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Experimental Studies of Terrestrial mm-Wave Links– A Review. Part 2: Fading, Diversity and Data Processing

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This is the second part of the study intended for reviewing the major experimental works in mm-wave propagation. In the first part, effects of atmospheric particles and gases were presented. In this part, multi-path fading and depolarization experiments are described. Experimental studies of diversity improvement are dealt with as well. A note on the various methods of processing the propagation and meteorological data is given, followed by an outline of some areas where further experimental work is needed. Seven tables summarizing the major experiments are also included in the two parts.

1. Introduction

In the first part of this study [1], the measured parameters were given. Free space attenuation, and effects on propagation of fog, cloud and snow were described briefly. Attenuation due to rain was presented in detail, together with sand, dust and scintillation.

In this paper, experimental work on multi-path fading and depolarization is presented. An improved system reliability by utilizing diversity techniques is described. Various aspects of data processing used in these experiments are presented, followed by a mention of some areas of needed studies.

2. Multi-path Fading

The design and the transmission performance of terrestrial line-of-sight microwave radio paths are greatly influenced by two clear-air propagation phenomena, obstruction and multi-path fading. Both types of fading are caused by anomalous stratification of the atmosphere. In the case of obstruction fading, atmospheric stratification temporarily changes the transmission path to such an extent that it becomes blocked by the terrain. In the case of multi-path fading, a different type of atmospheric stratification temporarily creates multiple transmission paths that cause destructive interference of a number of waves at the receiving antenna. Multi-path fading (MPF) caused by ground reflection is frequency dependent, whereas in the atmospheric fading, caused by refractive bending in the atmosphere, a wide band of frequencies tend to fade simultaneously.

Several experimental studies aimed at studying both or either types of fading were reported. Allen *et al.* [2] studied the atmospheric-induced fading on 23 km links at 9.6, 11.4 and 28.8 GHz near Boulder, Colorado. A movable carriage on a 300 m tower enabled the measurement of signal strength and refractive index as a function of height. The transmitter terminals were located on the carriage, and the purpose of the experiment was to determine the mechanisms which cause signal fading. Ground reflection and diffraction and atmospheric ray bending were found to be mechanisms which caused the clear air types of fading observed. It was found that ground multi-path was the most common type of fading. Atmospheric ray bending events were rare.

Tattersall *et al.* [3] used a stepped frequency test signal, instead of frequency sweeping, to detect MPF by measuring received signal level variation with frequency. Different analogue and digital fade simulators were used in the study which took place near Mendlesham, UK using various frequencies at 11, 20 and 37 GHz and various hop lengths of 4, 8, 16 and 23 km. No fades of duration greater than one nanosecond were detected.

Stephensen *et al.* [4], used frequency swept signal in the frequency band 13.5–15 GHz to obtain results on fade durations. A horizontally polarized carrier, frequency modulated by a 10 MHz tone, was transmitted over a 44.7 km near Copenhagen during August 1974–77. Differential gain and differential fade measurements were carried out to identify MPF parameters. They concluded that:

$$p \propto L^2, \tag{1}$$

$$t \propto L^{2/3}, \tag{2}$$

$$N_0 \propto L^{4/3}, \tag{3}$$

where p is the probability of fade, L is the received signal level, t is the average fade duration, N_0 is the number of fades and α means proportionality.

Babler [5] experimented with a 6 GHz link at Palmetto, Georgia in the summer of 1971. Over a base band of 33 MHz he measured the magnitude and phase of 62 tones and used the data to model the MPF phenomena.

Inoue and Sakagami [6] used frequency swept measurements to study overwater propagation of 18–22 GHz signal. During summer and autumn periods of 1970–71, a 16 dBm vertically polarized signal was transmitted and received between two parabolic antennas 1.8 m diameter with 45 dB gain. They obtained results for the variations of the received signal due to duct-type fading, multi-path fading and possible frequency diversity improvements. Similar observations were made at both SHF band [7] and the EHF [8].

Sandberg [8] devised a computerized method of obtaining MPF parameters from swept measurements of amplitude and phase. The measurements were carried out for a 75 km link at a frequency of 13.5–15 GHz near Copenhagen. The frequency swept measurements were used by Crawford and Jakes in 1952 for a 4 GHz system [7] and by Kaylor in 1953 [9] in 1966; all of these experiments were aimed at modelling MPF using two or more rays.

Barnett [11] monitored the received signal level for 4, 6 and 11 GHz links of 40 km in Ohio during summer 1971. He established the interesting frequency dependence relation of fade probability in the form

$$P = rL^2; \tag{4}$$

$$r = c \cdot \left(\frac{f}{4}\right) \cdot D^3 \times 10^{-5} \tag{5}$$

where P and L are the probability and signal level, respectively, f is the frequency in GHz and D is the path length in miles. The parameter c is chosen as

$c = 4$: for very smooth terrain, including overwater.

$= 1$: for average terrain with some roughness.

$= \frac{1}{4}$: for mountainous, very rough, or very dry.

A summary of the multi-path fading experiments is given in Table 1.

3. Depolarization

Many terrestrial analogue radio systems are employing orthogonal diversity on adjacent channels to minimize RF interference. Some digital radios are using orthogonal polarization on the same frequency to improve spectrum utilization. Adequate cross-polarization isolation (XPI) must be maintained between the cross-polarized channels. A major limiting factor to the reliability of operation, however, is the deterioration of XPI caused by propagation effects. Several papers reviewed the subject of XPI during clear air and precipitation conditions [12]; our treatment is intended for mm-wave propagation on terrestrial links.

Table 1. Multi-path Fading Measurements

Author	Path Length (km)	Frequency GHz	Main Results
Allen [2]	23	9, 11, 26	Ground MPF is the most common type. Atmospheric MPF is a rare event
Tattersall [3]	4, 8, 16, 23	11, 20, 37	Fade duration <1 nsec was only detected
Stephansen [4]	44.7	13.5-15	(i) Fade prob. $P \propto L^2$; (ii) Fade duration $\bar{t} \propto L^{2/3}$; (iii) Fade no. $N_0 \propto L^{4/3}$. L received level voltage
Ho [10]	4.1	36, 110	Atmospheric MPF caused scintillation of ~1.3 dB on 37 GHz and 3 dB on 110 GHz
Sanberg [8]	75	13.5-15	Obtained atmospheric MPF parameters from frequency swept measurement of amplitude and phase
Barnett [11]	40	4, 6, 11	Established frequency dependence of amplitude with fade probability $P = rL^2$; $r = C(f/4)D^3 \times 10^{-5}$
Babler [6]	37	6	Sampled the amplitude and phase of 62 coherent tones to identify linear and quadratic fades as detected from linear and quadratic amplitude distortion

Ghobrial and Watson [13] in 1971 reported measurements on a 13.6 km link in UK at 11 GHz using a cutler-fed paraboloid with 45° cross-polar lobes 22 dB below the maximum co-polar level. They concluded that care should be taken in the choice of antenna for dual polarization transmission since some antennas, such as cassegrain, have a better performance.

Turner [14] in 1972 investigated the effects of variations in the refractive index, precipitation and wind on a system transmitting two orthogonal linearly polarized signals over the same path at the same frequency. A 4 km link at Mendlesham, UK was used to transmit a 22 GHz signal. His results indicated that depolarization due to rain on the 4 km path will not cause problems and that multi-path fading (MPF), together with water drops on the radome will cause depolarization.

Watson *et al.* [15] experimented on a 13.6 km link on Bradford, UK during 1974-75 where 36 GHz signals were transmitted at both horizontal and vertical polarizations. They found that attenuation was the dominant cause of outage and not depolarization.

Neves and Watson [16] used the same link at Bradford during March-August 1976, transmitting at an angle of 45° and receiving the vertical and horizontal polarization components. They concluded that measurements of differential phase at this frequency are extremely sensitive to the drop size distribution of rain.

Butler [17] presented results for two 16 km adjacent paths in Ottawa at 17 GHz which suggest that cross-polarization induced by refractive bending of the single direct wave is less serious than that caused by multi-path.

Lin [18] obtained experimental data describing the statistics of signal depolarization during MPF. The experiment was conducted near Atlanta, Georgia and included reception of 6 GHz and 11 GHz signals on two paths of 42 and 25 km.

Valentin [19] in 1980 estimated instantaneous values of XPI for a 20 km path at 18.8 and 28.8 GHz using: 1) Integrated point rain rate measurements from a dense rain gauge network and 2) simultaneous measurements of the mean vertical wind velocity gradient.

Virtually, all experiments have indicated that rain is the most significant form of precipitation causing the reductions in cross-polarization discrimination (XPD) observed on terrestrial paths. The major factors contributing to this depolarization are the non-sphericity of falling rain drops and their tendency towards alignment in one direction (canting angle). On short links, rain is the dominant cause of outage due primarily to cross-polarization interference, and that on long links, multi-path is the dominant cause. The smallest path length for which multi-path effects dominate will depend on the frequency, climate and the type of terrain (e.g. water, flat, mountainous). A summary of the cross-polarization experiments is given in Table 2.

Table 2. Cross Polarization Measurements

Reference	Frequency GHz	Path Length km	Polarization	Main Results
Ghobrial and Watson [13]	11	13.6	Switched V & H	Careful choice of antennas for dual polarization is necessary for improved cross-polarization regetion
Turner [14]	22	4	H & V	1. Depolarization due to rain is not serious 2. MPF and water drops on the radome will cause depolarization
Watson *et al.* [15]	36	13.6	H & V	Attenuation is the main cause of outage and not depolarization
Neves and Watson [16]	36	13.6	TR45°, Rec. V & H	Measurement of diff. phase at this frequency is extremely sensitive to variations
Butler [17]	11, 17	16	H & V	Cross-polarization induced by refractive bending is less serious than that caused by MPF
Valentin [19]	18.8, 28.8	20	V	Determined canting angle parameters from measurements of differential phase
Lin [18]	11.6, 6 11.46	42.5 25.6	V V	Obtained statistics of depolarization during MPF

H: Horizontal
V: Vertical

In connection with cross-polarization discrimination (XPD), it is useful to report the following semi-empirical formula, $XPD = (XPD)_0 + 20 \log (f) - 20 \log (A) - 40 \log \cos \theta_{er} + I(\tau) \pm \Delta A/2$, [20], where f = frequency in GHz; A = attenuation in dB; θ_{er} = elevation angle in degrees; $I(\tau) = -20 \log 2 \sin (/\phi - \tau/)$; $\phi(\simeq 0)$ is the mean canting angle and τ is the polarization tilt angle; both $I(\tau)$ and ΔA vanish for circular polarization; for linear polarization, $I(\tau) = -10 \log 0.5[1 - \cos (4\tau) e^{-0.0024}\sigma_m^2]$, with $\sigma_m = 3°$, ΔA is the differential attenuation between quasivertical and quasihorizontal polarizations; $(XPD)_0 = 8.5 - 0.0053\sigma^2$, σ = standard deviation. It is also interesting to compare this formula with the CCIR approximate formula, namely: $XPD = 30 \log (f) - V \log (A) - 40 \log (A) - 40 \log \cos (\theta_{er} + 0.0053\sigma^2 + I(\tau))$. With special attention to frequency dependence, where

$$V = 20, \qquad 0 \leq f \leq 15 \text{ GHz},$$

$$V = 23, \qquad 15 < f \leq 35 \text{ GHz},$$

$$I(\tau) = -20 \log 2 \sin (/\phi - \tau/).$$

Although the empirical formula is for earth-space paths, it is helpful in terrestrial mm-wave links.

4. Diversity Improvement

Diversity reception as used in the SHF band with line-of-sight links tended to reduce depth of fades on combined outputs and improve signal-to-noise ratio S/N, when proper combiners are used. Diversity reception is based on the fact that radio signals arriving at a point of reception over separate paths may have uncorrelated signal levels. The separation of paths may be in frequency, space (including angle of arrival and polarization), time and path (signals arrive on geographically separate paths). The most common forms of diversity in radiolink systems operating in the SHF band are those of frequency and space. Diversity reception may be of aid in the millimetre wave band as well. However, due to the fact that rain fading is considered 'flat' (i.e. it is power or attenuation type fading), the usual frequency and/or space diversity employed at lower microwave frequencies would not work in this case. Route or path diversity has generally been considered as the proper type of diversity protection against outage caused by rain. Still, for dry regions, where outage due to rain is not the dominant factor in the link design, other types of diversity may be worthwhile considering.

Dougherty [21] experimented with a 400 Mbits/sec quadriphase shift-keyed system operated at 13.3 and 14.9 GHz over a 22.8 km line-of-sight path. Signals received on two antennas vertically separated by 4 m were monitored at intermediate frequency (IF) using a spectrum analyser and at baseband (BB) by counting bit-error-rate (BER). Two frequencies where transmitted, 13.3 and 14.9 GHz, to investigate possible frequency diversity improvement. Both the IF spectra and the meteorological measurement showed the occurrence of atmospheric MPF. The test results indicated that either space or frequency diversity could reduce the bit error due to MPF, if properly implemented.

Chamberlain *et al.* [22] experimented with two links at 18 GHz over west London during an extended period of ten years starting in 1962. A common receiver and two transmitters separated by about 10 km were used to investigate the improvement of route diversity for protection against deep fading caused by rain attenuation. It was concluded that deep fades rarely occur simultaneously over the two paths and this was attributed to the different orientations of the links with respect to the direction of the prevailing wind [23]. It was also concluded that doubling the hop length is possible if route diversity is employed.

Harden *et al.* [24] obtained results for a network of 33 links at Mendlesham, UK during a three year period of observation from 1973–75, which coincided with a total rainfall slightly less than the average. The aim was to investigate possible diversity improvement (defined as the ratio of outage probability without and with diversity) for excess rain attenuation at frequencies of 22 and 37 GHz on parallel paths. The link lengths varied from 2.8 to 12.3 km with nominal spacing of 4, 8 and 12 km between paths. Parabolic antennas with 60 cm diameter having 38 and 43 dB gains at 22 and 37 GHz, respectively, were used. Transmitter powers of 3 dBm and receiver noise figures of 10 dB enabled a minimum resolvable level of −103 dBm. They concluded that diversity improvement increases as the path separation increases from 4 to 8 km, but there was no further significant improvement as the separation was increased from 8 to 12 km.

Christensen and Mogensen [24], in their frequency sweep set up in Denmark, measured various propagation parameters with variable (swept) frequency between 13.5 and 15 GHz over a 44.7 km link. They considered the possibility of utilizing frequency diversity for protection against ducting and multi-path propagation. Precipitation has been excluded in order to make the results usable at lower frequencies. They observed that virtually no gain was obtained by using frequency diversity of up to 280 MHz frequency difference when precipitation is the dominant cause of fading.

Sasaki and Nagamune [25] conducted propagation tests on 13 tandem links, described therein in Section 2.2.4, in Japan, using vertically polarized 19.9 GHz signals, to measure attenuation due to rain. They examined the enlargement of hop length obtained through route diversity and concluded that an enlargement of about 3.3 was obtainable at a route separation of 20 km (enlargement of hop length due to diversity may be defined as the ratio of hop lengths with and without diversity at a given link reliability).

Table 3 summarizes the above diversity experiments.

Table 3. Diversity Measurements

Reference	Frequencies GHz	Type of Diversity	Freq. Sep. GHz Antenna Sep. mt	Path Length km	Main Results
Dougherty [21]	13.3, 14.9	S, F	4 mt	22.8	Either S or F, if properly implemented, can reduce errors due to MPF
Harden *et al.* [23]	22, 37	R		4, 8, 12	Diversity improvement increases as the path separation increases from 4→8 km but no further significant improvement as it increases from 8→12 km
Chamberlain *et al.* [22]	18	R		8.2 and 8.9 and TRS at 10 km	Path diversity provides protection against deep fade caused by rain. Doubling hop length is possible with path diversity
Christensen and Mogensen [24]	13.5–15	F	0.28 GHz	44.7	Frequency diversity up to 280 MHz difference did not offer any improvement against rain-fades and multi-path propagation
Sasaki *et al.* [25]	20	R		13 hops with average length 4.6	Path diversity can provide reliability improvement against outage caused by rain. The path length enlargement effect is a consequence of the route diversity effect.

F: frequency diversity, S: space diversity, R: route

5. Data Processing

In mm-wave experimental systems, simultaneous measurements are taken for signal parameters as well as various nearby meteorological observations. The data obtained from the weather station and from the radio links are then processed to correlate various propagation phenomena and meteorological parameters. Figure 1 shows the common steps usually adopted by most of experimental systems. The equipment used in processing the data are given in Table 4.

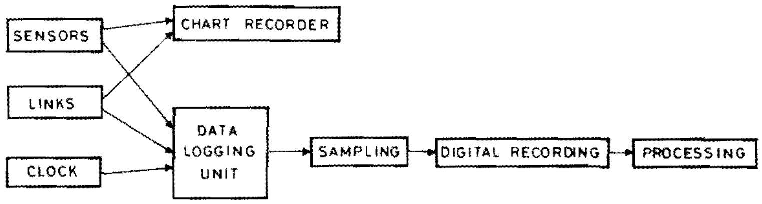

Fig. 1: Block Diagram of Common Experimental Systems.

i) *Analogue-Digital Recording*

Besides recording on a paper chart, data may be also recorded on magnetic tape in their analogue form or digital form [26]. The analogue signal could be served for transmission on the transmission line [26] or for obtaining rapid fluctuations of the received signal [27]. This signal may be digitized for later processing on a digital computer.

ii) *Sampling Rate*

Although different sampling rates were considered, radio data are usually sampled at 1 min intervals or less. Slower sampling rates are usually employed for the meteorological data collection.

iii) *Data Recording*

Data are usually recorded on a continious basis or on a semi-continuous basis, or when important events are detected. In continuous recording, the recording rate

Table 4. Data Processing

Authors	Recording	Sampling	Equipment
Hewitt *et al.* [28]	Magnetic tape— slow (every 5 min.) fast (every 1 sec.)	One per sec.	Small digital computer
Norbury *et al.* [29]	Paper tape	Over 10 sec. intervals	Data logging unit
Robinson *et al.* [30]	Paper tape— floppy disks	10 sec.	Microprocessor of 48K-RAM, microcomputer
Watson *et al.* [15]	Magnetic tape	1 min.-10 sec.	Data logger—on line computer
Davies [26]	Magnetic tape— paper tape	Once per minute	Data-logging system, computer
Gunn [31]	Cassette tape, disk file	30 sec.	Microprocessor
Fujita *et al.* [32]	Magnetic tape	200 msec. (for radio) 1 min. (for meteo.)	Data acquisition computer, main computer system

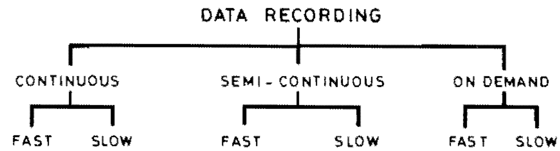

Fig. 2: Modes of Data Recording.

is the same as the sampling rate, and sometimes less, for instance when data are sampled every second but recorded every minute. The first is called a fast mode of recording [15, 28], and the latter is called a slow mode of recording [28].

In semi-continuous recording, data are collected continuously over a period of time during an hour, or a day, and then not collected during the remaining period. It is more economical to collect data whenever important events occur [26], as data collected otherwise have no meaning. Therefore, data recording can be summarized as shown in Fig. 2.

The medium of recording is usually magnetic tape, cassette tape, or punched paper tape. Floppy disks are sometimes used for long-term storage.

iv) *Data Processing Equipment*

According to the purpose of use, equipment may be divided into:

a) data acquisition controller usually included in order to have good performance of the experiments. It is used for collecting, storing, sampling and recording radio or meteorological data.

b) a computer used in processing the sampled and digitized data in real time mode. However, in non-real time processing, the recorded data are used for later analysis by the computer.

Many authors use two different devices, one for collecting data, and the other for processing such data. However, some others [30] use the computer as a controller as well as a processor to control the whole system and manipulate received signals.

6. Some Areas of Needed Measurements

Although a sizable amount of results have been reported, further studies are still needed to unveil the properties and to determine the optimum design strategies of new radio bands. Some aspects of the propagation properties and design criteria have been emphasized more than others; rain attenuation is an example. However, little experimental work has yet been done on fading rate and information capacity at mm-wave lengths. Both wide band FM and high capacity digital systems should be considered. In order to improve our understanding of the propagation at mm-wave band there is a need for:

1) Measurements of diversity advantage for line-of-sight terrestrial links. Such measurements are extremely costly; consequently there have been few studies resulting in little data at present.

2) More experimental information is required to characterize the relative effects of rain and multi-path depolarization under various conditions. More experimental information on the relative importance of cross-polarization during multi-path and precipitation conditions is required.

3) Direct measurement of rain drop shape and canting angle characteristics, particularly during the turbulent conditions on an actual path. Simultaneous indirect measurement of path averaged 'instantaneous' canting angle parameters from model orientated transmission experiments and direct measurement of wind gradient, speed and direction are also needed.

4) Relative importance of the depolarization mechanisms during clear-air condition should be investigated under various path conditions and with different types of antenna.

The design of mm-links for arid-land weather conditions should also be considered. While precipitation is considered as the main offender of propagation at EHF in most places of the world, such is not the case for dry regions with very little rainfall. Different design concepts may be adopted for arid land conditions, which may result in much longer hops, wider bandwidth and/or different types of diversity protection. To explore such possibilities, many clear-air studies are required such as 1) investigation of the small-scale structure of the atmospheric refractive index variations and its relation to meteorology and to radio wave propagation, 2) investigation of the variation of propagation reliability with hop length for various weather regions (dry, humid, over water, etc.), 3) examination of various types of diversity improvement and to study bandwidth limitations.

7. Conclusions

A review of recent experimental progress in the study of mm-wave propagation has been presented. Much of the emphasis has been given to various mechanisms of losing signal power loss due to absorption, interaction with atmospheric particles, depolarization and fading. Improving system reliability using diversity has been treated as well. A summary of methods of data processing, together with an outline of areas requiring further studies, has been given.

Although much progress has been achieved recently in the study of mm-wave propagation, some aspects are left unclear. Free space attenuation and attenuation due to rain, for example, have received a sizable attention, whereas effect of sand and similar particles on propagation is not fully understood to date. The relation between hop length, rain attenuation and multipath fading is not clear. The maximum usable bandwidth as well as the use of dual (orthogonal) polarizations are areas where further work should also be carried out. Short hop concept adopted for temperate climates may not apply to dry areas with little rainfall. This has to be examined as well.

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استعراض للدراسات الميدانية عن وصلات الراديوم الملليمترية الأرضية
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عادل علي ، محمد حسن و محمد الحيدر
قسم الهندسة الكهربائية ، جامعة الملك سعود ، الرياض ، المملكة العربية السعودية

هذا هو الجزء الثاني من ورقة علمية تهتم بمراجعة التجارب الرئيسية في مجال انتشار الموجات الملليمترية . في الجزء الأول استعرضنا دراسة تأثير العوالق الجوية والغازات . وفي هذا الجزء سنصف تجارب تهتم بتعدد المسارات وعدم الاستقطاب . كما نستعرض الدراسات التجريبية التي تهتم بتحسين التنوع ، وكذلك نستعرض الطرق المختلفة لمعالجة الانتشار والمعلومات المناخية . يلي ذلك موجز لبعض المجالات التي تحتاج الى دراسة أكثر . ويشمل الجزئين سبعة جداول توضح التجارب الرئيسية .