millimetre wave (≃40 GHz) and one near infrared (0.880 μm) with different path distances of 14 km and 0.75 km, respectively; (ii) meteorological instrumentation situated at the receiving site; which includes dust passive collectors (DPC) and high volume samplers (HVS) at different heights above ground, along with dust particle-size analyser (PSA). Visibility reduction is measured using the near infrared link. A rainfall rate gauge (RRG) and meteorological station (MS) for the measurement of temperature (T), relative humidity (RH), windspeed and direction (WS, WD) and barometric pressure (P); (iii) a data collection and processing laboratory which includes a microcomputer (μc), tape (p), printer, data acquisition system (DAS), 40 GHz spectrum analyser (SA) with supporting hardware and multichannel recorder (MCR). The following is a brief description of the meteorological sensors used in the measurement.

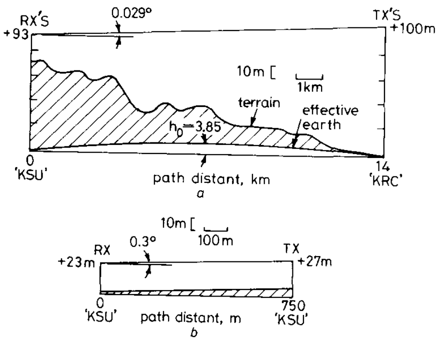

Fig. 2 *Paths profile*
a KRC
b KSU[1]

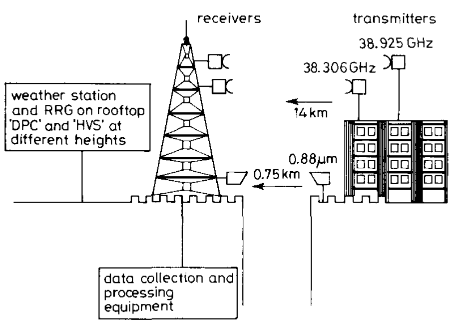

Fig. 3 *Block diagram of experimental system*

(i) The high volume sampler is an active dust collector which consists of an air motor/blower of constant air flow, a glass fibre filter, and a manometer. Dust/sand particles are collected and deposited on the filter. By measuring the air flow and particle mass, dust concentration can be calculated.

(ii) The particle-size analyser consists mainly of a sensitive (0.5 μg) electrobalance, sedimentation unit and a chart recorder. Particle-size distribution is calculated from the chart recorder of accumulated weight of settled particles and time using Stock's law.

(iii) The rain rate gauge is a fast response gauge with 1-minute integration time and photoelectric drop counter, corresponding to a precipitation rate of 100 mm/h. It has a collecting area of 300 cm^2 and a sensitivity of 0.0083 mm of rain drop.

(iv) The dust passive collectors are open top cylinders of specified size and material. They have the advantage of simplicity, and can collect the total settleable particles of sizes larger than the capability of active collectors.

2.3 Links parameters

Table 1 lists the basic parameters of the different links. In this Table the maximum fade (margin) is the difference between the normal received signal during clear atmosphere and the lowest usable signal approximately 3 dB above the receivers noise floor. No attempt has been made to air condition the transmitters and the receivers, but they are protected against solar radiation using sunshades.

The millimetre receivers are calibrated by radiating a calibration signal to the receiver antennas. Readings are made at 0.5 dB intervals over the AGC range from saturation to noise floor.

2.4 Data collection and processing system

The data collection and processing system is based on a microcomputer based real-time system. The system is

Table 1: Parameters of the link systems

Parameter Link	Hughes	NEC	IR
Transmitter frequency, GHz	39.306	38.925	0.880 μm
Transmitted power, dBm	+23	+10	+14.77
Transmitter	DRO and impatt	Impatt	Ga AlAs
Polarisation	Vertical	Vertical	Random
Antenna type	Cassegrain	Cassegrain	Fresnel lens
Antenna size, inches	9	14	6 × 6
Antenna gain, dB	35	40	—
beamwidth, °	2.5	1.6	0.17 divergent
Receiver type	SH	SH	Silicon avalanche diode
Radome	Kapton	No	glass
First IF, GHz	1.142	1.70	–
Second IF, MHz	300	70	–
Band width, MHz	42.5	35	40 nm
AGC range, dB	30	50	30

DRO: dielectric resonator oscillator.
SH: superhetrodyne.

built using an HP 9825B microcomputer, together with a 20-channel HP 3497A automatic data acquisition system. Among the main features of the system is the adaptive scanning mode which allows a scanning rate that varies with the speed of the sensed signals (down to 1 second is feasible). A database of the calibration tables of fade in dB, and the meteorological parameters in their physical values, are incorporated. Only significant information is stored on tapes to provide a source for further processing.

Multichannel recorders (12 channels) are also employed for recording the fade events and meteorological parameters as well as a backing up system. The radio system calibrations, adjustments and monitoring are carried out using the spectrum analyser (HP 8566A); and the associated signal generator (HP 8350A), frequency doubler (HP 940A) and harmonic mixer (HP 11970A).

3 Measured attenuation due to multipath fading

Fading of signal level over line-of-sight links strongly depends on the hop length, frequency, terrain and climate. For short hops, the probability of occurrence of deep fades becomes dimenshingly small. However, since an extended hop length at 10 to 20 km is possible for regions with rare rain activities, clear weather fading can affect the link reliability in a similar way as rain- and sand storms. Fade events were observed during the course of measurements with fade durations ranging from a fraction of a minute to several hours. The fade was repeated for hours with occasional enhancement, or scintillation or with power fading. Power fading is characterised by marked increase in the free-space signal level for extended time periods [8]. The shape of this fade indicates the possibility of multipath propagation due to atmospheric layer with strong refraction gradient or due to ground reflection. Table 2 shows the number of minutes during which fades exceed 1 to 16 dB per time of measurement and the different types of multipath fade. The average temperature and relative humidity during the period of occurrence of multipath fade events are also given. Months during which no events have been observed are omitted.

Table 3 presents the fade attenuation measured on the two radio channels operating at 39.306 GHz and 38.925 GHz and sharing the same path of 14 km length. Also shown is the fade attenuation measured on the 0.75 km–0.88 μm infrared link. From the fade data recorded by data acquisition system, and the chart recorder, it is observed that:

(i) Multipath propagation which is characterised by fast variations in amplitude more than 2 dB occurred during the period from midnight to noon time. Probably nonuniform distribution of temperature and relative humidity occurred in this time.

Table 3: Measured fade attenuation on various links between (1.3 and 15.12.1987) in Riyadh

Fade depth	Number of minutes of fade		
	Hughes (39 306 GHz)	NEC (38.925 GHz)	NIR (0.88 μm)
dB			
2	4800	4500	830
4	2000	3060	590
6	1200	1300	510
8	760	870	480
10	630	590	460
12	520	350	330
14	270	250	—
Total number of minutes	10180	10920	3200

(ii) Scintillation which is characterised by fast variations in amplitude not exceeding 2 dB occurred simultaneously with multipath fade. Signal enhancement and power fading are relatively rate.

(iii) The probability of multipath propagation is higher in winter (November to February) than in summer (March to June). This may be explained by the fact that the winter is characterised by relatively moderate temperature (of the order of 15°C) and high relative humidity (50 to 80%). On the other hand, summer is hot (25 to 48°C) but dry.

(iv) Fades experienced by the two channels at 39.306 GHz and 38.925 GHz are correlated. Simultaneous fades occurred for more than 77% of the time with fade depths differing by less than 20% on the average.

3.1 Fade occurrence factor

Based on three years of measurements, the average yearly probability of fading is calculated as 0.033 for the 14 km, 40 GHz links. The well known fading occurrence factor, used at microwave frequencies is given by Reference 9:

$$R = 2.5 \times 10^{-6} \times a \times b \times f \times D^3 \tag{1}$$

where R is the fade occurrence factor (probability of fading), f is the centre frequency in GHz, D is the hop length in miles and a, b are terrain and climate factors, respectively, given by

$a = 4$; 1; $\frac{1}{4}$ for very smooth (including overwater); average with some roughness; and very rough for very dry terrain, respectively.

Table 2: Number of minutes and type of multipath fading on the 40 GHz, 14 km links, in Riyadh, during 1987

Month	Time of measurement ×10³	Period of fade occurence	Average temperature	Average relative humidity RH	Number of minutes of fade events during which fade depth exceeds 1 to 16 dB			
					With scintillation	With enhancement	With power fade	Total number of minutes
	min		°C	%				
March	28.8	DN	14	78.0	735	–	–	735
April	43.2	MD	22.5	40.0	590	–	500	1090
May	28.8	DN/MD	29.5	33.0	740	–	–	740
June	28.8	DN/NS	25	26.0	500	–	–	500
November	43.2	DN/MN	16	50.0	1342	213	–	1555
December	44.64	MD	14	68.0	826	290	–	1116

DN: day period from dawn to noon.
MD: day period from midnight to dawn.
NS: day period from noon to sunset

$b = \frac{1}{2}; \frac{1}{4}; \frac{1}{8}$ for gulf coast or similar hot humid area; normal interior temperature mountainous or very dry, respectively.

For the 14 km links, operating at 40 GHz, an occurrence factor of $\simeq 0.03$ is calculated using the above expression with $a = 2$ and $b = 0.25$. Such values of a and b are the proper values for the path, and the measured occurrence factor (0.033) is fairly close to the calculated 0.03. Hence it seems that eqn. 1, which is well in use for microwave frequencies is still holding accurately at the extremely high frequency band (EHF).

3.2 Amplitude and duration statistics

3.2.1 40 GHz links: Table 4 presents the measured fade statistics based on the average of the two 40 GHz links

Table 4: Average value of measured fade attenuation: Riyadh (1986–1988)

Fade depth	Percentage of time fade depth exceeded		
	Rayleigh	40 GHz links	0.88 μm link
dB			
2	2	1.9	0.7
4	1.3	1.1	0.5
6	0.8	0.65	0.4
8	0.5	0.36	0.3
10	0.33	0.2	0.25
12	0.2	0.1	0.15
14	0.13	0.055	-

sharing the 14 km path. The data can be closely approximated (using least-square error algorithm) by an exponential or a normal law in the form

$$P(F) = 0.033 \exp(-0.284F) \quad F < 16\,\text{dB} \qquad R^2 = 0.97 \tag{2a}$$

or

$$P(F) = 0.033 \times 9.52 \exp[-0.0054(F + 20.43)^2] \quad F < 16\,\text{dB} \qquad R^2 = 0.98 \tag{2b}$$

where F is the fade depth in dB, $P(F)$ is the probability that a fade depth F is exceeded and R^2 is the correlation coefficient of the measured and the fitted laws.

It is also interesting to note that the experienced fade over the 14 km links can be approximated by a Rayleigh distribution in the form:

$$P(F) = 0.033 \times 10^{-F/10} \tag{3}$$

Fade duration is essentially of exponential distribution; however, small fade has a normal distribution of fade duration. The probability $Y(t)$ that fade duration exceeds t minutes is given by

$$Y(t) = \exp(-t/T_0) \tag{4}$$

where T_0, the average fade duration is an inverse linear function of fade depth in the form

$$T_0 = 5 + 37/F \quad F < 15\,\text{dB} \tag{5}$$

where T_0 and F are in minutes and dB, respectively, and the above equations were derived for the 14 km, 40 GHz, hop in Riyadh.

3.2.2 Near infrared link: Even for the short hop of 0.75 km operating at 0.88 μm wavelength, multipath fading was observed with an occurrence probability of about 0.01, one-third of the occurrence probability of multipath fading over the 14 km, 40 GHz links. Table 3 shows the measured attenuation for the infrared link. The data can be represented by an exponential or a log-normal distribution and the yearly average probability $P(F)$ of a fade depth in excess of F dB is

$$P(F) = \exp(-0.15\,F) \quad F \leqslant 12\,\text{dB} \tag{6}$$

Fade duration for fade depths of 3, 5, 7, 9 and 11 dB occurred with an exponential distribution of about 10 minutes average duration, hence the probability that a fade duration exceeds t minutes is written as

$$Y(t) = \exp(-t/10) \tag{7}$$

From the measurements of multipath, it has been observed that multipath propagation occurred during the period from midnight to noon time, probably nonuniform distribution of temperature and relative humidity occurred in this time. Scintillation occurred simultaneously with multipath fading. Signal enhancement and power fading were relatively rare.

4 Conclusion

A field study aimed at studying the propagation of millimetric waves in aridland was under way in the city of Riyadh for a period of four years. The paper presented the results of measuring signal attenuation caused by multipath fading at 40 GHz and near infrared frequencies during 1987. Various meteorological parameters were measured simultaneously and analysed statistically. The essence of the results can be summarised as follows:

(i) Multipath path fading was experienced by the 40 GHz links during the experiment. It is interesting that the Raleigh amplitude distribution and the well known occurrence factor for the microwave band [eqn. 1] still hold accurately at 40 GHz.

(ii) Even at the short hop of 0.75 km operating at near infrared frequency, multipath fading was experienced. Fade amplitude and duration statistics are given for both the 40 GHz and the infrared links.

Although reliability and outage analysis are not included in this paper, such analysis can be easily pursued based on the complete statistics of rain attenuation, sandstorms, rain and multipath fading may play equally important roles in determining the link reliability for the long hops in arid climate.

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