Polarization Diversity in Mobile Communications

RODNEY G. VAUGHAN, MEMBER, IEEE

Abstract—**Signals in the vertical and horizontal polarizations at the base station have been measured by transmitting from a principally vertically polarized mobile. There was no direct line-of-sight path between the mobile and base. The envelopes were uncorrelated and the means differed by 7 dB and 12 dB when the mobile was in urban and suburban areas, respectively. The discussion of the results includes theoretical curves showing the relationship between the envelope correlation coefficient and the mean levels difference of Rayleigh distributed signals in orthogonal linear polarizations at the base station. The variable parameters are the rotation angle of the base station antenna and the cross polar discrimination of the incident fields.**

I. Introduction

POLARIZATION diversity seems to have received disproportionately little attention in the literature. Lee and Yeh's [4] polarization path diversity proposal was the first step in this direction, but the idea of using just one transmit antenna at the mobile and receiving orthogonal polarizations at the base station was not considered. Kozono *et al.* [3] measured linear polarizations at a ±45° orientation, received from a vertical dipole antenna on a mobile in Tokyo. Their base station antenna was variable in the sense that the arms could rotate in opposite directions, from both arms lying in the horizontal plane to being orthogonal to each other at ±45°; they also accounted for the azimuthal dependence. Herein, base station elements that are always orthogonal and rotatable together are considered. The measurements described are confined to a vertical-and-horizontal configuration. The azimuthal dependence is not considered: incident signals are assumed to be broadside to the plane of the antenna. Preliminary results were published by Vaughan and Bach Andersen [8]. Bergmann and Arnold [1] have also discussed measurements for (handheld) polarization diversity. The aforementioned publications seem to be the only ones that regard polarization diversity. This is surprising, considering the advantages and simplicity of the scheme.

At the base station, space diversity is considerably less practical than at the mobile because the narrow angle of incident fields calls for large spacings of the antennas. For example, Lee [5, p. 201] notes that for an azimuthal angle width of sources of 0.4° and an envelope correlation coefficient of 0.7, base station antennas must be spaced by 25 wavelengths for the broadside propagation case and well over 100 wavelengths for the in-line propagation case. The high cost of space diversity at the base station prompts the consideration of using orthogonal polarizations. This may permit only two diversity branches (without resorting to antenna spacing), but it does allow the antenna elements to be colocated. Currently, there is considerable interest in many-branched diversity at the base station motivated by the potential for reduced interference. Glance and Greenstein [2] discuss six branches, for example. If the polarization diversity scheme can be made to work, then the physical extent of base station diversity antennas is halved relative to conventional space diversity.

At the mobile, use of orthogonal polarizations only to produce diversity branches has not been very successful. Measured horizontal and vertical polarization paths between a mobile and a base station are reported to be short-term uncorrelated by Lee and Yeh [4]. Their mobile polarization diversity antenna consisted of colocated vertical electrical and magnetic (implemented as a horizontal wire loop) elements sited 1.5 λ above the vehicle's conducting roof. The presence of the vehicle roof gives rise to an array pattern, which is discussed in the appendix. For an infinite, perfectly conducting groundplane, it turns out that the array patterns alone are sufficient to decorrelate the signals received by the mobile antenna elements.

The mechanism of decorrelation for the signals in each polarization is the multiple reflections undertaken between the mobile and base antennas. The reflection coefficient for each polarization is in general different (cf. Fresnel's formulas), which results in the phases of orthogonal polarizations undergoing different changes for each (or at least some) of the reflections. The path of the signal occupies three dimensions and includes reflection and refraction, which causes coupling between orthogonal polarizations. After sufficient random reflections, the polarization state of the signal will be independent of the transmitted polarization. This is ideally what happens to signals propagating through an urban environment. In practice, and as noted from the measurements of Lee and Yeh, there is apparently some dependence of the received polarization on the transmitted polarization, even in urban environments. The multiple scattering cannot be sufficient for a given polarization to decouple half its power into the orthogonal polarization. Still, an antenna at the mobile need not be of pure polarization (in fact, achieving true polarization purity from an antenna mounted on an average car would be virtually impossible). A sloping monopole and the roof-mounted circular patch antenna [7] offer some possibility of designing for a given (approximate) ratio of radiated polarizations. However, this may not be necessary to get a considerable return from a polarization diversity system.

There are too many unknowns regarding the propagation from the mobile to the base station to establish from theoretical considerations how well a polarization diversity sys-

Manuscript received August 16, 1986; revised February 1990.

The author is with the Department of Scientific and Industrial Research, Physics and Engineering Laboratory, Gracefield Road, Gracefield, Private Bag, Lower Hutt, New Zealand.

IEEE Log Number 9035261.

0018-9545/90/0800-0177$01.00 © 1990 IEEE

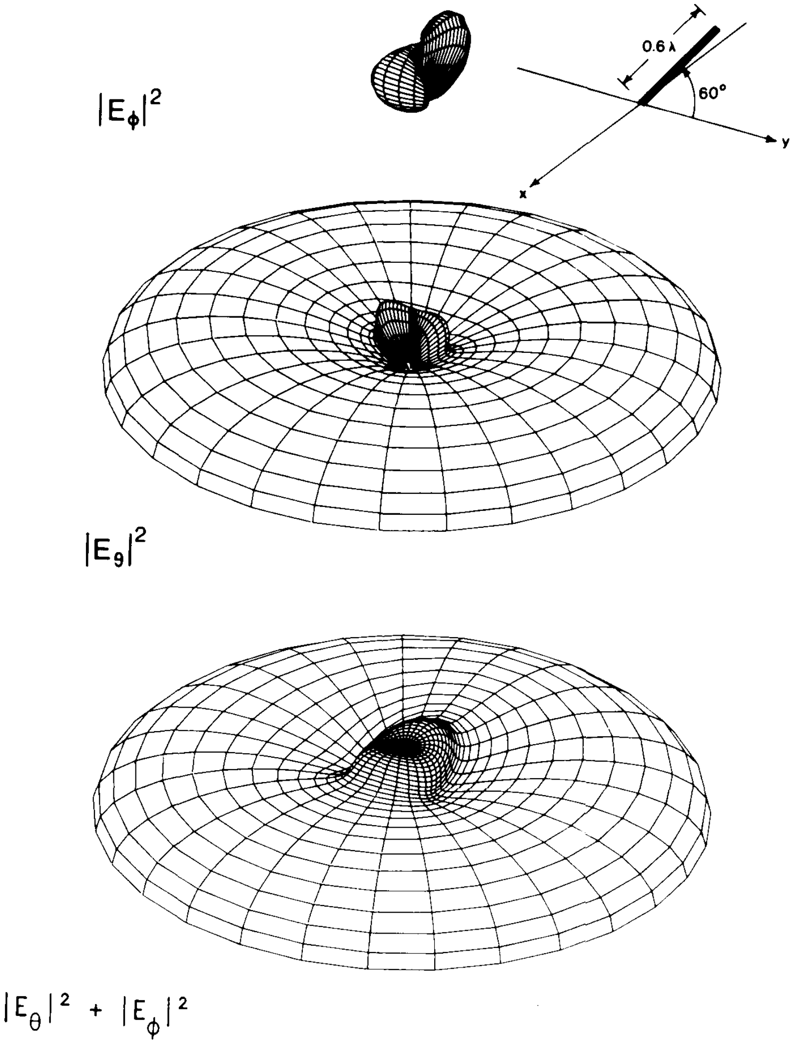


Fig. 1. Pseudo-three-dimensional far-field linear power patterns for a sloping monopole of length 0.6 λ and elevation angle 60°. Infinite ground plane and sinusoidal current distribution is assumed. Vertical polarization is clearly dominant at lower elevation angles.

tem will work, so empirical techniques are called for. The measurement scheme is relatively simple to implement and is described in the following section. The ensuing discussion includes an analysis using Rayleigh distributed signals incident on the rotatable base station antenna. This shows the tradeoff between the envelope correlation coefficient and the mean signal level different between the signals of the orthogonal polarizations, with the cross-polar discrimination as a parameter. Maximum ratio combining is assumed.

II. Measurements and Discussion

A. Measurement Setup

Any two orthogonal polarizations for receiving at the base station will suffice for the measurements. There seems little justification for not using vertical and horizontal components. The transmitting mobile antenna was a sloping monopole of length 0.6 λ and elevation angle 60°. The antenna pattern, assuming an infinite groundplane, is depicted in Fig. 1. The polarization is dominantly vertical for the lower elevation angles. The monopole was mounted on the center of an aluminium groundplane, which was larger than 2 × 1 wavelengths at the measurement frequency of 463 MHz.

The base station antenna comprised two identical four-element dipole arrays, one for vertical and the other for horizontal polarization reception. These antennas were mounted adjacently, at a height of 100 m (~160 λ), on a mast at Frejlev, Denmark. The land near the mast is basically rural. The mobile was driven in urban and suburban areas of the city of Aalborg, which is about 20 km from Frejlev. The terrain between Frejlev and Aalborg is that of slightly rolling plains with occasional foliage and dwellings. Fig. 2 is a map giving the layout around the measurement zone. The urban measurement run was taken at Vestergade, in Nϕrresundby,

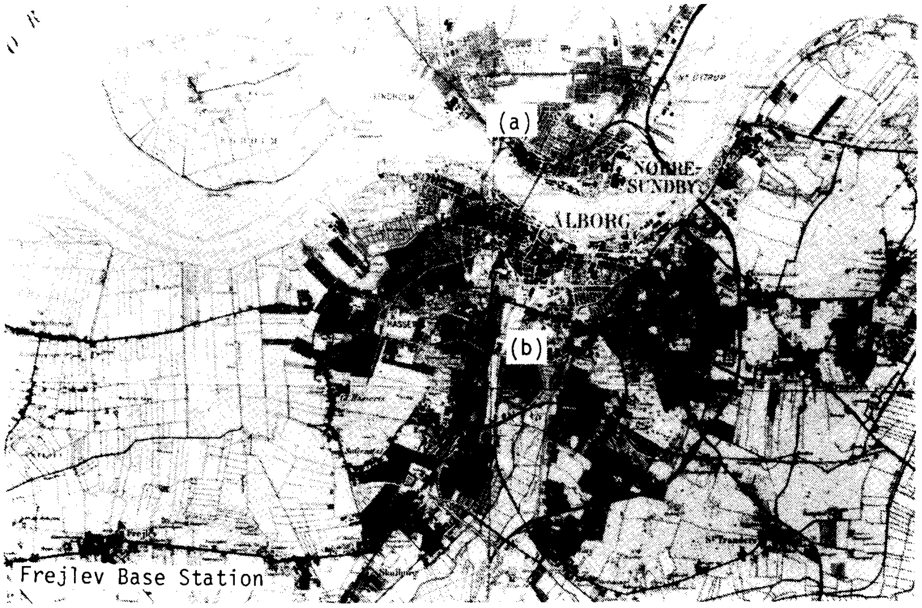


Fig. 2. Map showing layout. (a) Between base station measurement site at Frejlev and urban transmitting route. (b) Between base station measurement site at Frejlev and suburban transmitting route. (Open terrain is gently rolling plains.)

which is parallel to the water edge on the other side of a wide strip of water, the Limfjord, to Frejlev. The street is lined on both sides with 4-5 story buildings and runs at right angles to the direction of the base station. There is no direct line-of-sight path to the base station. The suburban measurement was taken in Hobrovej, beside the Southern Hospital. Hobrovej lies in a shadow area, caused by a hill, and this street runs at near right angles to the direction of the base station. Looking toward the base station, there is suburban housing and some large buildings on the hill. In the opposite direction, there is a row of large trees in front of suburban houses.

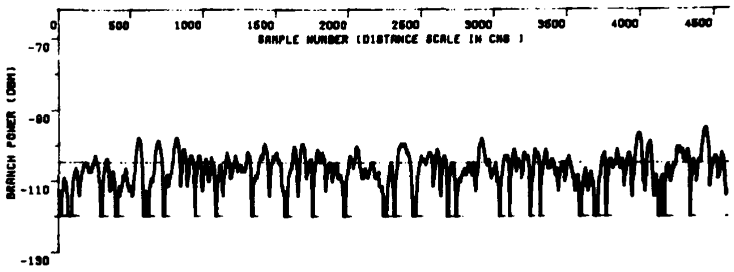
B. Measurement Results

The measured envelopes, their lossless maximum ratio combination, and the Rayleigh diagrams are given in Figs. 3 and 4 for the suburban and urban measurement runs. The noise level was chosen to be the lowest value of signal power that could be measured. The standard deviation noted in the figures is defined by $\sigma \text{ dB} = 10 \log \left(\frac{\mu + \sigma/2}{\mu - \sigma/2} \right)$, where μ and σ are the conventional mean and standard deviations of the envelope power. A Rayleigh signal has σ dB = 4.77, and an uncorrelated two-branch maximum ratio has σ dB = 3.21.

For the suburban measurement, the horizontal polarization is limited at the noise level, restricting its dynamic range to about only 25 dB. The dynamic range of the vertically polarized signal is about 31 dB, and departs from the Rayleigh distribution at about 15 dB below its mean level. The envelope correlation coefficient is 0.02. For the urban measurements, the horizontal polarization curve follows a Rayleigh distribution over its full dynamic range of about 36 dB. The vertical polarization departs from the Rayleigh distribution at about 18 dB below its mean value. The envelope correlation coefficient is -0.003. The results are summarized in Table I.

The exact mechanism causing domination by the vertical polarization is not clear. There are several possible contributing factors: the urban and suburban environments are both rather transparent at 450 MHz so that an effective line-of-sight exists between mobile and base station; there is insufficient polarization coupling in the multipath reflections for the vertically polarized transmission to decouple into equal levels of vertical and horizontal polarizations; and the open terrain between the base station and the mobile environment plus the height of the antenna act to favor propagation of the vertical polarization to the base station. This suggests that future measurements could involve repeating the experiment with mobile antennas of varying polarization. The mobile antenna need not be in a vehicle—a simple handheld apparatus could be sufficient to find some useful information. It would also be useful to compare these measurements with those taken with the base station sited in the same urban environment as the transmitting mobile, rather than being well separated from the urban area.

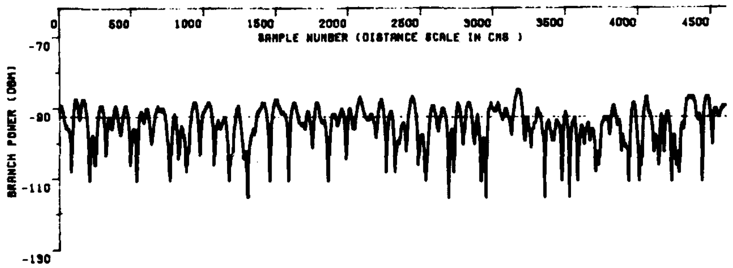
In the Rayleigh diagrams of Figs. 3 and 4, the reference $\langle \text{SNR} \rangle$ is that of the vertically polarized signal. The diversity gain, which is referred to as a "vertical-vertical" system, can be read directly off the diagrams. The curves have not been smoothed; they represent a direct mapping from the finite number (4600) measurement points. For the suburban measurements, the diversity gain is less than 1 dB at the 80% level (i.e., for 80% of the time), and increases to about 3 dB at the 95% level, and nearly 5 dB at the 95% level (a smoothed curve for the distribution is imagined). In the urban measurements, there is over 3 dB diversity gain at the 80% level, increasing to nearly 7 dB at the 99.5% level. In practice, there will be combination losses of perhaps 1 dB, so that the return from polarization diversity in suburban environments is negligible for this definition of diversity gain.



Horizontal

CHANNEL 1 SIGNAL POWER

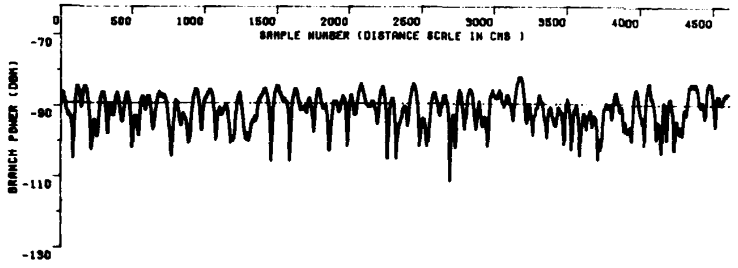
MEAN SNR (DB) = 15.07
MINIMUM VALUE SNR (DB) = 0.00
MEAN SIGNAL LEVEL (DBM) = -104.93
STANDARD DEVIATION (DB) = 5.48



Vertical

CHANNEL 2 SIGNAL POWER

MEAN SNR (DB) = 27.32
MINIMUM VALUE SNR (DB) = 4.53
MEAN SIGNAL LEVEL (DBM) = -92.68
STANDARD DEVIATION (DB) = 4.34

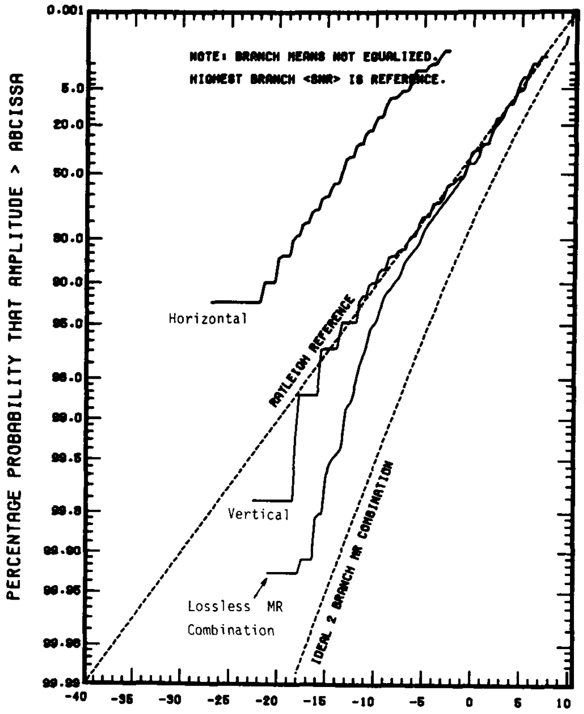


MAXIMAL RATIO SIGNAL POWER

MEAN SNR (DB) = 27.57
MINIMUM VALUE SNR (DB) = 5.84
MEAN SIGNAL LEVEL (DBM) = -89.42
STANDARD DEVIATION (DB) = 4.07

(a)

Fig. 3. Measurements from mobile transmitting from suburban environment. Transmitted polarization was principally vertical. (a) Fading envelopes of each polarization and maximum ratio combination. (b) Rayleigh diagram.



(SNR)/<SNR> IN DB.

(b)

Fig. 3. (*Continued*)

In both the urban and suburban measurements, the received horizontal polarization appears genuinely Rayleigh-distributed. The vertical polarization looks more Rician, caused by a dominant component, as discussed in the preceding. The lack of a dominant component in the horizontal polarization is quite reasonable, since essentially all the received power results from polarization coupling by reflection and refraction, of which no individual contribution continually dominates. It is noteworthy that the figure found here for the polarization cross-coupling agrees with that of Lee and Yeh [4]. This indicates that the effects of the open terrain may not be particularly relevant. The figure measured here also agrees with the measurements of Kozono *et al.* [3], albeit in an indirect sense (see Table I), further supporting this possibility.

C. Discussion

In Kozono *et al.*'s [3] results, the base station was in urban Tokyo. Their base station antenna was arranged so that the received polarizations were ±45°, in order to equalize the received mean signal levels. This equalization works, of course, but only at the expense of raising the correlation coefficient. Note that the total energy in the incident signal is being collected, assuming maximum ratio combining, irrespective of the angles (or senses) of the orthogonal polarizations.

A trade-off between the mean level difference and the branch signal correlations is evident. An investigation similar to that of Kozono *et al.* [3] can be arranged by assuming an incident signal of horizontal polarization

$$E_x = r_1 \cos(\omega t + \phi_1) \tag{1}$$

and vertical polarization

$$E_y = r_2 \cos(\omega t + \phi_2) \tag{2}$$

in which r_1 and r_2 are Rayleigh-distributed and uncorrelated. ϕ_1 and ϕ_2 are assumed to be random, uniformly distributed, and uncorrelated. An antenna receiving orthogonal linear polarizations, such as crossed dipoles broadside to the incident propagation vector (the situation is depicted in Fig. 5(a), receives voltages proportional to

$$V_1 = E_y \cos\alpha + E_x \sin\alpha \tag{3}$$

$$= (r_2 \cos\alpha \cos\phi_2 + r_1 \sin\alpha \cos\phi_1) \cos\omega t$$
$$- (r_2 \cos\alpha \sin\phi_2 + r_1 \sin\alpha \sin\phi_1) \sin\omega t \tag{4}$$

and

$$V_2 = E_y \sin\alpha - E_x \cos\alpha \tag{5}$$

$$= (r_2 \sin\alpha \cos\phi_2 + r_1 \sin\alpha \cos\phi_1) \cos\omega t$$
$$- (r_2 \cos\alpha \sin\phi_2 - r_1 \sin\alpha \sin\phi_1) \sin\omega t \tag{6}$$

whose respective envelopes are

$$R_1 = [r_2^2 \cos^2\alpha + r_1^2 \sin^2\alpha$$
$$+ 2r_1 r_2 \cos\alpha \sin\alpha \cos(\phi_1 - \phi_2)]^{1/2} \tag{7}$$

and

$$R_2 = [r_1^2 \cos^2\alpha + r_2^2 \sin^2\alpha$$
$$+ 2r_1 r_2 \cos\alpha \sin\alpha \cos(\phi_1 - \phi_2)]^{1/2}. \tag{8}$$

The problem of the square root can be circumvented by considering the power correlation coefficient (known to be similar to the envelope correlation coefficient [6])

$$\rho_e \approx \frac{\langle (R_1^2 - \langle R_1^2 \rangle)\rangle \langle (R_2^2 - \langle R_2^2 \rangle)\rangle}{[\langle (R_1^2 - \langle R_1^2 \rangle)^2 \rangle \langle R_2^2 - \langle (R_2^2 \rangle)^2 \rangle]^{1/2}} \tag{9}$$

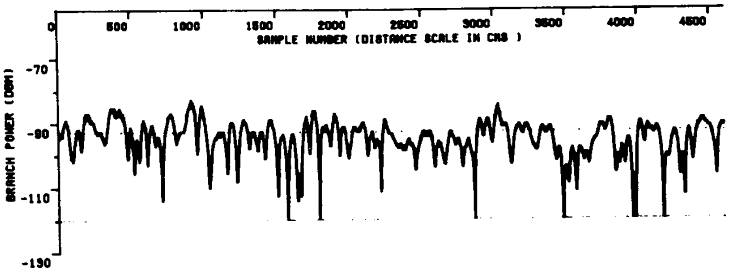
$$= \frac{\langle R_1^2 R_2^2 \rangle - \langle (R_1^2 \rangle \langle R_2^2 \rangle}{[(\langle R_1^4 \rangle - \langle R_1^2 \rangle)(\langle R_2^4 \rangle - \langle R_2^2 \rangle)]^{1/2}}. \tag{10}$$

The required moments and moment products are

$$\langle R_1^2 \rangle = \langle r_2^2 \cos^2\alpha + r_1^2 \sin^2\alpha$$
$$+ 2r_1 r_2 \cos\alpha \sin\alpha \cos(\phi_1 - \phi_2)\rangle$$
$$= \langle r_2^2 \rangle \cos^2\alpha + \langle r_1^2 \rangle \sin^2\alpha; \tag{11}$$

$$\langle R_2^2 \rangle = \langle r_1^2 \rangle \cos^2\alpha + \langle r_2^2 \rangle \sin^2\alpha; \tag{12}$$

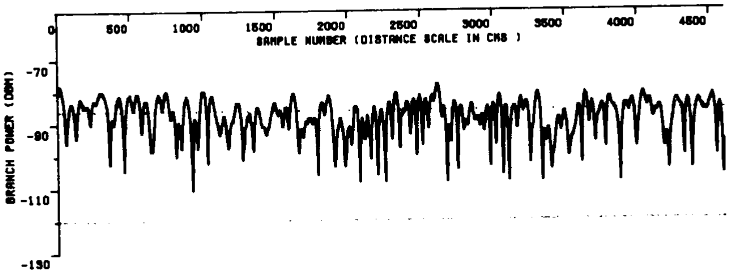
$$\langle R_1^2 \rangle \langle R_2^2 \rangle = \langle r_1^2 \rangle \langle r_2^2 \rangle (\cos^4\alpha + \sin^4\alpha)$$
$$+ \cos^2\alpha \sin^2\alpha (\langle r_1^2 \rangle^2 + \langle r_2^2 \rangle^2); \tag{13}$$



Horizontal

CHANNEL 1 SIGNAL POWER

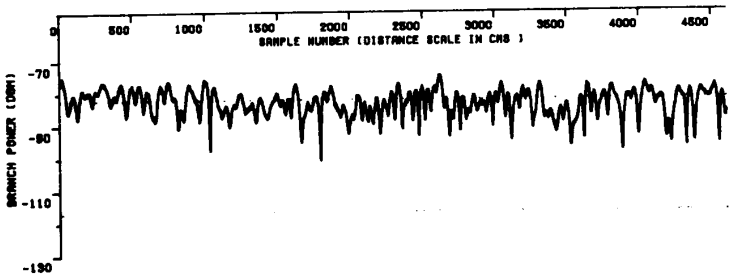
MEAN SNR (DB) = 27.25
MINIMUM VALUE SNR (DB) = 0.00
MEAN SIGNAL LEVEL (DBM) = -92.75
STANDARD DEVIATION (DB) = 5.31



Vertical

CHANNEL 2 SIGNAL POWER

MEAN SNR (DB) = 34.08
MINIMUM VALUE SNR (DB) = 9.24
MEAN SIGNAL LEVEL (DBM) = -85.92
STANDARD DEVIATION (DB) = 4.49

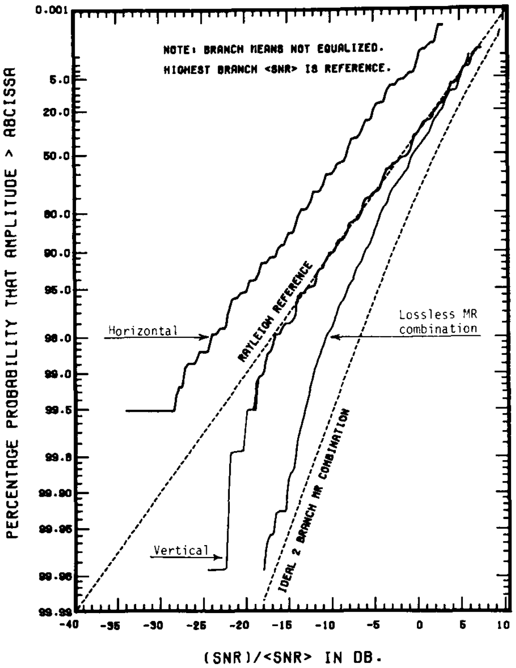


MAXIMAL RATIO SIGNAL POWER

MEAN SNR (DB) = 34.90
MINIMUM VALUE SNR (DB) = 15.83
MEAN SIGNAL LEVEL (DBM) = -82.09
STANDARD DEVIATION (DB) = 3.73

(a)

Fig. 4. Measurements from mobile transmitting from urban environment. Transmitted polarization was principally vertical. (a) Fading envelopes of each polarization and maximum ratio combination. (b) Rayleigh diagram.



(b)

Fig. 4. (*Continued*)

$$\begin{aligned}\langle R_1^4\rangle &= \langle r_2^4\rangle \cos^4\alpha + \langle r_1^4\rangle \sin^2\alpha\\ &\quad + 4\langle r_1^2\rangle\langle r_2^2\rangle \cos^2\alpha \sin^2\alpha\\ &= 2(\langle r_2^2\rangle \cos^2\alpha + \langle r_1^2\rangle \sin^2\alpha), \end{aligned} \tag{14}$$

because

$$\begin{aligned}\langle r_1^4\rangle &= 2\langle r_1^2\rangle\\ \langle r_2^4\rangle &= 2\langle r_1^2\rangle;\end{aligned} \tag{15}$$

$$\langle R_2^4\rangle = 2(\langle r_1^2\rangle \cos^2\alpha + \langle r_2^2\rangle \sin^2\alpha)^2; \tag{16}$$

and finally,

$$\begin{aligned}\langle R_1^2R_2^2\rangle &= \langle r_1^2\rangle\langle r_2^2\rangle \cos^4\alpha + \langle r_1^2\rangle\langle r_2^2\rangle \sin^4\alpha\\ &\quad - 2\langle r_1^2\rangle r_2^2\rangle \cos^2\alpha \sin^2\alpha + 2\langle r_1^2\rangle \cos^2\alpha \sin^2\alpha\\ &\quad + 2\langle r_2^2\rangle \cos^2\alpha \sin^2\alpha \qquad (17)\\ &= 2\cos^2\alpha \sin^2\alpha(\langle r_1^2\rangle + \langle r_2^2\rangle)^2\\ &\quad + \langle r_1\rangle\langle r_2\rangle(\cos^2\alpha - \sin^2\alpha)^2. \qquad (18)\end{aligned}$$

The envelope correlation coefficient becomes

$$\rho_e \approx \frac{\cos^2\alpha \sin^2\alpha(\langle r_1^2\rangle - \langle r_2^2\rangle)^2}{(\langle r_2^2\rangle \cos^2\alpha + \langle r_1^2\rangle \sin^2\alpha)(\langle r_1^2\rangle \cos^2\alpha + \langle r_2^2\rangle \sin^2\alpha)} \tag{19}$$

and using the cross-polar discrimination

$$\chi = \frac{\langle r_1^2\rangle}{\langle r_2^2\rangle}, \tag{20}$$

the result is

$$\rho_e(\alpha, \chi) = \frac{\tan^2\alpha(\chi^2 - 1)^2}{(\tan^2\alpha + \chi)(\chi \tan^2\alpha + 1)}. \tag{21}$$

The limiting cases serve as checks:

1) $\chi = 0 \rightarrow \rho_e = 1$, independent of α, (22)

2) $\chi = 1 \rightarrow \rho_e = 0$, independent of α, (23)

3) $\alpha = 0 \rightarrow \rho_e = 0$, independent of χ, (24)

4) $\alpha = 45° \rightarrow \rho_e = \left[\frac{\chi - 1}{\chi + 1}\right]^2$, (25)

which is in agreement with the result of Kozono *et al.* [3, eq. (13) with $\beta = 0$].

$$\begin{aligned}L &= \frac{\langle R_2^2\rangle}{\langle R_1^2\rangle}\\ &= \frac{\langle r_1^2\rangle \cos^2\alpha + \langle r_2^2\rangle \sin^2\alpha}{\langle r_2^2\rangle \cos^2\alpha + \langle r_1^2\rangle \sin^2\alpha}\end{aligned} \tag{26}$$

that is,

$$L(\alpha, \chi) = \frac{\chi + \tan^2\alpha}{1 + \chi \tan^2\alpha}. \tag{27}$$

The limiting case checks are as follows:

1) $\alpha = 0 \rightarrow L = \chi$. (28)

2) $\alpha = 45° \rightarrow L = 1$, independent of χ. (29)

3) $\chi = 0 \rightarrow L = \tan^2\alpha$; $\alpha = 0 \rightarrow L = 0$ (30)

$\alpha = 45° \rightarrow L = 1$. (31)

4) $\chi = 1 \rightarrow L = 1$, independent of α. (32)

The ratio of powers $L(\alpha, \chi)$ is plotted against the envelope correlation coefficient $\rho_e(\alpha, \chi)$ for various parametric values of χ and α in Fig. 5. The range of α is from 0° to 45°. The curves of constant χ intersect the ordinate for the constant value of χ. The value of α at this point is 0° and increases to 45° where the abscissa is intersected. The curves of constant α emanate from the origin where $\chi = 1$, and migrate out to $\rho_e = 1$ where $\chi = 0$ ($-\infty$ dB).

For the urban measurements at Frejlev, for example, the mean level difference of 7 dB between branches could have been traded with an envelope correlation coefficient of about 0.44 (for similar branch levels) by rotating the base station antenna to ± 45° polarizations. The locus of the mean levels and the equivalent correlation coefficient is given by the curve

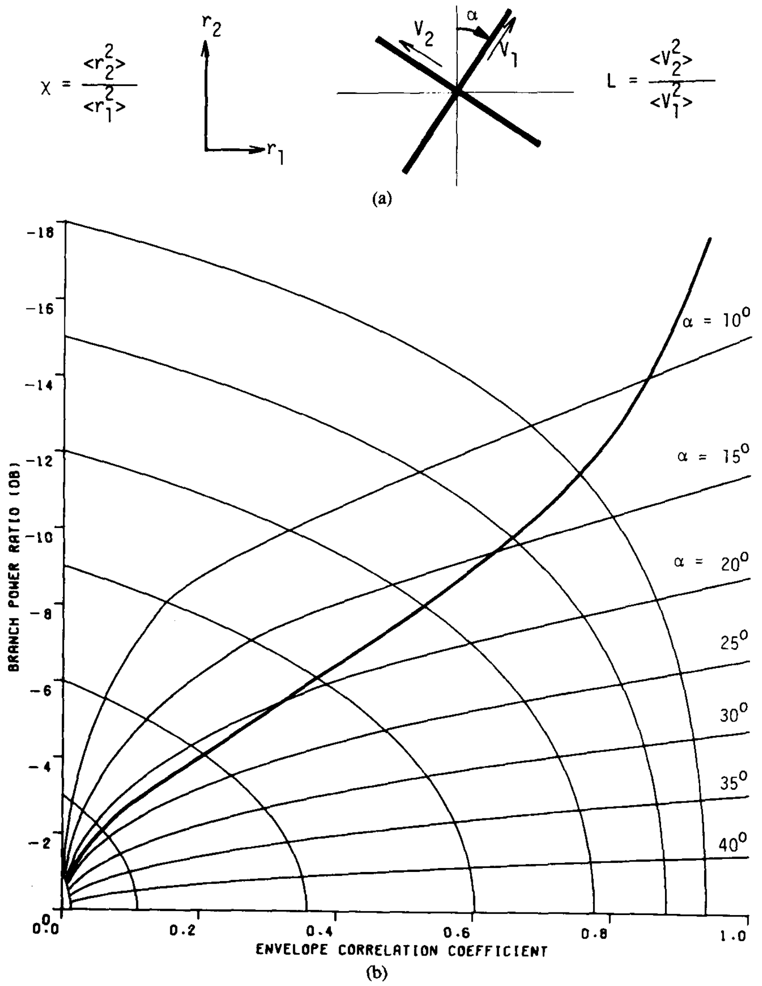
$$L(0°, \chi) = \rho_e(45°, \chi). \tag{33}$$

By rotating the antenna, the mean level difference is traded with the correlation coefficient for constant (maximum) energy reception. In comparing Kozono *et al.*'s [3] result for $\alpha =$

TABLE I
SUMMARY OF RESULTS FOR THE POLARIZATION DIVERSITY MEASUREMENTS[a]

	Suburban		Urban	
	Vertical	Horizontal	Vertical	Horizontal
Envelope dynamic range	31 dB	25 dB (limited)	32 dB	36 dB
Level (cf. mean) where distribution departs significantly from Rayleigh	− 18 dB	—	− 18 dB	—
Mean level difference between polarizations	12 dB		7 dB	
Envelope correlation coefficient between vertical and horizontal polarizations	0.019		− 0.003	

[a] Vertical and horizontal polarizations were received at the rural base station and the mobile-transmitted principally vertical polarization. Each measurement run was 45 m ($\approx 70\ \lambda$ at 463 MHz). There was no direct line-of-sight between mobile and base in either run.



(a)

(b)

Fig. 5. (a) Polarization diversity antenna and incident field schematic and relations. (b) Branch power ratio L and envelope correlation coefficient ρ_e behavior. (Circumferential lines are of constant cross-polar discrimination χ (value of line at ordinate), with α increasing from 0° (on ordinate) to 45° (on abscissa); radial lines are for constant α, with χ decreasing from 0 dB (at origin) to $-\infty$ dB; thick radial line is mean branch power ratio/envelope correlation trade-off.)

45°, of $L \approx 2$ dB and $\rho_e \approx 0.3$, the graph suggests $\chi \approx -5$ dB, comparable with the 6 dB measured by Lee and Yeh [4], and the 7 dB measured by this author.

Returning to the Rayleigh diagrams of Figs. 3(b) and 4(b), there is some diversity gain available from the polarization diversity system described. In discussing only the $\langle \mathrm{SNR} \rangle$ gain, not a great deal of information is revealed regarding the channel capacity of a digital link. Bit error rate (BER) measurements may have revealed a considerable improvement when using the diversity system—relative to using just the vertically polarized signal—because of the reduced random FM. Lee and Yeh's measurements indicate that the transmitted polarization has more effect than the environment on the relative levels of the received polarizations. It is felt that by arranging the mobile antenna pattern to have, e.g., equal amounts of each polarization (for example, by using a more horizontally oriented sloping monopole or by varying the diameter of a circular microstrip patch antenna [10]), then dual polarization reception at the base station would offer significant gains over the usual "vertical-vertical" system, even in suburban environments.

The "vertical-vertical" system effectively corresponds to the case when $\langle R_1 \rangle$ at $\alpha = 0$ is much larger than $\langle R_2 \rangle$. There is no diversity action because the power contribution from the R_2 signal is negligible. Maximum diversity gain is achieved when the envelope correlation coefficient is zero (this is the minimum value possible for the assumed Rayleigh distributed envelopes) and the branch power ratio is 0 dB. The antenna system must be arranged for this condition, as was already mentioned.

III. CONCLUSION

Measurements of uncorrelated Rayleigh-like envelopes in the vertical and horizontal polarizations at the base station have been presented. There was no direct line-of-sight to the mobile. For suburban base stations, the dominance of the vertical polarization makes the diversity gain rather small—only a couple of dB at the 99.5% probability level. In urban environments, however, the diversity gain is nearly 7 dB at the 99.5% level, offering much promise for system design using polarization diversity. The mean levels of the orthogonally polarized signals agree well with existing measurements from different cities by other workers (viz. [4], [3]). General expressions and their graphical interpretation for a rotatable polarization diversity antenna at the base station have been given.

APPENDIX

Signal Decorrelation by Array Patterns of Electric and Magnetic Elements over a Ground Plane

Lee and Yeh's [4] classic polarization path diversity measurements automatically include signal decorrelation by the differing array factor of the electric and magnetic elements above the ground plane (roof) of the mobile. For an infinite, perfectly conducting ground plane, the following analysis indicates that the array factor is important for the decorrelation of the signals.

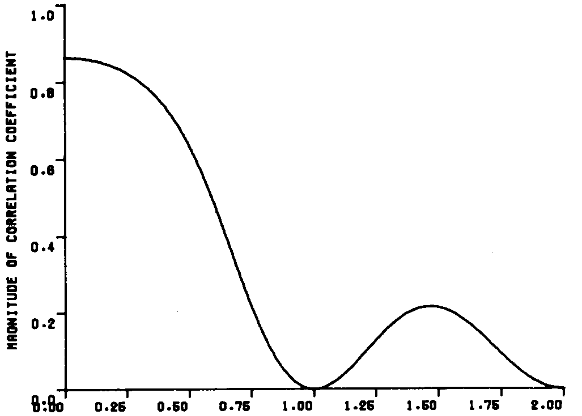


Fig. 6. Correlation coefficient expected as result of array patterns of electric and magnetic elements above infinite ground plane. Curve can be interpreted as magnitude of open-circuit signal correlation coefficient (i.e., square root of envelope correlation coefficient) for two colocated antennas of same polarization with far-field patterns given by $A^{(e)}(\theta)$ and $A^{(m)}(\theta)$. Inclusion of scalar element factor does not alter curve significantly.

If the polarization diversity antenna elements can be considered as minimum scattering antennas (they are good approximations since they are operated in a single mode), then the open-circuit correlation coefficient at the mobile is approximated as [10]

$$\rho_0 \approx \int E^{(m)}(\Omega) \cdot E^{(e)*}(\Omega)\, d\Omega \tag{34}$$

where $E^{(m)}$ and $E^{(e)}$ are the normalized far-field patterns of the elements in the presence of the groundplane, and the integration is over the sources generating the incident fields. In an urban situation, a reasonable and convenient source model is an even-distribution model, surrounding the mobile, and from zero to 30° in elevation from the mobile [9]. The scalar element patterns are similar, and the correlation coefficient is unity. The presence of an infinite ground plane a distance h below the elements gives rise to array patterns for the electric and magnetic elements

$$A^{(e)}(\theta) = 1 + e^{jk_0 2h \cos\theta} \tag{35}$$

$$A^{(m)}(\theta) = 1 - e^{jk_0 2h \cos\theta} \tag{36}$$

which alone produce a correlation coefficient

$$\rho_a \approx \frac{1}{D} \int_{\pi/3}^{\pi/2} A^{(m)}(\theta) A^{(e)}(\theta) \sin\theta\, d\theta \tag{37}$$

$$= -\frac{j2}{D} \int_{\pi/3}^{\pi/2} \sin(k_0 2h \cos\theta) \sin\theta\, d\theta. \tag{38}$$

Here D is the normalization factor

$$D = \left[\int |A^{(e)}(\theta)|^2 \sin\theta\, d\theta \int |A^{(m)}(\theta)|^2 \sin\theta\, d\theta \right]^{1/2} \tag{39}$$

$$= \left[\frac{1}{4} - \left(\frac{\pi}{6} J_0 \left(4\pi \frac{h}{\lambda} \right) \right)^2 \right]^{1/2}. \tag{40}$$

ρ_a can be interpreted as the magnitude of the open-circuit correlation coefficient for two colocated antennas of the same polarization, with far fields given by $A^{(e)}(\theta)$ and $A^{(m)}(\theta)$. It is plotted in Fig. 6 against the height of the elements above the groundplane. Inclusion of a $\sin\theta$ scalar element factor in (36)–(38) does not alter the curve significantly, the main effect being a slight raising of the minima. Under the assumptions of the analysis (especially (34) and the scenario characteristics), any height greater than about 0.5 λ produces decorrelation by elevation angle diversity. Any decorrelation by polarization alone must be observed in the absence of a ground plane for this type of polarization diversity antenna.

ACKNOWLEDGMENT

The author owes much to Professor J. Bach Andersen of Aalborg University, Denmark, for suggesting the polarization diversity measurements and for his assistance and encouragement. The Danish Post and Telegraph Administrations and Storno A/S are gratefully acknowledged for providing base station facilities and a mobile radio unit for the measurements.

REFERENCES

[1] S. A. Bergman and H. W. Arnold, "Polarization diversity in the portable communications environment," in *Proc. Nat. Radio Sci. Meet.*, Univ. Colorado, Boulder, 1986, p. 193.

[2] B. Glance and L. J. Greenstein, "Frequency selective fading effects in digital mobile radio with diversity combining," *IEEE Trans. Commun.*, vol. COM-31, no. 9, pp. 1085–1094, 1983.

[3] S. Kozono, H. Tsuruhara, and M. Sakamoto, "Base station polarization diversity reception for mobile radio," *IEEE Trans. Veh. Technol.*, vol. VT-33, no. 4, pp. 301–306, 1984.

[4] W. C. Y. Lee and Y. S. Yeh, "Polarization diversity system for mobile radio," *IEEE Trans. Commun.*, vol. COM-20, no. 5, 1972.

[5] W. C. Y. Lee, *Mobile Communications Engineering*. New York: Wiley, 1981.

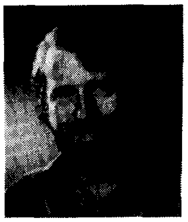
[6] J. R. Pierce and S. Stein, "Multiple diversity with nonindependent fading," *Proc. IRE*, vol. 48, pp. 89–104, 1960.

[7] R. G. Vaughan and J. Bach Andersen, "A multiport patch antenna for mobile communications," in *Proc. 14th European Microwave Conf.*, Liege, Sept. 1984, pp. 607–612.

[8] ——, "Antenna diversity in mobile communications," in *Proc. Nordic Seminar on Digital Land Mobile Radio Communications*, Espoo, Finland, Feb. 1985, pp. 87–96.

[9] R. G. Vaughan, "Signals in mobile communications: A review," *IEEE Trans. Veh. Technol.*, vol. VT-35, no. 4, 1986.

[10] R. G. Vaughan and J. Bach Andersen, "Antenna diversity in mobile communications," *IEEE Trans. Veh. Technol.*, vol. VT-36, pp. 149–172, Nov. 1987.



Rodney G. Vaughan (M'82) received the B.E. and M.E. degrees in electrical engineering from the University of Canterbury, New Zealand, in 1976 and 1977, respectively, and the Ph.D. degree from Aalborg University, Denmark, in 1985.

From 1977 to 1978 he was with the New Zealand Post Office working with toll traffic analysis and forecasting. Since 1979, he has been with the Physics and Engineering Laboratory, Department of Industrial and Scientific Research, New Zealand, developing a variety of computer-based industrial and scientific equipment. He studied in Aalborg from 1982 to 1985, as a recipient of a New Zealand government study award. His current interests include mobile and satellite communications, antenna arrays, and signal processing.

Dr. Vaughan is a member of the IEEE Antennas and Propagation and Vehicular Technology Societies.