LECTURE 1: Introduction into Antenna Studies

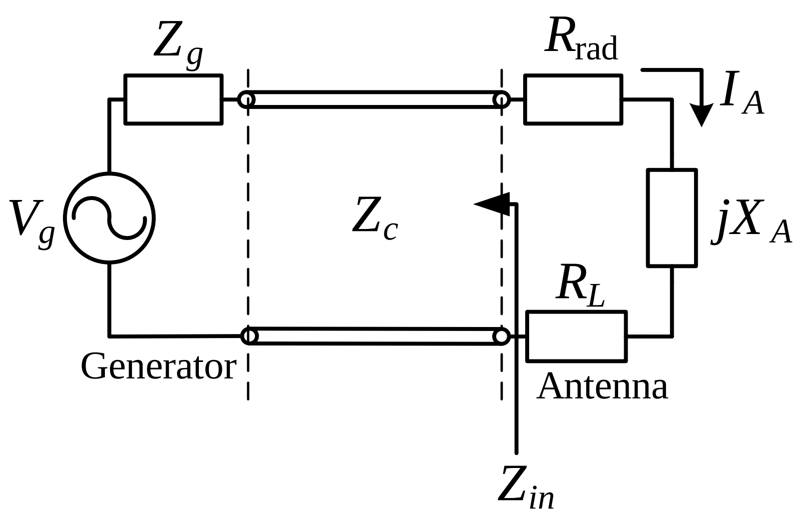
(*Definition and circuit theory description. Brief historical notes. General review of antenna geometries and arrangements. Wireless vs. cable communication systems. The radio-frequency spectrum.*)

1. Definition and circuit theory description

The antenna (aerial, EM radiator) is a device, which radiates or receives electromagnetic waves.

The antenna is the transition between a guiding device (transmission line, waveguide) and free space (or another usually unbounded medium). Its main purpose is ***to convert the energy of a guided wave into the energy of a free-space wave (or vice versa) as efficiently as possible, while at the same time the radiated power has a certain desired pattern of distribution in space***.

a) transmission-line Thevenin equivalent circuit of a radiating (transmitting) antenna



V_g - voltage-source generator (transmitter);

Z_g - impedance of the generator (transmitter);

R_{rad} - radiation resistance (related to the radiated power as $P_{rad} = I_A^2 \cdot R_{rad}$)

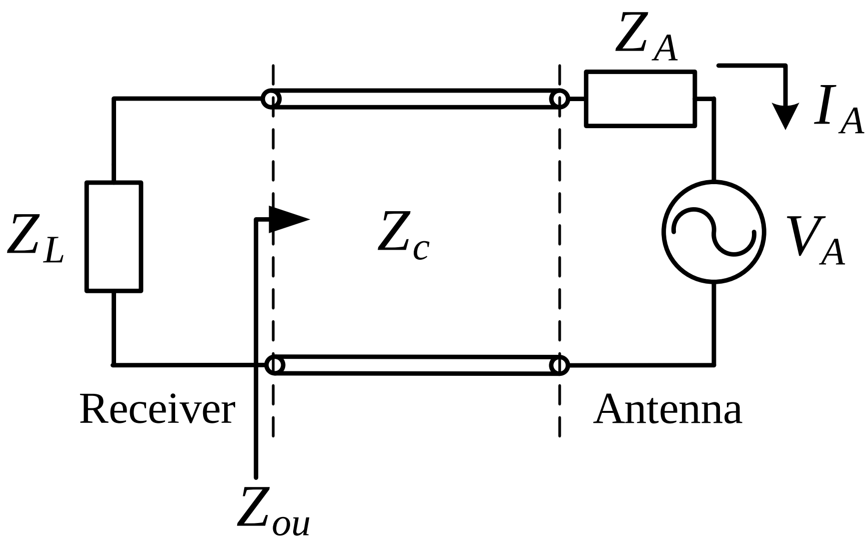
R_L - loss resistance (related to conduction and dielectric losses);

jX_A - antenna reactance.

The antenna impedance is $Z_A = (R_{\text{rad}} + R_L) + jX_A$.

One of the most important issues in the design of high-power transmission systems is the matching of the antenna to the transmission line (TL) and the generator. Matching is specified most often in terms of voltage standing-wave ratio (VSWR). Standing waves are avoided because they may cause arching or discharge in the TL. The resistive/dielectric losses are undesirable, too. They decrease the efficiency of the antenna.

b) transmission-line Thevenin equivalent circuit of a receiving antenna



The antenna is a critical component in a wireless communication system. A good design of the antenna can relax system requirements and improve its overall performance.

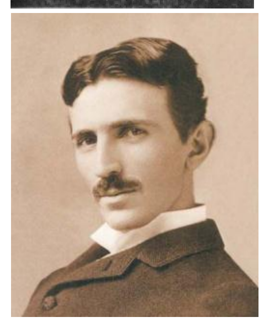
2. Brief historical notes

- James Clerk Maxwell formulates the mathematical model of electromagnetism (classical electro-dynamics), "*A Treatise on Electricity and Magnetism*", 1873. He shows that light is an electromagnetic (EM) wave, and that all EM waves propagate through space with the same speed, the speed of light.

- Heinrich Rudolph Hertz demonstrates in 1886 the first wireless EM wave system: a $\lambda/2$-dipole is excited with a spark; it radiates predominantly at $\lambda \approx 8$ m; a spark appears in the gap of a receiving loop some 20 m away. In 1890, he publishes his memoirs on electrodynamics, replacing all potentials by field strengths.[1]

- May 7, 1895, a telegraph communication link is demonstrated by the Russian scientist, Alexander Popov. A message is sent from a Russian Navy ship 30 miles out in sea, all the way to his lab in St. Petersburg, Russia. This accomplishment is little known today.

- In 1892, Tesla delivers a presentation at the IRE of London about "transmitting intelligence without wires," and, in 1895, he transmits signals detected 80 km away. His patent on wireless links precedes that of Marconi.



- Guglielmo Marconi sends signals over large distances and successfully commercializes wireless communication systems. In 1901, he performs the first transatlantic transmission from Poldhu in Cornwall, England, to Newfoundland, Canada. He receives the Nobel prize for his work in 1909.

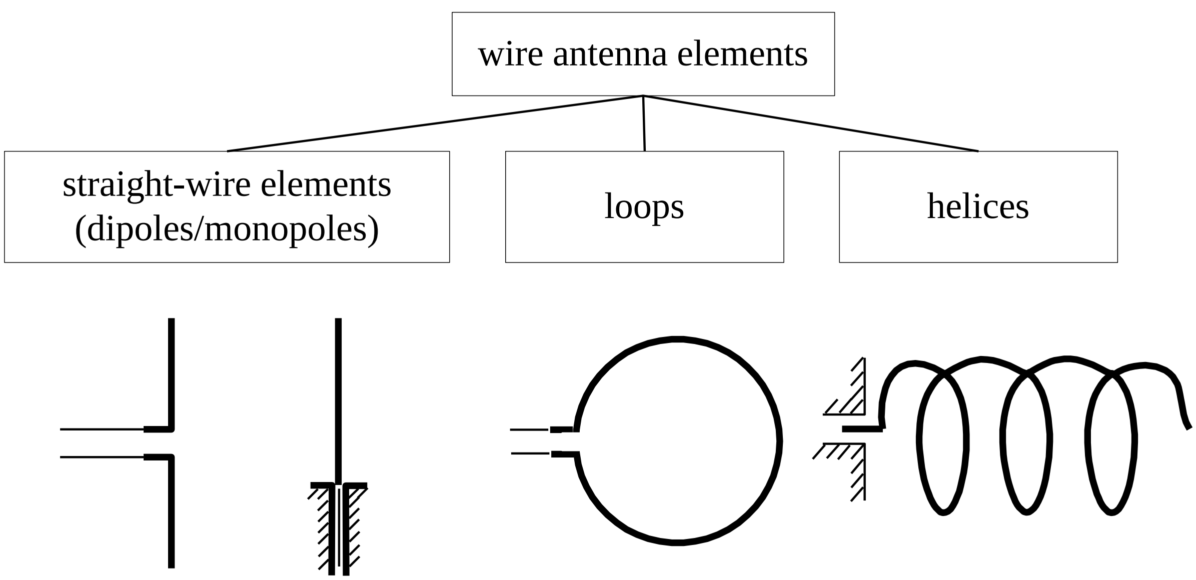
[1] Similar work is done at about the same time by the English scientist Oliver Heaviside.

- The beginning of 20th century (until WW2) marks the boom in wire-antenna technology (dipoles and loops) and in wireless technology as a whole, which is largely due to the invention of the DeForest triode tube, used as radio-frequency generator. Radio links are possible up to UHF (about 500 MHz) and over thousands of kilometers.
- WW2 marks a new era in wireless communications and antenna technology. The invention of new microwave generators (magnetron and klystron) leads to the development of the microwave antennas such as waveguide apertures, horns, reflectors, etc.

3. General review of antenna geometries and arrangements

3.1. Single-element radiators

A. <u>Wire radiators (single-element)</u>



There is a variety of shapes corresponding to each group. For example, loops can be circular, square, rhombic, etc. Wire antennas are simple to make but their dimensions are commensurable with the wavelength. This limits the frequency range of their applicability (at most 1-2 GHz). At low frequencies, these antennas become increasingly large.

Aperture antennas (single element)

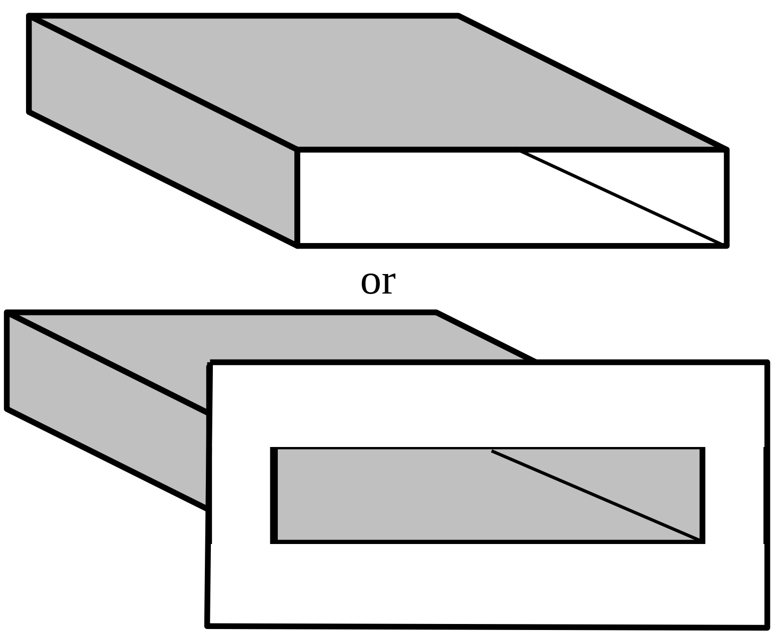

(Q-par Angus)

(a) pyramidal horn

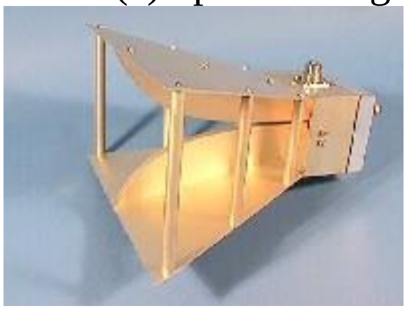

(Radiometer Physics Gmbh)

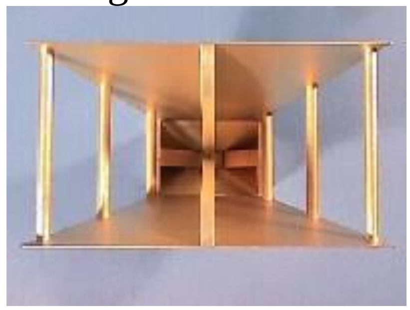
(b) conical horn

Aperture antennas were developed before and during the WW2 together with the emerging waveguide technology. Waveguide transmission lines were primarily developed to transfer high-power microwave EM signals (centimeter wavelengths), generated by powerful microwave sources such as magnetrons and klystrons. These types of antennas are preferable in the frequency range from 1 to 20 GHz.



(c) open rectangular waveguide



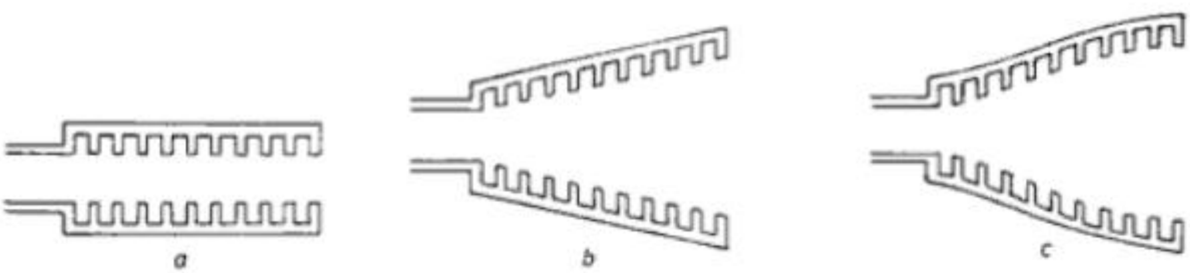


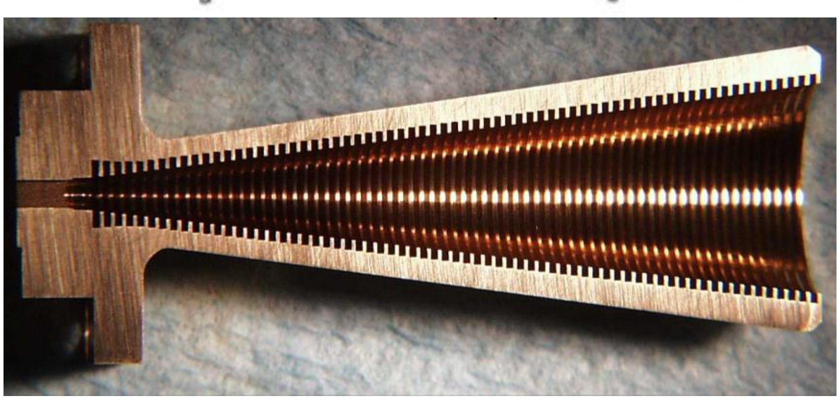
(Quinstar Technology Inc.)

(d) double-ridge horns (TEM, linear polarization, ultra-wide band)

(TMC Design Corp.)

(e) quad-ridge horns (TEM, dual linear polarization allowing for many types of polarization depending on feed , ultra-wide band)





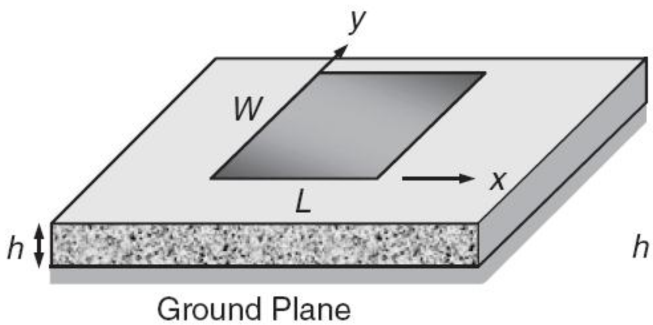
(ZAX Millimeter Wave Corp.)

(f) corrugated horns (symmetric patterns, low side lobes, low cross-polarization)

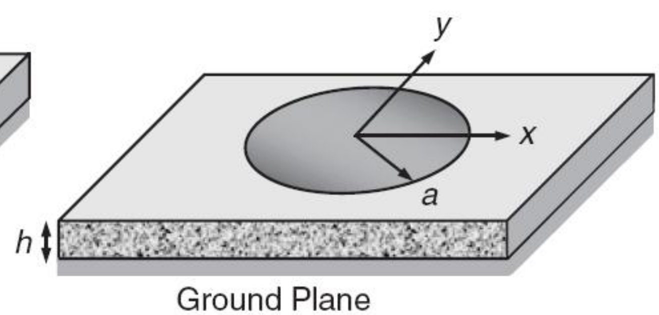
C. <u>Printed antennas</u>

The patch antennas consist of a metallic patch etched on a dielectric substrate, which has a grounded metallic plane at the opposite side. They are developed in the beginning of 1970s. There is great variety of geometries and ways of excitation. Modern integrated antennas often use multi-layer designs with a feed coupled to the radiator electro-magnetically (no galvanic contact).

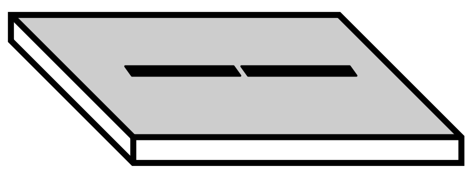
PRINTED PATCH RADIATORS

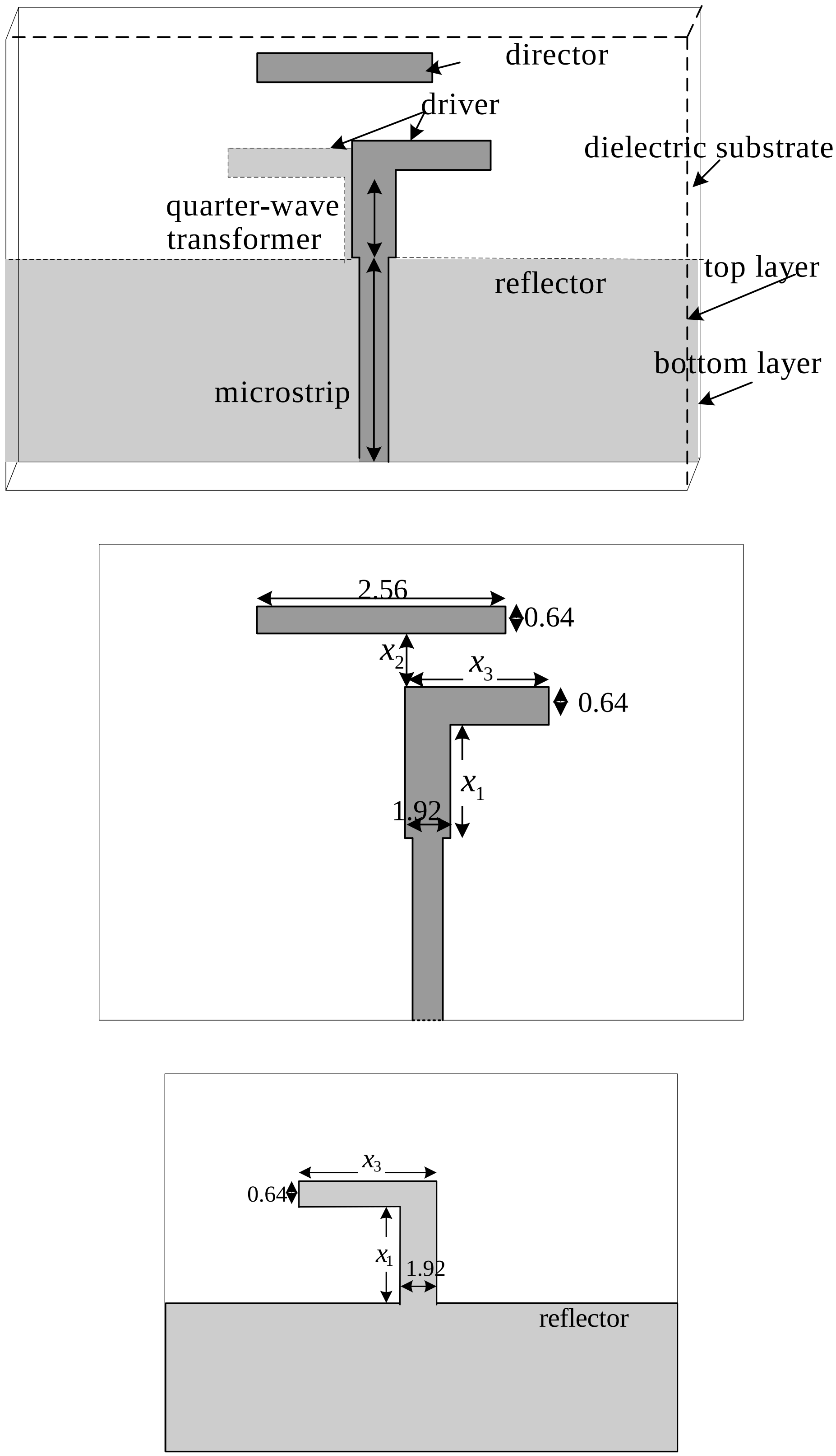


(a)
rectangular patch



(b)
circular patch

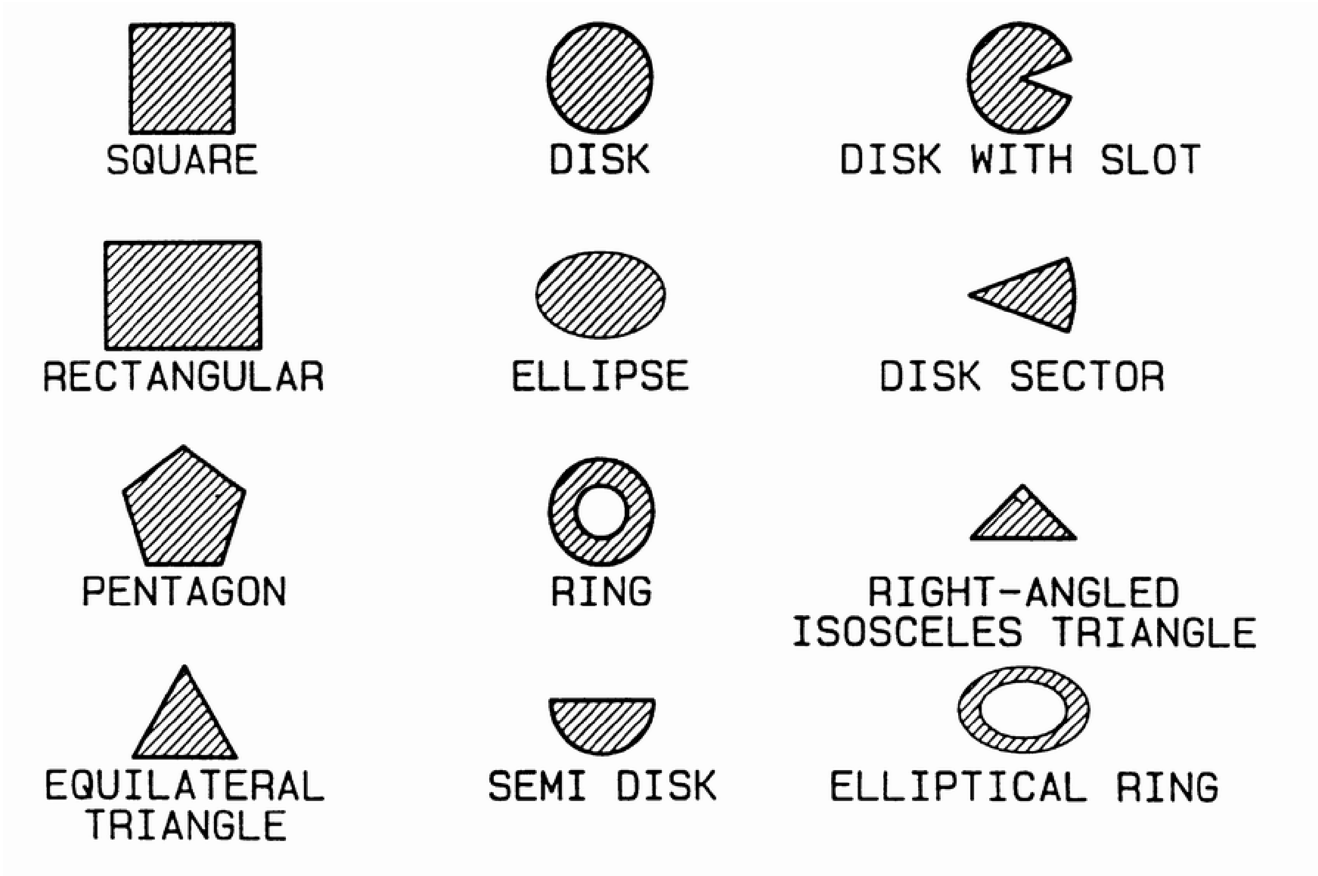

(c)
printed dipole

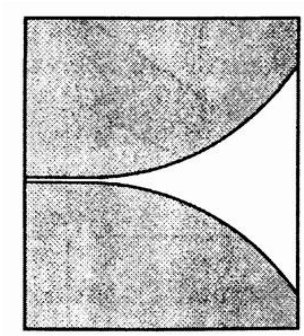


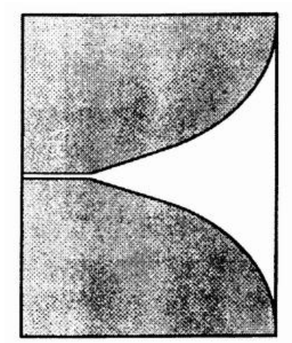
(d)

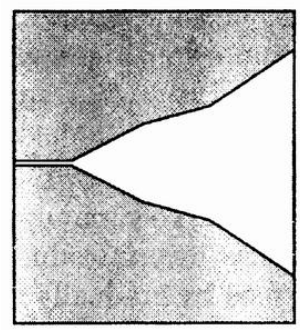
double-layer printed Yagi with electromagnetically-coupled feed

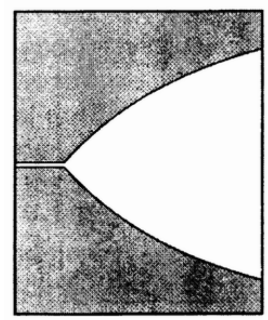
Classical and not so classical shapes used to form a radiating patch:

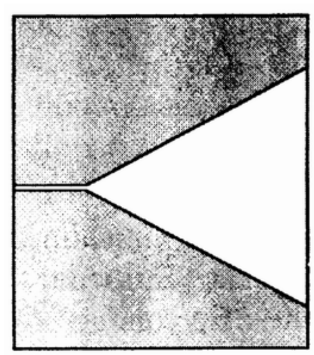


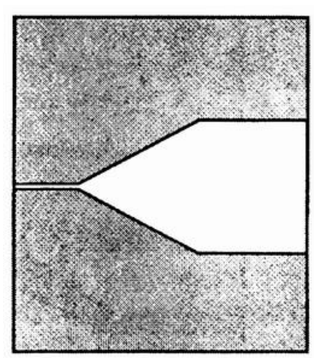

(a)

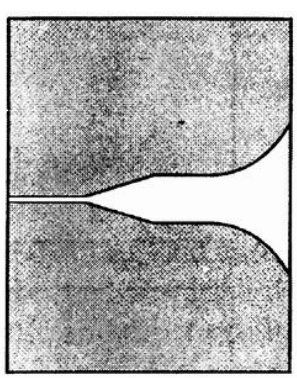

(b)

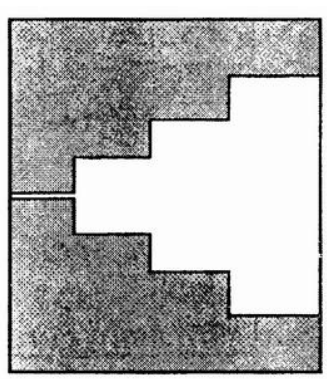

(c)


(d)


(e)


(f)


(g)

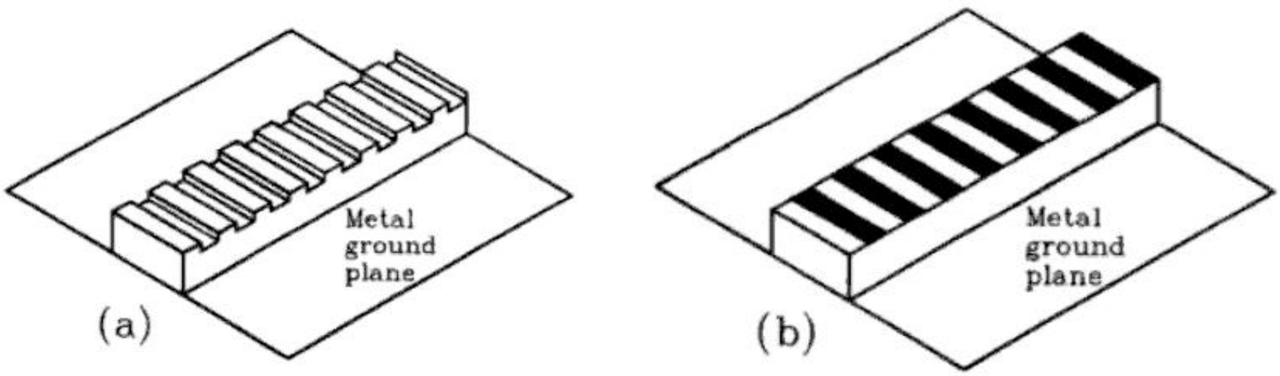

(h)

Slot antennas were developed in the 1980s and there is still intensive research related to new shapes and types of excitation. They are suited for integration with slot-line circuits, which are usually designed to operate at frequencies > 10 GHz. Popular slot antenna in the microwave range is the Vivaldi slot (see a).

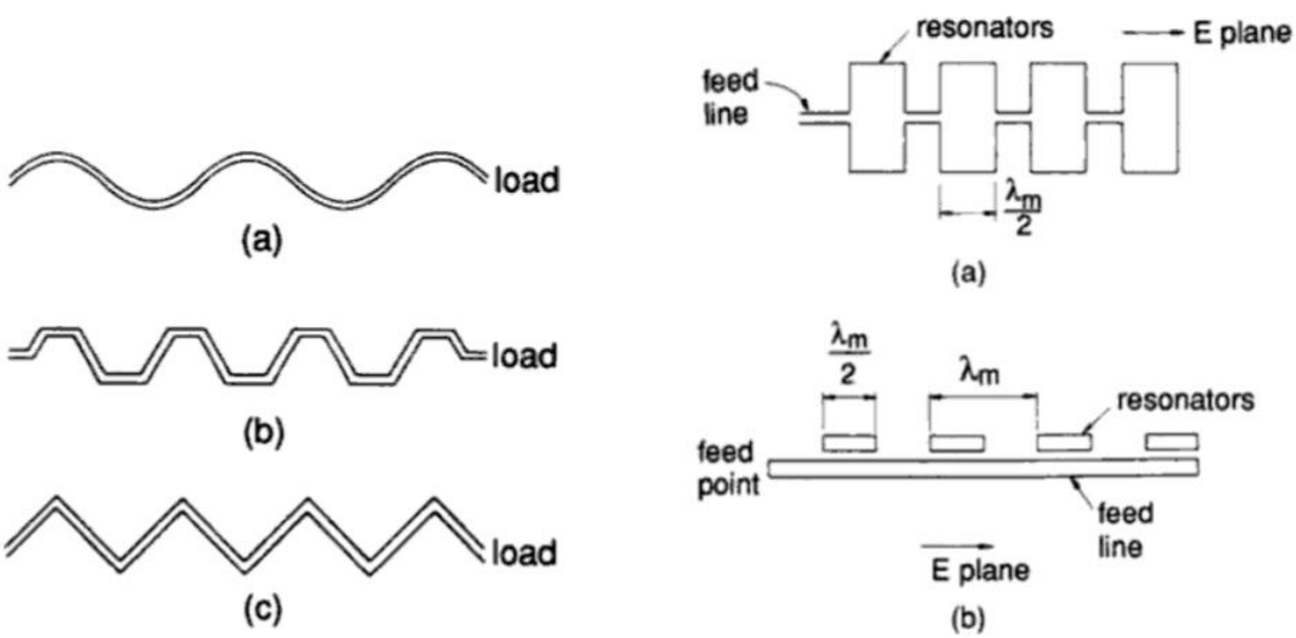
Both patch and slot antennas share some common features. They are easy and cheap to fabricate. They are easy to mount; they are light and mechanically robust. They have low cross-polarization radiation. Their directivity is not very high. They have relatively high conducting and dielectric losses. These radiators are widely used in patch/slot arrays, which are esp. convenient for use in spacecraft, satellites, missiles, cars and other mobile applications.

D. Leaky-wave antennas

These are antennas derived from millimeter-wave (mm-wave) guides, such as dielectric guides, microstrip lines, coplanar and slot lines. They are developed for applications at frequencies > 30 GHz, infrared frequencies included. Periodical discontinuities are introduced at the end of the guide that lead to substantial radiation leakage (radiation from the dielectric surface). These are traveling-wave antennas.



Dielectric-image guides with gratings



Printed leaky-wave antennas

The antennas in the mm-wave band are of big variety and are a subject of intensive study.

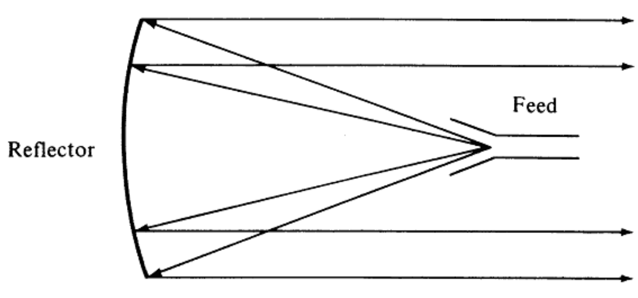
E. Reflector antennas

A reflector is used to concentrate the EM energy in a focal point where the receiver/feed is located. Optical astronomers have long known that a parabolic cylinder mirror transforms rays from a line source on its focal line into a bundle of parallel rays. Reflectors are usually parabolic. A parabolic-cylinder reflector was first used for radio waves by Heinrich Hertz in 1888. Sometimes, corner reflectors are used. Reflector antennas have very high gain and directivity. Typical applications: radio telescopes, satellite communications. They are not easy to fabricate and, in their conventional technology, they are rather heavy. They are not mechanically robust.

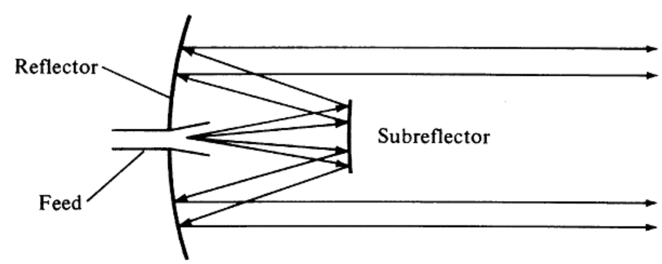
The largest radio telescopes:

- Max Plank Institüt für Radioastronomie radio telescope, Effelsberg (Germany), 100-m paraboloidal reflector
- National Astronomy and Ionosphere Center (USA) radio telescope in Arecibo (Puerto Rico), 1000-ft (304.8-m) spherical reflector
- The Green Bank Telescope (the National Radio Astronomy Observatory) – paraboloid of aperture 100 m

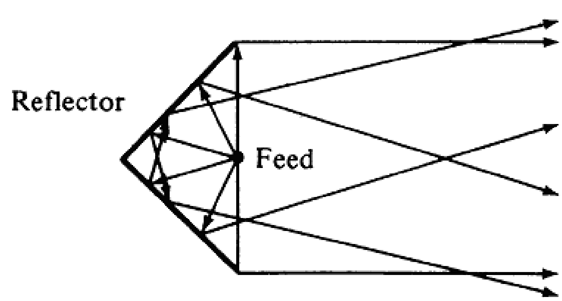
TYPICAL REFLECTORS



(a) Parabolic reflector with front feed



(b) Parabolic reflector with Cassegrain feed

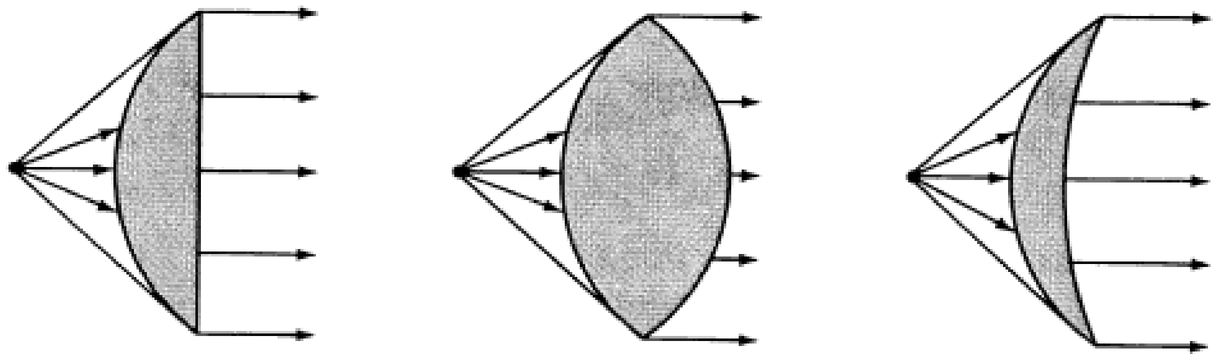


(c) Corner reflector

The Arecibo Observatory Radio Telescope

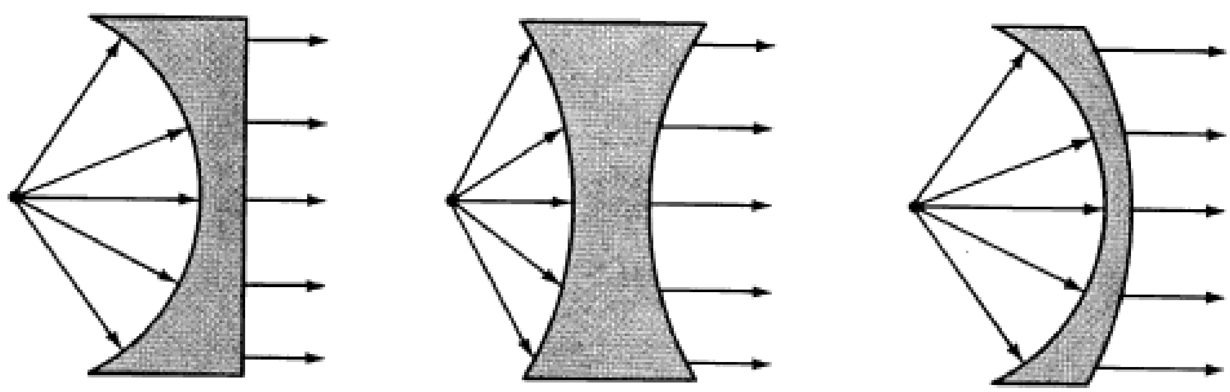
F. Lens antennas

Lenses play a similar role to that of reflectors in reflector antennas. They collimate divergent energy into more or less plane EM wave. Lenses are often preferred to reflectors at higher frequencies (f > 100 GHz). They are classified according to their shape and the material they are made of.



Convex-plane Convex-convex Convex-concave

(a) Lens antennas with index of refraction $n > 1$

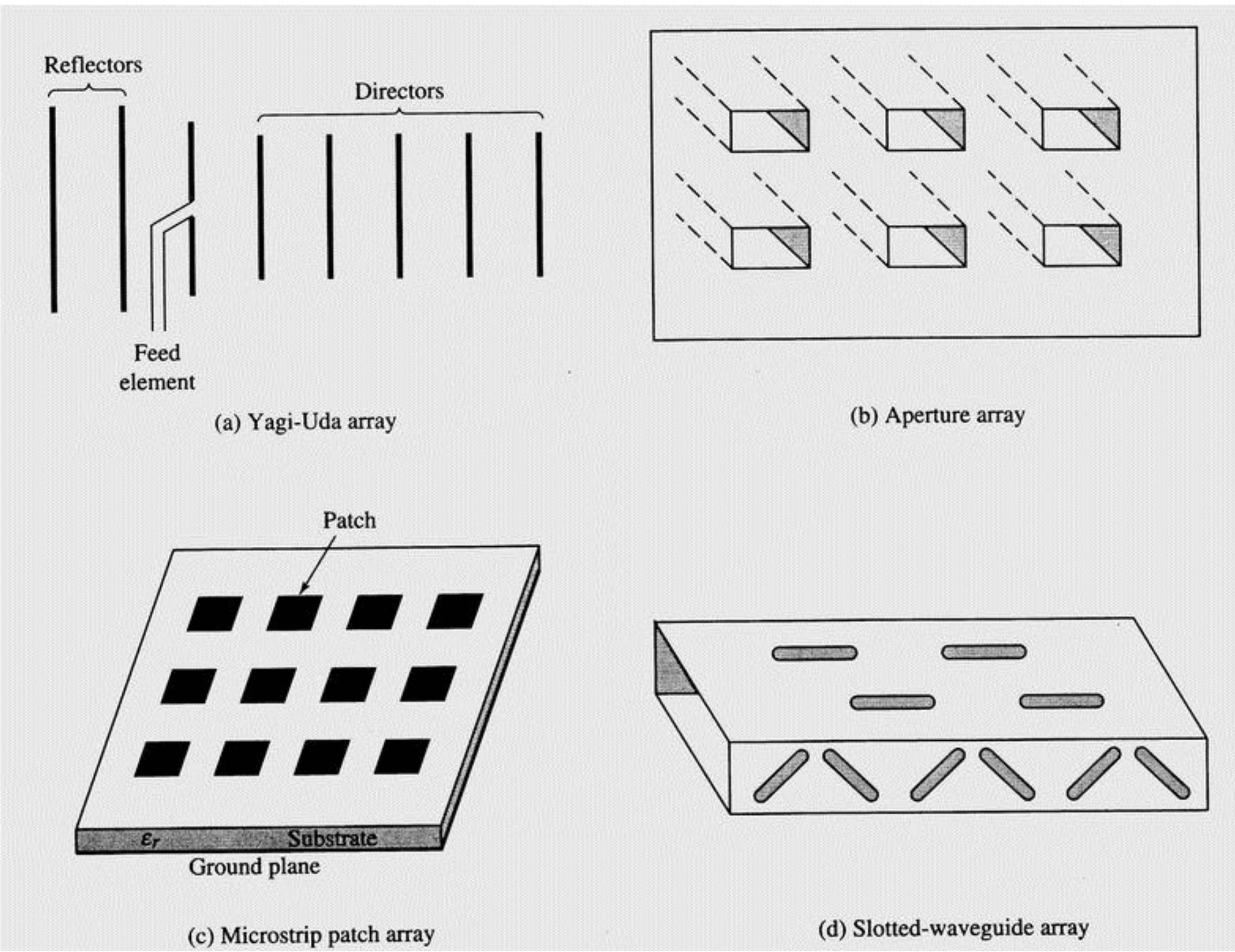


Concave-plane Concave-concave Concave-convex

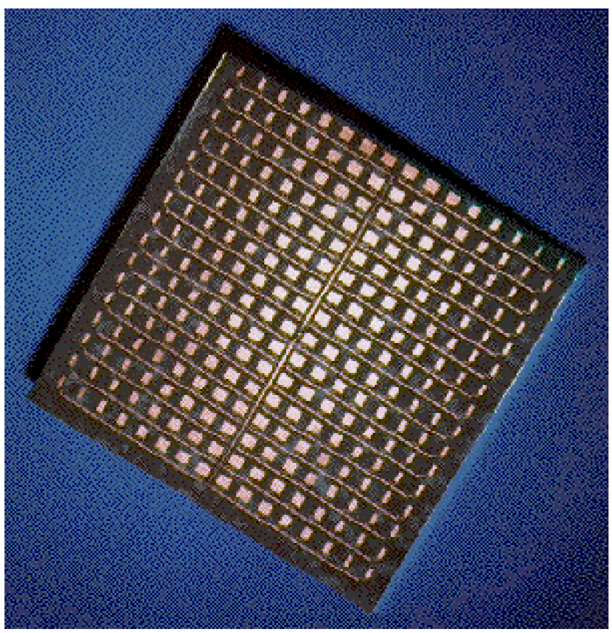
(b) Lens antennas with index of refraction $n < 1$

3.2. Antenna arrays

Antenna arrays consist of multiple (usually identical) radiating elements. Arranging the radiating elements in arrays allows achieving unique radiation characteristics, which cannot be obtained through a single element. The careful choice and control of the phase shift and the amplitude of the signal fed to each element allows the change of the radiation pattern electronically – electronic scanning. Such arrays are called phased arrays. The design and the analysis of antenna arrays is a subject of its own, which is also related to signal processing. Intensive research goes on nowadays, concerning smart antennas, signal-processing antennas, tracking antennas, etc. Some commonly met arrays are shown in the figure below.



NRAO/ALMA (Atacama Large Millimeter Array): array of radio telescopes



Array of Microstrip Patches

4. Wireless vs. cable communication systems

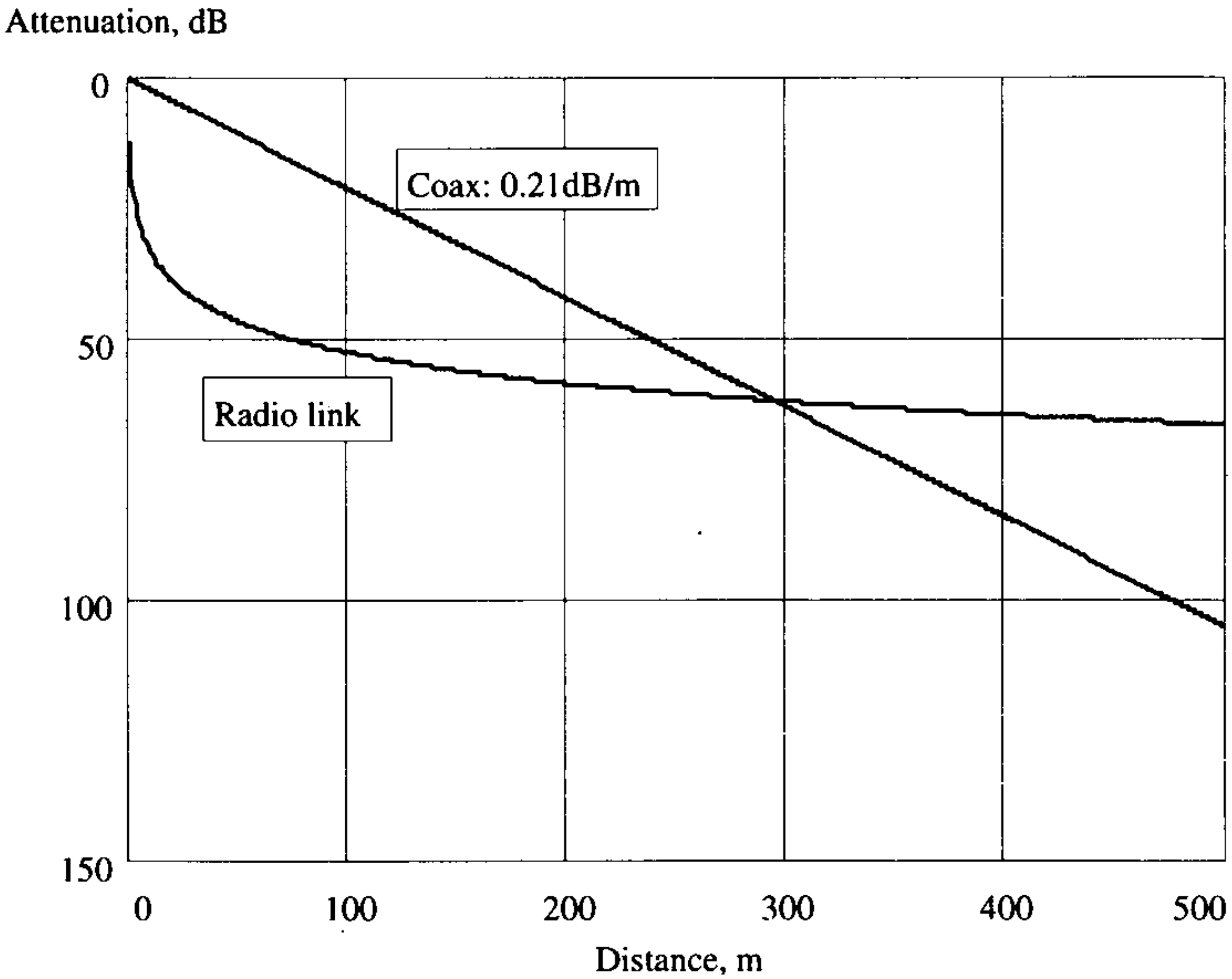
There are two broad categories of communication systems: those that utilize transmission lines as interconnections (*cable systems*), and those that use EM radiation with an antenna at both the transmitting and the receiving end (*wireless systems*).

In areas of high density population, the cable systems are economically preferable, especially when broadband communication is in place. Even for narrow-band communication, such as voice telephony and low-data-rate digital transmission, it is much simpler and cheaper to build wire networks with twisted-pair cables, when many users are to be interconnected. Such lines introduce very little attenuation at low frequencies, e.g., at about 10 kHz the loss is 2-3 dB/km. At higher frequencies, however, the losses increase and so does the signal dispersion. At 10 MHz, a twisted-pair cable has a typical loss value of 7 dB per 100 meters.

At high-frequency carriers for broadband signals (TV transmission and high-data-rate digital transmission), coaxial cables are commonly used. At 1 GHz, the loss of a typical high-quality coaxial cable is around 2 dB per 100 meters (power decreases about 1.6 times). In the USA, the cable loss is rated in dB per 100 feet, so a good coaxial cable has about 0.6 dB/100ft loss.

The least distortion and losses are offered by the optical-fiber transmission lines, which operate at three different wavelengths: 850 nm (≅ 2.3 dB/km), 1300 nm (≅ 0.25 dB/km) and 1550 nm (≅ 0.25 dB/km). Optical fibers are relatively expensive and the respective transmitting/receiving equipment is also costly. Transmission lines provide a measure of security and noise-suppression (coaxial, optical-fiber), but they are not the best option in many cases (long distance, wide spread over large areas, less frequency dispersion).

A fundamental feature of all transmission lines is the exponential increase of loss power. Thus, if the loss is 5 dB/km, then a 20-km line will have 100 dB power loss (input power is reduced by a factor of 10^{-10}), a 40-km line will have a 200 dB power loss. This makes it obvious why wireless systems are preferred for long-range communications, and in scarcely populated areas. In most wireless channels, the radiated power per unit area decreases as the inverse square of the distance r between the transmitting and the receiving point. Doubling the distance r would decrease the received power by a factor of 4 (or 6 dB are added to the loss). Thus, if a particular system has a 100 dB loss at r = 20 km, doubling the distance will result in 106 dB loss (as compared to 200 dB loss in a cable system). The comparison between the coaxial-line losses and free-space attenuation at f=100 MHz is given in the figure below.



(Fig. 33 in Siwiak, *Radiowave Propagation and Antennas for Personal Communications*)

Modern personal mobile communications services

- cordless telephony
- cellular telephony
- mobile data transport (3G and 4G PCS)
- computer network communications: WLANs and bluetooth
- personal satellite communications
- global positioning and navigation systems

Besides, there is a variety of special application of wireless technology in

- radar systems (navigation, collision, guidance, defense, missile, etc.)
- remote-control vehicles (RCV), also known as *drones*
- microwave relay links
- satellite systems (TV, telephony, military)
- radio astronomy
- biomedical engineering
- RF identification (RFID)
- animal (migration) tracking

etc.

5. The radio-frequency spectrum

Table 1.1: General designation of frequency bands

Frequency band	EM wavelength	Designation	Services
3-30 kHz	100-10 km	Very Low Frequency (VLF)	Navigation, sonar[♣], submarine
30-300 kHz	10-1 km	Low Frequency (LF)	Radio beacons, navigation
300-3000 kHz	1000-100 m	Medium Frequency (MF)	AM broadcast, maritime/ coast-guard radio
3-30 MHz	100-10 m	High Frequency (HF)	Telephone, telegraph, fax; amateur radio, ship-to-coast and ship-to-aircraft communication
30-300 MHz	10-1 m	Very High Frequency (VHF)	TV, FM broadcast, air traffic control, police, taxicab mobile radio
300-3000 MHz	100-10 cm	Ultrahigh Frequency (UHF)	TV, satellite, radiosonde, radar, cellular (GSM, PCS)
3-30 GHz	10-1 cm	Super high Frequency (SHF)	Airborne radar, microwave links, satellite, land mobile communication
30-300 GHz	10-1 mm	Extremely High Frequency (EHF)	Radar, experimental

Table 2.1: Microwave-band designation

Frequency	Old	New
500-1000 MHz	VHF	C
1-2 GHz	L	D
2-3 GHz	S	E
3-4 GHz	S	F
4-6 GHz	C	G
6-8 GHz	C	H
8-10 GHz	X	I
10-12.4 GHz	X	J
12.4-18 GHz	Ku	J
18-20 GHz	K	J
20-26.5 GHz	K	K
26.5-40 GHz	Ka	K

[♣] Sonar (an acronym for Sound, Navigation and Ranging) is a system for underwater detection and location of objects by acoustical echo. The first sonars, invented during World War I by British, American and French scientists, were used to locate submarines and icebergs. Sonar is an American term dating from World War II.