Diversity

Introduction

Multipath propagation causes fading which in turn can cause errors in the received data. Digital communication system use checksums to check for errors and usually require that each frame of data be received without errors before any of it can be used.

Frame repetition protocols such automatic repeat request (ARQ) can be used to retransmit the data until it is received correctly. However, ARQ is often ineffective over fading channels because it can take a relatively long time for the fading conditions to change. ARQ retransmissions also reduce the efficiency of the system. Therefore wireless systems often use additional techniques to reduce the effects of multipath fading. One of the most effective techniques is diversity.

The signal level due to multipath fading is a function of position, frequency, and (if the paths are time-varying) time. Diversity reception makes use of multiple independently[1]-fading signal sources to mitigate the effects of fading.

For example, if the signal at one location is faded, at another position a fraction of a wavelength away it may be unfaded.

Diversity techniques differ in the ways of obtaining independently-fading signal sources (called "branches"). The branches can come from different:

- locations (space diversity)
- frequencies (frequency diversity)
- times (time diversity)
- antenna polarizations (polarization diversity)

Exercise 1: Which of these might lead to a reduction in system efficiency by requiring more time or bandwidth? Which of these would require additional or more complex antennas?

Diversity techniques also differ in how the different branches are combined. The different branches can be used by:

- selecting the best branch (selection diversity)
- combining the branches (combining diversity)
- switching between the branches (switching diversity)

and each of these can be done in different ways. The various techniques are described below.

Diversity Sources

Space Diversity

In this case the branches are antennas separated in space. This diversity technique is is used in nearly all cellular base stations by utilizing 2 or 3 receive antennas per sector:

Space diversity is also used by many point-to-point microwave links by placing two antennas separated vertically on the same tower.

The fading is less correlated as the separation between antennas increases. The fading also becomes less correlated as the scattering objects get closer to the receiving antenna. For mobile stations a separation of a fraction of a wavelength is sufficient because the scattering objects are typically nearby. For base stations, which are typically located on top of tall towers, the separation has to be ten or more wavelengths for space diversity to be effective. Space diversity is less effective in handsets because of limited space, although it is common in larger form factor devices such as tablets and laptops.

Exercise 2: What spacing is required for 10λ separation at 900 MHz?

[1] Ideally independent. The degree of correlation between the paths can vary.

Polarization Diversity

Radio wave polarization is given by the direction of the E-field. Polarization of the signal changes when it is reflected or diffracted. We can thus use multiple antennas that are sensitive to different polarizations to obtain independently-fading diversity branches. We can use vertical and horizontal or different circular (left- or right-hand) polarizations. The advantage of polarization diversity is that we don't need spatial separation between antennas.

Frequency Diversity

separated by more than the coherence bandwidth then the fading on the different frequencies will be uncorrelated. The disadvantage is that the bandwidth required grows linearly with the number of diversity branches. For this reason frequency diversity is not often used, although many wireless systems combine FEC coding with multi-carrier or spread-spectrum techniques that use bandwidths larger than the coherence bandwidth and thus obtain the advantages of frequency diversity.

Exercise 3: What time difference results from a path length difference of d m? If the frequency is f, What is the resulting phase difference? What difference in f is required for two equal-gain paths to cancel each other? How far apart would the frequency nulls be for a channel with two equal-gain paths with path lengths that differ by 300m? By 30m? What time delay differences does this correspond to?

Time Diversity

If we transmit the same signal multiple times with intervals separated by at least the time between fades we can then use these transmissions as separate diversity branches. As with frequency diversity this reduces the capacity of the channel so it is not commonly used. However, when a frame needs to be retransmitted a technique called hybrid ARQ can be used to combine the different transmissions. This can provide most of the advantages of time diversity.

Exercise 4: Would time diversity be more or less effective as the receiver's speed increased? What would happen if the receiver was stopped (such as a traffic light)?

Transmit Diversity

It is possible to obtain the advantages of space diversity with a single receive antenna (as on a handset) by using a technique called space-time coding. Two base station antennas transmit the same information at two time intervals with different phases on the two antennas and times. This does not reduce the bandwidth efficiency of the system. However, the two transmissions at two times represent a set of linear equations that can be solved by the receiver to separate the signals from the two antennas. This achieves space diversity with a single receive antenna.

Diversity Combining Techniques

Maximal-Ratio Combining Diversity

This is the optimum way of using multiple branches. We phase-shift the signals from the branches so the received signals have the same phase and weight them according to their signal voltage to noise power ratios. The result is that the output SNR is the sum of the branch SNRs since the signals add coherently (voltage addition) but the noise signals are uncorrelated and their powers add. Maximal-ratio combining also requires one receiver per branch but has better performance than selection diversity.

Exercise 5: Assuming maximal-ratio combining, what would be the resulting SNR if the branch SNRs were $+10$ dB and $+20$ dB? If they were both $+10$ dB?

Selection Diversity

Selection diversity is conceptually simple: at any given time the receiver chooses the branch with the best signal. For digital modulation if the probability that one branch is "faded" (for some definition of "faded") is p, and the fading on the different branches is independent, then the probability that all M branches are faded is p^M and the probability that not all branches are faded is $1-p^M$. The disadvantage of of selection diversity is that one receiver is required per branch.

Exercise 6: Assuming independent Rayleigh fading, the same SNRs as in the previous exercise and that the signal is considered "faded" if the SNR is below 0 dB, what fraction of time would be signal be faded with and without two-branch selection diversity?

Switching ("Scanning") Diversity

Maximal-ratio and selection diversity require one complete receiver per branch (and for maximal-ratio also an adaptive co-phasing and combining processor).

A simpler approach, "switching" diversity, uses a switch to connect the various branches to one receiver in sequence. The receiver waits until the signal fades below a certain threshold, then switches to the next branch. This approach is much less expensive: only an RF antenna switch is required.

Exercise 7: What type of diversity would you expect to be implemented in an (inexpensive) WLAN card? In a cellular base station?