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A COMPUTER SIMULATION OF FADING IN
THE LAND MOBILE RADIO ENVIRONMENT

submitted by K J Gladstone
for the degree of Ph.D.
of the University of Bath
1979

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TO MY PARENTS

And God said, "Let there be light"; and there was light. And God saw that the light was good;

Gen 1:3-4
ACKNOWLEDGEMENTS

I must thank my supervisor Dr J P McGeehan and the Head of the School of Electrical Engineering, University of Bath for allowing me to proceed with this work. I am very grateful to the many friends and colleagues who have aided me over the past three years. I would like to make special mention of Richard Hughes and Andy Rauling both of whose assistance has been well beyond the call of duty.

I have been supported financially by the Science Research Council, UK. They have provided a substantial Research Grant towards this work in addition to my Studentship.
SYNOPSIS

A major problem with the reception of radio in a moving vehicle is caused by the variability of the field strength. There is rarely a good direct signal path between the transmitter and the mobile and, hence, any wave received will have been scattered by the buildings and other objects in the immediate locality. After showing the complexity of this process from a proposed theoretical model this thesis continues by describing a computer simulation of the environment. The model for the simulation is based on a statistical plan of the area and the program traces the paths of the various waves arriving at the mobile.

A simulation is of little use until it has been shown to be valid, within specified limitations. A series of practical field trials has been conducted in and around the City of Bath. These are fully described with emphasis on both the methods and analysis employed. A chapter containing selected results verifies the basic simulation for a wide range of different environments.

The value of the simulation is demonstrated toward the end of this thesis by applying it to the Sideband Diversity Scheme. Only an outline of the statistical theory is included but this is supplemented by some interesting predictions from the program. The final chapter discusses some further work that could be carried out to optimise the simulation and to apply it to further types of radio scheme.
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SYMBOLS

a  Arrival Angle  
c  Speed of Light (3 \times 10^8 \text{ ms}^{-1})  
C  Covariance  
d  Modulation Phasing  
\text{E}(x)  Expected Value of x (i.e. the mean)  
\text{E}(x^2)  Expected Value of x^2 (i.e. the mean square)  
f, f \ \text{Frequency}  
f(x)  Probability Density Function  
F(x)  Cumulative Distribution Function  
\text{F}(x < X)  Cumulative Distribution Function  
J_0 , I_0  Bessel Functions  
r  Envelope Function  
R  Specified Level  
R_n  Normalised Level  
S(f)  Spectral Function  
T_c , T_s  Orthogonal Signal Components  
\nu  Mobile Speed  
Z, z  Complex Signal  
\lambda  Wavelength  
\sigma^2  Variance  
\rho  Correlation Coefficient  
\delta(f)  Dirac Delta Function  
|x|  Modulus or Magnitude of x  

Note: This list is not exhaustive but includes those symbols which are used regularly throughout this thesis.
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<td>c</td>
<td>Carrier</td>
<td>$f_c, \omega_c$</td>
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<td>e</td>
<td>Electric</td>
<td>$z_e$</td>
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<td>l</td>
<td>Lower Sideband</td>
<td>$z_1, T_{cl}$</td>
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<td>m</td>
<td>Maximum</td>
<td>$f_m$</td>
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<td>n</td>
<td>One of a Number</td>
<td>$a_n, c_n, d_n$</td>
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<td>o</td>
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<td>$z_o$</td>
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<td>p</td>
<td>Direct Component</td>
<td>$a_p, f_p$</td>
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<td>r</td>
<td>Envelope</td>
<td>$\rho_r$</td>
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<td>T</td>
<td>Total</td>
<td>$\sigma^2_T$</td>
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<tr>
<td>u</td>
<td>Upper Sideband</td>
<td>$z_u, T_{su}$</td>
</tr>
<tr>
<td>z</td>
<td>Complex Signal</td>
<td>$\rho_z$</td>
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<tr>
<td>*</td>
<td>Conjugate</td>
<td>$z^*$</td>
</tr>
<tr>
<td>.</td>
<td>Differential</td>
<td>$\delta, \delta$</td>
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Note: This list is not exhaustive but includes those symbols which are used regularly throughout this thesis.
INTRODUCTION

1.1 Prologue
The use of radio for communication with moving vehicles of all kinds began in its earliest days. The maritime service was the first to benefit and encouraged the development of long range, low frequency ship-to-shore links. The advent of broadcasting and the use of radio for aviation soon caused spectrum congestion. In order to increase the channel availability research was continued in the use of higher frequencies and narrower bandwidths. The introduction of VHF radio, with its large channel capability, brought the added advantages of localised communication. For broadcasting this allowed both high quality regional services and, later, the addition of stereophonic operation. The move to VHF and UHF for aviation permitted the use of sector traffic control, of especial importance in the current congested airways.

Radio has for many years provided two-way land mobile communication in both the military and emergency services. This has been progressively extended to taxis, commercial vehicles and, more recently, buses. Now more interest is being shown in the private sector, specially by top executives to whom constant contact with clients and colleagues is becoming a necessity. The consequent explosion in channel allocation has forced authorities to reduce channel spacing from 50 kHz to the present 12.5 kHz. In the next few years this may possibly be decreased to 6.25 kHz or even 5 kHz. The authorities
also restrict the power of each transmission in an attempt to reduce the channel degradation caused by adjacent and co-channel interference. Under these conditions it is essential that any radio link should be as efficient as is possible.

1.2 Land Mobile Service

The majority of civil land mobile radio operates in urban or suburban areas. Even when the transmitter is sited in a high open space the signal to the mobile is generally obstructed by buildings and other objects. In hilly environments this obstruction is accentuated by features of the terrain. A vehicle moving through such an area receives a number of waves scattered by the surrounding objects. The mutual interference of these waves can cause the signal level to vary by more than 30dB several times per second, at VHF.

For speech channels this fluctuation of received signal level, often termed fading, can significantly degrade intelligibility of the audio output. For data transmissions the fading, with its inherent rapidly changing phase shifts, produces an unacceptably high error rate with many forms of modulation.

Before any work can be carried out to counteract fading the propagation process itself must be studied theoretically. This has been done in the past both by mathematicians and by engineers. After a review of their work the next chapter presents the theory from a statistical perspective.
1.3 **Simulation**

Since the analytic calculation of the multipath fading statistics is very complex other methods are required to enable a detailed study of the process to be carried out. One such method is that of simulation, using either software or hardware, which can provide a system in which the parameters can be easily changed to represent a wide range of radio environments and systems. The technique to be described, Chapter 3, uses a package of programs implemented on a digital computer and allows a full simulation and analysis of multipath fading.

Previous simulations have tended to use a model which includes a number of assumptions that are only valid within narrow limitations. The most important of these implies that buildings and other objects which scatter the waves are randomly placed. This is clearly not the case in urban environments where the buildings are generally arranged along each side of the road. This discrepancy can lead to inaccuracies in some of the statistics, especially those concerned with frequency.

The present simulation seeks to overcome these difficulties by allowing the user to specify many of the variable parameters. Its starting point is a plan of the environment which represents the statistical spread of scatterers. From this plan the waves arriving at the mobile receiver are traced and summed to produce the composite signal. This technique can be extended for the simulation of complete radio schemes to assist in implementation and optimisation.
1.4 Verification

The statistical analysis of the output from the simulation can be compared with both theoretical and practical results. The information thus gained indicates how much confidence can be placed in the simulation and its model. The only theoretical analysis available is for the generalised "Rayleigh" model with or without an additional coherent wave. With the present simulation the "Rayleigh" model can be represented by a random placing of the scatterers on the plan. The results closely agree with the theoretical prediction.

For this simulation the more important comparison is with practical results. An extensive series of field strength recordings have been made in and around the City of Bath. To start with the AGC voltage of a standard communications receiver was used as the measure of signal level. When this proved unsatisfactory a new system was constructed around a logarithmic amplifier, Chapter 4. After the field strengths have been recorded they are quantised and processed on a mini-computer.

The corrected data is transferred from the small to the main computer for the majority of the analysis. The routines used are common to both the simulation and the field trials, Chapter 5. In Chapter 5 the detailed statistical analysis is presented for three areas in the City of Bath, each of which exhibits some notable features. All three areas have been simulated and these results are included, in most cases superimposed over the relevant practical curve.
1.5 Sideband Diversity

The basic simulation has been extended to include a diversity scheme of particular interest within the department. In order to provide acceptable coverage to complete service areas the base transmitter is often supplemented by a remote slave station. It has been noted that any phase difference in the modulation of the transmitted signals gives rise to harmonic distortion at the receiver. The analysis of this distortion shows that it is caused by differing summation of the complex components for each sideband. In the Sideband Diversity scheme this process is enhanced in order that the fading of each sideband should be statistically independant. By demodulating the sidebands separately and selecting the larger the degree of fading for the output can be substantially reduced.

The derivation of the density function for the selected signal, Appendix C, demonstrates the complexity of the theoretical analysis of the scheme. Modification of the simulation program, however, is reasonably straightforward, see Chapter 7. The new program has again been compared both with theoretical and practical results and has been shown to be a good representation of the scheme. In Chapter 8 the application of the simulation is described with respect to changes within the diversity scheme. The results have led to some interesting advances in the understanding of previous work.
2. MULTIPATH FAIDING

2.1 Propagation

Almost all radio signals received at a mobile will tend to consist of a number of significant, independant waves. One set of these waves will have been scattered and reflected by objects in the vicinity of the mobile receiver. It can be assumed that these waves have undergone a number of reflections from rough surfaces and, hence, their phases will be random and incoherent. The remainder of the signal will be composed of a line of sight wave or waves which have been reflected only once and, therefore, whose phase is solely dependant on the length of the path between the transmitter and the receiver. These waves are often grouped under the term coherent or direct components. Work has been carried out in an attempt to identify the paths of the individual waves (1,2) but the results have only been able to indicate the delay and direction of the longer paths which contain the minority of the energy of the signal. A better approach has concentrated on providing a statistical model of an essentially random process.

Since the received signal is the resultant of a number of waves, its magnitude varies with the phases and amplitudes of all the components arriving at the mobile. These parameters change with the position of the receiver causing the signal level to fluctuate as the mobile travels through the environment. The interaction of all these waves can also be considered
Figure 2.1  Multipath Interference Pattern
to set up a standing wave interference pattern. Since the process is complex both quadrature components must be evaluated to determine the resultant signal. The isometric diagram, Figure 2.1, shows the locus of the signal vector as the receiver moves through a pattern set up by three independent, isotropic sources. Even with this simple situation the complexity of the signal is evident, demonstrating the requirement for statistical analysis for any practical model in which neither the number nor the amplitudes nor the phases of the sources will be well defined.

2.2 Mean Signal Level

Multipath propagation, as introduced above, causes rapid variations in the received signal level, usually referred to as fading. To obtain meaningful, short term statistics this fading must be a stationary process and, hence, the slower alteration of the mean signal level has to be compensated for by normalisation.

The mean level of the signal received at the mobile is dependant on a wide range of factors, most of which only vary gradually with major changes in the overall environment. Okamura et al. (3) have shown that the mean loss of the field strength as the distance between the transmitter and the receiver increases is very much higher than that predicted by the free space loss. Allsebrook and Parsons (4) have concentrated on a model for propagation prediction taking account of aerial height, terrain and ground slope. Some changes in mean
level can occur over a fairly short distance, for instance at a road junction, but even this variation occurs over many wavelengths of the carrier signal, at VHF and UHF.

The changes in mean signal level can usually be adequately compensated for by the automatic gain control of a communications receiver, unless the signal falls below the noise threshold of the various amplifiers. For this reason the simulation to be described only models the faster, multipath fading which causes a large reduction in the information carrying capability of the channel and which cannot be easily counteracted by the receiver.

2.3 Rayleigh Model

Ossanna (5) was one of the first to study multipath fading by use of statistics. He postulated that, in general, a mobile receiver would receive one reflected wave and one direct wave which would interfere. As the mobile moved it would receive other reflected waves, but still only one at a time. From this model he computed the theoretical power spectra by means of numerical iteration. All his theoretical analysis assumed a mobile receiver while his experimental work used a mobile transmitter since he assumed that the process was reciprocal.
He was able to show a close correlation between his theoretical and experimental spectra since his model was, within limits, valid for a mobile transmitter scheme.

In order to provide some information to allow a comparison of aerial diversity techniques, Gilbert (6) proposed three different models of the mobile radio environment. In each model he assumed that a number of waves were received simultaneously, their phases having a uniform, random distribution between $-\pi$ and $+\pi$. In the first model he supposed that the amplitudes of the waves had complex Gaussian statistics and that the angles with which the waves arrived at the mobile were equally spaced around the unit circle. In the other two models he assumed that the angles of arrival had random, uniform distributions but he set the amplitudes equal for one and random for the other. For each case he showed that, in the limit, the distribution function would be the same. It is simpler, however, to follow Clarke's (7) derivation of this function since it also leads to the derivations of many of the other statistics.

Clarke's model was basically the same as the second one proposed by Gilbert, except that he restricted the distribution of the arrival angles to $\sqrt{2}\pi$. The general equation for the field strength is:

$$Z_b(t) = Z_0 \sum_{n=1}^{N} \exp(j\theta_n)$$ ...

(2.1)

which can be expanded, with the amplitudes no longer
held at unity, to:

$$Z_E(t) = Z_0 \sum_{n=1}^{N} C_n \cos(\omega_c t + \theta_n) \quad \ldots (2.2)$$

By following Rice (8) the electric field can be expressed as:

$$Z_E(t) = T_c(t) \cos(\omega_c t) - T_s(t) \sin(\omega_c t) \quad \ldots (2.3)$$

where:

$$T_c(t) = Z_0 \sum_{n=1}^{N} C_n \cos(\omega_n t + \phi_n) \quad \ldots (2.4)$$

$$T_s(t) = Z_0 \sum_{n=1}^{N} C_n \sin(\omega_n t + \phi_n) \quad \ldots (2.5)$$

The "noise" frequency, $\omega_n$, is equivalent to the Doppler frequency shift of the individual waves, caused by the movement of the receiver. This frequency shift is dependent on the arrival angle, Figure 2.2, by:

$$\omega_n = \frac{\omega_c v}{c} \cos(a_n) \quad \ldots (2.6)$$
Since the phases, $\phi_n$, and the arrival angles, $a_n$, are both assumed to have uniform distributions and the amplitudes, $C_n$, are either all equal or are Gaussian variables, the quadrature components $T_c(t)$ and $T_s(t)$ tend, by the Central Limit Theorem (9), to Gaussian processes as the number of waves, $N$, becomes large. The received signal level, $r(t)$, is equal to the magnitude of the electric field strength:

$$r(t) = |Z_e(t)| = (T_c(t)^2 + T_s(t)^2)^{\frac{1}{2}} \quad \text{(2.7)}$$

and, using the assumptions above, tends, by definition, to follow the Rayleigh density function (10).

The Rayleigh function is well defined (9) and has the general form:

$$f(r) = \frac{r}{\sigma^2} \exp\left(\frac{-r^2}{2\sigma^2}\right) \quad \text{for } r > 0 \quad \text{(2.8)}$$

in which $\sigma^2$ represents the mean power level. The plot of this function, Figure 2.3, shows its general form. The cumulative distribution is given by:

$$F(r < R) = \int_{-\infty}^{R} f(r) \, dr = 1 - \exp\left(\frac{-R^2}{2\sigma^2}\right) \quad \text{(2.9)}$$

Gilbert (6) has shown that with only three waves, i.e. $N = 3$, the signal level tends to follow the Rayleigh function, although it is more usual to define a model with at least six independent waves. If the variation in signal level does follow this function it is often termed "Rayleigh Fading". It has been noted, however, that the secondary statistics frequently deviate from those suggested by this model, even when the cumulative
Figure 2.3 Rayleigh and Rician Probability Functions

a) Density Functions

Rayleigh ($\sigma^2 = 0.5$)

Rician ($\sigma = 3\sigma$, $\sigma_T^2 = 5.5$)

b) Distribution Functions

Probability that Signal $\leq$ Level $R$

Normalised Level - $R/r_{rms}$

Normalised Level - $r/r_{rms}$

Rayleigh ($\sigma^2 = 0.5$)

Rician ($\sigma = 3\sigma$, $\sigma_T^2 = 5.5$)
Figure 2.4 Double-sided Input Spectrum

distribution fits closely to the theoretical curve.

2.4 Power Density Spectra

As previously shown, the received signal consists of a number of waves, each of which is shifted in frequency due to the movement of the mobile. The interaction of these waves spreads the frequency content of the composite signal, thereby causing some frequency distortion of the demodulated output. Gans (11) obtained an expression for the input signal spectrum, at carrier frequency, by considering the strength of the signal received as a function of the Doppler shifts. This spectrum can also be computed by equating the total power as a function of the arrival angle with the total power as a function of the frequency:

\[ \frac{z_a}{z_b} \int_{-\infty}^{\infty} C^2(a) \, da = \int_{-\infty}^{\infty} S_1(f) \, df \]  \quad \text{...}(A.5)
In each case the input spectrum, see Appendix A.2, is given by:

\[ S_1(f) = \frac{\sigma^2}{2\pi \sqrt{I_m^2 - (f - f_c)^2}} \]  

...(A.9)

and can be plotted as a double sided power spectrum. Figure 2.4.

The spectral content of the demodulated signal is of more interest since it describes the effect of the fading on the final output. The power density spectrum is equivalent to the Fourier transform of the autocorrelation function of the baseband signal. The autocorrelation function for the envelope of the fading waveform, assuming the "Rayleigh" model, has been shown (12) to be:

\[ R_1(\tau) = \frac{\pi}{2} \sigma^2 f(-\frac{1}{2}, \frac{1}{2}, 1; |\phi_z|^2) \]  

...(A.18)

in which \( f(s, t; c; z) \) represents the hypergeometric function. The coefficient \(|\phi_z|\) is equal to the amplitude of the normalised autocorrelation function for the orthogonal components, see Appendix A.3:

\[ |\phi_z| = \frac{1}{\sigma^2} R_{cc}(\tau) = J_0(\omega_m \tau) \]  

...(A.22)

By expanding the hypergeometric function, see Eq. A.23, Phillips (13) evaluated the power density spectrum. He used numerical techniques to perform the actual Fast Fourier transform. By disregarding terms above \(|\phi_z|^6\) he estimated the round off error of the FFT algorithm to be \(10^{-5}\), corresponding to a range of 50dB. This spectrum, Figure 2.5, shows clear discontinuities at 2.10
multiples of twice the maximum Doppler frequency, $f_m$.

This type of spectrum is well supported by experimental evidence (5,7), although above the first discontinuity most measurements are suspect due to the inherent noise of both measuring and recording equipment.

Employing a more purely mathematical analysis, Gilbert (6) was able to obtain an equation for the power density spectrum:

$$S_r(f) = \frac{\pi f_m^2}{2} S(f) + \frac{\sigma^2}{8\pi f_m} K((1 - \frac{f}{2f_m})^2)^{\frac{1}{2}} \quad \cdots (A.25)$$

The first term is a spectral line at zero frequency, representing the carrier component, and the second term, with a complete elliptical integral of the first kind, represents the spectrum of the fading waveform, Figure 2.5. It has been noted (7) that this spectrum was derived for the output of a square law detector but is also an approximation to that for an envelope detector,

![Figure 2.5 Baseband Power Spectrum](image-url)
ignoring terms above $|Dz|^2$. In each case the most
notable feature of the spectrum is the sharp drop at
twice the maximum Doppler frequency. In practical
situations this drop is rarely greater than 20dB.

2.5 Other Statistics

From the cumulative distribution, Figure 2.3, for
the fading envelope, it can be ascertained that,
although some fades are very deep, the signal rarely
falls far below its mean level. The fading rate is
frequently quoted as the number of times the signal
decreases below its rms value, per unit time. This
rate can be generalised to provide a function of the
rate at which the signal crosses any predetermined
level. Rice (8) has shown that the rate at which a
stochastic process increases through a level, $R$, is
given by:

$$N(R) = \int_{0}^{\infty} \hat{f}(r,f) df$$

...(B.1)

This has been used by Jakes (14) to evaluate the
crossing rate (see Appendix B.1) as:

$$N(R^*) = \left(2 \pi \right)^{\frac{3}{2}} f_m R^* \exp(-R^*_n)$$

...(B.9)

where $R^*_n$ is the normalised level. This function is
similar in shape to the probability density function,
from which it is derived. It can be seen, Figure 2.6,
that the maximum crossing rate is slightly in excess of
the maximum Doppler frequency and occurs at 3dB below
the rms level of the signal.
Figure 2.6 Normalised Crossing Rates

Figure 2.7 Normalised Mean Durations of Fades
The mean duration of fades is a measure of the average period for which the signal falls below any specified level. The function is equivalent (see Appendix B.2) to the cumulative distribution divided by the level crossing rate (14) and is given by:

\[ t(R^2) = \frac{\exp(R^2) - 1}{R f_m (2\pi)^3} \]  \( \text{...(B.10)} \)

The duration of fades, Figure 2.7, increases with the specified level, rising very rapidly above the rms value of the signal.

Many other statistics can be calculated for the "Rayleigh" fading model (15) but, as yet, these have not been studied in relationship to the simulation to be described.

2.6 Coherent Waves

So far this discussion has been concerned basically with the "Rayleigh" fading model as originally proposed by Clarke (7). As stated at the beginning, however, the signal received at a mobile frequently includes a coherent wave, the composite signal now becoming:

\[ Z(t) = Q \cos(\omega_q t + \phi_q) + Z_e(t) \]  \( \text{...(2.10)} \)

The first term of this expression represents a coherent wave of amplitude \( Q \), frequency \( \omega_q \) and relative phase \( \phi_q \). The statistics of this signal have been evaluated by various workers (16,17,18) but they all refer back to the classic paper by Rice (19), from which the results quoted here are taken.
By considering the probability densities for the orthogonal components of Eq. 2.10, Rice computed the probability density of the total envelope to be:

\[ f(r_t | Q) = \frac{r_t}{\sigma^2} \exp\left(\frac{-r_t^2 + Q^2}{2\sigma^2}\right) J_0\left(\frac{r_t Q}{\sigma^2}\right) \quad \ldots (2.11) \]

This function, often referred to as the Rician distribution, is superimposed onto the Rayleigh plots, Figure 2.3, for a coherent amplitude, Q, of 3σ. The cumulative distribution is evaluated by numerical calculation since the integration has no precise analytic form. From Eq. 2.11 Rice obtained the moments for the envelope in general form. He derived the mean square value as:

\[ \mathbb{E}(r_t^2) = Q^2 + 2\sigma^2 \quad \ldots (2.12) \]

suggesting that the coherent and incoherent waves are independent and uncorrelated.

The only other function that can simply be expressed as a single equation, so far as the envelope of the signal is concerned, is the level crossing rate:

\[ N(R) = (2\pi)^{-\frac{1}{2}} \int_{\infty}^{\infty} f(R_t | Q) \quad \ldots (2.13) \]

This crossing rate is superimposed on Figure 2.6, after normalising the specified level using Eq. 2.12, again with Q = 3σ. By setting the coherent wave to zero both Eq. 2.11 and Eq. 2.13 can be seen to be equivalent to their respective "Rayleigh" expressions. The plot for mean duration of fades, for the situation with a coherent wave, was obtained by numerically dividing the
cumulative distribution by the level crossing rate, normalising in the same manner as for the latter.

Since the coherent wave is, by definition, not dependant on scatterers its frequency shift is constant within the limits of the model, regardless of the position of the mobile. This wave, therefore, adds a single spectral line to the input spectrum of the composite signal, Eq. A.9. The power density spectrum can be obtained, assuming a square law detector, (7,12) by convolving the input spectrum with itself. This baseband spectrum, Figure 2.8, has the same basic shape as before with the addition of two peaks at frequencies of:

\[ f_p = f_m (1 + \cos(a_p)) \]  \quad (2.14)
in which \( a_p \) represents the arrival angle of the coherent wave, cf. Figure 2.5.

arrival angle \( a_p = 60^\circ \)
2.7 Non-Rayleigh Fading

It has been shown that multipath fading does not necessarily, in all cases, conform to the "Rayleigh" model. Lin (20) suggests that the two most extreme examples of this effect occur in certain over-water paths, where the fading is very deep, and in radio links for which the received signal consists of very few independent waves and which suffer relatively little multipath fading, compared to the theoretical model. Jao and Elbaum (16) list many further examples, both for mobile communications and for radar, in which the fading is not purely "Rayleigh".

In the land mobile service, for urban and suburban areas without strong, coherent waves, the cumulative distribution function of the fading envelope does usually follow the Rayleigh function fairly closely (21). However, it has been noted, see Chapter 6, that this does not imply that the secondary statistics, such as power spectra, must also accord with the "Rayleigh" curves. An indication of the reason for these results is provided by Cox (22) from his plots of the RF Doppler spectrum. These show that, although the distribution function is nearly Rayleigh, the arrival angles of the individual waves are not all equally probable. In this discussion, the term "Rayleigh Fading" is only applied with reference to Clarke's (7) original model, with all its assumptions.
2.8 Doppler Shift or Standing Wave

In many papers (6,7,11) fading is described by considering a mobile travelling through a standing wave interference pattern and then the statistics are evaluated in terms of Doppler shifts. Ossanna (5) used both models for his analysis and obtained "nearly identical results". These two points of view have caused considerable confusion and misunderstanding since they are only equivalent, in their simple forms, under certain limitations.

If a mobile moves from point \(u_1\) to point \(u_2\) in time \(t\), Figure 2.9, the received signal undergoes a relative phase change of:

\[
\Delta \phi_d = \int_0^t w_d(t) \, dt \quad \ldots (2.15)
\]

in which the Doppler shift, \(w_d(t)\), is given by:

\[
w_d(t) = \frac{w_c v}{c} \cos \left( \frac{\alpha(t)}{c} \right) \quad \ldots (2.16)
\]

By changing the variable to \(u = vt\) and rewriting the cosine in terms of the positions of the mobile and the isotropic source, the phase change becomes:

\[
\Delta \phi_d = \int_{u_1}^{u_2} \frac{w_c v}{c} \frac{x - u}{\left( (x - u)^2 + y^2 \right)^{\frac{1}{2}}} \, du
\]

\[
= \left[ \frac{-w_c v}{c} \left( (x - u)^2 + y^2 \right)^{\frac{1}{2}} \right]_{u_1}^{u_2}
\]

\[
= \frac{-2\pi}{\lambda} \left( (x - u_2)^2 + y^2 \right)^{\frac{1}{2}} + (x - u_1)^2 + y^2 \right)^{\frac{1}{2}} \right) \ldots (2.17)
\]

In the case of the standing wave pattern, the phase at any point is equal to the distance between the source
and that point divided by the wavelength:

\[ \phi_s = \frac{2\pi}{\lambda} ((x-u)^2 + y^2)^{\frac{3}{2}} \text{sgn}(x-u) \] \hspace{1cm} ...(2.18)

The change in phase as the mobile moves from \( u_1 \) to \( u_2 \) can be simply computed and will be equivalent to Eq. 2.17, except for a change of sign. Hence:

\[ \Delta \phi_s = -\Delta \phi_d \] \hspace{1cm} ...(2.19)

In the theoretical model the arrival angles are assumed to be constant and, thus, the Doppler shifts are not time dependant. From Eq. 2.2 to Eq. 2.5:

\[ \theta_n = \tan^{-1}\left(\frac{-T_s}{T_c}\right) = -\omega_n t \] \hspace{1cm} ...(2.20)

which agrees with Eq. 2.19.

---

**Figure 2.9** Changes in Arrival Angle with Time
3 SIMULATION

3.1 Previous Models

The study of the effects of multipath fading for different types of mobile radio scheme by the use of field trials is both wasteful in time and expense. It can also lead to spurious or inconclusive results due to peculiarities of the environment or an overall lack of information. The investigation of several different radio schemes has been carried out by means of a number of simulations which have been based on a variety of propagation models (23-28). These have indicated the possibilities of simulation techniques as an attractive alternative to field trials.

The majority of previous simulations, involving hardware or software, have sought to represent the pure "Rayleigh" model. The most fundamental of these forms its Rayleigh distributed fading signal by adding two Gaussian noise sources in quadrature. Although this model would seem to conform to Eq. 2.3 it ignores the

![Diagram of Noise Source Fading Simulator]

Figure 3.1 Noise Source Fading Simulator
frequency band-limiting inherent in Eq. 2.4 & 2.5. Arredondo et al. (23) overcame this problem by shaping the spectra of their noise sources, Figure 3.1. They were able to demonstrate a marked similarity between the theoretical secondary statistics, such as level crossing rate, and those for the output signal of their hardware simulator. Smith (24) used the same model for his software simulation, from which he was interested in the amplitude of the fading envelope.

Davis (25) used the same basic principle for his simulator but realised it by replacing the Gaussian noise sources by pseudo-random binary sequences. The spectrum shaping he achieved by a transversal filter, which he implemented by simply weighting the shift register outputs. He obtained the fading signal itself by modulating the carrier's quadrature components with independent binary sequences. Ralphs and Sladen (26) used a similar system for their HF simulator but they developed it to incorporate both ionospheric noise and specular frequency components.

A second basic type of simulator depends on the quadrature summation of the outputs from several low frequency oscillators, Figure 3.2. In order to produce a "Rayleigh" output the distribution function for the frequencies of the oscillators must be equivalent to the carrier spectral density (27), Figure 2.4. It has been shown that the output signal corresponds closely to that for the theoretical model if the simulator consists of at least six oscillators (29). A coherent
wave can be added by simply including a separate oscillator set at the required frequency and level.

Cox (1,22) has made many recordings of the excess delay caused to signals due to multipath, as compared to direct, propagation. This work has been extended by Turin et al. (30) who have measured the distortion in the shapes of pulses as a function of excess delay. Suzuki (28) has further analysed these results and has proposed a propagation model in terms of path lengths, rather than phase shifts. A simulation based on this model could be useful for studying the effects of the excess delay for various forms of digital modulation. As a general model, however, its complexity is not justified since the majority of the received energy has a minimum of excess delay (22).

The original program for the present software simulation was based on the multiple oscillator model.
The frequencies of these "oscillators" were derived by calculating the Doppler shifts from the angles of arrival, $\text{Eq. 2.6}$. These angles, $\alpha_n$, and the phases, $\phi_n$, were selected by means of a uniform random number generator and bounded to $\pm \pi$. The amplitudes were also assigned randomly but the generator was chosen to have a narrow Gaussian distribution as proposed by Gilbert (6). The "oscillators" were varied in number up to a maximum of twenty but even with only five the cumulative distribution of the envelope approximated to the Rayleigh curve. This simulation was not analysed to produce other statistics since it had already pointed to the scope for development of a full program package. The fundamental purpose of the new simulation would be to more faithfully represent the actual, rather than the theoretical, mobile radio environment.

This initial simulation demonstrated the benefits of employing a computer in the study of fading due to multipath propagation. Hardware simulators are very useful for on-line testing of equipment performance in which portability is of prime importance. For studying individual radio schemes, however, it is essential to be able to easily alter any parameter, for example relative power levels, without affecting the rest of the model. This requirement can be more easily met by a software simulation, which can also be arranged to analyse or repeat interesting results. A computer program can also be modified to represent a wide range of different radio schemes without difficulty.
3.2 Basic Simulation

It has already been noted, Section 2.7, that not all multipath fading can accurately be described as "Rayleigh". One reason for this is suggested by the results of Doppler shift measurements (22) which show that the arrival angles of the received waves are not necessarily all equally probable, as assumed for the model proposed by Clarke (?). This will tend to modify the envelope spectrum of the fading signal, although it may leave the cumulative distribution unchanged. In order to take account of this deviation from the true "Rayleigh" model, the simulation is based upon a statistical plan of the physical locality, Figure 3.3. In this way the arrival angles are specified by the relative positions of the scatterers and the receiver. By suitably siting the individual scatterers it should be possible to achieve a more accurate representation.
of the fading process.

In an urban or suburban area a mobile receives a very large number of scattered waves, of which only a proportion are significant. In the simulation model the waves are grouped statistically, each group being presumed to have been dispersed isotropically from a single point. The arrangement of these scatterers determines the type of environment under consideration; open, suburban areas have a random spread of points while they are spaced at regular intervals along each side of an urban street.

Another feature of this simulation is that the mobile is empowered to move along the road and, thus, the arrival angles of the waves change with time. The phase of each wave that is received cannot be simply computed as a function of the Doppler shifts but instead the calculation is performed with the equations for the standing wave model, cf. Section 2.8. The composite signal at any increment of time is equal to the complex summation of all the waves, Eq. 2.2.

If the plan is arranged in such a way that all of the arrival angles are equally probable, in other words if the points are distributed randomly, then the model becomes similar to that proposed by Clarke (7). This is confirmed by the analysis of the fading envelope generated from the random plan, Figure 3.4. Both the primary and secondary statistics showed a marked agreement with those for the "Rayleigh" model.

In the simulation for an urban street the analysis
Environmental Plan

Cumulative Distribution

Figure 3.4 Results for Random Simulation
Figure 3.4 Results for Random Simulation
shows both the benefits and the deficiency of the model. In some streets the signal tends to become channeled and this alters the statistics as though there were a strong coherent wave from each end of the street, cf. the results for the Paragon in Chapter 6. The analysis of the output from the simulation shows the same type of effect but to a far greater extent, Figure 3.5.

After consideration of the results from many different runs it was deduced that the scatterers at each end of the road were very much too dominant. This shows most clearly on the power density spectrum as a large peak at twice the maximum Doppler frequency.

Two methods of overcoming this problem were examined in detail. In the first the waves were each attenuated in direct proportion to the lengths of their paths. This was included in the simulation but to be effective the attenuation had to be so great that it could not be supported from a physical viewpoint. The second method required modification of the isotropic nature of the scatterers. This could not be directly incorporated into the program due to the lack of information pertaining to the directivity pattern to be employed. However, since the plan is a statistical representation the exact pattern is not required. A close approximation was developed by redefining the plan in terms of reflection and shadowing. Kozono (31) has considered the effect of buildings on the mean level of the signal but little work has been done with respect to their relation to multipath fading.
Environmental Plan

Cumulative Distribution

![Diagram showing cumulative distribution with Rayleigh distribution and simulated points.]

Figure 3.5 Results for Ordered Simulation
Figure 3.5  Results for Ordered Simulation
In order to be able to include shadowing into the simulation model the scatterers are drawn as rectangles rather than as points. Although the plan is now very similar to a map it must be remembered that it is still a statistical representation, Figure 3.6. The edges of the rectangles delineate the sides of the buildings and are used as plane reflectors. Their centres act in the same manner as the points they replace while the areas of the rectangles can obstruct a signal and, thereby, shadow the receiver. These blocks are again grouped statistically in order to mirror the distribution of the scatterers, for example a terrace would be replaced by a series of equal sized, adjacent blocks.

The mobile can receive waves either directly from one of the point scatterers or by a single reflection. The direct, or primary, waves can only pass through the
block from which they originate. If the path crosses another rectangle the wave is presumed to be invalid, Figure 3.7. A primary wave can be supplemented by a plane reflection at its point of intersection with the source block, so long as this secondary wave could have been scattered from another block. The composite signal is the complex sum of all the individual waves, as with the basic simulation.

This model is a considerable simplification of the physical situation and ignores many effects such as diffraction and change of polarisation. However, these properties are included into the approximation by the choice of amplitudes, reflectivities and phases for each block. It has been suggested that the reflectivity should follow a cosine law as in some optical systems. The basic assumption for this characteristic is that the reflecting surface is rough, the roughness being of the order of a number of wavelengths (32). This is not the

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Figure 3.7 Simulation Rules
case for VHF radio propagation in which the roughness extends from just less than a wavelength, for windows and doors, to very much less, for the texture of the stone. The model does, however, tend to restrict the waves from distant scatterers by reason of its inherent shadowing. In particular this is true for plans on which the blocks are sited along each side of the road. With this arrangement, if a wave makes a small angle to the mobile's direction of travel then it is very likely that it will be obstructed by the corner of an adjacent block, Figure 3.7.

3.4 Realisation

During a run of the simulation using a plan with 50 scatterers there would be 100 waves to be traced at each time increment. A check must be made for each of these waves to ensure that they are not obstructed by any of the rectangles, a possible 14 million checks for a typical run of 3000 increments. These figures make it imperative that the wave tracing routine is very efficient with regard both to the algorithm and to the programming. The latter has been achieved by writing the three central subroutines in assembler language, Appendix D.14.

To simplify the calculations each of the paths is traced backwards from the receiver. Every scatterer is considered in turn and the primary wave traced from the mobile to its centre. If the path does not cross any other rectangle then a valid primary wave exists. The
wave tracing continues from the point of intersection of the primary wave with the side of its source block. The direction of the new wave is chosen such that the angle of incidence equals the angle of reflection. This wave is only considered valid if its path coincides with another block on the plan. The waves and the sides of each rectangle are replaced by vectors for the actual tracing. If an intersection occurs on the extension, rather than within the length, of either vector it is disregarded.

The resultant signal is computed by summing the quadrature components of all the individual waves. The amplitudes and initial phases of each are specified by their source scatterers. The received phase is equal to the path length divided by the carrier wavelength and added to the initial phase. For the reflected waves the total path length is used for this calculation. The amplitudes for these waves are modified by the degree of reflectivity which is common to all the scatterers.

Each of these routines has been individually checked by inputting known data and comparing the output with results calculated by hand. This has showed up many weaknesses in the programs, especially when a horizontal and a vertical vector intersect each other. These tests also provided valuable information about the timing for different algorithms. Using these results, much of the data has been rearranged in order to permit sequential accessing and, hence, faster addressing modes.
3.5 **Coherent Waves**

This model of the mobile radio environment is only defined for small areas with a maximum radius from the mobile of 250 metres. The majority of the scattered waves originate within this area but there is at times a significant proportion of energy which is received either directly from the transmitter or from a prominent feature of the terrain. The path of such a signal is presumed, in the program, to be much longer than the distance of a simulation run. Its angle of arrival at the mobile is, therefore, almost constant and it can be considered to constitute a coherent wave.

Although the source of a coherent wave is assumed to exist outside the area of the plan its path is still traced in a similar manner to any other wave. It can be received by the mobile either directly or by a single reflection, Figure 3.8. The path is traced by computing the possible angles at which the wave could arrive and

![Diagram of Coherent Waves](image)

---

**Figure 3.8 Coherent Waves**
is considered to be valid if it does not cross any rectangle on the plan. Its received phase is calculated from the Doppler shift equation, Eq. 2.6, since its arrival angle is constant. Its amplitude is assigned at the start of the program and it is added to the composite signal in the same way as the other waves.

3.6 On-line Plan

Setting up and checking the input file for the simulation can be complicated and tedious if there are any number of scatterers. Each rectangle is defined on input by the co-ordinates of its centre and by its length and width, see Appendix D.2. At the start of the file there is also all the initialising data, for example carrier frequency and vehicle speed. An on-line program has been written for the small computer which allows the user to draw or modify a plan and which then outputs the data in the correct format for the main simulation routine.

The statistical plan is built up around a straight road running horizontally across it. This is also the starting point for the on-line program and is displayed on the VDU. A simple keyword command allows the user to insert a rectangle anywhere on the plan by typing in the parameters as they are requested. Each rectangle is numbered, the numbering being ordered from top to bottom and from left to right, and this allows another command to delete any rectangle. A combination of the first two commands is used to move a block within the plan. After
each operation the complete plan is redisplayed, the numbers also being superimposed unless the user switch register is set to zero.

A second section of the PLAN program draws all the possible scattered waves which are able to arrive at the mobile. It traces the waves by using similar routines to those in the main QUASIM package. The mobile itself can be positioned anywhere on the plan by use of the VDU cursor control, which shows on the screen as a bright spot. The cursor can also be used to find the relative co-ordinates of any point on the plan or, alternatively, any point can be identified by its co-ordinates. The wave tracing has been very helpful in demonstrating how the model operates and has led to some unexpected conclusions with regard to shadowing.

Other facilities within the program allow the plan and the wave traces to be drawn on an X-Y plotter, Figure 3.9. The simulation input data is entered by a separate command and is then stored on disk with all the information about the plan, see Appendix E. The complete file can be transferred to the main University computer for use with the simulation.

3.7 Programming

Most of the programming for the simulation program is straightforward and is described in Appendix D. The central section concerned with the wave tracing has been described, Section 3.4, and the analysis is discussed in Chapter 5. The remaining portion of the program which
Figure 3.9 On-line Plan Showing Wave Traces

Note: Road only shown for clarity.
requires some explanation is that which assigns each of the rectangles with their respective amplitudes and phases.

The input data includes two random numbers which are used as seed numbers for the random number generators. To produce numbers which have a uniform distribution the rounding errors of the computer are used. The central equation of the generators is:

\[ r_{n+1} = \text{REM}((r_n + k)^m, 1) \]  \( \ldots (3.1) \)

where \( r_n \) is less than and \( k \) is greater than unity. The \( \text{REM} \) function returns the remainder of a division and, in this case, returns the fractional part of the number. The value of \( m \) is not important but it should be greater than 2 and less than 10. This function has been checked and does produce a flat distribution between 0 and 1.

Also, the smallest change in the seed numbers produces a complete change in the random numbers returned by the function. So far no seed has been identified which is its own inverse or which produces a closed ring of values. These numbers, however, must exist and the data should be carefully scrutinised after each run of the simulation.

The phases are assigned to each rectangle after changing the bounds of the random number generator to 0 and \( 2\pi \). The phases are then uniformly distributed in the unit circle. Without further information to the contrary this would seem to be a reasonable choice. The amplitudes, however, are chosen to have a narrow Gaussian
distribution, as suggested by Gilbert (6). This seems, intuitively, to be better than Clarke's (7) use of equal amplitudes. The distribution has a variance of 0.1 times the value of the mean. The mean itself is defined by the transmitter power, one of the input parameters to the simulation.

The complete QUASIM package is segmented to allow the majority of the core to be overlayed and, thus, conserve space. This is especially important for the routines which employ large arrays. It also reduces the amount of storage required on disk for the complete program.
4 FIELD TRIALS

4.1 Verification

Before any simulation can be used with confidence it must be shown to be valid within specified limits. The statistical analysis of the output signal from this simulation was initially compared with that for field strength measurements recorded in many areas throughout the world (7,21). None of these gave sufficient useful information to verify the program adequately. Since it was necessary to obtain more results a comprehensive scheme of field trials was conducted in the locality of the City of Bath. The majority of these trials were concentrated on the centre of the city since it offered the widest range of environments, Chapter 6. The analysis of the recordings has established that the model for the simulation is valid for many types of urban and suburban area.

The simulation has been primarily designed to aid the study of amplitude modulated mobile radio schemes. The analysis of its output has, therefore, tended to concentrate on the magnitude rather than the phase of the received signal. This same argument applies to the field trials in which only field strength measurements have been recorded and analysed. It is highly probable, however, that if the amplitude variations of the signal are accurately reproduced then the phase shifts will be also, since the model for the simulation approximates to the physical process. This would need confirmation before the program was used with digital systems.
4.2 **Recording System**

Field trials conducted with any mobile system accentuate the normal problems of obtaining meaningful signal strength measurements. Much of the equipment is not suitable for transporting or operating in a moving vehicle. The remainder has to be carefully selected to withstand the inherent vibrations and to be able to operate from a low voltage power supply. Ossanna (5) evaded the difficulty by transmitting from the mobile and analysing the received field strength at his fixed station. Unfortunately the reciprocity which he assumed rarely occurs in practice and thus, to agree with the proposed model, the receiver must be operated in the mobile. It was decided for this project to carry out all the analysis in the laboratory and keep the amount of equipment in the vehicle to a minimum. This implies that the signal level must be recorded in a suitable form for transfer after each set of trials.

The envelope of the signal has a frequency cut off at twice the maximum Doppler shift, Figure 2.5. For a carrier at 100 MHz and a vehicle speed of 30 mph about 98% of the power in the signal is contained in the band below 9 Hz (13). Since these frequencies are so low it is not possible to directly record the envelope level onto magnetic tape. Both chart (33) and digital (21) recording have been used but the former is unable to provide the required accuracy and the expense of the latter could not be justified. Parsons (34) has made use of an FM instrumentation recorder for some of his
field trials and the same method was adopted for this work. The first trials used a two channel machine, the field strength being recorded onto one track and a control signal onto the other. Later a further recorder was purchased which had three FM channels and one direct channel, this last being used for making vocal notes during each trials' run.

4.3 Signal Compression

An FM recorder rarely has a usable dynamic range of more than 20dB. The signal level, however, generally experiences fades in excess of 30dB below the mean level which may itself vary by another 20dB. To allow the signal to be accurately recorded, therefore, it must be compressed according to a well defined law to enable it to be expanded again for processing. It is possible to use the inherent compression of the AGC voltage (33, 34) but a more recent, and more reliable, system involves a true logarithmic amplifier (21).

In a standard communications receiver the AGC voltage is derived by detecting and filtering the signal at the end of the IF strip. This voltage is fed back to both the RF front end and the first IF transistor. In each case it is used to control the gain of the stage in order to maintain a reasonably constant level at the audio output. In general the AGC voltage is designed to follow an approximately logarithmic characteristic with respect to the received signal level. The RF control is usually "delayed", that is it only operates at higher
levels, and this causes a knee in the characteristic curve. This effect is clearly evident in the AGC curve for the receiver used in the trials, Figure 4.1.

The second method of measuring field strength uses an amplifier whose gain varies logarithmically over a dynamic range of over 60dB. If the amplifier is chosen to operate at IF then it is still possible to receive the signal with the normal RF stages of the radio and extract it just prior to any IF AGC. The gain of the front end can be set at a value which corresponds to the mean level of the input signal and can be altered to maintain the dynamic range as this mean varies.

All the early trials used the AGC voltage as the measure of the field strength. It was soon noted that this voltage did not follow the signal down into the deeper fades because of the duration of the AGC time constant. The circuit was modified to ensure that this...
time constant did not exceed 30ms and, since the network could not be easily analysed, this was confirmed by on-line measurements. After this alteration the trials' recordings appeared to be more reliable but they still occasionally produced spurious or inconsistent results. From the characteristic curve, Figure 4.1, it is clear that fairly large signal variations around -110dBV can only cause small changes in the output voltage. This tended to reduce the accuracy of the recordings for signal levels in that region but could be compensated for simultaneously with the other departures from a perfect system. It was also discovered, however, that the knee on the characteristic could move by up to 10dB during a half hour series of trials due to thermal instability. Even when the receiver was allowed to attain ambient temperature before being characterised, it was noted that the knee was still apt to shift. The system was finally abandoned after it became obvious that the system could not be relied on to provide either accurate or consistent results.

After careful consideration, the logarithmic amplifier was adopted as an alternative method for the measurement of field strength. These are widely used in video and microwave systems to provide a constant level output signal and a logarithmic control voltage. Most commercial amplifiers, including the one chosen by French (21), operate above 10 MHz. The receiver being used had a very low output at the higher IF and, thus, a 455 kHz amplifier was constructed based around a
monolithic integrated circuit, see Appendix G.3. This system was subjected to the same type of environmental tests as before and showed no perceptible change in the characteristic for an ambient increase in temperature of more than 20°C. Even if there had been a slight change its effect would have been negligible since the curve is almost smooth, Figure 4.1. The integrated circuit has a frequency range of 0C to 10 MHz over which it provides true logarithmic compression. There is, therefore, no difficulty in tracking at the maximum fading rate but, instead, the output has to be low-pass filtered to remove unwanted noise.

4.4 Characterisation

The gain of the RF stages in a commercial receiver is liable to alter with large variations in the level of the input signal. The consequence of this is that, even when using the logarithmic amplifier, the measured voltage seldom has any simple relationship to the field strength. The function is further complicated when the output voltage is generated by the AGC, Figure 4.1. The absolute signal level can be most easily recovered from the recordings by interpolation of the system's characteristic curve.

An automatic test procedure has been devised which allows the complete system to be quickly and efficiently recharacterised before and after each series of trials. When the AGC voltage was employed as the measure of the signal level this facility was very useful in order to
determine how much confidence could be placed in the results. Even with the logarithmic amplifier the system is checked before each run to ensure that any changes in the equipment do not affect the analysis. It has also been useful in preventing measurements being made with any part of the system set incorrectly.

For the characterisation the input signal is fed to the receiver through an attenuator, Figure 4.2. The computer controls the level of attenuation and, at each step, records the voltage by means of its A/D convertor. To maintain the accuracy of the system, the input signal is incremented in steps of 1dB between -60 and -130dBV. At each step the computer waits five seconds, samples the convertor, waits again, and then resamples. This process continues until two consecutive samples have the same value and ensures that both the attenuator and the receiver are given sufficient time to settle.

![Figure 4.2 Automatic Characterisation](image)
Plate 1  PDP8/e Mini-Computer

Plate 2  Equipment Set Up For Characterisation
4.5 Trial's Procedure

After characterising the complete recording system it is placed in the vehicle. All the equipment has been designed to operate from a standard lead-acid 12V battery, although the instrumentation recorder also requires a mains inverter. The signal is received with a quarter-wave, vertical, whip aerial mounted centrally on the roof of the vehicle. Only the control box, which provides facilities for adding both a voice track and markers, need be available to the experimenter. The rest of the equipment is arranged at the back of the vehicle, Figure 4.3.

All the measurements can be made if only a carrier is transmitted but this is usually modulated with a tone to permit the system to be monitored audibly. The base station also includes a talk-back link in order to maintain contact with the mobile. Most of the trials have been conducted within the City of Bath since it offers a very wide range of environments. The model for the simulation is only defined for straight, short distances for which there is no major change in the immediate locality. These constraints limit the areas in which practical measurements can be made but a number of roads have been selected in the city which provide the right conditions, see Chapter 6.

The control box simplifies the recording of the output voltage in the vehicle and its subsequent analysis in the laboratory. The FM tape recorder is set to run before each trial with the output voltage fed to
one track and the control signal to a second. This latter signal is held at 0V until the vehicle reaches a predetermined speed and the signal is then increased to 1V. This speed is held constant throughout the run, the speedometer being presumed to be accurate enough for these trials. As the vehicle passes prominent features the tape can be marked by reducing the control signal to ½V momentarily. The voice track can also be used to make notes but this will be inherently less accurate. At the end of the run the control signal is again reduced to zero and the tape stopped. Since the sampling of the tape is solely controlled by this signal fairly long leader and trailer sections can be left to separate the individual trials. The system has been arranged so that one person could, if necessary, conduct the trials alone but, for reasons of safety, there is usually a separate driver.
After a series of field trials has been completed, the equipment is moved back to the laboratory. When necessary the recording system is immediately checked and its characteristic compared with the one obtained before the run. The next stage is to quantize the data and reduce it to a number of meaningful statistics.

The data is quantized by a computer, Figure 4.4, and stored directly on disk. Both tracks of the FM recorder are connected to the A/D convertors before the sampling program is initialised. The program begins by requesting parameters such as the carrier frequency and opens an unformatted data file, see Appendix F.4. It then waits for the tape recorder to be started, and the keyboard flag raised, before it commences sampling the
control signal. As soon as this signal rises above $V$ the computer begins to sample both tracks and continues until the control again falls to zero. The data file is then closed and the program repeats the dialogue to initialise the next run.

In previous work the sampling rates have varied widely, from 1.34 (33) to 43.54 (21) samples per carrier wavelength. The compression of the signal variation, by giving prominence to the fades, tends to spread the frequency content of the data. This would suggest that the sampling rate should be well above the Nyquist rate to give good definition to the statistics. For these trials the rate was gradually increased until no further significant alteration was observed in the statistics. At this rate, nearly 20 samples per carrier wavelength, there should be practically no aliasing and this was later confirmed by the power density spectra which had decayed to near zero well within the frequency limit. By not using an excessively high sampling rate the volume of data was kept to a minimum, a very important consideration when using a small computer.

The original sampling program was written in a high level language and used straightforward techniques. This later had to be altered to permit sampling at the required rate. The program now in use operates under interrupt processing, transferring data to disk from one buffer while sampling into a second. This routine could be used at much higher rates than used so far and will be of use if the work is extended to UHF.
4.7 Initial Processing

The majority of the statistical analysis is done on the main University computer network. Before the data is transferred from the small computer, on which it was sampled, it must be corrected and formatted. A number of routines are available on this computer to also check that the data is worth analysing, especially with regard to avoiding large variations in the mean level of the signal.

After the recorded tape has been sampled the data is stored on disk. Since the recording system does not have a perfect characteristic, Figure 4.1, this data has to be corrected by interpolating the curve. At the same time the markers are noted and all the information is written to a new file, Appendix F.4.

The signal level for each run can be plotted and, if required, the mean level can also be superimposed. This mean is calculated as a running average, see Chapter 5, and is also given as the absolute mean between any two markers. From the plots, Figure 4.5, a very general impression of the fading can be gained and also an idea of how stationary the statistics are. If there is a large change in the mean level at any point it suggests that there was also a significant change in the environment. This can be seen in the plot for Great Pulteney Street, Figure 4.5, at about 16 seconds through the run when the mean level increases by almost 10dB. When compared with the markers this corresponds to a short side road which permits the mobile to receive
Figure 4.5  Time and Mean Profiles for Gt. Pulteney St.

Figure 4.6  Distribution of Fades for Gt. Pulteney St.
a fairly large coherent wave.

The small computer can also calculate a cumulative distribution for any part of the data. The signal level is first normalised with respect to the running mean and then analysed over 50 increments. The output is again plotted, Figure 4.6, and the Rayleigh distribution curve is superimposed. The lack of core store limits this analysis to short sections but it is useful in checking that the distribution is stationary through the run.

4.8 Formatting

The data files on the small computer are mostly unformatted to save storage space and to reduce access time. Before the data can be transferred to the main University computer these files must be divided into sections and formatted to suit the QUASIM package, see Appendix D.2.

Using the results provided by the processing on the small computer, the files can be divided in such a way as to avoid any unwanted sections of the data. The markers are again very useful as guides. The new files provide all the information needed by the QUASIM package and are correctly structured to be used directly as its input file.

The formatted files are transferred to the main University computer by means of an asynchronous link. The handlers at each computer ensure that the data, although differently coded, is correctly transferred. A simple batch file initiates the rest of the analysis.
5  ANALYSIS

5.1 Initialising

The analysis routines for this project provide the statistical results for both the simulation and the field trials. By using the same routines for both functions it is possible to directly compare all of the statistics with confidence. The QUASIM package has been developed to include all the necessary processing within the one main program.

The data collected during field trials, cf. Chapter 4, is transferred to the University computer as a file which can be used directly with QUASIM. The first line of the file identifies it as trial data and, after some basic information, the magnitude of the envelope is presented in dBV. The input file for a simulation run is similarly identified but it contains information pertaining to the environmental plan, see Appendix D.2.

After the simulation itself is complete the complex signal is reduced to the magnitude of the envelope and the rest of the package is common to the two sets of data.

A number of different statistics can be selected for use in the analysis. In each case the outputs can be plotted on an incremental graph plotter or on the line printer or on both. The line printer graphs are of necessity scaled with linear axes but give a rough impression of the output. The scaling on the graph plotter can be very much more complex to allow faster interpretation of the results. This is used especially
for the cumulative distribution which is plotted on computer generated probability paper, on which the true Rayleigh curve is a straight line. The "Rayleigh" curves are superimposed on most of the statistics to aid comparison between separate runs. It should be stressed that, since the simulation aims to represent the actual fading in different environments, neither the simulated nor the field trial results are expected to conform to the "Rayleigh" curves. However, these curves are useful as well defined standards for each statistic.

The individual parts of the analysis, and how each is plotted, are selected by a second input file. The data in this file consists of a keyword followed by one or more numbers, Appendix D.2. The first number selects the type of output and the others, when required, provide essential data for the analysis, for instance the number of steps for the cumulative distribution. The program automatically chooses default values for any data not given.

5.2 Running Mean

The model for the simulation only represents the multipath fading. It is not defined for variations in the mean level and, hence, these must be removed before the analysis starts. With the field trials changes in the mean in excess of 20dB occur not infrequently but these are avoided when selecting the portions of data for analysis, see Section 4.8. There still remains a
significant variation in the mean level which is also evident in the simulated signal.

In the past the mean level has been obtained by reducing the sampling rate (33) but it is now accepted that a more accurate measure is the sliding, or running, mean. Okamura (3) used a basic form of this technique by averaging over small sections of the data and using these small sector means to build up a complete mean profile for any run. French (21) computed his mean by starting with a small sector but, instead of continuing with a totally new sector, he then removed the first 400 data points, added the next 400 data points and calculated the next mean with this modified sector. In this work the method is further refined by only sliding the sector by one point at a time.

![Diagram](image)

**Figure 5.1 Averaging Methods**

In many previous discourses about fading in the mobile radio environment multipath fading and variations in the mean level have been assumed to be totally separate processes, often referred to as fast and slow
Fading respectively. Any distinction of this kind must be made with the upmost care since the received signal level is dependant on a very wide range of factors. A strong coherent wave will tend to increase the mean level of the signal but it will also interfere with the other scattered waves and, thus, contribute to multipath fading as well. The two types of fading are usually divided with respect to their frequency components which tend to occupy separate bands. The choice of any cut off frequency between the bands must be a compromise and widely differing values have been selected in the past.

The methods of obtaining the mean, as described above, all approximate to a digital low pass filter. If this mean is divided into the original data then the quotient corresponds to the output from a normalising filter. The filter cut off frequencies are directly related to the size of the small sector, that is the averaging period. The rate of fading, due to multipath propagation, is proportional to the carrier frequency. It is thus more meaningful to express the averaging period in wavelengths rather than in time or distance.

Clarke (7) averaged his data over a period of 7.5 wavelengths and French (21) over a period of more than 65 wavelengths, in both cases seeking to analyse the multipath fading. In order to analyse the variation in mean level Okamura (3) used a period of between 30 and 100 wavelengths, depending on the carrier frequency. As with the sampling rate, the averaging period for this work was chosen by increasing the period until no more
change was observed in the statistics. After repeating this procedure for many different sets of data the value selected was 10 wavelengths. This could have been increased up to 30 wavelengths before the mean variation significantly affected the results. It was maintained at the shorter length to conserve both time and space.

Peritsky (35) records a method of estimating the mean signal strength even if the data is expressed in decibels. An essential assumption of the estimator is that the distribution of the data is Rayleigh. Since this assumption is alien to this work all the data has to be translated to its linear form before the mean is computed. After the data is divided by the sliding mean it is normalised to unity rms and is then in a suitable form for further analysis. Facilities are available for plotting both the mean and normalised envelope profiles.

5.3 Cumulative Distribution

A cumulative distribution is easily computed for any set of sampled data. The range under consideration is divided into a specified number of equal intervals and each sample is matched to its relevant level. The corresponding step, and all those above it, are then incremented. By repeating the procedure for the complete set of data the distribution is gradually built up.

The realisation of this process is simplified in FORTRAN IV by the way in which the data arrays are organised. Instead of having to compare the samples with each interval on the distribution to find a match
they can be directly related to the correct element of the array. The rest of the elements above that which is selected are then incremented. The distribution is computed for the data expressed in decibels in order to accentuate the probabilities of deep fades.

When the distribution is plotted on the incremental graph plotter the probability axis is stretched. The equation for this axis is:

$$y(r) = 10 \times \log_{10}(-\log_{10} P(r > R))$$  \hspace{1cm} \text{(5.1)}$$
in which the specified level, $R$, is plotted in decibels on the other axis. Using this scaling the Rayleigh curve becomes a straight line, Figure 5.2.

### 5.4 Power Density Spectra

The power spectrum of a random process can be defined by the Fourier transform of its autocorrelation function.
function. Using sampled data the autocorrelation can be computed as:

\[ R_n = E(r(t)r(t+nT)) \quad 0 \leq n \leq N \quad \ldots (5.2) \]

where \( T \) is the sampling interval. This gives a function of \( N \) points which should have decayed to nearly zero.

Before the data is presented to the FFT routine it is reflected about its end point to create a double sided function. Since the data in the time domain is real and symmetric the spectral output is also real and symmetric.

Both the autocorrelation function and the power density spectrum can be plotted. The spectrum is more usually drawn against logarithmic axes. Before the magnitudes of the spectral components are converted to their decibel form they are averaged in order to remove the fine structure inherent in the data. The maximum frequency is defined by the sampling interval while the frequency intervals are equal to \( 1/(\cdot T) \), (36).

5.5 Other Statistics

At present only two other statistics can be found using the QUASIM package. These are the crossing rate and the mean duration of fades. In each case their calculation is not complicated and is achieved by comparing each envelope sample with a number of levels specified by the program, Appendix D.4. Both of these statistics are plotted against logarithmic axes in order to accentuate the characteristics of the signal in the deeper fades.
6 RESULTS

6.1 Specification

The main purpose of this section is to demonstrate the validity of the simulation model and its software realisation. Three particular sets of statistics are included which illustrate individual characteristics of multipath fading. The first is a general suburban road which is well represented by the "Rayleigh" model. The second has a very significant coherent wave and the last shows the effects of signal channeling. In each case statistics are presented for the practical field trials and a simulated run using QUASIM. All the results are plotted over the theoretical "Rayleigh" curves in order to facilitate comparisons.

Each of the sets of field trials were conducted within the City of Bath. The transmitting site was at the School of Electrical Engineering using a standard commercial communications radio, see Appendix G. The carrier had a frequency of 86.2875 MHz and was modulated by a 1kHz tone to a depth of about 30%. This tone was only used to provide an audible check in the mobile.

The tests were carried out as outlined in Chapter 4 using a vehicle speed of 20 mph, 8.94 ms⁻¹. Most of the runs covered a distance of more than 300 m but analysis was performed for no more than 100 m at a time. After the measurements had been made the data was quantised at a rate of 50 samples per second. The true signal levels were recovered by interpolating the system characteristic and the data was transferred to the main computer.
The simulation runs were initialised with the same parameters as used for the field trials, for example the mobile speed and carrier frequency. The plans of the areas were compiled by considering the physical locality for each trials' run. These were inspected using the on-line plan program to gain an impression of the signals arriving at the mobile receiver. Using this information modifications were made to the plans in order to improve the representation. Many of these changes concerned the sizes of the individual blocks. Further changes were implemented after the simulated results had been interpreted although no significant deviations were noted in the statistics.

The analysis for both practical and simulated data was performed by QUASIM. The slow variations in the mean level of the signal envelope were removed by averaging over 10 wavelengths, 3.9 seconds. All of the statistics were plotted after the signal was normalised to unity variance. The cumulative distribution, fade duration and crossing rate were calculated for 100 steps between -25dB and 15dB but are only plotted here at 2.5dB intervals. The autocorrelation function and power density spectrum were computed over 512 points.

6.2 Great Pulteney Street

The City of Bath offers few, if any, truly urban environments. Great Pulteney Street is a long, straight, wide road bordered on each side by tall terraced houses. It runs in a SW-NE direction with the transmitting site...
to the SE at an angle of approximately $50^\circ$ to the road, Figure 6.1. It has three side roads which lead to open areas. The trials' runs can use the full length of the road but the signal increases sharply at one point where a significant coherent wave is reflected from the side of a building, Figure 4.5.

The environmental plan, Figure 6.1, reflects the general layout of the buildings along Great Pulteney Street. The blocks are 10 m wide and from 20 m to 40 m long. Using different lengths reduces the regularity of the plan which can introduce large, but spurious, frequency components. The whole plan is offset by 5 m to allow the mobile to travel along one side of the road rather than down the middle. The blocks have been included well beyond each end of the run to diminish any end effects. These blocks tend to contribute more reflected, rather than primary, waves.

The statistics for both the practical and simulated signals are plotted in Figures 6.2 to 6.4. The mean level of the practical signal was around $-100$ dBm. The cumulative distribution, crossing rate and fade duration all show a marked similarity to the statistics for the theoretical "Rayleigh" model for both signals. This result agrees with measurements made by many other researchers (6,7,27). The power density spectra have the general form of the theoretical curve. Their most prominent feature is the sharp cut off at twice the maximum doppler frequency. The statistic is sensitive to almost any change and is very difficult to interpret.
6.3 Newbridge Road

Newbridge Road is about 5 km from the transmitting site and is very wide with two-storey semi-detached houses spaced along each side. Since it is very open it receives a strong coherent wave directly from the transmitter. The road runs from NW to SE at an angle of $20^\circ$ to the direct wave. The environmental plan, Figure 6.5, illustrates the physical characteristics of the area. The angle of its coherent wave has been reduced to $5^\circ$ since otherwise it would be obstructed by the blocks. In the practical situation the coherent wave passes above the buildings because the transmitter is over 200 m above them.

The statistics demonstrate the effect of a strong coherent wave, Figures 6.6 to 6.8. The time profile of the fading signal shows a smaller variation than for Great Pulteney Street, Figure 6.2. This is supported by the cumulative distribution which suggests a range of $-12\,\text{dB}$ to $5\,\text{dB}$ with respect to the mean power level. The level crossing rate shows an equally reduced range but this is less pronounced for the fade duration. The simulated run had a coherent wave amplitude of $5\,\text{dB}$ above the mean power for the non-coherent part of the signal. The mean level for the practical signal was $-96\,\text{dB}$. The power spectrum includes a very sharp peak at twice the maximum Doppler frequency. This agrees with Eq. 2.14 since the arrival angle of the wave is small. Once again the spectra are reasonably different and suggest that some modifications to the plan are needed.
6.4 The Paragon

Cox (1) has recorded the effects of channeling in the heavily built-up areas of New York. Allen (54) noted an increased error rate in his digital scheme for some roads in the City of Bath. In many environments channeling can cause unexpected results. The Paragon demonstrates some of these effects, although not to a very marked degree.

This street runs from N to S at right angles to the transmitting site. Between the mobile and the transmitter there is a very long terrace of about 12 m high. On the other side of the road a raised pavement runs in front of a varied set of buildings which back onto a steep hillside. The road itself gently curves and has fairly open areas at each end. The statistical plan represents the general layout, Figure 6.9, although it cannot be accurate since the mobile is constrained to travel in a straight line. The blocks are chosen to be only 5 m wide to permit primary waves to make small angles with their fronts.

Although this street is blocked from all direct waves from the transmitter it is remarkable that the received signal is up to 10dB higher than that in Great Pulteney Street. An examination of the statistics reveals the peak on the power spectrum at nearly twice the Doppler frequency. This suggests a coherent wave from the ends of the street, although the transmitter is at right angles to it. The simulation also shows this feature on its spectrum with no coherent wave.
included in the model. The signal appears to be caught in the street and to be reflected back and forth along its length. In more open areas the signal would tend to disperse but here it can only escape at the ends of the road. This channeling causes the received wave to arrive from either directly behind or in front of the mobile, which produces the peak on the spectrum. The curve of the actual street channels the signal at a small angle to the direction of travel and, therefore, the peak occurs at a slightly lower frequency.

The other results show similar characteristics as for the "Rayleigh" model. The peak of the crossing rate is higher than for the theoretical model and increases with the channeling effect. The interference of the channeled waves can increase the incidence of very deep fades. This is not evident from the cumulative distribution, Figure 5.10, since the channeling effect in this case is not very marked.

6.5 Conclusions

These results have demonstrated the versatility of the simulation. No attempt has been made to accurately reproduce the received signal but, for each case, the statistics of the two signals are very similar. The model has been shown to be valid for these three areas but more testing is required to ascertain its limitations and to develop its applications.
Plate 3  Great Pulteney Street, Bath  (looking SW)

Plate 4  Great Pulteney Street, Bath  (looking NE)
Map of Test Area

Environmental Plan

Figure 6.1  Parameters for Great Pulteney Street, Bath
Figure 6.2 Statistics for Great Pulteney Street, Bath
**Level Crossing Rate**

**Mean Duration of Fades**

Figure 6.3  *Statistics for Great Pulteney Street, Bath*
Figure 6.4  Statistics for Great Pulteney Street, Bath
Plate 5  Newbridge Road, Bath  (looking SE)

Plate 6  Newbridge Road, Bath  (looking NW)
Figure 6.5  Parameters for Newbridge Road, Bath
Figure 6.6 Statistics for Newbridge Road, Bath
Level Crossing Rate

Mean Duration of Fades

Figure 6.7  Statistics for Newbridge Road, Bath
Figure 6.8  Statistics for Newbridge Road, Bath
Plate 7  The Paragon, Bath  (looking N)

Plate 8  The Paragon, Bath  (looking S)
Map of Test Area

Environmental Plan

Figure 6.9 Parameters for The Paragon, Bath
Simulated Time Profile

Cumulative Distributions

Figure 6.10  Statistics for The Paragon, Bath
Level Crossing Rate

Mean Duration of Fades

Duration of Fades Below $R - t[R]$ (s)

Figure 6.11 Statistics for The Paragon, Bath
Figure 6.12  Statistics for The Paragon, Bath
7 SIDEBAND DIVERSITY

7.1 Principles of Diversity

As may be appreciated, the variations of the signal level received at the mobile can cause a severe loss of intelligibility in a speech channel. This restriction is accentuated with data transmission for which signal fading often entails an unacceptable error rate. Many techniques have been studied in order to increase the reliability for all types of mobile radio channel. They can be broadly split into two main categories; those that operate solely within the receiver and those that employ some form of diversity.

All communications' receivers employ AGC to reduce the effect of fluctuations in input level on the final output. In order to retain the stability of all of the amplifiers the AGC usually has an integral filter which increases its response time. If the AGC is required to also counteract the effects of multipath fading, at VHF or UHF, then its time constant must be reduced with the consequent decrease in stability. The use of Forward Acting AGC (37,38) can realise both a fast response and good stability, but the circuits are, so far, complex and require very critical setting up.

Work has also been carried out to reduce the phase errors due to the random frequency modulation of the received signal. The front end local oscillator in the receiver is modified such that it is phase locked to a tone transmitted within the coherence bandwidth of the signal (39). Since the phase errors of this tone are
almost equal to those for the rest of the received signal they should cancel out, producing a demodulated output which is only distorted in amplitude. Another version of this principle uses the carrier as its reference (40). These techniques are not limited to double sideband systems but are now being employed in single sideband receivers as well (41).

A receiver can only operate down to a specified threshold level below which point both AGC and phase correction circuits cease to be of any benefit. Since it is these deeper fades that reduce the information capability of a mobile radio channel it is essential to lessen their probability of occurrence. In diversity schemes two or more separate signals are simultaneously received and combined to produce an output that suffers less from fading. When the signals are uncorrelated the greatest advantage is gained from the system. The benefit is still significant, however, at correlation coefficients as high as 0.7 (42).

Of the many types of diversity system which have been developed the most widely used is space diversity (14,43-47). The autocorrelation function for a random Rayleigh distributed variable is given by:

\[ R_r(\tau) = \frac{11}{2} \left( 1 + \frac{D^2(\tau)}{4} + \frac{D^4(\tau)}{64} + \frac{D^6(\tau)}{256} + \ldots \right) \quad \ldots (A.23) \]

in which the correlation coefficient is:

\[ \rho(\tau) = R_{cc}(\tau) = J_0(\omega_0 \tau) \quad \ldots (A.22) \]

This can be plotted as a spatial correlation in terms of wavelengths, \( \lambda_c \), at carrier frequency, Figure 7.1.
Figure 7.1 Envelope Correlation Functions

This function demonstrates that the correlations for signals received by aerials spaced more than a quarter wavelength apart will be less than 0.2. This spacing can be easily achieved on most vehicles when operating at 100 MHz since the aerials need have a spacing of only 0.75 m. Above this frequency it is possible to use an array of aerials and, thereby, employ techniques such as self-phasing (47).

Field diversity can be accomplished by use of a specially designed aerial. If the electric and magnetic fields are received at the same point then, from Figure 7.1, their coefficient of correlation is zero. Similar principles are considered with other forms of diversity. The differentiation in the signals can be of many sorts and has included frequency, polarization and time (15).

After reception the signals are processed in order to provide the optimum output. The most fundamental
The other principle method of processing involves combination of all the signals to generate the output. Kahn (50) proposed that each signal should be weighted according to its SNR. The slight improvement of this over the equal gain combiner seldom justifies its extra complexity. The combiners do have significantly better performance than the selection system so long as the correlation between the signals is low (14), Figure 7.3.

7.2 Multiple Transmitter Schemes

Although the diversity systems described above can reduce the short term fading they are unable to counter the variations in the mean level of the signal. Remote stations are often required, especially in hilly areas, to provide a reasonable service to all sectors within a mobile radio scheme. The same technique can also reduce the effects of channeling in urban environments. These have been shown to causes changes in mean signal level
Figure 7.2 Types of Switch Combiners

Figure 7.3 Improvement in SNR Using Combiners

Note: Zero correlation between signals
in excess of 20dB within New York City (1).

The mutual interference of the transmissions at a mobile receiver produces short term fading which has similar statistics to that for a single transmitter scheme. This presumes that the individual signals are uncorrelated and have "Rayleigh" statistics and is a consequence of the Central Limit Theorem (9). If the signals are partially correlated, however, the degree of fading can be very substantially increased. In some early schemes (5) the spacing of the carrier frequencies was much greater than the audio bandwidth. This allowed the use of frequency diversity at the receiver. The reduction of channel spacing from 50 kHz to 12.5 kHz in recent years has made this type of scheme unacceptable. Current multiple transmitter schemes use synchronous or quasi-synchronous carriers, the latter now being more popular due to advances in system design. The standing wave interference pattern caused by the combination of scattered waves from each transmitter, moves slowly over the service area in a quasi-synchronous system. In this situation the receiver experiences the same degree of fading whether it is moving or stationary. This also overcomes the problem of a vehicle stopping in a null of the signal.

In a quasi-synchronous scheme the frequencies of the carriers are usually separated by no more than a few hertz. When the relative signal levels are nearly equal the beat frequency is masked by the multipath fading, so long as the signals are uncorrelated. If the difference
in mean levels is significant then their mutual interference can be neglected. It has been noted that when the phases of the received modulation are not the same for each signal then the output suffers harmonic distortion (52,53). This distortion occurs because of the way that the complex signals interact. The phasors of the upper and lower sidebands rotate in opposite directions with respect to the carrier component. Any phase difference in the modulation, however, is added in the same direction for each sideband, Figure 7.4. It can be seen that the resultant sidebands have unequal amplitudes. By demodulating the sidebands separately a further type of diversity reception can be achieved, namely Sideband Diversity.

7.3 Sideband Diversity

Gosling and Petrovic (33) were the first to study Sideband Diversity in connection with VHF mobile radio. This work has been extended both theoretically and practically by Allen (54). This form of diversity can only be utilized in a multiple transmitter scheme, the individual stations operating quasi-synchronously or synchronously. For the basic system the sidebands transmitted from each station are the same as in a standard AM transmission. The sidebands can also be amplitude or frequency modulated sub-carriers (55). In each case the theoretical analysis is similar and only the basic system will be considered here.
Total Received Signal

- $f_c$: Carrier frequency
- $f_t$: Tone frequency
- $d_2$: Modulation phasing

Sidebands after Demodulation

Figure 7.4 Phasor Diagram for Two Station Scheme
Within small service areas the distance between a transmitter and receiver is much smaller than the audio wavelengths, 100 km at 3 kHz. This means that there is a negligible phase error between signals received from separate stations. In order to ensure that there is a reasonable phase difference between the modulations of the received signals, therefore, they must be phased before being transmitted.

The complex vectors for each sideband can be found by considering the phasor diagram for the total signal received, Figure 7.4. The system has been assumed to be synchronous in order to simplify the diagram. The analysis can be extended to quasi-synchronous operation also. The complex sidebands are defined as:

\[ Z_u = T_{cu} - jT_{su} \]
\[ Z_1 = T_{cl} - jT_{sl} \]

where the quadrature values \( T_{cu}, T_{cl}, T_{su}, & T_{sl} \), are given by the vector sums of the individual components, see Appendix C.1. If the distributions of the fading for each transmitter are assumed to be independant and Rayleigh then the quadrature components are normal random variables with zero means and equal variances, Eq. C.5. The magnitudes of the sidebands are then, by definition, Rayleigh distributed random variables, cf. Section 2.3.

\[ r_u = |Z_u| = (T_{cu}^2 + T_{su}^2)^{\frac{1}{2}} \]
\[ r_1 = |Z_1| = (T_{cl}^2 + T_{sl}^2)^{\frac{1}{2}} \]
The only improvement in quality for either of the sidebands, with respect to a single transmitter scheme, is due to the increased mean power level. However, if the magnitudes of the sidebands are not correlated, the final output can be derived by selection or combination to produce a signal which experiences less variation in level. When the sidebands are statistically independent then the joint density function is equivalent to the product of the individual density functions:

\[ f(r_u, r_l) = f(r_u) f(r_l) = \frac{r_u r_l}{\sigma_T^4} \exp\left(-\frac{(r_u^2 + r_l^2)}{2\sigma_T^2}\right) \quad \ldots (7.1) \]

The variance, \( \sigma_T^2 \), is the same for each sideband and is equal to the sum of the individual variances, Eq. C.5. The distribution function for the selected signal is:

\[ F(r < R) = (1 - \exp\left(-\frac{r^2}{2\sigma_T^2}\right))^2 \quad \ldots (7.2) \]

This distribution, Figure 7.5, shows the maximum degree of improvement obtainable with this diversity scheme, since it is limited to two branches, i.e. the sidebands.

In general the sidebands are partially correlated and this tends to degrade the system. The coefficient of correlation cannot be expressed simply for the two envelopes except in terms of the correlation of the complex sidebands, Eq C.19. This coefficient can be shown to be, see Appendix C.2:

\[ |P_2|^2 = \frac{|C_z|^2}{4 \sigma_T^4} = \frac{\left( \sum \sigma_n^2 \cos(2 d_n) \right)^2 + \left( \sum \sigma_n^2 \sin(2 d_n) \right)^2}{(\sum \sigma_n^2)^2} \quad \ldots (C.15) \]

for which \( d_n \) is the relative phase of the modulation and \( \sigma_n^2 \) the variance for each transmitted signal.
Figure 7.5 Distributions for the Diversity Scheme

- Probability that Signal Specified Level

- Specified Level - R (dB relative to rms)

- Correlation Coefficient:
  - 0.0
  - 0.6
  - 0.8
  - 0.9
  - 0.95
  - 0.98
  - 1.0
The joint density function for the complex sidebands can be found by considering the joint density for four normal random variables (9). In this case the variables are $T_{cu}$, $T_{su}$, $T_{cl}$, & $T_{sl}$. By changing the variables to polar, Eq. C.31, the density function becomes:

$$f(r_u, r_l, \beta, \delta) = \frac{r_u r_l}{4 \pi^2 \sigma^4_T (1 - \rho^2_T)} \exp\left(-\frac{1}{2 \sigma^2_T (1 - \rho^2_T)} \right) \exp\left(-\frac{r^2_u + r^2_l - 2 r_u r_l (\rho_{13} \cos(\delta) + \rho_{14} \sin(\delta))}{2 \sigma^2_T (1 - \rho^2_T)}\right) \quad \ldots \quad (C.34)$$

where $\beta$ and $\delta$ are the phases of the upper and lower sidebands respectively and $\delta = \beta - \delta$. By integrating with respect to both phase shifts the joint density function for the magnitudes of the envelopes can be expressed in terms of a modified Bessel function, $I_0(x)$:

$$f(r_u, r_l) = \frac{r_u r_l}{\sigma^4_T (1 - \rho^2_T)} \exp\left(-\frac{r^2_u + r^2_l}{2 \sigma^2_T (1 - \rho^2_T)}\right) \cdot I_0\left(\frac{\sqrt{2} r_u r_l}{\sigma^2_T (1 - \rho^2_T)}\right) \quad \ldots \quad (C.39)$$

When the final output signal is derived by selection the system is analogous to Downton’s parallel reliability (56). He has manipulated Eq. C.39 in order to obtain an expression for the density function of the selected signal. This equation, Eq. C.44, still contains an integral and can only be evaluated numerically. Using computer techniques the second integral, Eq. C.47, has been computed for various values of correlation. This family of curves, Figure 7.5, demonstrates how the system performance changes with correlation. However, even with $\rho_T$ at 0.8 there is 7dB improvement at a level of 0.95.
7.4 Two Station Scheme

Some useful information can be gained about the implementation and effect of the system by applying the above theory to a two station Sideband Diversity scheme. With one transmitter acting as a reference, plots can be made of the correlation coefficient as the mean level and the modulation phasing changes. Letting \( d_1 \) be zero, Eq. C.15 simplifies to:

\[
D_r = \frac{(\sigma_1^2 + \sigma_2^2 \cos(2d_2))^2 + (\sigma_2^2 \sin(2d_2))^2}{(\sigma_1^2 + \sigma_2^2)^2} \quad \cdots (7.3)
\]

By differentiating this expression with respect to the phase the minimum correlation can be shown to occur when the modulation phase, \( d_2 \), is \((2n-1)\pi/2\). Similarly, the minimum correlation occurs when the variances of the two signals are equal. This can also be deduced from plots of the function, Figures 7.5.

With \( d_2 = \pi/2 \) the sidebands can be derived from Eqs. C.1 to C.3 as:

\[
Z_u = (T_{c1} - T_{s2}) - j(T_{s1} + T_{c2}) \quad \cdots (7.4)
\]

\[
Z_1 = (T_{c1} + T_{s2}) - j(T_{s1} - T_{c2})
\]

This can be expressed in polar form as:

\[
Z_u = r_1 \cos(\theta_1) - r_2 \sin(\theta_2) - j(r_1 \sin(\theta_1) + r_2 \cos(\theta_2)) \quad \cdots (7.5)
\]

\[
Z_1 = r_1 \cos(\theta_1) + r_2 \sin(\theta_2) - j(r_1 \sin(\theta_1) - r_2 \cos(\theta_2))
\]

and therefore the magnitudes are:

\[
r_u = (r_1^2 + r_2^2 + 2 r_1 r_2 \sin(\theta_d))^{\frac{1}{2}} \quad \cdots (7.6)
\]

\[
r_1 = (r_1^2 + r_2^2 - 2 r_1 r_2 \sin(\theta_d))^{\frac{1}{2}}
\]
Figure 7.5 Correlations for Two Station Scheme
With a synchronous system the phase angle $\theta_d$ represents the difference between the random phase shifts of the two signals. In a quasi-synchronous system, however, this phase angle also includes the shift due to the offset in carrier frequency, $\omega_q$, between the stations:

$$\theta_d = \theta_1 - \theta_2 + \omega_q t \quad \ldots \quad (7.7)$$

If the mobile is stationary then the magnitudes and phases of the received signals are constant over short intervals. However, the amplitudes of the envelopes vary with time due to the frequency offset, Figure 7.7.

If the output is derived by selecting the larger of the sidebands then its amplitude is given by:

$$r_s = (r_1^2 + r_2^2 + 2r_1r_2\sin(\theta_d))^\frac{1}{2} \text{ for } 0 < \theta_d < \pi \quad \ldots \quad (7.8)$$

The minimum value of this signal is $(r_1^2 + r_2^2)^{\frac{1}{2}}$ and it can increase by a further 3dB. The mean square level of the selected signal is:

$$E(r_s^2) = E(r_1^2) + E(r_2^2) + 2(\epsilon_1 E(r_2) E(\sin(\theta_d)))$$

$$= \sigma_1^2 + \sigma_2^2 + 2 \sigma_1 \left(\frac{\pi}{2}\right)^{\frac{1}{2}} \sigma_2 \left(\frac{\pi}{2}\right)^{\frac{1}{2}} \frac{1}{\pi} \quad \ldots \quad (7.9)$$

$$= \sigma_1^2 + \sigma_2^2 + \sigma_1 \sigma_2$$

If the variances are equal for each signal then:

$$\sigma_s^2 = 3 \sigma^2 = 1.5 \sigma^2 \quad \ldots \quad (7.10)$$

Eq. 7.9 can be rearranged in terms of the correlation coefficient as:

$$\sigma_s^2 = \sigma_1^2 \left(1 + \frac{1}{2}(1 - \rho^2)^{\frac{1}{2}}\right) \quad \ldots \quad (7.11)$$
Figure 7.7 Sidebands for Quasi-synchronous System

Figure 7.8 Distributions for Two Station Scheme
This expression agrees with that obtained by Downton (55) for the general situation, Eq. C.45. It suggests that the maximum mean square level of the selected signal is 1.5 times the variance of each sideband. As the mean level of one station decreases relative to the other the variance of the selected signal tends to that for one sideband. If only one station is significant then, as might be expected, the mean power level drops to the level of that station. The correlation of the sidebands becomes unity and there is no longer any benefit from the diversity scheme.

The distribution function can be replotted for the two station scheme in terms of relative power levels in place of correlation coefficients, Figure 7.8. The phasing of the modulation is still presumed to be $\pi/2$. From this plot it is evident that even with the relative levels 15dB apart the 99% confidence limit is still increased by more than 7dB with respect to the single transmitter system.

7.5 **Simulation**

The Sideband Diversity scheme requires that two major modifications are made to the simulation program. The first of these is to enable the inclusion of more than one transmitter and the second involves the final selection of the signal.

The environmental plan is common to all the signals received by the mobile. Since the fading for each of the transmissions should be independent, the magnitudes
and phases assigned to the blocks are unique for each station. The transmitters can also contribute separate coherent waves, as required. The wave tracing need only be performed once per increment of time since the positions of the blocks are common for all the signals. The resultant received signal is calculated for each transmission separately. The frequency offsets, in a quasi-synchronous scheme, are included as modifications to the phases of the waves.

The complex sidebands of the composite received signal are calculated using Eqs. C.1 to C.3. The phase shifts, \( d_n \), for the modulation are set by default as:

\[
    d_n = \frac{(n - 1)}{N} \pi \tag{7.12}
\]

for a scheme involving \( N \) stations. By differentiating Eq. C.15 with respect to \( d_n \) Allen (54) has shown that equally spaced phasing produces the lowest correlation between the two sidebands, cf. Eq. 7.3 ff. These phases can also be specified as part of the input to the program.

The final output is obtained by selecting the larger, in amplitude, of the two sidebands. A record is also maintained of the instantaneous phase of the output signal. The majority of the analysis for the simulated signal is the same as was used in the original QUASIM package. In addition the mean and variance for both sidebands and the selected signal are calculated and printed. From these and the covariance of the sidebands the correlation coefficient is also computed.
7.6 **Field Trials**

In order to confirm that the modified simulation is a good representation of the Sideband Diversity scheme a series of field trials have been undertaken. In principle these trials are very similar to those for the single transmitter system, Chapter 4. However, in practice they are very much more complex and soon proved the value of simulation techniques.

As has been noted Sideband Diversity can only be employed in a multiple transmitter scheme. In order to meet the requirement that the fading for each signal should be independent the transmitters have to be operated at separate sites. The original choice for these tests was to have two remote sites; one on top of a high rise block at the University and the other at a local school. These were selected to provide good coverage throughout the City of Bath. Unfortunately the site at the school had to be abandoned and instead the transmitter was co-sited with the base control.

The modulation phasing for the transmissions has to be carefully controlled. In order to ensure that no errors are introduced by the equipment both remote stations are controlled from the base by use of FM link radios. Since the FM sets are similar and the link paths are not excessively long the modulation phase shift introduced by each is approximately the same. The actual phasing is achieved by using two all-pass filters which have a phase difference between them of \( \frac{\pi}{2} \) over a range of 300 Hz to 3 kHz, Appendix G.2.
Plate 7  Base Station Aerial Array

Plate 10  Base Control Panel and Remote Station
It was decided to operate the two transmitters quasi-synchronously. In order to achieve the necessary stability, $1:10^8$, the carrier frequencies are derived from phase-locked synthesizers, Appendix G.3. These allow the carriers to be set within 1 Hz of each other. For these trials the signal has to be modulated with a single tone since it is the sidebands which carry the required information.

The major change in the mobile equipment is that the sidebands are independently demodulated before each is logarithmically compressed and recorded. The signal is still extracted from the test receiver at IF but is now fed to the input of an ISB receiver. The outputs are connected to two AF logarithmic amplifiers which have a dynamic range in excess of 80 dB. The ISB receiver uses the phasing method of demodulation and has a SNR of more than 45 dB.
With a full AM system the receiver's first local oscillator need not be very stable since any errors are compensated for by the demodulation process. With the ISB receiver the "carrier" frequency is fairly critical. In order to achieve the necessary stability at IF the test receiver's first oscillator has been replaced by a TCXO. The second oscillator has been modified by the addition of a varicap diode across the crystal. This allows the IF to be adjusted to the same frequency as the ISB receiver.

7.7 Processing

The main difference in the processing for these trials, as compared to those for the single transmitter scheme, is the need to sample both sideband signals. The two channels of the recording system tend not to give uniform results and, therefore, each has to be characterised separately. In order to maintain the benefits of the trials system the automatic procedure has been extended to characterise both channels at the same time, Appendix F.4. The DC offset evident between the channels, Figure 7.10, is caused by the final Zener diodes in the logarithmic amplifiers. These are used to drop the output levels from the half rail voltage.

After the signals have been sampled from the tape the actual field strength measurements are recovered by interpolating the two characteristic curves. Before any further analysis can be accomplished the output has to be selected from the two sidebands. An additional
program has been written which permits the output to be chosen as either sideband singly or it can select the larger of the two at any instant of time. This program could also be modified to simulate any other type of combination system.

The output file from the selection program is in the correct format for the rest of the processing on the small computer. For a full analysis of the trials the data can again be transferred to the University computer and submitted as the input to the QUASIM package.

Another program which has been added to the trials' package calculates the means, variances and correlation coefficient for the two sidebands. These values can be compared with both theoretical and simulated results. In order to draw meaningful conclusions they must also be related to the relative transmitter powers.
8 APPLICATIONS

8.1 Verification

As with the single transmitter scheme the results from the modified simulation have been compared with those from field trials using Sideband Diversity. The whole propagation process is very much more complex and, therefore, the testing has concentrated on a general type of environment. Section 6.2 has demonstrated that Great Pulteney Street and its simulation plan both have fading statistics which approximate to the "Rayleigh" model. These areas were used to obtain the results for the diversity scheme, Figures 8.1 to 8.3.

The modifications required for the diversity scheme have been described in the previous chapter. After the system was set up trials were conducted using each of the remote stations separately. It was noted that the mean level of the signal from Wessex House was about 20dB higher than that from the School of Electrical Engineering. The output of the former station was attenuated but the output stages of the VHF transmitters proved to be not very stable which prevented the powers being set closer than 10dB apart. No variation in their levels was detected during a series of runs but it was evident between different series. The signals from the two stations were checked for correlation but again none was detected.

The offset between the carrier frequencies was almost 1.0 Hz and this figure was used for the input to the simulation. The same plan, Figure 6.1, was used
Plate 11  Base Station From Wessex House

Plate 12  The City of Bath From Wessex House
Simulated Time Profile

Cumulative Distributions

Figure 8.1  Statistics for the Diversity Scheme
Simulated Points
Practical Points

Figure 8.2 Statistics for the Diversity Scheme
Figure 8.3  Statistics for the Diversity Scheme
for the simulation with the addition of a transmitter whose power was set at -10dB. The time profile and the cumulative distribution both show the benefit of the scheme even with the relative power difference. These statistics will be discussed in more detail in the next two sections. Here it is sufficient to note the similarity between the practical and simulated statistics.

3.2 Synchronous Scheme

In order to gain a clearer understanding of the Sideband Diversity scheme a series of runs of the program have been made with different conditions. The first set all use a synchronous scheme since this can be compared directly with the theory in the last chapter. All the runs have used the plan for Great Pulteney Street, Figure 6.1.

The first series of tests employed 1, 2, and 3 transmitter schemes. The first of these just proves that the additional routines have not modified the basic program. In the other two the signals all have equal power levels. The cumulative distribution for the envelope of the selected signal shows the predicted improvement for the 2 transmitter scheme, Figure 8.4. The addition of a third transmitter has no significant effect on the multipath fading although it does increase the mean power level by 2dB. The similarity of the 2 and 3 transmitter schemes is also apparent from the crossing rates and fade durations, Figures 8.5 and 8.6. This result is to be expected since the main diversity
occurs between the sidebands of which there are only two. From the crossing rate it is evident that the signal does not cross the lower levels so often as in a single transmitter scheme. When it does cross these levels, however, it stays below them for approximately the same period, Figure 8.5.

The second series of tests, still with a synchronous system, use a 2 transmitter scheme with a range of relative power levels between the signals. From the plots of the cumulative distribution, Figure 8.4, the fading for these simulated signals would appear to be slightly worse than predicted by theory. However, the simulated points still follow the general trend of the theoretical curves. As the difference in the power levels increases so the crossing rate gradually moves towards the curve for the "Rayleigh" model. The fade durations show no significant deviation from the single transmitter scheme.

The power gain due to the selection of the signal and the correlation of the two sidebands can also be compared with Eqs. 7.9 and 7.3 respectively. The phasing of the modulation is constant at 90° for all of these tests. The plots of both these functions shows a very close correspondence between the theory and the simulation, Figure 8.8. The power gain is expressed in terms of the total power in either of the sidebands, that is the power level that would be received if there was no selection.
Figure 8.4 Simulated Distributions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>No. of Tx</th>
<th>Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>■</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>•</td>
<td>2</td>
<td>0 dB</td>
</tr>
<tr>
<td>□</td>
<td>2</td>
<td>5 dB</td>
</tr>
<tr>
<td>△</td>
<td>2</td>
<td>10 dB</td>
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<tr>
<td>○</td>
<td>2</td>
<td>20 dB</td>
</tr>
<tr>
<td>▲</td>
<td>3</td>
<td>0 dB</td>
</tr>
</tbody>
</table>

Probability that signal specified level

Specified Level - R (dB relative to rms)
Figure 8.5  Simulated Crossing Rates
Figure 8.6 Simulated Fade Durations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>No. of Tx</th>
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<tr>
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<tr>
<td>▲</td>
<td>3</td>
<td>0 dB</td>
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</table>

"Rayleigh"
Figure 8.7  Power Gain for the Diversity Scheme

Figure 8.8  Correlation for the Diversity Scheme
8.3 Quasi-Synchronous Scheme

In a quasi-synchronous scheme the individual signals tend to beat together at a rate proportional to the offset between the carrier frequencies. Sideband Diversity overcomes this extra signal fluctuation by always selecting the larger of the sidebands. When the receiver is stationary then incoming signal sidebands experience the beats at different times, see Figure 7.7. With the phasing set at 90°, for a 2 transmitter system, then the correlation of the sidebands approaches -1 as the relative power levels of the signals become equal. When the mobile moves then the signal also undergoes multipath propagation with its consequent fading. The envelope correlation increases with the mobile's speed till it becomes positive again.

No theoretical work has succeeded in evaluating the relationship between the maximum Doppler shift of the received signal and the offsets in carrier frequency with regard to the correlation of the sideband envelopes. Using the same plan as before with a 2 transmitter scheme and equal power levels the simulation has been run for a number of different offsets. From the plot of the correlation coefficient it can be seen that the offset frequency has a marked effect. The maximum Doppler shift is 2.57 Hz. There is a reasonably small change in the cumulative distribution, Figure 8.10. There is also evidence that the offset frequency can decrease the duration of deep fades although it also increases their incidence (57).
Figure 8.9  Correlation for the Diversity Scheme

Figure 8.10  Distributions for Increasing Offsets
9 FURTHER WORK

9.1 Review

This thesis has described a simulation of the land mobile radio environment and has demonstrated that it is valid for a wide range of conditions. The basic program has then been extended and applied to a scheme which uses Sideband Diversity. In its modified version the simulation has been used to provide more information about the diversity scheme and has predicted some very interesting results.

The work discussed here is a framework which could be developed in many directions. Within the simulation itself the most important change would involve the wave tracing routines. At present these attempt to find intersections between the wave vectors and every block on the plan. When considering the plan it is evident that any particular vector can only pass through a very limited number of the blocks. This restriction could be included in the program by only searching within a narrow angle to each side of the vector. The routine which would effect this change would have to be very carefully written to ensure that it does not take more time than the original algorithm.

9.2 Statistics

As has been noted, the only analysis contained within the QUASIM package at present is carried out on the magnitude of the envelope. Before any work can be done involving most types of digital modulation this
analysis must be extended to provide statistics about
the phase and random FM of the received signal. There
are no particular problems envisaged in calculating
these statistics for the simulation. Confirmation of
the validity of these characteristics by comparing them
with those for practical field trials could be very
much more difficult. The work carried out by Parsons
(2) and by Cox (22) could be a useful starting point
for developing a system which could record the phase of
a received signal in the mobile. The modifications
required for the sampling and processing programs would
be straightforward.

9.3 Schemes

A comprehensive series of runs should be made with
the simulation for the Sideband Diversity scheme in
order to increase the understanding of its operation.
It would be especially interesting to compare various
types of channel combination as the offsets between the
carrier frequencies are changed.

There are many different radio schemes which could
be included within the simulation. It could provide
some very useful information about the implementation
of diversity schemes when changing from analogue to
digital modulation. The fundamental basis of the model
could also be used for a simulation of co- and adjacent
channel interference and their effects on diversity
systems. These could also include transient interference
carried by ignition and other similar noise.
9.4 Epilogue

This research has realised a fundamentally new model of the mobile radio environment. It has also implemented a field trials system which includes a unified package of sampling and processing programs. This is only the beginning of work which could make a valuable contribution to the overall understanding of radio propagation.
REFERENCES


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A POWER SPECTRA FOR RAYLEIGH FADEING

A.1 Input Spectrum

The spectrum of the signal received at the mobile can be evaluated by considering the average total power of that signal:

\[ W = \frac{1}{T} \int_{0}^{T} Z_e(t) \, dt \]  \hspace{1cm} \text{(A.1)}

in which the field strength, \( Z_e(t) \), is given by:

\[ Z_e(t) = Z_0 \sum_{n=1}^{N} C_n \cos(2\pi(f_c + f_n)t + \varphi_n) \]  \hspace{1cm} \text{(A.2)}

and the Doppler shifts, \( f_n \), are:

\[ f_n = f_m \cos(a_n) = \frac{f_c v}{c} \cos(a_n) \]  \hspace{1cm} \text{(A.3)}

The total power, \( W \), is then:

\[ W = \frac{Z_0^2}{2} \sum_{n=1}^{N} C_n^2 \]  \hspace{1cm} \text{(A.4)}

which in the limit can be expressed in terms of the arrival angles of the waves, \( a \), or as a function of frequency, \( f \):

\[ W = \frac{Z_0^2}{2} \int_{-\infty}^{\infty} C(a)^2 \, da = \int_{-\infty}^{\infty} S_i(f) \, df \]  \hspace{1cm} \text{(A.5)}

where \( S_i(f) \) represents the input power spectrum. From Eq. A.3:

\[ \frac{df}{da} = f_m (- \sin(a)) = \left( f_m^2 - (f - f_c)^2 \right)^{\frac{1}{2}} \]  \hspace{1cm} \text{(A.6)}

Replacing Eq. A.6 into Eq. A.5 and differentiating:

\[ \frac{Z_0^2}{2} C(a)^2 = S_i(f) \left( f_m^2 - (f - f_c)^2 \right)^{\frac{1}{2}} \]  \hspace{1cm} \text{(A.7)}

The arrival angles for the "Rayleigh Fading" model.
(see Section 2.3) are uniformly distributed around the unit circle and, therefore, after normalisation:

\[ \frac{Z_o}{2} C(a)^2 = \frac{\sigma^2}{2\pi} \]  \hspace{1cm} \text{(A.8)}

The power spectrum is then given by:

\[ S_i(f) = \frac{\sigma^2}{2\pi(f_m^2 - (f - f_c)^2)^\frac{1}{2}} \]  \hspace{1cm} \text{(A.9)}

and is defined as a double sided spectrum over the range:

\[ |f - f_c| > f_m \]  \hspace{1cm} \text{(A.10)}

\textbf{A.2 Correlation Functions}

The autocorrelation function for the orthogonal components of the envelope of the received signal is defined as:

\[ R_{cc}(\tau) = E(T_c(t)T_c(t+\tau)) \]  \hspace{1cm} \text{(A.11)}

where:

\[ T_c(t) = Z_o \sum_{n=1}^{N} \cos(\omega_n t + \phi_n) \]  \hspace{1cm} \text{(A.12)}

hence, in the limit:

\[ R_{cc}(\tau) = \frac{Z_o}{2} \int_{0}^{\infty} C(f)^2 \cos(2\pi f \tau) \, df \]

\[ = \int_{0}^{\infty} S_i(f) \cos(2\pi f \tau) \, df \]  \hspace{1cm} \text{(A.13)}

The other auto and cross correlation functions are:

\[ R_{ss}(\tau) = R_{cc}(\tau) \]  \hspace{1cm} \text{(A.14)}
If the input spectrum is symmetric about the carrier frequency, as in the "Rayleigh" model Eq. A.9, then the correlation functions become:

\[ R_{cc}(\tau) = R_{ss}(\tau) = \sigma^2 J_0 (2 \pi f_m \tau) \]  \hfill (A.16)

\[ R_{cs}(\tau) = R_{sc}(\tau) = 0 \]  \hfill (A.17)

### A.3 Envelope Spectrum

The autocorrelation function for the envelope has been derived (58) as:

\[ R_z(\tau) = \frac{\pi}{2} \sigma^2 F\left(-\frac{1}{2}, -\frac{3}{2}; 1; |D_z|^2\right) \]  \hfill (A.18)

where:

\[ |D_z|^2 = \frac{1}{\sigma^4} (R_{cc}^2(\tau) + R_{cs}^2(\tau)) \]  \hfill (A.19)

and the hypergeometric function, F, is defined by:

\[ F(a,b;c;z) = \frac{(a)_n (b)_n z^n}{(c)_n n!} \]  \hfill (A.20)

and:

\[ (a)_n = a (a+1) \ldots \ldots (a+n-1) \]  \hfill (A.21)

Using the "Rayleigh" model:

\[ |D_z| = \frac{1}{\sigma^2} R_{cc}(\tau) = J_0(\omega_m \tau) \]  \hfill (A.22)

A.3
Expanding Eq. A.18:

\[ R_r(\tau) = \frac{\pi}{2} \sigma^2 \left( 1 + \frac{|\rho_z|^2}{4} + \frac{|\rho_z|^4}{64} + \frac{|\rho_z|^6}{256} + \ldots \right) \quad \ldots (A.23) \]

The power spectrum for the envelope is equivalent to the Fourier transform of the autocorrelation function:

\[ S_r(f) = \int_{-\infty}^{\infty} R_r(\tau) \exp(-j\omega \tau) \, d\tau \quad \ldots (A.24) \]

An approximate expression can be obtained for this spectrum by neglecting terms above the second:

\[ S_r(f) = \frac{\pi}{2} \sigma^2 \delta(f) + \frac{\sigma^2}{3 \pi f_m} K\left(1 - \left(\frac{f}{f_m}\right)^2\right)^{\frac{1}{2}} \quad \ldots (A.25) \]

in which \( K \) is a complete elliptical integral of the first kind.
3 CROSSING RATE AND DURATION OF FADES

3.1 Level Crossing Rate

The expected rate, \( N(R) \), at which the envelope, \( r(t) \), of the fading waveform increases through any specified level, \( R \), is given by (3):

\[
N(R) = \int_0^\infty r f(r, t) dt
\]  

(3.1)

Rice (3) gives the joint density function, for the case of a Gaussian variable, in polar form as:

\[
f(r, \theta, \dot{\theta}) = \frac{r^2}{4 \pi^2 \sigma^2 b} \exp\left(-\frac{r^2}{2 \sigma^2} - \frac{\dot{\theta}^2}{2 b}\right) \]  

(3.2)

where \( \tan(\theta) = -\frac{b}{\sigma^2} \) and:

\[
\sigma^2 = E(T_c^2) = E(T_g^2) = \text{average total power} \]  

(3.3)

\[
b = E(T_g^2) = E(T_g^2) = 2 \pi^2 r_m \sigma^2 \]  

(3.4)

Integrating Eq. 3.2 with respect to \( \theta \) and \( \dot{\theta} \) over their complete ranges, the joint probability becomes:

\[
f(r, \dot{r}) = \frac{r^2}{4 \sigma^2} \exp\left(-\frac{r^2}{2 \sigma^2}\right) \frac{1}{2 \pi b} \]  

(3.5)

Hence:

\[
f(r, \dot{r}) = f(r) f(\dot{r}) \]  

(3.6)

and, therefore, the envelope and its derivative are uncorrelated and independent. Substituting Eq. 3.6 into Eq. 3.1 and integrating gives:

\[
N(R_n) = \left(\frac{b}{\pi \sigma^2}\right)^{\frac{1}{2}} R_n \exp\left(-\frac{R_n^2}{2 \sigma^2}\right) \]  

(3.7)

where \( R_n \) is the normalised level:

\[
R_n = \frac{R}{(E(r^2))^{\frac{1}{2}}} = \frac{R}{r_{\text{rms}}} \left(2 \sigma^2\right)^{\frac{1}{2}} \]  

(5.8)
Inserting Eq. B.3 and Eq. B.4 into Eq. B.7 gives the normalised crossing rate for the electric field as:

\[ N(R_n) = (2\pi)^{\frac{1}{2}} R_n \exp(-R_n^2) \]  

...(B.9)

### B.2 Mean Duration of Fades

The mean duration of fades, \( t(R) \), is the average time that the signal stays below any specified level, \( R \). This is equivalent to dividing the total time that the signal stays below the set level by the number of times it crosses that level, that is the cumulative distribution, Eq. 2.9, by the crossing rate, Eq. B.9:

\[ t(R_n) = \frac{\exp(R_n^2) - 1}{R_n \left( \frac{2\pi}{2} \right)^{\frac{1}{2}}} \]  

...(B.10)
C THEORY FOR SIDEBAND DIVERSITY

C.1 Received Signal

In the Sideband Diversity scheme the mobile receives signals simultaneously from two or more transmitters which are spatially separated. It is assumed that their fading due to multipath propagation is uncorrelated. The modulation for each transmission is shifted in phase with respect to the first. The received signal is the complex sum of all the individual waves, Figure 7.4. The quadrature components of the demodulated sidebands are:

\[
T_{cu} = \sum_{n=1}^{N} T_{cn} \cos(d_n) - T_{sn} \sin(d_n)
\]
\[
T_{su} = \sum_{n=1}^{N} T_{sn} \cos(d_n) + T_{cn} \sin(d_n)
\]
\[
T_{cl} = \sum_{n=1}^{N} T_{cn} \cos(d_n) + T_{sn} \sin(d_n)
\]
\[
T_{sl} = \sum_{n=1}^{N} T_{sn} \cos(d_n) - T_{cn} \sin(d_n)
\]

where \( T_{cn} \) and \( T_{sn} \) are the quadrature components of the received signal for each transmitter and \( d_n \) is the phasing of the modulation. The sidebands are then:

\[
Z_u = T_{cu} - j T_{su}
\]
\[
Z_1 = T_{cl} - j T_{sl}
\]

and their magnitudes:

\[
r_u = (T_{cu}^2 + T_{su}^2)^{\frac{1}{2}}
\]
\[
r_1 = (T_{cl}^2 + T_{sl}^2)^{\frac{1}{2}}
\]

If the fading of each transmitted signal is assumed to
fit the "Rayleigh" model then $T_{cn}$ and $T_{sn}$ are normal uncorrelated random variables with zero mean and equal variance, for any individual transmitter. By the Central Limit Theorem (9) $T_{cu}$, $T_{su}$, $T_{cl}$, and $T_{sl}$ are also normal random variables with zero means and equal variances:

\[
E(T_{cn}) = E(T_{sn}) = 0 \\
E(Z_u') = E(Z_1') = 0 \\
E(T_{cn}^2) = E(T_{sn}^2) = \sigma_n^2 \\
E(T_{cn} T_{sn}) = 0 \\
E(T_{cu}^2) = E(T_{su}^2) = \sum_{n=1}^{N} \sigma_n^2 = \sigma_T^2 \\
E(T_{cl}^2) = E(T_{sl}^2) = \sigma_T^2 \\
E(Z_u Z_u^*) = E(Z_1 Z_1^*) = 2 \sigma_T^2 \\
\]

C.2 Complex Covariance

The complex covariance of two random variables is given by (9):

\[
C_z = E((Z_u - E(Z_u))(Z_1^* - E(Z_1^*))) \\
\]

Since the means for both sidebands are zero Eq. C.6 can be simplified and from Eq. C.3:

\[
C_z = E(Z_u Z_1^*) \\
= E(T_{cu} T_{cl}) + E(T_{su} T_{sl}) - j(E(T_{su} T_{cl}) - E(T_{cu} T_{sl})) \\
\]

Each term of the covariance can be evaluated by consideration of Eqs. C.1, C.2, and C.5:
\( E(T_{cu} T_{cl}) = E(\sum_{n=1}^{N} T_{cn}^2 \cos^2(d_n) - T_{sn}^2 \sin^2(d_n)) \)
\( = \sum_{n=1}^{N} \sigma_n^2(\cos^2(d_n) - \sin^2(d_n)) \)
\( = \sum_{n=1}^{N} \sigma_n^2(\cos(2d_n)) \) \( \ldots \)(C.8)

\( E(T_{su} T_{sl}) = \sum_{n=1}^{N} \sigma_n^2(\cos(2d_n)) \) \( \ldots \)(C.9)

\( E(T_{su} T_{cl}) = E(\sum_{n=1}^{N} T_{cn}^2 \cos(d_n) \sin(d_n) + \sum_{n=1}^{N} T_{sn}^2 \cos(d_n) \sin(d_n)) \)
\( = \sum_{n=1}^{N} \sigma_n^2(\sin(2d_n)) \) \( \ldots \)(C.10)

\( E(T_{cu} T_{sl}) = -\sum_{n=1}^{N} \sigma_n^2(\sin(2d_n)) \) \( \ldots \)(C.11)

\[ \text{Hence:} \]
\[ C_Z = 2 \sum_{n=1}^{N} \sigma_n^2(\cos(2d_n) - j \sin(2d_n)) \] \( \ldots \)(C.12)

and:
\[ |C_Z|^2 = 4(\left( \sum_{n=1}^{N} \sigma_n^2 \cos(2d_n) \right)^2 + \left( \sum_{n=1}^{N} \sigma_n^2 \sin(2d_n) \right)^2) \] \( \ldots \)(C.13)

C.3 Correlation Coefficients

Papoulis (9) gives the correlation coefficient for two complex random variables as:

\[ \rho_Z = \frac{C_Z - E(Z_u)E(Z_1)}{\sqrt{E(Z_u - E(Z_u))^2} \sqrt{E(Z_1 - E(Z_1))^2}} \]
\[ = \frac{C_Z}{\sqrt{E(Z_u)^2 E(Z_1)^2}} \] \( \ldots \)(C.14)

The square of the magnitude of the complex correlation coefficient is then:

C.3
The correlation coefficient can be found in a similar manner for the envelopes of the sidebands:

\[ \rho_r = \frac{E(r_u r_1) - E(r_u) E(r_1)}{\left[ E(r_u^2) - E(r_u)^2 \right]^{1/2} \left[ E(r_1^2) - E(r_1)^2 \right]^{1/2}} \]  

...(C.16)

The cross correlation between two Rayleigh distributed random variables is given by Uhlenbeck (58) in terms of complete elliptical integrals which he expands as:

\[ E(r_u r_1) = \frac{\pi}{2} \sigma_T^2 \left( 1 + \frac{|D_z|^2}{4} + \frac{|D_z|^4}{64} + \frac{|D_z|^6}{256} + \cdots \right) \]  

...(C.17)

The mean and mean square values of the envelopes are:

\[ E(r_u) = E(r_1) = \int_0^\infty r_u f(r_u) \, dr_u = (\frac{\sigma_T \pi}{2})^{1/2} \]  

...(C.18)

\[ E(r_u^2) = E(r_1^2) = \int_0^\infty r_u^2 f(r_u) \, dr_u = 2 \sigma_T^2 \]

Inserting Eqs. C.17 and C.18 into Eq. C.16:

\[ \rho_r = \frac{E(r_u r_1) - \sigma_T^2 \frac{\pi}{2}}{\sigma_T^2 \left( 1 + \frac{|D_z|^2}{4} + \frac{|D_z|^4}{64} + \frac{|D_z|^6}{256} + \cdots \right)} \]

...(C.19)

Pierce and Stein (59) have shown that the approximation is within 10% for all values of correlation and within 5% for \( \rho_r > 0.5 \).

C.4 Joint Density Function

The joint density function for \( n \) normal random variables can be expressed in the form:

\[ |D_z|^2 = \frac{|z|^2}{4 \sigma_1^2} = \left( \sum \sigma_n^2 \cos(2 \phi_n) \right)^2 + \left( \sum \sigma_n^2 \sin(2 \phi_n) \right)^2 \]  

\[ (\sum \sigma_n^2)^2 \]

...(C.15)
\[ f(x_1, \ldots, x_n) = \frac{\exp\left(-\frac{1}{2} x^T V^{-1} x\right)}{((2\pi)^n |V|)^{\frac{1}{2}}} \] ... (C.20)

in which \( x^T \) is the transpose of the vector \( x \):
\[ x = (x_1, \ldots, x_n) \] ... (C.21)

The matrix \( V^{-1} \) is the inverse of the covariance matrix:
\[ V = \begin{pmatrix} V_{11} & V_{12} & \cdots & V_{1n} \\ V_{21} & V_{22} & \cdots & V_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ V_{n1} & V_{n2} & \cdots & V_{nn} \end{pmatrix} \] ... (C.22)

where:
\[ v_{ij} = \mathbb{E}( (x_i - \mathbb{E}(x_i))(x_j - \mathbb{E}(x_j)) ) \] ... (C.23)
\[ v_{ij} = \sigma_i \sigma_j \rho_{ij} \]

For the Sideband Diversity scheme the joint density is required for the four components of the sidebands:
\[ f(T_{cu}, T_{su}, T_{cl}, T_{sl}) = \frac{1}{(2\pi)^2 |V|^{\frac{1}{2}}} \exp\left(-\frac{1}{2} (T_{cu}, T_{su}, T_{cl}, T_{sl}) V^{-1} \begin{pmatrix} T_{cu} \\ T_{su} \\ T_{cl} \\ T_{sl} \end{pmatrix} \right) \] ... (C.24)

and the covariance matrix becomes:
\[ V = \sigma_T^2 \begin{pmatrix} 1 & 0 & \rho_{13} & \rho_{14} \\ 0 & 1 & -\rho_{14} & \rho_{13} \\ \rho_{13} & -\rho_{14} & 1 & 0 \\ \rho_{14} & \rho_{13} & 0 & 1 \end{pmatrix} \] ... (C.25)

and:
\[ \rho_{13} = \frac{\mathbb{E}(T_{cu} T_{cl})}{\sigma_T^2} = \frac{\mathbb{E}(T_{su} T_{sl})}{\sigma_T^2} \]
\[ \rho_{14} = \frac{\mathbb{E}(T_{su} T_{cl})}{\sigma_T^2} = \frac{-\mathbb{E}(T_{cu} T_{sl})}{\sigma_T^2} \] ... (C.26)
The determinant of the matrix is:

\[ |u|^{\frac{1}{2}} = \sigma_{\tau}^{4}(1 - \rho_{13}^{2} - \rho_{14}^{2}) \]  \hspace{1cm} \text{...(C.27)}

but from Eqs. C.15 and C.19:

\[ |\rho_{2}|^{2} = \rho_{13}^{2} + \rho_{14}^{2} \rho_{r} \]  \hspace{1cm} \text{...(C.28)}

and hence:

\[ |u|^{\frac{1}{2}} = \sigma_{\tau}^{4}(1 - \rho_{r}) \]  \hspace{1cm} \text{...(C.29)}

Expanding Eq. C.26 gives:

\[ f(T_{cu}, T_{su}, T_{cl}, T_{s1}) = \frac{1}{4\pi^{2} \sigma_{\tau}^{4}(1 - \rho_{r})} \cdot \exp\left(\frac{-1}{2\sigma_{\tau}^{2}(1 - \rho_{r})}\left(\frac{T_{cu}^{2}}{2} + \frac{T_{su}^{2}}{2} + \frac{T_{cl}^{2}}{2} + \frac{T_{s1}^{2}}{2} - 2(\rho_{13}(T_{cu} T_{cl} + T_{su} T_{s1}) + \rho_{14}(T_{cu} T_{s1} - T_{su} T_{cl}))\right)\right) \]  \hspace{1cm} \text{...(C.30)}

Changing the variables such that:

\[ T_{cu} = r_{u} \cos(\beta) \quad T_{su} = r_{u} \sin(\beta) \]  \hspace{1cm} \text{...(C.31)}

\[ T_{cl} = r_{1} \cos(\delta) \quad T_{s1} = r_{1} \sin(\delta) \]

then the Jacobian is given by:

\[ J(r_{u}, \beta, r_{1}, \delta) = \begin{vmatrix}
\cos(\beta) & -r_{u} \sin(\beta) & 0 & 0 \\
\sin(\beta) & r_{u} \cos(\beta) & 0 & 0 \\
0 & 0 & \cos(\delta) & -r_{1} \sin(\delta) \\
0 & 0 & \sin(\delta) & r_{1} \cos(\delta)
\end{vmatrix} = r_{u} r_{1} \]  \hspace{1cm} \text{...(C.32)}

Papoulis (9) gives:

\[ f(T_{cu}, T_{su}, T_{cl}, T_{s1}) = \frac{f(r_{u}, \beta, r_{1}, \delta)}{J(r_{u}, \beta, r_{1}, \delta)} \]  \hspace{1cm} \text{...(C.33)}

C.6
The density function, substituting \( \phi = \beta - \delta \), is now:

\[
f(r_u, \beta, r_1, \delta) = \frac{r_u r_1}{4 \pi^2 \sigma_T^4 (1 - \rho_r)} \exp\left(\frac{-1}{2 \sigma_T^2 (1 - \rho_r)} \left(r_u^2 + r_1^2 - 2 r_u r_1 (\rho_{13} \cos(\phi) + \rho_{14} \sin(\phi))\right)\right). \tag{C.34}
\]

The joint density function, Eq. C.34, must be averaged over \( \beta \) and \( \delta \) in order to obtain the density function for the magnitudes of the envelopes:

\[
f(r_u, r_1) = \int_0^{2\pi} \int_0^{2\pi} f(r_u, \beta, r_1, \delta) \, d\beta \, d\delta \quad \tag{C.35}
\]

Since the integrand is periodic in \( \beta \) the integration can be carried out over \( \beta \) to \( \beta + 2\pi \). The density then becomes:

\[
f(r_u, r_1) = \frac{r_u r_1}{2 \pi \sigma_T^4 (1 - \rho_r)} \exp\left(\frac{-1}{2 \sigma_T^2 (1 - \rho_r)} \int_0^{2\pi} \exp\left(\frac{-r_u^2 + r_1^2}{\sigma_T^2 (1 - \rho_r)} \left(\rho_{13} \cos(\phi) + \rho_{14} \sin(\phi)\right)\right) \, d\phi\right). \tag{C.36}
\]

However:

\[
\rho_{13} \cos(\phi) + \rho_{14} \sin(\phi) = |\rho_z| \cos(\phi - \tan^{-1}(\rho_{14}/\rho_{13})) \tag{C.37}
\]

and:

\[
\int_0^{2\pi} \exp(x \cos(\phi)) \, d\phi = 2 \pi I_0(x) \tag{C.38}
\]

where \( I_0(x) \) is a modified Bessel function. The density can now be expressed as:

\[
f(r_u, r_1) = \frac{r_u r_1}{\sigma_T^4 (1 - \rho_r)} \exp\left(\frac{-1}{2 \sigma_T^2 (1 - \rho_r)} \left(\frac{1}{\rho_r^2} r_u^2 + r_1^2\right)\right) I_0\left(\frac{1}{\rho_r^2} \frac{r_u r_1}{\sigma_T^2 (1 - \rho_r)}\right) \tag{C.39}
\]
C.5 Density for Selected Signal

If the output from the receiver is selected as the larger of the two sidebands then the system is analogous to Downton's parallel reliability (56). From Eq. C.39 he obtains the density for the selected signal, \( r_s \), as:

\[
f_2(r_s^2) = \frac{1}{\sigma_u^2} \exp\left(\frac{-r_s^2}{\sigma_u^2}\right) + \frac{1}{\sigma_1^2} \exp\left(\frac{-r_s^2}{\sigma_1^2}\right) - f_1(r_s^2) \quad \ldots (C.40)
\]

where:

\[
f_1(r_s^2) = \int_{r_s^2}^{\sigma_u^2} f(r_u^2, r_s^2) \, dr_u + \int_{r_s^2}^{\sigma_1^2} f(r_s^2, r_1^2) \, dr_1 \quad \ldots (C.41)
\]

After normalising such that \( \sigma_u^2 = \sigma_1^2 = 1 \) he shows:

\[
f_1(r_s^2) = \exp(-r_s^2) \left( 1 + h(r_s^2) - \int_0^{r_s^2} h(t) \, dt \right) \quad \ldots (C.42)
\]

where:

\[
h(x) = \exp\left( - \frac{1}{1 - \rho_t} \right) I_0\left( \frac{2 \times \rho_t^\frac{1}{2}}{1 - \rho_t} \right) \quad \ldots (C.43)
\]

therefore:

\[
f_2(r_s) = 2 r_s \exp(-r_s^2) \left( 1 + h(r_s^2) - \int_0^{r_s^2} h(t) \, dt \right) \ldots (C.44)
\]

Downton uses Laplace transforms to derive the mean of the square of the signal:

\[
\mathbb{E}(r_s^2) = 1 + \frac{1}{2} (1 - \rho_t)^{\frac{1}{2}} \quad \ldots (C.45)
\]

By comparison with the 2-transmitter scheme, Section 7.4, this variance can be denormalised to give:

\[
\mathbb{E}(r_s^2) = (1 + \frac{1}{2} (1 - \rho_t)^{\frac{1}{2}}) \sigma_1^2 \quad \ldots (C.46)
\]

The maximum power of the selected signal is, therefore, 1.5 times that of either sideband.
C.6 Distribution Function

The probability that the selected signal is above a specified level $R$ is given by:

$$F(r_s > R) = 1 - \int_0^R f_2(r_s) \, dr_s$$

...(C.47)

This integration does not have any precise analytic solution and, hence, must be carried out numerically. This has been performed by use of routines from the NAG library for various values of correlation, Figure 7.5.
D SIMULATION PROGRAM

D.1 Philosophy

The basic simulation program, as described in Section 3.2, was developed by adding various routines within the main program. The analysis was performed by three separate subroutines. At the same time as the environmental plan was introduced the program was also entirely rewritten in such a way that subsequent changes could be more easily implemented. The structure of the new program is organised on a "tree" principle to allow the maximum degree of overlaying, Figure D.1. This has enabled the program to run with less store and, hence, it can be used in a smaller and faster RIRO stream.

Another important consideration for the modified program was the need to reduce the running time to a minimum. The most obvious result of this requirement is that the central wave tracing routines have been written using assembler code rather than a high level language, cf. Section 3.4. The "tree" structure of the program necessitates the use of a large number of subroutines, most of which are only accessed once. The transfer of data between the individual routines can be a time consuming process. In this simulation package the data is almost all stored within COMMON areas which can be accessed by all the relevant routines. Since the plotting and titling subroutines can be entered from any part of the program they reside in a separate region of the core store. The FORTRAN library must never be overlayed and, thus, is located in the root segment.
Figure D.1 Overlay Map for QUASIM
**D.2 Procedure**

The complete QUASIM package requires a store area in excess of 100 KBytes and, thus, cannot be used on the ICL 4-50 at the University of Bath. The SWUCN, however, provides facilities for moving the complete program to the ICL 4-75 at the University of Exeter, where it is currently held on disk. The computer network allows the data files to be set up at the local site and permits a simple batch procedure to be used for initialising the complete simulation, Table D.1.

Two data files are required for each run of the program. The first is common to both the simulation and the field trials' analysis and controls the form of the results output. It contains a number of keywords which specify various sections of the analysis routines and are followed by one or more parameters, Table D.2. The first parameter defines the output medium, either the incremental graph plotter or the line printer or both, and must be given. The other parameters are optional and are used to provide information for the analysis, for example the number of increments in the cumulative distribution, if the default value is not required. The keywords can be in any order and can contain up to 20 characters, although only the first four are significant. The parameters are entered in free format and must be placed after column 20.

The second data file required by the program is identified by its first record as either a SIMULATION or an ANALYSIS file. In both cases they start with
// LOGIN BEEAS®, PSSURD
// TASK QUASI
// GROUP DATA
// COPY SIMUL(S)/@SIMUL(S)
// SITE E
// REPLACE @CNTRL(S)

POUE 2 512
TIME PROFILE 1 400
MEAN 3 500 15.
CUMULATIVE 2
FADE 2 50
CROS 3 100
*/

// GROUP QUASIM
// RUN QUASIM(P),10000
// FILE DSET1,RA,@CNTRL(S)
// FILE DSET97,RA,@SIMUL(S)
// ENDTASK

Notes:
1) Assumes that the input file DATA.SIMUL(S) already exists.
2) Output will consist of 4 graphs on the incremental plotter and 5 on the line printer.
3) Both the crossing rate and fade duration are computed over 100 steps.

Table D.1 Sample Batch Procedure File
<table>
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<th>Keyword</th>
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<th>Type</th>
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<td>IP NP</td>
<td>A20 210</td>
</tr>
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<td>TIME PROFILE</td>
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<td>IP NS</td>
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<td>A20 210</td>
</tr>
<tr>
<td>FADE DURATION</td>
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<td></td>
</tr>
<tr>
<td>=3</td>
<td>plot on line printer</td>
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</tbody>
</table>

+ If NT is specified for both statistics then the higher value is used.
² If NC is specified for both statistics then the higher value is used. It must also be a power of 2.
³ Only first 4 letters are significant.

Table D.2  Data Available for Control File
general data such as carrier frequency and mobile speed. The simulation file then continues with the definition of the environmental plan and information about the type of scheme required, Table D.3. The analysis file is completed with the list of signal levels recorded during the relevant field trial, Table D.4. Both of these files can be set up on the mini-computer and transferred by means of the asynchronous link between the computers.

D.3 Program Name

The program name "QUASIM" is a contraction for QUASI-synchronous SIMulation. It was originally used when the Sideband Diversity scheme was included in the program. This was due to the assumption that the scheme could only be operated with a quasi-synchronous system. Although this has been shown not to be the case the name has been retained as being representative of the overall capability of the program.

In the early stages of the work two independent programs were employed, one for the simulation and the other for the analysis of field trials. In order to facilitate the operation of the simulation three other interactive programs were used to set up both the data and procedure files. These had to be abandoned when the main systems control was updated and this encouraged the change to a single program which could perform both functions. The term "simulation package" still tends to be used when discussing the program but it does not usually include any of the other secondary routines.
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<td>IØ</td>
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</tr>
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<td>Scatterer data*</td>
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<td></td>
</tr>
<tr>
<td>XC(M) YC(M) XL(M) YL(M)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>IØ</td>
<td>No. of transmitters</td>
</tr>
<tr>
<td>TM(1) TO(1) DM(1) DA(1)</td>
<td>4F0.Ø</td>
<td>Transmitter data†</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TM(L) TO(L) DM(L) DA(L)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Scatterer data:*

XC(n) YC(n) Co-ordinates for centre of n\textsuperscript{th} block

XL(n) YL(n) Lengths of sides for the n\textsuperscript{th} block

†Transmitter data:

TM(n) Output power for n\textsuperscript{th} transmitter

TD(n) Frequency offset of n\textsuperscript{th} transmitter

DM(n) Magnitude of n\textsuperscript{th} coherent wave

DA(n) Arrival angle for n\textsuperscript{th} coherent wave

Table D.3  Input File Format for Simulation
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANALYSIS</td>
<td>A4</td>
<td>File identifier</td>
</tr>
<tr>
<td>NSAMP</td>
<td>IØ</td>
<td>Sampling rate</td>
</tr>
<tr>
<td>NTIT</td>
<td>A4Ø</td>
<td>Title</td>
</tr>
<tr>
<td>VEL</td>
<td>FØ.Ø</td>
<td>Mobile speed</td>
</tr>
<tr>
<td>FREQ</td>
<td>FØ.Ø</td>
<td>Carrier frequency</td>
</tr>
<tr>
<td>TRUN</td>
<td>FØ.Ø</td>
<td>Run duration</td>
</tr>
<tr>
<td>DATA(1)</td>
<td>FØ.Ø</td>
<td>Signal levels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table D.4  Input File Format for Field Trials

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Use</th>
<th>Size*</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control input</td>
<td>8Ø</td>
<td>Input linefile</td>
</tr>
<tr>
<td>2</td>
<td>Testing</td>
<td>8Ø</td>
<td>Output linefile</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>Equivalent to 97</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>Equivalent to 99</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>Equivalent to 98</td>
</tr>
<tr>
<td>8Ø</td>
<td>Transient data</td>
<td>8Ø</td>
<td>Core buffer</td>
</tr>
<tr>
<td>97</td>
<td>Data input</td>
<td>8Ø</td>
<td>Input linefile</td>
</tr>
<tr>
<td>98</td>
<td>Data output</td>
<td>8Ø</td>
<td>Output linefile</td>
</tr>
<tr>
<td>99</td>
<td>Graphs &amp; results</td>
<td>133</td>
<td>Output printer file</td>
</tr>
</tbody>
</table>

*Size given in characters per record

Table D.5  Datasets Available for QUASIM
D.4 Program Descriptions

This section seeks to give a brief description of each of the routines and subroutines which are included within the QUASIM package. In some cases the text is supported by a flow diagram where the algorithm is of prime importance to the simulation and analysis. Each section also includes notes on data transferred, common areas used and the language the routine is written in. No attempt has been made to provide a detailed treatise on the individual routines since that information would be more easily gained by a study of the source programs. The only systems subroutines used, apart from the FORTRAN and USERCODE libraries, are general utilities, for example TIMDAY which returns the time and date. All the routines are included on the overlay map, Figure D.1, although the root segment also includes the FORTRAN library, the DATAD module and the BLOCK DATA.

QUASIM
Language: FORTRAN IV
Common areas: GEN, PARAM, HEAD, AXES, DATA

This is the main program and acts as a link with all of the subroutines. It also handles the plotting for the phase and time profiles, Figure D.2.

BCD1
Language: FORTRAN IV
Common areas: GEN, PARAM, AXES

Block data initialises many common arrays.
DATAD
Language: USERCODE

The DATAD module controls the input and output for a FORTRAN program. In this case it provides all of the standard DATASETS and an additional two linefiles. The complete set available is shown in Table D.5.

INIT
Language: FORTRAN IV
Common areas: GEN,HEAD,AXES

After reading the general input data this routine initialises many of the constants in the program. It also prints these constants at the start of the output.

CHOOSE
Language: FORTRAN IV
Common areas: PARAM

This routine sets up the parameter array which controls the analysis and the input. It reads the first record of the input file, which specifies the run as a simulation or a field trials' analysis, and then each record of the control file. Each keyword is verified and the parameters are then read into the relevant elements of the array. If an invalid keyword is detected the program is halted.

HEADER
Language: FORTRAN IV

Writes header on the line printer output.
**SIGNAL**

Language: FORTRAN IV  
Common Areas: REF, DATA, GEN

This subroutine computes the magnitudes and phases of the sidebands from the signals received from each of the transmitters. After calculating the new position of the mobile at each time increment it calls REFSET. It also selects the larger sideband and evaluates the means, variances and correlation coefficient for the envelopes.

**SIMSET**

Language: FORTRAN IV  
Common Areas: REF, GEN

All the data pertaining to the plan and the radio scheme is read by this program and then correctly stored in the various arrays. Each block is assigned its phase and magnitude and then the data is printed on the main output.

**REFSET**

Language: FORTRAN IV  
Common Areas: GEN, REF, SET  
Arguments: TC, TS

The first part of this routine, Figure D.3, finds the valid coherent waves which arrive at the mobile. It then chooses each block in turn and computes the valid primary and reflected waves by use of REFLEX. It ends by calculating the signal components for each station.
REFLEX
Language: USERCODE
Common area: REF
Arguments: XNGW,ISID,XHIT,IREF,*

This routine finds the intersection between a block on the plan and a vector presented by REFSET, Figure D.4. It compares all the possible intersections and returns that which is nearest to the mobile along with the block number and the side. If there are no intersections it takes the alternative return address.

WAVES
Language: USERCODE
Arguments: REFL,N,POS,SECT,*

REFLEX presents WAVES with the number of a block and the vector. WAVES calculates which, if any, sides the vector intersects with, Figure D.5. It returns via an alternative address if there is either no intersection or the vector has only passed through one side, in which case it must end within a block.

QUEST
Language: USERCODE
Arguments: FGNE,FTWO,SECT,*

QUEST calculates the intersection between two vector segments, Figure D.6. It starts by calculating where the extended vectors would meet and then finds whether this point is within the segments of both. It uses its alternative address if there is no intersection.
After zeroing the mean of the data this routine computes the autocorrelation function. It slides all the data by one point at a time and then cross multiplies the two versions, Figure D.7. It employs FFT to compute the power density spectrum and smooths the data before plotting it.

This is a standard Fast Fourier transform routine and is described by Gentleman and Sande (35). It can be used for direct or inverse transforms. The only error condition occurs if the number of data points is not a power of two.

Both the crossing rate and mean fade duration are computed by this subroutine, Figure D.8. It notes when the signal level falls below a specified level and how long it stays below. Both statistics are plotted against logarithmic axes and, therefore, their values are prevented from falling below a minimum calculated from the total quantity of data.
SCALE
Language: FORTRAN IV
Arguments: N,ASET,DATA,MAX,DMIN
Scales data in order to suit the GRAPH routine.

CUMDIS
Language: FORTRAN IV
Common areas: DATA,PARAM,HEAD,GEN
The calculation of the cumulative distribution is carried out by relating each data level to an element of the output array. Since this statistic can be more readily studied when plotted on "probability" axes the plotting routine is also included in this program. It is similar to GRAPH except in the way it scales the axes, and therefore plots the points, Figure D.9.

OUTPUT
Language: FORTRAN IV
Common areas: DATA,GEN,HEAD
This writes the signal data to a file in the same format as for field trials data. This allows a run to be analysed at a later date.

ANLSET
Language: FORTRAN IV
Common areas: DATA,GEN
After reading the trials input file all the data is converted from decibels to linear form. This data is then ready for the rest of the analysis routines.
MEAN

Language: FORTRAN IV
Common areas: GEN, PARAM, AXES, DATA, HEAD

This routine computes the running average for all the data over a period set by the user. It normalises the data by dividing it by the mean and then ensuring it has a variance of unity. MEAN ends by plotting the mean profile, if required.

DECibel

Language: FORTRAN IV
Common areas: GEN, DATA

Converts the data from linear to decibel form. If it finds any negative values it prints a warning and uses the previous data point.

GRAPH

Language: FORTRAN IV

This is a general graph plotting routine which also labels and identifies each graph, Figure D.10. The axes are scaled such that there are between 2 and 20 segments for each. Up to 10 graphs can be plotted with additional theoretical points superimposed when required. There are many error conditions which terminate the plot and a few recoverable error conditions which just print a message.

VALu

Language: FORTRAN IV

Returns co-ordinates for each data point for GRAPH.
GPLOT
Language: FORTRAN IV
Arguments: NP, X0, DELTAX, DATA
Plots graphs on the line printer. The X-axis starts at X0 and is incremented in steps of DELTAX. The Y-axis is scaled in equal steps between the minimum and maximum values of the data. The values of each point are also printed.

RMAX
Language: FORTRAN IV
Arguments: DATA, NP
Returns largest value in an array.

RMIN
Language: FORTRAN IV
Arguments: DATA, NP
Returns smallest value in an array.

TITLE
Language: FORTRAN IV
Common area: HEAD
Prints title and data at the head of each line printer graph.
Figure D.2  Flow Diagram for QUASIM
Figure D.3 Flow Diagram for REFSET
Figure D.4  Flow Diagram for REFLEX
Figure D.5  Flow Diagram for WAVES
Figure D.6  Flow Diagram for QUEST
Figure D.7 Flow Diagram for AUTO
Figure D.8  Flow Diagram for FSTAT

Note:

FD = Fade Duration
CR = Crossing Rate
Figure D.9 Flow Diagram for CUMDIS
More Graphs? Yes

Theoretical Graph? Yes

Plot Points

No

Plot Points

Return

Figure D.10 Flow Diagram for GRAPH
ON-LINE PLAN PROGRAM

1. Description

The on-line plan was originally developed in order to study the possible algorithms to be used for the modified simulation, Section 3.3. The program starts by allowing the user to specify the positions and sizes of the blocks, the plan being redisplayed on the VDU at each change. When the plan is complete a single command starts the wave tracing routine. After the computer has ascertained the position of the mobile it draws each of the wave paths as they are calculated.

The first wave tracing routine incremented along each wave vector in turn until it crossed the side of a block. This algorithm was very inefficient. Later the method of wave tracing by calculating intersections, cf. Section 3.4, was tried in this program before being included in the main simulation. This was very useful in verifying the realisation of the algorithm and showed some of the inherent complications. An example of these occurs when a wave vector passes through the exact corner of a block. The program has to decide whether the vector intersects with either or both of the sides adjacent to the corner. This problem was partially overcome by finding if the intersection occurred within a small extension of the vectors and not necessarily within their exact lengths.

The program maintains the blocks in strict order, starting from the top left hand corner of the plan. Each block is given a number which is superimposed on
it when the plan is displayed. With complicated plans this numbering can cause confusion and can therefore be suppressed by setting the user switch register to zero.

When the user finishes with the program all the data pertaining to the plan is written to the disk into a named file. This file can be accessed by a subsequent run of the PLAN program for modification or correction. The file is also in the correct format for use with the main simulation package and can be transferred to the University computer by means of the link.

**E.2 Commands**

The command structure for the PLAN program is very simple. When the computer is ready to accept a command it prints "&" as a prompt. Any of the commands listed below may then be entered by typing the first two letters of the keyword. If more information is required the program asks for it interactively, Table E.1. The commands which are available are:

**CURSOR** The computer displays a bright spot on the VDU which can be moved by the joystick cursor control. When the spot is in the position required the user hits RETURN and the program replies by printing the co-ordinates of that point.

**DELETE** The program asks which block is to be deleted and then displays the modified plan after reordering the numbers. If the specified block does not exist an error is reported.
After the plan is complete this command will cause all the data to be transferred to disk and the computer will return control to the system monitor.

The complete plan and all the buffers can be cleared by this command. Since the effect could be annoying, at least, if the command was entered inadvertently the program asks "ARE YOU SURE?". If any other key than Y is hit the program returns with a prompt and takes no further action.

This utility command types out a full list of all the commands available.

As its name implies, new blocks can be added to the plan by the keyword INSERT. It first requests the centre of the block and displays a dot at that position. It then asks for the size of the block before redrawing the plan with the new rectangle included. All of the values required by the computer are assumed to be measured in metres.

This is a combination of DELETE and INSERT. The plan may be redrawn on the X-Y plotter with this command. On its first call it allows the user to centre and scale the axes as necessary. The program then draws out the complete plan with titling and numbers if required. The scaling is assumed to be the same for all subsequent calls.
POSITION
A dot is displayed at the co-ordinates entered after this command is given. This routine is the same as that used at the start of the INSERT command.

REFLECT
The computer starts this routine by issuing a call to CURSOR and uses this to discover the position of the mobile. It also asks whether the waves are to be traced on the VDU or the X-Y plotter. When this has been decided it starts the wave tracing algorithm and draws each primary and reflected wave as it is calculated.

TITLE
All the initial data required by the main simulation is entered after this command.

VIEW
The plan can be completely redrawn by use of this keyword. Its main use is for clearing the screen of all but the basic plan after the program has been used for tracing wave paths.

The program is also able to handle two keyboard control characters:

CNTRL/C This is the main abort character. As with ERASE the computer checks whether it was really meant before destroying the buffers by returning to the system monitor.

CNTRL/O Any command can be stopped by this character and control returned to the programs own keyboard monitor. This cannot affect any of the data buffers.
PLAN OF SIMULATION AREA. 14/10/77

*PROCT

&CURSOR
X= 135  Y= -93

&INSERT
REFLECTOR POSITION ? 135 -95
REFLECTOR SIZE ? 10 40

&MOVE
REFLECTOR NO.? 30
REFLECTOR POSITION ? 135 -80
REFLECTOR SIZE ? 10 20

&INSERT
REFLECTOR POSITION ? 110 -80
REFLECTOR SIZE ? 10 20

&MOVE
REFLECTOR NO.? 27
REFLECTOR POSITION ? 105 -80
REFLECTOR SIZE ? 10 20

&REFLEXIONS
XY- PLOTTER ? NO
WHERE IS THE MOBILE?

&CURSOR
X= -25  Y= 0

&VIEW

&REFLEXIONS
XY- PLOTTER ? NO
WHERE IS THE MOBILE?

&PLOT
CENTRALIZE PEN
SET PEN TO TOP LEFT

&REFLEXIONS
XY- PLOTTER ? YES
WHERE IS THE MOBILE?

&ERASE
ARE YOU SURE? NO

&END

Table C.1  Sample Program Run - PLAN
FIELD TRIALS' PROGRAMS

F.1 Scope

When recordings of signal level have been made during field trials they have to be quantised and then prepared for analysis by the main QUASIM package. The actual recordings are described in Chapter 4 which also includes a brief discussion of some of the processing routines. This Appendix provides a detailed study for each of the main routines with brief notes on some of the subroutines.

F.2 Running

All the main routines are interactive. After the initial RUN command they commence with a dialogue, Tables F.1 to F.9. As can be seen, the programs have been designed as a package and, hence, the question and answer scheme is similar for each. Wherever possible data is transferred within the files from one program to the next.

F.3 Filenames

This series of programs have a large number of separate data files. In order to ensure that each routine accesses the correct data the filenames are made up from a number of parts. This also allows the user to keep the disk storage tidy and to quickly ascertain how much data is currently held on disk for any particular trials' series. The files can be transferred to other forms of mass storage but must be available on disk.
when the routines themselves are being used.

The general format of the filenames is:

DEV:IXXNNK.EX

where:

DEV  device on which file is held (SYS or DSK)
I  program identifier
XX  file series
NN  run number
K  plot identifier (incremented when required)
EX  file extension (either DT or DA)

The sample program runs, Tables F.1 to F.3, demonstrate how these filenames are used. Usually the file series is common to all the files for a trials' series while the run number is incremented for each run. The file extension differentiates between unformatted, DT, and formatted, DA, data. All the plot files and the final output file for transfer to the main computer are of the latter type.

F.4  Program Descriptions

This section provides a detailed description of each of the eight main routines with special emphasis on their use. Each program is written in FORTRAN II as the basic language with SABR assembler code wherever necessary. Brief notes are also included on the library of subroutines which have been written for this series of programs. The section concludes with a look at the LINK and PLOT routines.
This program provides the automatic test procedure for characterising the recording system. It can be used for both the single transmitter and the diversity schemes. The recording equipment should be arranged as shown in Figure 4.2. The USB signal is connected to A/D 1 and the LSB to A/D 2. If only one signal is being used it is connected to A/D 1. The RF signal level is set at the maximum required not forgetting the insertion loss due to the attenuator. The attenuator itself is set to zero.

After the program asks whether or not diversity is to be used it enters a test sequence. The user can type in a value of attenuation and the computer returns the levels of the A/D convertors. This serves as an initial check on the state of the equipment, for example the values will be out of range if the input attenuator on the FM recorder is incorrectly set. When the user is ready the program will automatically increment the attenuator between specified limits and record the A/D level at each step, Figure F.1. It finishes by plotting the characteristic curves on the VDU.

When a series of trials is complete the recording equipment is returned to the laboratory and arranged as shown in Figure 4.4. Care must be taken to ensure that the correct signal is connected to the correct A/D convertor. The tape is positioned just before the first...
run and the control signal is fed to the computer via A/D 0.

The program starts by requesting various parameters connected with the trials, Table F.2. The sampling rate is set by the user and controlled by the internal real time clock. When all the initial data is entered to the computer it prints the message:

"READY WHEN YOU ARE!!!"

After the tape is started RETURN is hit on the keyboard and the computer starts sampling when the control rises above \( \frac{1}{4} V \). This procedure is used to prevent the large transient spikes generated when the recorder starts from giving a false control signal.

While the control stays above \( \frac{1}{4} V \) the program will continue to sample all three A/D convertors. In order to achieve the required sampling rate the program uses interrupt processing, Figure F.2. Much of its time it is in a wait loop and just checks the control signal. After a sample is read the program checks the buffer pointer and if necessary writes the complete buffer to the disk. At this point the interrupt is essential since the disk transfer takes a significant time. When the control falls below \( \frac{1}{4} V \) the program writes out the last of the data, records the run time and closes the data file. It prints the run time in seconds and also the filename and is then ready to proceed to the next trials' run. To reduce the amount of dialogue it asks if all the initial constants remain.
AGCOK

In order to recover the absolute signal levels from the sampled data the characteristic curves are linearly interpolated by AGCOK. The name of this program was chosen when the AGC voltage was used as the measure of field strength but the program is still required for the logarithmic amplifier system. The computer starts by requesting the name of the file created by AUTFIT. From this it gains the characteristics and whether or not a diversity scheme is being studied. It forms the input and output filenames from the file series and the run number, Table F.3.

Apart from interpolating the curves this routine also tidies up the control signal. If the control falls below the specified value for more than five samples it assumes that a marker pulse was inserted at that point. It prints the number and time of the marker and also writes this information to its output file.

After closing the output file the program is ready to correct the next set of data. It presumes that the same characteristic curves are to be used. The only information it then requires about the next file is its run number.

The output files for the diversity runs still have both sidebands' data. Before they can be fully analysed they must be reduced to only one signal, see SELECT. If a single transmitter scheme is being studied the output file is directly ready for further analysis. These are differentiated by the initial letter of their filenames.
SELECT

This program is only used when processing trials' data for a diversity scheme. After creating the name of the file the program reads the relevant initial data and prints the title, Table F.4. It then asks the user whether it should select the larger of the sidebands at any increment of time to produce the output signal. If the answer to this question is "NO" it requests the number of the sideband required for further analysis. In both cases it also transfers the marker data to the output file.

MEAN

Before any meaningful analysis can be performed on the data it must be normalised with respect to its mean. The central section of this program is equivalent to the subroutine MEAN in the QUASIM package. After the dialogue it requests the length of the averaging period in seconds, Table F.5. This period is limited by the store size which prevents the sliding array from being longer than 500 samples. Apart from calculating the sliding mean the program also prints the absolute mean level between any two markers.

The first part of the mean output file, equal to half the averaging period, is set to the value of the first mean sample. This ensures that the samples in the data and mean files are coincident. At the end of the mean file the data points are omitted and the total length is reduced accordingly.
PLOTS

One of the most useful facilities of this package of programs is the ability to plot any part of the data on the VDU or the X-Y plotter. If required the sliding mean can be superimposed onto the main plot. The system PLOT routine limits the total number of points to 900, including the X-axis. If the user attempts to plot more than this number of points the program automatically groups the data samples before selecting the points for the graph. At the end of each run the user has the option of continuing with another plot. When the same file is selected then the program increments the last digit of the filename and continues with its dialogue, Table F.6.

CUMDIS

An impression of the characteristics of the trials' data can be gained by a study of the cumulative distribution. The small computer is not able to provide a very accurate estimate of this statistic due to its long processing time and limited precision. The program does, however, give an idea of the distribution of the multipath fading.

The store size again limits the analysis period to 500 samples and this is entered at the end of the dialogue, Table F.7. If a longer period is given then the program resets it. The computer reads the relevant data from both files and normalises the samples with respect to the mean. This process tends to reduce the
overall accuracy because of the small number of data points. The main algorithm for obtaining the statistic is the same as that used in the subroutine CUMDIS in the QUASIM package. The output is in the form of a plot file which can be used directly with the system PLOT routine. The program allows processing to continue on either the same or a different data file. If the same file is used the last digit of the plot filename is incremented.

**DIVIDE**

The last of the main processing programs formats the data ready for transfer to the University computer. The majority of the data files are very much too long for meaningful analysis and have to be split into sections. This routine allows each section to be started anywhere within the original file and to be of any length. After one new formatted file is produced the user can continue with the next section from the same file by entering a negative number for the start time. The last digit for each new file is incremented as necessary. If the user attempts to exceed the length of the original file at any time a warning is printed and the period reset to the end of the file. Currently the markers are ignored by DIVIDE since they are not required by QUASIM. This situation could easily be altered which would enable the main analysis to be more simply related to the physical environment of the field trials' run.
USEFUL

USEFUL is a library of special subroutines for use with the main programs described above. The routines included in the library are:

ATTN  Sets the programmable attenuator for AUTFIT.
CALC  Contains the main algorithm for computing the cumulative distribution
CLAG  Clears and resets the RT clock and the A/D convertors
DECIDE Used during the initial dialogues when the answers YES or NO are required.
DECIPH Interpolates the characteristic curves for AGCOK
FILSET Writes the filename to the command decoder area for automatic plotting
FNAME Generates the filenames from the file series and run number.
IDAT  Reads unformatted data when the core is very full.
IODAT Reads and writes unformatted data to and from disk.
ITOA  Translates integers to alphanumerics.
NOTAIL Removes trailing spaces from filenames.
SAMPLE Reads the specified A/D convertor after the input signal has settled.
TRAN  Transfers blocks of data to disk.
USR1  Finds, opens and closes files on any of the mass storage devices.
**LINK**

The asynchronous link between the two computers is accessed by the simple command "LINK", Table F.9. The user logs in to the main system with a personal username and password. The data transfer is achieved by means of a dialogue between separate programs running at the same time on the two systems. The program on the University computer is started by typing CNTRL/B. After some general information the program requests the filename to be created on the main computer. When this is accepted the user types CNTRL/X to initiate the transfer itself and CNTRL/P to inhibit the echoing on the small computer. The transfer continues until the end of file is reached when the new file is closed and the small computer returns to its monitor. The transfer is fairly slow since the link is limited to 1200 baud. This is further reduced since the University computer works on time sharing.

**PLOT**

The small computer's plot routines are very versatile. They are initiated by the command "PLOT" followed by the filename and any options required, Table F.10. If no options are given the routines default to automatic scaling and draw the graph on the VDU. The options can be used to provide manual scaling, log axes, suppressed axes, suppressed titles and plotting on the X-Y plotter.
Figure F.1 Flow Diagram for AUTFIT
Figure F.2 Flow Diagram for ATOD
.R AUTFIT

* * * * * * * * * * *

DIVERSITY? # YES
ATTENUATION (DB)? 0
A/D 1 LEVEL 0.684
A/D 2 LEVEL 0.653

ANOTHER TEST? # YES
ATTENUATION (DB)? 40
A/D 1 LEVEL 0.495
A/D 2 LEVEL 0.432

ANOTHER TEST? # NO
OUTPUT FILENAME? 29MA79
DB RANGE: FROM -60.
TO -130.
IN STEPS OF 1.

* * * * * * * * * * *

XAXIS MIN=-1.3E+03 MAX=-0.6E+02
YAXIS MIN= 0.3E+00 MAX= 0.7E+00

Table F.1 Sample Program Run - AUTFIT
Table F.2 Sample Program Run - ATOD
FILE FOR AGC LAW? 29MA79
MARKER LEVEL? 400
FILE SERIES? M2
RUN NUMBER? 01
INPUT FILE:- SYS:YM2010.DT
OUTPUT FILE:- DSK:XM2010.OT
TITLE:- 01) GT. PULTENEY ST. (TX 1)

MARKER 1 TIME 1.3
MARKER 2 TIME 11.4
MARKER 3 TIME 18.3
MARKER 4 TIME 26.5
ANOTHER RUN? # YES

SAME FILE SERIES? # YES
RUN NUMBER? 02
INPUT FILE:- SYS:YM2102.DT
OUTPUT FILE:- DSK:XM2102.OT
TITLE:- 02) GT. PULTENEY ST. (SBD)

MARKER 1 TIME 0.4
MARKER 2 TIME 8.7
MARKER 3 TIME 15.3
MARKER 4 TIME 23.0
ANOTHER RUN? # NO

Table F.3 Sample Program Run - AGCOK
R SELECT

* * * * * * * * * *

FILE SERIES? M2
RUN NUMBER? 01
INPUT FILE: DSK:XM2010.DT
OUTPUT FILE: DSK:OM2010.DT
TITLE: 01) GT. PULTENEY ST. (TX 1)

SELECT SIDEBAND? # NO
SIDEBAND? 2
ANOTHER RUN? # YES

* * * * * * * * * *

SAME FILE SERIES? # YES
RUN NUMBER? 02
INPUT FILE: DSK:XM2020.DT
OUTPUT FILE: DSK:OM2020.DT
TITLE: 02) GT. PULTENEY ST. (SGD)

SELECT SIDEBAND? # YES
ANOTHER RUN? # NO

* * * * * * * * * *

Table F.4 Sample Program Run - SELECT
**Table F.5 Sample Program Run - MEAN**

<table>
<thead>
<tr>
<th>MARKERS</th>
<th>MEAN (dB)</th>
<th>TIME (SECS)</th>
<th>START TIME (SECS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 2</td>
<td>-88.4</td>
<td>9.88</td>
<td>1.50</td>
</tr>
<tr>
<td>2 &amp; 3</td>
<td>-88.0</td>
<td>7.44</td>
<td>11.40</td>
</tr>
<tr>
<td>3 &amp; 4</td>
<td>-83.3</td>
<td>7.76</td>
<td>18.84</td>
</tr>
<tr>
<td>4 &amp; END</td>
<td>-85.9</td>
<td>6.78</td>
<td>26.60</td>
</tr>
</tbody>
</table>

ANOTHER RUN? # YES

<table>
<thead>
<tr>
<th>MARKERS</th>
<th>MEAN (dB)</th>
<th>TIME (SECS)</th>
<th>START TIME (SECS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 2</td>
<td>-84.8</td>
<td>7.18</td>
<td>1.50</td>
</tr>
<tr>
<td>2 &amp; 3</td>
<td>-86.0</td>
<td>7.12</td>
<td>8.70</td>
</tr>
<tr>
<td>3 &amp; 4</td>
<td>-82.6</td>
<td>7.22</td>
<td>15.82</td>
</tr>
<tr>
<td>4 &amp; END</td>
<td>-83.7</td>
<td>5.58</td>
<td>23.04</td>
</tr>
</tbody>
</table>

ANOTHER RUN? # NO

---

.R MEAN

* * * * * * * * *

FILE SERIES ? M2
RUN NUMBER ? 01
INPUT FILE: DSK:DM2010.DT
OUTPUT FILE: DSK:SM2010.DT
TITLE: 01) GT. PULTENEY ST. (TX 1)
TOTAL TIME: 34.9 SECS
SAMPLING RATE: 100 SAMPLES/SEC
AVERAGING PERIOD ? 3.

MARKERS MEAN (dB) TIME (SECS) START TIME (SECS)
1 & 2 -88.4 9.88 1.50
2 & 3 -88.0 7.44 11.40
3 & 4 -83.3 7.76 18.84
4 & END -85.9 6.78 26.60
ANOTHER RUN ? # YES

* * * * * * * * *

SAME FILE SERIES ? # YES
RUN NUMBER ? 02
INPUT FILE: DSK:DM2020.DT
OUTPUT FILE: DSK:SM2020.DT
TITLE: 02) GT. PULTENEY ST. (SBD)
TOTAL TIME: 30.1 SECS
SAMPLING RATE: 100 SAMPLES/SEC
AVERAGING PERIOD ? 3.

MARKERS MEAN (dB) TIME (SECS) START TIME (SECS)
1 & 2 -84.8 7.18 1.50
2 & 3 -86.0 7.12 8.70
3 & 4 -82.6 7.22 15.82
4 & END -83.7 5.58 23.04
ANOTHER RUN ? # NO

* * * * * * * * *
Table F.6  Sample Program Run - PLOTS

F.18
Table F.7  Sample Program Run - CUMDIS

F.19
FILE SERIES? M2
RUN NUMBER? 01
INPUT FILE: DSK:DM2010.DT
TITLE: 01) GT. PULTENEY ST. (TX 1)
TOTAL TIME: 34.9
START TIME? 0.
PERIOD OF FILE? 12.
OUTPUT FILE: DSK:MM2010.DA
ANOTHER RUN? # YES
SAME FILE? # YES
START TIME? -1
PERIOD OF FILE? 12.
OUTPUT FILE: DSK:MM2011.DA
ANOTHER RUN? # YES
SAME FILE? # YES
START TIME? -1
PERIOD OF FILE? 12.
PERIOD RESET TO 10.9 SECS
OUTPUT FILE: DSK:MM2012.DA
ANOTHER RUN? # YES
SAME FILE? # NO

FILE SERIES? M2
RUN NUMBER? 02
INPUT FILE: DSK:DM2020.DT
TITLE: 02) GT. PULTENEY ST. (SBD)
TOTAL TIME: 30.1
START TIME? 8.7
PERIOD OF FILE? 10.
OUTPUT FILE: DSK:MM2020.DA
ANOTHER RUN? # YES
SAME FILE? # YES
START TIME? 15.8
PERIOD OF FILE? 10.
OUTPUT FILE: DSK:MM2021.DA
ANOTHER RUN? # NO

Table F.8 Sample Program Run - DIVIDE
Table F.9  Sample LINK Transfer

Table F.10  Sample Program Run - PLOT
G EQUIPMENT

G.1 Outline

The majority of the equipment utilized during this project is standard commercial apparatus. In some cases modifications have been made to suit the specialised requirements of a particular section of the work. This appendix gives brief specifications of most of the items of equipment used with notes on any alterations. It also includes descriptions of some circuits designed and constructed during the course of the work. Much of the discussion concentrates on the equipment for the diversity scheme since this also was without doubt the major part of the hardware. However, descriptions are included about items used in earlier stages of the work as well.

G.2 Fixed Stations

The fixed transmitting station for the results in Chapter 6 consisted of a Pye R70A transmitter and a single element, folded dipole aerial. The transmission was full AM modulated with a tone of 1kHz at 30% and a nominal output power of 30 W. The station was located at the top of the School of Electrical Engineering at the University of Bath.

For the diversity scheme there are two remote stations controlled by a single base located in the School of Electrical Engineering. One remote station is situated on top of the University's high rise block called Wessex House at almost 215m above sea level. The
Figure G.1 Base Station Control

- Audio Amplifier
- Audio Oscillator
- Microphone Amplifier
- Transmit Select

Symbols:
- M - Modulation
- K - Transmit Key
- G - Ground
second remote station is co-sited with the base. The base controls the two remote transmitters by use of FM links, Figure G.1. The control panel has been designed to provide a high degree of flexibility. It includes a general purpose audio amplifier, audio oscillator and microphone preamplifier. The central section of the panel contains the phasing network, Figure G.3. When both of the inputs are connected to the same signal, the outputs of the network are shifted by $90^\circ$ with respect to each other over the full audio bandwidth, Figure G.2.

The modulation inputs to the Pye U450L UHF FM sets can be connected to either a shifted or an unshifted version of any signal input to the panel. Each of the transmitters can be keyed separately in order to control the two remote stations. The nominal power of the UHF transmitters is 6W at carrier frequencies of 461.750 MHz and 467.450 MHz using 12 element Yagi aerials.

---

![Phase Response of Phasing Network](image_url)
Figure G.3  Circuit for 90° Phasing Network
In the remote stations there is a Pye U450L UHF FM receiver connected, via a buffer amplifier, to a Pye M201 VHF AM transceiver, Figure G.4. The squelch relay in the UHF set controls the power supply to the VHF set. The transceiver is permanently keyed to transmit. Its first oscillator has been replaced with a phase-locked synthesiser which has a stability of better than $1:10^3$ at an output frequency of 43.14375 MHz. This frequency is doubled before being transmitted.

The output power of the VHF sets is nominally 6W and the full AM signal is normally modulated by a 1 kHz tone to a depth of 50%. This higher modulation level is used to increase the sideband power since this is what is being measured. Both of the remote stations include a keyswitch which can be used for maintenance purposes. This switch dekeys the transceiver and supplies it with power by overriding the squelch relay.

G.3 Mobile Station

All of the field trials have used a Pye W20 VHF AM/FM transceiver to receive the signal in the mobile. The aerial is a quarter wave whip mounted vertically at the centre of the car roof. For all the later trials a Volvo 144 Estate has been used which provides ample room for all the equipment. The general arrangement is shown in Figure 4.3.

The fundamental circuit for the logarithmic amplifier is constructed round a TL441, Figure G.5. The circuit as shown can be used at IF by selecting the
Figure G.4  Remote Station Control
op-amps or replacing them with wideband amplifiers. The integrated circuit itself will operate up to 10 MHz.

For the diversity scheme the compression is performed at AF and, hence, a four pole Butterworth filter, Figure G.6, is included just prior to the amplifier. The complete circuit responds to input signals over a range of almost 90 dB, Figure G.7. Its frequency response, within the filter pass band, is nearly flat although the output exhibits some ripple at the lower frequencies.

The ISB receiver can be separated into a number of distinct blocks, Figure G.6. The oscillator, its phase shifter and the balanced demodulator all uses digital techniques. The demodulator has to be very precisely set up to ensure that both outputs have equal amplitude. The main phasing network uses exactly the same circuit as for the control panel, Figure G.4. The final sum and difference amplifiers are constructed around op-amps. The frequency response of the receiver shows an unwanted sideband suppression of at least 45 dB over the full audio bandwidth.

Since the ISB receiver uses coherent demodulation the frequency of its input has to stable and precise. The standard first oscillator in the trials' receiver was not adequate for this purpose. It has been replaced by a TCXO and the IF can be finely adjusted by use of a varicap diode connected across the IF crystal.

The signals are recorded onto a Tandberg TIR 115 Instrumentation Tape Recorder. This has three FM and one direct channels.
Figure G.5  Circuit for Logarithmic Amplifier

All op-amps: TL071 or similar
Power supply: 12V
Figure G.6  Filter Frequency Response

Figure G.7  Logarithmic Amplifier Dynamic Response
Figure G.8  ISB Receiver Block Diagram
Figure G.9  ISB Receiver Output Characteristic
G.4 *Computers*

The majority of the data processing has been done on three computers. The sampling and characterisation uses the Digital PDP8/e in the School of Electrical Engineering. The data is then transferred to the main University computer, an ICL 4-50 running under Multijob. Although the simulation package was created, compiled and composed on this machine it has to be run at the University of Exeter on the ICL 4-75. These computers are linked within 31JUCN to other ICL machines at the Universities of Bristol, Cardiff and Wales (UWIST).