Chapter: Small Scale Fading & Multipath concept & detail.

More detail of some topics from:

Wireless Communications (Rappaport)

Wireless Communications & Networks (william stallings)

Wireless Communications & Networking (JonW.Mark)

Internet & Other materials

Note: Calculations & Numerical details are attached on separate sheets

5.1 Multipath Propagation

In wireless telecommunications, multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths. Causes of multipath include atmospheric ducting, ionospheric reflection and refraction, and reflection from water bodies and terrestrial objects such as mountains and buildings. The effects of multipath include constructive and destructive interference, and phase shifting of the signal. In digital radio communications (such as GSM) multipath can cause errors and affect the quality of communications. We discuss all the related issues in this chapter.

5.2 Multipath & Small-Scale Fading

Multipath signals are received in a terrestrial environment, i.e., where different forms of propagation are present and the signals arrive at the receiver from transmitter via a variety of paths. Therefore there would be multipath interference, causing multipath fading. Adding the effect of movement of either Tx or Rx or the surrounding clutter to it, the received overall signal amplitude or phase changes over a small amount of time. Mainly this causes the fading.

5.2.1 Fading

The term fading, or, small-scale fading, means **rapid fluctuations of the amplitudes, phases, or multipath delays of a radio signal over a short period or short travel distance**. This might be so severe that large scale radio propagation loss effects might be ignored.

5.2.2 Multipath Fading Effects

In principle, the following are the main multipath effects:
1. Rapid changes in signal strength over a small travel distance or time interval.
2. Random frequency modulation due to varying Doppler shifts on different multipath signals.
3. Time dispersion or echoes caused by multipath propagation delays.

5.2.3 Factors Influencing Fading

The following physical factors influence small-scale fading in the radio propagation channel:
(1) Multipath propagation – Multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths.
The effects of multipath include constructive and destructive interference, and phase shifting of the signal.
(2) Speed of the mobile – The relative motion between the base station and the

mobile results in random frequency modulation due to different doppler shifts on each of the multipath components.

(3) Speed of surrounding objects – If objects in the radio channel are in motion, they induce a time varying Doppler shift on multipath components. If the surrounding objects move at a greater rate than the mobile, then this effect dominates fading.

(4) Transmission Bandwidth of the signal – If the transmitted radio signal bandwidth is greater than the "bandwidth" of the multipath channel (quantified by coherence bandwidth), the received signal will be distorted.

Doppler Spread

- Measure of spectral broadening caused by motion
- We know how to compute Doppler shift: f_d
- Doppler spread, B_D, is defined as the maximum Doppler shift: $f_m = v/\lambda$
- If the baseband signal bandwidth is much greater than B_D then effect of Doppler spread is negligible at the receiver.

5.3.3 Doppler Shift

The Doppler effect (or Doppler shift) is the change in frequency of a wave for an observer moving relative to the source of the wave. In classical physics (waves in a medium), the relationship between the observed frequency f and the emitted frequency f_o is given by:

$$f = \left(\frac{v \pm v_r}{v \pm v_s}\right) f_0 \tag{5.10}$$

where v is the velocity of waves in the medium, v_s is the velocity of the source relative to the medium and v_r is the velocity of the receiver relative to the medium.

The phase change in the received signal due to the difference in path lengths is therefore

$$\Delta\varphi = \frac{2\pi\Delta l}{\lambda} = \frac{2\pi v\Delta t}{\lambda}\cos\theta \tag{5.11}$$

and hence the apparent change in frequency, or Doppler shift (f_d) is

$$f_d = \frac{1}{2\pi}\cdot\frac{\Delta\varphi}{\Delta t} = \frac{v}{\lambda}\cdot\cos\theta. \tag{5.12}$$

Parameters of Mobile Multipath Channels

- Time Dispersion Parameters
  - Grossly quantifies the multipath channel
  - Determined from Power Delay Profile
  - Parameters include
    - Mean Access Delay
    - RMS Delay Spread
    - Excess Delay Spread (X dB)
- Coherence Bandwidth
- Doppler Spread and Coherence Time

5.4 Multipath Channel Parameters

To compare the different multipath channels and to quantify them, we define some parameters. They all can be determined from the power delay profile. These parameters can be broadly divided in to two types.

5.4.1 Time Dispersion Parameters

These parameters include the mean excess delay,rms delay spread and excess delay spread. The mean excess delay is the first moment of the power delay profile and is

defined as

$$\bar{\tau} = \frac{\sum a_k^2 \tau_k}{\sum a_k^2} = \frac{\sum P(\tau_k)\tau_k}{\sum P(\tau_k)} \tag{5.34}$$

where a_k is the amplitude, τ_k is the excess delay and $P(\tau_k)$ is the power of the individual multipath signals.

The mean square excess delay spread is defined as

$$\bar{\tau^2} = \frac{\sum P(\tau_k)\tau_k^2}{\sum P(\tau_k)} \tag{5.35}$$

Since the rms delay spread is the square root of the second central moment of the power delay profile, it can be written as

$$\sigma_\tau = \sqrt{\bar{\tau^2} - (\bar{\tau})^2} \tag{5.36}$$

As a rule of thumb, for a channel to be flat fading the following condition must be satisfied

$$\frac{\sigma_\tau}{T_S} \leq 0.1 \tag{5.37}$$

where T_S is the symbol duration. For this case, no equalizer is required at the

No equalizer is required at the receive

.4.2 Frequency Dispersion Parameters

To characterize the channel in the frequency domain, we have the following parameters.

1-Coherence bandwidth

1. 5.3 Small-Scale Multipath Measurements

Because of the importance of the multipath structure in determining the small-scale fading effects, a number of wideband channel sounding techniques have been developed. These techniques may be classified as direct pulse measurements, spread spectrum sliding correlator measurements, and swept frequency measurements.

2. 5.3.1 Direct RF Pulse System

A simple channel sounding approach is the direct RF pulse system (see Figure 5.6). This technique allows engineers to **determine rapidly the power delay profile of any channel**, as demonstrated by Rappaport and Seidel [Rap89], [Rap90]. Essentially a wideband pulsed bistatic radar, this system transmits a repetitive pulse of width T_{bb} s, and uses a receiver with a wide bandpass filter (*BW=2/T_{bb} Hz)*. The signal is then amplified, detected with an envelope detector, and displayed and stored on a high speed oscilloscope. This gives an immediate measurement of the square of the channel impulse response convolved with the probing pulse (see Equation (5.17)).

If the oscilloscope is set on averaging mode, then this system can provide a local average power delay profile. Another attractive aspect of this system is the lack of complexity, since off-theshelf equipment may be used.

The minimum resolvable delay between multipath components is equal to the probing pulse width T_{bb}. The main problem with this system is that it is subject to interference and noise, due to the wide passband filter required for multipath time resolution. Also, the pulse system relies on the ability to trigger the oscilloscope on the first arriving signal. If the first arriving signal is blocked or fades, severe fading occurs, and it is possible the system may not
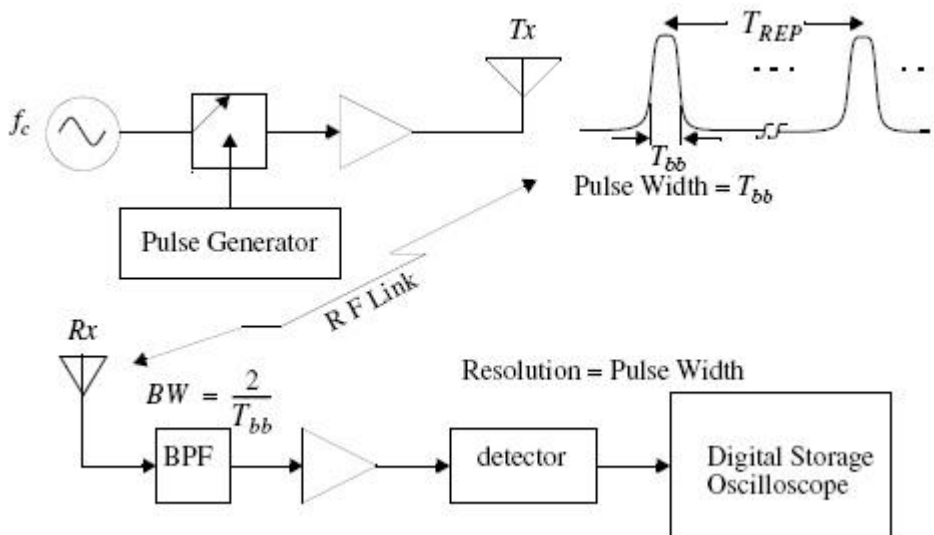

Figure 5.6 Direct RF channel impulse response measurement system.

trigger properly. Another disadvantage is that the phases of the individual multipath components are not received, due to the use of an envelope detector. However, use of a coherent detector permits measurement of the multipath phase using this technique.

3. 5.3.2 Spread Spectrum Sliding Correlator Channel Sounding

The basic block diagram of a spread spectrum channel sounding system is shown in Figure 5.7. The advantage of a spread spectrum system is that, while the probing signal may be wideband, it is possible to detect the transmitted signal using a narrowband receiver preceded by a wideband mixer, thus improving the dynamic range of the system as compared to the direct RF pulse system.

In a spread spectrum channel sounder, a carrier signal is "spread" over a large bandwidth by mixing it with a binary pseudo-noise (PN) sequence having a chip duration T_c and a chip rate R_c equal to $1/T_c$ Hz. The power spectrum envelope of the transmitted spread spectrum signal is given by [Dix84] as

$$S(f)= \left[\frac{\sin\pi(f-f_c)T_c}{\pi(f-f_c)T_c}\right]^2 = \mathrm{Sa}^2(\pi(f-f_c)T_c) \tag{5.26}$$

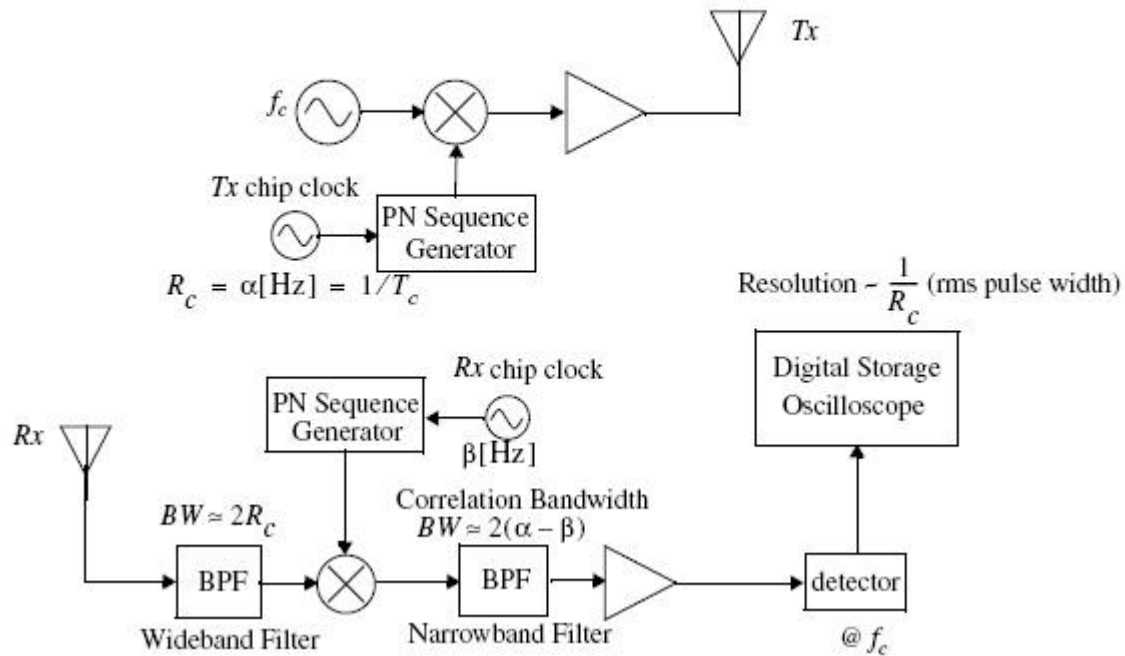and the null-to-null RF bandwidth is

$$BW = 2R_c \tag{5.27}$$

Figure 5.7 Spread spectrum channel impulse response measurement system.

The spread spectrum signal is then received, filtered, and despread using a PN sequence generator identical to that used at the transmitter. Although the two PN sequences are identical, the transmitter chip clock is run at a slightly faster rate than the receiver chip clock. Mixing the chip sequences in this fashion implements a sliding correlator [Dix84]. When the PN code of the faster chip clock catches up with the PN code of the slower chip clock, the two chip sequences will be virtually identically aligned, giving maximal correlation. When the two sequences are not maximally correlated, mixing the incoming spread spectrum signal with the unsynchronized receiver chip sequence will spread this signal into a bandwidth at least as large as the receiver's reference PN sequence. In this way, the narrowband filter that follows the correlator can reject almost all of the incoming signal power. This is how processing gain is realized in a spread spectrum receiver and how it can reject passband interference, unlike the direct RF pulse sounding system.

Processing gain (PG) is given as

$$PG = \frac{2R_c}{R_{bb}} = \frac{2T_{bb}}{T_c} = \frac{(S/N)_{out}}{(S/N)_{in}} \tag{5.28}$$

where T_{bb} 1 R_{bb}, is the period of the baseband information. For the case of a sliding correlator channel sounder, the baseband information rate is equal to the frequency offset of the PN sequence clocks at the transmitter and receiver.

When the incoming signal is correlated with the receiver sequence, the signal is collapsed back to the original bandwidth (i.e., "despread"), envelope detected, and displayed on

an oscilloscope.

Since different incoming multipaths will have different time delays, they will maximally correlate with the receiver PN sequence at different times. The energy of these individual paths will pass through the correlator depending on the time delay. Therefore, after envelope detection, the channel impulse response convolved with the pulse shape of a single chip is displayed on the oscilloscope. Cox [Cox72] first used this method to measure channel impulse responses in outdoor suburban environments at 910 MHz. Devasirvatham [Dev86], [Dev90a] successfully used a direct sequence spread spectrum channel sounder to measure time delay spread of multipath components and signal level measurements in office and residential buildings at 850 MHz. Bultitude [Bul89] used this technique for indoor and microcellular channel sounding work, as did Landron [Lan92], while Newhall and Saldanha measured campuses and train yards [New96a]. A detailed description of a practical sliding correlator is given in [New96b]. The time resolution ($\Delta\tau$) of multipath components using a spread spectrum system with sliding correlation is

$$\Delta\tau = 2T_c = \frac{2}{R_c} \tag{5.29}$$

In other words, the system can resolve two multipath components as long as they are equal to or greater than two chip durations, or $2T_c$ seconds apart. In actuality, multipath components with interarrival times smaller than $2T_c$ can be resolved since the rms pulse width of a chip is smaller than the absolute width of the triangular correlation pulse, and is on the order of T_c. The sliding correlation process gives equivalent time measurements that are updated every time the two sequences are maximally correlated. The time between maximal correlations (ΔT) can be calculated from Equation (5.30)

$$\Delta T = T_c \gamma l = \frac{\gamma l}{R_c} \tag{5.30}$$

where T_c = chip period (s)
$\qquad R_c$ = chip rate (Hz)
$\qquad \gamma$ = slide factor (dimensionless)
$\qquad l$ = sequence length (chips)

The slide factor is defined as the ratio between the transmitter chip clock rate and the difference between the transmitter and receiver chip clock rates [Dev86]. Mathematically, this is expressed as

$$\gamma = \frac{\alpha}{\alpha - \beta} \tag{5.31}$$

where α = transmitter chip clock rate (Hz)
$\qquad \beta$ = receiver chip clock rate (Hz)

For a maximal length PN sequence, the sequence length is

$$l = 2^n - 1 \qquad\qquad (5.32)$$

where n is the number of shift registers in the sequence generator [Dix84].

Since the incoming spread spectrum signal is mixed with a receiver PN sequence that is slower than the transmitter sequence, the signal is essentially down-converted ("collapsed") to a low-frequency narrowband signal. In other words, the relative rate of the two codes slipping past each other is the rate of information transferred to the oscilloscope. This narrowband signal allows narrowband processing, eliminating much of the passband noise and interference. The processing gain of Equation (5.28) is then realized using a narrowband filter ($BW = 2(\alpha - \beta)$). The equivalent time measurements refer to the relative times of multipath components as they are displayed on the oscilloscope. The observed time scale on the oscilloscope using a sliding correlator is related to the actual propagation time scale by

$$\text{Actual Propagation Time} = \frac{\text{Observed Time}}{\gamma} \qquad\qquad (5.33)$$

This effect is due to the relative rate of information transfer in the sliding correlator. For example, ΔT of Equation (5.30) is an observed time measured on an oscilloscope and not actual propagation time. This effect, known as time dilation, occurs in the sliding correlator system because the propagation delays are actually expanded in time by the sliding correlator. Caution must be taken to ensure that the sequence length has a period which is greater than the longest multipath propagation delay. The PN sequence period is

$$\tau_{PNseq} = T_c l \qquad\qquad (5.34)$$

The sequence period gives an estimate of the maximum unambiguous range of incoming multipath signal components. This range is found by multiplying the speed of light with τ_{PNseq} in Equation (5.34).

There are several advantages to the spread spectrum channel sounding system. One of the key spread spectrum modulation characteristics is the ability to reject passband noise, thus improving the coverage range for a given transmitter power. Transmitter and receiver PN sequence synchronization is eliminated by the sliding correlator. Sensitivity is adjustable by changing the sliding factor and the post-correlator filter bandwidth. Also, required transmitter powers can be considerably lower than comparable direct pulse systems due to the inherent "processing gain" of spread spectrum systems.

A disadvantage of the spread spectrum system, as compared to the direct pulse system, is that measurements are not made in real time, but they are compiled as the PN codes slide past one another. Depending on system parameters and measurement objectives, the time required to make power delay profile measurements may be excessive. Another disadvantage of the system described here is that a noncoherent detector is used, so that phases of individual multipath components can not be measured. Even if coherent detection is used, the sweep time of a spread spectrum signal induces delay such that the phases of individual multipath components with different time delays would be measured at substantially different times, during which the channel might change.

4. 5.3.3 Frequency Domain Channel Sounding

Because of the dual relationship between time domain and frequency domain techniques, it is possible to measure the channel impulse response in the frequency domain. Figure 5.8 shows a frequency domain channel sounder used for measuring channel impulse responses. A vector network analyzer controls a synthesized frequency sweeper, and an S-parameter test set is used to monitor the frequency response of the channel. The sweeper scans a particular frequency band (centered on the carrier) by stepping through discrete frequencies. The number and spacings of these frequency steps impact the time resolution of the impulse response measurement. For each frequency step, the S-parameter test set transmits a known signal level at port 1 and monitors the received signal level at port 2. These signal levels allow the analyzer to determine the complex response (i.e., transmissivity $S_{21}(\omega)$) of the channel over the measured frequency range. The transmissivity response is a frequency domain representation of the channel impulse response. This response is then converted to the time domain using inverse discrete Fourier transform (IDFT) processing, giving a band-limited version of the impulse response. In theory, this technique works well and indirectly provides amplitude and phase information in the time domain. However, the system requires careful calibration and hardwired synchronization between the transmitter and receiver, making it useful only for very close measurements (e.g., indoor channel sounding). Another limitation with this system is the non-real-time nature of the measurement. For time varying channels, the channel frequency response can change rapidly, giving an erroneous impulse response measurement. To mitigate this effect, fast sweep times are necessary to
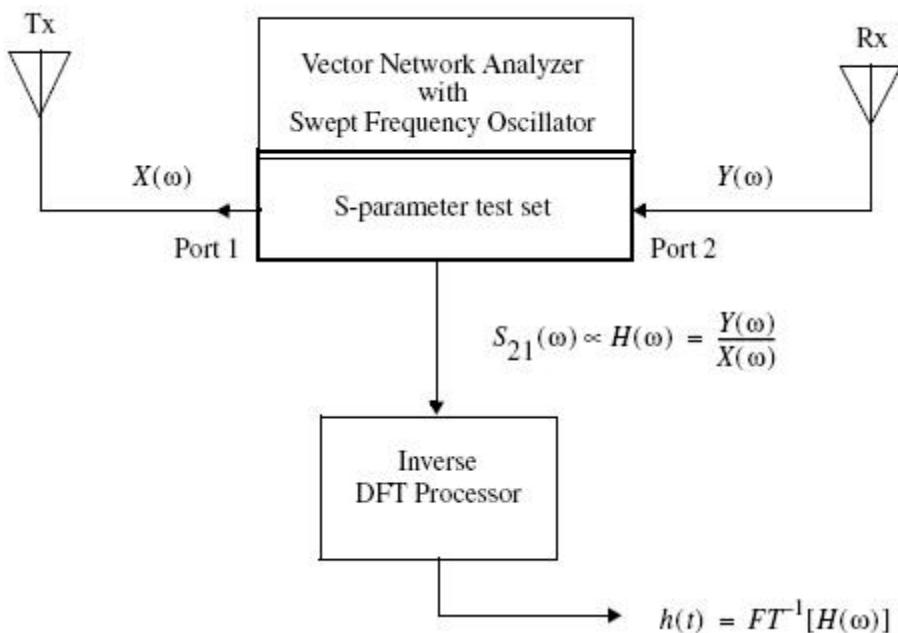

Figure 5.8 Frequency domain channel impulse response measurement system.

keep the total swept frequency response measurement interval as short as possible. A faster sweep time can be accomplished by reducing the number of frequency steps, but this sacrifices time resolution and excess delay range in the time domain. The swept frequency system has been used successfully for indoor propagation studies by Pahlavan [Pah95] and Zaghloul et al.