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Diversity is a good thing

Combining multiple receiver antennas improves performance in multipath fading

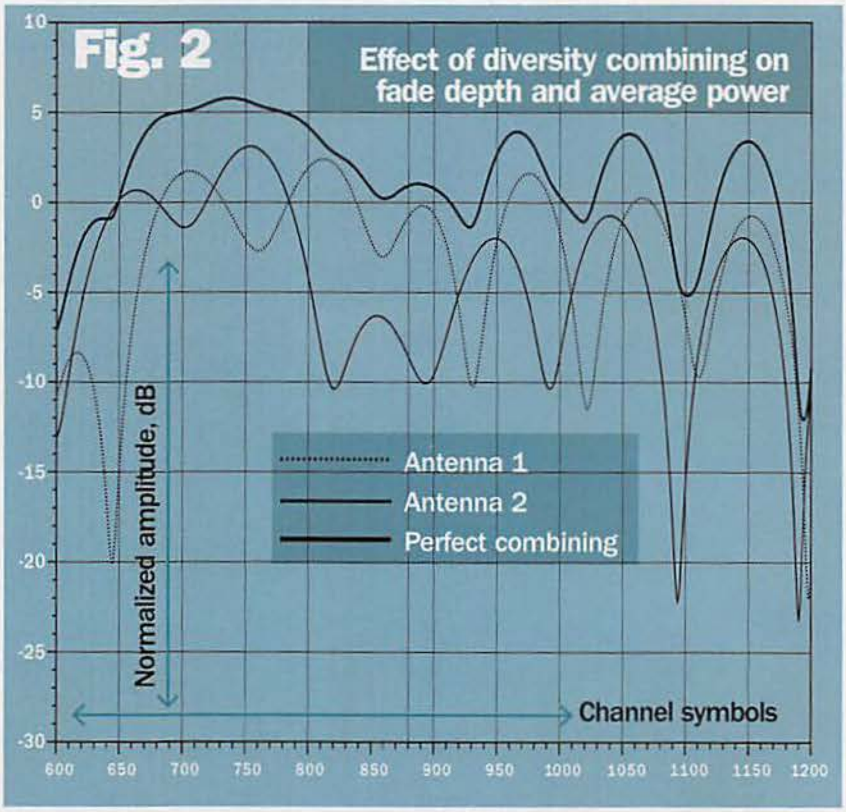
Antenna diversity is a method for combining multiple, independent, fading signals in a diversity receiver. It is a powerful technique for improving receiver performance in the presence of multipath fading. Interestingly, antenna diversity is used almost universally at cellular sites, but it is rarely used in public-safety or private land mobile radio systems.

At a high level, the advantage of antenna diversity is simple—two signals are better than one. Figure 1 illustrates this basic concept.

In theory, diversity receivers can combine signals from any number of antennas, but in practice, it is rare to combine more than two antennas. At a minimum, two antennas combined optimally will double the average received power and provide a 3 dB improvement in link performance. But if the signals from each antenna are independent and arrive via a Rayleigh fading channel, the potential improvement is much greater than 3 dB, as we will demonstrate shortly [1].

Fig. 2

Effect of diversity combining on fade depth and average power



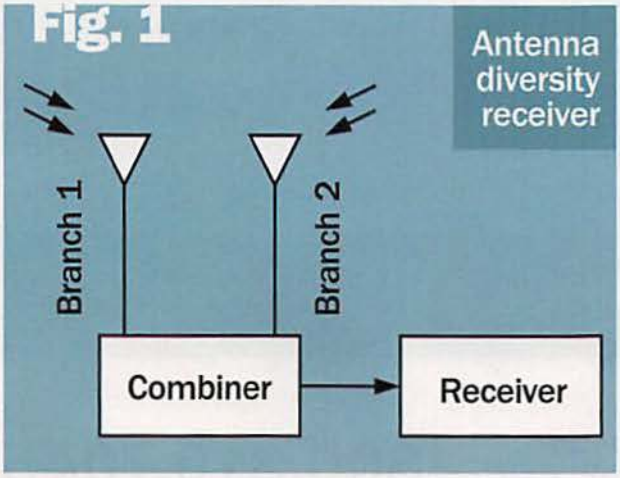
There are two popular types of antenna diversity for mobile radio channels:

- Space diversity.
- Polarization diversity.

In each case, the objective is to capture multiple independent (or nearly independent) signals and combine them in an optimal manner. With space diversity, antennas are separated by some horizontal or vertical distance that is sufficient to de-correlate arriving signals. Point-to-point microwave links often use vertical separation, but early experiments on LMR channels showed that horizontal separation was more effective because of the nature of scattering on the mobile radio channel [1]. Space diversity has been used on mobile radio channels since at least the 1970s.

Fig. 1

Antenna diversity receiver



A signal that originally was transmitted with a fixed polarization (usually vertical) does not arrive at the receiver with the same polarization because objects in the path reflect and diffract (bend) the signal and cause the polarization to rotate. In fact, energy at the receiver is spread unequally over many polarization angles from vertical to horizontal.

Polarization diversity, a relative newcomer, exploits this phenomenon of polarization rotation. It is common in the cellular radio industry to employ 45° "slant" polarization, using two antenna arrays in one radome with the antenna elements orthogonal to each other and at a 45° angle to vertical. One of the advantages of polarization diversity is that it limits the number of required antenna assemblies, reducing the wind load on the tower and making zoning approval more likely.

There also are two popular methods for combining the outputs of diversity antennas:

- Switched combining.
- Maximal ratio combining.

Combining is a misnomer for switching combiners because only one branch is selected at a time. A switching combiner samples each antenna output and selects the path with the best signal, usually the one with the greatest amplitude, but signal-to-noise ratio and other metrics also are used. Switching combiners improve the signal quality in multipath fading, but they are not optimal.

In contrast, maximal ratio combining performs an optimal weighting of the individual signals and combines all diversity signals into one output. It is the optimal form of combining [1].

Despite the advantages of maximal ratio combining, switched combining is still very popular, especially with time division duplexed (TDD) antenna systems that transmit and receive on the same frequency and on the same antenna, but at different time slots. TDD combiner systems attempt to pick the optimal antenna for receiving and transmitting.

Diversity antenna systems are most effective in the presence of multipath fading. By selecting the best antenna signal (switched combiner) or combining the antenna outputs (maximal ratio combining), the net effect is to reduce the depth of fades. This effect is shown in Figure 2, where we have plotted two independent Rayleigh fading channels and their combined output, assuming maximal ratio combining.

We now know that diversity combining reduces the fade depth on a Rayleigh fading channel and can increase the average power by a factor proportional to the number of diversity antennas. But we also want to know how this improvement is put to use in the receiver and exactly how much improvement should be expected in a modern digital radio.

Using the Rayleigh fading channel model, we can derive expressions for error probability for the non-diversity and two-branch diversity cases. We'll assume binary frequency shift keying (FSK), and note that the derivations for C4FM and CQPSK, the Project 25 modulation techniques, are similar.

On the static Gaussian noise channel, the probability of bit error for binary FSK is given by Equation 1 [2, pp. 717].

One can show that on a Rayleigh fading channel, E_b/N_0 is exponentially distributed. If we calculate the mean bit-error rate over the exponential probability density function, we get the probability of bit error shown in Equation 2 [2, pp. 717].

Note from Equation 2 that instead of decreasing exponentially with signal-to-noise ratio, now the error rate decreases only inversely with signal-to-noise ratio. Consequently, the required E_b/N_0 at a bit-error rate of 10^{-5} is 37 dB higher in Rayleigh fading (Figure 3 on page 69). So we incur a tremendous power penalty simply by operating in a fading environment.

The obvious way to recover this lost performance is to increase the transmitter power, but increasing the power of a battery-operated radio by 37 dB is far from practical—a 3 W radio would turn into a 15,000 W radio. Diversity is a more practical technique. The probability of bit error for an L-branch diversity combiner with FSK modulation is found in many textbooks [2, pp. 723-726].

An important principle is that the probability of bit error for an L-branch diversity system decreases as the inverse of the signal-to-noise ratio raised to the Lth power. For example, for $L=2$ branch diversity, the probability of bit error decreases according to the inverse squared signal-to-noise ratio. This behavior is shown in Figure 3, where we have plotted the probability of bit error for a two-branch FSK diversity receiver.

Note from Figure 3 the large improvement in required E_b/N_0 for a bit error rate of 10^{-5}. However, we are still 17.3 dB shy of non-fading performance. More diversity antennas would help, but most systems stop at two antennas for cost reasons and try to make up the difference with forward error correction and interleaving.

Diversity systems normally operate

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Equation 1

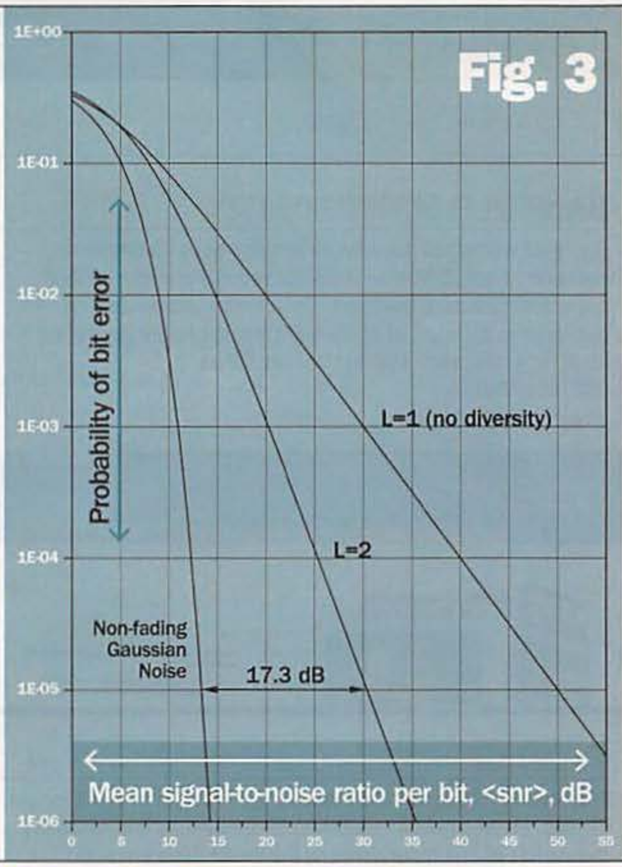
Probability of bit error (FSK) = 1/2exp(-snr/2)

where *snr* is the ratio of energy per bit to noise power spectral density, also denoted by E_b/N_0.

Equation 2

Mean probability of bit error in Rayleigh fading (FSK) = 1/(2 + <snr>)

where <*snr*> is the mean value of E_b/N_0 in Rayleigh fading.



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from the cellular base station or, in rare cases, from the two-way radio repeater site. Diversity also works at the mobile receiver. Smaller antenna separations are required for space diversity at the mobile receiver because the scatterers are relatively close to the receiver. Mobile diversity antenna systems are not common today for cost and space reasons, but several companies are working on mobile diversity systems, and IEEE 802.11 radios may be the first to use them widely. ■

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[1] W.C. Jakes, ed., Microwave Mobile Communications, IEEE Press Reissue, 1994.

[2] J.G. Proakis, Digital Communications, 2nd edition, New York: John Wiley & Sons, 1989.