Background on wireless PHY layer
RF Properties

- **Understanding Radio Frequency**
  - Generation, coverage and propagation issues
  - Fundamental for wireless planning and management

- **Radio Frequency Signals**
  - Electromagnetic energy generated by high frequency alternate current (AC) in antennas
  - Antenna: converts the wired current to RF and vice versa

![RF Energy Diagram](image1)

- **Amplitude**
  - Higher amplitude RF signals go farther
  - Transmission Power (Watts) = Energy / Time = Joule / Sec
    - More energy (voltage) moves more electrons (current)
    - Power = Voltage * Current

![RF Energy Diagram](image2)
RF Properties

- **Frequency (and Wavelength)**
  - Wireless Spectrum (see next slides)
  - Portion of wireless spectrum regulated by regional authorities and assigned to wireless technologies

  ![Graph showing frequency and wavelengths](image)

  **Wavelength** = \( \frac{c}{\text{frequency}} \)

  **E.g. 2.4 GHz (ISM band)**
  
  Wave Length = \( \frac{300,000,000 \text{(m/s)}}{2,400,000,000 \text{ Hz}} = 0.125 \text{ m} = 12.5 \text{ cm} \)

  **In practice:**
  Antennas work better with size = 1, ½, ¼ of wavelength (try to measure antenna size of your IEEE 802.11 device)

RF propagation

- **Radio transmission coverage**

  ![Diagram showing radio transmission coverage](image)

  The range is a function of power transmission (Ptx)
  
  Signal strength reduces with \( d^k \) (K=2..3, no obstacles, isotropic radiator)

  **In 3D, sphere:**
  
  \[ V=(4 \pi r^3/3) \]
  
  \[ S=(4 \pi r^2) \]
Wireless networks’ technology

- **Radio transmission coverage**

  ![Illustration of radio transmission coverage](image)

  A

  **Rules of thumb:**
  - High frequencies are good for short distances and are affected by obstacles.
  - Low frequencies are good for long distances and are less affected by obstacles.

  Obstacles can reflect or absorb waves depending on materials and wave frequencies.

---

RF Properties

- **Phase: shift of the wave (in degrees or radians)**
  - Positive phase (left-shift), early wavefront
  - Negative phase (right-shift), late wavefront

![Example of signal composition with phase variations](image)

**In practice:**

RF echoes arriving at receivers with different phase may have positive or negative effects... Why?
RF Properties

Phase: shift of the wave (in degrees or radians)

- Positive phase (left-shift), early wavefront
- Negative phase (right-shift), late wavefront

In practice:
RF echoes arriving at receivers with different phase may have positive or negative effects... Why?
RF Properties

- **Polarization: (physical orientation of antenna)**
  - RF waves are made by two perpendicular fields:
    - Electric field and Magnetic field
  - Electric field (red) and Magnetic field (green)

  *Horizontal Polarization* (electric field is parallel to ground)

  *Vertical Polarization* (electric field is perpendicular to ground)

  [Diagram showing electric and magnetic fields with horizontal and vertical polarizations]

  [Links for further reading]
  - http://faraday.physics.utoronto.ca/PV/B/Harrison/Flash/EMEMWave/EMWave.html

  © Luciano Bononi 2007  Sistemi e Reti Wireless
**RF Properties**

**Vertical Polarization: typically used in WLANs**

OK  Transferred radiation OK

100% radiation captured

OK  Transferred radiation NO

80% radiation captured

Intuitively....

Vertical Polarization (electric field is perpendicular to ground)

N.B. the polarization problem is very much important when using distant devices and directional antennas. With short distances signal reflections help!
RF Behaviors

- Radio transmission interference
  http://www.met.rdg.ac.uk/clouds/maxwell/

- Radio effects on human head (do not try this at home 😊)
  http://temf.de/Radiation-of-a-mobile-phone-P.58.0.html?&L=1

- Credits: Technische Universität Darmstadt, Computational Electromagnetics Laboratory
Wireless transmission: Electromagnetic waves

- Different parameters of electromagnetic waves:
  - amplitude $M$ proportional to transmission energy (loudness)
  - frequency $f$ (tone) measured in Hertz (Cycle/sec)
  - phase $\phi$ (peak shift with respect to reference signal) (rad)

![Diagram of electromagnetic waves]

Wireless transmission

- Signal Gain: (measured in Decibels, Db)
  - Increase in amplitude $M$ proportional to transmission energy
    - Active gain (amplifiers)
    - Passive gain (antennas focusing signal energy, and additive
      signal effects)

![Diagram of signal gain]

passive gain: a pitfall vs. regulations?
Wireless transmission

- **Signal Loss: (Db)**
  - Decrease in amplitude $M$ proportional to energy waste
    - Intentional (resistance, signal attenuation -> heat)
    - Obstacles, e.g. (walls, water for 2.4 Ghz) and distance (wireless)

Wireless 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

Ranges depend on receiver’s sensitivity!
Wireless Signal propagation effects

- Propagation in free space always like light (straight line)
- Receiving power proportional to $1/d^2$  
  \(d\) = distance between sender and receiver
- Receiving power additionally influenced by
  - fading (frequency dependent)
  - shadowing
  - reflection at large obstacles
  - refraction depending on the density of a medium
  - scattering at small obstacles
  - diffraction at edges

Real world example

Raytracing examples

Low signal

high signal
**Multipath propagation**

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction

- Time dispersion: signal is dispersed over time
  - interference with “neighbor” symbols, Inter Symbol Interference (ISI)

- The signal reaches a receiver directly and phase shifted
  - distorted signal depending on the phases of the different parts

**Effects of mobility**

- Channel characteristics change over time and location
  - signal paths change
  - different delay variations of different signal parts
  - different phases of signal parts

  ➔ quick changes in the power received (short term fading)
  [http://wireless.per.nl/reference/chaptr03/rayjava/rayjava.htm](http://wireless.per.nl/reference/chaptr03/rayjava/rayjava.htm)

- Additional changes in
  - distance to sender
  - obstacles further away

  ➔ slow changes in the average power received (long term fading)
**Voltage Standing Wave Ratio (VSWR)**

- **VSWR** occurs with different impedance (Ohm) = resistance to AC current flow between transmitter and antenna
  - **VSWR** is the cause of “return loss” energy towards the transmitter
  - Measured as ratio between impedance (before and after)
    - E.g. 1.5:1 (impedance ratio before/after is 1.5 times the ideal value)
    - 1 = normalized ideal impedance (1:1 means perfect VSWR)
  - **VSWR** Causes burnout of transmitter circuits, and unstable output levels

**VSWR solution:** always use same impedance circuits, cables, connectors (typical 50Ω in LANs)

---

**Intentional radiator and EIRP**

- **(Intentional) radiator:** (def.) RF device specifically designed to generate and radiate RF signals.
  - ...Includes Tx RF device, cables and connectors (antenna excluded)
  - IR Power output: (subject to regulations) is the power output of last connector just before the antenna

- **Equivalent Isotropically Radiated Power (EIRP):** the power radiated by the antenna (including the passive antenna gain effect of directional antennas)

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx Out power 30mW</td>
<td></td>
</tr>
<tr>
<td>Cable: -3mW</td>
<td></td>
</tr>
<tr>
<td>Connector: -2mW</td>
<td></td>
</tr>
<tr>
<td>IR Power output: 30-14 = 16mW</td>
<td></td>
</tr>
<tr>
<td>EIRP (antenna gain +10dBi): 160mW</td>
<td></td>
</tr>
</tbody>
</table>
System design (under power viewpoint)

- Many factors must be considered in the design of Wireless systems:
  - Power of transmitting device
  - Loss and gain of connectivity devices (cables, connectors, attenuators, amplifiers, splitters) between transmission device and transmitter’s antenna
  - Power of the intentional radiator (last connector just before antenna)
  - Power radiated by antenna element (EIRP)
  - Propagation properties of the medium (attenuation before signal reception)
  - Loss and gain of connectivity devices (cables, connectors, attenuators, amplifiers, splitters) between receiver’s antenna and receiver device.

Power measurement

- WATT: electric power unit
  - 1 Watt = 1 Ampere * 1 Volt (P=V*I) also  P= R*I^2 and P = L/t
    - Current (ampere) is the amount of charge (electrons) flowing as current in a wire
    - Voltage (Volt) is the “pressure” applied to the flow of charge
    - Resistance (impedance) is the obstacle to current flow
    - Power is the energy needed (in a given time unit) to apply a given “pressure” to a given “amount of charge”, by resulting in a flow of current.
  - Watt and dBm are units used for absolute power measurement

- Typical RF power for WLANs:
  - AP: 30..100 mW (up to 250 mW outdoor), PCMCIA: 15..30 mW
**Power measurement**

- Decibel (dB): a power measurement unit designed to express power loss
  - It is more practical to use given the logarithmic decay of wireless signals
  - It allows to make easy calculations on “resulting power”
- Decibel (dB) measures the logarithmic relative strength between two signals (mW are a linear absolute measure of energy)
  - \[ \log_{10}(X) = Y \iff 10^Y = X \]
  - \[ 1 = 10^0, \ log_{10}(1) = 0 \]
  - \[ 10 = 10^1, \ log_{10}(10) = 1 \]
  - \[ 100 = 10^2, \ log_{10}(100) = 2 \]
  - \[ 1000 = 10^3, \ log_{10}(1000) = 3 \]
- How strong is a 10 dB signal? (It depends on the reference signal)

**Power measurement**

- Decibel (dB): 1/10 of a Bel
- E.g. 1000 is one Bel greater than 100 => 1000 is 10 dB greater than 100
  - \[ 1 = 10^0, \ log_{10}(1) = 0 \]
  - \[ 10 = 10^1, \ log_{10}(10) = 1 \]
  - \[ 100 = 10^2, \ log_{10}(100) = 2 \]
  - \[ 1000 = 10^3, \ log_{10}(1000) = 3 \]
- How strong is a 10 dB signal? (It depends on the reference signal)
  - Positive dB value is power gain, negative dB value is power loss
  - e.g. given 7 mW power, a +10 dB signal gain is 70 mW
  - e.g. given 7 mW power, a -10 dB signal gain (loss) is 0.7 mW
- Power Difference (in dB) between Tx and Rx signal:
  - Power Difference (dB) = 10 * log(Power Tx(Watt) / Power Rx (Watt))
- Gain and Loss are relative power measurements: dB is the unit
Power measurement

Advantage of dB: what is better?

- E.g.: A signal transmitted at [TX] 100 mW is received at [RX] 0.000005 mW
  - Power Difference (dB) = 10 * log([RX]/[TX]) = 10 * log(0.000005mW/100mW) = -73
  - A signal transmitted at 100 mW is received with gain (loss) -73 dB

Advantage of dB: what is better?

- E.g.: A signal transmitted at 100 mW is received at 0.000005 mW, then it is amplified (*100) to 0.0005 mW ???
- A signal transmitted at 100 mW is received with gain (loss) -73+20= -53 dB

<table>
<thead>
<tr>
<th>dB</th>
<th>Power change</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3 dB</td>
<td>½ power in mW (÷ 2)</td>
</tr>
<tr>
<td>+3 dB</td>
<td>2x power in mW (* 2)</td>
</tr>
<tr>
<td>-10 dB</td>
<td>1/10 power in mW (÷ 10)</td>
</tr>
<tr>
<td>+10 dB</td>
<td>10x power in mW (* 10)</td>
</tr>
</tbody>
</table>

Approximated table (values defined for ease of calculations)

Practical example:

- Signal Tx at 100 mW, cable –3dB loss, amplifier +10 dB gain
  - 100 mW / 2 (-3dB) = 50 mW * 10 (+10 dB) = 500 mW IR power output
- Signal TX at 30 mW is received at the antenna as 6 mW (2/10 of TX power)
  - Intentional Radiator Gain (loss) = 30mW / 10 = 3mW *2 = 6 mW
  - Intentional Radiator Gain (loss) = -10 dB + 3 dB = -7 dB (=1/5, 7dB ≈ 5x)
- N.B. dBs are additive measures of gain (loss): e.g. 6dB = +3+3 dB, 7dB = 10-3 dB
  - E.g. 100 mW -6 dB = 100 mW -3 -3 dB = 100 /2 /2 = 25 mW
  - E.g. 100 mW +7 dB = 100 mW +10 -3 dB = 100 *10 /2 = 500 mW
  - E.g. 10 mW + 5 dB = 10 mW (+10+10-3-3-3-3-3)dB = 1000/32 = 31.25 mW
  - E.g. 10 mW + 11 dB = ?
  - E.g. 50 mW – 8 dB = ?

N.B. Approximated values (values defined for ease of calculations)
Power measurement

- **dBm**: dB-milliWatt, the absolute measure of signal power
  - Assumption: reference signal is 1 mW = 0 dBm (normalization factor)
  - Useful for gain/loss calculation without passing through mW
    - E.g. access point transmits 100 mW = 1mW (*10*10) = +20 dBm
    - PCMCIA card transmits at 30 mW = 1mW (*10*3) = +14.7 dBm
  - E.g. Tx = 30 mW, cable –2 dB, amplifier +9 dB:
    - 30 mW = 1mW *10 *3 = 14.7 dBm
    - IR power : 14.7 dBm –2dB +9dB = 21.7 dBm (147.91 mW)
  - In general, for converting mW to dBm and viceversa:
    - \[ P_{\text{dBm}} = 10 \log(P_{\text{mW}}) \] and \[ P_{\text{mW}} = 10^{(P_{\text{dBm}} / 10)} \]

---

Power measurement

- **mW - dBm**: conversion table

<table>
<thead>
<tr>
<th>dBm</th>
<th>dBm</th>
<th>dBm</th>
<th>dBm</th>
<th>dBm</th>
<th>dBm</th>
<th>dBm</th>
<th>dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>-30</td>
<td>-20</td>
<td>-10</td>
<td>0</td>
<td>+10</td>
<td>+20</td>
<td>+30</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td>1</td>
<td>100</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 mW</td>
<td>1 uW</td>
<td>10 uW</td>
<td>10 mW</td>
<td>1 mW</td>
<td>100 mW</td>
<td>1 mW</td>
<td>10 mW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>dBm</th>
<th>dBm</th>
<th>dBm</th>
<th>dBm</th>
<th>dBm</th>
<th>dBm</th>
<th>dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>-12</td>
<td>-9</td>
<td>-6</td>
<td>-3</td>
<td>0</td>
<td>+3</td>
<td>+6</td>
</tr>
<tr>
<td>62.5</td>
<td>125</td>
<td>250</td>
<td>500</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>1 uW</td>
<td>2 uW</td>
<td>5 uW</td>
<td>10 uW</td>
<td>1 mW</td>
<td>2 mW</td>
<td>4 mW</td>
</tr>
</tbody>
</table>

© Luciano Bononi 2007  Sistemi e Reti Wireless
dBi: dB-isotropic, the normalized measure of antenna passive gain

- Assumption: an isotropic radiator has 100% efficiency in radiating energy in uniform way in every direction (e.g. the Sun)
- Antennas concentrate energy in non-isotropic way, resulting in passive gain (space dependent). Ideal antenna: zero length dipole

If an antenna located in the origin (0,0,0) has twice the radiated energy of an isotropic radiator in a given point (x,y,z), then the antenna gain in (x,y,z) can be defined as +3 dBi. If the energy is 10x the isotropic radiator, the gain is +10 dBi, etc.etc.

Q: If the antenna gain is 7 dBi in (x,y,z)?
Power measurement

- **dBi**: dB-isotropic, the normalized measure of antenna passive gain
  - Real antennas always have a preferred direction where the power is greater than isotropic radiator: gain is always positive in the preferred direction!
  - Example: 1 mW IR power applied to directional antenna with +10 dBi gain in the preferred direction, would translate in EIRP?
    - EIRP = 1mW + 10 dBi = (10x) = 10 mW EIRP

  N.B. this does not mean that antenna generates more power! Antenna concentrates power in preferred direction.

- **dBd**: dB-dipole, the normalized antenna passive gain vs. 2.14 dBi half-wave dipole
  - Reference is a half wave dipole with 2.14 dBi gain in preferred direction!
  - Conversion rule:
    - 0 dBd = 2.14 dBi, 
    - dBd = (dBi - 2.14), 
    - dBi = (dBd + 2.14)
Power monitoring (e.g. IEEE 802.11 devices)

- (received) Power monitoring in IEEE 802.11 devices is needed for making device driver to work properly (typical sensitivity range is \([-90..+10]\) dBm):
  - Detect signal (below or above the sensitivity threshold?)
  - Detect signal power (selection of coding technique... That is bitrate!)
- Received Signal Strength Indicator (RSSI)
  - Index defined for IEEE 802.11 devices (check device analyzer, if any)
  - RSSI = function (dBm or mW received) = pure number reported to device driver!
  - Unfortunately the RSSI scale is not standard, that is, device dependent!
    - This fact does not allow to compare if device A receives better than device B (assuming different manufacturer) based on RSSI measurement
  - Problem: device A indicates maximum RSSI=255 (8 bits) with \(-10\) dBm signal (0.1 mW), and device B indicates maximum RSSI=32 (5 bits) with \(-15\) dBm (0.03 mW). Q: when both A and B in (x,y,z) receive \(-15\) dBm, which one is better device? That is, which one would you buy if you are a system admin?
  - A: the one with the minimum cost! Why?

Antennas

- Illustration of general issues
  - Convert electrical energy in RF waves (transmission), and RF waves in electrical energy (reception)
  - Size of antenna is related to RF frequency of transmission and reception
  - Shape (structure) of the antenna is related to RF radiation pattern
- Radiation patterns of different antenna types
- Positioning antennas
  - Maximum coverage of workspace
  - Security issues
- Real antenna types: omni-directional, semi-directional, highly-directional
Omnidirectional antenna

- Omni-directional antenna: radiates RF power equally in all directions around the vertical axis.

- Most common example: dipole antenna (see Access Points)
  - See how to make it (disclaimer: do not try this at home):
    http://www.nodomainname.co.uk/Omnicolinear/2-4collinear.htm
    http://www.tux.org/~bball/antenna/

Q: Why TV dipole is bigger?
A: 100 Mhz vs. 2.4 Ghz

Omnidirectional antennas: simple dipoles

- Real antennas are not isotropic radiators but, e.g., dipoles
  ➔ shape of antenna proportional to wavelength

- Example: Radiation pattern of a simple Hertzian dipole

- Gain: maximum power in the direction of the main lobe compared to the power of an isotropic radiator (with the same average power)
**Omnidirectional antennas: simple dipoles**

- Dipole: passive gain is due to concentration (shape) of radiation

  ![Diagram of Low Gain Dipole](image1)
  ![Diagram of High Gain Dipole](image2)

- Dipole: active gain is obtained with power amplifiers (needs external source of energy)

  - N.B. near (below) the dipole the signal is weak! And better radiation is obtained in sub-areas around the dipole!

**Problem: how and when to mount omidirectional antennas? And which gain is ok?**

- Low Gain Dipole (e.g. 2 dBi)
- High Gain Dipole (e.g. 8..10 dBi), very flat coverage

  ![Diagram of Room A](image3)
  ![Diagram of Room B](image4)

- How: Ceiling? Wall? Client positions? Area? Many factors influence the planning...

- When:
  - need for uniform radio coverage around a central point
  - Outdoor: point-to-multipoint connection (star topology)
Omnidirectional antennas: simple dipoles

- **Antenna Tilt**: degree of inclination of antenna with respect to perpendicular axis

  - High Gain Dipole (e.g. 8..10 dBi), very flat coverage mounted on the ceiling
  - High Gain Dipole (e.g. 8..10 dBi), very flat coverage mounted on the ceiling with downtilt

  ![Antenna Diagram](image)

  - Room A
  - Room B

- Some antennas allow a variable degrees **downtilt**.

- Half signal dispered “in the sky”, 2\textsuperscript{nd} half better exploited.

---

Semi-directional antennas

- **Patch** (flat antennas mounted on walls)

- **Panel** (flat antennas mounted on walls)

- **Yagi** (rod with tines sticking out)

  - Side view (xy-plane) **Patch**
  - Side view (yz-plane) **Panel**
  - Top view (xz-plane) **Yagi**

  ![Antenna Diagram](image)

  - Beamwidth cone: -3dB signal boundary off-axis
### highly-directional antennas

- **Parabolic Dish**
- **grid**

![Diagram of highly-directional antennas](image)

<table>
<thead>
<tr>
<th>Antenna type</th>
<th>H beamwidth</th>
<th>V beamwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omni-dir.</td>
<td>360°</td>
<td>7°..80°</td>
</tr>
<tr>
<td>Patch/panel</td>
<td>30°..180°</td>
<td>6°..90°</td>
</tr>
<tr>
<td>Yagi</td>
<td>30°..78°</td>
<td>14°..64°</td>
</tr>
<tr>
<td>Parabolic dish</td>
<td>4°..25°</td>
<td>4°..21°</td>
</tr>
</tbody>
</table>

*Semi-directional antenna*

Beamwidth cone: -3dB signal boundary off-axis

### highly-directional antennas

- **Common use: Point-to-point link**

Out of beam alignment

- Wind effect: better to have lower gain and wider beam

Up to 60 km (LOS)
highly-directional antennas

- **Line of sight (LOS):**
  - Straight line between transmitter and receiver
  - No obstructions (outdoor long range reduces reflections)
    - Polarization is more important than in indoor scenarios

- **Fresnel Zone: RF is not laser light, RF signals diffuse energy in space**
  - Ellipse shaped area centered on the LOS axis
  - Most additive RF signal is concentrated in the Fresnel Zone
  - It is important that Fresnel Zone is free from obstacles

Red zone: additive phase signal

Yellow zone: inverse phase signal

---

**Fresnel Zone (FZ)**

- Blockage of Fresnel Zone causes link disruption
  - Caused by buildings, (growing) trees, foliage, etc.
  - Rule of thumb: < 20% obstruction of Fresnel Zone
  - Practical rule: calculate the radius of FZ leaving 60% unobstructed radius
    - \( R_{60\%} = 43.3 \times \sqrt{\frac{d}{4f}} \)
    - \( R_{100\%} = 72.2 \times \sqrt{\frac{d}{4f}} \)

Point source

1st FZ

2nd FZ

R=radius of 60% central FZ (feet)
\( d= \)distance(Miles), \( f= \)freq (GHz)

R=radius of 100% FZ (feet)
\( d= \)distance(Miles), \( f= \)freq (GHz)
highly-directional antennas

- **Fresnel Zone (FZ)**
  - N.B. the FZ radius depends only on the distance \(d\) between antennas, and frequency \(f\) of RF signal!
  - Type of antenna, beam width (degree), and gain (dBi) have no effects!
    - E.g. +13 dBi Yagi (30 degree beam) vs. +24 dBi Dish (5 degrees) have the same FZ!!!
  - In practice: if FZ is partially obstructed, it is not useful to use higher gain antennas (with small degree beam) !!!

Consider the Earth bulge!!!

- **Fresnel Zone (FZ)**
  - Is not relevant in indoor scenarios (due to reflections...)

- **Consider the Earth bulge!!!**
  - Very long point-to-point connections may have more than 40% FZ obstructed by Earth surface! Earth Bulge height = \(h\) (feet) = \(D^2/8\)
  - Minimum antenna height (link > 7 miles) \(H = (43.3 \sqrt{D/4F} ) + D^2/8\)
Sectorized-directional antennas

- Arrays of sectorized directional antennas

  ![Top view, 3 sector](image1)
  ![Top view, 6 sector](image2)

- Space multiplexing (channel reuse)

Azimuth and Elevation antenna charts

- Charts for understanding antenna coverage pattern
  - **Azimuth chart** (pattern seen from front/right/behind/left)
    - Obtained with spectrum analyzer with central antenna frequency
    - Signal measured in dB around the antenna
      - E.g. Dipole pattern: almost circular
      - E.g. yagi pattern: high in front, low beside
    - N.B. distance and Tx power is not relevant (signal strength in a location is relative to every other location in the chart, like with dB)
  - **Elevation chart** (pattern seen front/below/behind/above)
Antennas: diversity

- **Grouping of 2 or more antennas**
  - multi-element antenna arrays

- **Antenna diversity**
  - switched diversity, selection diversity
    - receiver chooses antenna with largest output
  - diversity combining
    - combine output power to produce gain
    - cophasing needed to avoid cancellation (phased antenna array... Requires processor)

  \[ \frac{\lambda}{4}, \frac{\lambda}{2}, \frac{\lambda}{4} \]
  ground plane

Path Loss

- **Path Loss: RF signal “dispersion” (attenuation) as a function of distance**
  - E.g. Possible formulas (36.6 or 32.4)
    - Free space: Loss (in dB) = 36.6 + \(20 \times \log_{10}(F)\) + \(20 \times \log_{10}(D)\)
    - \(F\) (Mhz), \(D\) (miles)

- **Link budget issue: 6 dB rule**
  - Each 6 dB increase in EIRP (signal x 4) implies double Tx range (e.g. see table below: 2.4Ghz Path Loss vs distance)

<table>
<thead>
<tr>
<th>Distance (meters)</th>
<th>Path Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>-50.33 dB</td>
</tr>
<tr>
<td>200</td>
<td>-56.25 dB</td>
</tr>
<tr>
<td>500</td>
<td>-94.21 dB</td>
</tr>
<tr>
<td>1000</td>
<td>-108.23 dB</td>
</tr>
<tr>
<td>2000</td>
<td>-108.25 dB</td>
</tr>
<tr>
<td>5000</td>
<td>-114.21 dB</td>
</tr>
<tr>
<td>10000</td>
<td>-120.23 dB</td>
</tr>
</tbody>
</table>

© Luciano Bononi 2007 Sistemi e Reti Wireless
**Link Budget Calculation**

- **“Link Budget” or “System Operating Margin”**
  - Excess of signal between transmitter and receiver
    - Calculated for outdoor point-to-point connections
  - Measured in dB (relative) or dBm or mW (absolute)
  - Calculation:
    - Receiver sensitivity $RS$ (weakest detectable signal)
      - The lower the better: e.g. IEEE 802.11 card (see device manual), -95 dBm (1Mbps), -93 dBm (2 Mbps), -90 dBm (5.5 Mbps), -87 dBm (11 Mbps)
      - Link Budget: received power (in dBm) - $RS$ (in dBm)
      - E.g. $RS = -82$ dBm, received power = -50 dBm
        - Link budget = -50 – (-82) = +32 dBm
    - This means the signal has margin of +32 dB before it becomes unviable
  - **Fade margin**: extra margin for link budget (to cope with multipath variation in indoor/outdoor scenarios): typical [+10..+20] dB

**Link Budget Calculation: example**

- **Example: design of transmission system, needs amplifier?**

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Transmission power = 15 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Fresnel zone free (free space)</td>
<td>10 Km = -120 dB</td>
</tr>
<tr>
<td>+24 dBi</td>
<td>+24 dBi</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Loss:</th>
<th>Total Gain:</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.0</td>
<td>+15 dBm</td>
</tr>
<tr>
<td>-1.3</td>
<td>+24 dB</td>
</tr>
<tr>
<td>-2.4</td>
<td>+24 dB</td>
</tr>
<tr>
<td>-0.7</td>
<td>+24 dBi</td>
</tr>
<tr>
<td>-1.0</td>
<td>+24 dBi</td>
</tr>
<tr>
<td>-1.3</td>
<td>+24 dBi</td>
</tr>
</tbody>
</table>

Total loss = -1.0 -1.3 -0.7 -2.4 -120 -2.4 -0.7 -1.3 -1.0 = -130.8 dB

Condition: $(gain + loss) > (RS + fade margin)$???

- $(+63 +(-130.8)) > -82 \times ???$
- Received Power = -67.8 dBm
- Link Budget = -67.8 -(-82) = +14.2 dBm

**OK! Fade margin = +14.2 dBm**

No need for amplifiers or high gain antennas

**Receiver sensitivity $RS = -82$ dBm**