Lecture 2
Radio Propagation
Topics

1. Introduction
2. Definition of Electromagnetic Wave
3. Description of a Waveform
4. The Electromagnetic Spectrum
5. Signal Propagation
6. RF Power Conversion
7. Link budget
8. Fresnel Zone
1. Introduction

- **RADIO WAVE** is the wireless transmission and reception of electric impulses or signals by means of electromagnetic (EM) waves.
- Waves are present at all frequencies.
- We can utilize only a small part of this total spectrum to transmit communication signals referred to as the Radio Frequency (RF) spectrum and ranges from about 9 KHz to 300 GHz.
2. Definition of Electromagnetic Wave

- An Electromagnetic wave is the propagation of electrical energy caused by oscillating electric fields inducing oscillating magnetic fields, which then induce further oscillating electric fields, which then induce further oscillating magnetic fields, and so on.

![Figure 1](image-url)
3. Description of a Waveform

- **Distance**: $\lambda$ (meters)
- **Wavelength**: $\lambda$
- **Time**: $T$ (seconds)
- **Period**: $T$
Description of a Waveform - continued

A **cycle** is the smallest portion of a waveform that, if repeated, would represent the entire waveform. Waveforms can be described as having the following properties:

**a = Amplitude**
The measurement of a waveform above a center reference. With EM waves this is usually measured in volts or watts.

**v = Velocity of Propagation**
The velocity of propagation of a wave is the velocity that a wave travels through a medium, and is usually measured in meters per second.

**τ = Period**
The period of a wave is the time it takes for one cycle to pass a fixed point and is usually measured in seconds. It is designated by the Greek letter tau (τ).
Description of a Waveform - continued

\( \lambda = \text{Wavelength} \)
The wavelength of a wave is the distance that the wave will propagate in one cycle and is usually measured in meters and designated by the Greek letter lambda (\( \lambda \)).

\( f = \text{Frequency} \)
The frequency of a wave is the rate at which individual cycles pass a given point and is usually measured in cycles per second or Hertz (Hz), named after Heinrich Hertz, who discovered EM waves.

All of these properties except amplitude are related by the following formula: \( f = \frac{1}{\tau} = \frac{v}{\lambda} \)
The velocity of propagation for EM waves is equal to the speed of light \( (3 \times 10^8 \text{ m/s}) \).
Substituting this constant for velocity yields the following:

\( f = \frac{(3 \times 10^8 \text{ m/s})}{\lambda} \)
4. The Electromagnetic Spectrum

- The EM spectrum is the ENTIRE range of EM waves in order of increasing frequency and decreasing wavelength.

- As you go from left → right, the wavelengths get smaller and the frequencies get higher. This is an inverse relationship between wave length and frequency.
Types of EM Waves

**Radio Waves**: Have the longest wavelengths and the lowest frequencies; wavelengths range from 1000s m to .001 m. Used in: Wireless Communication (will be explained further).

**Infrared waves (heat)**: Have a shorter wavelength, from .001 m to 700 nm, and therefore, a higher frequency. Used for finding people in the dark and in TV remote control devices.

**Visible light**: Wavelengths range from 700 nm (red light) to 30 nm (violet light) with frequencies higher than infrared waves.

**Ultraviolet Light**: Wavelengths range from 400 nm to 10 nm; the frequency (and therefore the energy) is high enough with UV rays to penetrate living cells and cause them damage.
Types of EM Waves

**X-Rays**: Wavelengths from 10 nm to .001 nm. These rays have enough energy to penetrate deep into tissues and cause damage to cells; are stopped by dense materials, such as bone.

- Used to look at solid structures, such as bones and bridges.

**Gamma Rays**: Carry the most energy and have the shortest wavelengths, less than one trillionth of a meter (10^-12).

- Gamma rays are released by nuclear reactions in nuclear power plants, by nuclear bombs, and by naturally occurring elements on Earth.

- Sometimes used in the treatment of cancers.
Radio Frequencies Spectrum
(not required in the Exam)
Frequency Bands with Usage
(not required in the Exam)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Wavelength</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>50–60 Hz</td>
<td>6000–5000 km</td>
<td>AC electricity transmission</td>
</tr>
<tr>
<td>3–30 kHz</td>
<td>100–10 km</td>
<td>Sub-marine communication</td>
</tr>
<tr>
<td>30–300 kHz</td>
<td>10–1 km</td>
<td>Long-wave radio broadcast</td>
</tr>
<tr>
<td>180–1600 kHz</td>
<td>1.7 km–188 m</td>
<td>AM radio broadcast</td>
</tr>
<tr>
<td>1.8–30 MHz</td>
<td>167–10 m</td>
<td>Shortwave radio</td>
</tr>
<tr>
<td>88–108 MHz</td>
<td>3.4–2.7 m</td>
<td>FM broadcast</td>
</tr>
<tr>
<td>300–3000 MHz</td>
<td>1–0.1 m</td>
<td>UHF point to point</td>
</tr>
<tr>
<td>800–2200 MHz</td>
<td>0.375–0.136 m</td>
<td>Mobile base station</td>
</tr>
<tr>
<td>1–60 GHz</td>
<td>0.3–0.005 m</td>
<td>Microwave links</td>
</tr>
<tr>
<td>60–300 GHz</td>
<td>0.005–0.001 m</td>
<td>Millimeter-wave links</td>
</tr>
<tr>
<td>352, 230, 193 THz</td>
<td>1550, 1300, 850 nm</td>
<td>Fiber-optic links</td>
</tr>
<tr>
<td>420–750 THz</td>
<td>714–400 nm</td>
<td>Visible light</td>
</tr>
</tbody>
</table>
Practical Spectrum Analyzer – WiFi Analyzer App

2.4 GHz

5 GHz
5. Signal Propagation

In a radio system, the path between the transmit and the receive antennas has obstacles (including hills, forests, buildings etc). Here we look at key channel properties that it is important to understand.

- 1) Reflection occurs when a radio wave hits a smooth surface that is much greater than a wavelength and effectively bounces off.
- 2) Diffraction (or shadowing) occurs when the path between the transmitter and receiver is blocked by a dense object that is much greater than a wavelength, forming secondary waves behind the obstruction.
- 3) Scattering occurs when a radio wave hits either a rough surface or a surface with dimensions of a wavelength or less, causing reflected energy to scatter.
Signal propagation ranges

- Transmission range
  - communication possible
  - low error rate

- Detection range
  - detection of the signal possible
  - no communication possible

- Interference range
  - signal may not be detected
  - signal adds to the background noise
Attenuation

- Strength of signal falls off with distance over transmission medium
- Attenuation factors for wireless 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
6. RF Power Conversion

- **Power, strength of a signal (absolute)**
  - **dBm or dB(mW)** (decibel milliwatt, power ratio) — absolute power in decibels relative to 1 mW.

The conversion between Power in mW and Power in dBm can be done by

\[
P_{dBm} = 10 \log_{10}(P_{mW})
\]

\[
P_{mW} = 10^{\frac{P_{dBm}}{10}}
\]

- 0 dBm = 1 mW
- 20 dBm = 100 mW
- 30 dBm = 1 W
## Typical Practical Radio Power in dBm Values

(Not required in the Exam)

<table>
<thead>
<tr>
<th>dBm level</th>
<th>Power</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 dBm</td>
<td>100 kW</td>
<td><em>Typical transmission power of FM radio station with 30-40 miles range</em></td>
</tr>
<tr>
<td>60 dBm</td>
<td>1 kW</td>
<td><em>Typical combined radiated RF power of microwave oven elements</em></td>
</tr>
<tr>
<td>36 dBm</td>
<td>4 W</td>
<td><em>Typical maximum output power for a Citizens' band radio station (27 MHz) in many countries</em></td>
</tr>
<tr>
<td>30 dBm</td>
<td>1 W</td>
<td><em>Typical RF leakage from a microwave oven - Maximum output power for DCS 1800 MHz mobile phone</em></td>
</tr>
<tr>
<td>27 dBm</td>
<td>500 mW</td>
<td><em>Typical cellular phone transmission power</em></td>
</tr>
<tr>
<td>20 dBm</td>
<td>100 mW</td>
<td><em>Bluetooth Class 1 radio, 100 m range (maximum output power from unlicensed FM transmitter). Typical wireless router transmission power.</em></td>
</tr>
<tr>
<td>18 dBm</td>
<td>70 mW</td>
<td><em>Maximum output power of a Typical WLAN card</em></td>
</tr>
<tr>
<td>4 dBm</td>
<td>2.5 mW</td>
<td><em>Bluetooth Class 2 radio, 10 m range</em></td>
</tr>
<tr>
<td>0 dBm</td>
<td>1.0 mW</td>
<td><em>Bluetooth standard (Class 3) radio, 1 m range</em></td>
</tr>
<tr>
<td>-10 dBm</td>
<td>100 μW</td>
<td><em>Typical max received signal power (−10 to −30 dBm) of a wireless network</em></td>
</tr>
<tr>
<td>-70 dBm</td>
<td>100 pW</td>
<td><em>Typical range of Wireless received signal power over a network</em></td>
</tr>
<tr>
<td>-127.5 dBm</td>
<td>0.178 fW</td>
<td><em>Typical received signal power from a GPS satellite</em></td>
</tr>
</tbody>
</table>
Example of Signal Attenuation in Different Material (not required in the Exam)

<table>
<thead>
<tr>
<th>Signal attenuation through</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window in brick wall</td>
<td>2</td>
</tr>
<tr>
<td>Metal frame, glass wall in building</td>
<td>6</td>
</tr>
<tr>
<td>Office wall</td>
<td>6</td>
</tr>
<tr>
<td>Metal door in office wall</td>
<td>6</td>
</tr>
<tr>
<td>Cinder wall</td>
<td>4</td>
</tr>
<tr>
<td>Metal door in brick wall</td>
<td>12.4</td>
</tr>
<tr>
<td>Brick wall next to metal door</td>
<td>3</td>
</tr>
</tbody>
</table>
Decibel version of free space path loss equation

- Most RF comparisons and measurements are performed in decibels. This gives an easy and consistent method to compare the signal levels present at various points. Accordingly it is very convenient to express the free space path loss formula, FSPL, in terms of decibels.

\[
FSPL \ (\text{dB}) = 20 \log_{10}(d) + 20 \log_{10}(f) + 32.44
\]

- Where:
  - \(d\) is the distance of the receiver from the transmitter (km)
  - \(f\) is the signal frequency (MHz)
7. Link budget

- **Link budget** is a way of evaluating the link performance of the link.

- The received power in the wireless link is determined by three factors: *transmit power, transmitting antenna gain*, and *receiving antenna gain*.

- If that power, minus the *free space loss* of the link path, is greater than the *minimum received signal level* of the receiving radio, then a link is possible.

- The difference between the minimum received signal level and the actual received power is called the *link budget* or *link margin*.

- The link margin must be positive, and should be maximized (should be at least 10dB or more for reliable links).
Link Budget calculation
Link Budgets

- Link budgets
  - Calculate whether you will have enough signal strength to meet the receiver’s minimum requirements

- A simple link budget equation looks like this:

\[
\text{Received Power (dBm)} = \text{Transmitted Power (dBm)} + \text{Gains (dB)} - \text{Losses (dB)}
\]

- Information needed to calculate link budget includes:
  - Gain of the antennas
  - Cable and connector losses for receiver and transmitter
  - Free space loss figure, ... etc
Link Budget Formula

Receive Signal Level (RSL)
\[ \text{RSL} = P_o - L_{ctx} + G_{atx} - L_{crx} + G_{atx} - \text{FSL} \]

Link feasibility formula
\[ \text{RSL} \geq \text{Rx} \] (receiver sensitivity threshold)
\( P_o \) = output power of the transmitter (dBm)
\( L_{ctx}, L_{crx} \) = Loss (cable, connectors, branching unit) between transmitter/receiver and antenna (dB)
\( G_{atx} \) = gain of transmitter/receiver antenna (dBi)
\( \text{FSPL} \) = free space path loss (dB)
**Example of Wireless AP Specifications**

<table>
<thead>
<tr>
<th>Processor Specs</th>
<th>Atheros MIPS 4KC, 180MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory Information</td>
<td>16MB SDRAM, 4MB Flash</td>
</tr>
<tr>
<td>Networking Interface</td>
<td>1 X 10/100 BASE-TX (Cat. 5, RJ-45) Ethernet Interface</td>
</tr>
</tbody>
</table>

**REGULATORY / COMPLIANCE INFORMATION**

<table>
<thead>
<tr>
<th>Wireless Approvals</th>
<th>FCC Part 15.247, IC RS210, CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>RoHS Compliance</td>
<td>YES</td>
</tr>
</tbody>
</table>

**SYSTEM INFORMATION**

**RADIO OPERATING FREQUENCY 2412-2462 MHz**

<table>
<thead>
<tr>
<th>TX SPECIFICATIONS</th>
<th>RX SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>802.11b</strong></td>
<td><strong>802.11b</strong></td>
</tr>
<tr>
<td>DataRate</td>
<td>TX Power</td>
</tr>
<tr>
<td>1Mbps</td>
<td>20 dBm</td>
</tr>
<tr>
<td>2Mbps</td>
<td>20 dBm</td>
</tr>
<tr>
<td>5.5Mbps</td>
<td>20 dBm</td>
</tr>
<tr>
<td>11Mbps</td>
<td>20 dBm</td>
</tr>
<tr>
<td><strong>802.11g/OFDM</strong></td>
<td><strong>802.11g/OFDM</strong></td>
</tr>
<tr>
<td>DataRate</td>
<td>TX Power</td>
</tr>
<tr>
<td>6Mbps</td>
<td>20 dBm</td>
</tr>
<tr>
<td>9Mbps</td>
<td>20 dBm</td>
</tr>
<tr>
<td>12Mbps</td>
<td>20 dBm</td>
</tr>
<tr>
<td>18Mbps</td>
<td>20 dBm</td>
</tr>
<tr>
<td>24Mbps</td>
<td>20 dBm</td>
</tr>
<tr>
<td>36Mbps</td>
<td>18 dBm</td>
</tr>
<tr>
<td>48Mbps</td>
<td>16 dBm</td>
</tr>
<tr>
<td>54Mbps</td>
<td>15 dBm</td>
</tr>
</tbody>
</table>
Example link budget calculation

Let’s estimate the feasibility of a 5 km link, with one access point and one client radio. The access point is connected to an antenna with 10 dBi gain, with a transmitting power of 20 dBm and a receive sensitivity of -89 dBm. The client is connected to an antenna with 14 dBi gain, with a transmitting power of 15 dBm and a receive sensitivity of -82 dBm. The cables in both systems are short, with a loss of 2dB at each side at the 2.4 GHz frequency of operation.
Solution for link budget calculation Part 1

Free Space Loss Calculation

FSPL = (20\log_{10} (f)) + (20\log_{10} (D)) + 32.4
FSPL = path loss in dB
f = frequency in MHz
D = distance in kilometers between antennas

In the example f= 2.4 GHz = 2400 MHz
D = 5 Km

FSPL = (20\log_{10} (2400)) + (20\log_{10} (5)) + 32.4
FSPL = 20 \times 3.38 + 20 \times 0.7 + 32.4 = 114 dB
AP to Client link

+20 dBm

Tx power

EIRP

Path loss

-114 dB @ 5 km

-82 dBm

Rx sensitivity

Margin

Rx power

??
Link budget: AP to Client link

20 dBm (TX Power AP)
  - 2 dB (Cable Losses AP)
  + 10 dBi (Antenna Gain AP)
-114 dB (free space loss @5 km)
+ 14 dBi (Antenna Gain Client)
- 2 dB (Cable Losses Client)

-74 dBm (expected received signal level)
--82 dBm (sensitivity of Client)

8 dB (link margin)
- Solution for link budget calculation Part 1

- Free Space Loss Calculation

FSPL = \((20\log_{10}(f)) + (20\log_{10}(D)) + 32.4\)

FSPL = path loss in dB
f = frequency in MHz
D = distance in kilometers between antennas

In the example f= 2.4 GHz = 2400 MHz
D = 5 Km

FSPL = \((20\log_{10}(2400)) + (20\log_{10}(5)) + 32.4\)
FSPL = 20 \times 3.38 + 20 \times 0.7 + 32.4 = 114 \text{ dB}
Client to AP

+15 dBm

Tx radio

-2 dB

cable

EIRP

+14 dBi

antenna

-114 dB @ 5 km

path loss

+10 dBi

antenna

-2 dB

cable

Rx radio

-89 dBm

Rx power

Margin

Rx sensitivity

+10 dBi

Client to AP

+15 dBm

Tx radio

-2 dB

cable

EIRP

+14 dBi

antenna

-114 dB @ 5 km

path loss

+10 dBi

antenna

-2 dB

cable

Rx radio

-89 dBm

Rx power

Margin

Rx sensitivity

+10 dBi
Link budget: Client to AP link

15 dBm (TX Power Client)
- 2 dB (Cable Losses Client)
+ 14 dBi (Antenna Gain Client)
-114 dB (free space loss @5 km)
+ 10 dBi (Antenna Gain AP)
- 2 dB (Cable Losses AP)

-79 dBm (expected received signal level)
--89 dBm (sensitivity of AP)

10 dB (link margin)
8. Fresnel Zone

- The Fresnel Zone is a volume around the Line of Sight (LOS) that must be clear of any obstacle for the maximum power to reach the receiving antenna.

- Objects in the Fresnel Zone as trees, hilltops and buildings can considerably attenuate the received signal, even when there is an unobstructed line between the TX and RX.

- It is better that no more than 20% blockage of the Fresnel Zone.