Radio Wave Propagation

EE442 Analog & Digital Communication Systems
Principles of Modern Communication Systems

Lecture 14

https://www.g0hrs.org/propagation

Textbook: Samuel O. Agbo and Matthew N. O. Sadiku
Principles of Modern Communication Systems
The Four Great Enablers of the Communication Age
(from ES 101A “Communications in the Information Age”)

1. Harnessing of Electricity
   - Alessandra Volta – Battery (1800)
   - Electric Power Generation (1880s)

2. Radio Waves
   - Guglielmo Marconi
     - Radio Waves (began in 1896 with wireless telegraphy)
     - Telegraph 1844 & Telephone 1876

3. Digitization
   - Started in 1940s (but accelerated in the 1970s)

4. Transistors & Integrated Circuits
   - Transistor 1948
     - IC invented 1958 (Jack Kilby & Robert Noyce)

Source: D. B. Estreich from ES101
Wireless Channel: Line-of-Sight Radio Wave Propagation

Is this transmission channel analogous to a linear time-invariant network?

Some Frequency Allocations of Interest in EE442

- **AM radio**: 540 to 1720 kHz
- **TV broadcast**
- **FM radio**: 88 to 108 MHz
- **3G/4G LTE cellular**
- **Wi-Fi**: 2.402 to 2.484 GHz
- **28 GHz – LMDS (5G cellular)**
- **77 GHz vehicular radar**
- **Active CMOS IC research**
- **38 GHz 5G cellular**
- **60 GHz unlicensed WiGig (802.11 ad)**

See next slide

## Radio Frequency Designations and Bands

<table>
<thead>
<tr>
<th>Designation</th>
<th>Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELF (extremely low frequency)</td>
<td>3-30 Hz</td>
</tr>
<tr>
<td>SLF (super low frequency)</td>
<td>30–300 Hz</td>
</tr>
<tr>
<td>ULF (ultra low frequency)</td>
<td>300–3000 Hz</td>
</tr>
<tr>
<td>VLF (very low frequency)</td>
<td>3 – 30 kHz</td>
</tr>
<tr>
<td>LF (low frequency)</td>
<td>30 kHz – 300 kHz</td>
</tr>
<tr>
<td>MF (medium frequency)</td>
<td>300 kHz – 3 MHz</td>
</tr>
<tr>
<td>HF (high frequency)</td>
<td>3 MHz – 30 MHz</td>
</tr>
<tr>
<td>VHF (very high frequency)</td>
<td>30 MHz – 300 MHz</td>
</tr>
<tr>
<td>UHF (ultra high frequency)</td>
<td>300 MHz – 3 GHz</td>
</tr>
<tr>
<td>SHF (super high frequency)</td>
<td>3 GHz – 30 GHz</td>
</tr>
<tr>
<td>EHF (extremely high frequency)</td>
<td>30 GHz – 300 GHz</td>
</tr>
</tbody>
</table>

- **Power**
- **Submarine comm**
- **Radio navigation**
- **AM radio**
- **Shortwave radio**
- **FM radio; VHF TV**
- **PCS; GPS; UHF TV**
- **Microwave links; & Satellite comm**
The Radio Spectrum

## Radio Bands (1)

<table>
<thead>
<tr>
<th>Band name</th>
<th>Abbreviation</th>
<th>Frequency and wavelength in air</th>
<th>Example uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tremendously low frequency</td>
<td>TLF</td>
<td>&lt; 3 Hz &gt; 100,000 km</td>
<td>Natural and man-made electromagnetic noise</td>
</tr>
<tr>
<td>Extremely low frequency</td>
<td>ELF</td>
<td>3 Hz – 30 Hz 100,000 km – 10,000 km</td>
<td>Submarine communications</td>
</tr>
<tr>
<td>Super low frequency</td>
<td>SLF</td>
<td>30 Hz - 300 Hz 10,000 km – 1,000 km</td>
<td>Submarine communications</td>
</tr>
<tr>
<td>Ultra low frequency</td>
<td>ULF</td>
<td>300 Hz – 3,000 Hz 1,000 km – 100 km</td>
<td>Submarine communications; Communications within mines</td>
</tr>
<tr>
<td>Very low frequency</td>
<td>VLF</td>
<td>3 kHz – 30 kHz 100 km – 10 km</td>
<td>Navigation; time signals; heart monitoring; geophysics research</td>
</tr>
</tbody>
</table>
## Radio Bands (2)

<table>
<thead>
<tr>
<th>Band Name</th>
<th>Abbr</th>
<th>Frequency and wavelength in air</th>
<th>Example uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low frequency</td>
<td>LF</td>
<td>30 – 300 kHz 10 km – 1 km</td>
<td>Navigation, time signals, AM long wave broadcasting, RFID, amateur radio</td>
</tr>
<tr>
<td>Medium frequency</td>
<td>MF</td>
<td>300 – 3000 kHz (3 MHz) 1 km – 100 m</td>
<td>AM medium wave broadcasting, amateur radio, avalanche beacons</td>
</tr>
<tr>
<td>High frequency</td>
<td>HF</td>
<td>3 – 30 MHz 100 m – 10 m</td>
<td>Shortwave broadcasts, citizens’ band radio, amateur radio, over-the-horizon communications, marine and mobile radio telephony</td>
</tr>
<tr>
<td>Very high frequency</td>
<td>VHF</td>
<td>30 – 300 MHz</td>
<td>FM radio and television broadcasts, line of sight ground- to-aircraft and aircraft-to-aircraft, Land mobile and Maritime mobile, amateur radio, weather radio</td>
</tr>
</tbody>
</table>

Radio Communication Geoff Partridge. The Radio Spectrum Radio Spectrum refers to the part of the electromagnetic spectrum corresponding to radio frequencies. -- ppt download (slideplayer.com)
### Radio Bands (3)

<table>
<thead>
<tr>
<th>Band name</th>
<th>Abbr</th>
<th>Frequency and wavelength in air</th>
<th>Example uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra high frequency</td>
<td>UHF</td>
<td>300 MHz – 3 GHz 1 m – 10 cm</td>
<td>TV broadcast; Microwave comm; radio astronomy; mobile phones; wireless LANs; Bluetooth; GPS</td>
</tr>
<tr>
<td>Super high frequency</td>
<td>SHF</td>
<td>3 GHz – 30 GHz 10 cm – 1 cm</td>
<td>TV broadcast; Microwave comm; radio astronomy; Radar; Satellite comm; Wireless LAN; Microwave relay links</td>
</tr>
<tr>
<td>Extremely high frequency</td>
<td>EHF</td>
<td>30 GHz - 300 GHz 1 cm – 1 mm</td>
<td>Secure Satellite comm; Radio astronomy; Microwave relay links</td>
</tr>
<tr>
<td>Tremendously high frequency (Terahertz)</td>
<td>THF</td>
<td>&gt; 300 GHz &lt; 1 mm</td>
<td>Terahertz imaging; Terahertz communications</td>
</tr>
</tbody>
</table>
Selected Frequency Allocations in Cellular Telephony

All US frequencies in megahertz (MHz)
Note: 3G & 4G are 3\textsuperscript{rd} & 4\textsuperscript{th} generations of cellular mobile

<table>
<thead>
<tr>
<th>CARRIER</th>
<th>NETWORK</th>
<th>3G BANDS</th>
<th>3G FREQUENCIES</th>
<th>4G LTE BANDS</th>
<th>4G LTE FREQUENCIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT&amp;T</td>
<td>GSM/UMTS/HSPA+</td>
<td>2, 5</td>
<td>1900, 850</td>
<td>2, 4, 12, 17</td>
<td>1900, 1700 abcde, 700 bc</td>
</tr>
<tr>
<td>VERIZON</td>
<td>CDMA</td>
<td>0, 1</td>
<td>850, 1900</td>
<td>2, 4, 13</td>
<td>1900, 1700 f, 700 c</td>
</tr>
<tr>
<td>T-MOBILE</td>
<td>GSM/UMTS/HSPA+</td>
<td>2, 4</td>
<td>1900, 1700/2100</td>
<td>2, 4, 12</td>
<td>1900, 1700 def, 700 a</td>
</tr>
<tr>
<td>SPRINT</td>
<td>CDMA</td>
<td>10, 1</td>
<td>800, 1900</td>
<td>25, 26, 41</td>
<td>1900 g, 850, 2500</td>
</tr>
<tr>
<td>US CELLULAR</td>
<td>CDMA</td>
<td>0, 1</td>
<td>850, 1900</td>
<td>5, 12</td>
<td>850, 700 ab</td>
</tr>
</tbody>
</table>

This represents some of the best part of the EM spectrum.

Radio and Optical Windows in the Atmosphere

Just as sight depends upon the “Visible Window,” wireless communication depends upon the existence of the “Radio Window” in the EM spectrum.

Total (Dry Air and Water-vapor) Zenith Attenuation at Sea Level

- **V-band** is 50 to 75 GHz
- **W-band** is 75 to 100 GHz

**Why W/V band for satellite communications?**

- W & V bands have less crowding in frequency; this provides reduced interference, large bandwidth availability, reduced antenna and electronic components size, and more security in point-to-point links from smaller beamwidths.
Unlicensed Spectrum – ISM and & UNII RF Bands

ISM: Industrial, Scientific & Medical & UNII: Unlicensed National Information Infrastructure

<table>
<thead>
<tr>
<th>Band</th>
<th>Applications</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISM I</td>
<td>Cordless phones; 1G Wireless Cellular</td>
<td>902 – 928 MHz</td>
</tr>
<tr>
<td>ISM II</td>
<td>Wi-Fi; Bluetooth; ZigBee; Microwave ovens</td>
<td>2.4 – 2.4835 GHz</td>
</tr>
<tr>
<td>ISM III</td>
<td>Cordless phones; Wireless PBX</td>
<td>5.725 – 5.85 GHz</td>
</tr>
<tr>
<td>UNII I</td>
<td>Wi-Fi 802.11a/n</td>
<td>5.15 – 5.25 GHz</td>
</tr>
<tr>
<td>UNII II</td>
<td>Short-range indoor; Campus applications</td>
<td>5.25 – 5.35 GHz</td>
</tr>
<tr>
<td>UNII III</td>
<td>Long-range outdoor; Point-to-Point links</td>
<td>5.725 – 5.875 GHz</td>
</tr>
</tbody>
</table>

Other ISM bands: 24.0 to 24.25 GHz, 61 to 61.5 GHz, 122 to 123 GHz and 244 to 246 GHz.

# Unlicensed Spectrum – ISM Bands

<table>
<thead>
<tr>
<th>Range</th>
<th>Center frequency</th>
<th>Bandwidth</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.765–6.795 MHz</td>
<td>6.78 MHz</td>
<td>30 kHz</td>
<td></td>
</tr>
<tr>
<td>433.05–434.79 MHz</td>
<td>433.92 MHz</td>
<td>1.84 MHz</td>
<td></td>
</tr>
<tr>
<td>61–61.5 GHz</td>
<td>61.25 GHz</td>
<td>500 MHz</td>
<td>Subject to special authorization.</td>
</tr>
<tr>
<td>122–123 GHz</td>
<td>122.5 GHz</td>
<td>1 GHz</td>
<td></td>
</tr>
<tr>
<td>244–246 GHz</td>
<td>245 GHz</td>
<td>2 GHz</td>
<td></td>
</tr>
<tr>
<td>13.553–13.567 MHz</td>
<td>13.560 MHz</td>
<td>14 kHz</td>
<td>Apple Pay</td>
</tr>
<tr>
<td>26.957–27.283 MHz</td>
<td>27.120 MHz</td>
<td>326 kHz</td>
<td>Amateur radio and radio control</td>
</tr>
<tr>
<td>40.66–40.70 MHz</td>
<td>40.68 MHz</td>
<td>40 kHz</td>
<td></td>
</tr>
<tr>
<td>902–928 MHz</td>
<td>915 MHz</td>
<td>26 MHz</td>
<td>Services operating within these bands must accept harmful interference.</td>
</tr>
<tr>
<td>2.4–2.5 GHz</td>
<td>2.45 GHz</td>
<td>100 MHz</td>
<td>Wi-Fi and Bluetooth</td>
</tr>
<tr>
<td>5.725–5.875 GHz</td>
<td>5.8 GHz</td>
<td>150 MHz</td>
<td></td>
</tr>
<tr>
<td>24–24.25 GHz</td>
<td>24.125 GHz</td>
<td>250 MHz</td>
<td></td>
</tr>
</tbody>
</table>
Antennas are Required in Wireless Communication

Cellular base station antennas

Yagi antenna

Mast antenna (Monopole)

Parabolic antenna

Cell phone antenna (internally mounted)

Dipole antenna
Free Space Path Loss (FSPL)

\[
FSPL = \left( \frac{4\pi r}{\lambda} \right)^2 = \left( \frac{4\pi rf}{c} \right)^2
\]

where \( c = \lambda f \)

\[
FSPL (\text{dB}) = 10 \cdot \log_{10} \left( \left( \frac{4\pi rf}{c} \right)^2 \right)
\]

\[
FSPL (\text{dB}) = 20 \cdot \log_{10} \left( \frac{4\pi rf}{c} \right)
\]

\[
FSPL (\text{dB}) = 20 \cdot \log_{10} (r) + 20 \cdot \log_{10} (f) + 20 \cdot \log_{10} \left( \frac{4\pi}{c} \right)
\]

\[
FSPL (\text{dB}) = 20 \cdot \log_{10} (r) + 20 \cdot \log_{10} (f) - 147.55 \text{ dB}
\]

No reflections, diffraction or scattering

https://en.wikipedia.org/wiki/Free-space_path_loss
Antenna-to-Antenna Path Loss – The Friis Formula

\[ P_r = P_t \left( G_t \cdot G_r \right) \left( \frac{\lambda}{4\pi r} \right)^2 \]

- Transmitting Antenna (Gain \( G_t \))
- Receiving Antenna (Gain \( G_r \))
- Transmitted Power
- Received Power
- Wavelength
- Antenna Gains
- Separation Distance
- No reflections, diffraction, or scattering.
Antenna-to-Antenna Path Loss – The Friis Formula

\[ P_r = P_t \left( G_t \cdot G_r \right) \left( \frac{c}{4\pi rf} \right)^2 \]

- Transmitted Power
- Received Power
- Transmitting Antenna (Gain $G_t$)
- Receiving Antenna (Gain $G_r$)
- Frequency
- Separation Distance
- Speed of Light

No reflections, diffraction, or scattering.
Radiation from a Dipole Antenna

http://askthephysicist.com/ask_phys_q&a_old5.html
Radiation Associated With a Dipole Antenna
Wireless Channel Limitations and Challenges

- **Propagation loss** – The greater the distance, the greater the loss (All channels are *lossy* unless they have gain built into them)
- **Frequency selectivity** – Most media are transmitted over selective frequency bands (FCC assigns these bands)
- **Time variability** – Many channels have natural varying conditions which change transmission properties (e.g., temperature and moisture content changes; motion in objects)
- **Nonlinearity** – Ideally a channel is linear; however, exceptions exist such as satellite communication through the ionosphere
- **Shared usage** – Most channels are not dedicated to a single user so they must contend with multiple users
- **Noise** – All channels contribute noise to the signal as it travels through the medium
- **Interference** – Channels can pick up adjacent communication signals and noise which interfere with the intended signals
- **Fading** – Shadowing, reflection, multipath, diffraction, etc.

*All of these influence and/or limit the choice of modulation schemes & transmitter/receiver (transceiver) design.*
Space Waves (Line of Sight), Surface Waves & Sky Waves

Describe briefly, by drawing suitable diagrams, the (i) sky wave and (ii) space wave.
Sky Waves and Reception Skip Zones

SIDspot - Sudden Ionspheric Disturbance Monitor (starfishprime.co.uk)
Structure of the Ionosphere

- **F-layer is dominant at night**: (F1 & F2 layers combine at night)
- **E-layer refracts during the day**
- **D-layer absorbs signals during the day**
- **Ionosphere is mostly hydrogen and helium; ionized by UV from Sun**
- **Troposphere is mostly Nitrogen (78%) & oxygen (21%); Determines our weather**

Sky Waves Are Refracted by Ionospheric F and E Regions

SWS - Other Topics - Introduction to HF Radio Propagation (bom.gov.au)
Space & Sky Waves Ray Tracing by Angle of Launch - I

Radio Communication Geoff Partridge. The Radio Spectrum Radio Spectrum refers to the part of the electromagnetic spectrum corresponding to radio frequencies. - ppt download (slideplayer.com)
Space & Sky Waves Ray Tracing by Angle of Launch - II

https://i.pinimg.com/736x/8b/29/59/8b29590edaae82c7a9--6f38de475e485b--radio-wave-physics.jpg
Complex Sky Wave Propagation
Sky Wave Propagation Characteristics

Attributes of Sky Waves:
1. Especially effective from 1 MHz to approximately 40 MHz.
2. Frequencies less than 3 kHz have wavelengths greater than the distance between the Earth and ionosphere.
3. During the daytime D-region absorption makes it impossible to support sky waves – D-layer absorbs signals below 5 MHz.
4. The reflection by the ionosphere due to wave refraction
5. The F2 region of F-layer ( > 210 km) is the most important layer because it is present 24 hours each day.
6. Sky Wave intensities are dependent upon solar cycles, day versus night, the path, angle of signal, etc.
7. Multiple hops make it possible to increase the distance.

Specific Applications:
1. Used for HF band International broadcasting (shortwave radio) and stations from the other side of the Earth can be received.
2. Some AM radio stations can be received at night from far away and are known “clear channel” stations.
Clear Channel AM Radio Broadcasting

Class A designated – broadcast with 50 kW power (omni-directional)

<table>
<thead>
<tr>
<th>frequency</th>
<th>Station</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>650 kHz</td>
<td>WSM</td>
<td>Nashville, TN – Home of Grand Ole’ Oprey</td>
</tr>
<tr>
<td>700 kHz</td>
<td>WLW</td>
<td>Cincinnati, OH – From 1934 to 1939 it was the “Flamethrower” at 500 kW (highest power ever broadcast in the US)</td>
</tr>
<tr>
<td>810 kHz</td>
<td>KGO</td>
<td>San Francisco, CA – Located in Southeast part of SF Bay (300-foot high antennas which are lowest used in the US)</td>
</tr>
</tbody>
</table>

Uses Sky Waves and can be heard for hundreds of miles depending upon the ionosphere.

https://en.wikipedia.org/wiki/Clear-channel_station
Surface or Ground Waves Follow the Earth’s Contour

Signals spreading out from the transmitter’s antenna

Diffraction from Earth’s surface angles the wave fronts to follow the curvature of the Earth. Ground currents flowing in the Earth attenuate the wave propagation.

What is Ground Wave: Radio Signal Propagation » Electronics Notes (electronics-notes.com)
Uses for Ground Waves in Radio Communication

Attributes of Ground Waves:
1. Confined to low frequencies (generally less than 2 MHz)
2. Best for terrain with higher conductivity and flat
3. Provides for communication beyond the horizon
4. Conducted along boundary between ground & atmosphere
5. Requires vertical polarized E-field
6. Lower frequencies work better in general
7. Best propagation over sea water
8. Generally requires high transmitter broadcast power levels
9. Higher attenuation than space wave (LOS) communications

Specific Applications:
1. AM broadcast radio uses ground waves (535-1605 kHz)
2. Amateur radio bands of 160-meter & 80-meter wavelengths
3. Used for submarine communications (base-to-submarine)
# Radio Spectrum

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Frequency range</th>
<th>Wavelength, $\lambda$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELF</td>
<td>$&lt; 300$ Hz</td>
<td>$&gt; 1000$ km</td>
<td>Earth-ionosphere waveguide propagation</td>
</tr>
<tr>
<td>ULF</td>
<td>$300$ Hz $-$ 3 kHz</td>
<td>$1000$ $-$ 100 km</td>
<td></td>
</tr>
<tr>
<td>VLF</td>
<td>$3$ kHz $-$ 30 kHz</td>
<td>$100$ $-$ 10 km</td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>$30$ $-$ 300 kHz</td>
<td>$10$ $-$ 1 km</td>
<td>Ground wave propagation</td>
</tr>
<tr>
<td>MF</td>
<td>$300$ kHz $-$ 3 MHz</td>
<td>$1$ km $-$ 100 m</td>
<td></td>
</tr>
<tr>
<td>HF</td>
<td>$3$ $-$ 30 MHz</td>
<td>$100$ $-$ 10 m</td>
<td>Ionospheric sky-wave propagation</td>
</tr>
<tr>
<td>VHF</td>
<td>$30$ $-$ 300 MHz</td>
<td>$10$ $-$ 1 m</td>
<td>Space waves, scattering by objects similarly sized to, or bigger than, a free-space wavelength, increasingly affected by tropospheric phenomena</td>
</tr>
<tr>
<td>UHF</td>
<td>$300$ MHz $-$ 3 GHz</td>
<td>$1$ m $-$ 100 mm</td>
<td></td>
</tr>
<tr>
<td>SHF</td>
<td>$3$ $-$ 30 GHz</td>
<td>$100$ $-$ 10 mm</td>
<td></td>
</tr>
<tr>
<td>EHF</td>
<td>$30$ $-$ 300 GHz</td>
<td>$10$ $-$ 1 mm</td>
<td></td>
</tr>
</tbody>
</table>

\[
c = f \cdot \lambda \quad c = 3 \times 10^8 \text{ meters/sec}
\]
Line of Sight Wireless Communications

Radio and Microwave Links (Point-to-Point)

[Image of a city with buildings and a line of sight between two locations]

LOS vs NLOS | Difference between LOS and NLOS wireless_channels (rfwireless-world.com)
First Fresnel Zone for Antenna to Antenna
Importance of the Fresnel Zone in Communications

Radius = \left( \frac{n \lambda d_1 d_2}{d_1 + d_2} \right)^{3/2}

n is index of refraction  
\lambda is wavelength

Conceptual view of the first Fresnel zone and the 3D Partial Fresnel zone. | Download Scientific Diagram (researchgate.net)
Size of Fresnel Zone versus Distance

Zone radius = 17.3 \sqrt{\frac{D \text{(in km)}}{4 \times f \text{(in GHz)}}} \text{ meters}

Zone radius = 72.1 \sqrt{\frac{D \text{(in miles)}}{4 \times f \text{(in GHz)}}} \text{ feet}

[Graph showing the size of the 1st Fresnel Zone versus distance for different frequencies (900 Mhz, 2.4 Ghz, 5.8 Ghz)]
Wireless Channel Wave Propagation

Signal Propagation through Wireless Channels

- The mechanisms behind electromagnetic wave propagation are diverse, but can generally be attributed to reflection, diffraction, and scattering.

- Most cellular radio systems operate in urban areas where there is no direct line-of-sight path between the transmitter and the receiver, and where the presence of high rise buildings causes severe diffraction loss.

- Due to multiple reflections from various objects, the electromagnetic waves travel along different paths of varying lengths.

- The interaction between these waves causes multipath fading at a specific location, and the strengths of the waves decrease as the distance between the transmitter and receiver increases.

- Propagation models that predict the mean signal strength for an arbitrary transmitter-receiver (T-R) separation distance are useful in estimating the radio coverage area of a transmitter.

https://slideplayer.com/slide/12737878/
Challenges in Wireless: Fading in Cellular Telephony

Radio Waves

Base Transceiver Station

Also, Moisture in atmosphere causes attenuation in radio signal strength.

Multipath Reception

Mobile Station: MS or UE
Transmitted signals encounter multiple reflectors in the environment during its propagation before reaching the receiver. This creates **multiple paths** and as a result, the receiver sees multiple copies of the transmitted signal, each traversing in a different path.

https://www.everythingrf.com/community/what-is-signal-fading
Channel Distortion from Multi-Path in Cellular Telephony

Eye diagram for transmitted signal

Eye diagram for received signal

Multi-path is a dominant source of channel distortion

https://dsp.stackexchange.com/questions/51346/intersymbol-interference-due-to-limited-channel-bandwidth/51402
Simplified Path-Loss Model for Wireless Wave Propagation

\[ P_r = P_t K \left( \frac{d_0}{D} \right)^\gamma \]

\( d_0 \) = reference distance from antenna to onset of the far-field region
(often 1 to 10 meters indoors and 10 to 100 meters outdoors), and
\( K \) = “path-loss factor” constant (consists of antenna and average channel
attenuation). If unknown, then use \( K = \left( \frac{\lambda}{4\pi d_0} \right)^2 \)

\( \gamma \) = “path-loss exponent” (empirically determined)

<table>
<thead>
<tr>
<th>Environment</th>
<th>Path-loss exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>2</td>
</tr>
<tr>
<td>Urban area cellular radio</td>
<td>2.7 to 3.5</td>
</tr>
<tr>
<td>Shadowed area cellular radio</td>
<td>3.0 to 5.0</td>
</tr>
<tr>
<td>In-building line of sight</td>
<td>1.6 to 1.8</td>
</tr>
<tr>
<td>Obstructed path in building</td>
<td>4.0 to 6.0</td>
</tr>
</tbody>
</table>
Wireless Signal Strength Variation With Distance

Reflection, refraction, scattering of wireless signal

Base Station

MS or UE
Categories of Large-Scale and Small-Scale Fading

- Large-Scale Fading
  - Path Loss (dB/distance)
  - Shadow Loss (varies around the path loss)
- Small-Scale Fading
  - Multi-Path Rayleigh Fading
In a radio link, the RF signal from the transmitter may be reflected from objects such as hills, buildings, or vehicles. This gives rise to multiple transmission paths at the receiver. 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. The following figure shows the level of attenuation that can occur due to the fading.

Rayleigh fading while Mobile Unit (ME) is moving ( \( f = 900 \text{ MHz} \) )

http://sna.csie.ndhu.edu.tw/~cnyang/MCCDMA/sld034.htm
Two Receiving Antennas to Cancel Rayleigh Fading

Transmitter has one antenna
Receiver has two antennas
Doppler shift occurs when the transmitter of a signal is moving in relation to the receiver. The relative movement shifts the frequency of the signal, making it different at the receiver than at the transmitter.

\[
f_1 = f_c \left(1 - \frac{V}{C}\right) \quad \text{Received Frequency} = f_1
\]

\[
f_2 = f_c \left(1 + \frac{V}{C}\right) \quad \text{Transmitted Frequency} = f_c \quad \text{Received Frequency} = f_2
\]

C = speed of radio wave

https://www.sciencedirect.com/topics/computer-science/doppler-frequency-shift
How Does Doppler Shift Affect Radar Signals?

What is going on in this situation?
Causes of Deterioration of Wireless Signals

1. Free-space loss (scattering, molecular absorption, fog or rain, and wavefront spreading) – large-scale fading
2. Multipath (scattering from objects: reflection, diffraction and refraction) – small-scale fading
3. Shadowing – large-scale fading
4. Mobility (Doppler shifting, rapid environment changes from motion)
5. Interference (from other communication systems)
6. Noise pickup from the channel (also transmitters and receivers add noise) – generally AWGN

Added Complication: The channel is continually changing over time.
Present Wireless Communication Challenges

Today’s biggest wireless challenges:

1. Scarcity of radio spectrum (limited “sweet spot”)
2. Ever increasing data rates are required (think 5G)
3. Multitude of different environments factors: scattering, shadowing, reflection, diffraction, fading, etc.
4. Power consumption in portable user equipment
5. Software complexity of to support user mobility, IoT and Mission-Critical Communication (Smart Highway and autonomous driving vehicles)
6. Cost of infrastructure

→ All of this impacts the challenges of 5G Cellular.
Types of Radio Wave Propagation in Atmosphere

- **Space-wave propagation**
  - Satellite to ground and vice versa

- **Sky-wave propagation**
  - Limited to 2 to 30 megahertz (MHz)
  - Long-distance coverage is due to ionosphere reflection (U-shape due to variation in index of refraction)
  - Used in international broadcasting, amateur radio, & military communication

- **Line of Sight (LOS) propagation**
  - Above 30 MHz (SHF band)
  - EM propagates in straight line (LOS)
  - FM radio & TV analog broadcasting

- **Ground-wave propagation**
  - Below 2 MHz (LF band)
  - EM wave follows the Earth’s contour due to diffraction
  - Applies to AM radio broadcasting

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