DIVERSITY TECHNIQUES
FOR LEAKY FEEDERS

by

A G Chadney

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SUMMARY

This thesis examines the use of diversity techniques for improving the performance of a leaky feeder communication link.

Tests have been carried out at frequencies of 40 and 80 MHz on an experimental system with the cable buried in soil just beneath ground level along side a road. The system was originally installed to establish the feasibility of transmitting high transmission rate (100kbs\(^{-1}\)) data from a vehicle to a cable for a vehicle manufacturers test track telemetry system.

Coupling to both loop and dipole aerials were examined and compared against the coupling to a vehicle mounted loop and monopole. Severe fading, characterised by a Rayleigh distribution, was experienced at the extremes of radial range, regardless of aerial configuration, which could result in severe error bursts on a data link.

Close to the cable, within a radial range of half of a freespace wavelength, this work has established that fading can be completely eliminated with the appropriate choice of aerial, despite the scattering of the coupling mode.

Various diversity mechanisms and techniques are then considered primarily as a means of mitigating the fading outside this radius.

Three mechanisms, frequency, space and field-component were chosen for a detailed study in conjunction with a transmission, frequency offset technique.

For each mechanism, the improvements afforded by diversity are found to be substantial and under Rayleigh fading conditions, the correlation coefficient of the diversity signals was found to be an adequate descriptor of the diversity gain. The factors determining the correlation function are also identified.
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1. INTRODUCTION

Historically, mobile communication services have been available to a very restricted number of users owing to the limited availability of spectrum and the lack of suitable technology to exploit this spectrum efficiently. Recently, advances in technology have led to the development of cheap, compact processing components, from analogue radio frequency functions to numerical processors, resulting in the use of higher frequency bands and spectrally efficient schemes such as trunking and cellular. Consequently, there has been a dramatic change in the nature of mobile radio services. For instance, high capacity cellular services are now firmly established in America, Japan and Western Europe together with cordless telephones which are increasingly required for business as well as domestic use.

The demand for these services will lead to systems saturating within the next few years, and new systems are under development to relieve the anticipated congestion.

Despite new technologies, the frequency spectrum is still a scarce resource to be managed efficiently. Many systems require only limited radio coverage, and the potential of leaky feeders, or radiating cables, for efficient spectrum use in these applications has been recognised for a number of years. A characteristic leaky feeder systems share with more conventional coverage techniques is the degradation of the communication link by multipath fading. However, techniques for mitigating the effects of multipath have received limited attention for leaky feeder use, despite the substantial advantages that such techniques have brought to other radio systems, particularly data transmission links, where a high reliability is required.

This thesis examines one of these techniques, diversity, which is potentially efficient in spectrum use, and simple to implement, for leaky feeder applications.
1.1 Project Background

The work for this study, primarily experimental, has centred on a feeder system installed at the University of Surrey. The system arose from the need of a French car manufacturer, Peugeot, to transmit data at $100\text{kb}^{-1}$ to a fixed location from a vehicle travelling around a 6Km test track. Tests had shown that conventional broadcast methods were unsuitable given Peugeot's low power budget, and so a leaky feeder system was proposed to assist propagation. An experimental system was established at the University to investigate the performance of various feeder layouts. Initial results indicated that a promising configuration was obtained with the feeder buried in soil just beneath ground level.

Tests were then carried out to determine the performance of high bit rate data transmission between a moving vehicle and the nearby feeder. The application of diversity was also examined and after limited work it was concluded that the technique was capable of considerably enhancing the system performance and further studies were recommended.

The aims of this particular study, using the test track system as an example, are:

1. To establish suitable mechanisms for achieving diversity.
2. To quantify the performance of diversity.
3. To identify the features and parameters of the feeder and its environment which affect diversity performance.

Although it has only been possible to examine one particular configuration of leaky feeder, the study has enabled some more general conclusions to be drawn, which, given the lack of reports on this subject, should hopefully be of benefit to other workers interested in diversity for feeders in different environments.
1.2 Review

Both leaky feeders and diversity techniques have received extensive attention resulting in a wealth of publications in both fields. Since there are few publications linking the two, the review will deal with each of the topics separately, concentrating on the areas which have been of particular interest during this study.

1.2.1 Leaky Feeders

The earliest work on leaky feeders can be traced to the accidental discovery by Monk and Winbigler in 1956. However, it was not until the late sixties and early seventies that a concentrated effort was made on their application and development. Key figures at this time were Martin in England and Delogne working in Belgium.

In 1974, workers in the field were brought together at the University of Surrey, marking an important step in the process of understanding these systems through a wide range of practical and experimental papers. Two of the papers, one by Cree and Giles and the other by Delogne, are of particular interest. Cree's work was the first systematic experimental investigation of the properties of various leaky feeders undertaken on the surface. Delogne, in his theoretical study, had considered the electromagnetic theory of such cables and for the first time, used the transfer impedance as an electromagnetic characteristic of the outer conductor to impose boundary conditions on the braid. This technique has since been effectively used to characterise the propagation conditions of feeders mounted above a ground plane and buried in soil.

Coupling loss was widely used at the Surrey meeting in many of the papers to describe performance, but the term, although useful and still widely used, has not been standardised. In this study it is taken to be "the transmission loss between the power radiated from a mobile
transmitter and the power in the coaxial mode at the receiver end of the cable, minus the corresponding coaxial mode attenuation between this end and the mobile transmitter".

It was also Delogne\textsuperscript{7} who, in 1976, explained the mechanism of the random nature of the coupling which had been observed in experimental investigations. Since then, workers investigating leaky feeders for use in tunnels\textsuperscript{8,9}, buildings\textsuperscript{10}, and surface systems\textsuperscript{11}, have reported the variations in coupling loss along a leaky feeder approximately follow a Rayleigh distribution. Delogne\textsuperscript{12}, in his excellent book on leaky feeders, briefly presents a model for describing the random coupling that predicts such a distribution. This remains at present, the only attempt to characterise the coupling by any form of statistical model, rather than the deterministic of empirical studies previously mentioned.

Requirements for data transmission over leaky feeders have been identified for a wide variety of systems. Martin\textsuperscript{13} discusses the need and problems of data transmission for mining applications; the most likely degradation being seen as the corruption of data by receiver noise during the deep fades set up by multimode interaction. Transmission rates of several kbs\textsuperscript{-1} are envisaged for such applications but Delogne\textsuperscript{14} has also examined the problems associated with rates of 1.25Mbs\textsuperscript{-1} in a tunnel environment. Here the main problem was the frequency selectivity of the coupling causing intersymbol interference. The solution adopted was to prevent any mode other than the coaxial from being excited, thereby eliminating the dispersion of multimode transmission.

Data transmission from trains is considered by Sakata\textsuperscript{15} for the Japanese railway system and Glatzel\textsuperscript{16} for a magnetic levitation propulsion train, although the characteristics of the leaky feeder transmission channel are not reported. Motley\textsuperscript{1} in a study of a motor vehicle telemetry system is the only worker who has presented
details of impairments to data resulting from leaky feeder transmission. He adopted a technique used by French\textsuperscript{17} for determining the error statistics. The occurrence of an error is assumed to be solely a function of the signal strength at the receiver input and the self generated noise of the receiver. Hence by knowing the distribution of the received signal level and the receiver characteristics, the error statistics can be calculated. Errors are shown to occur in bursts when the signal level comes close to the noise level during the deep fades set up by multimode interaction. Motley carried out his tests using vehicle speeds of 20 m.p.h or less, but Arrendondo\textsuperscript{18} has reported that as vehicle speed increases in a land mobile environment the random FM due to random phase variations of the received signal puts a limit on the achievable error rate for FM systems. Critchley\textsuperscript{19} has presented the phase characteristics of the coupling along a leaky feeder in a tunnel; the results clearly show rapid fluctuations about the mean level. Treen also mentions a similar effect noticed during his studies, but the details are not presented. There presently appears to be no explicit report on the effects of these variations on FM data links with high speed vehicles.

1.2.2 Diversity

The primary objective of a diversity scheme is to reduce the effect of excessively deep fades set up by multipath propagation. An alternative strategy to combating the deep fades is to increase transmitter power. On leaky feeder systems, as with other forms of radio communication, this is not always possible or desirable owing to other system requirements. In a mining environment for instance, intrinsic safety considerations limit the power levels which can be used and on the surface, spectrum pollution must be considered. In any two way communication over a leaky feeder employing repeating amplifiers, keeping power levels low will help ensure the amplifiers meet the stringent intermodulation requirements. Indeed a decrease in power levels would be
welcomed, easing specifications and increasing system capacity. The range of a system, both radially and longitudinally can also be increased through the use of diversity, which in a repeatered system, enables the span between repeaters to be increased.

The use of diversity techniques to combat fading was first used as long ago as 1927\textsuperscript{20}. Since then the literature has been replete with descriptions of various forms of diversity and their application to fixed radio links. Over the past twenty years, these techniques have been receiving increasing attention from the workers in the land mobile field, particularly for data transmission. Transmission over a land mobile link suffers from the same effects as those found on leaky feeder systems. Frequency selectivity, random FM and envelope fading, discussed in the previous section in relation to leaky feeders, have been identified as sources of impairment in the land mobile environment, and detailed consideration is given to these topics by Jakes\textsuperscript{21} and Lee\textsuperscript{22}. Also, the mobile part of the link on the particular leaky feeder system being considered in this thesis, a motor vehicle, is another common feature with land mobile systems. Consequently the work on diversity techniques for land mobile use has been an important and useful source of reference during this study.

The diversity method requires a number of transmission paths to be available, all carrying the same information, but having independent fading statistics. The mean signal strengths should also be approximately the same. Both Stein\textsuperscript{23}, for fixed radio links, and Lee\textsuperscript{22}, for mobile radio links, classify the mechanisms which can be exploited to achieve independently fading signals. Between the two, there are seven headings which are worth considering as classifications for leaky feeder diversity mechanisms. These are:
1. Space diversity.

2. Angle of arrival diversity.

3. Frequency diversity.

4. Polarisation diversity.

5. Field component diversity.

6. Time (signal repetition) diversity.

7. Multipath diversity.

The first three, each of which will be considered separately in the following paragraphs, have already received limited attention for use with leaky feeders.

1.2.2.1 Space Diversity

An examination of the longitudinal variations in coupling loss along a feeder suggests two or more suitably spaced aerials could help mitigate the fading. The requirement on the spacing is to ensure the signals on the various aerials are sufficiently uncorrelated for effective diversity operation. Although Martin and Treen have advocated such a system, no details are presently available on suitable spacings. Another factor to be considered, important for the vehicle test track, is the limitation on spacings that can be accommodated on a vehicle. Aerial interaction may have to be taken into account and here the work done by Lee is especially relevant. The alternative to multiple aerials on the vehicle, is the use of multiple feeders. Again, these must be spaced to ensure the signals received on the different cable terminations are uncorrelated. This particular technique has yet to be considered in the literature.
1.2.2.2 Angle of Arrival Diversity

Work in both the troposcatter and mobile radio fields show that signals received from different directions can be sufficiently uncorrelated to enable effective diversity operation.

The directional diversity technique discussed by Motley and Critchley for leaky feeders is in fact a form of angle of arrival diversity. Both workers have demonstrated how the signals received at the two ends of a feeder, if appropriately combined, effectively mitigate the fading. Martin has also considered the possibility of exploiting the same mechanism on a tailback system. However, there has yet to be any consideration of a directional arrangement which can be implemented on the mobile.

1.2.2.3 Frequency Diversity

Frequency diversity takes advantage of the selective nature of the fading in the frequency domain. Different carrier frequencies are used for simultaneous transmission of the information to establish the independent diversity branches. The spacings between the frequencies must be sufficient to ensure the fading statistics of the various carriers are uncorrelated. Motley has already carried out limited experimental work on the mechanism for application to the test track system, concentrating on the selectivity characteristics of the fading set up by a single discontinuity. The results are a useful indicator to the frequency spacings required for such a system, but the performance of the technique was never quantified. Delogne has also considered the selectivity characteristics of leaky feeder coupling. His study was concerned with eliminating the effects of selectivity on broadband transmissions, rather than the advantages afforded to a narrowband diversity.
system. Even so, the theory presented gives a useful insight into the characteristics of leaky feeder selectivity.

1.2.2.4 Polarisation and Field Component Diversity

The precise definition of polarisation diversity varies according to the type of system under consideration but in all instances there is an assumption that propagation is through TEM radiation modes: if modes of different polarisation can be supported while displaying uncorrelated fading statistics, there is a mechanism for achieving diversity. Whether such modes are the dominant coupling mechanisms on a leaky feeder system will be determined by the characteristics of the configuration, but on most systems there is significant coupling to non radiating modes. However, differences between the field distributions of the supported modes could still result in several of the field components displaying uncorrelated fading characteristics. Therefore the mechanisms for achieving a diversity advantage remain. To describe the mechanism as polarisation diversity would seem confusing since this traditionally implies that propagation is by TEM radiation. A less confusing term would simply be field component diversity. Here it is worth noting the mobile radio work. Field component diversity has already been proposed for mobile radio systems by Clarke\textsuperscript{26}, who showed that the E and H fields are uncorrelated as are orthogonal components of the H field. J R Pierce\textsuperscript{27} has also proposed the use of an array of loops and a monopole specifically for combating standing waves set up by the interaction of two waves travelling in opposite directions. Lee\textsuperscript{28} has since followed up these ideas with experimental investigations that clearly show the substantial improvements gained with such an array.
In this work, the term field component diversity will be used as a classification for all diversity arrangements exploiting differences between various field components.

1.2.2.5 Time and Multipath Diversity

Time diversity is only effective for moving vehicles. In order to ensure the fading characteristics of transmissions bearing the same information are uncorrelated, the period between the transmissions must be at least as great as the reciprocal of the fading bandwidth. Apart from vehicle speed, the fading bandwidth on a leaky feeder will be a function of the periods of the standing waves set up through multimode interaction. Since the propagation velocities of the modes determine these periods, the fading bandwidth is also a function of the propagation velocities.

Multipath diversity techniques rely on their ability to separate the various multipath components. The interarrival times of the different multipath signals determine the bandwidth required for the transmission with the relationship between the two being inverse. Therefore, an environment exhibiting a low spread in arrival times requires greater bandwidth than one with a large spread.

The leaky feeder environment can usually support several modes that couple it with the equipment connected to the cable. The different velocities of the modes will result in a small degree of delay spread when the modes travel in the same direction, but the largest spreads will occur, as chapter 3 will detail, when there is coupling to modes travelling in opposite directions.
1.2.3 Combining Techniques

Space, field component and angle of arrival systems share an advantage over the other systems discussed in the previous section. Techniques can be employed which enable all the necessary equipment required for diversity operation to be placed at the receiver, enabling the transmitting equipment to be left unmodified. There are numerous publications on suitable combining methods for reception diversity, many being realisations or variations of the classic Maximal Ratio, equal gain, selection or switched configurations. Parsons has produced an excellent review of such techniques, and the principles, along with the many possible realisations are discussed in the texts of Jakes and Lee. Pre or post detection implementations of all four of the basic configurations are possible. However, predetection techniques can offer better performance for non linear demodulation processes and also strip off the random FM from angle modulated signals.

Withers and Rogers discuss a phase sweeping method for pre-detection combining on reception diversity systems. The same technique can also be employed for transmission diversity. In some applications it can be advantageous to place some of the extra hardware required for diversity operation at the transmitting site. Transmission diversity is the term used to describe such systems, although unlike the reception schemes, the equipment at both ends of the link will require modifications for diversity use. Martin has already proposed the phase sweep method for use with the tailback leaky feeder configuration, particularly for data communication. However, suitable modulation formats and bandwidth requirements are not considered. These points are specifically examined by Hirade for transmission diversity employing differential phase shift keying (DPSK) and minimum shift keying (MSK).
Several other workers have also considered schemes for digital transmission diversity. Frequency deviation offset\textsuperscript{34} and modulation waveform offset\textsuperscript{35} are two which have been proposed by the Japanese, while Allen\textsuperscript{36} in this country has evaluated a method of sideband diversity.

All the techniques discussed so far, transmission and reception, can be applied to space, polarisation and angle of arrival systems. Time, frequency and multipath systems will be classified in this work as forms of transmission diversity, since both the transmitter and receiver must be designed for diversity use. However, frequency diversity systems can take advantage of some of the reception combining techniques in order to bring the signals together in the receiver. All the post detection implementations are applicable along with the phase sweep method\textsuperscript{13}.

1.3 Assessment of Diversity Performance

The purpose of a diversity system, as discussed in the previous sections, is to reduce the probability of excessively deep fades. It is convenient to express the fading in terms of the Cumulative Probability Distribution (CPD) which shows the probability of the signal level falling below a given reference. The improvement offered by any system over another can then be assessed by a direct comparison of the two distributions.

Motley\textsuperscript{1} has demonstrated the CPD for a system without diversity maybe used to estimate the mean error rate. The same principle could also be applied to a diversity system if the characteristics of the combining system are known in addition to the characteristics of the receiver. This analysis assumes that random FM and multipath dispersion do not contribute to the error generating mechanism. Random FM effects can be substantially reduced using techniques similar to Cutler’s\textsuperscript{37} proposal. The degree of multipath dispersion will be a function of the cable environment and must be considered for wideband data transmission. However, Motley’s
results indicate that for bit rate up to at least 100 kbs\(^{-1}\), the feeder system at the University can be treated as non dispersive. An estimate of error rate using the CPD therefore represents an upper limit on the system performance.

Although there are other criteria for assessing performance, such as level crossing rates (LCRs) the CPD is a particularly good indicator of the degree of correlation between the diversity branches. Since the objectives of this work have been not only to quantify diversity performance but also to establish suitable mechanisms for achieving uncorrelated diversity signals, the CPD will be used as the main characteristic for assessing the different mechanisms.

1.4 Thesis Organisation

The details of the feeder layout at the University are introduced in Chapter 2. Here the characteristics of the coupling between various aerial configurations and the feeder are given, together with a description of the measurement system. Small loops, monopoles and dipoles were chosen for examination and tests were carried out with the aerials mounted on either a vehicle or non conducting trolley the latter being used in order to ascertain the degree of the vehicle's effect on the coupling characteristics. The results enabled the performance of the system to be quantified and helped identify potentially suitable mechanisms for achieving a diversity advantage. The potential of Delogne's statistical description for modelling the Surrey feeder configuration is also considered.

Chapter 3 is a discussion of reception and transmission diversity techniques suitable for the test track leaky feeder system, subsequently, a decision is taken on the technique and mechanisms to be studied. Frequency, space and field component are the chosen mechanisms, to be used in conjunction with a transmission phase sweep technique, also known as frequency offset\(^{33}\). The results and conclusions of Chapter 2 allow the performance of this technique to be predicted from theory. In addition, the chapter includes a more detailed
examination of the mechanisms through which the diversity is obtained.

The experimental work on all three diversity systems is covered in Chapter 4. Details are given of the implementation and features of each of the systems, followed by a presentation and discussion of the results.

Finally in Chapter 5, summarising conclusions are given, along with recommendations for future studies.
2: THE BURIED FEEDER SYSTEM

Before beginning an investigation of diversity, the coupling to the leaky feeder must be characterised. This is not only necessary in order to determine the quantitative advantage of diversity, but also to study the mechanism of fading in order to assess which forms of diversity are likely to be suitable.

This chapter begins with a description of the University feeder layout. After considering the choice of test frequencies and aerials adopted for the experimental work, a theoretical study of the propagating modes on a buried feeder is used to try and establish likely fading mechanisms.

This is followed by a presentation of the coupling characteristics of the University feeder for the chosen aerials at the frequencies of interest. Finally a theoretical model is developed to describe the fading.

2.1 System Layout

A 300 metre section of leaky feeder (BICC 3522) had been buried in soil about 10 cm beneath the surface of the ground alongside the perimeter access road of the University. Figures 2.1 and 2.2 show the cable layout at the time of cable laying. The trench for the cable is approximately 2 metres from the curbside and it runs close to a number of lamposts and roadsigns which substantially modify the fields set up by the cable.

At the start of this project, connection to the cable was only possible at a small cabin situated a few metres from the cable end. This necessitated taking large quantities of equipment outside. At the end of the first year of the project a link between the leaky feeder and a measurement laboratory was successfully installed. Most of the measurements were taken with this arrangement.

A schematic of the system is shown in Figure 2.3. The far end of the leaky cable is terminated in the characteristic
Figure 2.3: Buried feeder layout.
Figure 2.1: View from car park end of the central section of cable
Figure 2.2: View towards Senate end from the central section of the cable
impedance of the coaxial mode while the other end is connected to a non-leaky section of cable. After 100 metres of non leaky cable, the signal is amplified before a final 200 metre section of non leaky cable which terminates in the measurement laboratory. The cable was used exclusively for reception, rather than transmission, as it was expedient to keep the data logging equipment within the laboratory.

2.2 Frequencies and Aerials

Most of the previous work had been carried out at 40MHz. The decision to use the low end of the V.H.F. band was made as a consequence of the practical work of Martin and Cree. Martin, whose work had been carried out in tunnels, considered that just above 30 MHz is near optimum. Here a balance is reached between rising cable attenuation at higher frequencies and increasing coupling loss at lower frequencies. Strictly speaking Martin's work cannot be extrapolated to the earth's surface as the modes of propagation will be different. However, Cree's work had been carried out on the surface with the cable at ground level. The frequencies tested ranged from 42MHz to 460MHz. Both the coupling loss and longitudinal attenuation were least at 42MHz. Within this band it was believed that around 40MHz was the most likely frequency for a channel to be allocated. 40MHz had therefore been chosen as the test frequency.

Some work had also been carried out at 80MHz, which lies within a mobile band used for subsurface feeder systems. Results at this frequency provide a useful comparison of the performance in different environments, and give some indication of its frequency dependence. Data would also be available for a test track system should an allocation be made in this band.

The performance at 40MHz had been promising. In addition the characteristics at this frequency were becoming particularly interesting with the release of Band I by the broadcasters. It was therefore decided to continue the work at 40MHz as well as at 80MHz for the reasons given above.
Aerials at 40 and 80MHz will be electrically small and therefore confined to configurations based on simple dipoles/monopoles or loops. The coupling of a monopole to a buried feeder was investigated by Motley. However, the coupling to loops has received no attention. Combinations of loops, or loops with a monopole are particularly attractive for implementations of field component diversity. Both types of aerial, loop and monopole, are therefore considered in this study.

For the type of system under consideration here, the aerials will be vehicle mounted. Motor vehicles can have a marked influence on aerial characteristics particularly at the low end of the V.H.F band. Consequently their presence could effect the coupling. Gaining an insight into the mechanisms of both the coupling and diversity would then be difficult without being able to gauge the vehicle's effect. The method adopted here for doing so, which only gives an approximate indication but is simple to implement, is to compare the coupling characteristics of isolated loops and dipoles against their vehicle mounted counterparts.

2.3 Coupling Mechanism on a Buried Feeder

A relevant analysis of a buried leaky feeder system has been carried out by Plate et al for a feeder positioned within a skin depth of the surface. They found the configuration was capable of supporting three modes, the conventional bifilar or coaxial mode, the monofilar mode and a wave described by the authors as "surface-attached". The coaxial mode has a specific attenuation and phase velocity very close to the values when in free space, with most of the field confined between the two conductors of the cable. The monofilar mode, supported by the outer conductor, is heavily attenuated since the field distribution is concentrated outside of the cable in the surrounding earth. Both the monofilar and coaxial fields will penetrate the surface but they are non-radiating modes and their radial attenuation will be exponential. The fields of the two modes will therefore be concentrated within a
limited radius of the cable. Beyond this the fields are rapidly attenuated.

The surface-attached mode can only exist for certain cable depths. Even when the mode does exist, its complex propagation constant is very similar to that of a surface-wave (Zenneck wave) supported by an earth/air interface. For this reason the fields of the surface-attached mode closely resemble the surface-wave fields which are spread out over the entire surface. Independent excitation of these two modes would be difficult so regardless of whether or not the surface attached mode exists, a mode with very similar characteristics could be excited. The fields of the surface wave are not bound to the cable and those of the surface-attached mode are only loosely bound; they will therefore extend beyond the effective radii of the coaxial and monofilar fields in the radial direction.

When a wave is incident upon an irregularity in its path, the wave will be scattered. Mode conversion will occur and consequently all the modes supported by the cable and its environment will be re-excited. This will occur on the University feeder at the cable ends and also around the lamposts and road signs which are only 1 metre from the cable.

The pattern of interference set up by a scatterer can be very complex. To illustrate the mechanism we assume that transmission is from the cable, and that only the incident coaxial mode is scattered by an obstacle located at Z₀ in Figure 2.4. Mode conversion will generate cable supported modes as indicated.

\( \gamma_c, \gamma_s, \gamma_m \) are the propagation constants of the coaxial, surface attached and monofilar modes respectively. \( K_{cr} \) is the coupling coefficient of the reflected coaxial mode and \( K_{cf} \) the coupling coefficient of the forward coaxial mode about the point \( Z_0 \). The other symbols follow the same convention.
Figure 2.4
Scattering of the coaxial mode by a single obstacle

The fields of the guided modes along an axial path will vary as

\[ \exp \left[ -\Gamma_c (Z - Z_o) \right] + K_{cr} \exp \left[ \Gamma_c (Z - Z_o) \right] + K_{mr} \exp \left[ \Gamma_m (Z - Z_o) \right] + K_{sr} \exp \left[ \Gamma_c (Z - Z_o) \right] \]

for \( Z < Z_o \) and

\[ K_{cf} \exp \left[ -\Gamma_c (Z - Z_o) \right] + K_{mf} \exp \left[ -\Gamma_m (Z - Z_o) \right] + K_{sf} \exp \left[ -\Gamma_s (Z - Z_o) \right] \]

for \( Z > Z_o \)

Since the scatterer is only illuminated by the leakage fields of the coaxial mode, the latter is barely disturbed and so \( K_{cr} \approx 0 \) and \( K_{cf} \approx 1 \). Two waves travelling in opposite directions will produce a short standing wave with a period of \( \left( \lambda_1^{-1} + \lambda_2^{-1} \right)^{-1} \) and when travelling in the same direction they will produce a pattern with a long period of \( \left( \lambda_1^{-1} - \lambda_2^{-1} \right)^{-1} \) where \( \lambda_{1,2} \) are the...
the respective wavelengths of the two waves interfering. A typical pattern of interference around the scatterer, when there is significant coupling to the coaxial as well as the regenerated modes is illustrated in Figure 2.5.

Apart from the modes already mentioned, the lamposts and road signs could act as monopoles generating ground-wave radiation which is conventionally divided between a space wave and the Norton Surface Wave. These waves, along with a radial Zenneck Surface Wave could also be excited at the scattering points and would have to be included in the above scenario. They were omitted for the sake of clarity in illustrating the mechanism.

Table 2.1 shows attenuation constants of the supported modes for typical values of soil conductivity and permittivity. Although the monofilar mode is heavily attenuated, the Zenneck and surface attached modes have a relatively low attenuation constant. A spatially broad fade could therefore be generated when these waves travel in the same direction, and interact with, the coaxial mode.

Outside the effective radius of the coaxial mode, coupling will be predominantly through the fields of the surface mode, the surface attached mode and radiation. A different mechanism of fading can then occur. Consider Figure 2.6 where two scatterers lie within the effective radius of the coaxial mode but the observer is outside this radius at some point A. Modes generated because of the two obstacles, say radiation, can interact and produce a short standing wave with a period of \([\frac{1}{\lambda_R} + \frac{1}{\lambda_R}]^{-1}\) somewhere between the two scatterers. This mechanism whereby waves from different scatterers interfere, can also occur within the effective radius of the coaxial mode but close positioning of the scatterers is necessary in order to prevent the coaxial mode dominating the coupling between the scattering points.

The examples given here serve to illustrate how the fading mechanism is a function of the radial attenuation of the waves supported and generated by the cable and its surrounding environment.
Figure 2.5. Localised interference to the coaxial mode field caused by scattering from a single obstacle.

Figure 2.6. Interference resulting from the interaction of waves scattered by two obstacles.

\[ R = \text{Effective radius of the coaxial mode.} \]
<table>
<thead>
<tr>
<th>WAVE TYPE</th>
<th>ATTENUATION CONSTANT</th>
<th>VELOCITY RATIO ALONG THE SURFACE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 MHz</td>
<td>80 MHz</td>
</tr>
<tr>
<td>COAXIAL</td>
<td>2.2</td>
<td>3.1</td>
</tr>
<tr>
<td>MONOFILAR</td>
<td>230</td>
<td>260</td>
</tr>
<tr>
<td>SURFACE ATTACHED</td>
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<td>5.7</td>
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<tr>
<td>SURFACE (ZENNECK)</td>
<td>5.2</td>
<td>5.7</td>
</tr>
<tr>
<td>RADIATION</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

SOIL CONSTANTS

\[ \sigma = 50 \times 10^{-3} \text{ mho/metre} \]
\[ \varepsilon_R = 35 \]

**TABLE 2.1**

PROPAGATION CONSTANTS OF WAVES GENERATED BY A BURIED LEAKY FEEDER

* : Attenuation has terms proportional to \( \frac{1}{R} \), \( \frac{1}{R^2} \), \( \frac{1}{R^3} \), ....

where \( R \) is the distance to the scatterer
Typical velocity ratios of the relevant waves are also given in Table 2.1. With the exception of the monofilar mode, the velocity of all the waves are reasonably close to the velocity in free space. The monofilar mode has a very high attenuation constant which will prevent it generating any sustained interference patterns. Its effect will tend to be localised but it will still be capable of generating deep fades.

Table 2.2 shows the periods of the standing waves both long and short, that are generated by the interaction of any two waves. With the exception of the waves generated by the monofilar mode, the period of the short standing wave is approximately half of a free space wavelength. A long standing wave generated by the interaction of a surface and coaxial mode will also have a similar period to that of the interaction of radiation with the coaxial mode. It will therefore not be easy to distinguish which waves are interacting simply by measuring the periods of fades.
<table>
<thead>
<tr>
<th>WAVE TYPE</th>
<th>COAXIAL</th>
<th>MONOFILAR</th>
<th>SURFACE ATTACHED</th>
<th>RADIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.44</td>
<td>0.6</td>
<td>0.25</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>0.46</td>
<td>6.7</td>
<td>0.46</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>6.7</td>
<td>0.46</td>
<td>6.7</td>
<td>0.46</td>
</tr>
</tbody>
</table>

1. ALL VALUES RELATIVE TO A FREESPACE WAVELENGTH

2. SOIL CONSTANTS, SEE TABLE 2.1

**TABLE 2.2**

APPROXIMATE PERIOD OF STANDING WAVES ALONG A BURIED LEAKY FEEDER AT 40 & 80 MHz
2.4 Coupling Characteristics of the University Feeder: Initial Details

Motley's work has been exclusively carried out with a one metre monopole mounted on a vehicle. However, it was necessary to re-examine the coupling of this configuration as the feeder layout had significantly changed since the original measurements were made. (Two lamp posts close to the cable were removed just before the start of the diversity study).

2.4.1 Experimental Procedure (Measurement System)

A schematic of the experimental system is shown in Figure 2.7. A vehicle with a roof mounted monopole or loop, when travelling along the road is separated from the cable by approximately 3 metres on the nearside and 7 metres on the far side (to the centre of the car). Vehicle speed on the University site is restricted to 20 m.p.h. and most of the measurements were made at a speed of approximately 5 m.p.h. A dipole or a loop could also be mounted on a non-conducting trolley in order to determine the influence of the vehicle on the coupling. The distance between the cable and the trolley aerial could be varied from 1.5 metres to 9 metres by varying the aerials position on the trolley and also the trolley's position on the road.

Measurements were taken between a point 10 metres from the Senate end of the cable and a point 20 metres from the car park end of the cable. Scattering from the terminated cable ends should therefore show up on the results. A termination of the co-axial mode at a line repeater will also scatter the guided waves. For a long repeatered feeder system this type of scattering will occur at regular intervals along the cable and is therefore of interest.

The feeder is used exclusively for reception. Crystal oscillators generating the required frequency are connected via amplifiers to the vehicle or trolley mounted aerials. After being detected the received signal level
Figure 2.7: Illustration of the measurement system.
is sampled by an analogue-to-digital converter (ADC) before being stored on floppy disk. The data is subsequently transferred to a main-frame computer for analysis. Up to 24,000 samples could be taken for each measurement run. The sample rate of the ADC was too slow using the microcomputer (CBM3032) interpretive language, and this necessitated the use of machine code for all the data-logging programmes.

In this study, owing to limitations on time, only three aerial configurations were considered in detail. The vertical dipole or vehicle-mounted monopole and two orientations of the loop. The plane of the loop was either parallel or perpendicular to the direction of the cable but always vertical. For convenience, these orientations will from now on be referred to as either the parallel or perpendicular loop.

A brief examination of other orientations revealed that no significant advantages in terms of mean coupling loss or less severe fading could be obtained over the chosen three configurations.

2.4.2 Aerial Configurations

a) Vehicle: The measurements were made with a Morris Marina saloon car with the monopole or loop mounted centrally on the roof. The monopole used for both the 40 and 80 MHz measurements was a 0.75 metre length of $\frac{1}{8}$" diameter copper. Matching at each frequency was achieved with simple detachable Ell networks.

The loops illustrated in Figure 2.8 have a radius of 30 cm and were constructed out of $\frac{1}{4}$" outside diameter copper tubing. A balanced feed was obtained by running the cable around the inside of the loop to the feed point, where the loop is matched. Separate loops with the same dimensions were constructed for each frequency in order to avoid continual retuning. Other aspects of the loop
FIGURE 2.8: SCHEMATIC OF LOOP CONSTRUCTION

oscillator ground connected to box
diecast boxes

Figure 2.9: Feed configuration and dimensions of the dipole assembly.
characteristics are left to chapter 4 where field component diversity is considered.

The aerials were fed with approximately 250 mW at the aerial input. Both forward and reverse power were measured using a directional coupler and power meter, and the match on the aerials was good enough to keep the return loss better than 10 dB.

b) Trolley Mounted Aerial: The arrangement was such that a loop or a dipole could be positioned in any orientation on a wooden framework mounted on a wooden trolley. Measurements were made exclusively with the aerials at a height of 1.5 metres, which corresponds to the height of the car roof. The trolley could be pulled along either curb with a 4 metre long handle in order to minimise the interaction with the person pulling it.

A dipole 1 metre long, constructed from $\frac{1}{8}$" diameter copper, was used at both frequencies. It was fed via a balancing transformer from one of a set of small battery-powered crystal oscillators housed in diecast boxes, in order to keep the effect of the feed arrangement on the dipole to an absolute minimum. A schematic of the dipole and oscillator is shown in Figure 2.9. The loops used with the vehicle were also used for the trolley measurements, and these were fed directly from the oscillators. No balancing was required as this is an inherent feature of the feed arrangement of the loop.

2.5 Coupling Characteristics of Buried Feeder: Measurements

2.5.1 Dipole/Monopole at 40 MHz

Figure 2.10 illustrates the variation in coupled signal for the trolley mounted vertical dipole 1.5 metres from the cable. At this distance there are only a few minor ripples about the mean level. Increasing the distance to 3 metres, Figure 2.11, raises the coupling loss by 7 dB and introduces strong interference patterns close to the
Figure 2.10: Variation of the coupling with the trolley mounted dipole, 1.5 metres from the cable at 40MHz.

Figure 2.11: Variation of the coupling with the trolley mounted dipole, 3 metres from the cable at 40MHz.

Figure 2.12: Variation of the coupling with the trolley mounted dipole, 7 metres from the cable at 40MHz.
obstacles. The period of the short standing wave pattern is approximately half of a free space wavelength with fades in excess of 20 dB below the mean level.

At a 7 metre distance, Figure 2.12, the coupling loss has risen by a further 8 dB and the fading has become much worse, and now stretches along the entire cable. In addition to the short-period standing waves there is also a pattern with a much longer period. Also note how the local mean signal level rises in the areas of the obstacles and near the feed end of the cable.

The characteristics of the vehicle mounted monopole are illustrated in Figure 2.13 for both the 3 and 7 metre distances. A comparison indicates the patterns at each distance are very similar to the corresponding dipole patterns, although at 3 metres, the maximum fade depth is about 10 dB greater than for the dipole coupling at the same spacing. The difference in mean coupling loss between 3 and 7 metres is 10 dB - slightly higher than for the trolley dipole. Typical cumulative probability distributions for the 3 and 7 metre coupling are given in Figure 2.14. At 7 metres the distribution is approximately Rayleigh.

2.5.2 Loops at 40 MHz

a) Parallel loop: In the case of a parallel loop the striking feature of both the vehicle and trolley coupling at the three metre distance is the absence of any deep fading. Typical variations are shown in Figure 2.15 where the ripples are only a few dB in amplitude. However, at the 7 metre distance the coupling loss has increased by about 15 to 16 dB for both the vehicle and the trolley.

Figure 2.16 illustrates how the coupling for the vehicle at 7 metres suffers from severe fading. An interesting feature of this trace is the well defined pattern of fading on the right hand side of the figure. It shows quite clearly a short period standing wave superimposed on
Vehicle 3 metres from the cable

Vehicle 7 metres from the cable

Figure 2.13: Variation of the coupling with the vehicle mounted monopole at 40MHz.
FIGURE 2.14: DISTRIBUTION OF THE VEHICLE MONOPOLE COUPLING AT 40MHz
Figure 2.15: Coupling loss variation with the parallel loop, 3 metres from the cable.

Figure 2.16: Coupling loss variation with the vehicle mounted parallel loop, 7 metres from the cable.
a long period standing wave. This nicely illustrates the two types of pattern that can occur: those set up by waves travelling in the same direction but with different phase velocities produce the 'long' standing wave, and those set up by waves travelling in the opposite direction produce the 'short' standing wave. The effects of scattering are particularly pronounced near the feed end of the cable.

Cumulative probability distributions for the 3 and 7 metre separations are given in Figure 2.17 which emphasise the dramatic change in coupling. Fading at the 7 metre distance is again approximately Rayleigh.

b) Perpendicular loop: As with the parallel loop and dipole, the patterns of the trolley and vehicle coupling were found to be very similar. At 3 metres, Figure 2.18, the coupling of an otherwise constant signal is broken by localised fades which can be in excess of 30 dB below the mean. Although the dipole has similar features, the pattern of the two configurations can be distinguished. A comparison of the loop with the dipole at the 3 metre distance reveals that the loop has no apparent long standing wave component. Moving closer to the 1.5 metre distance virtually eliminates the standing wave; a characteristic shared with the dipole.

Moving from 3 metres to 7 metres increases the coupling loss of the vehicle aerial by 12 dB, and that of the trolley aerial by 10 dB. Fading at 7 metres is again approximately Rayleigh in distribution, Figure 2.19, Figure 2.20.

Again the level of the coupling is noticeably influenced by the presence of the obstacles. However, this configuration is particularly sensitive to the obstacles at a and b, on Figure 2.19. These are roadside warning signs which are approximately 3 metres in length and are therefore approaching half a freespace wavelength at 40 MHz.
- VEHICLE 3 METRES FROM CABLE
- VEHICLE 7 METRES FROM CABLE

FIGURE 2.17: DISTRIBUTION OF THE VEHICLE PARALLEL LOOP COUPLING AT 40MHz
Figure 2.18: Coupling loss variation with the vehicle mounted perpendicular loop, 3 metres from the cable.

Figure 2.19: Coupling loss variation with the vehicle mounted perpendicular loop, 7 metres from the cable.
FIGURE 2.20: DISTRIBUTION OF THE VEHICLE PERPENDICULAR LOOP COUPLING AT 40MHz
2.5.3 Summary of 40 MHz Coupling and Comparison of Aerials

Fading can be completely avoided if the correct aerial configuration is used, but only within a limited radius from the cable. Fading beyond a few metres quickly became severe and at a distance of 7 metres could be approximated by a Rayleigh distribution regardless of aerial configuration.

Each vehicle configuration had very similar characteristics to its trolley mounted counterpart, even with Rayleigh fading. The relative variations in mean coupling loss are also very similar as shown in Table 2.3 and Table 2.4. The latter table indicates that of the two loops, the parallel loop always has the lower coupling loss.

It should be noted that the relative values of Table 2.3 and 2.4 were collected over a dry period during the summer months in order to minimise the uncertainties of varying ground conditions. The variation in coupling loss due to variations in the soil parameters is discussed in section 2.7.

The performance of a diversity system with the aerials mounted on a vehicle will be dependent on the difference in mean coupling loss between the branches. Table 2.5 gives typical values of the absolute coupling loss for the three vehicle mounted aerials. At the 3 metre distance, the spread in value is 9 dB, but at 7 metres where the fading is more severe and where the diversity is most required, it has been reduced to about 4 dB.

Each of these aerials will therefore provide an effective signal level for a diversity system made up of a combination of such aerials.
<table>
<thead>
<tr>
<th>VEHICLE AERIAL</th>
<th>Co(dB)</th>
<th>TROLLEY AERIAL</th>
<th>Co(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MONOPOLE</td>
<td>9</td>
<td>DIPOLLE</td>
<td>8</td>
</tr>
<tr>
<td>PARALLEL LOOP</td>
<td>15</td>
<td>PARALLEL LOOP</td>
<td>16</td>
</tr>
<tr>
<td>PERPENDICULAR LOOP</td>
<td>12</td>
<td>PERPENDICULAR LOOP</td>
<td>10</td>
</tr>
</tbody>
</table>

\[ Co = (\text{Coupling loss at 7 metres} - \text{coupling loss at 3 metres}) \]

Table 2.3
Variation in coupling loss as a function of radial distance at 40 MHz

<table>
<thead>
<tr>
<th>AERIAL CONFIGURATION</th>
<th>Xo (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td>3 METRES</td>
</tr>
<tr>
<td>VEHICLE LOOP</td>
<td>6</td>
</tr>
<tr>
<td>TROLLEY LOOP</td>
<td>4</td>
</tr>
</tbody>
</table>

\[ Xo = (\text{Coupling loss of perpendicular loop} - \text{coupling loss of parallel loop}) \]

Table 2.4
Variation in coupling loss between the two orientations of the loop
Table 2.5

Typical variation on absolute coupling loss for vehicle mounted aerials at 40 MHz

<table>
<thead>
<tr>
<th>AERIAL CONFIGURATION</th>
<th>COUPLING LOSS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 METRES</td>
</tr>
<tr>
<td>MONOPOLE</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>7 METRES</td>
</tr>
<tr>
<td></td>
<td>88</td>
</tr>
<tr>
<td>PARALLEL LOOP</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>85</td>
</tr>
<tr>
<td>PERPENDICULAR LOOP</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>88</td>
</tr>
</tbody>
</table>

2.5.4 Monopole/Dipole at 80 MHz

At 80MHz, the coupling to both vehicle monopole and trolley dipole is Rayleigh distributed at distances of three metres or more from the cable. Figure 2.21 shows the variation of coupling to the vehicle monopole as a function of distance along the cable at the three and seven metre positions, while Figure 2.22 gives the respective probability distributions. Both long and short standing wave patterns are in evidence in Figure 2.21 with the long pattern most prominent around obstacles and the cable end.

The coupling loss increases by about 5dB when the aerial is moved from three metres to seven metres spacing regardless of whether it is vehicle or trolley mounted. There are also similarities in the pattern of coupling between the two mountings as can be seen from Figure 2.23.

In order to reduce the severity of the fading, it is necessary to be close to the cable. Figure 2.24 illustrates the coupling to the trolley dipole at a distance of 1.5 metres, where the standing waves are mainly concentrated around the obstacles.
Figure 2.21: Coupling loss variation with the vehicle mounted monopole at 80Mhz.
VEHICLE 3 METRES FROM CABLE

VEHICLE 7 METRES FROM CABLE

FIGURE 2.22: DISTRIBUTION OF THE VEHICLE MONOPOLE COUPLING AT 80MHz
Figure 2.23: Coupling loss variation with the monopole and dipole, 7 metres from the cable at 80Mhz.
Figure 2.24: Coupling loss variation with the trolley mounted dipole, 1.5 metres from the cable at 80Mhz.

---

**Figure 2.25: Distribution of the Vehicle Loop Coupling.** 3 metres from the cable.
2.5.5 Loops at 80 MHz

Figure 2.25 shows that both orientations of the loop suffer Rayleigh type fading 3 metres from the cable. The two traces of the coupling, Figure 2.26, appear very similar and the sudden rise in signal strength which characterised the monopole/dipole coupling is also a feature of the two loop orientations. Variations in mean coupling loss from one orientation to another is about 4 - 6 dB for both the trolley and the vehicle, with the parallel loop always exhibiting the lowest absolute coupling loss. This difference is maintained at the 7 metre radial distance and the fading remains Rayleigh distributed, Figure 2.27, but the absolute coupling loss has increased by approximately 5 dB.

Even though the relative levels of mean coupling loss are sustained, there are now marked differences between the fading patterns at the seven metre separation, Figure 2.28, that are also exhibited by the coupling of the trolley mounted loops, Figure 2.29. The rise in signal level at the feed end that characterises other 80 MHz coupling has virtually disappeared from the perpendicular loop coupling but is greatly accentuated on the parallel loop coupling. Another feature of the parallel loop coupling is a well defined short standing wave pattern which suggests two waves with low attenuation travelling in opposite directions.

2.5.6 Summary of 80MHz Coupling and Comparison of Aerials

At 80 MHz a Rayleigh distribution characterises the fading for all aerial configurations when at distances of 3 metres or more from the cable. From Table 2.5 it can be seen that the monopole and perpendicular loop have similar losses at both 3 and 7 metre distances. The loss of the parallel loop is consistently 4 to 5 dB less than that of the other aerial configurations. Again, the similarity in mean levels is encouraging for a diversity system based on these aerials.
Figure 2.26: Coupling loss variation with the vehicle mounted loop, 3 metres from the cable at 80Mhz.
FIGURE 2.27: DISTRIBUTION OF THE VEHICLE LOOP COUPLING. 7 METRES FROM THE CABLE
Figure 2.28: Coupling loss variation with the vehicle mounted loop, 7 metres from the cable at 80Mhz.
Figure 2.29: Coupling loss variation with the trolley mounted loop, 7 metres from the cable, at 80Mhz.
The similarities between the coupling patterns of all three configurations, at the three metre separation, with either the vehicle or trolley, made it difficult to differentiate between the six traces by simply inspecting the patterns. However, at seven metres, the coupling to the parallel loop can be easily distinguished from the other two configurations, although for all of the three configurations, there remains a high degree of similarity between the trolley and vehicle coupling. It therefore appears that the vehicle mounted aerials are retaining significant characteristics of their trolley mounted counterparts.

<table>
<thead>
<tr>
<th>AERIAL CONFIGURATION</th>
<th>COUPLING LOSS (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 METRES</td>
</tr>
<tr>
<td>MONOPOLE</td>
<td>81</td>
</tr>
<tr>
<td>PARALLEL LOOP</td>
<td>77</td>
</tr>
<tr>
<td>PERPENDICULAR LOOP</td>
<td>81</td>
</tr>
</tbody>
</table>

Figure 2.6
Typical values of coupling loss at 80 MHz with vehicle mounted aerials

2.6 Discussion of Coupling

A striking feature of the 40 MHz coupling is the absence of any strong standing wave patterns for certain aerials close to the cable. It has previously been suggested that this effect is produced by the directional properties of the aerial. If the beam of radiation is directed towards the receiver end of the cable, the signal will only propagate in that direction, while propagation in the other direction is suppressed. Thus the destructive interference, supposedly set up by reflections of waves travelling away from the receiver, is eliminated.
However, in section 2.5 the coupling to a vertical dipole is shown to be free of all but a few minor ripples. This aerial has no directional properties and couples equally to signals travelling in either direction. Therefore, directional properties are not necessary and some other explanation must be sought. The only other possibility is that just one mode predominates the coupling.

This contention is supported by noting the level of the coupling loss with the aerials 3 metres from the cable. The parallel loop configuration which suffers no fading has a lower coupling loss than the two configurations that do suffer fading. If the level of one signal is 6 dB greater than the level of a second interfering signal, the maximum standing wave ripple will be just 8 dB. Whereas when the two waves have similar amplitudes, fades of 30 to 40 dB can easily occur.

The deep fades that affect the other two configurations are localised around the metal poles close to the cable, indicating that the modes generated by the scattering have a higher attenuation constant than the coaxial mode, as predicted from Table 2.1.

Moving away to 7 metres there are two major changes in the coupling characteristics. First, all three aerial configurations suffer increases in coupling loss of at least 10 dB and secondly all the coupling distributions are approximately Rayleigh. The high increase in coupling loss, particularly with the parallel loop (15 dB) demonstrates a high radial attenuation of the mode that dominates at the three metre distance. A Rayleigh distribution indicates that the coupling is no longer primarily through a single mode and therefore the waves generated at the obstacles and cable ends are beginning to dominate. The radial attenuation of these waves must therefore be less than that of the mode dominating at 3 metres. Figure 2.19 is a good illustration of the substantial mode conversion that can be set up by the obstacles with the coupling peaking very strongly around the posts.
These observations are consistent with the theory of section 2.4. Close to the cable the coupling is dominated by the leakage field of the coaxial mode. The level of any wave generated by mode conversion is not sufficient to interfere with the fields of this mode. However, the surface modes and radiation generated by the obstacles are more spread out than the fields of the coaxial mode and will eventually become the main coupling mechanism as the radial distance from the cable increases.

At 80MHz, the fading distribution is Rayleigh at or beyond a radial distance of 3 metres, but a move to 1.5 metres significantly reduces the severity of the fading. This demonstrates how the fields of the coaxial mode are more closely confined to the cable at the higher frequency. Waves generated by mode conversion are therefore dominating the coupling closer to the cable compared to 40MHz. The 40MHz coupling characteristics suggested these waves had a lower radial attenuation than the coaxial fields and this is now supported by the 80MHz characteristics: the difference in coupling loss between 3 and 7 metres at 40MHz is at least 10 dB but at 80MHz it is only about 5 dB. The small spread in coupling loss between the vehicle mounted aerials at 7 metres is encouraging for a diversity system based on loop/dipole combinations. It is also a feature of the 80 MHz coupling at both the 3 and 7 metre distances.

The similarities between the coupling of the trolley and vehicle suggests the influence of the vehicle does not have much effect on the coupling. The aerial with the most distinctive characteristics at both frequencies is the parallel loop. At 40MHz it is the only configuration to be free of standing waves at a distance of 3 metres from the cable, and the response at 7 metres, 80MHz, can easily be distinguished from those of the other aerials. In the former instance, the coupling is through the leakage fields of the coaxial mode but in the latter case the other modes supported by the cable environment will be the predominant mechanism.
Similarity between the vehicle and trolley coupling also indicates that any mode conversion generated by the presence of the vehicle has little impact on the coupling. The strongest interaction is likely to occur with the vehicle close to the cable where the fields of the coaxial mode at 40MHz will be particularly sensitive to discontinuities. However, Motley\textsuperscript{11} has shown that provided a metal structure is not in contact with the ground, the coupling characteristics are not modified. Nor are they if the structure is in contact with the ground, but with no buried portion, provided the post is at least two metres from the cable. As the vehicle moves farther away from the cable, its effectiveness as a scatterer will become negligible compared to the obstacles closer to the line. At 80MHz the fields of the coaxial mode are more closely bound to the cable and consequently will be less sensitive to the vehicle at a distance of 3 metres. The sensitivity of the coaxial mode to disturbances caused by the line side obstacles could be caused by the buried portion of the obstacles as the fields in the soil will be more concentrated than above the surface.

Variations in coupling loss as a function of soil moisture were found to be similar to those reported by Motley. At the two frequencies of interest the mean coupling loss had a spread of about $\pm 5$ dB over the two year measurement period. The values of absolute coupling loss presented earlier are the mean values for this period. The lower coupling loss is obtained with high moisture content but this also increases the severity of the fading. This implies that the increase in the soil permittivity caused by a high moisture content is making the coaxial mode more leaky. Consequently the level of the scattering will increase, which could account for the more pronounced fading.

Variations in fade depth at distances of less than half of a freespace wavelength from the cable, on both the monopole and perpendicular loop, were as much as 15 dB; fades of 40 dB in wet conditions being reduced to about 25 dB in dry conditions. However, fading of more than a few dB never occurred with the
parallel loop at the same distance and frequency, regardless of the ground condition.

When the fading was Rayleigh in nature, and above a probability level of 1.0%, variations on the CPD could not be distinguished at all with any certainty. At the lower probability levels uncertainty will increase simply because of the low number of samples, twenty four or less below 0.1, making it difficult to detect variations due to other causes, such as changing soil conditions. Generally, the variation at the lower probability levels was about 5 dB, and therefore, changing weather conditions have little effect when the fading can be approximated by a Rayleigh distribution.

2.7 Statistical Model

In section 2.6 it is shown that the fading, as a function of increasing radial distance from the cable, is very quickly approximated by a Rayleigh distribution. This suggests that a statistical model of the propagation could help to characterise system performance.

Consider a system where the coupling is exclusively through the scattered waves generated by disturbances in the fields of the coaxial mode. Following Delogne, the coupled signal \( V(z) \) at a position \( Z \) along the cable can then be represented by Equation 2.1

\[
V(z) = \sum_{i} a_i \exp \left(-\Gamma_c (Z_i)\right) F(Z - Z_i)
\]

The scattering coefficient of an obstacle located at \( Z_i \) is \( a_i \), \( \Gamma_c \) is the propagation constant of the coaxial mode and \( F(Z - Z_i) \) is a function describing the propagation of the scattered wave. In order to keep the model general, three simplifying assumptions are now made. We assume that the obstacles are randomly distributed along the cable i.e. follow a Poisson distribution, and that the scattering coefficients \( a_i \) are random, complex numbers, all having the same probability distribution, which is independent of location. The third assumption is that the number of scattering points is very
large i.e. $n \gg 1$. It is then possible to show that the distribution is Rayleigh. The detailed proof of this statement, which is not given by Delogne\textsuperscript{12}, has been derived in Appendix A. Essentially the Central Limit Theorem can be invoked when $n \gg 1$. This leads to a normal distribution for the real and imaginary components of $V(z)$.

In a real environment, the conditions that exist are unlikely to be those assumed above. However, results reported by Stein\textsuperscript{23} show that as few as five sine waves with independently fluctuating random phases will give a resultant envelope that approximately follows a Rayleigh distribution. This illustrates that a good approximation to the distribution can be obtained even with a significant departure from the assumed conditions. However, the assumptions make the model very convenient for describing the coupling. In subsequent chapters we shall see how well such a model predicts the performance of a practical diversity system.

The model can also be extended to take account of coupling to the coaxial mode. Intuitively we could expect the distribution to remain approximately Rayleigh provided the level of this mode remains small compared to the level of the resultant signal. This is indeed the case and a proof is given by Beckmann\textsuperscript{42}.
3: CHOICE OF DIVERSITY MECHANISMS AND TECHNIQUES FOR THE STUDY

The choice of a particular diversity technique will to some extent be governed by the constraints of the system configuration.

Economic, technical or a number of other factors may make a specific technique unattractive and preclude its adoption. For instance, the cost of implementation maybe too high or the technique may require more than the system's allocated bandwidth. Alternatively the technique may not be satisfactory given the operational constraints of the system.

In chapter 1 it was pointed out that a diversity configuration can be classified as either transmission or reception, and may exploit a number of different mechanisms for achieving independent fading on the diversity branches.

In this chapter both transmission and reception techniques will be considered specifically for the test track leaky feeder system. One technique known as frequency offset, transmission diversity appears particularly attractive and its performance is predicted from the model of section 2.8.

Further consideration is then given to the propagation conditions on the buried feeder configuration to establish how the coupling mechanism can be exploited to effect a diversity advantage using the frequency offset technique.

3.1 Reception Diversity

Consider Figure 3.1, where there is independent access to each of the diversity branches at the input to the receiver. We assume there is simultaneous transmission on both paths at the same frequency, but the instantaneous amplitude and phase on the two branches will vary as a function of the transmission path. Direct linear combining of the two paths would mitigate the effect of a deep fade on one channel, provided the signal on the other channel does not fade simultaneously. However, the receiver will generate its own fades when the
Complex transfer function of the propagation paths $R_1, 2 \exp(j\phi_1, 2)$

Figure 3.1: Diversity implemented at the Receiver.

$T_a, T_b =$ propagation delay of the feeders

Figure 3.2: Reception diversity realised with multiple feeders
levels on the two branches are equal but 180° out of phase. If the signals are combined at RF they must be co-phased before being summed. This technique is generally referred to as predetection combining. Post-detection combining of the two paths is also possible and eliminates the need for any predetection co-phasing of the signals. However, a separate receiver is required for each diversity branch since the combining is carried out after the two signals have been demodulated.

An alternative to combining is to select a single branch for use at any given instant. In an ideal configuration, the branch with the highest signal-to-noise ratio is used making it necessary to continuously monitor all of the branch levels. The system can never operate on a truly instantaneous basis as the response of the system will be limited by the internal time constants of the receiver. An alternative technique is switched diversity. Here a branch is used until its level drops below a predetermined threshold when the receiver switches to another branch. Now only the level on the channel in use has to be monitored.

An important characteristic of all the above systems is that no extra transmission bandwidth is required for diversity operation. This makes reception diversity particularly attractive for conventional mobile radio where there is severe spectrum congestion. Consequently it has received a great deal of interest from this community particularly with the increasing demand for data communication. However, the receiver must be capable of processing the various branch signals separately and so a separate input is required for each branch. For the test track system, where transmission is to the cable, this requirement can be met in one of two ways.

Motley\(^1\) has shown that the fading of the signals received at the two ends of a leaky feeder are sufficiently dissimilar to be used as the two inputs to the receiver. A link would therefore be required to connect a receiver located at one end of the leaky feeder with the output of the other end. Several complications can arise from such an arrangement. Where line
repeaters are used to compensate for the loss of the coaxial mode, they must be bidirectional at the same frequency and consequently more complex and costly than a unidirectional device. Also with high bit rate data transmission, the difference in the arrival times of the signals at the two ends of the feeder could be a significant proportion of the period of the data symbols. The performance of the system could as a consequence be severely degraded. Taking the Peugeot system as an example, the symbol period of the proposed two level modulation scheme at 100 kbs\(^{-1}\) will be 10 \(\mu s\). This corresponds to the delay along a length of BICC 3522 cable of just over 2.5 km. The delay set up by a 6 km system is therefore substantial and would have to be mitigated in the design of the system. A lumped delay could be added to the receiver end of the cable in order to equalise the two path delays. However, the delay is a function of the transmitter’s position along the cable which makes effective equalisation difficult to implement.

The alternative is to install a second feeder along the whole length of the system, and so spaced from the other feeder as to ensure different fading characteristics. A schematic illustrating this technique is shown in Figure 3.2. Performance will not be degraded by the differential delay \(|t_a - t_b|\) provided the relationship \(|t_a - t_b| < T_b\) holds where \(T_b\) is the symbol period.

The major disadvantage of the technique is the cost of installing a second cable. In many feeder systems, installation accounts for a major proportion of the total system cost. Using two cables could therefore virtually double the price of the system making the technique unattractive.

Bearing the disadvantages of the forementioned schemes in mind it seems well worth considering transmission diversity for the test track leaky feeder system.
3.2 Transmission Diversity

The previous section illustrates the problems associated with diversity systems that require multiple feeders or access to signals that travel in opposite directions along the cable. It is therefore important when considering transmission diversity to determine if these features can be avoided. In other words, it is necessary to establish whether diversity can be achieved with a single cable which is connected to the receiver at just one end.

An analogy of this arrangement is a receiving system with a single aerial that has one signal port and static electrical characteristics. For frequency, time and multipath schemes, such an arrangement is a standard implementation. However, particular care must be taken with field-component, angle of arrival and space diversity schemes. When it is possible to exploit these mechanisms, the signals on the separate diversity branches are combined directly at RF by either the receiving aerial, or for the leaky feeder configuration, by the cable. If the frequencies of the signals are identical, the system suffers from the same problem as reception diversity when the branch signals are summed at RF without co-phasing, namely, self generated fades when there is 180° phase difference between the two signals.

Without a feedback path from the receiver to the transmitter the problem can be overcome at the transmitter in one of two ways. First, the data can be sent sequentially over just one of the transmission paths so that only a single channel is used for transmission at any instant. Following a transmission on this path, the data is then retransmitted over one of the other available paths. To maintain the average throughput of the original system necessitates at least a doubling of the instantaneous throughput and consequently an increase in transmission bandwidth. Secondly, the data may be sent simultaneously over the two paths by a number of techniques all of which increase the transmission bandwidth.
Several schemes have been proposed for the technique of simultaneous transmission which share a similar objective. In order to reduce the additional costs incurred by implementing diversity, the system designers try to make use of conventional receivers which require only minor modifications for diversity use.

Allen\textsuperscript{36} has proposed an ingenious technique for SSB systems which is capable of transmitting 1200 b/s in a 6 KHz bandwidth. The Japanese\textsuperscript{34, 35} have also investigated several novel schemes known as frequency deviation offset and modulation waveform offset. Both these schemes have a low transmission efficiency with data rates of 300 – 1200 b/s requiring 16 KHz of RF bandwidth. All three systems keep the additional receiver costs for diversity implementation to a minimum, but are also inefficient in their use of the available bandwidth. A scheme with a high transmission efficiency that uses a conventional receiver with few modifications has been proposed by Hirade et al\textsuperscript{33} which they have termed frequency offset transmitter diversity. In the following sections this particular technique is given further consideration.

3.3 Frequency Offset: Background

The principle of frequency offset was examined before Hirade by Withers\textsuperscript{30} and Rogers\textsuperscript{31}, who considered the technique for reception diversity. The original proposal is illustrated in Figure 3.3. A variable phase shifter is placed in one of the diversity paths with the phase shift continually varying from 0 to \(2\pi\) radians. When the two inputs of the combiner are in phase, the output will peak and provided the sweep rate is at least twice the highest modulation frequency, then peaks occur at a rate to satisfy the sampling theorem. With a peak detector and a suitable filter it is possible to recover AM signals having the improvements of diversity reception. The method used for sweeping out the phase is important if Spectrum Spreading is to be kept to a minimum. A linear phase sweep appears to minimise the spreading and is also equivalent to frequency translating the whole of the spectrum passing
Figure 3.3: Phase sweep/frequency offset combining technique
through the phase shifter by an amount of $1/T$ Hz where $T$ is
the repetition rate. Broadband phase shifters which could
degrade the noise figure and intermodulation performance can
now be avoided provided separate RF stages and different IF
frequencies are acceptable for each of the branches. If the
two IF frequencies have a relative offset of $1/T$ Hz then the
required phase sweep on one branch relative to other is
obtained.

Hirade\textsuperscript{33} has considered the frequency offset implementation
specifically for transmission diversity and MSK modulation.
Two MSK modulated carriers are generated which differ in
frequency by $\delta f$, as illustrated in Figure 3.4. A single
receiver may be used to differentially demodulate the two
carriers with a low pass filter at the output of the detector
to remove the baseband components at harmonics of $\delta f$.
The output of the filter is then directly proportional to the
combined baseband signal that would result from separate
differential demodulation of the two channels. The expense of
a second receiver has been avoided with the only additional
requirement being the post detection filter. In addition, the
required bandwidth for the single receiver implementation is
just $2/T$ where $T$ is the symbol period of the modulating data.
Thus transmission of 1200 b/s would only require 2.4 KHz of
bandwidth.

The MSK system's efficient use of bandwidth together with the
need for only a single receiver makes it attractive for the
test track application.

In the next section it will be shown how two frequency offset
carrier wave signals may be used to determine the performance
of the MSK system subjected to envelope fading.

3.4 Frequency Offset Analysis

Assume two tones are transmitted at $f$ and $f + \delta f$ over
different transmission paths as illustrated in Figure 3.5.
The characteristics of the system can be conveniently analysed
using the exponential representation of the signals, so
Figure 3.4: Hirade's frequency offset transmitter diversity technique
Figure 3.5: Carrier wave method of determining frequency offset, transmitter diversity performance
\[ V_1 = \text{Re} \{ e^{j2\pi ft} \} \quad 4.1 \]

\[ V_2 = \text{Re} \{ e^{j2\pi (f+\delta f)t} \} \quad 4.2 \]

The transmission path modifies the envelope and the phase of the two signals so that the signals at the receiver are now

\[ V_{1R} = \text{Re} \{ R_1 e^{j\phi_1} e^{j2\pi ft} \} \quad 4.3 \]

\[ V_{2R} = \text{Re} \{ R_2 e^{j\phi_2} e^{j2\pi (f+\delta f)t} \} \quad 4.4 \]

where \( R_1 e^{j\phi_1} \) and \( R_2 e^{j\phi_2} \) are the transfer functions of the two transmission paths. The two signals are summed directly at the input to a receiver having an envelope detector. Since the output of an envelope detector follows the envelope of the incoming signal then:

\[ V_{op} = |R_1 e^{j\phi_1} + R_2 e^{j(2\pi(\delta f)t + \phi_2)}| \quad 4.5 \]

After some algebraic manipulation, the output may be written as

\[ V_{op} = \sqrt{(R_1^2 + R_2^2 + 2R_1 R_2 \cos(2\pi\delta ft + \phi_1 - \phi_2))} \quad 4.6 \]

Using the binomial expansion we find the output has a D.C. term plus components at harmonics of \( \delta f \). A low pass filter with a cut off below \( \delta f \) will leave only the D.C. term which is simply

\[ V_{DC} = \sqrt{2(R_1^2 + R_2^2)} \quad 4.7 \]

Refering to the characteristics of the frequency offset MSK system\(^{33}\) we find that the output of the data demodulator at the sampling instant is given by

\[ V(nT) = \pm \frac{1}{2}(R_1^2 + R_2^2) \quad 4.8 \]

where \( nT \) is the time when sampling occurs. \( V(nT) \) is therefore directly proportional to the square of \( V_{DC} \) which can be easily computed when a recording of \( V_{DC} \) is processed on a computer. Thus the performance of the MSK system subjected to envelope...
fading can be directly determined from the carrier wave measurement.

Where $R_1$ and $R_2$ are two uncorrelated Rayleigh variables with the same mean, the probability distribution of the sum of the two squares is given by a Chi squared function.

The probability density function of $R_1^2 + R_2^2$ is then

$$p(r) = re^{-r/2\sigma^2/(2\sigma^2)^2}$$

where $r = R_1^2 + R_2^2 = a_1^2 + b_1^2 + a_2^2 + b_2^2$

and $a_1$, $a_2$, $b_1$ and $b_2$ are independent Gaussian variables of equal variance, $\sigma^2$, and zero mean.

A plot of the cumulative probability distribution of the above function is shown in Figure 3.6, curve (a), together with the distribution for the system without diversity, curve (b). The substantial improvements offered by diversity are immediately seen. If the model of section 2.8 is a good approximation of the transmission channel, then curve (a) represents the maximum improvement that can be obtained with diversity.

So far, it has been assumed that the signal fading on the two branches are completely uncorrelated, which in some circumstances may be difficult to achieve. However, it is still possible to predict the diversity performance if the correlation between the two branches is known.

A useful parameter that describes the correlation is the normalized covariance, defined as

$$\rho = \frac{\text{Covariance } (E_1, E_2)}{\sqrt{\text{Variance } (E_1) \text{ Variance } (E_2)}}$$

where $E_1$ and $E_2$ are the complex envelopes of the signals on the two branches. With the measurement system used for this
Figure 3.6: Theoretical performance of frequency offset diversity in a Rayleigh fading environment.
work, it is not possible to measure both the magnitude and phase of the envelope, only the magnitude. However, Uhlenbeck has shown that for two, jointly Rayleigh processes then,

$$\rho_e = |\rho|^2$$

where $\rho_e$ is the normalised covariance or correlation coefficient of the magnitudes of the two envelopes, and can take values between 0 and 1. Brennan’s work demonstrates that completely uncorrelated signals are not necessary as the efficiency of a two branch diversity system is negligibly impaired if the correlation coefficient between the signals on the branches is less than 0.3. Also much of the diversity advantage is still apparent with coefficients as high as 0.7. Curves (c), and (d), of Figure 3.6, showing the diversity performance with correlations of 0.6 and 0.8 respectively corroborate Brennan’s findings.

The correlation coefficient can be predicted from the theoretical model and measured on the university feeder along with the CPD of a two branch transmission frequency offset diversity system. It will then be possible to ascertain the suitability of the theoretical model for predicting diversity performance.

3.5 Diversity Mechanisms Applicable to a Frequency Offset System

Transmitter offset diversity can be applied to all the mechanisms discussed in section 1.2, except time and multipath. This enables the performance of a transmission diversity system exploiting one of the four mechanisms, frequency, space, angle of arrival and field component, to be compared directly against that obtained with any of the other three mechanisms. Thus, with the simple and convenient carrier wave (cw) method of section 3.4 for determining performance, transmitter offset appears as an attractive technique for an examination of most of the diversity mechanisms identified in chapter 1. As a consequence, and
bearing in mind the advantages discussed in previous sections, attention was focused on mechanisms which lend themselves to frequency offset implementations.

Before the experimental work on such mechanisms is discussed in the next chapter, further consideration is given to leaky feeder propagation conditions in order to establish the nature of each of the diversity mechanisms which are of interest.

3.5.1 Frequency Diversity

In a frequency offset diversity system, the required frequency difference between the signals on the diversity branches, at the input to the demodulator, is determined by the signalling rate. However, the frequency difference between the transmissions of a frequency diversity system have to be determined by the selectivity of the transmission channel. Therefore, the appropriate spacing for demodulation, has to be realised by suitable heterodyning and filtering before the differential demodulator.

Most of the factors controlling the selectivity can be determined by considering the scattering mechanisms of a single discontinuity. We therefore take the scenario illustrated in Figure 2.4 as the basis of the selectivity analysis. Then, the only incident mode on the scatterer is the coaxial with \( K_{cr} \approx 0 \) and \( K_{cf} \approx 1 \). The scattered waves to be considered are the surface, monofilar and radiation modes. However, the monofilar mode will be ignored for reasons that will be clear after the analysis.

The coupling along the cable will then have the form:

\[
\exp(-\Gamma_c(Z-Z_0)) + K_{sf}\exp(-\Gamma_s(Z-Z_0)) + K_{rf}\exp(-\Gamma_R(Z-Z_0)) \frac{4.1}{|Z-Z_0|}
\]

for \( Z > Z_0 \)

and

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\[ \exp(-\Gamma_c(Z-Z_0)) + K_{sr}\exp(\Gamma_s(Z-Z_0)) + K_{rr}\frac{\exp(\Gamma_r(Z-Z_0))}{|Z-Z_0|} \quad (4.2) \]

for \( Z < Z_0 \)

The symbol notation follows that adopted in chapter 2. Here, \( \Gamma \) represents the propagation constant of the radiation and \( K_{rr} \) and \( K_{rf} \) the coupling coefficients from the coaxial mode to the reflected and transmitted components of the radiation, respectively. The dominant radiation term is assumed to be proportional to \( 1/R \) and all others are ignored.

Equation 4.2, which includes the terms for the reflected waves has a factor of:

\[ (1 + a_1 \exp(j\omega \tau_{1R}) + a_2 \exp(j\omega \tau_{2R})) \quad (4.3) \]

where \( a_1 = \exp(-(\alpha_c + \alpha_s)l) \quad \tau_{1R} = -(c_c^{-1} + c_s^{-1})l \)

\( a_2 = \exp(-\alpha_c l) \quad \tau_{2R} = -(c_c^{-1} + c_r^{-1})l \)

\( l = Z - Z_0 \)

\( c = \) propagation velocity

\( \alpha = \) attenuation constant

The frequency periods of the two complex terms in 4.3 are \( \tau_{1R}^{-1} \) and \( \tau_{2R}^{-1} \) which are both inversely proportional to \( l \), the distance of the observer from the scatterer. Therefore, the amplitude of equation 4.2 becomes more sensitive to changes in frequency as the distance \( l \) increases.

The same treatment can be applied to equation 4.1 which describes the transmitted signal. The amplitude of the resultant envelope will then have factors with periods of
\[ (c_c^{-1} - c_s^{-1})^{-1} \] and \[ (c_c^{-1} - c_R^{-1})^{-1} \]

These terms are again inversely proportional to \( l \). However, their values for a given \( l \), are substantially greater than the corresponding terms of \( \tau_{1R}^{-1} \) and \( \tau_{2R}^{-1} \) illustrating that coupling becomes more frequency selective when reflected waves are present.

It can now be seen why the monofilar mode can be neglected. Since the selectivity increases with \( l \), the monofilar mode will have little effect on the selectivity owing to its high attenuation constant.

The only other factor affecting selectivity on the buried feeder configuration is revealed by considering the coupling with two scatterers rather than one.

Appendix B examines such a scenario and it is shown that the selectivity can also be a function of the spacing between scatterers.

3.5.2 Space and Angle-of-Arrival Diversity

Space diversity systems for use with leaky feeders will be classified as either radial or axial, depending on the position of the aerials relative to the cable: with the aerials mounted along a line parallel to the cable axis, the arrangement will be termed axial, whereas an arrangement with the aerials positioned along a radial line from the cable will be termed radial.

The mechanisms of the spatial fading along the cable axis, which an axial space diversity system will exploit, has already been discussed at some length in chapter 2. Consequently it will not receive any further attention in this section. Apart from the improvements afforded by space diversity, the variation in performance as a function of aerial spacing will need to be examined.
Aerial spacings up to several tens of wavelength have been considered owing to the presence of a long standing wave pattern. However, the performance with restricted aerial spacings that can be accommodated on a motor vehicle will be of particular interest; such spacings being a requirement of the test track system. A quantitative comparison can then be made against any maximum advantage that the system was found able to offer.

The possibilities of producing a diversity gain with radially mounted aerials cannot be readily seen from the results of chapter 2. However, a brief consideration of the propagation mechanisms on the buried feeder shows that fading patterns in a radial direction could occur. The coaxial mode propagates along the axis of the cable, whereas the modes generated by scatterers may also propagate in other directions. Therefore, the phase fronts will not necessarily be perpendicular to the cable axis. Consequently, the varying phase relationship between the supported modes, as a function of radial distance, may set up a radial fading pattern. Differences in the radial attenuation characteristics of the various modes could also lead to a deep fade being generated at positions along a radial line from the cable. In determining diversity performance as a function of aerial spacing, the restricted spacings that can be accommodated on a vehicle will again be of interest.

The use of frequency offset diversity with spatially separated aerials, makes the division between angle-of-arrival and space diversity unclear. If the frequency offset is viewed as a phase shift varying linearly with time, and the aerials are considered as a single array, then the transmitter appears to be connected to a scanning directional aerial. Thus, the technique is also a form of angle-of-arrival, or directional diversity. In the next section, the field component aerial that is considered displays similar directional properties. However, although both can be considered as angle of arrival systems, they still exploit different
characteristics of the coupling; the spatially separate aerials exploit the same field component but at different spatial positions, whereas the loop/monopole arrangement exploits different field components at the same spatial position.

To avoid confusion, the term angle-of-arrival will not be used to describe implementations of the frequency offset technique.

FIELD-COMPONENT DIVERSITY

Several authors\textsuperscript{27, 28} have discussed the use of an array of two colocated loops and a monopole for achieving a diversity advantage in the land mobile environment. Of these, it was the work of J R Pierce that led to the array being considered for leaky feeder use.

Pierce considered the interference pattern set up by two TEM waves travelling in opposite directions, noting that the nodes of the $E$ field coincide with the antinodes of the $H$ field. He then proposed the use of two orthogonal loops to detect the $H$ field, and a monopole to detect the $E$ field, as a means of mitigating the effects of the standing wave pattern. Although the leaky feeder supports other modes besides TEM, the manifestation of the short standing wave pattern occurs through the interaction of waves travelling along the cable in opposite directions. It was therefore decided that an experimental investigation should be carried out to ascertain if the same form of aerial array mitigates the fading on the buried feeder configuration.

In Pierce's proposal, the size of the loops is not critical since, by knowing the polarisation of the field, the loops can be orientated such that they will only couple to the $H$ field and the $E$ field. On the buried feeder system, if radial surface waves are generated at discontinuities, then it is impossible to find a similar orientation for the loop, given the path a vehicle follows in passing the discontinuity. An alternative would be to use a small loop which only couples to
the H field regardless of orientation. However, this may create problems with matching and efficiency.

It would therefore seem useful to investigate other properties of the loop/monopole array for a suitable diversity mechanism. When the loops do respond to an E field, they respond to a component that is orthogonal with the E field coupling to the monopole. Thus, the loops and monopole still couple to different field components even though the loop responds to a combination of the E and H field.

A diversity advantage will be achieved if the fading of the signal generated by the loops is uncorrelated with that generated by the monopole. Two loops may not be necessary if the signal generated by either one or the other is uncorrelated with the signal generated by the monopole. Alternatively, the monopole could be dispensed with if the signals generated by the two orthogonal loops are uncorrelated.

The other requirement for successfully achieving a diversity advantage, namely, similar mean levels on each of the diversity branches, could be met for each of the above three configurations with the loop and monopole considered in chapter 2.
4: PERFORMANCE OF EXPERIMENTAL DIVERSITY SYSTEMS

The performance of the three experimental diversity systems, which this chapter examines, are considered individually. Initially the features of a particular system are described, followed by a presentation of the results. Finally the performance, together with other characteristics of the technique are discussed, leading to some tentative comments on the implications for other environments.

The Marina saloon car is again used for all three diversity systems at the cable to vehicle separations considered in chapter 2 (see section 2.4.2). For the sake of brevity, a two symbol notation will be used in the following sections to identify the operating frequency of the equipment and the position of the vehicle on the road. The first symbol is either a 4 or an 8, followed by either a letter N or F. The number 4 or 8, indicates the operating frequency, 40 and 80 MHz respectively, and the letter denotes the distance of the vehicle from the cable; N for nearside, the 3 metre spacing, and F for farside, the 7 metre spacing. For instance, 4N indicates an operating frequency of 40 MHz, with the vehicle 3 metres from the cable.

4.1 Frequency Diversity

4.1.1 Measurement System

A schematic illustrating the measurement system is shown in Figure 4.1. Two carrier wave signals are transmitted simultaneously from a 1 metre monopole mounted centrally on the roof of the vehicle. At the receiver, the envelope of each signal is detected separately before being recorded for subsequent analysis. This approach allowed a degree of flexibility when examining the selectivity characteristics including the emulation of the frequency offset technique described in section 3.3.
Vehicle transmitter for frequency diversity measurements

Receiving system for frequency diversity measurements

Figure 4.1
Measurements were taken with one of the signals at either 40 or 80 MHz and with channel spacings of between 1 and 10 MHz.

4.1.2 Experimental Results

At 4N, because the interference patterns are clearly defined, being concentrated around the metallic lineside obstacles, it enabled the selectivity characteristics of each particular fade to be investigated with the measurement system described above. Figure 4.2 illustrates the coupling at 4N, and the fades at (a) and (b) were found to be less selective than any of the other fades close to the senate end. At fade (a) in particular, a difference in frequency of 3 MHz was necessary to reduce the fade depth by approximately 10 dB. Fade (c) was also found to be less selective than the other fades in its vicinity, and again a difference of several MHz was required to reduce the fade depth by 10 - 15 dB. Fades (a) and (b) are noticeably broader than the other fades, indicating that there could be interaction between two waves travelling in the same direction. At fade (b), this may well be a surface mode generated at the nearby leaky to non-leaky join. Since the frequency period of these broad fades will be greater than the period of fades generated by the interaction of waves travelling in opposite directions, some of the spatially shorter fades can be expected to display the higher selectivities that were measured. Where the shorter fades, such as fade (c), exhibit a low selectivity, it is an indication that the fade is close to the origin of the scattering. The high selectivity characteristics are reflected in the performance of the frequency offset diversity system. Figures 4.3 illustrates with a CPD the improvements that are possible for channel spacings of 3 and 8 MHz. An increase from 3 to 8 MHz reduces the maximum null depth by approximately 10 dB, but the 3 MHz spacing is still able to reduce the maximum null depth by approximately 15 dB, which in a data transmission system could substantially reduce the number of errors generated.
Figure 4.2: Variation of the 40MHz coupling at a 3 metre radial distance from the cable.

- SINGLE CHANNEL, NO DIVERSITY
- DIVERSITY WITH CARRIERS OF 40MHz AND 43MHz
- DIVERSITY WITH CARRIERS OF 40MHz AND 48MHz

Figure 4.3: 40MHz frequency diversity performance at a 3 metre radial distance from the cable.
The measured correlation coefficient for the 40 MHz coupling at a vehicle to cable spacing of 7 metres is shown in Figure 4.4. One transmission is kept at 40 MHz while the frequency of the second channel is given by the abscissa. The graph shows how the coefficient only drops below 0.7 at channel separations above 5 MHz, and doesn't fall to 0.3 until the separation is 10 MHz.

The performance of the frequency offset diversity system as a function of the correlation coefficient, is illustrated by the cumulative probability distributions in Figure 4.5. The plots display the trend exhibited by the theoretical curves of Figure 3.6 which illustrates most of the diversity advantage being realised with correlation coefficients as high as 0.6. Even at a measured coefficient of 0.9 (2 MHz separation) there is some advantage gained by using diversity, but this is substantially improved for a coefficient of 0.6 (6 MHz separation). For greater channel separations with lower coefficients there is little improvement in the performance, with the diversity gain appearing to reach an upper limit typified by the 6 MHz curve of Figure 4.5. Diversity gain is also dependent on the difference in the mean coupling loss between the two transmissions. As the difference increases, so the advantage of diversity will begin to be eroded. Variations in mean coupling loss between the two channels can increase as the frequency difference between the transmissions increases, owing to the frequency dependent characteristics of the vehicle aerial, coupling coefficient of the scatterers, and the longitudinal cable attenuation. Consequently there will be an upper limit on the transmission separation if the full diversity advantage is to be realised.

Figure 4.6 illustrates the variation in correlation coefficient with one of the transmissions at 80 MHz. The function at a 3 metre cable to vehicle separation is very similar to the 40 MHz function discussed earlier (Figure 4.4). However, moving away from the cable to a 7 metre separation increases the channel selectivity. The
Figure 4.4: Correlation coefficient at 40MHz, 7 metres from the cable.

Figure 4.5: 40MHz frequency diversity performance at a 7 metre radial distance from the cable.
Figure 4.6: Correlation coefficient at 80MHz

- Single channel, no diversity
- Diversity with carriers of 80 and 83MHz, 3 metres
- Diversity with carriers of 80 and 83MHz, 7 metres

Figure 4.7: 80MHz frequency diversity performance
coefficient now drops away rapidly at low channel spacings but as the separation increases, the rate of change of the coefficient decreases.

Apart from the difference in the function describing the correlation at the two separations, the relationship with diversity performance is identical to the 40 MHz, 7 metre measurements: most of the diversity advantage has been realised with coefficients around 0.6 - 0.7, and for values below this there is little improvement. Again, there is a limit on the diversity gain that can be realised, and this cannot be bettered despite increases in the separation of the transmission frequencies. Figure 4.7 typifies the performance as a function of correlation coefficient at 80 MHz. The 7 metre curve represents the upper limit on the performance at both 3 and 7 metre separations, whereas the 3 metre curve illustrates how the radial variation of selectivity can affect the diversity advantage if the frequency separation between the two channels is too low. In this instance a separation of at least 6 MHz is required if the performance at 3 metres is to be comparable with the 7 metre performance illustrated in Figure 4.7.

4.1.3 Discussion

Where the fading is localised to just a few areas along the cable, it has been possible to observe axial variations in the selectivity which appear consistent with the theory of section 2.3. Close to the scattering positions the selectivity is low, as predicted particularly at the spatially broader fades. However, this is also the area where the interaction is most pronounced resulting in very deep fades. Spacings of several MHz would be required for an effective frequency diversity system.

When the fading is approximately Rayleigh at both the transmission frequencies the theoretical and experimental results appear sufficiently similar to allow the
theoretical model to be used for estimating the diversity performance. The correlation coefficient is then the only parameter needed to estimate the cumulative probability distribution. An important feature of the theoretical and experimental results is that most of the diversity advantage can be realised with quite high values of correlation coefficient (0.6). Increasing the separation in order to further reduce the coefficient only improves the performance by a few dB.

The rate at which the coefficient decreases is observed to be a function of the radial distance from the cable. At 80 MHz the separation required to obtain a coefficient of 0.7 is halved from 6 MHz to 3 MHz as the distance from the cable increases from 3 to 7 metres. High selectivity, as previously illustrated, is likely to be caused by interaction between the coaxial mode and modes regenerated at scatterers. The increasing selectivity with increasing radial distance can then be explained in two parts. First, it was shown in Chapter 3 that increasing the axial distance from the scatterer increases selectivity, because the distance travelled by the regenerated mode increases. When the regenerated mode can propagate radially outwards, increasing the radial distance from the scatterer again increases the distance travelled by the regenerated mode and hence the selectivity will increase. This would not be so if the regenerated mode propagates solely along the cable axis, and for the sake of illustration, had the same attenuation and field characteristics, both radially and axially, as the coaxial mode. Selectivity would then be independant of radial distance. Second, the attenuation characteristics of the coaxial mode and regenerated modes do vary as a function of radial distance. As the distance from the cable increases, the coaxial mode suffers higher radial attenuation than the regenerated waves, but as the axial distance from the scatterers increases, the opposite holds, with the regenerated waves being attenuated more rapidly than the coaxial mode. The position of the deep fades will shift away from the scatterers to a position
where the increase in the coaxial mode coupling loss is balanced by the increase in the axial attenuation of the scattered signals. Since the fading has moved away from the scatterers, the selectivity will increase.

The experimental results indicate the selectivity is very sensitive to the distance between the cable and the vehicle. It could also be sensitive to changes in the feeder environment, such as the number and positioning of scatterers along the cable. Regenerated waves from different discontinuities may interact to produce deep fades; the position and selectivity of the fades being a function of the discontinuity spacing and the level at which the scattered waves are generated. In addition, the varying permitivity and conductivity of the earth can influence the selectivity, since these parameters determine the propagation constants of the surface waves generated by scattering. However, the spread in the correlation coefficient over a period of a year, including a hot summer, is no more than 1 MHz. Even so, further investigations which take account of the above points are necessary before predictions can be made for systems in a similar environment. What has emerged from the work is the order of spacings likely for a frequency diversity system (several MHz) and the potential of the Rayleigh fading model, together with the correlation coefficient to describe the diversity performance.

4.2 Space Diversity

4.2.1 General Considerations

The characteristics of vehicle mounted aerials are sensitive to mounting position and therefore a number of spatially separated aerials may have different coupling characteristics. Any diversity advantage resulting from their use could then be obtained through a mechanism other than the spatial variations of the field. For instance, mountings on the bonnet and boot are directional at 40MHz but in opposite directions along the cable.
Directional as well as space would then have to be considered as a possible diversity mechanism. Differences between aerial characteristics are minimal if the aerial positions are restricted to the vehicle roof and then diversity gain is more likely to be obtained through the space diversity mechanism. Since space diversity is under consideration, the aerials were only positioned on the vehicle roof.

Mutual coupling between the aerials may also effect performance as well as differences in electrical characteristics. The performance of an "ideal" space diversity system can be used to gauge the two effects. The "ideal" system for axial diversity is created by taking the measured data for a single aerial and deriving, on a computer, space shifted versions to represent the signals generated by other aerials of the diversity array. In other words, the aerials have identical properties, except for spatial position, and are non-interacting. The data used for this purpose was obtained with a suitably matched 1 metre monopole mounted centrally on the roof of the test vehicle.

However, the same process could not be applied for radially mounted aerials. Each measurement determines the axial variations of the field for a specific cable to vehicle separation. The necessary radial data would consequently have to be extracted from several measurements taken at different cable to vehicle/trolley separations. Obtaining adequate precision from one measurement run to another was impractical, making the approach unsuitable. Instead, it was decided to use two dipoles mounted together on the trolley, which although not eliminating the mutual coupling will give some indication of the radial characteristics of the field.

4.2.2 Measurement Details

The simulation of the axial system emulates the frequency offset technique described in section 3.3, where the
envelopes of the signal from the two aerials are squared before combining. The same technique was also realised in hardware for the experimental measurements. For the radial diversity trolley measurements, two of the dipoles and oscillators described in section 2.4, were used with a 1 KHz frequency difference between the two sources. Measurements were taken with the aerials mounted vertically at a height of 1.5 metres above the ground, which corresponds to the height of the vehicle roof, and separated by 0.5, 1.0, and 1.5 metres.

At the end of the cable, the two signals are demodulated together by a single receiver as described in section 3.3 before being recorded.

The vehicle system, illustrated in Figure 4.8 consists of two 1 metre monopoles mounted on the roof, and suitably matched at the two frequencies through simple E11 networks. Each is fed by a separate crystal oscillator to give a 1 KHz offset between the transmitter signals. The directional coupler and power meter could be inserted in either arm to check the forward and reverse powers enabling the radiated energy from the two aerials to be kept equal with adjustments to the two attenuators. Since this is also a frequency offset technique, the receiver system used for the trolley work, illustrated in Figure 4.8 remained applicable for the vehicle measurements.

4.2.3 Axial Diversity: Experimental Results

a) Axial Field Characteristics

Figures 4.9 and 4.10 illustrate the performance of the ideal diversity system where the characteristics of the two aerials are identical and there is no aerial interaction. These figures show the performance at the two transmission frequencies with the aerials 3 and 7 metres from the cable. In all cases, significant reductions in fade depth can be realised at separations as low as 0.1 of a freespace wavelength. Further
Laboratory based frequency offset receiving equipment

Figure 4.8

Vehicle transmission equipment

Laboratory based frequency offset receiving equipment

Figure 4.8
Figure 4.10

Prob Signal is Below Absissa

Prob Signal is Below Absissa

98
increases in separation to 0.3 produces an improved performance for both frequencies and cable to aerial separations, in particular, on the 4N graph the fade depth is shown to be reduced by another 8 dB. The same figure also indicates an erosion of the improvement if the aerial separation is taken up to 0.6λ. However, a similar degradation does not occur for any of the other combinations of frequency and cable to aerial spacing, where the fading on the two diversity branches is approximately Rayleigh. For those combinations, most of the diversity advantage is realised at 0.3 and then beyond this the advantage is relatively insensitive to further increases in aerial to aerial spacing. It can be seen from figures 4.9 and 4.10, particularly 4.10, how the curves approximate to the theoretical curves for the diversity advantage obtained with two Rayleigh fading signals that have a correlation coefficient less than 0.6. Plotting the correlation coefficient against aerial separation (Figure 4.11) reveals the coefficient rapidly decreasing up to 0.3 of a freespace wavelength and subsequently never rising above 0.6. Indeed the 40MHz plot of Figure 4.11 shows the coefficient remaining below 0.7 at all separations above 0.15 of a freespace wavelength or 1.13 metres.

b) Vehicle Measurements:

Mounting the aerials on the roof restricts the maximum aerial separation for axial diversity to 1.2 metres. Even so the results of the previous paragraph indicate that the diversity advantage with this spacing maybe substantial at 80 MHz and possibly at 40 MHz as well.

With the aerials positioned at the full 1.2 metre separation down the centre of the roof, it is necessary to establish the coupling characteristics to each one of the two aerials in order to quantify any advantage gained from the diversity system. This would also illustrate any variations in the mean coupling loss and probability distribution from the characteristics of a
Correlation coefficient at 40MHz, 7 metres from the cable.

Figure 4.11: Correlation coefficient of space diversity system
centrally mounted aerial. At both frequencies and vehicle to cable separations, the coupling characteristics were virtually unaltered for either the near or front aerial positions, regardless of the direction in which the vehicle is travelling.

The performance with diversity is shown in Figures 4.12 - 4.14. Figures 4.12 and 4.13 give typical improvements when the fading on both the front and rear aerials is near to Rayleigh, namely at 4F, 8N and 8F. Here the substantial improvements produced by the diversity system can be clearly seen, with the fade depths reduced by at least 15 dB. In Figure 4.14, which illustrates the 4N results, the addition of diversity restricts the deepest fades to around 18 dB, an improvement in this instance of approximately 12 dB.

4.2.4 Radial Diversity: Experimental Results

a) Dipole Measurements

With the centre of the trolley 3 metres from the cable, dropouts on both aerials at 40 MHz at an aerial spacing of 0.5 metres were in excess of 25 dB. Even at this low separation the diversity system reduced the fade depths by about 15 dB (Figure 4.15). However, as the aerial spacing is increased the fading on the aerial closest to the cable becomes less pronounced, a feature previously illustrated in chapter 2. As a result, with the aerial spacing at 1.5 metres, the aerial farthest from the cable appears to have little effect, since the fade depths with diversity are approximately equal to those on the aerial closest to the cable.

Where the fading on the two channels is approximately Rayleigh without diversity, there is a significant improvement in the performance at both 40 and 80 MHz with an aerial spacing of 1.5 metres. Figure 4.16 illustrates the improvements with the trolley 7 metres from the cable where the correlation coefficient for 40
FIGURE 4.12: 80MHz PERFORMANCE, AXIALLY MOUNTED AERIALS, VEHICLE 3 METRES FROM THE CABLE

FIGURE 4.13: DIVERSITY PERFORMANCE, AXIALLY MOUNTED AERIALS, VEHICLE 7 METRES FROM THE CABLE
MHz is 0.6 and at 80 MHz 0.5. Moving the trolley into the 3 metre distance at 80 MHz, has little effect on the CPD (Figure 4.16), but the correlation coefficient is now reduced to 0.3.

Therefore, despite the mutual coupling that exists between the aerials, it is apparent that substantial improvements are possible with diversity, particularly at the lower signal levels where the improvement is most required. However, reducing the aerial spacing with Rayleigh fading on both aerials increases the correlation coefficient. Coefficient values can rise to 0.9 for spacings of 0.5 metres at both transmission frequencies with a corresponding degradation in performance of up to 6 dB in the 0.1 to 0.01 probability range.

b) Vehicle Measurements

The maximum possible separation on the Marina test vehicle is approximately one metre and in view of the above probe results, the aerials were mounted solely at this separation, along the centre line of the roof. Initially, as with the axially mounted aerials, the performance of each aerial was determined separately to quantify the improvement offered by diversity. Table 4.1 shows the variation in mean coupling loss between the two aerials is never greater than 3 dB, enabling the array to effectively combat the fading if the signals on the branches are sufficiently uncorrelated. Figure 4.17 illustrates the differences and similarities in the distributions of the two aerials at 4N. The principle difference here is the increase in fade depth of the aerial farthest from the leaky feeder. Diversity performance is also shown in Figure 4.17, revealing an improvement of 14 dB at the low probability levels.

In Figure 4.18, the Rayleigh curve is typical of the distributions obtained for either aerial when the fading on a single centrally mounted aerial is also Rayleigh.
Figure 4.18: Vehicle performance with radially configured aerials under Rayleigh fading conditions.
Therefore, moving the aerial to either edge of roof leaves the coupling distribution virtually unaffected. The same figure shows the diversity system reduces fade depths of over 35 dB to about 20 dB. For clarity, the figure only illustrates the improvements for three of the two situations where the fading on each of the aerials is Rayleigh, but a plot for the third case namely, 8F, would show a performance very similar to those illustrated.

<table>
<thead>
<tr>
<th>3 METRES</th>
<th>7 METRES</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 MHz</td>
<td>2 dB</td>
</tr>
<tr>
<td>80 MHz</td>
<td>3 dB</td>
</tr>
</tbody>
</table>

Table 4.1 Difference in coupling loss between near and offside aerials

4.2.5 Discussion

The previous section has shown that a separation of approximately one metre effectively mitigates the fading for both radial and axial configurations, at both transmission frequencies.

For the axial configurations the CPDs and correlation functions indicate the periodicity of the fading pattern is just over half of a freespace wavelength. All the propagating modes, with the exception of the highly attenuated monofilar mode, have velocities either slightly less or slightly greater than the freespace velocity. Therefore, the interaction between waves travelling in opposite directions along the cable axis could be expected to generate a standing wave pattern with a period of about half of a freespace wavelength. Despite the presence of the broad fades, substantial gains are possible for aerial spacings which combat the short standing wave pattern.
The 4N CPD of the 'ideal' diversity performance noticeably reflects the periodic characteristics of the fading; separations around half the period giving superior performance to separations equal to the period.

When the fading on the two branches is Rayleigh distributed, the 'ideal' performance becomes less sensitive to variations in aerial separation for separations in excess of a few tenths of a freespace wavelength. Here the correlation always remains below 0.6 and the diversity performance, particularly at 80 MHz, approaches the theoretical performance given by the Rayleigh model. The theoretical model therefore appears to be a useful descriptor for establishing the performance of the diversity system. However, the correlation function needs to be determined before estimations of the diversity improvements can be made. Because the correlation never rises above 0.6 on this system, when the aerial spacing exceeds a few tenths of a freespace wavelength, the insensitivity of the diversity advantage to increasing aerial separation is to be expected. On other systems, this may no longer be a feature of the correlation function. Without further experimental investigations or the development of a theoretical model, it is impossible to determine the correlation function for alternative environments.

Only supposition is possible based on a knowledge of the known mechanisms. For instance the number and positioning of scatterers could alter the correlation function which in some circumstances may result in a very high correlation at spacings equal to the period of the fading pattern. Variations in the soil parameters must also be considered. The velocities of the dominant propagating modes are less sensitive to variations in soil parameters than the corresponding attenuation constants. Therefore, although the period of the fading pattern may undergo a slight change, the degree of correlation as a function of spacing could again be significantly altered.
The limited nature of the radial diversity measurements precluded a detailed study of the radial field, but the results do indicate the potential of such a configuration. Again, the improvements afforded by the system under Rayleigh fading conditions are not dissimilar to the theoretical performance of the Rayleigh model, which assumes no mutual coupling between the aerials.

It is interesting to note that a theoretical study by Lee of a land mobile space diversity system concludes that mutual coupling does not have a noticeable effect on the performance of the system, particularly at the lower probability levels on the CPD.

The analysis, although for land mobile radio, is sufficiently general to allow its application to the radiating cable system since Lee makes only two assumptions about the coupled signals. These are that the signal received directly from each of the monopole aerials is Rayleigh distributed, and that the correlation between these signals is given by the spatial auto correlation of the coupling to just one of the aerials at a spacing equal to the aerial separation. In other words the electrical characteristics of the two aerials are identical. The effects of mutual coupling can then be calculated from the characteristics of the aerial array.

Obviously larger spacings than the 1.2 metres of the experimental axial configurations are possible on most vehicles and warrant attention. However, it should be borne in mind that other diversity mechanisms, besides space, are more likely to be present.

4.3 Field-Component Diversity

4.3.1 General Considerations

The required characteristics of the loop/monopole aerial configuration have already been discussed in chapter 3. For the experimental work, attention is restricted to two
configurations; a single loop together with a monopole, and two orthogonal loops, although measurements with the latter have only been possible at 80 MHz. The 0.75 metre monopole and 30 cm diameter loops used to form the two aerial arrays have previously been introduced in section 2.4, but it is worth noting that the loops have a significant response to horizontal electric fields at 40 and 80 MHz.

One important consideration of the loop design is to prevent coupling to the vertical E field, that is to say the loop must be well balanced. Lack of balance generates a 'dipole' mode on the loop which distorts the familiar figure of eight radiation pattern. The radiation characteristics of the dipole mode can shift the two null positions so they are no longer 180° apart and prevent perfect nulls from being formed, depending on the phasing with the circulating mode.

The characteristics of the loops were checked on an open site at the University, Figure 4.19 illustrates the system. A radiating loop could be attached to a rotating mount approximately 35 metres from the fixed receiving aerial. Since the loop would operate on a vehicle roof, the loop was fixed to a 1.3m by 1m sheet of aluminium and the whole assembly rotated remotely from the receiving aerial position. A terminated vertical monopole could also be placed parallel to the centre line of the loop, at a separation of approximately 2 cm, which enables the effect of the monopole's presence to be determined. Figure 4.20 illustrates the responses of the loop aerial for both test frequencies with and without the terminated monopole in position alongside the loop. The maximum to minimum ratio of the received signal level is in all cases better than 30 dB, with the spacing between the two minima measured to be 180° ± 5°. Any dipole mode present would therefore seem to be at least 20 dB below the level of the circulating mode.
Figure 4.19: Measurement system to determine loop balance
Figure 4.20: Vertical polarisation, radiation polar diagram of the experimental loop.
A further measurement, the cross coupling, was also made to check the aerial interaction. Initially, the aerials are matched to 50 ohm. Subsequently, one of the aerials is fed with a known power and the percentage of this power delivered to the load of the other aerial is noted. Cross coupling is then defined as the ratio of the power radiated by the transmitting aerial to the power absorbed in the load. Typical figures for the cross coupling of 18 dB at 40 MHz and 20 dB at 80 MHz confirm the indications from the field measurements of little interaction between the aerials.

The frequency offset technique used for the space diversity measurements is also used for the loop/monopole combinations considered here. Equipment details are given in section 4.2.2 and the only difference for the loop/monopole system is the aerial array. The 60% efficiency of the loop at 40 MHz was taken into consideration when adjusting the power levels to the aerials to ensure the radiated power from each was approximately equal. No compensation was carried out at 80 MHz since the loop efficiency is 90%.

Parallel and perpendicular orientations of the loop are considered for diversity operation with the monopole and these are also the orientations for the two loop configuration. The loop and dipoles used in the measurements have not been developed to represent suitable aerials for an operational system. Rather, the aim has been to determine whether such an array is capable of providing a useful diversity gain. Before examining the results of this form of diversity, it should be noted that, for the sake of conciseness, where a Rayleigh distribution appears in the graphs of the following section, it typifies the coupling to each of the aerials in the array under the specified operating conditions.
4.3.2 Experimental Results

a) Performance at 40 MHz

The striking feature of the coupling to a single loop mounted parallel to the cable axis, is the absence of severe fading when the vehicle is 3 metres from the cable. Using a diversity system with such an aerial is therefore going to provide very little improvement; a conclusion justified by the probability distributions in Figure 4.21 for the single loop and loop/monopole diversity system. However, with the vehicle 7 metres from the cable, the improvement offered by the diversity system, illustrated in Figure 4.22 is substantial. It is interesting to examine the nature of the fading with the diversity added. Figure 4.23 illustrates the coupling to the parallel loop and monopole in the diversity array together with the resulting diversity signal. The diversity trace reveals how the deepest fades occur at the same positions where broad fades exist on the coupling traces of the separate aerials. Adding diversity therefore appears to combat the short standing wave pattern better than the long pattern.

Returning to Figure 4.22, shows the performance is improved by a few dB, if the plane of the loop is rotated to the perpendicular position. This particular configuration also provides a spectacular reduction in fade depths when the vehicle is 3 metres from the cable (see Figure 4.24). Here, the coupling to both the aerials, unlike the characteristics of the parallel loop configuration, suffers from severe but localised fading. Even so, a comparison with Figure 4.21 indicates there is little difference between the distributions of the two diversity configurations.

b) Performance at 80 MHz:

The probability distributions for each configuration of the loop/monopole are plotted in Figure 4.25.
**FIGURE 4.21: 40MHz PERFORMANCE OF PARALLEL LOOP/MONOPOLE CONFIGURATION. 3 METRES FROM THE CABLE**

**FIGURE 4.22: 40MHz PERFORMANCE OF BOTH LOOP/MONOPOLE CONFIGURATIONS. 7 METRES FROM THE CABLE**
Figure 4.23: 40Mhz coupling with the parallel loop/monopole array 7 metres from the cable.
FIGURE 4.24: 40MHz PERFORMANCE OF THE PERPENDICULAR LOOP/MONOPOLE CONFIGURATION. 3 METRES FROM THE CABLE.
inspection of the graphs clearly shows how both configurations successfully mitigate the fading with only minor variations in performance between 3 and 7 metre distances. The performance of the two configurations are very similar, providing a diversity advantage of 12 - 15 dB at the 0.1% probability level. Despite the similarities, the coupling traces show some interesting differences. For the parallel loop arrangement, Figure 4.26 illustrates the same feature as Figure 4.23; namely the virtual elimination of the short standing wave, leaving just the long pattern. Changing the loop orientation to perpendicular results in a more pronounced short standing wave pattern, but the diversity is still able to eliminate the deep fades.

Finally Figure 4.27 illustrates the improvements possible with the two loop array. Once again, the advantage of the diversity system is substantial and comparable at both vehicle to cable separations to the loop/monopole performance.

4.3.3 Discussion

All three of the experimental configurations substantially reduce the severity of the fading. The parallel loop/monopole configuration in particular, virtually eliminates the short standing wave pattern, suggesting the fades on the two aerials are in antiphase. The longer pattern is not so readily suppressed and limits the improvement that can be realised. These characteristics indicate the mechanism of the advantage could be through the opposing propagation directions of the modes generating the interference patterns, as in Pierce's original scenario. However, Pierce did not consider how two loops could be used without the monopole to achieve a diversity advantage. A possible mechanism can be illustrated by considering the coupling of the loops to TEM radiation generated by two scatterers.
Figure 4.26: 80MHz loop/monopole diversity performance.
FIGURE 4.27: 80kHz PERFORMANCE OF THE TWO LOOP CONFIGURATION
In Figure 4.28 A and B represent discontinuities along the cable and C is the aerial position. The two arrows represent the horizontal H field vectors generated by vertically polarised radiation scattered from A and B. An examination of the figure reveals the two components coupling to the perpendicular loop add, whereas the two components coupling to the parallel loop subtract, resulting in complete cancellation if the amplitude of the two components are equal. The fade therefore exists on only one of the aerials and the fade is mitigated by using the signal on the other aerial.

The above example only considers vertically polarised radiation. Account must also be taken of the coaxial and surface modes which generate horizontal electric fields, as well as magnetic fields that couple to the loop. The characteristics of these modes have not been examined and further investigations are necessary to gain further insight into the diversity mechanisms. The sensitivity of the loop to the various field components is governed by the loop diameter, and consequently the diversity gain will be a function of this parameter. Any further studies should give consideration to this point, however, the diameter of the experimental loops maybe practicable for a system in a similar environment to the experimental system. At 80 MHz the loop efficiency is 90% and the bandwidth is 800 KHZ. Improvements in efficiency and bandwidth, particularly at 40 MHz, can be realised by increasing the radius of the tubing used for the loop, thereby decreasing the inductance and ohmic resistance. Further, in a transmission diversity system, compensation for the ohmic losses at 40 MHz can be made by simply increasing the power available to the loop. Given the low power budgets of typically several hundred milliwatts, this is unlikely to give rise to any problems.

Finally, attention is drawn to the similarities between the experimental performance under Rayleigh fading conditions and the theoretical performance of the Rayleigh model, for low values of correlation coefficient.
indicating the potential of the model for estimating the diversity performance.

Leaky feeder

Figure 4.28: Possible diversity mechanism with loop array
5: GENERAL SUMMARY AND CONCLUSIONS

5.1 Recapitulation

The work presented in this thesis has demonstrated that all three of the mechanisms studied for achieving diversity can be used to effectively mitigate the multipath fading. It has also been possible, through the obtained results, to gain further insight into the propagation conditions on a buried feeder.

The coupling to the cable is predominantly through the fields of the coaxial mode at distances of less than half of a freespace wavelength from the cable. However, metallic objects within this distance scatter the leakage field of the coaxial mode resulting in the generation of other modes supported by the environment, that can interact to produce the familiar long and short standing wave patterns which are a feature of leaky feeder coupling. An appropriate choice of aerial for use within this distance, such as the parallel loop, enables the fading to be avoided if the sensitivity to the fields of the coaxial mode is greater than that to the fields set up by the scattering of the coaxial mode. Delogne discusses the application of this technique to a tunnel environment in order to avoid coupling with the monofilar mode excited as a consequence of the scattering.

On the buried feeder configuration, the surface wave supported by the earth/air interface will also be excited by the scattering. Most of the scatterers are vertical posts and are likely to act as a source for a radial surface wave. The attenuation constant of such waves can be less than 10 dB/100 m at 40 and 80 MHz. The wave is therefore low loss in both the longitudinal and radial directions with respect to the cable. Consequently, the coupling to surface waves that arise from scattering may be a major component of the total coupling over substantial lengths of cable and at the extremes of radial range.
The increasingly random nature of the coupling, as the radial distance from the cable increases, indicates the modes set up through the scattering beginning to dominate the coupling over the coaxial mode. The Rayleigh fading distribution, which can be used to characterise the coupling, is also an indicator that there is no longer a strong, direct propagation path. The mechanisms of the coupling are therefore very similar to the mechanisms for a tunnel environment discussed by Delogne. Coupling close to the cable is dominated by the fields of the coaxial mode, but further away from the cable, where the fields of the coaxial mode are highly attenuated, the waves set up by the discontinuities, or scatterers, within the fields of the coaxial mode, are the main coupling mechanism.

For all the aerial configurations examined, the coupling outside the half wavelength radius rapidly approached a Rayleigh distribution as the radial distance increased. The performance of the various diversity systems, like the CPDs of the coupling, are also a function of the radial distance from the cable. In the instances where the fading on each of the diversity branches could be approximated by a Rayleigh distribution, it was found that it was possible to assume the signals on the two branches are jointly Rayleigh. This enabled a substantial amount of existing theoretical work to be used to establish performance limits and identify useful parameters for describing the performance. The theory predicts an upper limit to the obtainable diversity advantage under such fading conditions, and in practice this proved to be a good approximation to the upper limit of the experimental diversity performance. This upper limit could be achieved with all three of the mechanisms under investigation.

Theoretically, the performance can be predicted once the correlation coefficient between the various Rayleigh fading signals on the diversity branches is known. For coefficients below 0.7 the performance is within 3 dB of the maximum diversity gain, which at the 0.01% probability level on the CPD is 19 dB for the phase sweeping method. The experimental value of the correlation coefficient also proved to be a good indicator for establishing suitable frequency and aerial spacings for effective diversity operation.
The characteristics of the scattered waves, such as their number and propagation constants are a function of the cable environment. Hence the value of the correlation coefficient will also be environment dependent. Further work is really required before it is possible to determine to what extent the functions of the correlation coefficient presented in this work are representative for buried feeder systems in general. This is not to say that the correlation coefficient or the Rayleigh model are not useful for describing the conditions on other feeder configurations. Indeed, it is likely that in an environment where the number of multipath components exceeds the number on the experimental system, the Rayleigh model could be a more accurate description of the coupling.

The fading within half a freespace wavelength of the cable can be described by a Rician distribution, that is to say, the coupling to the feeder has a strong direct component. Under these conditions, the performance of the diversity system, for all three mechanisms, was found to be as good, and in most arrangements, far better than the performance in a Rayleigh fading environment. The latter therefore represents the "worst case" operating conditions which can be used as a guide during system design.

5.2 Discussion and Future Areas for Study

Apart from demonstrating the improvements afforded by diversity, this work has also indicated other aspects of the system design which, with further developments, could lead to more reliable communication on a buried feeder configuration.

The coupling to the parallel loop is an example of the improvements that can be realised if alternatives to monopoles, or dipoles can be considered. The advantages gained with the loop depend on its ability to couple to just one mode, in order to eliminate the standing waves, rather than any directional properties as previously suggested. As yet no attention has been given to optimising the aerial configuration to see if it is possible to improve on the parallel loop performance. This is certainly an area that
warrants further attention. It will be necessary during the study to examine in detail the field distributions of the propagating modes and here the work of Plate could be taken as a convenient starting point. The fields of the coaxial mode would be one choice for the coupling mechanism if the radial range is less than half of a freespace wavelength from the cable. Beyond this radius it becomes increasingly difficult to prevent the coupling to scattered waves setting up severe standing waves patterns.

The test track configuration is inevitably going to require a radial range in excess of the 1.75 and 3.5 metres offered by the fields of the coaxial mode at 40 and 80 MHz. One solution would be to try and prevent the scattering from occurring. However, this may not always be feasible. Alternatively, the operating frequency could be decreased until the required radial range is well illuminated by the fields of the coaxial mode. It will still be necessary to keep the level of scattering to a minimum and the possibilities of establishing guidelines, which will help identify the degree of scattering invoked by various types of scatterers could be investigated.

A license for the system may not always be granted for the required operating frequency. Consequently direct coupling to the coaxial mode maybe impossible. Successful communication is therefore reliant on the coupling to waves excited by the scattering of the coaxial mode. On the Surrey experimental system, the generation of scattered waves is entirely dependent as the obstacles within a metre or so of the cable. Trying to characterise the scattering characteristics of objects like this, in order to determine coupling loss, fading distribution, and, if required, the correlation coefficient will be extremely difficult without making measurements on the installed system. Also the characteristics and positions of the scatterers cannot be optimised for the leaky feeder system. The system operation is therefore dependent on what are essentially random features of the environment. An alternative is to introduce deliberate, but controlled, scattering through the use of mode converters. The technique developed by Delogne for tunnel systems, uses discrete converters which
are placed in a line of non leaky cable. The method involves breaking the cable to insert each mode converter; an operation which can add significantly to the installation cost. Another possibility, so far not discussed in the literature, and well worth attention, may be to design a converter which can be clamped around the outside of the cable. Hopefully, the necessary interaction of the coaxial leakage fields with the mode converter could be obtained with only a slight leakage of the coaxial mode, thereby minimising inadvertant mode conversion. The technique not only avoids any breaks in the cable, resulting in higher reliability and lower installation costs, but also has the advantage of allowing the arbitrary placement of converters along the line which could be particularly advantageous in a building.

On the buried feeder system, it would be advantageous to excite the low loss surface wave rather than conventional radiation since this will provide effective confinement of the fields to the required coverage area. The surface wave remains low loss at frequencies into the U.H.F. bands, making it a potential coupling mechanism if even higher frequencies are allocated to the system. However, the propagation constants of the surface wave are still a function of the soil parameters, and the variations in permittivity and conductivity with changing weather conditions must be considered.

Even with a system designed around mode converters, there may still be problems with multipath fading; waves generated by different converters may interact, or, radiation invoked at the converter could prove troublesome. To what extent these effects can be minimised would be tackled in any future studies. However, diversity could still be an attractive solution for combating any envelope fading. The use of directional or angle of arrival diversity may be particularly attractive for mitigating the interaction of waves, travelling in opposite directions, generated by different scatterers. Here the work on the diversity configurations employing combinations of loops and monopoles could be developed further, with careful examination being given to the allowable size of the loops.
In buildings, at V.H.F and U.H.F, the coupling to leaky feeders is also likely to be through the fields of waves scattered by random discontinuities which are illuminated by the fields of the coaxial mode. The use of mode converters, particularly a version which can be clamped to the cable, could provide a means for more effective and controlled coupling. Again, this is an area for further work. However, scattering from the building structure and objects within the building could still produce severe envelope fading on the coupled signal. Diversity also needs to be considered for this application as a means of mitigating multipath.

The use of leaky feeders for extending cellular services into tunnels has been a neglected area that is worthy of a great deal of attention. Most aspects of the tunnel system need to be studied, from the design of mode converters and repeating amplifiers to characterisation of the transmission channel. The performance of future digital services such as the proposed Pan European system, will have to be considered as well as the present analogue systems. Wideband techniques are under consideration for future systems and therefore the frequency selectivity characteristics of the leaky feeder transmission channel should be characterised. Particular attention will have to be paid to systems exploiting the selectivity characteristics for a diversity advantage, since a low selectivity in the tunnel could lead to an erosion of the diversity advantage obtained outside the tunnel. Other forms of diversity may also be a feature of future systems and these too would need to have their performances quantified for use with leaky feeders. Alternatively some form of diversity maybe considered specifically for use in the tunnels in order, for instance, to ease the intermodulation requirements of repeating amplifiers. The characteristics of random FM will need to be ascertained where mobile are moving at high speed. This will be particularly applicable if cellular networks are going to cover railway tunnels or sideway systems through the use of leaky feeders.

Many of the points mentioned above such as frequency selectivity, random FM and the use of diversity may also have
to be considered for other forms of communication service, employing leaky feeders.

It would appear, if publications in the open literature can be used as a guide, that leaky feeders are receiving very little attention, despite their potential, with respect to providing communication in confined spaces. Given the inevitable requirement of future public and private mobile radio systems, analogue and digital, for coverage in such places there are many avenues of work on aspects of leaky feeder communication that are well worth following.
REFERENCES


APPENDIX A: DERIVATION OF RAYLEIGH FADING

Take the equation given in section 2.7 to describe the coupling, that is,

\[ V(Z) = \sum_{i} a_i \exp(-T_{c} Z_i) F(Z-Z_i) \]

Resolving this into real and imaginary components gives:

\[ X = \text{Re} V(Z) = \sum_{i} A_i \cos \theta_i \]
\[ Y = \text{Re} V(Z) = \sum_{i} A_i \sin \theta_i \]

where

\[ A_i = |a_i| \exp(-\alpha C Z_i) |F(Z-Z_i)| \]
\[ \theta_i = \phi_i - \beta C Z_i - F(Z-Z_i) \]

where \( \phi_i \) = phase component of \( a_i \)
\( \alpha C \) = attenuation constant of the coaxial mode
\( \beta C \) = phase constant of the coaxial mode
\( F(Z-Z_i) \) = phase component of \( F(Z-Z_i) \)

If the number of terms in \( V(Z) \) is large and there is no dominant term, then the central limit theorem can be invoked such that \( X \) and \( Y \) will have a normal distribution with mean values:

\[ \langle X \rangle = \sum_{i} \langle A_i \cos \theta_i \rangle \]
\[ \langle Y \rangle = \sum_{i} \langle A_i \sin \theta_i \rangle \]

Now \( \phi_i \) is independent of all other terms in \( V(Z) \) and uniformly distributed from 0 to 360°.

Therefore, integrating w.r.t. \( \phi_i \) gives

\[ \langle X \rangle = \langle Y \rangle = 0 \]
Similarly the variances of $X$ and $Y$ will also be equal after integrating w.r.t. $\phi_i$, that is:

$$<X^2> = \sum_i <A_i^2 \cos^2 \theta_i> = \sum_i 0.5 <A_i^2>$$

$$<Y^2> = \sum_i <A_i^2 \sin^2 \theta_i> = \sum_i 0.5 <A_i^2>$$

Next, it is necessary to check if $X$ and $Y$ are correlated

$$<XY> = \sum_i \sum_j <A_i A_j \cos \theta_i \sin \theta_j> = 0$$

since $\cos \theta_i \sin \theta_j$, when integrated w.r.t $\phi_i$, equals zero for all $i$ and $j$.

Thus, $X$ and $Y$ are uncorrelated normal variables with zero mean and equal variance, which are the criteria for $V(Z)$ to be Rayleigh distributed.
APPENDIX B: EFFECT OF TWO SCATTERERS ON CABLE SELECTIVITY

Assume the positions of two scatterers are \( Z_1 \) and \( Z_2 \), then, at a point \( Z_0 \) between \( Z_1 \) and \( Z_2 \), the interaction \( V_0 \), between the same type of mode generated by the two scatterers can be represented as:

\[
V_0 = \exp(-\Gamma_c Z_1) F_1(Z_0-Z_1) + \exp(-\Gamma_c (Z_1+d)) F_2(Z_0-(Z_1+d))
\]

where \( Z_2 > Z_0 > Z_1 \) and \( Z_2 - Z_1 = d \)

\( d \) is the distance between the scatterers and \( F_1(Z_0-Z_1) \), \( F_2(Z_0-(Z_1+d)) \) describe the propagation of the regenerated modes. Assuming radial propagation from the scatterers, then:

\[
F_1(Z_0-Z_1) = k_1(l_1) \exp(-j \beta_r l_1)
\]

\[
F_2(Z_0-Z_1) = k_2(l_2) \exp(-j \beta_r l_2)
\]

where \( \beta_r \) = phase constant of the regenerated mode

\( k_1 \) and \( k_2 \) describe the coupling from the coaxial mode to the regenerated modes at \( Z_0 \), and,

\[
l_1 = \sqrt{((Z_0-Z_1)^2 + S^2)}
\]

\[
l_2 = \sqrt{((Z_0-(Z_1-d))^2 + S^2)}
\]

where \( S \) = the radial distance of the position of \( V_0 \) from the cable.

For the purpose of illustration let \( 1 << Z_0 - Z_1 \)

\( 1 << Z_0 -(Z_1 + d) \)

and assume the coaxial mode to be lossless.

\( V_0 \) will then have a factor

\[
k_1(l_1) + k_2(l_2) \exp(-j\omega(\tau_1 - \tau_2))
\]
where $\tau_1 = (c_c^{-1} + c_r^{-1})d$

$$\tau_2 = 2c_r^{-1} (z_0 - z_1)$$

where $c_c$ = propagation velocity of the coaxial mode.
$c_r$ = propagation velocity of the regenerated mode.

the period of this factor is $(\tau_1 - \tau_2)^{-1}$ and therefore the selectivity will increase as $d$ increases.
## APPENDIX C: LEAKY FEEDER DETAILS

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer’s designation (BICC)</td>
<td>T3522</td>
</tr>
<tr>
<td>Characteristic impedance</td>
<td>75 ohms</td>
</tr>
<tr>
<td>Coaxial mode attenuation at 30 MHz</td>
<td>21 dB/km</td>
</tr>
<tr>
<td>Velocity ratio</td>
<td>0.87</td>
</tr>
<tr>
<td>Surface transfer impedance at 30 MHz</td>
<td>2.1 ohm/m</td>
</tr>
<tr>
<td>D.C. resistance - outer</td>
<td>4.9 ohm/km</td>
</tr>
<tr>
<td>D.C. resistance - inner</td>
<td>4.1 ohm/km</td>
</tr>
<tr>
<td>Diameter of outer conductor</td>
<td>10.5 mm</td>
</tr>
<tr>
<td>Overall diameter of sheath</td>
<td>13.1 mm</td>
</tr>
</tbody>
</table>

Construction: PE sheathed, appertured copper type coaxial cable.
Figure C.1: BICC3522 Cable
FIG. 1 VARIATION OF SIGNAL LEVEL AT A RADIAL DISTANCE FROM THE CABLE OF 3 METRES. FREQUENCY 40MHZ

- SINGLE CHANNEL, NO DIVERSITY
- DIVERSITY WITH CARRIERS OF 40MHZ AND 43MHZ
- DIVERSITY WITH CARRIERS OF 40MHZ AND 46MHZ

SIGNAL LEVEL ABOVE MEAN (dB)

FIG. 2 40MHZ FREQUENCY DIVERSITY PERFORMANCE AT A 3 METRE RADIAL DISTANCE FROM THE CABLE

FIG. 3 40MHZ FREQUENCY DIVERSITY PERFORMANCE AT A 7 METRE RADIAL DISTANCE FROM THE CABLE

FIG. 4 80MHZ FREQUENCY DIVERSITY PERFORMANCE AT A 3 METRE RADIAL DISTANCE FROM THE CABLE
FIG. 5 50MHZ FREQUENCY DIVERSITY PERFORMANCE AT A 7 METRE RADIAL DISTANCE FROM THE CABLE

FIG. 6 40MHZ SPACE DIVERSITY WITH AERIALS AXIALLY MOUNTED AT A 3 METRE RADIAL DISTANCE FROM THE CABLE

FIG. 7 80MHZ SPACE DIVERSITY WITH AERIALS AXIALLY MOUNTED AT A 7 METRE RADIAL DISTANCE FROM THE CABLE

FIG. 8 50MHZ SPACE DIVERSITY WITH AERIALS RADIANLY MOUNTED AT AN AVERAGE RADIAL DISTANCE OF 3 METRES FROM THE CABLE