RF propagation (Lecture 18)

Propagation in UHF frequency band.

UHF Frequencies: \( f \in [300\text{MHz} - 3000\text{MHz}] \) (SHF band)
\( \lambda \in [10\text{cm} - 1\text{cm}] \)

Sometimes frequencies from 2GHz to 40GHz are considered as mm-wave frequencies.

Microwave Frequency bands are further subdivided into additional bands:

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency [MHz]</th>
<th>Wavelength [cm]</th>
<th>Common applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1 - 2</td>
<td>15 - 30</td>
<td>PCS, Remote sensing</td>
</tr>
<tr>
<td>S</td>
<td>2 - 4</td>
<td>7.5 - 15</td>
<td>Weather, AIDC control</td>
</tr>
<tr>
<td>C</td>
<td>4 - 8</td>
<td>3.75 - 7.5</td>
<td>Weather, Long range radar</td>
</tr>
<tr>
<td>X</td>
<td>8 - 12</td>
<td>2.25 - 6.75</td>
<td>SatCom, Missile guidance</td>
</tr>
<tr>
<td>Ku</td>
<td>12 - 18</td>
<td>1.6 - 2.75</td>
<td>SatCom, High Res Maps</td>
</tr>
<tr>
<td>Kα</td>
<td>18 - 37</td>
<td>18 - 27</td>
<td>Very High Res Maps, Broadband</td>
</tr>
<tr>
<td>Kα</td>
<td>27 - 40</td>
<td>0.75 - 1</td>
<td>Airport surveillance</td>
</tr>
</tbody>
</table>

2.4GHz - PCS, 3G systems, WiFi

4.9GHz - Long haul mm-wave link for telecom. Path lengths about 40 miles

60GHz - Broadband telecom, WiFi

100GHz - Point to point mm-wave
High density HFC - PSTN links. Dedicated broadband links

28-38 GHz Broadband Point to point and point to multipoint communication.

Microwave propagation

* In microwave frequency band the links are usually point to point
* Systems usually use narrow beam antennas
* Systems usually rely on the LOS propagation

In the first approximation the path loss of the microwave link can be estimated using Friis equation:

\[ PL[dB] = 26.5 + 20 \log(f [MHz]) + 20 \log d [km] \]

\[ PL[dB] = 32.44 + 20 \log f [MHz] + 20 \log d [km] \]

Additional propagation effects:

* Reflection
* Diffraction
* Scattering

* For communication purposes these are security effects.
* Usually microwave links are designed as LOS (no diffraction).
* Using non-uniform antennas (no reflection or scattering)

Note: There are many applications that rely on reflection and
by\* radars and remote sensing.
Earth curvature and geometric effects

- Earth curvature limits the distance between two terminals.
- Even if there are no obstructions, the LOS will be limited after some distance.

\[ s = 6378 \, \text{km} = 3964 \, \text{miles} \]

Earth bulge.

Using cosine theorem:

\[ x^2 = a^2 + d_1^2 - 2ad_1 \cos \delta \quad (1) \]

\[ x^2 = a^2 + d_2^2 - 2ad_2 \cos \delta \]

From (1), \[ \cos \delta = \frac{a^2 + d_1^2 - x^2}{2ad_1} \], substituting in (2)
\[ \chi^2 = c^2 + d_2^2 - 2sd_2 \cdot \frac{s^2 + d_1^2 - x^2}{2sd_1} \]

\[ \chi^2 = s^2 + d_2^2 - \frac{d_2}{d_1} \left( s^2 + d_1^2 - x^2 \right) \]

\[ \chi^2 \left( 1 - \frac{d_2}{d_1} \right) = s^2 \left( 1 - \frac{d_2}{d_1} \right) + d_2^2 - d_1d_2 \]

The Earth bulge can be expressed as:

\[ \Delta b = s - x \]

\[ \Delta b = 8 - [s^2 + \frac{d_2 (d_2 - d_1)}{d_1 - d_2}]^{1/2} \]

\[ = 8 \left[ 1 - \sqrt{1 - \frac{d_1d_2}{s^2}} \right]^2 \]

Having in mind that \( d_1d_2 \ll s^2 \)

\[ \Delta b \approx 8 \left( 1 - 1 + \frac{d_1d_2}{2s^2} \right) \approx \frac{d_1d_2}{2s^2} \]

\[ \Delta b \text{ maximum occurs when } d_1 = d_2 = d. \quad \Delta b_{\text{max}} = \frac{d^2}{2s^2} \]

Example. Consider two µ-wave siles having equal lengths of 40 m. Determine their maximum separation so that they fall on condition. Assume bolt Earth, with radius of \( s = 6378.15 \text{ km} \)
The maximum range for LOS communication occurs when $\Delta h = \Delta h_{\text{max}} = H$

$\Delta h_{\text{max}} = \frac{c^2}{2g} = H \Rightarrow d = \left(284\right)^{\frac{1}{2}}$

$D_{\text{max}} = 2d = 2\sqrt{6378 \cdot 10^3 \times 40} = 31.944 \text{ km}$

Radio horizon vs Earth curvature.

Distance to radio horizon can be estimated as

$D = (284)^{\frac{1}{2}}$

* In the discussion so far, we have assumed straight-line propagation of radio waves.
* In reality, due to changes in reflection coefficient of the atmosphere, the waves bend towards the Earth.
Bending of the radio waves can be modeled through an increase in Earth radius. This usually makes Earth slightly larger (more flat) and the radio waves propagate in the straight line.

\[ s_e = K s \]

where

- \( s_e \) - Effective radius of the Earth
- \( s \) - Real radius at the earth
- \( K \) - "K" factor.

Typical values of the \( K \) factor are given as

- \( K < 1/3 \) - low ground humidity, dry area, cold water,
- \( K = 4/3 \) - typical inland condition
- \( K > 4/3 \) - high ground humidity, dry area but avoid low layers.
Example: A 5 GHz microwave link is established in a typical
inland town (K = 4/3). Antenna towers are 20 meters high, and the
distance between tower is 200 m. If midpoint between the buildings is
a 18 m high building, is there a loss between terminals?

\[ \Delta h = \frac{d^2}{28K} = \frac{(D/2)^2}{28K} \]

\[ \Delta h = \frac{(2010^{3/2})^2}{2.6876 \times 10^{-4} \times 10^{2}} = 5.879 \text{ m} \]

Total height of the building

\[ h = h_0 + \Delta h = 18 + 5.879 = 23.879 \text{ m} \]

The building appears higher due to the curvature of the Earth.

Since path is observed in presence of the path loss we need to use
some diffraction model. Usually KED model is used.
For μ-wave design at least 65% of the first Fresnel zone clearance is required.

Microwave Link engineering:

* Microwave links are usually designed with high accuracy requirements.
* μ-wave links are used for broadband traffic and usually the data is not heavily encoded and protected.
* The reliability of the link is calculated through outage time.

The reliability of a μ-wave link is calculated as:

\[
R = 100 - \frac{\text{total down time in test period}}{\text{duration of the test period}}
\]

The reference hue (test period) is usually assumed as 1 year while for total down time is usually expressed in minutes.

<table>
<thead>
<tr>
<th>Outage Time [min]</th>
<th>Reliability [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99.998097</td>
</tr>
<tr>
<td>5</td>
<td>99.990487</td>
</tr>
<tr>
<td>10</td>
<td>99.9980974</td>
</tr>
<tr>
<td>15</td>
<td>99.9971461</td>
</tr>
</tbody>
</table>

1 year = 525,600 min.
Example. Consider a link with an outage time of 5 min per year. Assume that link comes TI. Calculate reliability and BER.

\[
R = 100 - 100 \cdot \frac{5}{525600} = 99.999\% \quad (5\text{ times})
\]

\[
BER = \frac{5}{525600} = 9.52 \cdot 10^{-6} \quad \text{probability of making an error}
\]

Number of errors per second.

\[
\text{Number} = 1.544 \text{ Mb/sec} \times 9.52 \cdot 10^{-6} = 14.68 \text{ bits}
\]

Even with reliability this high, the link experiences 14.7 erroneous bits every second.

Example. The link carrying TI data is not allowed more than 40 errors per minute. Calculate allowed down time.

\[
BER = \frac{90/60}{1.544 \cdot 10^4} = 9.715 \cdot 10^{-7}
\]

\[
\text{Total} = 525600 \times \text{BER} = 0.51 \text{ min} = 30.6 \text{ sec}
\]

The link can be down only 30 seconds during entire year.

To assure proper outage time, a substantial Pade margin needs to be built into the TI wire link design.