Frequency, Range and type of Wireless Communication

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NSA, UiO, Autumn 2016
Radio Frequency

<table>
<thead>
<tr>
<th>Designation</th>
<th>Frequency</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELF</td>
<td>3Hz to 30Hz</td>
<td>100'000km to 10'000 km</td>
</tr>
<tr>
<td>SLF</td>
<td>30Hz to 300Hz</td>
<td>10'000km to 1'000km</td>
</tr>
<tr>
<td>ULF</td>
<td>300Hz to 3000Hz</td>
<td>1'000km to 100km</td>
</tr>
<tr>
<td>VLF</td>
<td>3kHz to 30kHz</td>
<td>100km to 10km</td>
</tr>
<tr>
<td>LF</td>
<td>30kHz to 300kHz</td>
<td>10km to 1km</td>
</tr>
<tr>
<td>MF</td>
<td>300kHz to 3000kHz</td>
<td>1km to 100m</td>
</tr>
<tr>
<td>HF</td>
<td>3MHz to 30MHz</td>
<td>100m to 10m</td>
</tr>
<tr>
<td>VHF</td>
<td>30MHz to 300MHz</td>
<td>10m to 1m</td>
</tr>
<tr>
<td>UHF</td>
<td>300MHz to 3000MHz</td>
<td>1m to 10cm</td>
</tr>
<tr>
<td>SHF</td>
<td>3GHz to 30GHz</td>
<td>10cm to 1cm</td>
</tr>
<tr>
<td>EHF</td>
<td>30GHz to 300GHz</td>
<td>1cm to 1mm</td>
</tr>
</tbody>
</table>

Fig. 1: Frequency and Wavelength

Penetration - Use
- Seawater - Pipeline Inspection Gauge/Submarine Communication
- Seawater - Submarine Communication
- Earth - Communication in Mines / 40m in Saltwater - Wireless Telegraph
- Kilometer wave - Long Distance Communication
- Hectometer wave - AM Radio Broadcasting
- Decameter wave - Shortwave radio, aviation communication
- Decimeter wave - FM radio, Air Traffic Controller, TV Broadcast
- Centimeter wave - GPS, Satellite Comm, Wi-Fi, Bluetooth
- Milimeter wave - Radio Astronomy/5G Mobile phones (Expected)
- Radio Wave - Experimental medical imaging to replace X-rays, terahertz computing/communications, remote sensing
Electromagnetic Radiation Spectrum
Frequency and Approximate Scale of Wavelength
Location of 802.11 Spectrum
2.4 GHz and 5 GHz Signal Strength

![Signal Strength Graph](image)

**Free Space Path Loss**

\[
\text{Free Space Path Loss} = \left( \frac{4\pi d}{\lambda} \right)^2
\]

or

\[
\text{Free Space Path Loss} = \left( \frac{4\pi df}{c} \right)^2
\]

\[
\lambda := \frac{c}{f} \quad \text{Range(PL)} := \frac{\lambda}{4\pi} \cdot 10^{\frac{PL}{20}}
\]

Equation 1-1: Free Space Range
Towards THz Communications

Fig. 2: Development of data rates in wireline, nomadic and wireless systems
Time-domain Terahertz Spectroscopy

Spectrum of electromagnetic radiation

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Radiation</th>
<th>Wavelength (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^5$</td>
<td>Radio- and TV-waves</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$10^6$</td>
<td>Microwaves</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$10^7$</td>
<td>THz</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$10^8$</td>
<td>Infrared</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$10^9$</td>
<td>Ultraviolet</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$10^{10}$</td>
<td>X-rays and γ</td>
<td>$10^3$</td>
</tr>
</tbody>
</table>

1 THz ↔ 1 ps ↔ 33 cm$^{-1}$ ↔ 0.3 mm ↔ 48 K ↔ 4.1 meV
T-Rays on the Spectrum
C-DOT-rays shine through the modulator. With no voltage applied, electrons can flow across the gap in the gold structure. The electrons absorb a few T-rays as they flow easily around the two loops. Applying voltage prevents electrons from crossing the gap. But they absorb far more T-rays as they slosh back and forth between the upper and lower halves of the structure. Fewer T-rays pass through the device.
Communication Frequencies

Frequency and wavelength:

\[ \lambda = \frac{c}{f} \]

wave length \( \lambda \), speed of light \( c \cong 3 \times 10^8 \text{m/s} \), frequency \( f \)
Comparison of conventional and THz communication channels

<table>
<thead>
<tr>
<th></th>
<th>2.4 GHz, 5 GHz</th>
<th>60 GHz</th>
<th>300 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path loss at 10 m</td>
<td>≈ 60 dB</td>
<td>≈ 88 dB</td>
<td>≈ 101 dB</td>
</tr>
<tr>
<td>Output powers</td>
<td>Limited by regulations; ≈ 22 dBm</td>
<td>Limited by technology and regulations; typically ≈ 10 dBm</td>
<td>Currently limited by technology &lt;10 dBm</td>
</tr>
<tr>
<td>Antennas</td>
<td>Omnidirectional (≈ 3 dBi)</td>
<td>Medium directivities (15…25 dBi)</td>
<td>High directivities (20…40 dBi)</td>
</tr>
<tr>
<td>Bandwidths</td>
<td>40 MHz</td>
<td>≈ 2 GHz</td>
<td>10…100 GHz</td>
</tr>
<tr>
<td>Data rates</td>
<td>600 Mbit/s</td>
<td>≈ 4 Gbit/s</td>
<td>100 Gbit/s and beyond</td>
</tr>
</tbody>
</table>
Why Actual Range May Not Equal Stated Range???
RF Power And dBm

• RF power is expressed in db with milliwatt i.e., dBm

dBm to mW conversion:
• $P(\text{dBm}) = 10 \cdot \log_{10}(P(\text{mW}))$
• $P(\text{mW}) = 10^{(P(\text{dBm})/10)}$
Path Loss

• Path loss = transmit power - receiver sensitivity + gains - losses
• Received power = transmit power + gains - losses
• Maximum path loss = transmit power - receiver sensitivity + gains - losses - fade margin

RF Propagation
Basic loss formula

Propagation Loss

\[ P_k = P_r + G \cdot \left( \frac{\lambda}{4\pi d} \right)^2 \]

- \( P_k \) = receive power [mW]
- \( P_r \) = transmit power [mW]
- \( G \) = antennae gain
- \( d \) = distance between Tx and Rx antenna [meter]

\( Pr \sim 1/P \cdot D^2 \) which means
- 2X Frequency = 1/4 Power
- 2 X Distance = 1/4 Power
Once the maximum path loss has been found, you can find the range from the formula:

\[
\text{Distance (km)} = 10^{\frac{\text{maximum path loss} - 32.44 - 20\log(f)}{20}}
\]

Factors effecting the range:

1) Antenna gain
2) Antenna height
3) Interference
Wireless Channel Capacity

**Wireless Channel Capacity**

*Fundamental Limit on Data Rates*

*Capacity:* The set of simultaneously achievable rates \{R_1, \ldots, R_n\}

- Main drivers of channel capacity
  - Bandwidth and power
  - Statistics of the channel
  - Channel knowledge and how it is used
  - Number of antennas at TX and RX
Additive White Gaussian Noise

If the average received power is $\bar{P}$ [W] and the noise power spectral density is $N_0$ [W/Hz], the AWGN channel capacity is

$$C_{\text{AWGN}} = W \log_2 \left( 1 + \frac{\bar{P}}{N_0 W} \right) \text{[bits/s]},$$

where $\frac{\bar{P}}{N_0 W}$ is the received signal-to-noise ratio (SNR). This result is known as the Shannon–Hartley theorem.\(^6\)
Shannon-Hartley Theorem

Channel Capacity

Theoretical limit on the speed of information transmission is given by Shannon–Hartley theorem:

\[ C = B \log_2 \left( 1 + \frac{S}{N} \right). \]

Here:
- \( C \) — maximal theoretical channel capacity (bits/sec);
- \( B \) — bandwidth (hertz);
- \( S \) — signal power (watts);
- \( N \) — noise power (watts).

In case of wideband signal:

\[ C = \int_{f_{\text{min}}}^{f_{\text{max}}} \log_2 \left( 1 + \frac{S(f)}{N(f)} \right) df. \]
Signal to Noise Ratio

**SIGNAL-TO-NOISE RATIO (SNR)**

The sound level at the listener’s ear, above the background noise level.

If the Signal at listener’s ear is 47 decibels and the background Noise level is 45 decibels, the S/NR = +2 dB.
Power of transmitted signals

Sphere surface area = $4\pi r^2$

Intensity at a distance $r$ from the source:

$I = \frac{I_0}{4\pi r^2}$
Wave fades with distance

Wave Defraction
Wave fading types

Fading Types

- Slow (Long) Term
- Fast (Short) Term (*Also known as Rayleigh fading*)

Fading Models

- Nakagami fading
- Rayleigh fading
- Rician fading
- Dispersive fading models, with several echoes, each exposed to different delay, gain and phase shift, often constant. This results in frequency selective fading and inter-symbol interference. The gains may be Rayleigh or Rician distributed. The echoes may also be exposed to Doppler-shift, resulting in a time-varying channel model.
- Log-normal shadow fading

Exact representation of fading characteristics is not possible, because of infinite number of situations.
Range vs Rate

<table>
<thead>
<tr>
<th></th>
<th>802.11n</th>
<th>802.11ac</th>
<th>802.11ad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>600 Mbps</td>
<td>3.2 Gbps</td>
<td>Up to 7 Gbps</td>
</tr>
<tr>
<td>Coverage</td>
<td>Home, 70 m</td>
<td>Home, 30 m</td>
<td>Room, &lt;5m</td>
</tr>
<tr>
<td>Freq. Band</td>
<td>2.4/5 GHz</td>
<td>5 GHz</td>
<td>2.4/5/60 GHz</td>
</tr>
<tr>
<td>Antennas</td>
<td>4 x 4 MIMO</td>
<td>8 x 8 MIMO</td>
<td>&gt;10 x 10 MIMO</td>
</tr>
<tr>
<td>Applications</td>
<td>Data, Video</td>
<td>Video</td>
<td>Uncompressed Video</td>
</tr>
</tbody>
</table>
Range vs Rate cont…

- **Legacy 802.11a/g**
- **FAP-220B 802.11n 2x2:2**
- **FAP-320B 802.11n 3x3:3**
- **FAP-221C 802.11ac 2x2:2**
- **FAP-320C 802.11ac 3x3:3**

- Data Rate in Mbps:
  - 11ac (3-antenna)
  - 11n (1-antenna)
  - 11n (3-antenna)

- Distance in Meters:
  - 1 Room
  - 2 Rooms
  - 3 Rooms
  - 4+ Rooms
Propagation Characteristics

- Path Loss (includes average shadowing)
- Shadowing (due to obstructions)
- Multipath Fading
BER vs SNR

Bit error rate (BER) = Bit error probability = Pb

\[
\begin{align*}
P\{\text{single bit error}\} &= p \\
P\{\text{no error in single bit}\} &= (1 - p) \\
P\{\text{no error in 8 bits}\} &= (1 - p)^8 \\
P\{\text{unseen error in 8 bits}\} &= 1 - (1 - p)^8 = 7.9 \times 10^{-4}
\end{align*}
\]

Packet error rate (PER) = Packet error probability for packet length N bits:
\[
P_p = 1 - (1 - Pb)^N
\]

QAM solutions
Gain ICs

Bit Error Rate (BER) versus Signal to Noise Ratio (SNR)
For Various Data Transmission Methods

off charts
BER
POSSIBLE SIGNAL PATH FROM AP TO USER
WHAT COULD HAPPEN TO SIGNAL ALONG THE WAY TO RECEIVER

TRANSMITTED SIGNAL SPECTRUM

DISTORTED RECEIVED SIGNAL SPECTRUM
The frame format used with an 802.11 wireless LAN.

<table>
<thead>
<tr>
<th>CTL</th>
<th>DUR</th>
<th>Address 1 (destination)</th>
<th>Address 2 (source)</th>
<th>Address 3 (dest. 2)</th>
<th>SEQ</th>
<th>Address 4</th>
<th>Payload (0 to 2312 bytes)</th>
<th>CRC</th>
</tr>
</thead>
</table>

- **AP or wireless computer's MAC**
- **sender's MAC address**
- **router's MAC address**
- **used in ad hoc mode**

Payload is typically fewer than 1500 bytes.
Wireless Channel Bonding

<table>
<thead>
<tr>
<th>Number of Streams</th>
<th>Bitrate (Mbps)</th>
<th>Channel Width (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 stream</td>
<td>67</td>
<td>20 MHz</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>40 MHz</td>
</tr>
<tr>
<td></td>
<td>433</td>
<td>80 MHz</td>
</tr>
<tr>
<td>2 streams</td>
<td>173</td>
<td>20 MHz</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>40 MHz</td>
</tr>
<tr>
<td></td>
<td>866</td>
<td>80 MHz</td>
</tr>
<tr>
<td>3 streams</td>
<td>289</td>
<td>20 MHz</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>40 MHz</td>
</tr>
<tr>
<td></td>
<td>1300</td>
<td>80 MHz</td>
</tr>
</tbody>
</table>

- **Original 802.11a,g OFDM 54 Mbps**
- **Improved OFDM 52 subcarriers vs. 48 for original 65 Mbps**
- **Reduced guard interval between OFDM symbols 400 ns instead of 800 ns 150 Mbps**
- **Channel bonding combines two adjacent 20MHz channels into a single 40MHz channel providing increased throughput.**
References

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http://foresight.ifmo.ru/ict/shared/files/201311/1_143.pdf
Questions????

Thank you!