Data Communications: Channel Models

Introduction

• Propagation models are fundamental tools for designing any broadband wireless communication system.
• A propagation model basically predicts what will happen to the transmitted signal while in transit to the receiver.
• Traditionally, ‘propagation models’ is the term applied to those algorithms and methods used to predict the median signal level at the receiver.
• Such models include signal level information, signal time dispersion information and, in the case of mobile systems, models of Doppler shift distortions arising from the motion of the mobile.
Antennas and Propagation

• An antenna is an electrical conductor or system of conductors
  – Transmission - radiates electromagnetic energy into space
  – Reception - collects electromagnetic energy from space
• In two-way communication, the same antenna can be used for transmission and reception

Radiation Patterns

• Radiation pattern
  – Graphical representation of radiation properties of an antenna
  – Depicted as two-dimensional cross section
• Beam width (or half-power beam width)
  – Measure of directivity of antenna
• Reception pattern
  – Receiving antenna’s equivalent to radiation pattern
Types of Antennas

• Isotropic antenna (idealized)
  – Radiates power equally in all directions

• Dipole antennas
  – Half-wave dipole antenna (or Hertz antenna)
  – Quarter-wave vertical antenna (or Marconi antenna)

• Parabolic Reflective Antenna

Antenna Gain

• Antenna gain
  – Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (isotropic antenna)

• Effective area
  – Related to physical size and shape of antenna
Antenna Gain

• Relationship between antenna gain and effective area

\[ G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2} \]

• \( G \) = antenna gain
• \( A_e \) = effective area
• \( f \) = carrier frequency
• \( c \) = speed of light (\( \approx 3 \times 10^8 \) m/s)
• \( \lambda \) = carrier wavelength

Propagation Modes

• Ground-wave propagation
• Sky-wave propagation
• Line-of-sight propagation
Ground Wave Propagation

- Follows contour of the earth
- Can Propagate considerable distances
- Frequencies up to 2 MHz
- Example
  - AM radio
Sky Wave Propagation

- Signal reflected from ionized layer of atmosphere back down to earth
- Signal can travel a number of hops, back and forth between ionosphere and earth’s surface
- Reflection effect caused by refraction
- Examples
  - Amateur radio
  - CB radio
Line-of-Sight Propagation

- Transmitting and receiving antennas must be within line of sight
  - Satellite communication – signal above 30 MHz not reflected by ionosphere
  - Ground communication – antennas within effective line of site due to refraction
- Refraction – bending of microwaves by the atmosphere
  - Velocity of electromagnetic wave is a function of the density of the medium
  - When wave changes medium, speed changes
  - Wave bends at the boundary between mediums
Line-of-Sight Equations

• Optical line of sight
  \[ d = 3.57 \sqrt{h} \]

• Effective, or radio, line of sight
  \[ d = 3.57 \sqrt{Kh} \]
  
  - \( d \) = distance between antenna and horizon (km)
  - \( h \) = antenna height (m)
  - \( K \) = adjustment factor to account for refraction, rule of thumb \( K = 4/3 \)

Line-of-Sight Equations

• Maximum distance between two antennas for LOS propagation:
  \[ 3.57\left(\sqrt{Kh_1} + \sqrt{Kh_2}\right) \]
  
  - \( h_1 \) = height of antenna one
  - \( h_2 \) = height of antenna two
LOS Wireless Transmission Impairments

- Attenuation and attenuation distortion
- Free space loss
- Noise
- Atmospheric absorption
- Multipath
- Refraction
- Thermal noise

Attenuation

- Strength of signal falls off with distance over transmission medium
- Attenuation factors for unguided media:
  - Received signal must have sufficient strength so that circuitry in the receiver can interpret the signal
  - Signal must maintain a level sufficiently higher than noise to be received without error
  - Attenuation is greater at higher frequencies, causing distortion
Free Space Loss

- Free space loss, ideal isotropic antenna

\[
\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi fd)^2}{c^2}
\]

- \( P_t \) = signal power at transmitting antenna
- \( P_r \) = signal power at receiving antenna
- \( \lambda \) = carrier wavelength
- \( d \) = propagation distance between antennas
- \( c \) = speed of light (\( \cong 3 \cdot 10^8 \text{ m/s} \))

where \( d \) and \( \lambda \) are in the same units (e.g., meters)

\[
L_{dB} = 10 \log \left( \frac{P_t}{P_r} \right) = 20 \log \left( \frac{4\pi d}{\lambda} \right)
\]

\[
= -20 \log(\lambda) + 20 \log(d) + 21.98 \text{ dB}
\]

\[
= 20 \log \left( \frac{4\pi fd}{c} \right) = 20 \log(f) + 20 \log(d) - 147.56 \text{ dB}
\]
Free Space Loss

- Free space loss accounting for gain of other antennas

\[
\frac{P_t}{P_r} = \frac{(4\pi)^2 (d)^2}{G_r G_t \lambda^2} = \frac{(\lambda d)^2}{A_r A_t} = \frac{(cd)^2}{f^2 A_r A_t}
\]

- \( G_t \) = gain of transmitting antenna
- \( G_r \) = gain of receiving antenna
- \( A_t \) = effective area of transmitting antenna
- \( A_r \) = effective area of receiving antenna

Free Space Loss

- Free space loss accounting for gain of other antennas can be recast as

\[
L_{dB} = 20\log(\lambda) + 20\log(d) - 10\log(A_t A_r)
\]

\[
= -20\log(f) + 20\log(d) - 10\log(A_t A_r) + 169.54\text{dB}
\]
Propagation mechanisms

A: free space
B: reflection
C: diffraction
D: scattering

reflection: object is large compared to wavelength
scattering: object is small or its surface irregular

Data Communications Channels
Model

Multipath Propagation

• Reflection - occurs when signal encounters a surface that is large relative to the wavelength of the signal
• Diffraction - occurs at the edge of an impenetrable body that is large compared to wavelength of radio wave
• Scattering – occurs when incoming signal hits an object whose size in the order of the wavelength of the signal or less
Three main challenges, in communication channels
1. Path Loss,
2. Shadowing
3. Fading.

Path Loss refers to the decrease in signal power, which is mainly brought about by the physical distance between the communications devices.

Shadowing takes on a more local view and refers to the loss of power attributed to large obstacles such as hills and tall buildings.

Fading takes on a yet more microscopic view and is concerned with the interference caused by the reception of numerous scattered copies of the signal at the antenna.

The interference caused by fading produces significant random variations of signal power (in the scale of 10s of dB over fractions of the wavelength).

As a result, fading can be extremely destructive to the signal.

The transmission of a bandpass and narrowband signal to a mobile is modeled as a multipath channel structure shown in Following Figure
A simple mathematical derivation yields the following result for $y(t)$, the complex envelope of the received signal.

$$y(t) = \sum_{i} a_i e^{-j 2\pi f_D \cos(\theta_i)} s(t - \tau_i)$$

This shows that scatterer $i$ corresponds to a signal copy that is shifted in time by $\tau_i$ and in frequency by

$$f_D \cos(\theta_i) \text{ where } f_D = \frac{v}{\lambda}$$

is the *Doppler frequency*. We also define the *delay spread* $\tau_d$ as the largest delay $\tau_i$. 
The Effects of Multipath Propagation

- Multiple copies of a signal may arrive at different phases
  - If phases add destructively, the signal level relative to noise declines, making detection more difficult
- Intersymbol interference (ISI)
  - One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit

Fading

- Fluctuation in the strength of signal, because of variations in the transmission medium.
- Fading is a broad term applied to a wide range of variation in the signal amplitude, phase, and frequency characteristic.
- For example, the term ‘shadow fading’ is used to describe the decrease in signal strength that is observed when a mobile terminal is behind a building.
The relative phase of multiple reflected signals can cause constructive or destructive interference at the receiver. This is experienced over very short distances (typically at half wavelength distances), thus is given the term *fast fading*. These variations can vary from 10-30dB over a short distance. Figure shows the level of attenuation that can occur due to the fading.

![Typical Rayleigh fading while the Mobile Unit is moving (for at 900 MHz)](image)

Data Communications Channels
Model

31
The Rayleigh distribution is commonly used to describe the statistical time varying nature of the received signal power. It describes the probability of the signal level being received due to fading. The following Table shows the probability of the signal level for the Rayleigh distribution.

<table>
<thead>
<tr>
<th>Signal Level (dB about median)</th>
<th>% Probability of Signal Level being less than the value given</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>99</td>
</tr>
<tr>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>-10</td>
<td>5</td>
</tr>
<tr>
<td>-20</td>
<td>0.5</td>
</tr>
<tr>
<td>-30</td>
<td>0.05</td>
</tr>
</tbody>
</table>
**Frequency Selective Fading**

In any radio transmission, the channel spectral response is not flat. It has dips or fades in the response due to reflections causing cancellation of certain frequencies at the receiver. Reflections off near-by objects (e.g. ground, buildings, trees, etc) can lead to multipath signals of similar signal power as the direct signal. This can result in deep nulls in the received signal power due to destructive interference. For narrow bandwidth transmissions if the null in the frequency response occurs at the transmission frequency then the entire signal can be lost. This can be partly overcome in two ways.

1- By transmitting a wide bandwidth signal or spread spectrum as **CDMA**, any dips in the spectrum only result in a small loss of signal power, rather than a complete loss.

2- Another method is to split the transmission up into many small bandwidth carriers, as is done in a **COFDM/OFDM** transmission. The original signal is spread over a wide bandwidth and so nulls in the spectrum are likely to only affect a small number of carriers rather than the entire signal. The information in the lost carriers can be recovered by using forward error correction techniques.
Radio channel modelling

Narrowband Models
• Because the signal bandwidth is narrow, the fading mechanism will affect all frequencies in the signal passband equally.
• So, a narrowband channel is often referred to as a flat-fading channel.

Wideband Models
• The bandwidth of the signal, sent through the channel is such that time dispersion information is required.
• Time dispersion causes the signal fading to vary as a function of frequency, so wideband channels are often called frequency-selective fading channels.

Comparison

<table>
<thead>
<tr>
<th>Narrowband modelling</th>
<th>Wideband modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation of path loss e.g. taking into account</td>
<td></td>
</tr>
</tbody>
</table>
  - free space loss |
  - reflections |
  - diffraction |
  - scattering |
| Basic problem: signal fading |
| Deterministic models (e.g. ray tracing, playback modelling) |
| Stochastical models |
| Basic problem: signal dispersion |
Generic Wideband Channel Model

- Wideband generally indicates those channels in which time dispersion and frequency-selective fading have a significant impact on the signal being transmitted.

- For signals whose occupied bandwidth is narrow compared to the correlation bandwidth of the channel, the generic wideband model simplifies to a narrowband model in which many elements of the wideband model may be discarded.

If the channel is considered as a filter with some low-pass impulse response, then that impulse response would be given by:

\[ h(t) = A\delta(t - \tau) \exp(-j\theta) \]
• A sine wave signal at frequency $\omega$ leaving the transmitting antenna would arrive at the receiver reduced in amplitude by factor $A$, shifted in phase by $\theta$, and delayed by $\tau$ seconds.

• Such a model of the transmission channel is applicable for free-space propagation conditions in which signal energy arrives at the receiver directly (via one path) from the transmitter.

• If the channel consisted of two transmission paths for the transmitted energy to arrive at the receiver (for example, with the addition of a single ground reflection), the channel impulse response would be the sum of the effect of the two paths:

$$h(t) = A_1 \delta(t - \tau_1) \exp(-j\theta_1) + A_2 \delta(t - \tau_2) \exp(-j\theta_2)$$

• This is the impulse response of the so-called ‘two-ray’ channel model.
• For $N$ possible transmission paths, $h(t)$ becomes:

$$h(t) = \sum_{n=1}^{N} A_n \delta(t - \tau_n) \exp(-j\theta_n)$$

• This is the channel impulse response to a particular point $p_2(x_2, y_2, z_2)$ from a transmitter located at point $p_1(x_1, y_1, z_1)$.

**Delay Spread**

The received radio signal from a transmitter consists of typically a direct signal, plus reflections off objects such as buildings, mountings, and other structures. The reflected signals arrive at a later time then the direct signal because of the extra path length, giving rise to a slightly different arrival times, spreading the received energy in time. Delay spread is the time spread between the arrival of the first and last significant multipath signal seen by the receiver. In a digital system, the delay spread can lead to inter-symbol interference. This is due to the delayed multipath signal overlapping with the following symbols. This can cause significant errors in high bit rate systems, especially when using time division multiplexing (TDMA).
Figure shows the effect of inter-symbol interference due to delay spread on the received signal. As the transmitted bit rate is increased the amount of inter-symbol interference also increases. The effect starts to become very significant when the delay spread is greater than ~50% of the bit time.

Table shows the typical delay spread for various environments. The maximum delay spread in an outdoor environment is approximately 20ms, thus significant intersymbol interference can occur at bit rates as low as 25 kbps.

<table>
<thead>
<tr>
<th>Environment or cause</th>
<th>Delay Spread</th>
<th>Maximum Path Length Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor (room)</td>
<td>40ns – 200 ns</td>
<td>12 m – 60 m</td>
</tr>
<tr>
<td>Outdoor</td>
<td>1 µs – 20 µs</td>
<td>300 m – 6 km</td>
</tr>
</tbody>
</table>

Typical Delay Spread

Inter-symbol interference can be minimized in several ways. One method is to reduce the symbol rate by reducing the data rate for each channel (i.e. split the bandwidth into more channels using frequency division multiplexing, or OFDM). Another is to use a coding scheme that is tolerant to inter-symbol interference such as CDMA.
RMS Delay spread

- A common measure of the amount of time dispersion in a channel is the RMS delay spread.
- The RMS delay spread can be found from the power delay profile:

\[
\sigma_{\tau} = \left[ \sum_{n=1}^{N} (\tau_n - \bar{\tau})^2 p(\tau_n) \right]^{\frac{1}{2}}
\]

\[
\bar{\tau} = \sum_{n=1}^{N} (\tau_n) p(\tau_n)
\]

\[
p(\tau_n) = \frac{A_n^2}{\sum_{n=1}^{N} A_n^2}
\]
Doppler Shift

When a wave source and a receiver are moving relative to one another the frequency of the received signal will not be the same as the source. When they are moving toward each other the frequency of the received signal is higher then the source, and when they are approaching each other the frequency decreases. This is called the Doppler effect. An example of this is the change of pitch in a car’s horn as it approaches then passes by. This effect becomes important when developing mobile radio systems. The amount the frequency changes due to the Doppler effect depends on the relative motion between the source and receiver and on the speed of propagation of the wave. The Doppler shift in frequency can be written:

\[ \Delta f \approx \pm f_o \frac{v}{c} \]

where \( \Delta f \) is the change in frequency of the source seen at the receiver, \( f_o \) is the frequency of the source, \( v \) is the speed difference between the source and transmitter, and \( c \) is the speed of light.

For example: Let \( f_o = 1 \text{GHz} \), and \( v = 60 \text{km/hr} \) (16.7 m/s) then the Doppler shift will be:

\[ f_o = 10^9 \cdot \frac{16.67}{3 \times 10^8} = 55.5 \text{Hz} \]
This shift of 55Hz in the carrier will generally not effect the transmission. However, Doppler shift can cause significant problems if the transmission technique is sensitive to carrier frequency offsets (for example OFDM) or the relative speed is very high as is the case for low earth orbiting satellites.

**Example: multipath signal**

The received multipath signal is the sum of $N$ attenuated, phase shifted and delayed replicas of the transmitted signal $s(t)$:

$$a_0 e^{j\phi_0} s(t - \tau_0)$$
$$a_1 e^{j\phi_1} s(t - \tau_1)$$
$$a_2 e^{j\phi_2} s(t - \tau_2)$$

... 

Normalized delay spread $D = T_m / T$
Important Note:

The normalized delay spread is an important quantity.
When $D << 1$, the channel is
- narrowband
- frequency-nonselective
- flat
and there is no intersymbol interference (ISI).

When $D$ approaches or exceeds unity, the channel is
- wideband
- frequency selective
- time dispersive

BER vs. S/N performance

In a Gaussian channel (no fading) $BER \leftrightarrow Q(S/N) \text{ erfc}(S/N)$
**BER vs. S/N performance**

Flat fading: NB channel

\[ BER = \int BER(S/N|z) p(z) dz \]

\( z = \) signal power level

**Typical BER vs. S/N curves**

- Frequency-selective channel (no equalization)
- Flat fading channel
- Gaussian channel (no fading)

**BER vs. S/N performance**

Frequency selective fading \( \leftrightarrow \) irreducible BER floor

**Typical BER vs. S/N curves**

- Frequency-selective channel (no equalization)
- Gaussian channel (no fading)
- Flat fading channel
Time-Variant Channels

• To deal with a time-variant channel, we define the *input delay-spread function* $h(t, \tau)$.
• This is the low-pass response of the channel at some time $t$ to a unit impulse function input at some previous time $\tau$ seconds earlier.
• Note that this delay $\tau$ is different from the discrete $\tau_1, \tau_2 \ldots \tau_n$ arrival delay times, that define when the signal waves reach the receiver.

Channel is assumed linear!
Time- Variant Channels

- The output of the channel $y(t)$ can then be found by the convolution of the input signal $u_m(t)$ with $h(t, \tau)$ integrated over the delay variable $\tau$:

$$y(t) = \int_{-\infty}^{\infty} u_m(t-\tau) h(t, \tau) d\tau$$
Some Notes

- Using an impulse response from a ray-tracing propagation model, and convolving it with a raised cosine symbol pulse, the result is a *time signature* of the channel.
- The variations in signatures are due to the relative phase changes, and not changing amplitudes.
- By taking the Fourier Transform of the time signatures, it is possible to created *spectrum signatures*.
- The nonuniform frequency response, represents the frequency-selective nature of the channel.
Path Loss Modeling

- Maxwell’s equations
  - Complex and impractical
- Physical Models
  - Free space path loss model
    - Too simple
  - Ray tracing models
    - Requires site-specific information
- Empirical Models
  - Don’t always generalize to other environments

Empirical Models

*Commonly used in cellular system simulations*

- Are based on observations or measurements.
- measurements are typically done in the field to measure path loss, delay spread, or other channel characteristics.
- Site and field dependent
Physical Models

Free Space (LOS) Model

- Path loss for unobstructed LOS path
- Power falls off:
  - Proportional to $d^2$
  - Proportional to $\lambda^2$ (inversely proportional to $f^2$)
Two Path Model

• Path loss for one LOS path and 1 ground (or reflected) bounce
• Ground bounce approximately cancels LOS path above critical distance
• Power falls off
  – Proportional to $d^2$ (small $d$)
  – Proportional to $d^4$ ($d > d_c$)

Ray Tracing Approximation

• Represent wavefronts as simple particles
• Geometry determines received signal from each signal component
• Typically includes reflected rays, can also include scattered and defracted rays.
• Requires site parameters
  – Geometry
  – Dielectric properties
General Ray Tracing

- Models all signal components
  - Reflections
  - Scattering
  - Diffraction

- Requires detailed geometry and dielectric properties of site
  - Similar to Maxwell, but easier math.
- Computer packages often used

\[ E_r = \frac{1}{s'_f} \sqrt{\frac{P_T G_T Z_0}{4\pi}} \left[ \prod_i R_i \right] \left[ \prod_n A(s'_n, s_n) \overline{D_n} \right] \left[ \prod_l A_{scat,l} \right] \left[ \prod_k A_{tran,k} \right] \]

where:

- \( s'_f \) is the total ray trajectory length
- \( \sqrt{\frac{P_T G_T Z_0}{4\pi}} \) is the free-space attenuation component
- \( R_i \) is the reflection coefficient for the \( i \)th reflection on the ray path (a complex number)
- \( \overline{D_n} \) is the diffraction coefficient for the \( n \)th diffraction wedge on the ray path (a complex number)
- \( A(s'_n, s_n) \) the spatial attenuation factor diffraction coefficient
- \( A_{scat,l} \) is the scattering coefficient if scattering is included for objects in the model
- \( A_{tran,k} \) is the wall transmission coefficient if the model includes this feature.
2D view of ray trajectories for ray-tracing propagation model.
Simplified indoor model
SIM

- An effort to provide a fast and simple model that predicts indoor signal levels.

- Works in the area of 2.4 GHz Wi-Fi or 5.7 GHz U-NII band systems, intended to work over short ranges, especially indoors through walls and floors.

- SIM makes use of four basic propagation primitives: line-of-sight rays, wall transmission loss, corner diffraction, and attenuation due to partial Fresnel zone obstruction.

Signal strength contours for three access points for an indoor 802.11(b) 2.4 GHz wireless LAN system using simplified indoor model.