Antennas and radiowave propagation - UNIK4150/9150

- Course content
  - Antennas and radiowave propagation in the frequency range of about 100 MHz to 300 GHz, but including some up to infrared 350 THz (free space optics)
  - Some general antenna theory and practical antennas like wire (dipole), apertures (reflector), and micro-strip (phased array)
  - Free space loss, reflection, and obstruction/diffraction
  - Effects of atmospheric gases, clouds/fog, precipitation, refraction, penetration through materials
  - Radio channel models and system dimensioning
  - Emphasis on actual radio systems, e.g., mobile communications, broadband wireless access, point to point links, point to multipoint links, and radar
  - Radio front end introduction
- Learning outcome
  - Basic calculations for actual radio systems: dimensioning and interference
  - Take account for the effects terrain, buildings, and varying atmospheric and climatic conditions

Required reading

UNIK 4150/9150

- Book
  "**Antennas and propagation for wireless communication systems**", Second edition,
  Simon R. Saunders and Alejandro Aragón-Zavala
  ISBN: 978-0-470-84879-1
  Hardcover, 546 pages, March 2007
  All chapters
- Own lectures
  "**Radio front-end**" and "**Free space optics**"

UNIK 9150

- In addition for PhD
  One or two journal articles

Lectures and exercises 2016 – will probably change

No	Date	Topic
1	22 January	Ch. 1 & 4.1-3. Introduction
2	29 January	Ch. 2 - 3.4. EM waves & propagation mechanisms. Exercise
3	5 February	Ch. 3.5 & 4.4. Diffraction & Dipole. Exercise
4	12 February	Ch. 4.5 - 5. Array antennas & basic propagation. Exercise
5	19 February	Ch. 6. Terrestrial fixed link (clear air & diffraction). Exercise
6	26 February	Ch. 7. Satellite fixed link (rain & ionosphere). Exercise
7	4 March	Ch. 8-9. Macro cells & shadowing. Exercise
8	11 March	Own lecture on Radio front-end and Free-space optics. Exercise
	18 March	Lecture free
	25 March	Easter holiday
9	1 April	Ch. 10-11. Narrowband & wideband. Exercise
10	8 April	Ch. 12-13-14. Micro & pico & mega cells. Exercise
11	15 April	Ch. 15-16. Mobile system antennas & Overcome narrowband with diversity. Exercise
12	22 April	Guest lecture on MIMO and massive MIMO. Exercise
13	29 April	Wanted topics. Discuss written exercise
	6 May	Lecture free
	13 May	Lecture free
	20 May	Lecture free
	27 May	Oral exam

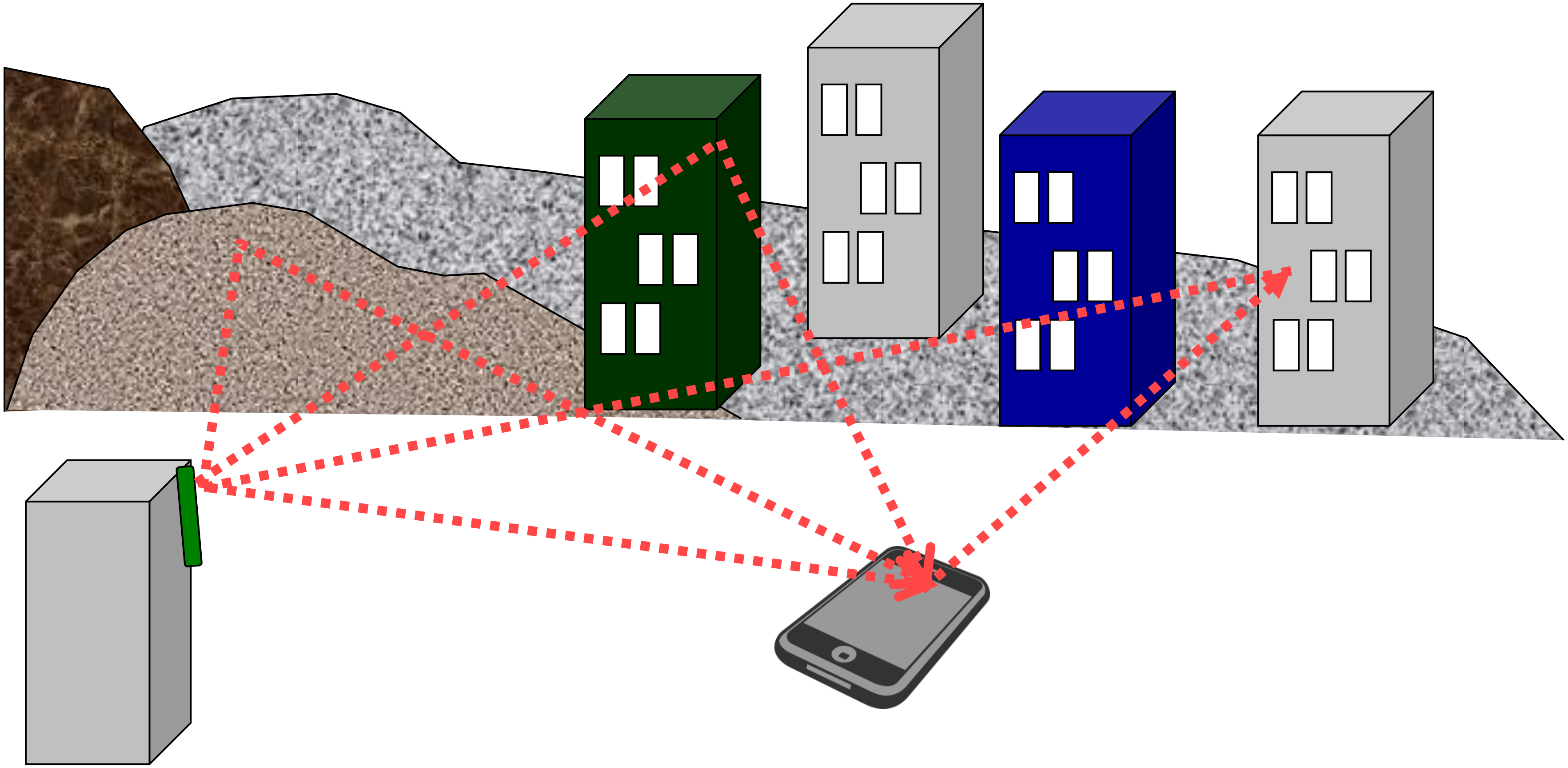
Chapter 1 Introduction

- Radio waves and radiowave propagation
- Radio communication system
- Radio spectrum
- Cells, orbits, access, capacity

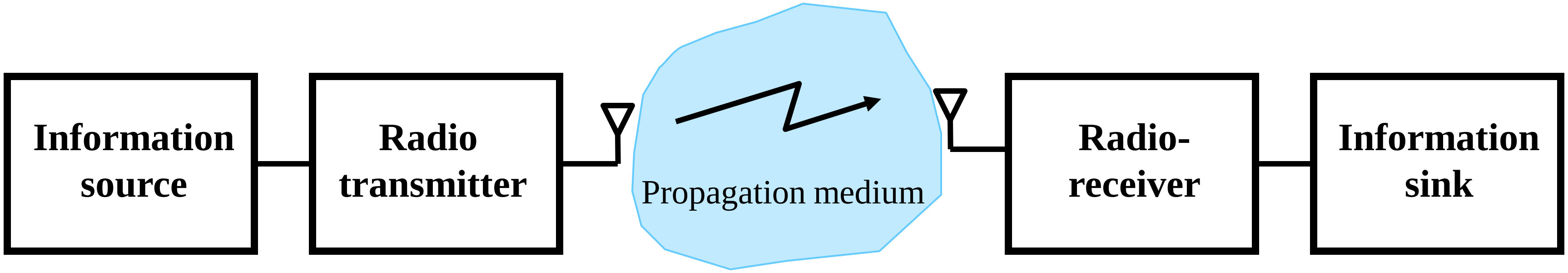
Radiowave propagation

- Radiowaves are electromagnetic waves, often limited in frequency to below 3000 GHz (3 THz)
- A radio system has a transmitter and receiver tuned to the same frequency and well recognised by coding and modulation, amplification, and antenna
- Radio systems is a general term used in telecommunication, broadcasting, positioning, and remote sensing (radar)

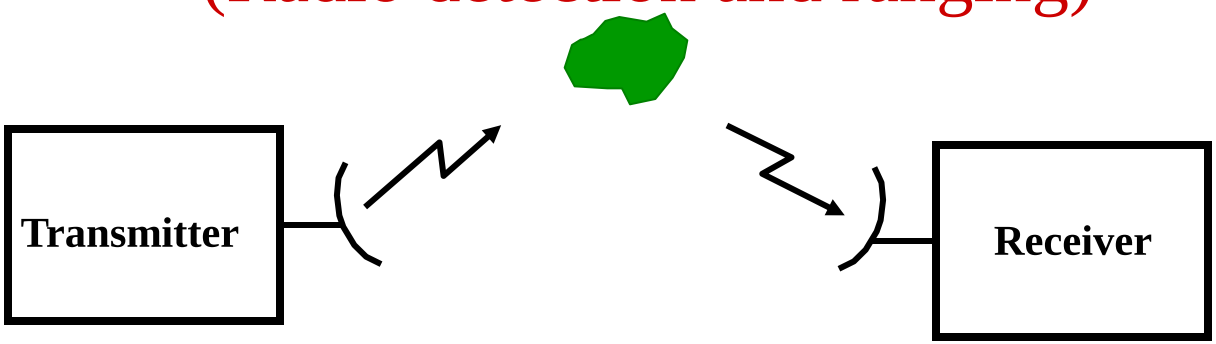
Mobile propagation environment



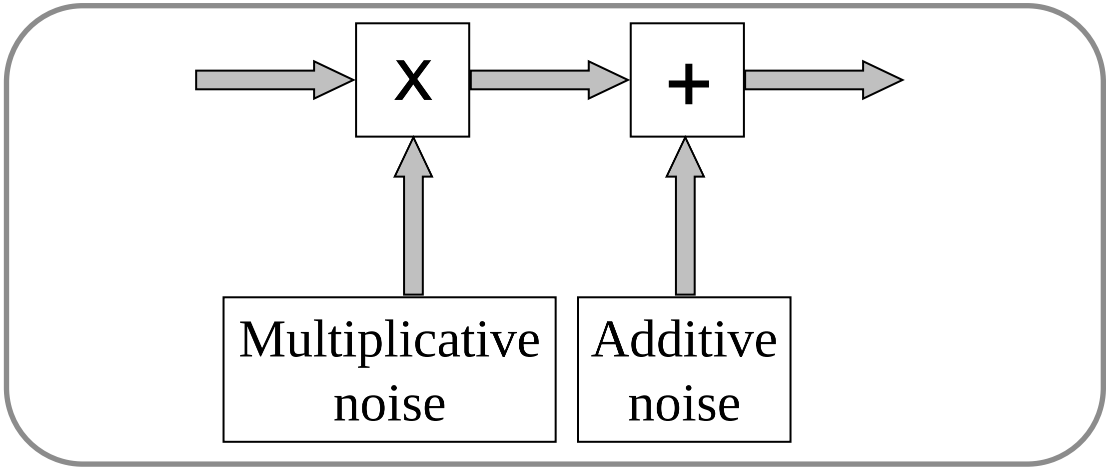
Radiocommunication

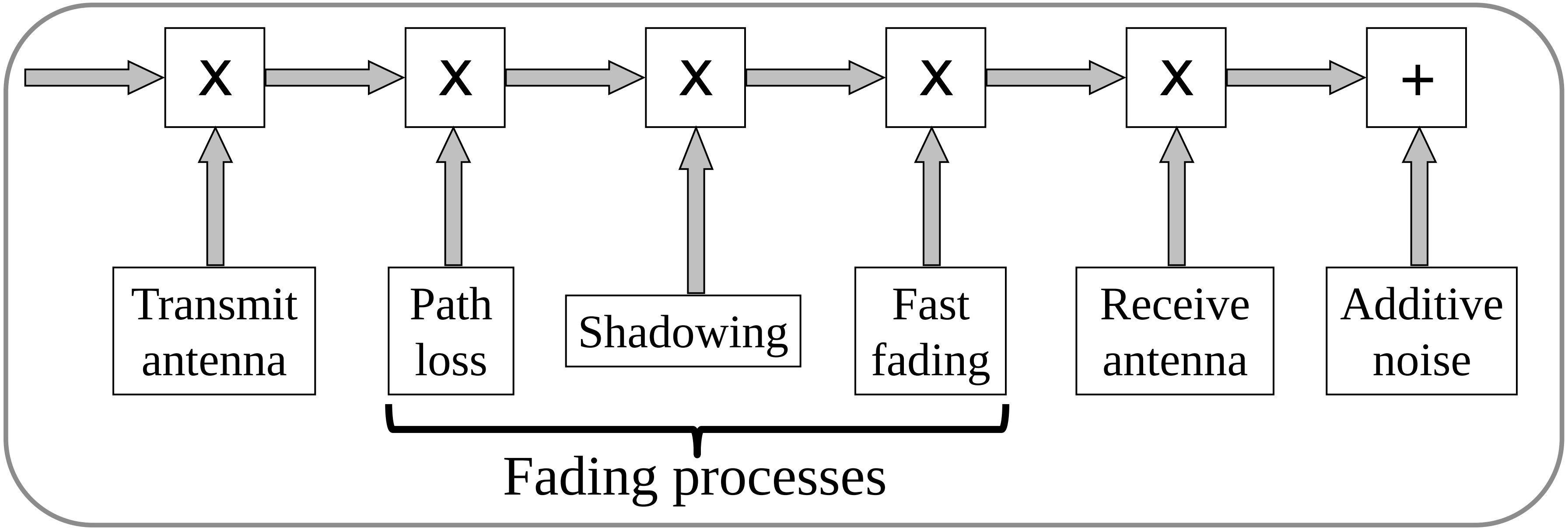


Radar
(Radio detection and ranging)

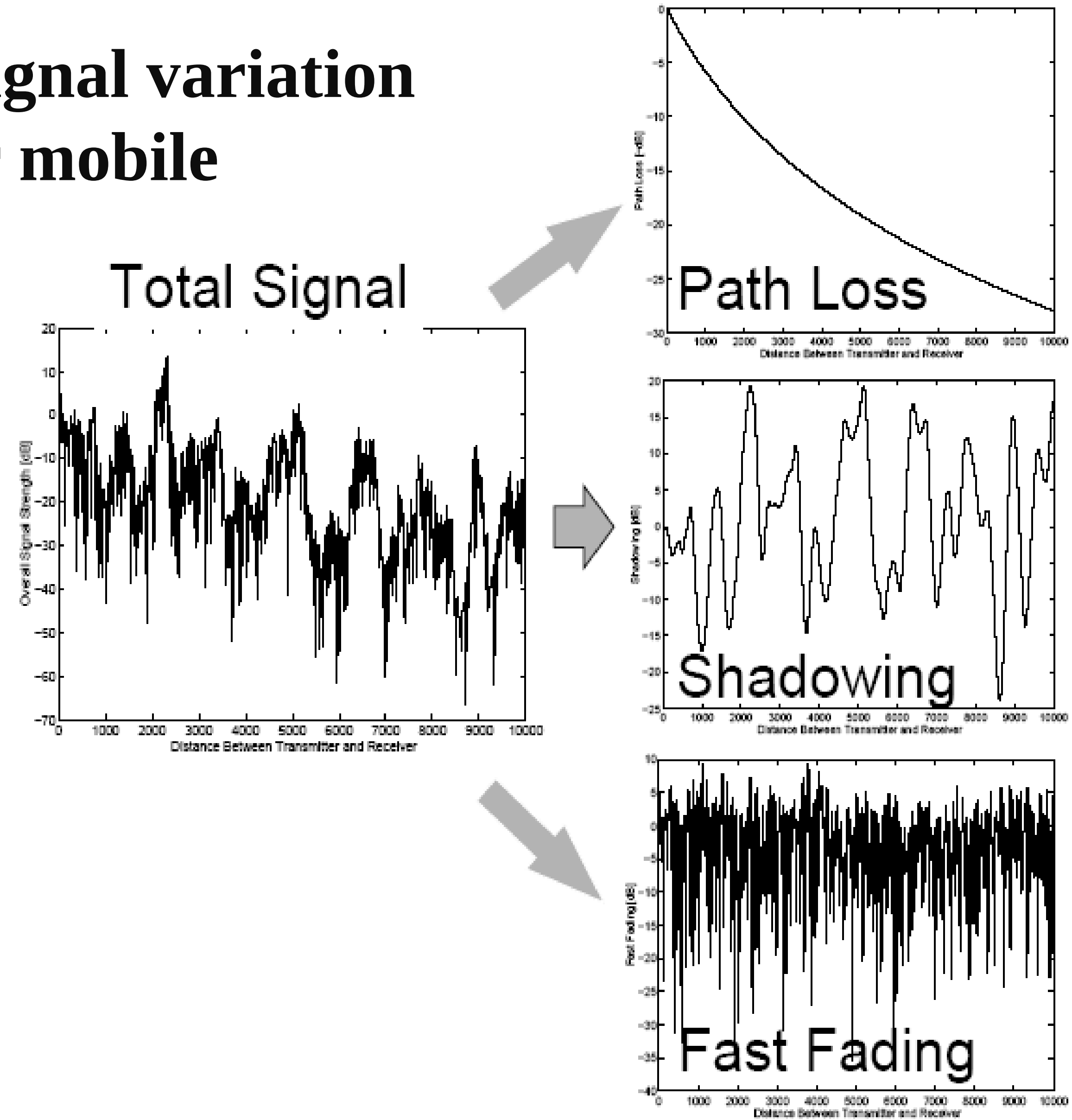


Wireless channel noise and fading

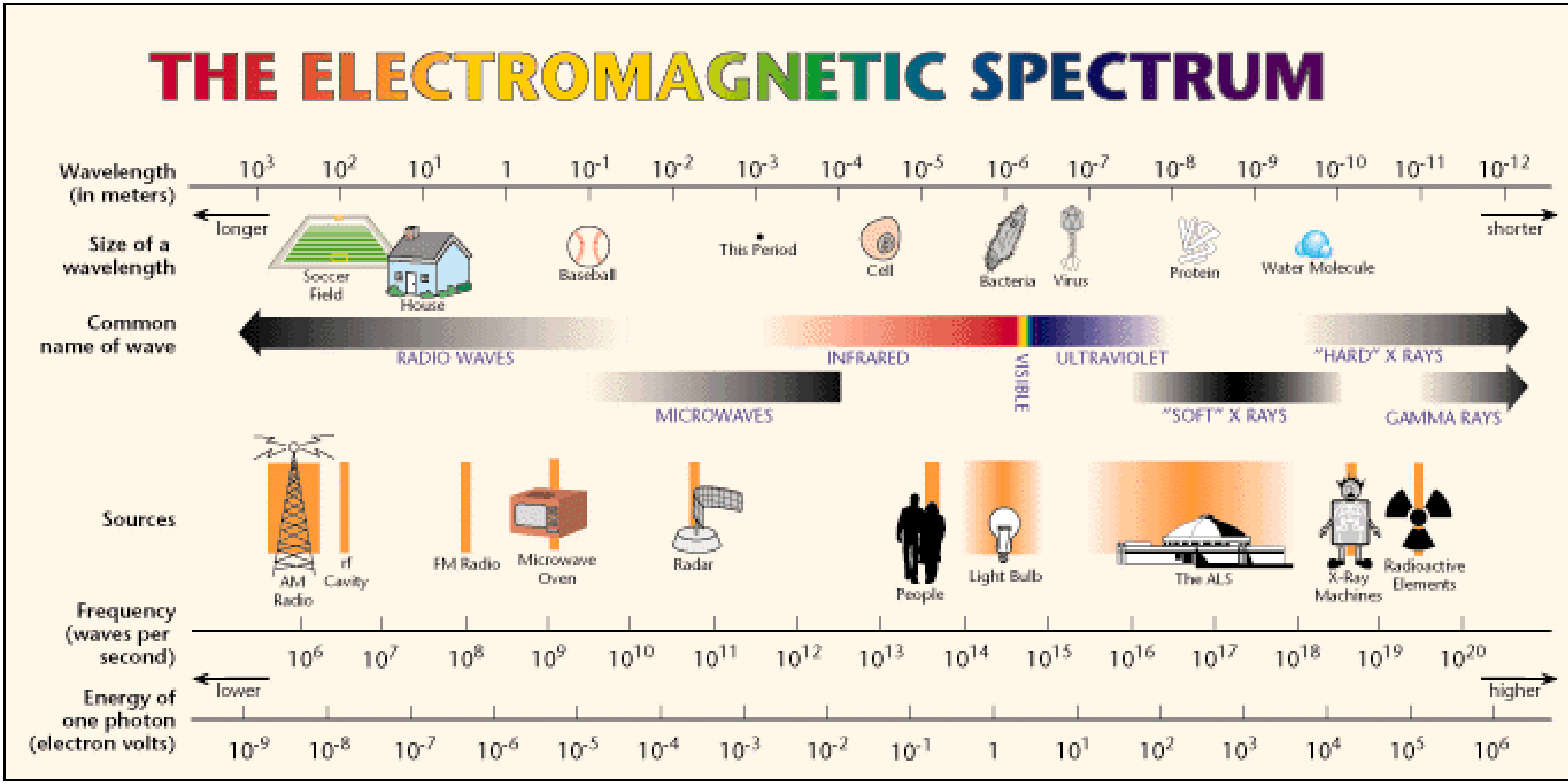




Typical signal variation for mobile



Electromagnetic spectrum



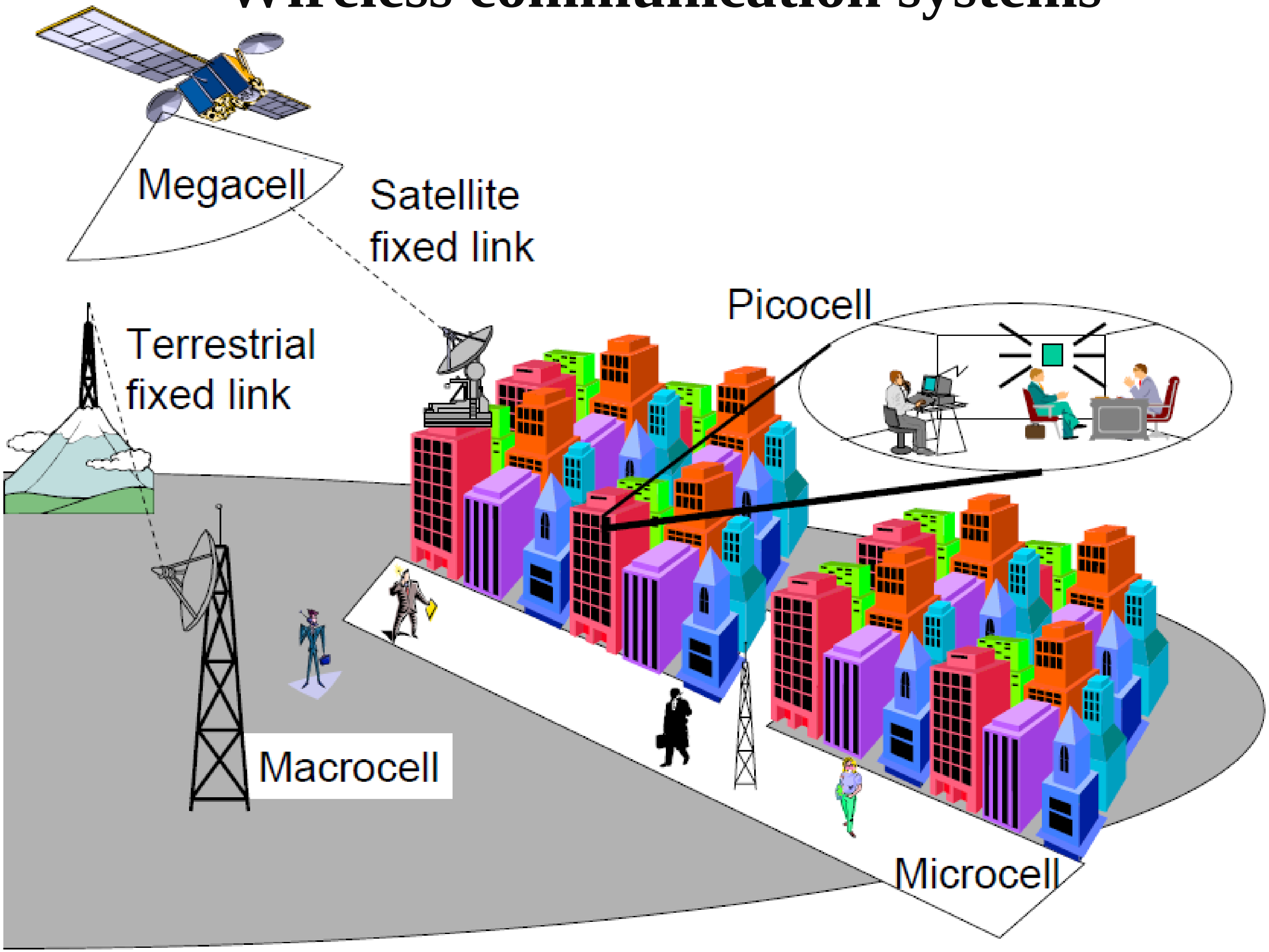
Source: www.rfsafe.com/research/rf_radiation/what_is_rf/emf_spectrum.htm

Radio frequency bands

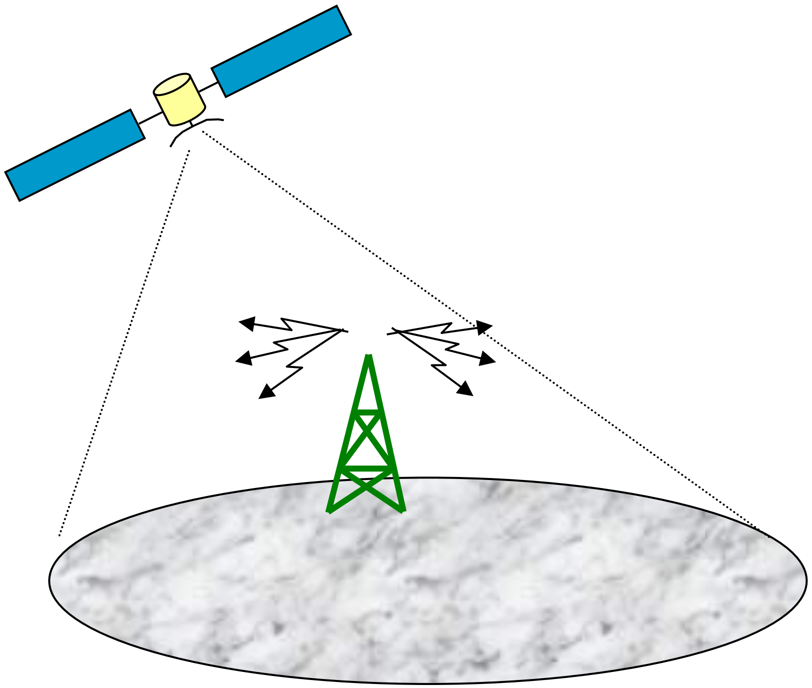
Frequency range	Wavelength	Descriptive designation	Name
Below 3 kHz	Above 100 km		ELF
3-30 kHz	10-100 km	Myriametric waves	VLF
30-300 kHz	1-10 km	Kilometric waves	LF
300-3000 kHz	100-1000 m	Hectometric waves	MF
3-30 MHz	10-100 m	Decametric waves	HF
30-300 MHz	1-10 m	Metric waves	VHF
300-3000 MHz	10-100 cm	Decimetric waves	UHF
3-30 GHz	1-10 cm	Centimetric waves	SHF
30-300 GHz	1-10 mm	Millimetric waves	EHF
300-3000GHz	0.1-1mm	'Sub-millimetric waves'	
3-30 THz	10-100 μm	'Far-infrared waves'	
30-430 THz	0.7-10 μm	'Near-infrared waves'	
430-860 THz	0.35-0.7 μm	'Optical waves'	

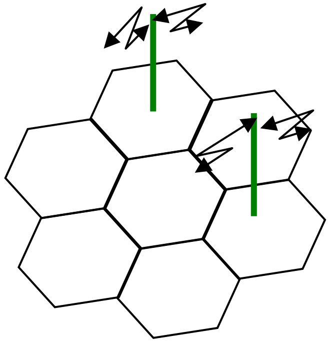
Band	Name
1-2 GHz	L
2-4 GHz	S
4-8 GHz	C
8-12 GHz	X
12-18 GHz	Ku
18-26 GHz	K
26-40 GHz	Ka
40-75 GHz	V
75-111 GHz	W

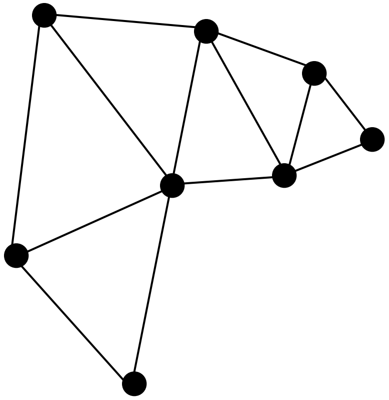
Wireless communication systems



Cellular networks, mesh networks



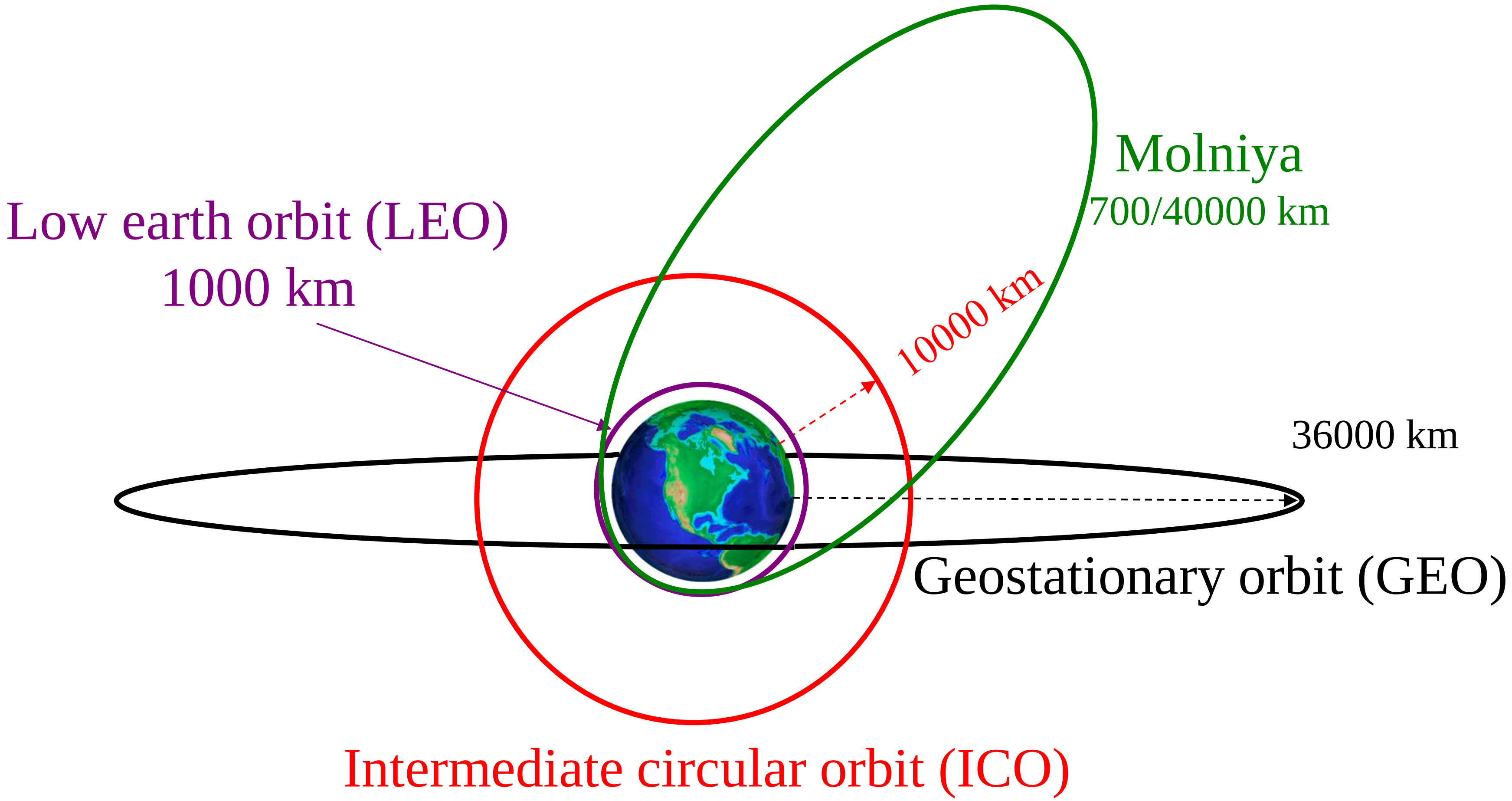




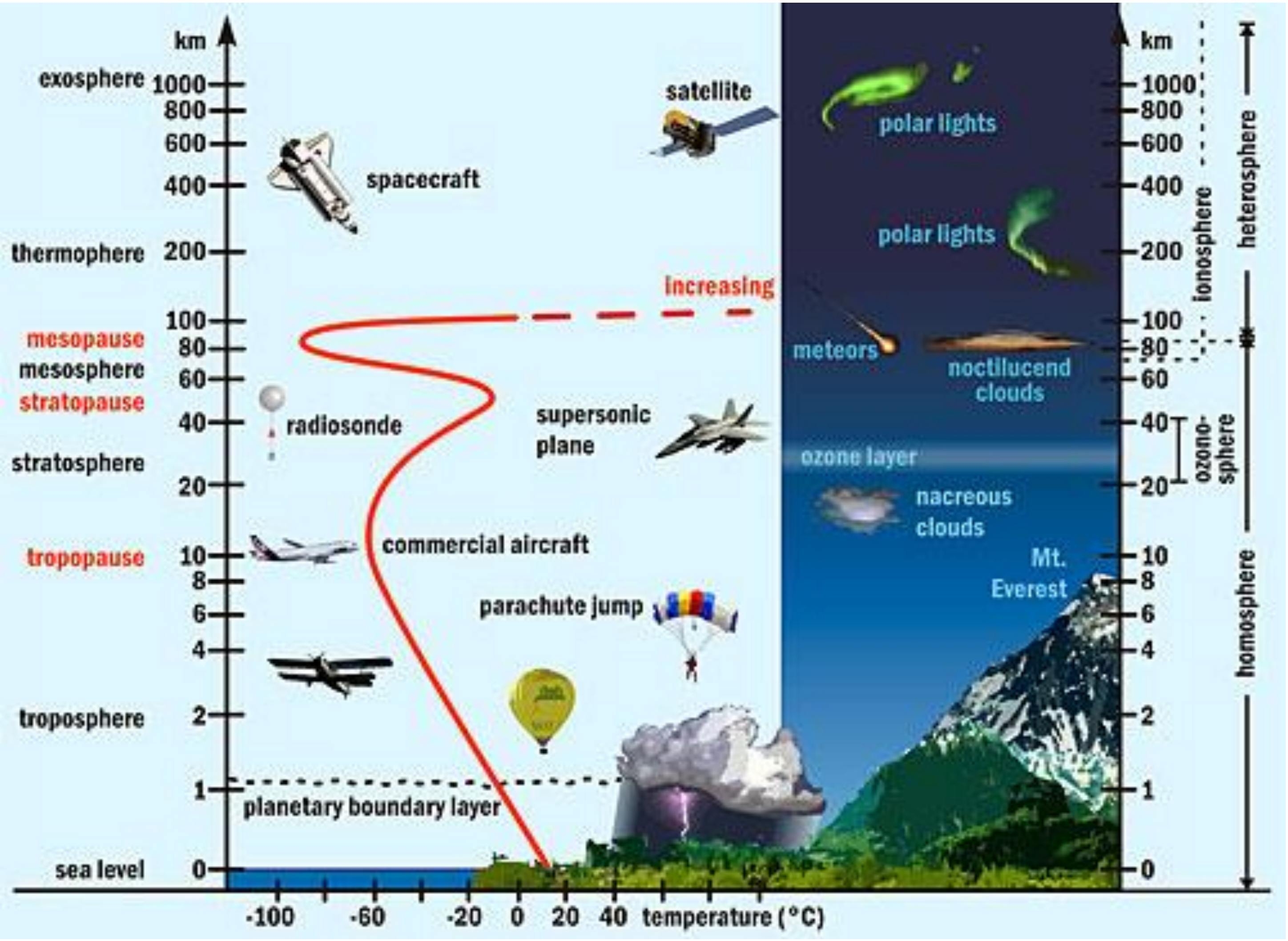
Broadcasting (DVB-T, DMB)
Radio (DAB)
Satellite (DVB-S)

Mobile (GSM, 3G/UMTS, 4G/LTE)
Radio local network (Wi-Fi)
Broadband access (Fixed LTE, WiMAX, VSAT)

Satellite orbits

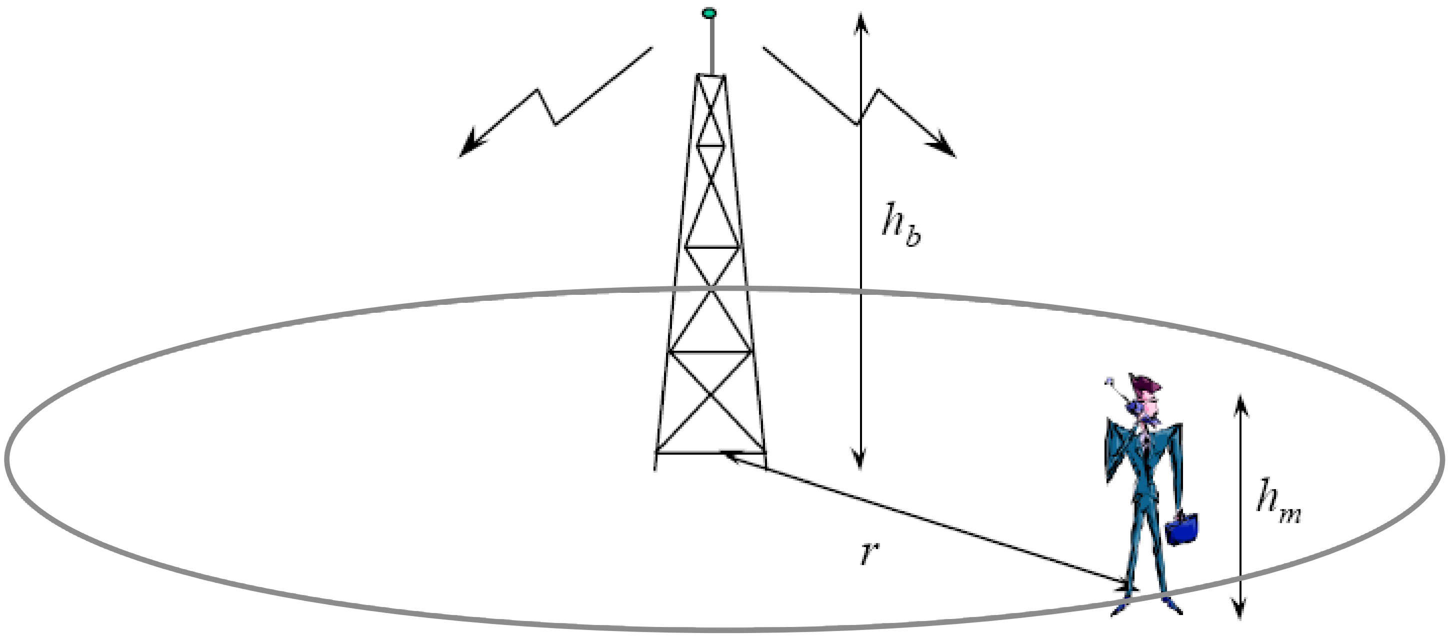


The atmosphere of the Earth



Source: GPS explained [www.kowoma.de]

Path loss *L* for a cellular system



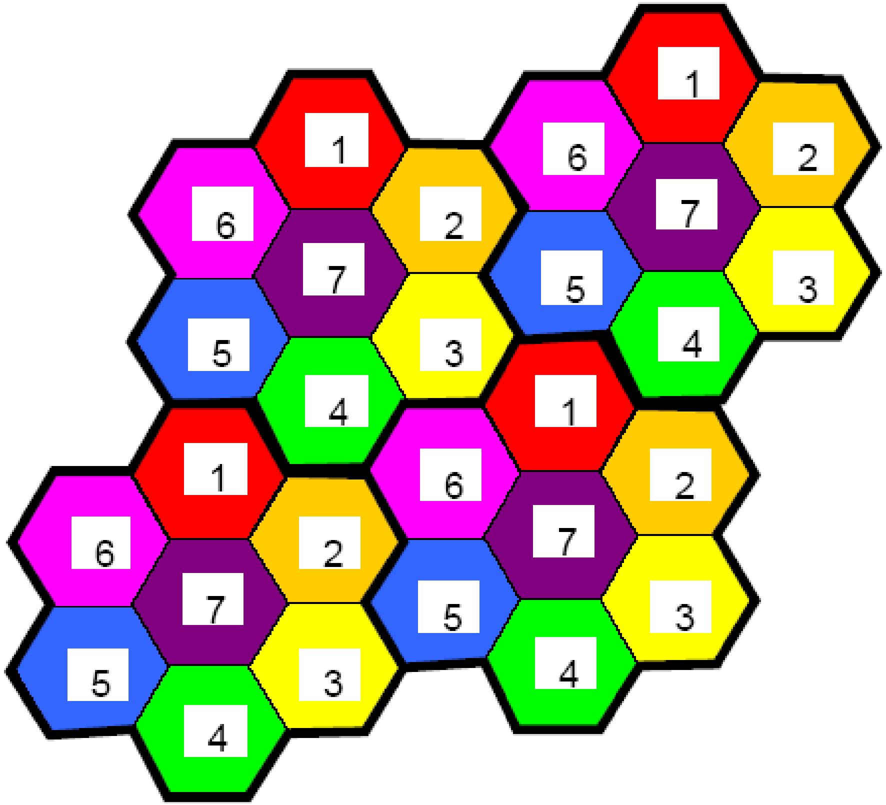
- Approximate Path loss model:

$$\frac{P_R}{P_T} = \frac{1}{L} = k\,\frac{h_m h_b^2}{r^4 f_c^2}$$

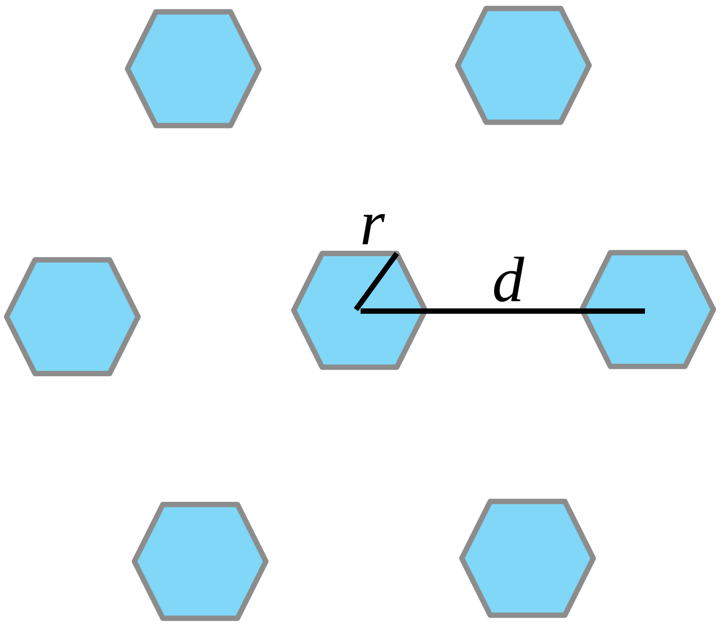
Cellular system for full coverage

7-cell cluster

Coverage area 'tiled' with 7-cell clusters



Signal strength and interference from reuse of frequencies



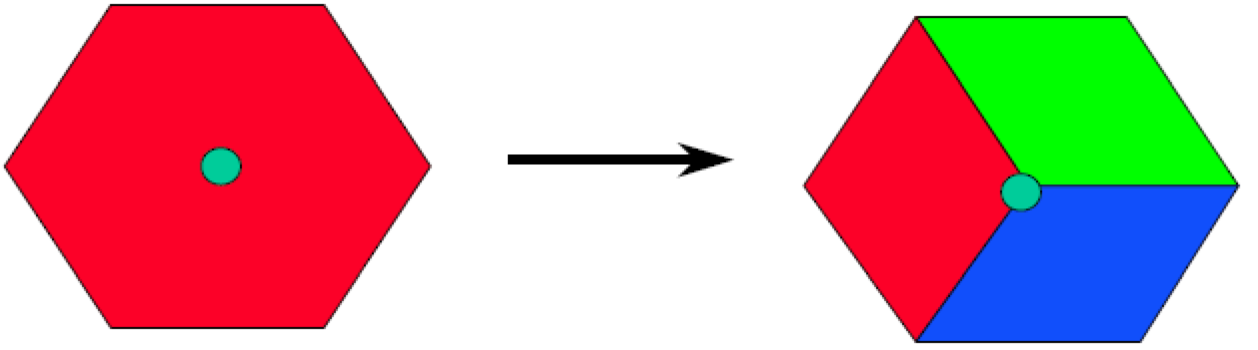
$$\frac{C}{I} = \frac{\frac{1}{r^4}}{\sum_{i=1}^{6} \frac{1}{d_i^{\,4}}} = \frac{1}{6}\left(\frac{d}{r}\right)^4$$

$$\frac{d}{r} = \sqrt{3N}$$

$$\frac{C}{I} = \frac{1}{6}(3N)^2$$

- Cluster size $N = 7$ for $C/I = 19$ dB
- Cluster size $N = 4$ for $C/I = 14$ dB
- Small C/I requirement allows large frequency reuse

Sectorisation



- Sectorisation reduces cluster size to increase capacity
- Reduced interference, now only from 2 and not 6
- But
    - Higher equipment cost
    - More handover (handoffs) and increased signalling
    - Pool of channels reduced

Access schemes and duplexing

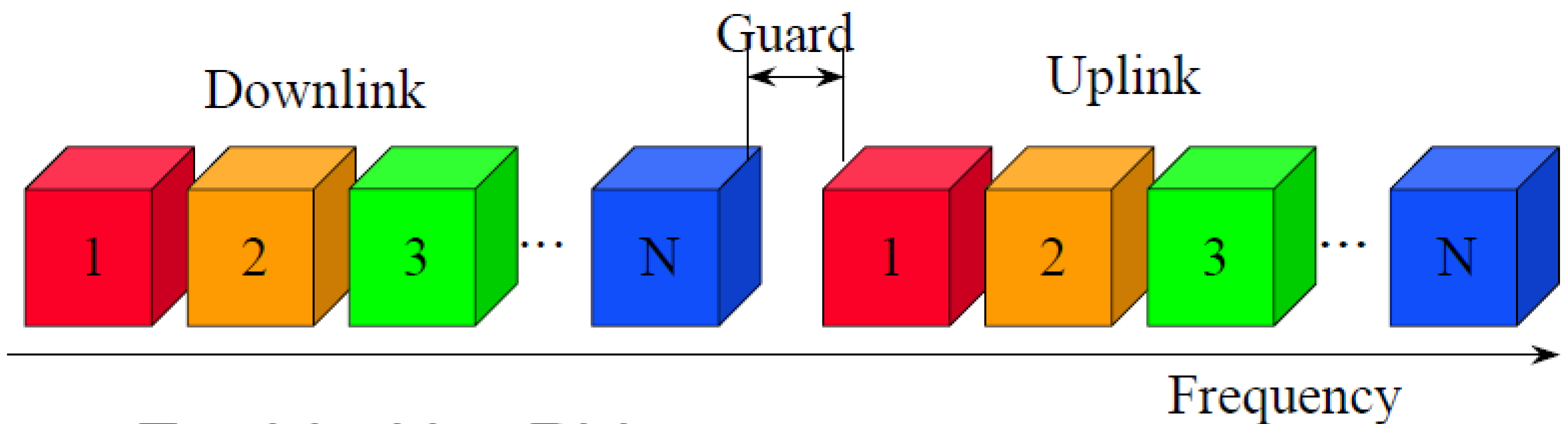
Access schemes

- Means of dividing limited radio resource amongst multiple users
- Frequency Division Multiple Access
- Time Division Multiple Access
- Code Division Multiple Access

Duplexing

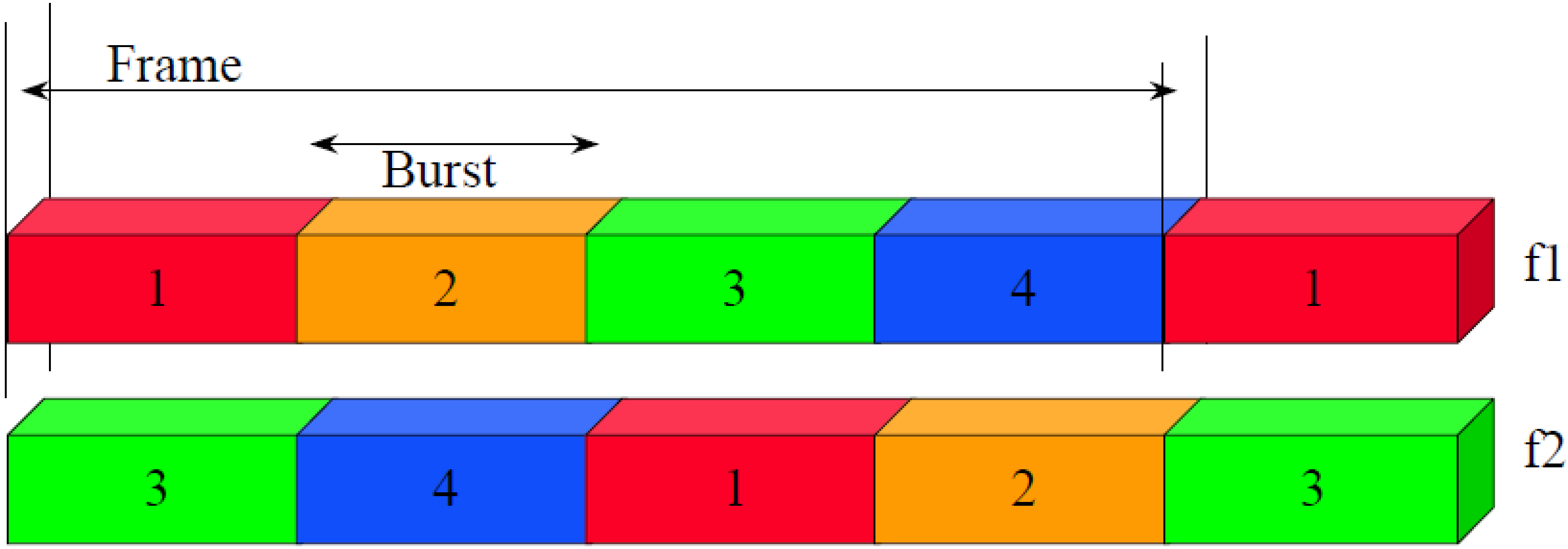
- ‘Simultaneous’ Two-way communication
- Frequency Division Duplex
- Time Division Duplex

FDMA/FDD



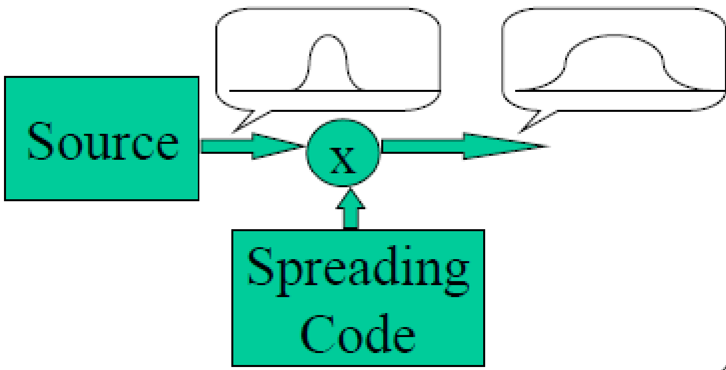
- Enabled by PLL
- One frequency pair per circuit
- Simultaneous Transmission & Reception
- Narrowband - Little Equalisation
- Inter-channel guard - but no wasted bits

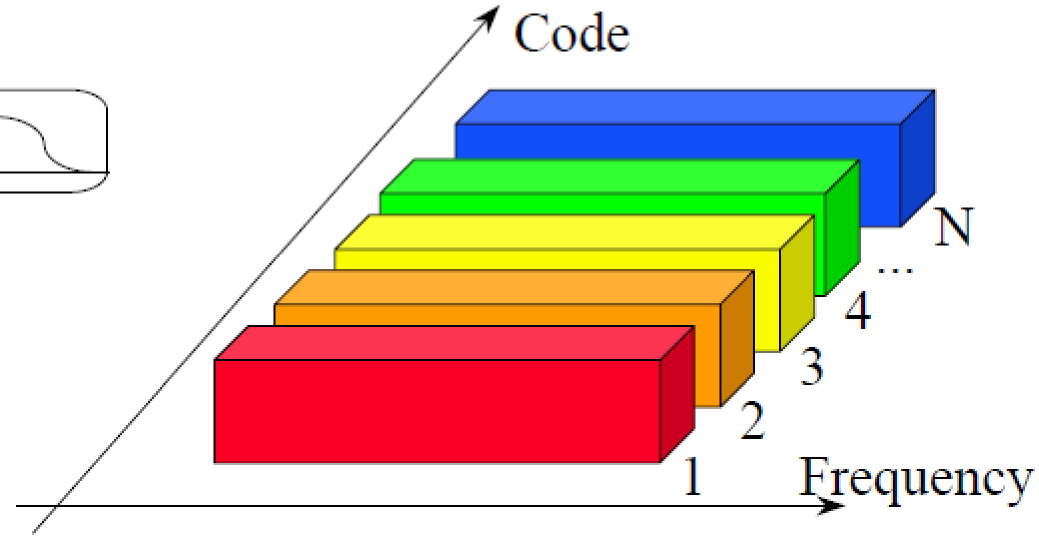
TDMA/FDD



- Transmission & Reception not simultaneous
- Wide Bandwidth - Equalisation
- Guard Time & Signalling Overhead

CDMA





- Soft Capacity Limit
- Frequency diversity - RAKE receiver
- Soft Handover
- Near-far Problem
- Complexity

Channel capacity

The maximum capacity *C* (bit/s) is

$$C = B \log2 (1 + S/N)$$

where

B is the channel bandwidth in Hz

S is the signal power in W

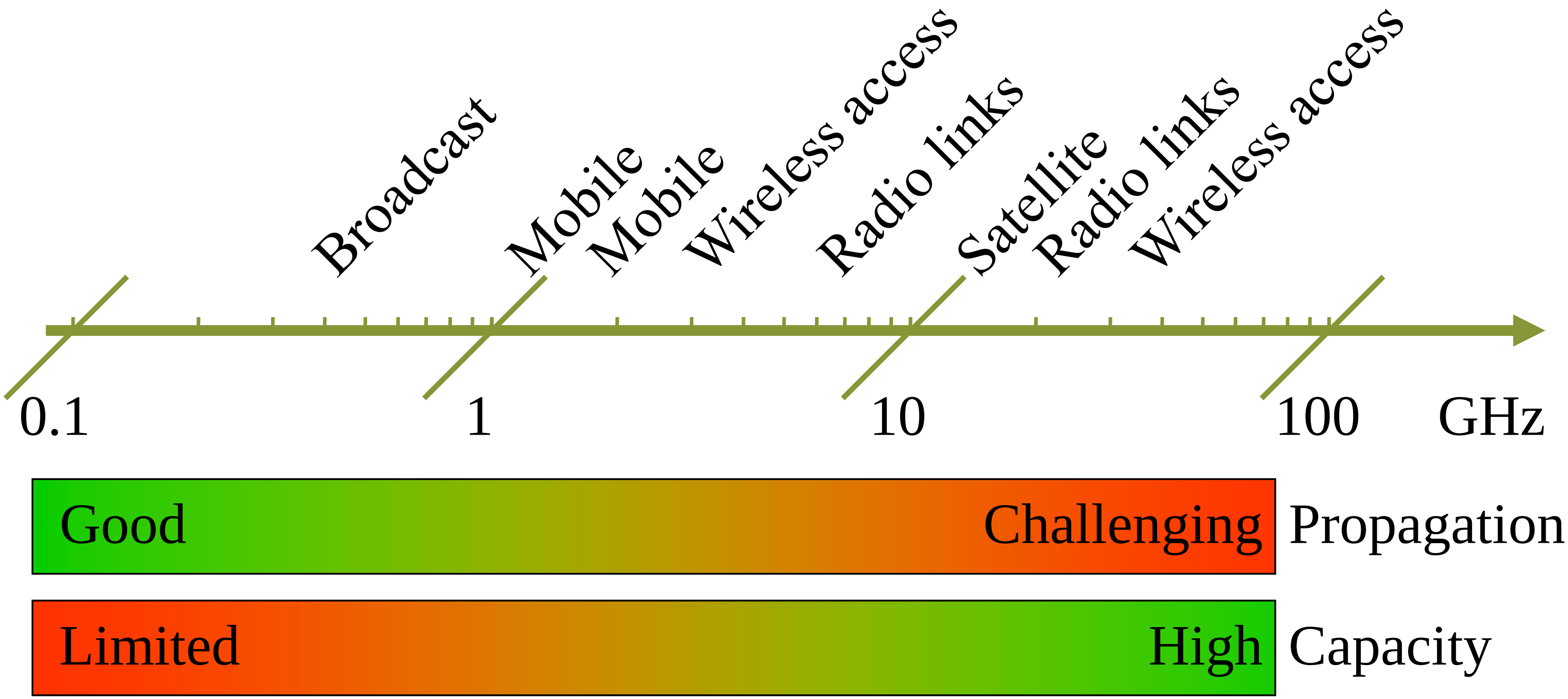
N is the noise power (W)

Ref. Shannon, 1948.

Example:

Assume 5 MHz bandwidth. If the signal to noise ratio (S/N) is 20 dB Shannon predicts maximum capacity to 25 Mbit/s

Radio frequencies for broadcast and communication



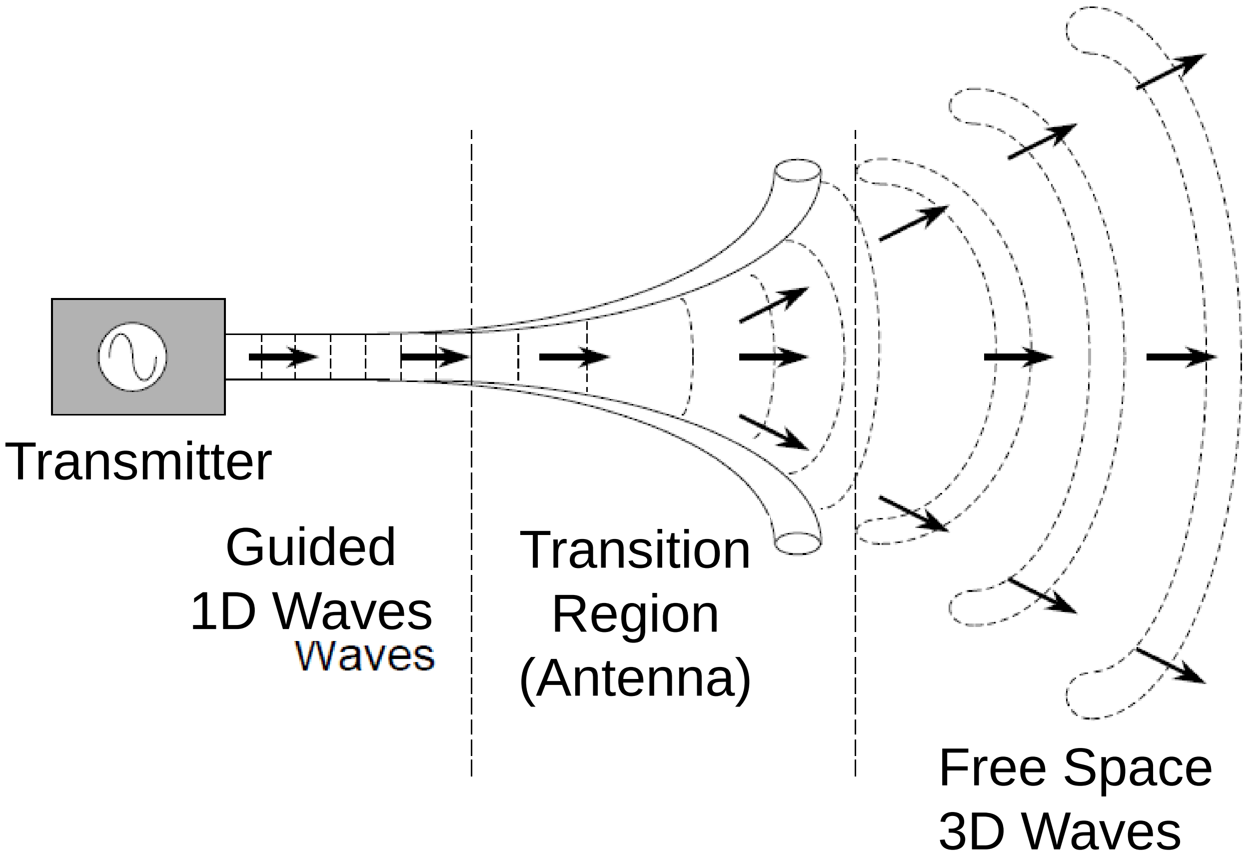
Conclusion

- Wide range of wireless communication systems and different technologies
- All rely on wireless channel for efficient delivery of information
- Need to understand, predict, and evaluate channel effects and impact on system performance

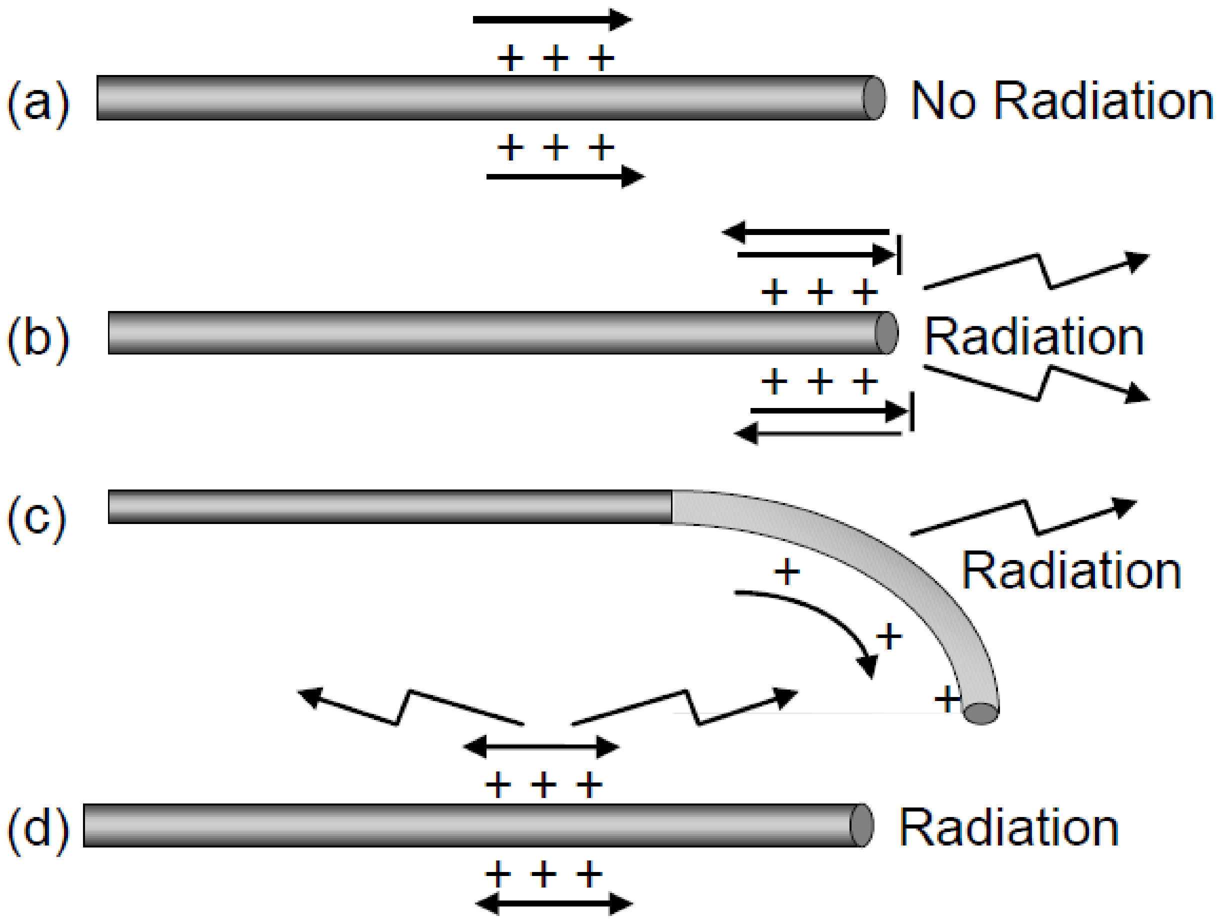
Chapter 4 Antenna fundamentals

- Fundamental theory
- Small antennas for mobile communication
- Free space loss

Antenna – the transition region between guided and propagation waves



Condition for radiation



a) Charges stationary or in uniform motion

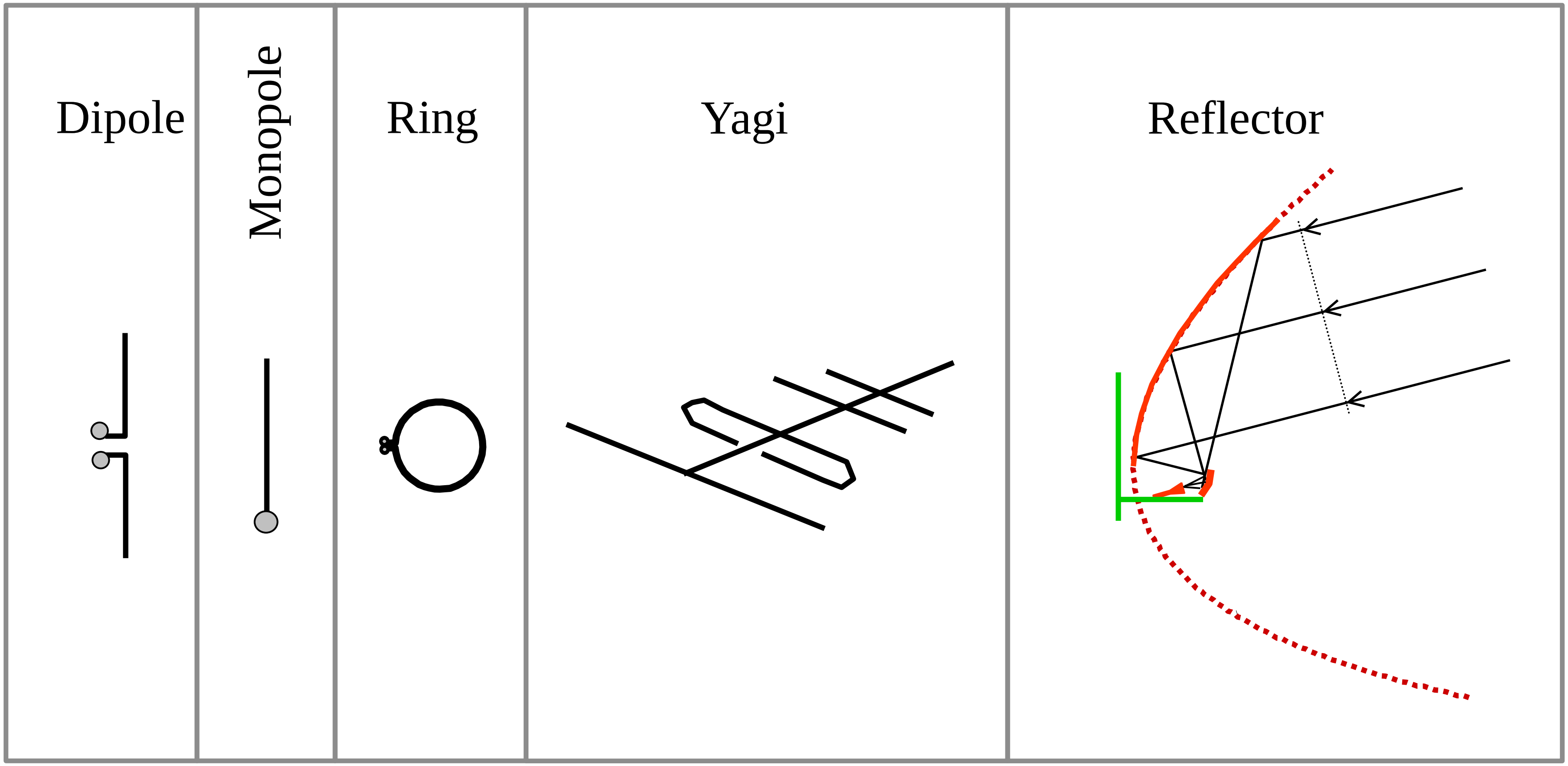
b-d) Charges accelerates

b) Charges reach the end and reverse direction

c) Charges in constant speed but change direction

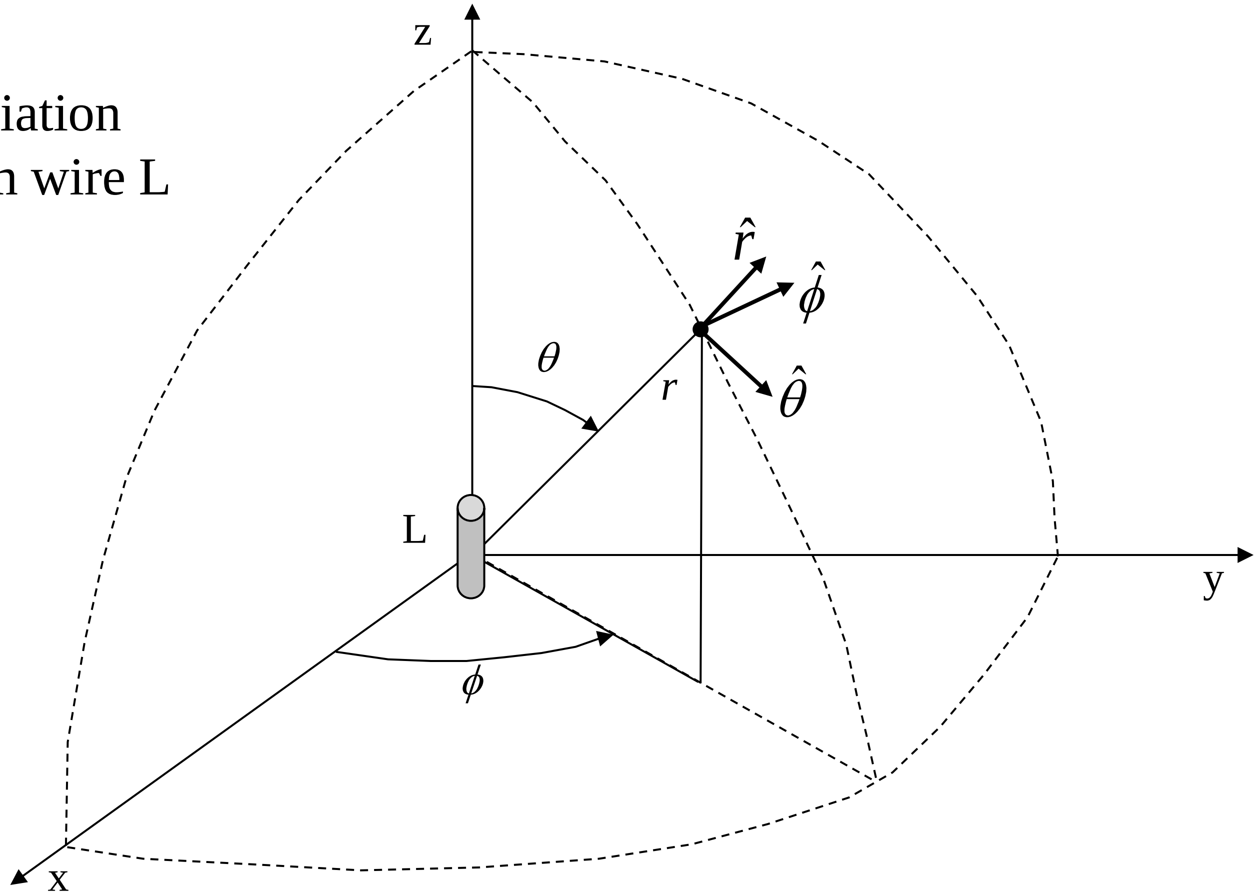
d) Charges oscillating in periodic motion

Antenna examples



Spherical coordinate system

Radiation
from wire L



Radiation from an infinitesimal dipole *L*

Electric field

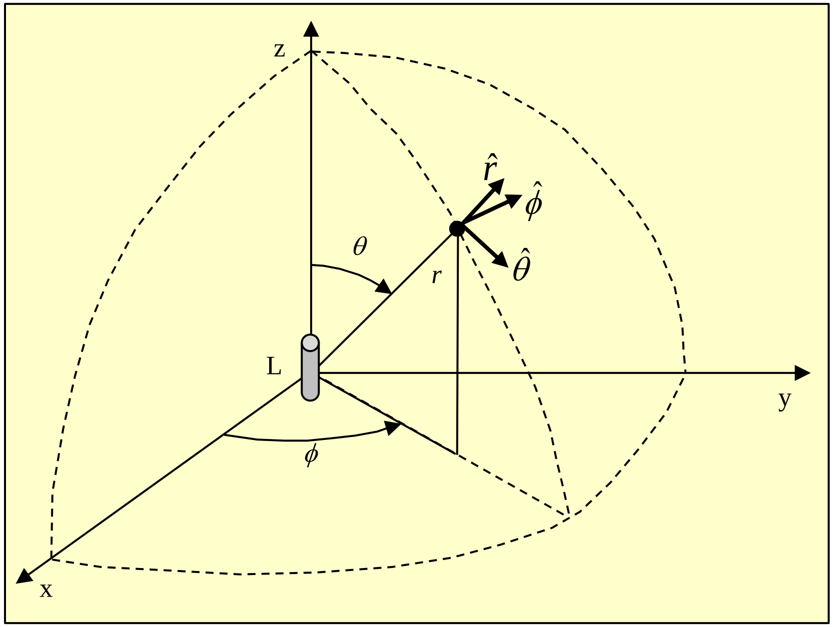
$$\mathbf{E} = \frac{jZ_0 IL}{2\pi k_0}\cos\theta\left(\frac{jk_0}{r^2}+\frac{1}{r^3}\right)e^{-jk_0 r}\mathbf{a}_r - \frac{jZ_0 IL}{4\pi k_0}\sin\theta\left(-\frac{k_0^2}{r}+\frac{jk_0}{r^2}+\frac{1}{r^3}\right)e^{-jk_0 r}\mathbf{a}_\theta$$

$$= E_r\mathbf{a}_r + E_\theta\mathbf{a}_\theta$$

Magnetic field

$$\mathbf{H} = j\frac{k_0 IL\sin\theta}{4\pi r}\left(1+\frac{1}{jk_0 r}\right)e^{-jk_0 r}\mathbf{a}_\phi$$

Note that the term e^{jwt} is dropped for simplicity



Far-field equations

Can neglect terms of r^2 or higher

$$E_\theta = jZ_0 \frac{k_0 I L e^{-jk_0 r}}{4\pi r} \sin\theta$$

$$H_\phi = j \frac{k_0 I L e^{-jk_0 r}}{4\pi r} \sin\theta$$

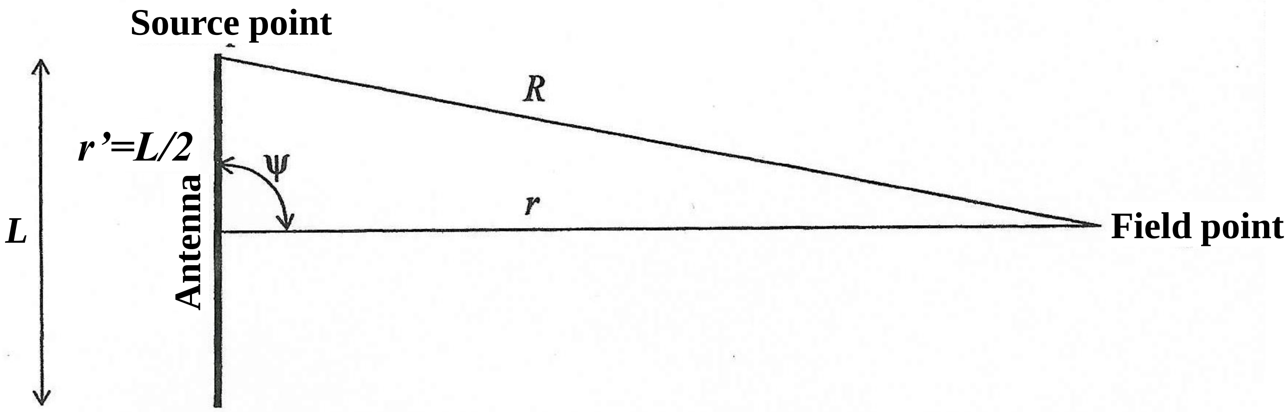
$$E_r = 0$$
$$E_\phi = 0$$
$$H_r = 0$$
$$H_\theta = 0$$

- The radiated field has transverse components
- Ratio $E_\theta/H_\phi = Z_0$: fields in phase and the wave impedance is $120\pi\ \Omega$
- The field is inversely proportional to r
- The fields re zero at $\theta = 0$ and π, but maximum at $\pi/2$; the x-y plane

Distance to the far field

The far field formulas are valid for large *r*, but exactly how large? The approximation for *R* is the most critical one

$$R \approx r - r'\cos\psi = r - \frac{L}{2}\cos\frac{\pi}{2} = r$$



The antennas maximum length or size is *L* perpendicular to the direction of the field point. Real distance from the edge of the antenna to the field point is

$$R = \sqrt{r^2 + \left(\frac{L}{2}\right)^2} = r\sqrt{1 + \frac{L^2}{4r^2}} \approx r + \frac{L^2}{8r}$$

Maximum error is $L^2/8r$. Requiring this less than $\lambda/16$ gives:

$$r > \frac{2L^2}{\lambda}$$

Radiation pattern

The <u>radiation intensity</u> U (Watt per unit solid angle) at a given distance r is

$$U = r^2 S = \frac{P}{4\pi}$$

where S (watt per square meter) is the <u>power density</u> is given by the magnitude of the time-averaged Poynting vector: $S = \dfrac{P}{4\pi r^2}$

The radiation intensity is independent of r: $U = r^2 S = \dfrac{P}{4\pi}$

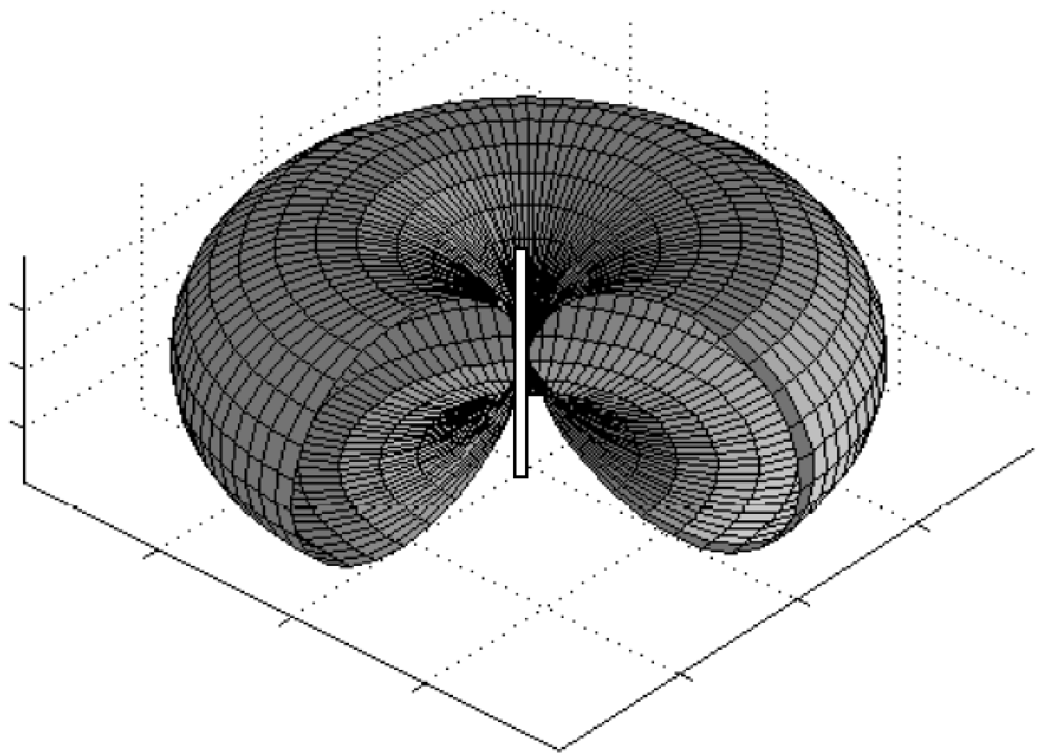
For a infinitesimal (Hertzian) dipole (of length L) the radiation pattern is

$$\mathbf{S}_{av} = \frac{1}{2} E_\theta H_\phi^* \hat{\mathbf{r}}$$

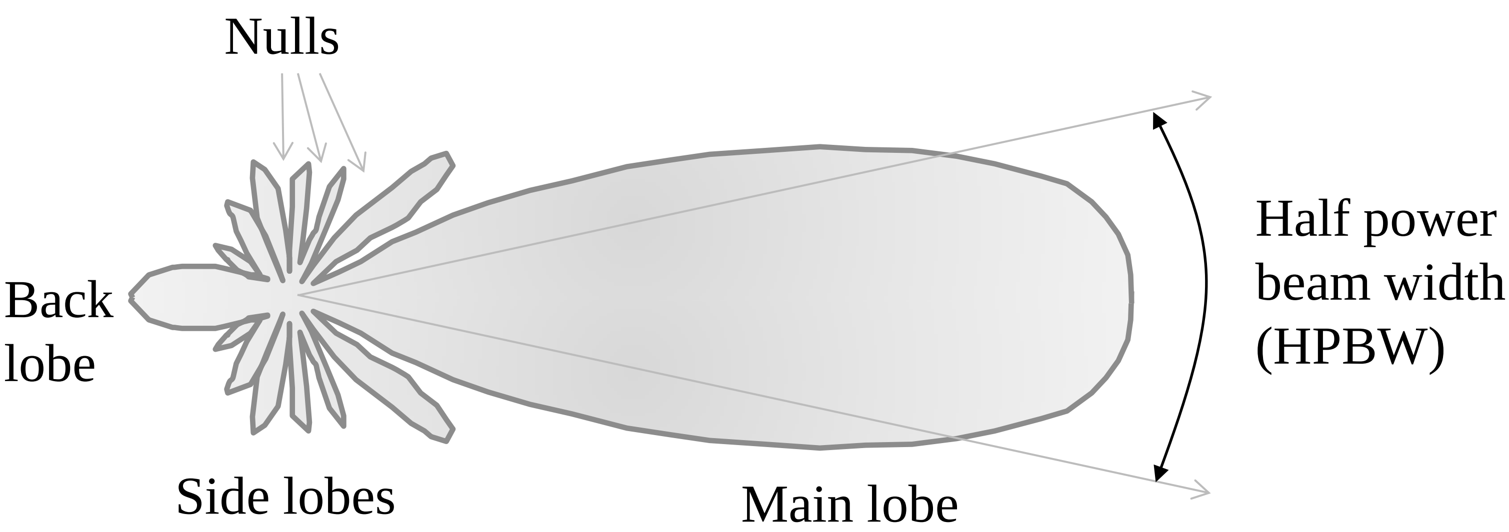
$$U = r^2 \frac{1}{2} \frac{|E_\theta|^2}{Z_0} = \frac{Z_0}{2} \left(\frac{k_0 I(0) L}{4\pi} \right)^2 \sin^2\theta$$

Often plotted normalised to its maximum $\dfrac{U}{U_{\max}} = \sin^2\theta$

Radiation pattern of a Hertzian dipole (infitetesimal)



Radiation pattern generic antenna



Directivity

The directivity D is the ratio between the antenna's radiation intensity in a direction and the average radiation intensity

$$P_{rad} = \int_{4\pi} U(\theta,\phi) d\Omega = \int_0^{2\pi} \int_0^{\pi} U(\theta,\phi) \sin\theta d\theta d\phi$$

The average radiation intensity is $U_0 = \frac{P_{rad}}{4\pi}$

$$D(\theta,\phi) = \frac{U(\theta,\phi)}{U_0} = \frac{4\pi U(\theta,\phi)}{P_{rad}} = \frac{4\pi U(\theta,\phi)}{\int_0^{2\pi} \int_0^{\pi} U(\theta,\phi) \sin\theta d\theta d\phi}$$

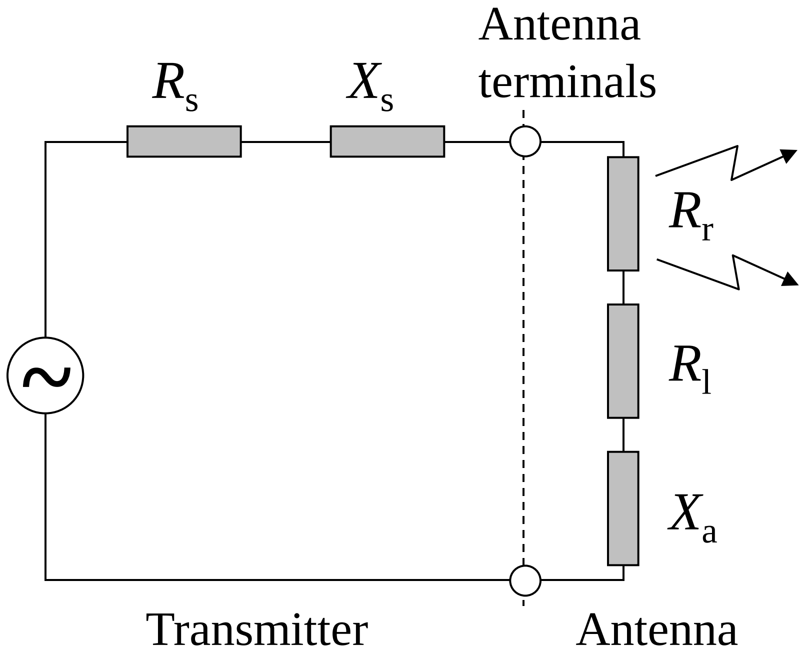
If D is integrated over all solid angles then

$$\frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} D(\theta,\phi) \sin\theta d\theta d\phi = 1$$

The antenna mean directivity is 1.

The directivity D is the ratio between the radiation intensity in a direction and the radiation intensity of an isotropic antenna with same radiated power

Radiation resistance and efficiency



Radiation resistance

Loss resistance

Equivalent circuit for a transmit antenna

Useful to define the antenna efficiency *e*: $e = \dfrac{\text{Power radiated}}{\text{Power accepted by the antenna}} = \dfrac{R_r}{R_r + R_l}$

The antenna is resonant if the reactance X_a=0.

Source matched to the antenna

The source impedance is $Z_s = R_s + jX_s$.
The total antenna impedance $Z_a = R_r + R_l + jX_a$.
The source is matched to the antenna of $Z_s = Z_a^*$.
Degree of mismatch measured using the reflection coefficient ρ :

$$\rho = \frac{V_r}{V_i} = \frac{Z_a - Z_s}{Z_a + Z_s}$$

where V_r and V_i are the amplitudes of the wave reflected form the antenna and the amplitude incident on the terminals, respectively.

Also common to measure the mismatch via the voltage standing wave ratio (VSWR):

$$\text{VSWR} = \frac{1+|\rho|}{1-|\rho|}$$

Power gain and bandwidth

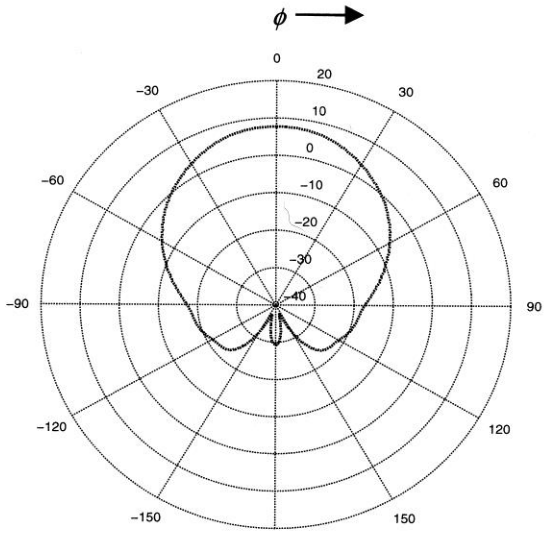
The power gain G, or simply gain, is the ratio between the radiation intensity in a direction and the radiation intensity to an isotropic loss free antenna with the same input power:

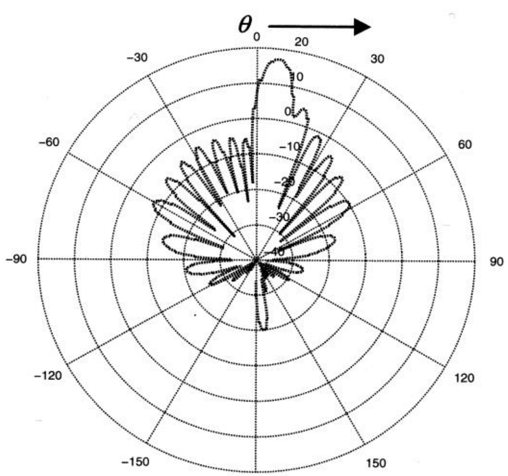
$$G(\theta,\phi) = eD(\theta,\phi)$$ common to specify two orthogonal planes or cuts

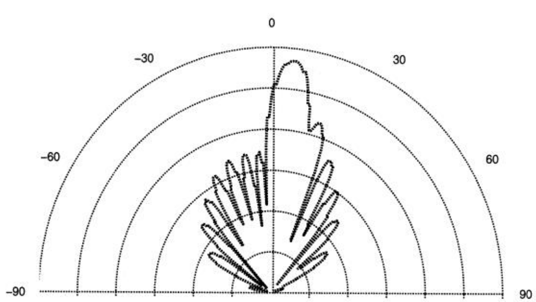
$$G(\theta,\phi) \approx G_\theta(\theta) G_\phi(\phi)$$

The antenna frequency bandwidth is the frequency range it operates satisfactory. Sometimes defined as the range where the gain remains within 3 dB, or the VSWR is no greater than 2:1, whichever the smaller.

Example power gain for a typical base station

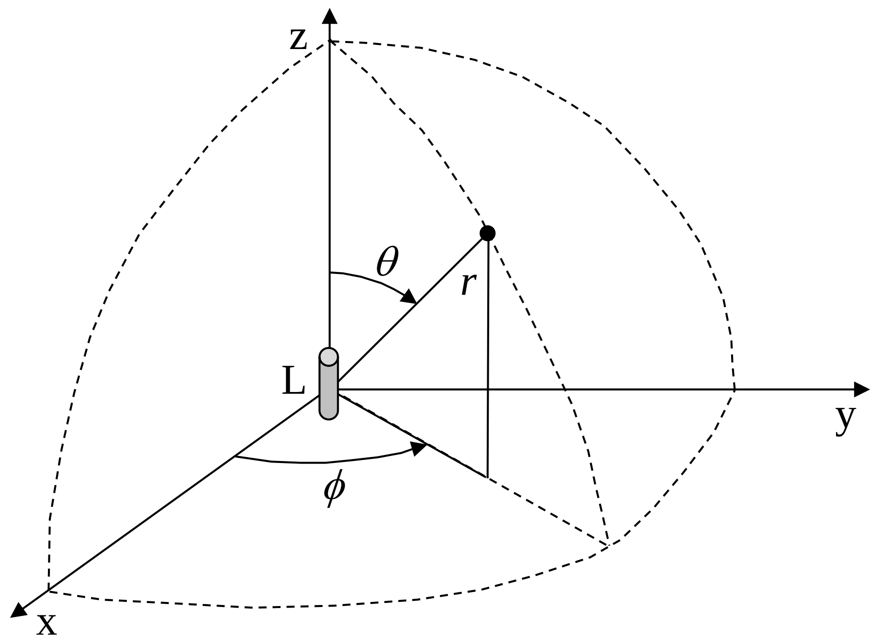






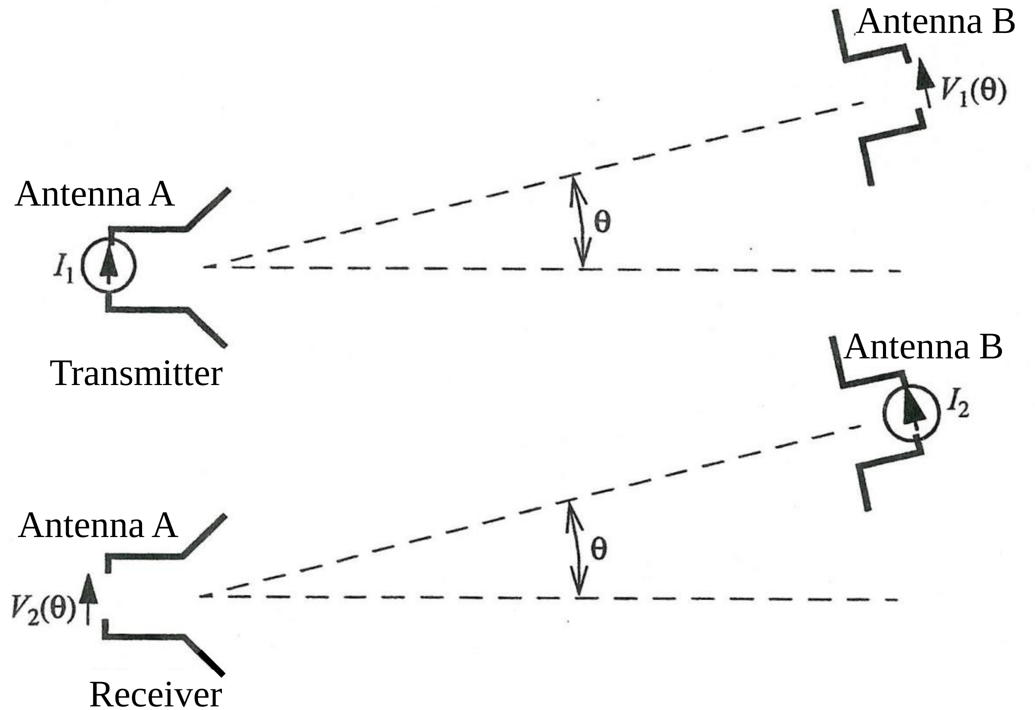
Pattern for $\phi = \theta$

$\phi = \theta$



Reciprocity

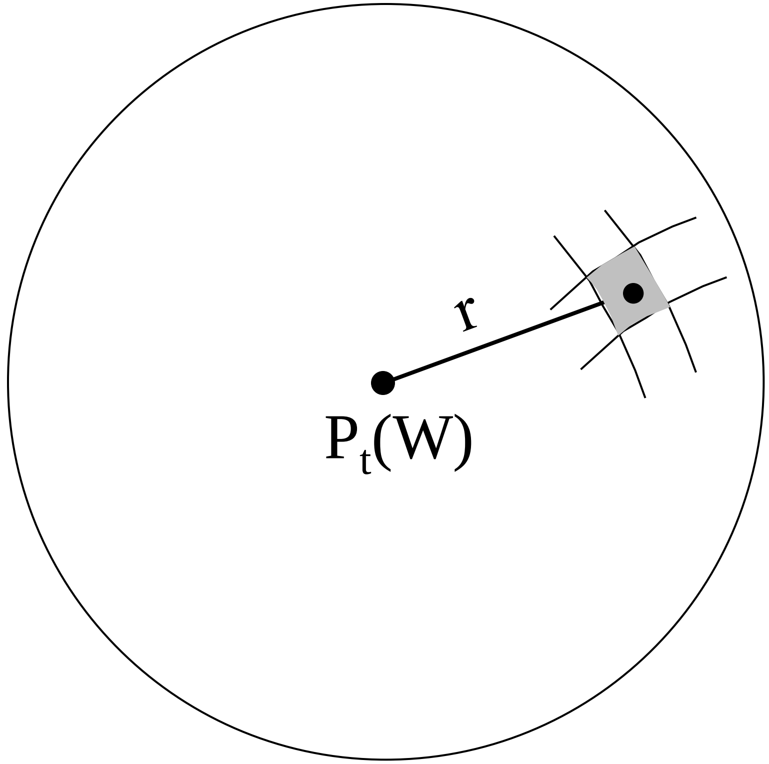
If a current source *I* for antenna A results in voltage *V* at antenna B the same voltage *V* will be generated at A if the current *I* is the source for the antenna in B



The reciprocity shows that the radiation pattern is the same for using the antenna in either transmitter or receiver mode

Receiving antenna aperture

Transmit power from a point source:



Power P_t radiates from a point.
At distance r consider an effective aperture A_e.
Power received P_r

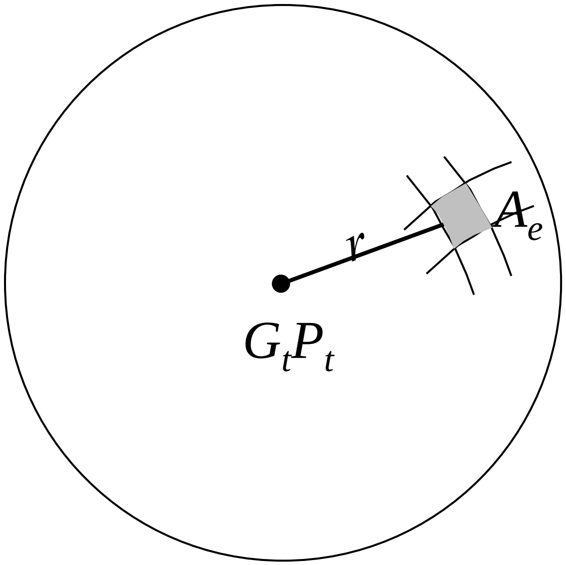
$$P_r = SA_e$$

where S is the power density (W/m^2). For the wave length λ the antenna gain is related to A_e

$$A_e = \frac{G}{4\pi}\lambda^2$$

Free space loss: receiver antenna size

Received power with physical antenna area *A*:



Received power P_r

$$P_r = \frac{P_t}{4\pi r^2} G_t \cdot A_e$$

A_e is the “effective” area.

$$P_r = \frac{P_t G_t}{4\pi r^2} \cdot \frac{G_r \lambda^2}{4\pi} = P_t G_t G_r \left(\frac{\lambda}{4\pi r} \right)^2$$

Sometimes called Friis transmission equation. Note r^2 dependency for received power. The term $(4\pi r/\lambda)^2$ is called free space loss.

Common to express this in dB, i.e. in a ***logarithmic form*** using frequency f rather than the wave length λ, $\lambda = c/f$, where c is the speed of light $3 \cdot 10^8$ (m/s). $P_r = P_t + G_t + G_r - L_{BF}$, L_{BF} is the free space loss: L_{BF} = constant+20log$r$+20log$f$.

Conclusion

- Antenna definitions
- Radiation pattern
- Free space loss