Polarization-diversity antennas for compact base stations

Brian S Collins BSc(Eng), CEng, MIEE, MIEEE

Technical Director, CSA Limited

Summary

This paper describes the use of diversity reception for mobile radio base stations and compares the performance of space and polarization diversity techniques. It is seen that in urban areas polarization diversity offers performance that is generally comparable with that of space diversity. The compact 3-antenna system of a polarization diversity base station is much more acceptable as a feature of the urban landscape. Performance trials in rural areas trials show a less clear picture – while most experimenters report that space diversity is a superior method, others have obtained results favoring polarization diversity. The paper discusses possible reasons for these differences.

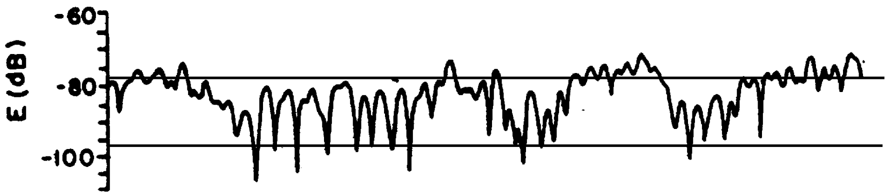
1 Introduction

The mobile radio environment is characterized by small, low-power mobile units operating with low transmitted power and restricted antenna performance, communicating with a base station which has a much higher operating power and more freedom to deploy high gain antennas. The radio path from the mobile to the base station is often physically blocked by buildings, trees and terrain features. As a mobile user moves through the environment, the signal received at the base station varies with time because the amplitudes and phases of the directly received signal and multiple reflected signals change from moment to moment. For some proportion of the total time, the received signal may fall to an unacceptably low level and the resulting reduction in BER (or Eb/No) will cause loss of effective communication.

It was found some years ago that the reliability of communication in a time-varying transmission environment can be improved by receiving the signal on two or more independent channels (known as branches, as they both relate to the same communications channel) and combining the output in some optimum manner. Methods used include branches separated by:

- Time (send everything more than once as fades will probably not occur at the same point in both transmissions)
- Frequency (send signals on more than one frequency at the same time as fades will be independent))
- Space (receive the signals at two separated locations where fades will be independent)
- Polarization (if the transmission medium has the property of coupling signals between polarizations, then they are unlikely to fade at the same time.)

• Angle (signals received at different arrival bearings have a different scattering and reflection history and will probably not fade together).



Horizontal distance about 20ft at 1900MHz

Figure 1: Field strength v distance for a mobile moving along a street

As an example, in Figure 1 we see a typical graph showing the way in which the signal received on a base station antenna changes as the mobile user moves along a street. At several points the received signal falls momentarily below some threshold at which an acceptable Eb/No is obtained.

In figure 2, a second receiving antenna receives the same mean signal level, but the moments at which fades occur on the first antenna occur in general at different moments from fades on the second antenna.

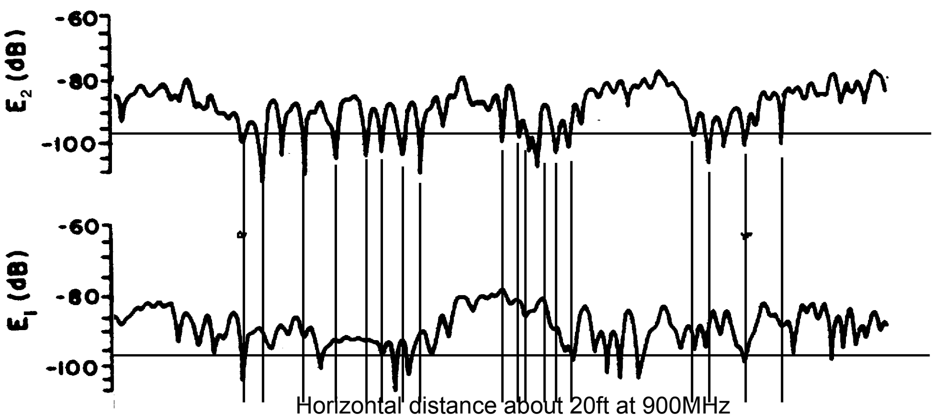


Figure 2: Field strength v distance in two receiving branches

Note that the fades on the two branches generally occur at different times as they occur randomly in each branch – only those marked with a • occur together.

With any diversity system the property we are trying to exploit is the lack of correlation between fades on each branch of the diversity system. The methods can be used separately or in combination. In digital systems, diversity methods are further combined with coding systems, which allow correction of errors caused by short losses of signal. In this paper we are concerned with a comparison between two-branch systems using either space or polarization diversity.

Diversity Gain

The effectiveness of a diversity system is measured by a quantity known as diversity gain. In a single branch system we can measure the level of signal which is exceeded for some fraction of time, for example 90%. If we now consider the diversity system we can again examine the system output and determine the signal level exceeded for the same proportion of the available time. The increase in the signal level available for the same proportion of time (reliability) is known as the diversity gain. It is important that the reliability is quoted together with the diversity gain, as different values of diversity gain are obtained when a different reliability is chosen.

For a given reliability, diversity gain is a function of two parameters – the correlation between the signals in the two diversity branches and their relative amplitudes. The relationship between these parameters for a 2-branch system is shown in Figure 3.

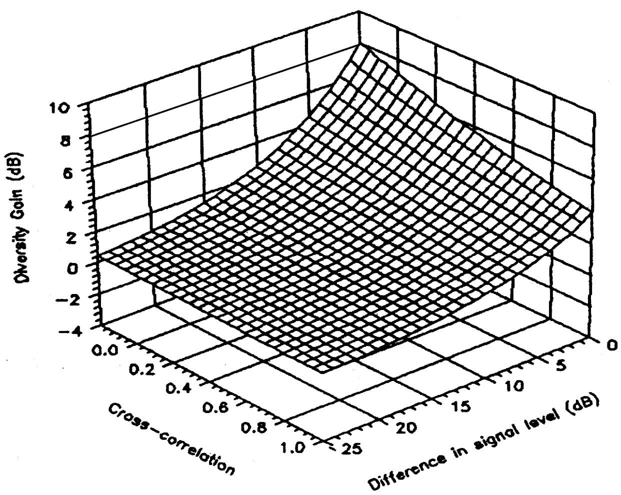


Figure 3: Diversity gain at 90% signal reliability as a function of cross-correlation and mean branch signal level difference for two-branch diversity using maximal ratio combining. (Turkmani et al, 1995)

The largest diversity gain is achieved when the mean levels of the signals from the two branches are equal and the correlation between them is low – fading is independent in the two branches. (When the correlation between signals is high, fades occur together and the system simply has 3dB more signal power than the single-branch system. When the amplitude of one channel is much lower than the other, diversity gain falls to zero.)

Diversity gain is also a function of the method by which the signals in the two branches are combined. The usual systems are:

- ***Selection*** *Choose the input with the highest SNR or (S+N)/N*
- ***Equal gain*** *Weight the paths before choosing the highest SNR*
- ***Switched*** *Switch channels when the signal falls below a threshold*
- ***Maximal ratio*** *Add all available signal power coherently, with time delay equalization*

Maximal ratio combining is the most effective method in a multipath environment, as it makes optimal use of the total signal power received in both branches at any instant. It is commonly (but not universally) used in mobile radio systems and its use will be assumed in this paper except where otherwise stated.

2 Polarization diversity systems

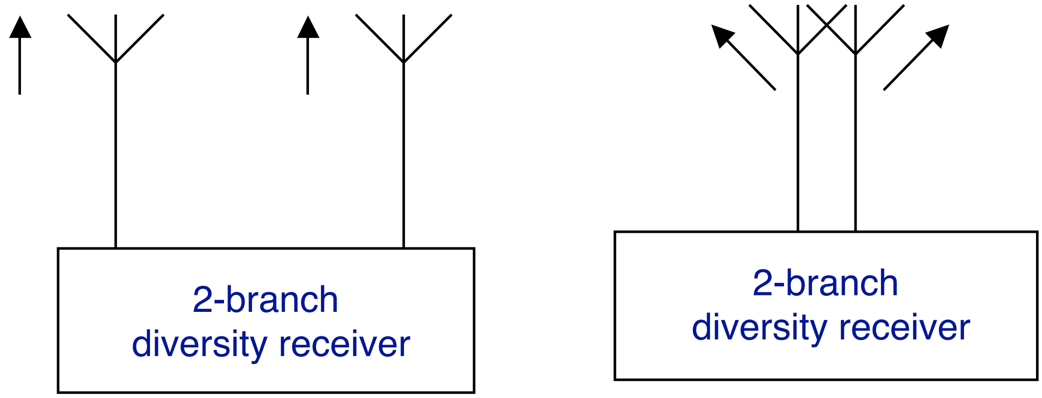


Figure 4: In a space diversity system the two branches receive signals from physically separate locations. In a polarization diversity system the signals are received at the same location, but with orthogonal polarizations.

Figure 4 shows two diversity methods in the uplink radio path. Space diversity has been the most commonly used method since the inception of mobile services, but there is increasing interest in polarization-diversity systems because the two receiving antennas can be physically co-located. This results in lower costs and a smaller visual profile for the base station.

2.1 Polarization characteristics of the received signal

The instantaneous polarization of the signal received from the mobile user is determined by

- the polarization of the signal radiated from the mobile
- the scattering characteristics of the transmission path.

Changes of orientation of the mobile unit will change the transmitted polarization. If the path is cluttered by multiple scatterers the received polarization will change randomly with time as the mobile moves through the environment.

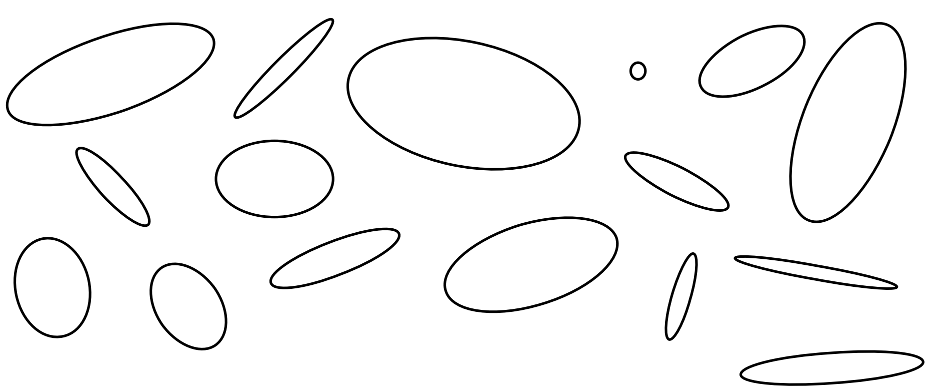


Figure 5: Instantaneous polarization of the received signal at the base station

Figure 5 shows typical states of the received polarization. For most of the time the polarization is elliptical, with arbitrary orientation (polarization angle) and ellipticity (axial ratio). This is to be expected — when a linearly polarized signal with an inclined polarization plane is reflected from either a horizontal or vertical surface, the resulting sum of direct and reflected waves has elliptical polarization.

There is no simple antenna which can receive all the power transmitted in a wave with time-varying polarization.

One strategy to exploit the situation is to use two antennas that respond independently to two orthogonal components of the incoming wave. We can regard the signals associated with each polarization component as the inputs to a two-branch diversity system and fading in the two channels is at least partially uncorrelated. By appropriately combining these branches we can make effective use of all the signal power available at any instant and obtain a useful level of diversity gain.

The effectiveness of the diversity scheme will depend on the correlation between the signal levels in polarizations chosen for the two receive branches. We can obtain the lowest correlation between branches and the highest total output power by choosing to receive two orthogonal polarization components. (Orthogonality is a complex mathematical concept, but is familiar from two simple limiting cases of a pair of linear polarizations mutually at right angles, and circular polarization with left-hand and right-hand rotation. The orthogonality of two wave polarizations is measured in dB and is the relative level received when an antenna perfectly matched to one polarization is illuminated with the other. (See also References 8 and 9)

2.3 Diversity gain in a polarization diversity system

We now examine the effectiveness of the polarization diversity system. Some simple examples will indicate the difficulty of arriving at clear conclusions without resorting to experimental data.

If the polarization transmitted from the mobile is vertical, scattering from buildings and the ground will have little effect on signal polarization as the reflected signals are also vertically polarized. Fades will occur when multipath signal components interfere destructively, but no significant coupling will exist between polarizations. If in this case we choose a vertical/horizontal pair of polarizations for the receiving antennas one of these channels (vertical) will receive most of the signal power and the other (horizontal) will receive a much lower level. Even if the samples were uncorrelated the diversity gain will be small (Figure 3).

If we choose to receive a pair of linear polarizations inclined at ± 45°, the signal levels will be very similar to one another and will have high correlation; each channel will contain half the total signal power.

If the polarization of the signal radiated by the base station is oblique, then each reflection of the signal will result in coupling between all possible polarization states and the received signal has the time-varying polarization characteristics shown in Figure 5. The same obviously applies when the mobile radiates with any non-linear polarization.

In a real environment the correlation between the orthogonal received polarizations depends both on the transmitted polarization and the extent of scattering of the signal in the transmission path. The difference between transmitted vertical (0°) and 45° polarizations arises because buildings present predominantly vertical reflecting surfaces and refracting edges; ground reflection of a vertically polarized signal does not couple signal to horizontal polarization. +45° polarization couples to -45° at each reflection at walls or ground.

In a rural environment there will in general be fewer scatterers, and their characteristics will be different from scatterers in cities.

2.4 Comparative diversity gain using space and polarization diversity

A number of investigators have reported the results of experimental comparisons between space diversity and polarization diversity in mobile radio systems. The results show broad qualitative agreement; the classification of environments is approximate and may account for some of the discrepancies between investigations. An 'urban' environment in downtown Chicago is entirely different from one in Paris France, or Melbourne Florida. 'Suburban' means one thing in Denver Colorado, and something entirely different in terms of the height and density of buildings in Hope Arkansas, or Stockholm Sweden. Similarly, 'rural' doesn't distinguish forested area, cornfields, mountains or flat plains. When specific locations are mentioned by investigators, their classification often appears to be very arbitrary. No reference is made to the height of buildings or to the presence of trees or open spaces in many cities.

Results from a typical and well-documented study in Stockholm, Sweden by Wahlberg (1997) are shown in Table 1. These results are typical of several studies in that polarization diversity usually appears slightly inferior to space diversity. As expected from the discussion in Para 2.3 above, polarization diversity using receive antenna polarization of ± 45° is superior to that obtained when the receiving antennas are horizontally and vertically polarized. Space diversity provides higher diversity gain in urban areas than it does in other environments; this might be expected, as there are more scatterers in urban environments and a maximal ratio combiner will make use of all the received signal energy added coherently.

		Urban	Suburban
Space diversity		***6.5dB***	***5dB***
Polarization diversity:			
Reduction in diversity gain with mobile at 45°			
± 45°		***-1.6dB***	***-0.9dB***
H/V		***-2.6dB***	***-1.1dB***
Reduction in diversity gain with mobile vertical			
± 45°	*(mean signal reduction)*		***-2.5dB***
H/V	*(unbalanced signals)*		***-3dB***
90% reliability, 90% confidence			

Table 1: A comparison of diversity gain using space and polarization diversity (Wahlberg,1997)

The arguments above suggest that while low correlation is obtained between space diversity branches, much of the available signal power is lost into the orthogonal polarization to which the receiving antenna does not respond. A combined 4-branch space/polarization diversity system would provide significantly higher diversity gain.

Wahlberg's comparison between urban and suburban areas is at variance with most other investigations. Usually, diversity gain is greater in urban areas than in suburban areas. However the city area in which he worked is characterized by regular street blocks with buildings of moderate height, while the suburb had several high-rise buildings and a less regular street plan.

Donaldson and his fellow workers (Donaldson et al, 1995) used a vertically-polarized antenna on their mobile unit and a H/V polarization pair at the base station; the mean reduction in diversity gain for polarization diversity v space diversity in Washington DC and Richardson TX was 0.5dB.

Figure 6: The difference in visual impact between base stations using space diversity (left) and polarization diversity (right)

In suburban trials conducted by Fuerter in California (Fuerter, 1998) polarization diversity emerged as superior to space diversity. Fuerter notes that the de-correlation between an H/V pair is always greater than between a +/- 45 degree pair, but as the signal levels in the two branches are less equal the slant-polarized option has higher diversity gain.

3 Practical considerations

Polarization diversity has an outstanding practical advantage over space diversity, as the two antennas required can be housed in a single unit no larger than that required for simple vertical polarization. No head frame is needed on the supporting structure, so the wind load to be supported by the structure is much lower. The structure can be of lighter design and installation times are reduced. These factors result in substantially lower cost and very much reduced visual impact (Figure 6).

4 Conclusions

Although there are some discrepancies between the findings of different investigators, in most situations there appear to be only small differences between the diversity gain obtained using space diversity and that obtained using polarization diversity. Any small differences are less significant as networks become more developed, as base stations are added to provide additional capacity rather than to increase the geographical area of coverage. The visual profile of a base station using three dual-polar antennas is much smaller than that of a conventional space diversity base station using six antennas; the cost of the dual-polar antennas and their supporting structure are substantially lower.

In a cluttered urban environment, four-branch diversity (space and polarization) is likely to provide significantly higher diversity gain than either technique used separately.

CSA Limited, Knight Road, Rochester, Kent, ME2 2AX, UK

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Appendix

Diversity gain at the sector edge

In many reports, no mention is made of whether the sample points lay in the middle of the azimuth beam of the receiving antenna or close to the ±60° azimuth directions where the beams of adjacent sectors overlap. In general the polarization orthogonality of a dual slant-polar antenna will fall at the beam edge, typically to around 10dB at ± 60°. Two effects reduce the relative effect of this fall-off.

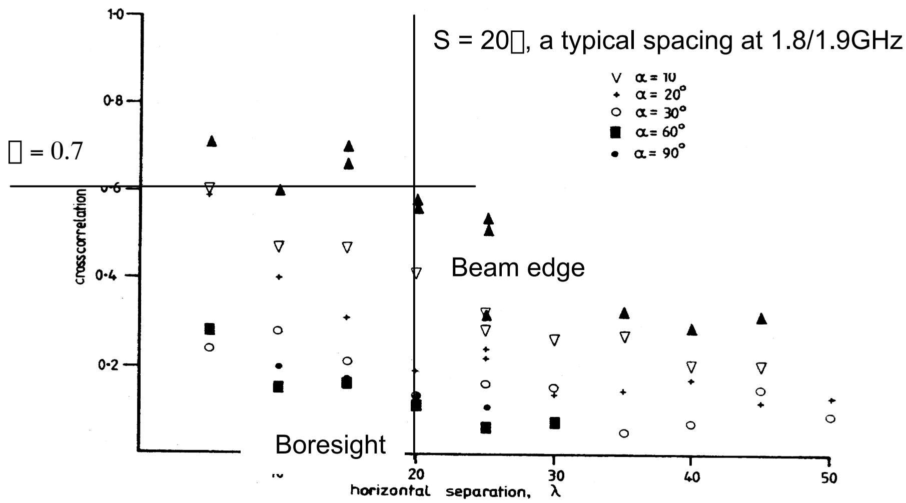

Figure 7: Relationship between correlation, antenna spacing and relative bearing for space diversity.

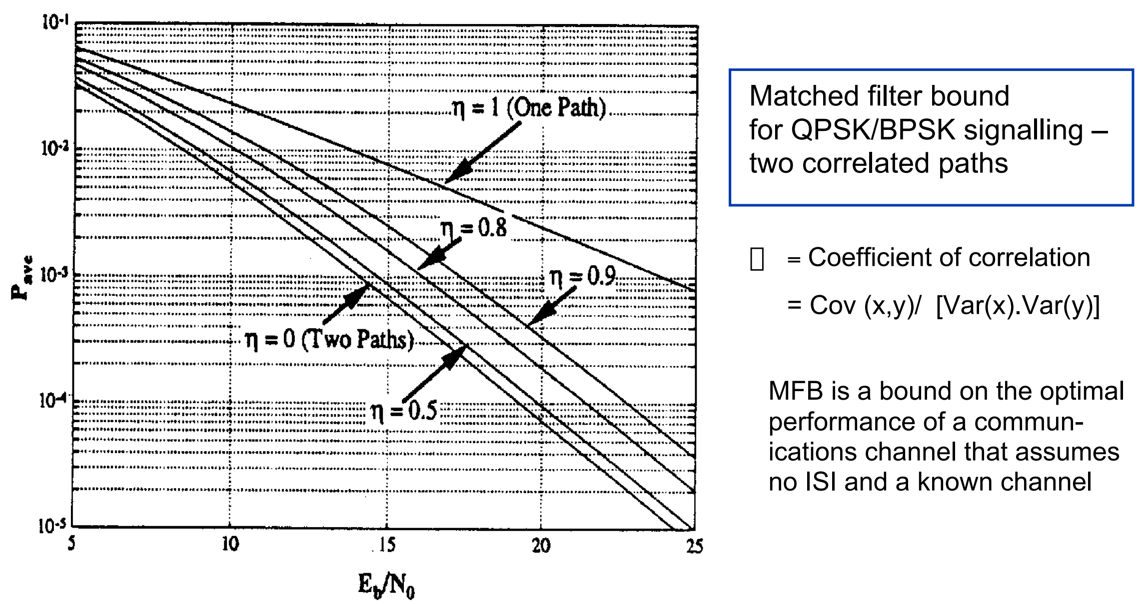

Figure 8: The effect of correlation between branches on the diversity gain of a 2-branch diversity system (Ling, 1995)

Firstly, the diversity gain of a space-diversity system also falls off at ± 60°, as the lateral spacing between the antennas is reduced when viewed obliquely. Spacing along the line of the transmission path is less effective than transverse spacing across the path. These effects are shown in Figure 7. Figure 8 indicates the signal power and corresponding Eb/No (the effective Signal/Noise ratio in a digital system). The upper curve indicates the performance of a system in which both channels receive the same signal, ie the correlation between the two paths (ρ) is 1.0. The bottom curve shows the performance of a two-branch system where the signals in the two channels are completely uncorrelated ($\rho = 0$). What is of great significance is that as the correlation between the two branches is allowed to rise, the performance of the system degrades only slowly, so for $\rho = 0.5$ only a very small reduction in performance has occurred relative to the ideal situation. In general it is taken that a correlation coefficient of 0.7 is acceptable for most practical systems, as the difference between 0.7 and 0 is very small.

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