Antennas

…and a bit physics.

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t} + \mu_0(\vec{J}_{free} + \frac{\partial \vec{P}}{\partial t} + \nabla \times \vec{M})$$

$$\nabla \cdot \vec{E} = \frac{\rho_{free} - \nabla \cdot \vec{P}}{\epsilon_0}$$

$$\nabla \cdot \vec{J}_{free} = -\frac{\partial \rho_{free}}{\partial t}$$

The famous "Maxwell Equations", a complete description of the EM field

James Clerk Maxwell

"Was it not the God who wrote these signs, that have calmed alarm of my soul and have opened to me a secret of nature?"

Ludwig Boltzmann quoting "Faust" as he first saw the Maxwell equations.

Decibels

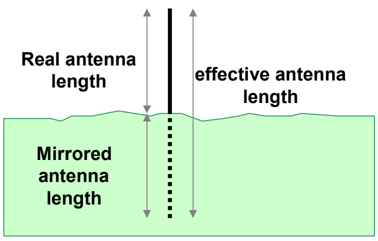
- Why use decibels?
  - Extremely large and extremely small factors are mapped into a small interval
  - Multiplication and division is transformed into addition and subtraction

Increase	Factor	Decrease	Factor
0 dB	1 x	0 dB	1 x
1 dB	1.25 x	-1 dB	0.8 x
3 dB	2 x	-3 dB	0.5 x
6 dB	4 x	-6 dB	0.25 x
10 dB	10 x	-10 dB	0.10 x
12 dB	16 x	-12 dB	0.06 x
20 dB	100 x	-20 dB	0.01 x
30 dB	1000 x	-30 dB	0.001 x
40 dB	10,000 x	-40 dB	0.0001 x

We mostly need dB, dBm, and dBi,
and only rarely dBw and dBd (at least in the WLAN context)

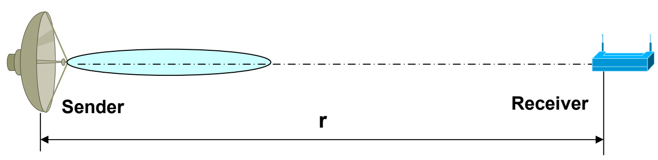
Generating Radio Waves

- Goal: Inject the waveguide wave from the sender into free space
- Antennas are "opened" oscillator-circuits
  - Radio waves are generated by accelerated electrons in the antenna
- Antenna length L
  - Good efficiency if L ≅ λ
  - L=λ/2 (dipole)
  - L=λ/4 (monopole)
- To concentrate power in a desired direction requires L > λ



Antenna Gain

$G = \dfrac{\text{maximum power density towards specific direction}}{\text{mean power density (isotropic radiation)}}$	$G = \dfrac{4 \pi A_e}{\lambda^2}$
▪ Hertz' Dipole: G = 1.5 ▪ $\lambda/2$ Dipole: G = 1.64 (= 2.14 dBi = 0 dBd) ▪ Parabolic dish with 4 m diameter and $\lambda_{2.4GHz}$: $G = 10^4$	$G_{[dBi]} = 10 \log G$



Power Density: $S_R = \dfrac{P_S G_S}{4 \pi r^2}$

Power at receiver's antenna output: $P_R = P_S \, G_S \, G_R \left(\dfrac{4 \pi r}{\lambda} \right)^{-2}$

Polarization

- Linear polarization
  - Vertical or horizontal
  - Requires linear antenna elements
- Elliptical polarization
  - Circular polarization is only a special case
  - Requires bended antenna elements
- Transmitter and receiver antennas should be aligned for same polarization to achieve best performance
  - Otherwise "infinite" attenuation with "opposite" antennas
  - Or 3 dB attenuation between linear and circular antennas
  - Polarization change with diffractions and reflection
- Vertical polarization is preferred for long range transmission (ground effect attenuate the signal power in horizontal polarization)
- Circular polarization antennas mitigate the effect of reflections
  - Principle also used for GPS
  - See helical antennas (for example)

Other Antenna Facts

- Impedance Matching
  - Free space impedance is 377 Ohm
  - Antenna cables have 50 Ohm (typically)
  - Antenna must transform 50 to 377 Ohm
- Without impedance matching
  - Reflections will result into standing waves
  - TX power will not be transferred efficiently to the antenna
- Voltage Standing Wave Ratio (VSWR)
  - s = Umax / Umin ≥ 1
  - s = 1 means ideal impedance matching
  - s > 1 means reflections and high ripples
    - => higher rms-values
    - => higher loss

Other Antenna Facts

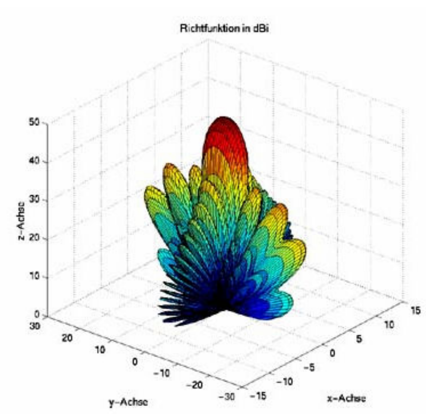
- Theorem of Reciprocity
  - Antenna impedance, Gain, as well as antenna diagrams are equivalent for RX and TX
- Near field versus far field
- Shortening effect
  - Slower wave propagation in antenna ($c_{wire} < c_0$) plus capacitive effects on antenna-ends demands for shortening the antenna
  - Typically 3-8 %

Wave Propagation

- **Free space:**
  - **Fields E, H ~ 1/r**
  - **Power density $S = E \times H \sim 1/r^2$**
  - **Compared to cables: attenuation ~ e^{-r}**
- **Along earth's surface also surface waves must be considered**
  - **Fields E, H ~ e^{-r}**
- **The higher the frequencies the lower the effect of surface waves**
  - **"Quasi-optical" propagation**

Antenna Patterns

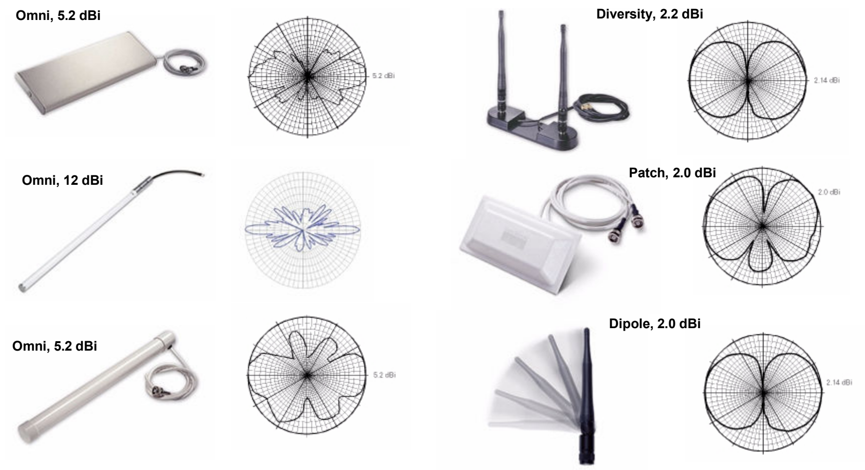
- **Field strengths as polar diagram**
  - **Scaled to maximum value (0 dB)**
  - **Logarithmic or linear (F~1/r)**
- **Elevation and Azimuth**
  - **Often used for simple linear polarized antennas**
  - **Often corresponds to co- and cross-polarized patterns**
- **E and H patterns**
  - **For linear polarized antennas**
  - **Distinguish:**
    - **E-Field and H-Field**
    - **Elevation and Horizontal**
    - **Both types are common (!)**
- **High-gain antennas have significant null-angles**



WLAN Antenna Examples

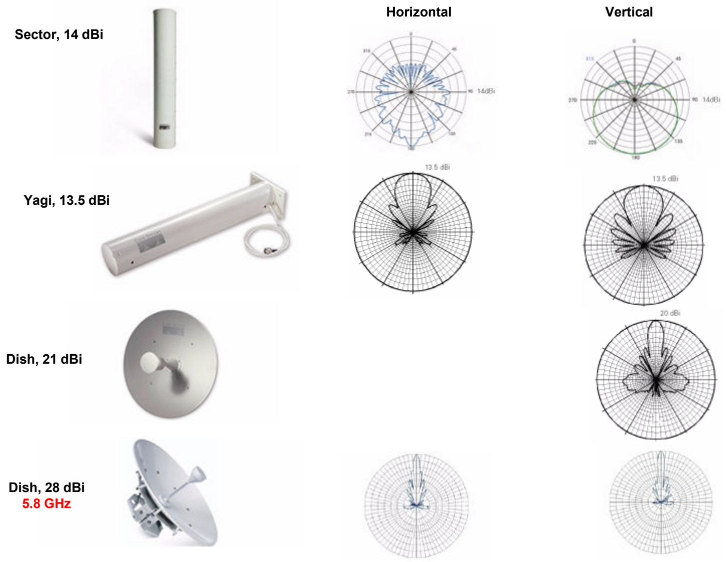
- Circular polarity (5 dBi)
- Microstrip patch (6-18 dBi)
- Omni (2-10 dBi)
- Parabolic dish (20-30 dBi)
- Sector (14 dBi)
- Yagi (8-16 dBi)

Antennas & Patterns



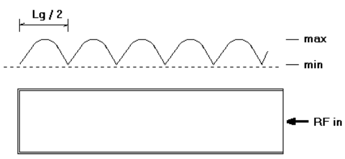
- Cisco WLAN Antennas and vertical radiation shown only

Some Cisco Antennas



Waveguide Antennas

- Standing wavelength λ_g depends on
  - Tube diameter D
  - Open air wavelength λ_o
- First maximum point is $\lambda_g/4$ from the closed end
  - Flat maximum area
- Total tube length: Open end should match (next) maximum
  - Ideally 3/4 λ_g



$\lambda_o = 300 / f_{[MHz]}$

$\lambda_{cut} = 1.706 \times D$

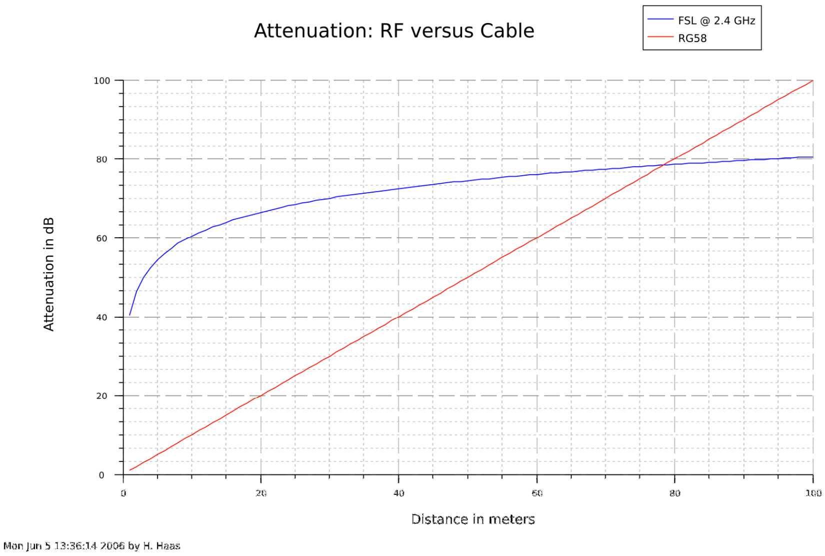
$1/\lambda_o = 1/\lambda_{cut} + 1/\lambda_g$

FSL

- **Free Space Loss (FSL)**
  - **Real Loss > FSL**
  - **Reflects the RF power law $P \sim 1 / r^2$**
  - **Defined as $10 \log P_S/P_R$**
- **Double distance means**
  - **Additional 6 dB loss**
  - **Because power decreases by factor 4**
  - **Only with cables the total loss can be multiplied by two**
    - **Exponential law**

$$FSL = \left(\frac{4 \pi r}{\lambda} \right)^2$$

Why Radio Is Better For Long Distances



FSL – Simple Formulas

General

FSL_{dB} = 22 + 20 log (r/λ)
FSL_{dB} = 20 log (f_{MHz}) + 20 log (r_{km}) + 32.45
FSL_{dB} = 20 log (f_{GHz}) + 20 log (r_{km}) + 92.45

2.4 GHz

FSL_{dB} = 20 log (r_{km}) + 100	r_{km} = 10^((FSL -100)/20)

5.3 GHz

FSL_{dB} = 20 log (r_{km}) + 107	r_{km} = 10^((FSL -107)/20)

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EIRP (for Spread Spectrum)

- Equivalent Isotropically Radiated Power
  - Theoretical power for an isotropic antenna to reach same PSD as directional antenna
  - EIRP = 10^(g_{dBi}/10) * P [W]
  - National band-specific EIRP limits
- Europe (ETSI) max EIRP
  - 100 mW or 20 dBm for DSSS
    - = 17 dBm (50 mW) + 3 dBi
  - 30 mW or 15 dBm for OFDM (typically)

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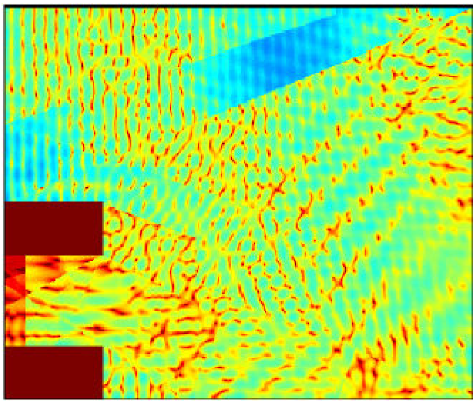
EIRP In Other Countries

- America (FCC)
  - Point-to-multipoint (typical AP usage)
    - 30 dBm (1 W) and 1:1 power/gain reduction/increase
  - Point-to-point (typical bridging usage)
    - 36 dBm (4 W) = 30 dBm + 6 dBi
    - G>6dBi requires minus 1dBm for each 3 dBi more gain
- Japan, China: EIRP 10 mW

Diversity Antennas

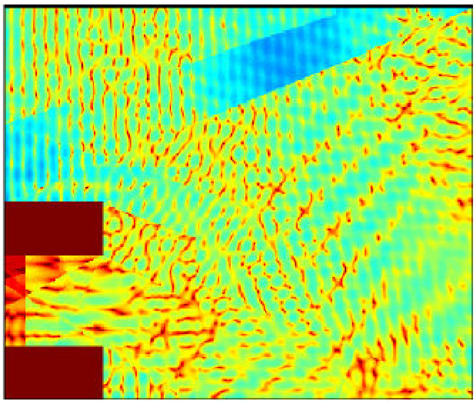
- For small distances (rooms) the speed of light is approximately infinite
- On the other hand, the data rate is limited and every frame produces a nearly instantaneous EM-field (for a short period of time)
- Due to reflections, a short-time standing field is produced – with ripples, peaks and lows
  - Same picture for every frame if "nobody moves"
- Therefore, use multiple antennas: one will likely pick up more energy than the other



Indoor office signal intensity map (source unknown)

The EM Field

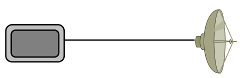
- **Reflections, diffractions and scattering are highly dynamic**
  - **Consider static and dynamic configurations**
- **Multipath problems**
  - **"High signal strengths but low quality"**

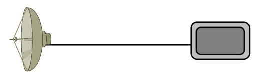


Indoor office signal intensity map
(source unknown)

Why are bigger antennas better?

- **Assume we comply to 20 dBm EIRP**
- **Then this can be reached in various ways:**

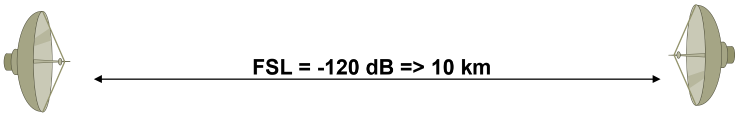




P_{TX}	Gain		Gain	P_{TX}
17 dBm	3 dBi	FSL + 17 dBm + 6 dBi	3 dBi	17 dBm
10 dBm	10 dBi	FSL + 10 dBm + 20 dBi	10 dBi	10 dBm
0 dBm	20 dBi	FSL + 0 dBm + 40 dBi	20 dBi	0 dBm

- **Additionally, SNR is improved with higher gains**
- **Therefore, try to maximize antenna gains !!!**

Practical 2.4 GHz Distance Limits

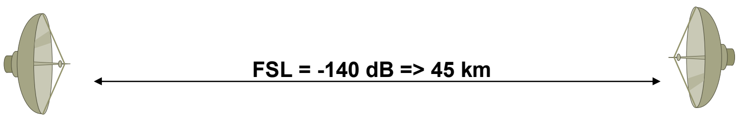


P=0 dBm, G=20 dBi

P=0 dBm, G=20 dBi

- ETSI limits 2.4 GHz EIRP to 20 dBm
  - (Also for P2P links)
- A minimum RX power of -80 dBm can be assumed as practical limit
- Then a maximum FSL of -120 dB is allowed
- This results in a maximum distance of 10 km

Practical 5 GHz Distance Limits



P=0 dBm, G=30 dBi

P=0 dBm, G=30 dBi

- Completely different situation
  - HIPERLAN band (5470-5725 MHz) released for WiFi
  - ETSI allows EIRP = 1 W = 30 dBi !!!
- Also a minimum RX power of -80 dBm can be assumed as practical limit
- Then a maximum FSL of -140 dB is allowed
- This results in a maximum distance of 45 km

Exploit Diversity (5.4 GHz)

- Example:
  - TX-Antenna is 30 dBi parabola
    (1 W = 30 dBm EIRP = 0 dBm + 30 dBi)
  - RX-Antenna is 40 dBi parabola
- Allows 150 dB FSL => 140 km !!!
- Optionally an additional preamp can be used
  - E. g. + 10 dB => 160 dB FSL => 444 km *theoretically*
- Problem: CSMA/CA timing must consider signal propagation time
  - 140 km => 466 usec delay (but SIFS = 16 usec)

SNR

- Sensitivity is not the only important parameter for the receiver quality
  - Low noise level: Sensitivity is limiting
  - High noise level: SNR is limiting
- Shannon 1948: Channel Capacity
  - Depends on Bandwidth and SNR
- Example: Required SNR for the Orinoco PCMCIA Silver/Gold
  - 11 Mbps — SNR_{min} = 16 dB
  - 5.5 Mbps — SNR_{min} = 11 dB
  - 2 Mbps — SNR_{min} = 7 dB
  - 1 Mbps — SNR_{min} = 4 dB
- Although TX-power regulated (EIRP) the RX-SNR has the same effect!
  - See e. g. RX 2400-o from SSB “Receive Booster” (8-10 db plus)

Typical Receiver Sensitivities

- Orinoco cards PCMCIA Silver/Gold
  - 11Mbps -82 dBm
  - 5.5Mbps -87 dBm
  - 2Mbps -91 dBm
  - 1Mbps -94 dBm
- CISCO cards Aironet 350
  - 11 Mbps -85 dBm
  - 5.5 Mbps -89 dBm
  - 2 Mbps -91 dBm
  - 1 Mbps -94 dBm
- Edimax USB client
  - 11Mbps -81 dBm
- Belkin router/AP
  - 11 Mbps -78 dBm

Typical noise floor: -95 dB, only +/- 2dB differences between a, b, g

Cable Loss

- Typical loss in common coaxial cables at 2.45 GHz
  - RG 58 (quite common, used for Ethernet): 1 dB per meter.
  - RG 213 ("big black", quite common): 0.6 dB per meter.
  - RG 174 (thin, seems to be the one used for pigtail adapter cables): 2 dB per meter.
  - Aircom : 0.21 dB/m.
  - Aircell : 0.38 dB/m.
  - LMR-400: 0.22 dB/m
  - IEEE 802.3 (thick 'yellow' Ethernet coax) 0.3 dB/m

Connector Loss

- Add connector loss to cable loss before calculating the Link Budget
  - Typically between 0.1 and 0,5 dB at 2,45 GHz
  - Use as few connectors as possible
- Loss depends on the quality of the connectors
  - Dielectric material, Geometry, etc
  - Best: N connectors or SMA connectors
  - Worse: Old BNC connectors
- Avoid Pigtails
  - (=short cables with different connectors on each side)
  - 30 cm may have ~ 1.5 dB!
  - Use single-unit converters instead

WLAN Connectors

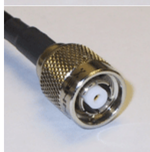
N Female

RP-SMA Female

RP-TNC Female

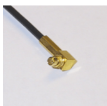
N Male

RP-SMA Male



RP-TNC Male

MC



MMCX

MC

Cisco uses reverse polarity for spread spectrum products to prevent connecting wrong antennas.

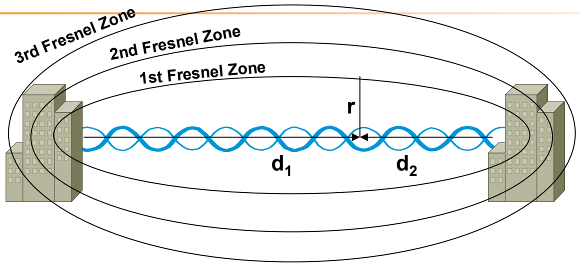
Link Example

- Given 24 dB dish
- Output power must be reduced to -4 dBm
  - That is 0.4 mW (!) to stay within the legal limits of 20 dBm in Europe
- Theoretical maximum range for a reliable link will be 8 km
  - Assuming 15 dBm fade margin
  - Due to highly increased antenna gain in the receiver path (SNR)

Quasi-optical Propagation

- Requires "line-of-sight"
  - Reliable connections due to steady field strengths (no variabilities)
  - Small TX powers possible
  - Free-space wave propagation
- Fading through interferences
  - Multiple waves with different phases
  - Fading-controllers at the receivers (GSM, UMTS)
  - Diversity antennas (WLAN, GSM and UMTS)

The Fresnel Zones (1)



Fresnel zones radius:

$$r = \sqrt{\frac{n\lambda \cdot d_1 \cdot d_2}{d_1 + d_2}} \text{ [m]}$$

- Surfaces where reflected rays would reach the receiver with an extended path by λ/2
  - => Destructive interference
- TX and RX located at focal points
  - Any path connecting F1, F2, and surface has same length
- Rule of thumb:
  - If 60% of first Fresnel Zone is clear of obstructions then nearly same link as a clear path
  - However might be unstable under bad weather conditions
  - Try to achieve full Fresnel zone clearance

The Fresnel Zones (2)

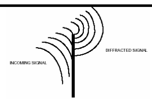
- Consideration especially important when Earth's bulge touches Fresnel zones
  - Distances >9 km => high poles are required for antenna mount

Distance (km)	Fresnel zone (radius)	Earth Curvature	Total
1,6	3	1	4
8	9	1,5	10,5
16	13	4	17
24	16	8,5	24,5
32	20	15	35
40	22	23	45

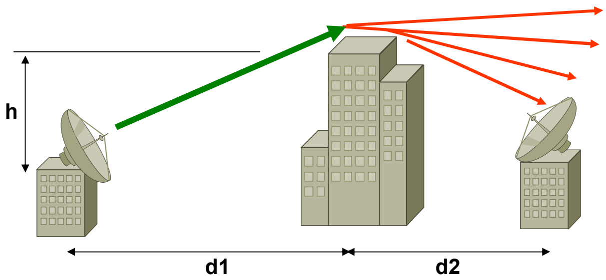
Optical horizon:
$R_{[km]}$ = 3.57 (sqrt(h_S) + sqrt (h_R))

Radio horizon:
$R_{[km]}$ = 4.12 (sqrt(h_S) + sqrt (h_R))

Diffraction



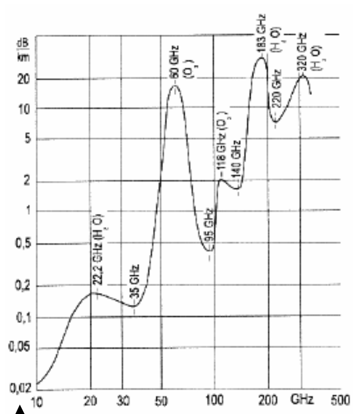
- Radio waves will be distracted on edges from objects.
- It is possible to catch receiver behind objects



$$\text{Loss} = 20 \log \left[\frac{0.225}{h} \left(\frac{0.12\, d_1\, d_2}{2\,(d_1 + d_2)} \right)^{1/2} \right]$$

Natural Attenuation

- Fog and rain:
  - Approx 0.5 dB/km @ 2,4 GHz—still little effect
- Dense snow storm is more critical
  - Signal scattering effect
- Problem becomes really serious for higher frequencies
  - Molecule absorption effects
  - Therefore be lucky with WLANs…



WLANs

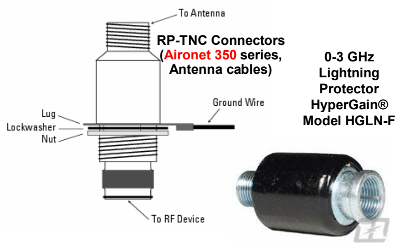
(No fog, no rain)

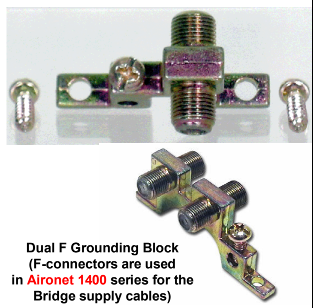
Delay Spread

- <u>Consequence of multipath propagation</u>
  - Receiver needs equalizer
  - Manufacturers specify delay spread limit
- Example: Orinoco Frame Error Rate (FER) < 1%
  - 11Mbps 65 ns
  - 5.5 Mbps 225 ns
  - 2 Mbps 400 ns
  - 1Mbps 500 ns
- Note: Delay spread in wide areas with lots of multipaths can reach several µs !
  - Rule of thumb: Path length difference of 15 meters leads to 50 ns spreading
- <u>Solutions:</u>
  - Directive antennas
  - Circular polarization
  - OFDM

Outdoor Antenna Safety

- Antenna cables connect indoor and outdoor EM-environment
  - Prone to (in-) direct lightning
  - Can pick up electrical fields (=> currents) through dry air or EMI
- There is no 100% solution to protect your equipment !!!
  - But good chances to protect the indoor area (health, fire)
- Use lightning arrestors (antenna cable) or grounding blocks (pwr/console coax) against surges
  - DC-continuity type needed for WLAN with coax power supply (gas tube or spark gap)
  - Proper low-impendance grounding critical (not that easy!)
  - Keep tower and coax at same potential (to prevent "side flashes)





Dual F Grounding Block
(F-connectors are used
in Aironet 1400 series for the
Bridge supply cables)

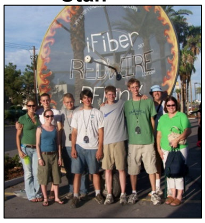
World Record (early 2005)

Nevada

4 m dish, 300 mW

200 km

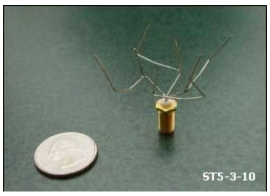
Utah

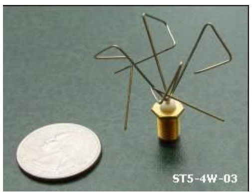


3 m dish, 300 mW

- 200 km without amplifiers
  - But an EIRP beyond legal limits
- See
  - http://www.wifiworldrecord.com/
  - http://www.wifi-shootout.com/

Tomorrow's Antenna Design





- Microwave antenna design using genetic algorithms
  - http://ic.arc.nasa.gov/projects/esg/research/antenna.htm