Fading in the Mobile Environment

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Outline I

Fading in the Mobile Environment I

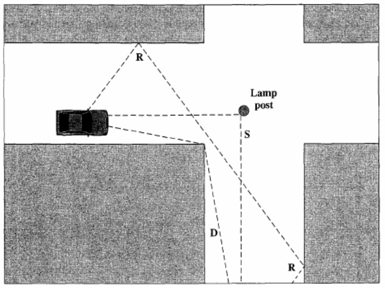
- Perhaps the most challenging technical problem facing communications systems engineers is fading in a mobile environment.
- The term fading refers to the time variation of received signal power caused by changes in the transmission medium or path(s).
- In a fixed environment, fading is affected by changes in atmospheric conditions, such as rainfall.
- But in a mobile environment, where one of the two antennas is moving relative to the other, the relative location of various obstacles changes over time, creating complex transmission effects.

Multipath Propagation I

- Reflection occurs when an electromagnetic signal encounters a surface that is large relative to the wavelength of the signal.
- For example, suppose a ground-reflected wave near the mobile unit is received. Because the ground-reflected wave has a 180^0 phase shift after reflection, the ground wave and the *LOS* wave may tend to cancel, resulting in high signalloss.
- Further, because the mobile antenna is lower than most human-made structures in the area, multipath interference occurs.
- These reflected waves may interfere constructively or destructively at the receiver.

Multipath Propagation II

Sketch of Three Important Propagation Mechanisms: *Reflection* (*R*), *Scattering* (*S*), *Diffraction* (*D*)



Multipath Propagation III

- Diffraction occurs at the edge of an impenetrable body that is large compared to the wavelength of the radio wave. When a radio wave encounters such an edge, waves propagate in different directions with the edge as the source.
- Thus, signals can be received even when there is no unobstructed *LOS* from the transmitter.
- If the size of an obstacle is on the order of the wavelength of the signal or less, scattering occurs.
- An incoming signal is scattered into several weaker outgoing signals.
- At typical cellular microwave frequencies, there are numerous objects, such as lamp posts and traffic signs, that can cause scattering.
- Thus, scattering effects are difficult to predict.

Multipath Propagation IV

- These three propagation effects influence system performance in various ways depending on local conditions and as the mobile unit moves within a cell
- If a mobile unit has a clear *LOS* to the transmitter, then diffraction and scattering are generally minor effects, although reflection may have a significant impact.
- If there is no clear *LOS*, such as in an urban area at street level, then diffraction and scattering are the primary means of signal reception.

The Effects of Multipath Propagation I

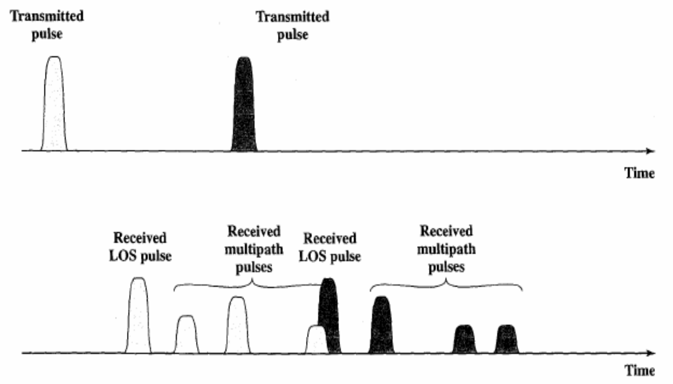
- As just noted, one unwanted effect of multipath propagation is that multiple copies of a signal may arrive at different phases.
- If these phases add destructively, the signal level relative to noise declines, making signal detection at the receiver more difficult.
- A second phenomenon, of particular importance for digital transmission, is *InterSymbol Interference* (*ISI*).
- Consider that we are sending a narrow pulse at a given frequency across a link between a fixed antenna and a mobile unit.
- The channel may deliver to the receiver if the impulse is sent at two different times.
- The upper line shows two pulses at the time of transmission.
- The lower line shows the resulting pulses at the receiver.

The Effects of Multipath Propagation II

- In each case the first received pulse is the desired *LOS* signal The magnitude of that pulse may change because of changes in atmospheric attenuation.
- Further, as the mobile unit moves farther away from the fixed antenna, the amount of *LOS* attenuation increases.

The Effects of Multipath Propagation III

Two Pulses in Time-Variant Multipath



The Effects of Multipath Propagation IV

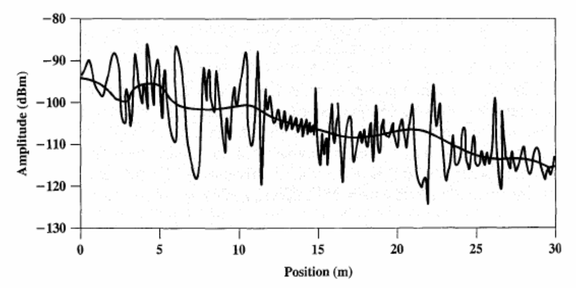
- But in addition to this primary pulse, there may be multiple secondary pulses due to reflection, diffraction, and scattering.
- Now suppose that this pulse encodes one or more bits of data.
- In that case, one or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit.
- These delayed pulses act as a form of noise to the subsequent primary pulse, making recovery of the bit information more difficult.
- As the mobile antenna moves, the location of various obstacles changes; hence the number, magnitude, and timing of the secondary pulses change.
- This makes it difficult to design signal processing techniques that will filter out multipath effects so that the intended signal is recovered with fidelity.

Types of Fading I

- Fading effects in a mobile environment can be classified as either fast or slow.
- The mobile unit moves down a street in an urban environment, rapid variations in signal strength occur over distances of about one-half a wavelength.
- At a frequency of 900 MHz, which is typical for mobile cellular applications, a wavelength is 0.33 m.

Types of Fading II

Typical Slow and Fast Fading in an Urban Mobile Environment



Types of Fading III

- The rapidly changing waveform in Figure shows an example of the spatial variation of received signal amplitude at 900 *MHz* in an urban setting.
- Note that changes of amplitude can be as much as 20 or 30 *dB* over a short distance.
- This type of rapidly changing fading phenomenon, known as fast fading, affects not only mobile phones in automobiles, but even a mobile phone user walking down an urban street.
- As the mobile user covers distances well in excess of a wavelength, the urban environment changes, as the user passes buildings of different heights, vacant lots, intersections, and so forth.
- Over these longer distances, there is a change in the average received power level about which the rapid fluctuations occur.

Types of Fading IV

- This is indicated by the slowly changing waveform in Figure and is referred to as slow fading.
- Fading effects can also be classified as flat or selective.
- Flat fading, or nonselective fading, is that type of fading in which all frequency components of the received signal fluctuate in the same proportions simultaneously.
- Selective fading affects unequally the different spectral components of a radio signal.
- The term selective fading is usually significant only relative to the bandwidth of the overall communications channel.
- If attenuation occurs over a portion of the bandwidth of the signal, the fading is considered to be selective; nonselective fading implies that the signal bandwidth of interest is narrower than, and completely covered by, the spectrum affected by the fading.

The Fading Channel I

- In designing a communications system, the communications engineer needs to estimate the effects of multipath fading and noise on the mobile channel.
- The simplest channel model, from the point of view of analysis, is the *Additive White Gaussian Noise* (*AWGN*) channel.
- In this channel, the desired signal is degraded by thermal noise associated with the physical channel itself as well as electronics at the transmitter and receiver (and any intermediate amplifiers or repeaters).
- This model is fairly accurate in some cases, such as space communications and some wire transmissions, such as coaxial cable.
- For terrestrial wireless transmission, particularly in the mobile situation, *AWGN* is not a good guide for the designer.

The Fading Channel II

Rayleigh fading -

- Rayleigh fading occurs when there are multiple indirect paths between transmitter and receiver and no distinct dominant path, such as an LOS path.
- This represents a worst case scenario.
- Fortunately, Rayleigh fading can be dealt with analytically, providing insights into performance characteristics that can be used in difficult environments, such as downtown urban settings.

The Fading Channel III

Rician fading -

- Rician fading best characterizes a situation where there is a direct LOS path in addition to a number of indirect multipath signals.
- The Rician model is often applicable in an indoor environment whereas the Rayleigh model characterizes outdoor settings.
- The Rician model also becomes more applicable in smaller cells or in more open outdoor environments.

The Fading Channel IV

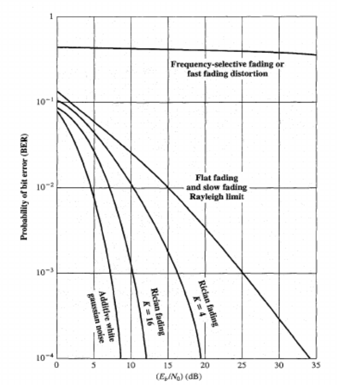
- The channels can be characterized by a parameter K, defined as follows:

$$K = \frac{\textit{power in the dominant path}}{\textit{power in the scattered paths}} \quad (1)$$

when, $K = 0$ the channel is *Rayleigh* (i.e., numerator is zero) and when, $K = \infty$, the channel is *AWGN* (i.e., denominator is zero).

The Fading Channel V

Theoretical Bit Error Rate for Various Fading Conditions



The Fading Channel VI

- Figure shows system performance in the presence of noise.
- Here bit error rate is plotted as a function of the ratio E_b/N_o.
- Of course, as that ratio increases, the bit error rate drops.
- The Figure shows that with a reasonably strong signal, relative to noise, an *AWGN* exhibit provides fairly good performance, as do *Rician* channels with larger values of K, roughly corresponding to microcells or an open country environment.
- The performance would be adequate for a digitized voice application, but for digital data transfer efforts to compensate would be needed.
- The *Rayleigh* channel provides relatively poor performance; this is likely to be seen for flat fading and for slow fading; in these cases, error compensation mechanisms become more desirable.

The Fading Channel VII

- Finally, some environments produce fading effects worse than the so-called worst case of *Rayleigh*.
- Examples are fast fading in an urban environment and the fading within the affected band of a selective fading channel.
- In these cases, no level of E_b/N_o will help achieve the desired performance, and compensation mechanisms are mandatory.

Error Compensation Mechanisms I

- The efforts to compensate for the errors and distortions introduced by multipath fading fall into three general categories:
    1. forward error correction,
    2. adaptive equalization, and
    3. diversity techniques.
- In the typical mobile wireless environment, techniques from all three categories are combined to combat the error rates encountered.

Forward Error Correction I

- Forward error correction is applicable in digital transmission applications, those in which the transmitted signal carries digital data or digitized voice or video data.
- The term forward refers to procedures whereby a receiver, using only information contained in the incoming digital transmission, corrects bit errors in the data.
- This is in contrast to backward error correction, in which the receiver merely detects the presence of errors and then sends a request back to the transmitter to retransmit the data in error.
- Backward error correction is not practical in many wireless applications.
- For example, in satellite communications, the amount of delay involved makes retransmission undesirable.

Forward Error Correction II

- In Mobile communications, the error rates are often so high that there is a high probabibly that the retransmitted block of bits will also contain errors.
- In these applications, forward error correction is required.
- In essence, forward error correction is achieved as follows:
  1. Using a coding algorithm, the transmitter adds a number 0 additional, redundant bits to each transmitted block of data. These bits form an error-correcting code and are calculated as a function of the data bits.
  2. For each incoming block of bits (data plus error-correcting code), the receiver calculates a new error-correcting code from the incoming data bits. If the calculated code matches the incoming code, then the receiver assumes that no error has occurred in this block of bits.

Forward Error Correction III

3. If the incoming and calculated codes do not match, then one or more bits are in error. If the number of bit errors is below a threshold that depends on the length of the code and the nature of the algorithm, it is possible for the receiver to determine the bit positions in error and correct all errors.

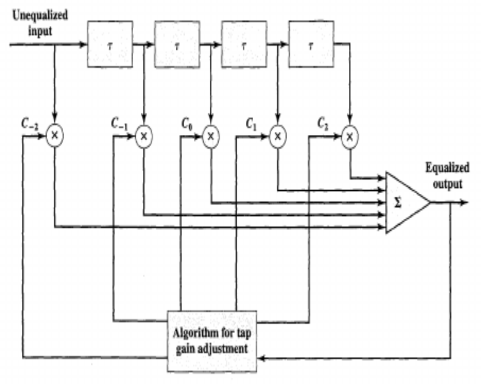
- Typically in mobile wireless applications, the ratio of total bits sent to data bits sent is between 2 and 3.
- This may seem an extravagant amount of overhead, in that the capacity of the system is cut to one-half or one-third of its potential, but the mobile wireless environment is so difficult that such levels of redundancy are necessary.

Adaptive Equalization I

- Adaptive equalization can be applied to transmissions that carry analog information (e.g., analog voice or video) or digital information (e.g., digital data, digitized voice or video) and is used to combat intersymbol interference.
- The process of equalization involves some method of gathering the dispersed symbol energy back together into its original time interval.
- Equalization is a broad topic; techniques include the use of so-called lumped analog circuits as well as sophisticated digital signal processing algorithms.
- Here we give a flavor of the digital signal processing approach.

Adaptive Equalization II

Linear Equalizer Circuit



Adaptive Equalization III

- Figure illustrates a common approach using a linear equalizer circuit.
- In this specific example, for each output symbol, the input signal is sampled at five uniformly spaced intervals of time, separated by a delay τ.
- These samples are individually weighted by the coefficients C_i and then summed to produce the output.
- The circuit is referred to as adaptive because the coefficients are dynamically adjusted.
- Typically, the coefficients are set using a training sequence, which is a known sequence of bits.
- The training sequence is transmitted.

Adaptive Equalization IV

- The receiver compares the received training sequence with the expected training sequence and on the bas of the comparison calculates suitable values for the coefficients.
- Periodically, a new raining sequence is sent to account for changes in the transmission environment.
- For Rayleigh channels, or worse, it may be necessary to include a new training sequence with every single block of data.
- Again, this represents considerable overhead but is justified by the error rates encountered in a mobile wireless environment.

Diversity Techniques I

- Diversity is based on the fact that individual channels experience independent fading events.
- We can therefore compensate for error effects by providing multiple logical channels in some sense between transmitter and receiver and sending part of the signal over each channel.
- This technique does not eliminate errors but it does reduce the error rate, since we have spread the transmission out to avoid being subjected to the highest error rate that might occur.
- The other techniques (equalization, forward error correction) can then cope with the reduced error rate.
- Some diversity techniques involve the physical transmission path and are referred to as space diversity.

Diversity Techniques II

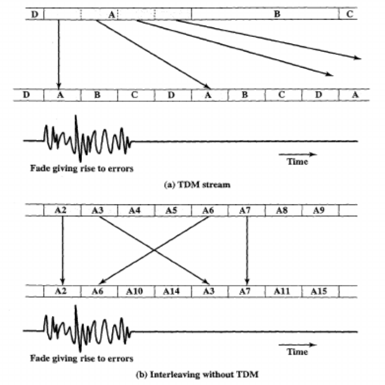
- For example, multiple nearby antennas may be used to receive the message, with the signals combined in some fashion to reconstruct the most likely transmitted signal.
- Another example is the use of collocated multiple directional antennas, each oriented to a different reception angle with the incoming signals again combined to reconstitute the transmitted signal.
- More commonly, the term diversity refers to frequency diversity or time diversity techniques.
- With frequency diversity, the signal is spread out over a larger frequency bandwidth or carried on multiple frequency carriers (spread spectrum).
- Time diversity techniques aim to spread the data out over time so that a noise burst affects fewer bits.

Diversity Techniques III

- Time diversity can be quite effective in a region of slow fading.
- If a mobile unit is moving slowly, it may remain in a region of a high level of fading for a relatively long interval.
- The result will be a long burst of errors even though the local mean signal level is much higher than the interference.
- Even powerful error correction codes may be unable to cope with an extended error burst.
- If digital data is transmitted in a *Time Division Multiplex* (*TDM*) structure, in which multiple users share the same physical channel by the use of time slots, then block interleaving can be used to provide time diversity.
- Figure illustrates the concept.

Diversity Techniques IV

Interleaving Data Blocks to Spread the Effects of Error Bursts



Diversity Techniques V

- Note that the same number of bits are still affected by the noise surge, but they are spread out over a number of logical channels.
- If each channel is protected by forward error correction, the error-correcting code may be able to cope with the fewer number of bits that are in error in a particular logical channel.
- If *TDM* is not used, time diversity can still be applied by viewing the stream of bits from the source as a sequence of blocks and then shuffling the blocks.
- In Figure, blocks are shuffled in groups of four.
- Again, the same number of bits is in error, but the error correcting code is applied to sets of bits that are spread out in time.
- Even greater diversity is achieved by combining *TDM* interleaving with block shuffling.

Diversity Techniques VI

- The tradeoff with time diversity is delay.
- The greater the degree of interleaving and shuffling used, the longer the delay in reconstructing the original bit sequence at the receiver.