Diversity and Coding

Introduction

- multipath propagation causes fading
- fading causes poor signal quality or bit errors on systems using digital modulation
- digital systems use checksums and require the complete frame to be error-free or none of it can be used
- frame repetition protocols (ARQ) often not feasible due to delay constraints
- wireless systems need to use one or more techniques to reduce the effects of multipath
- the two most effective techniques are diversity and channel (“forward-error correction”, FEC) coding

6.10 ## Diversity

- the signal level/phase 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-fading 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
- there are many ways of getting independently-fading sources:
- different locations (space diversity)
- different frequencies (time diversity)
- different antenna polarizations (polarization diversity)
- different time (repetition or RAKE receiver)
- by using receivers at multiple locations (space diversity) or transmitting the same message multiple time (time diversity) can reduce probability of fading
- diversity methods differ in:
- how the branches are separated (in space, polarization, time, etc)
- how the branches are combined (selection, maximal-ratio, switching, etc.)
- many combinations are possible, a few a practical

Selection Diversity 6.10.1

- assume we have M receivers each connected to a different sources, *M branches*
- assume signal received on each branch fades independently
- if we are able to select the receiver with the strongest signal, then
- for analog signals the quantity of interest might be the SNR improvement in average SNR:

$$\frac{\bar{\gamma}}{\Gamma} = \sum_{k=1}^{M} \frac{1}{k}$$

- for a digital system, we may be more interested in the probability that the signal falls below a threshold
- if the probability that one branch is “faded” is p, and the fading of 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 $1 - p^M$

Maximal-Ratio Combining Diversity

- optimum way of using multiple branches:
- 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 output SNR is the sum of the branch SNRs
- circuitry to provide maximal-ratio combining is complicated, so it's not often used

Switching ("Scanning") Diversity

6.10.3.2

- maximal-ratio and selection diversity require one complete receiver per branch and (for maximal-ratio) an adaptive co-phasing and combining processor (expensive)
- another approach, "switching" diversity, is to use an switch to connect various branches to the receiver
- the receiver waits until signal fades, then switches to next branch
- much cheaper: only need an RF antenna switch and some logic

Space Diversity

- branches are two or more antennas separated in space
- used in cellular systems in almost all base stations (2 or 3 antennas per sector)
- also used by most microwave point-to-point links (two antennas space vertically on same tower)
- location of scatterers is closer at mobile, need to move less (fraction of λ) to get uncorrelated fading
- at base, scatterers are further away, need larger
6.10.2 separation (10s of λ) for uncorrelated fading
- seldom used in mobiles due to cost, limited space

Polarization Diversity 6.10.4

- radio wave polarization given by direction of E-field
- polarization of the signal can change when it reflects
- can use antennas sensitive to different polarizations
- can make use of horizontal, vertical, or circular (left- and right-hand) polarizations
- may see uncorrelated fading on the different antennas
- the advantage is that don't need any spatial separation between antennas

Frequency Diversity 6.10.5

- if the same information is transmitted on frequencies separated by more than coherence bandwidth, the fading on the different antennas will be reasonably independent
- problem is that each diversity path (frequency) increases the bandwidth required
- not commonly used

Time Diversity 6.10.6

- if transmit same signal multiple times with interval separated by the coherence time of the channel then can combine these transmissions
- as with frequency diversity, this uses additional "bandwidth" and so is not commonly used

RAKE Receiver Diversity 6.11

- in DS-SS systems the chip duration may be shorter than the coherence time and a special receiver structure, the RAKE receiver, combines signals received with different delays and so provides diversity

Transmitter Diversity

- a recent development is a technique called transmitter diversity or “space-time” coding
- information is encoded into two or more symbols that are transmitted from two or more antennas
- the receiver combines the received symbols to estimate the original information

6.13 FEC Coding

- an encoder at the transmitter adds redundancy to transmitted data
- a decoder at the receiver uses this redundancy to detect and/or correct for possible errors in the received data
- two main types: block codes and convolutional codes
- a block code independently encodes each a block of k bits into a block of n bits
- a convolutional coder encodes every k bits into n bits, but the encoding depends on the previous input to the encoder. Typically k and n are small (e.g. k=1, n=2)

6.14 Definitions

- rate: ratio k/n
- distance: difference between two code words (number of bits that differ)
- systematic: the information bits are transmitted uncoded followed by additional parity bits

Commonly Used Block FEC Codes 6.14.1

- Hamming Codes

$$(n,k) = (2^m - 1, 2^m - 1 - m)$$

  for example, when m=3 n,k are 7,4

- BCH codes
- large family of codes
- block size $n = 2^m - 1$
- can correct up to $t < (2^m - 1)/2$ symbol errors
- can use non-binary m-bit symbols
- an example of a BCH code is a Reed-Solomon code (e.g. m=6, so n=63 6-bit symbols)
- correct errored symbols (any number of bits within the symbol may be in error) so they are called “burst error correcting” codes and are popular for radio applications
- convolutional codes use a state machine to generate the output symbols as a function of the input and the encoder state
- convolutional code decoder typically uses maximum-likelyhood solution that considers all possible transmitted sequences and chooses the one with smallest distance to received signal
- can make use of finite memory of the encoder to reduce complexity of the search for the ML sequence
- the algorithm that does this is the Viterbi algorithm
- concatenated codes use two encoders operating in tandem (series)
- called the inner and outer codes
- usually provide better performance than one code of the same net rate

- for example, errors from one decoder may be bursty, so a burst-error-correcting decoder is used after it
- "turbo" codes use two convolutional encoders separated by a "random" interleaver. with large-enough interleavers can operate very close to Shannon bound for AWGN (fraction of a dB)

6.12 Interleaving

- some types of FEC codes are only able to correct one error per block of bits
- errors causes by fading are usually bursty (duration of fade is inversely proportional to f_D) and many bits in a word will be affected
- by interleaving the bits before and after sending it through the channel, the locations of the bit errors can be randomized and performance of decoder improved
- a block interleaver uses a buffer arranged as a rectangular array
- bits are read into the array row-wise and read out column-wise
- this ensures a minimum separation between adjacent bits sent over the channel equal to the width or height of the array
- interleaving introduces delay

Combination of Methods

- frame error rate is important measure
- switching diversity may introduce errors during switching
- interleaving randomizes errors
- FEC is required corrects a few errors
- retransmission protocols such as ARQ often ineffective due to long-duration fades
- need to use physical-layer methods (diversity, FEC)
- a combination of methods usually required
- evaluation of the best combination of techniques is usually through simulation