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Diversity reception of telegraph signals

Summary

Angle, time and frequency diversity have application, in some form, where particular needs or constraints favour their use for particular circuits. Apart from simultaneous transmission on two channels during routine frequency changes and the use of frequency exchange (two-tone) keying, they are not often found on point-to-point circuits.

Space and polarization diversity dominate such circuits, combatting different causes of fading but showing very similar results in practice on both short and long distance circuits. For space diversity, passive LP arrays give the most consistent results, given at least half to one wavelength separation laterally or two wavelengths in-line for horizontal arrays. In-line positioning of vertical arrays is not recommended at any practical separation.

Polarisation diversity, using LP arrays sloped at 45° to the horizontal, saves considerably on space and installation costs and deserves to be more widely known and used.

Introduction

The ionosphere is essential to the propagation of high frequency radio signals over distances in excess of several tens of kilometers, Despite this, many practicing radio engineers have only a superficial knowledge of its effect on information-bearing sky-wave transmissions.

In particular the choice of antennas for diversity reception of telegraph signals frequently suggests an incomplete grasp of the needs and of the possibilities. The emergence of new antenna designs and their carelessly (or carefully) worded data sheets have often compounded the confusion for the non-specialist planning engineer.

This summary aims to present, in engineering language, the range of choice and the factors which should effect a decision.

Sky wave losses

Energy loss from a sky-wave signal due solely to path distance is proportional to the square of the distance and is constant. Deviative absorption loss, as its name suggests, occurs in the process of bending the path of the wavefront; while greater for signals very close to the maximum usable frequency (m.u.f), it is usually negligible compared with other losses. These losses can be considered effectively constant for a given system configuration.

Non-deviative absorption occurs as the wavefront passes through comparatively dense layers which are insufficiently ionized to cause reflection. This loss varies considerably and in a complex manner with time of day, season, etc., but normally fairly slowly. It increases steadily towards the lower frequencies and varies little over quite a wide area, although diversity antenna separations of several miles have been reported to counter the effects of slow fading.

A more rapid fluctuation in signal level, again not amenable to normal diversity techniques, may be experienced as the m.u.f rises at dawn or falls at dusk. The short-term m.u.f may oscillate about its changing median value. As a result, the skip distance for the frequency in use can pass quickly backwards and forwards through the path distance, giving rise to very deep fading.

Only careful frequency management and a wide receiver dynamic range with effective automatic gain control can minimize the effects of absorption fading and skip fading.

Non lossy fading

In general, diversity techniques are effective when the signal voltage induced in a given antenna alters for a small difference in location, frequency or time. Such highly localized variations in field are the result of interactions between a number of changing wavefronts, the physical changes which effect the individual paths occurring comparatively slowly.

a) Single-path interference fading

The signal reflected by the ionosphere is not a simple coherent wavefront. Inconsistences within the effective reflecting layer return the signal to earth over many slightly different and generally varying paths. The amplitude and phase of the detected field in the plane of the antenna is the sum of these components. As they vary in relative phase (although of virtually equal strength) these components may combine constructively or may result in partial cancellation. The result is a pattern of widely differing field strengths at closely spaced locations, the pattern depending on frequency and usually scintillating with time.

b) Multi-mode and multi-hop fading

Similar, more regular patterns occur when two or three paths of this type, with distinctively different path lengths, interact at the point of reception. These may be due to reflection of the signal both at low elevation from the E layer and at higher elevation, penetrating the E layer, from the higher levels of the ionosphere. Much the same occurs when the path is traversed in one, two and perhaps three 'hops' at the same time, although the greater attenuation of multi-hop signals due to ground reflections, longer signal paths and multiple absorption losses will cause greater differences between the individual signal levels and reduce fading severity.

c) POLARIZATION ROTATION FADING

A further effect of ionospheric reflection is the transfer of some energy from the radiated wavefront polarization to a reflected wavefront orthogonally polarized. Thus a horizontally polarized signal or a vertically polarized signal will give rise to a reflected signal comprising both horizontally and vertically polarized components, since excitation of the gas ions by the incident field is modified by the presence of the earth's magnetic field.

The vertically and horizontally polarized reflected signals do not, of course, have an independent existence. A composite tilted field exists in the vicinity of the receiving antenna, the angle of tilt depending on the ratio of the original polarization to the rotated polarization in the reflected wave. In practice an elliptically polarized wavefront exists at the receiving antenna, rotating and with its major/minor axis ratio and its major axis tilt constantly varying.

The result is that a dipole or similar antenna, sensitive to field polarization, gives an output signal which fluctuates as field polarization rotates, despite constant total field strength.

Dispersion

In addition to short-term and long-term fading, a signal propagated by ionospheric reflection also suffers from time and frequency dispersion. The effect of these on telegraph error rate depends on the modulation technique employed and on a number of the modulation parameters.

Frequency dispersion occurs due to movement, both vertically and horizontally, in the effective region or regions reflecting the signal towards the receiving station. Low speed telegraphy using frequency shift or two-tone frequency-exchange keying is little affected. Dispersion encountered in temperate latitudes is typically about 1Hz, although several times this value is not uncommon.

Time dispersion (multipath element distortion) takes the form of spill-over between adjacent signal elements due to reception over two or more paths of differing length. The effect is most pronounced at night on short (high angle) paths, when the path delay difference can approach ten milliseconds. One or two milliseconds is more normally encountered on longer paths, where circumferential path length predominates or during the day, when absorption attenuates multi-hop transmission. The discriminator form of demodulator generally used for frequency-shift keyed signals is particularly affected by time dispersion.

Angle, time and frequency diversity

In attempting to reduce telegraph error rate by comparison of two received signals, the system designer has a number of diversity techniques at his disposal. Some of these will be covered here only briefly and in rough order of increasing cost-effectiveness.

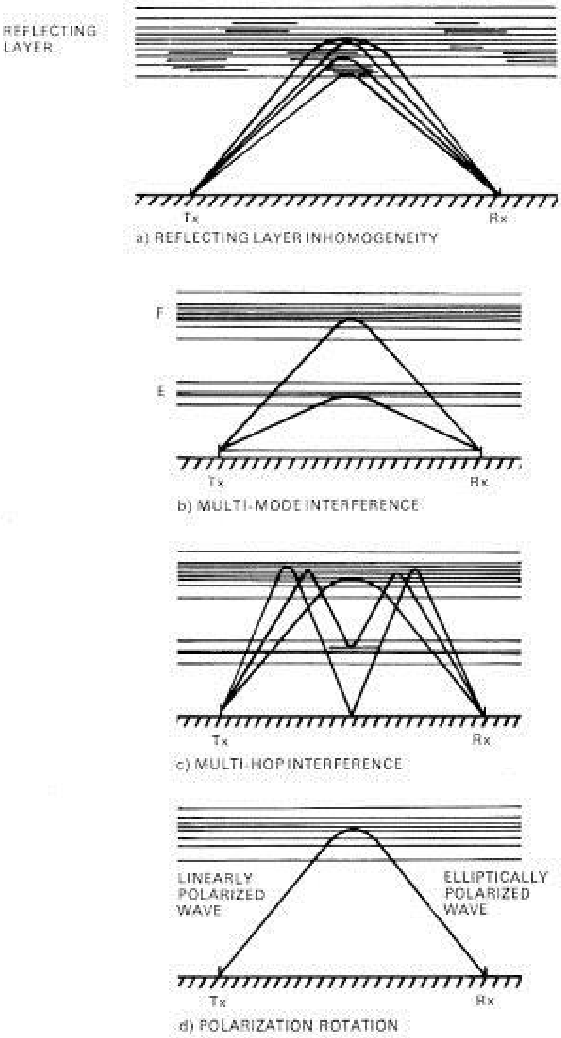

Figure 1. Causes of diversity-responsive fading

a) ANGLE DIVERSITY

Angle diversity employs two antennas each with a very narrow main lobe in elevation, designed to respond to the principal propagation modes. For use at high frequency such antennas, particularly if steerable in elevation, are large, costly and not particularly effective.

Some success is possible in distinguishing between the ground wave and sky waves for short over-sea paths, or between first and second hop sky waves at slightly longer ranges. Reduction of time dispersion is the main aim, increasing the baud speed possible on these notoriously difficult circuits.

b) TIME DIVERSITY

Time diversity requires transmission of the message

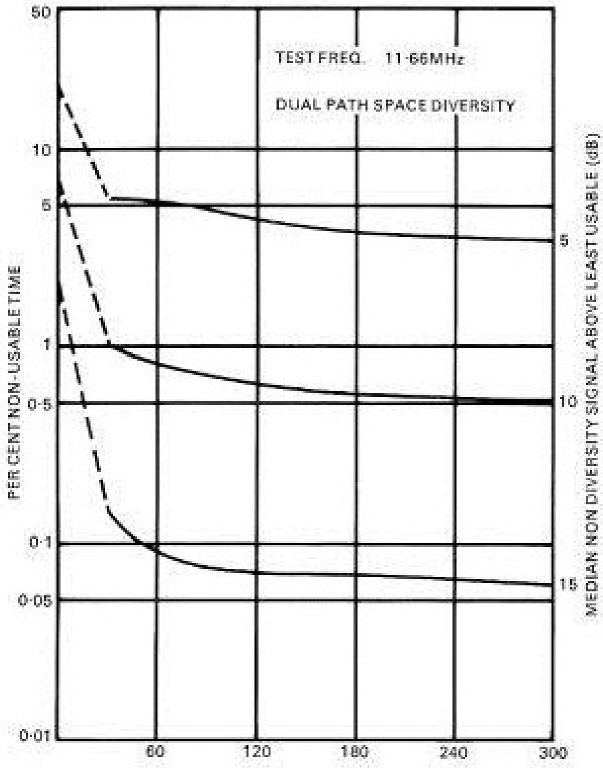

Figure 2. Antenna spacing effect on diversity performance

either twice, with error detection to identify the uncorrupted received signal, or three times in conjunction with majority voting. The technique therefore introduces appreciable traffic delay, reduces information transfer rate and requires special traffic signal storage and processing equipment at both transmitting and receiving station.

Its effectiveness is critically dependent upon optimizing the time separation, since interference fading and skip fading are usually cyclic with a period of the same order as the repetition delay. In certain applications, such as shipborne or embassy receiving installations where antenna space is severely limited, the need for only one radio receiving circuit can outweigh the disadvantages.

c) IN-BAND FREQUENCY DIVERSITY

Frequency diversity may be either in-band or out-of-band. The former again reduces the information capacity of the channel and, if two simultaneous f.s.k tones are used, sacrifices most of the nominal diversity gain (about 8dB in practice) by requiring reduction of each tone by 6dB below peak envelope power. Two-tone frequency exchange keying does not have this disadvantage, while the filter and envelope detector employed are fairly simple and less severely affected by frequency and time dispersion than a phase-conscious discriminator. Although it would appear that the tones allocated to a channel could be chosen for nearly perfect negative correlation in the presence of interference fading, there are practical problems in determining optimum separation. The tones are therefore spaced by 340Hz (hopefully avoiding positive fading correlation) or by 850Hz or more (with rapid fading essentially uncorrelated) and are frequently combined with space or polarization diversity for additional protection. Diversity between independent sidebands has also been used for certain forms of data transmission, where the modulating signal is itself multitone.

d) OUT-OF-BAND FREQUENCY DIVERSITY

Out-of-band frequency diversity aims for two paths with completely uncorrelated transmission characteristics. About the only application in practice is the simultaneous transmission of traffic on two radio channels for some time before and after a routine frequency change, one channel improving as the other deteriorates, where a break in traffic is unacceptable. Co-ordination of the change is not then critical, rationalization of the received traffic being an operator function. In terms of transmitter operating costs and spectrum occupancy, out-of-band frequency diversity (with for example, 100kHz channel spacing) is unattractive for continuous use.

Spaced antenna diversity

By far the most widely used form of diversity reception is space diversity, in which two antennas and receivers sample the signal at two locations on a common site. Maximum diversity advantage is obtained when the antenna and receiver characteristics on the two paths are matched over the full dynamic range and at all frequencies of interest.

a) OMNIDIRECTIONAL ANTENNAS

The antennas may be omnidirectional in azimuth, for use with transportable stations or for time-shared working between a base station and a number of outstations. Assuming wide band antennas, the choice here lies between various forms of horizontal fan dipole (such as the Marconi 'Conifan' antenna, with its compact single-mast construction) for short range, and the vertical monopole (such as the Marconipole) for longer ranges. The intermediate range between about 600km and 1500km represents a constant challenge in this respect, no entirely satisfactory omni antenna being available, although current development work looks promising.

b) RHOMBIC ANTENNAS

Unless omnidirectional antennas are needed, some reduction in atmospheric noise and interference can generally be achieved by using narrow-beam unidirectional antennas. Very narrow beamwidths are possible by the use of rhombic travelling-wave antennas which, at certain frequencies, also provide the highest sensitivity. Bandwidth is limited to just over an octave for a 2:1 v.s.w.r, but can extend to about two octaves if the impedance matching requirement is relaxed for reception, say to 5:1 v.s.w.r. Most severe limitations are its variations of vertical polar diagram and horizontal polar diagram with frequency. Both exhibit large secondary lobes, with consequent poor rejection of interference and noise from certain bearings and elevations. Even over an octave frequency range, the rhombic can have a 10dB range of sensitivity on the primary lobe, the elevation of which can change from 10° to 25° or more. This variability of its characteristics, its size and cost for use on the lower frequencies, and the inconvenience of selection from two or more antennas for wide-band cover have caused the rhombic to lose popularity for point-to-point use.

c) LOG-PERIODIC ANTENNAS

Almost standard for directional diversity reception is the logarithmically-periodic antenna – the LPA – in horizontally or vertically polarized form. Although its sensitivity is similar to the lower limit of rhombic sensitivity, both this and its polar diagrams are relatively constant over a frequency range spanning most of the high frequency radio band. The LPA and several of its many variants, like a number of historically-important antenna designs, are the outcome of intensive and continuing research by the Marconi Company, who hold the relevant patents.

d) HORIZONTAL LPA SEPARATION

If two horizontally polarized LPA arrays are erected side-by-side, pointing in the same direction, they exhibit negligible mutual coupling even when sharing a common mast. As a result, the effect of each on the polar diagrams of the other is also negligible. Minimum permissible separation is therefore determined by diversity needs. It has been shown that some 75 to 100 metres between antenna centres gives almost as much improvement against multi-mode, multi-hop and polarization-rotation fading as is possible. Little further gain is obtained without the separations of several kilometres which are necessary to counter slow fading.

When horizontal LPA arrays are in-line, one looking into the back of the other, separation of about one wavelength (150 metres at 2MHz) gives considerable distortion of the polar diagram of the rear antenna; the horizontal beamwidth increases by some 20 degrees and spurious lobes can rise to levels only about 6dB down on maximum sensitivity. To eliminate these effects, antenna separation of at least two wavelengths (say 300 metres) is desirable between corresponding elements. Diversity trials suggest similar minimum required separation as for the side-by-side configuration, so that mutual coupling is the dominant criterion when in-line.

e) VERTICAL LPA SEPARATION

With vertical LPA arrays, the effect of mutual interaction dominates the required diversity separation. In-line arrays even five wavelengths apart exhibit severe beam splitting on the rear array. With side-by-side arrays on the same bearing, two wavelengths separation at the lowest frequency is adequate. Appreciable 'stagger' is permissible provided the separation at right angles to the direction of fire is at least two wavelengths.

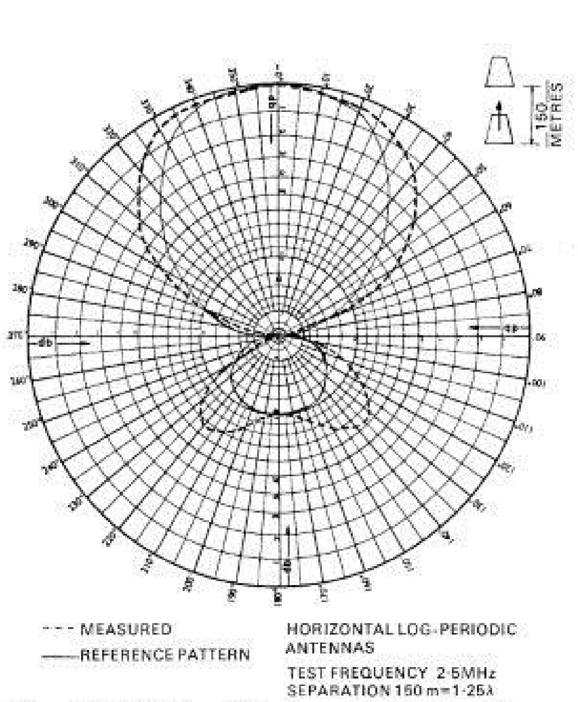

Figure 3. Distortion of horizontal LPA polar diagram due to inadequate in-line separation

These necessary separations mean that, despite the size advantage of the LPA over the rhombic, the antenna field for space diversity reception must be large and feeder runs long. Opportunities for sharing masts, important in reducing costs, may be severely restrained for these same reasons.

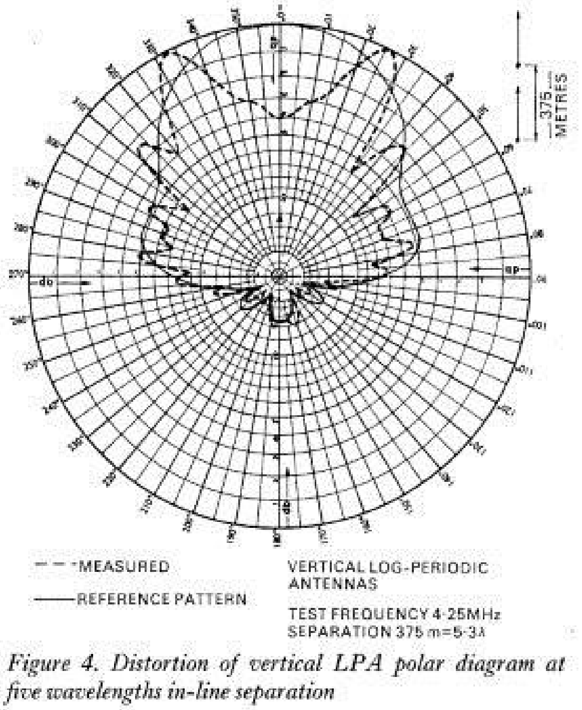

Figure 4. Distortion of vertical LPA polar diagram at five wavelengths in-line separation

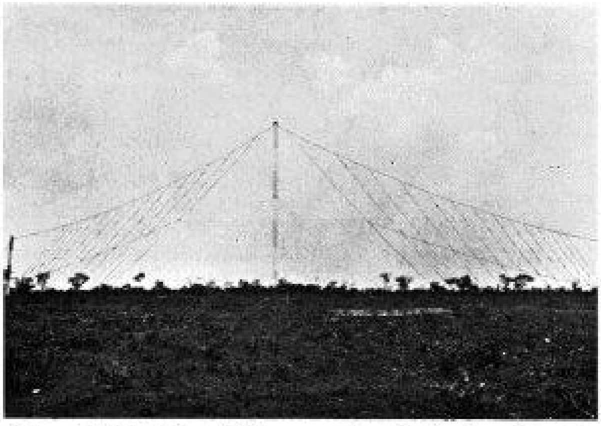

Figure 5. Receiving LPA arrays in polarization diversity (retouched to show curtains)

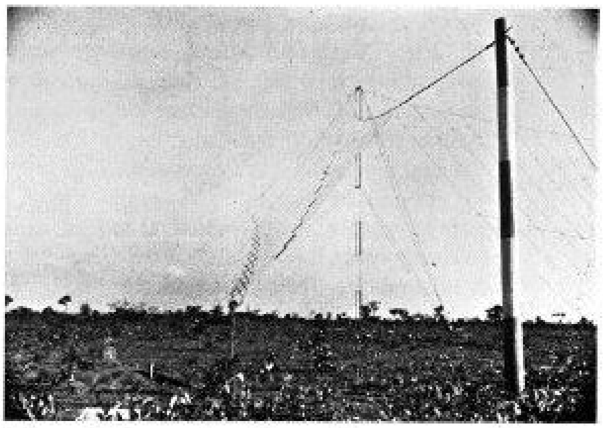

Figure 6. One curtain of the receiving antenna of figure 5.

f) ACTIVE ANTENNA ARRAYS

Active antennas of loop or rod form are very easily installed as broadside or endfire receiving arrays, or in any combination to give the required sensitivity and directivity. Suitable lengths of cable connecting the antennas to a signal combiner ensure correct phasing. Although an array of loops may be almost as expensive as a large wire antenna, site levelling and installation costs are normally only 20% to 30% of those for the larger structure. Shipping costs are also substantially lower.

Unfortunately the array displays some of the characteristics of a rhombic antenna, Antenna response decreases with decreasing frequency, although its impedance at the feeder connexion point is reasonably constant. Each element must be close to the ground plane and all are effective across the whole frequency range. The direct relationship between the height of the matched section and the signal wavelength, which gives the LPA its constant elevation response, is therefore absent; the vertical polar diagram varies considerably with frequency. Logarithmic spacing between loops can reduce, over a fairly wide range, the variation in azimuth directivity with frequency displayed by the basic endfire array.

Performance of any solid-state active antenna in the presence of strong interfering signals or local electrical noise must always be suspect, especially in view of the problems in filtering before the inbuilt amplifier. This limits its usefulness in transportable roles, where its flexibility and its small size and weight would otherwise be attractive.

g) ACTIVE ARRAY SEPARATION

Most active antennas available are vertically polarized. Maximum response of an individual element, or of an array at right angles to its centre line, therefore occurs at very low elevation. The low profile of the antenna, however, results in negligible effect on the polar diagrams given separation in excess of about 20 metres. At closer range the adjacent antenna will have a similar effect to that of any other conductive obstruction.

Interaction of these arrays when located along the line of fire is probably less than for vertical LPA arrays due to the lower antenna profile. There is little need to adopt this configuration with such a narrow strip of ground required, however, and it is best avoided.

h) TRIPLE DIVERSITY SYSTEMS

Spaced antennas seek to compensate for interference fading due to multi-hop or multi-mode propagation. Since it is impractical to seek negatively correlated fading on the two antennas, uncorrelated fading is aimed for. In these circumstances, triple space diversity has been found much more effective than simple space diversity for the same overall antenna separation. The cost and comparative complexity of the resulting receiving system, however, render triple diversity commercially unattractive.

Polarization diversity

Polarization diversity reception, by contrast, seeks to compensate for fading due to polarization rotation, which periodically reduces the field strength in any specified plane parallel to the direction of propagation. If the total field strength is constant (which presupposes no other fading mechanism and is a drastic simplification of reality), the signal levels in two orthogonally orientated antennas will be totally correlated with negative correlation. Alignment of the field with one antenna gives zero induced signal in the other; polarization at 45° to both will induce equal signals in them, each 3dB down on signal level for correct alignment. This is so no matter what angle the antennas make in relation to the earth's surface if the effect of the latter on signal attenuation is neglected.

Polarization diversity should therefore be much more effective against rotation fading than is space diversity against interference fading. Their comparative effecttiveness in a practical case, however, will depend upon the dominant fading mechanism. This accords with the variability in detail of reported results, which in general show little significant difference in performance between polarization and space diversity where median levels have been properly balanced.

a) ANTENNA DESIGNS

An antenna system which involves vertically and horizontally polarized antennas is difficult to balance over a range of frequency, elevation and azimuth due to their inherently different characteristics. To overcome this problem, antennas are needed which are orthogonal but are equally affected by the proximity of the earth's surface and equally sensitive to horizontally and vertically polarized fields, since these are subject to different degrees of attenuation.

Antennas which satisfy these needs slope at 45° to the horizontal, taking the form of a 'St. Andrew's' cross or of an inverted 'V'. This latter format has the advantage that it can be hung from a single mast and is typified by the Marconi R1709, in which two such antennas each consist of a logarithmically periodic array. Having a diversity advantage similar to that of spaced LPA arrays, this antenna occupies a much smaller total site area and is much cheaper to instal.

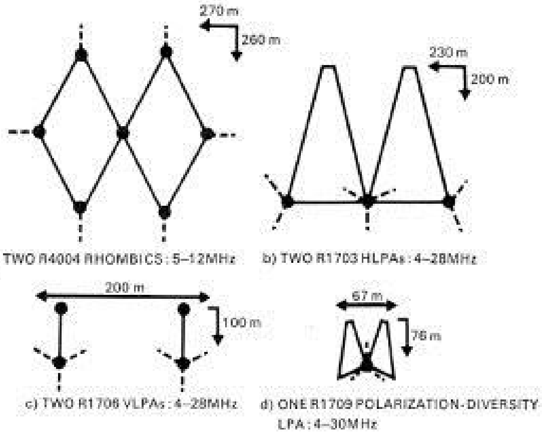

Figure 7. Relative site areas for various passive antenna arrays at minimum diversity separation

b) ALTERNATIVE METHODS

An interesting approach has been suggested in which a rhombic antenna, primarily sensitive to horizontal polarization, is used with a vertical active antenna array designed to match the characteristics of the rhombic. The limited frequency range of a practical rhombic and difficulties in maintaining polar diagram matching even over that range, plus the poor side lobe performance of the rhombic and suspect large-signal performance of the active antenna, serve to temper the interest.

A further variation uses active antennas in two orthogonally-orientated ground arrays. These will effectively respond to orthogonally-related components in a signal of nearly vertical incidence on a very short-range path. Unfortunately the response of individual aperiodic elements of the array is poor for high-angle signals, resulting in poor overall sensitivity.

It should be noted that separating the two arrays of a polarization diversity antenna does not add the benefits of space diversity to those of polarization diversity. At any separation great enough to be effective, the relative polarization of the antennas is irrelevant.

Acknowledgement

The author makes no claim to originality, but acknowledges blatant plagiarism from a wide variety of articles and internal memoranda spanning some 30 years, as well as indebtedness to discussions with colleagues both past and present.