Technology Brief 20
The Electromagnetic Spectrum

Electromagnetic Energy

The sun's rays, the signal transmitted by a cell phone, and the radiation emitted by plutonium share a fundamental property: they all carry electromagnetic (EM) energy. It is an interesting and fundamental observation that this energy can be described both as a ***wave*** moving through space and as a ***particle***. Neither model alone is sufficient to explain the phenomena we observe in the world around us. This correspondence, called the ***wave-particle duality***, sparked scientific debate as far back as the 1600s, and it was not until the 20th century and the advent of quantum mechanics that this duality was fully incorporated into modern physics.

When we treat EM energy as a wave with alternating electric and magnetic fields, we ascribe to the wave a wavelength λ and an oscillation frequency f, whose product defines the velocity of the wave u as

$$u = f\lambda.$$

If the propagation medium is free space, then u is equal to c, which is the speed of light in vacuum at 3×10^8 m/s. Because of the wave-particle duality, when EM energy is regarded as a particle, each such particle will have the same velocity u as its wave counterpart and will carry energy E whose magnitude is specified by the frequency f through

$$E = hf,$$

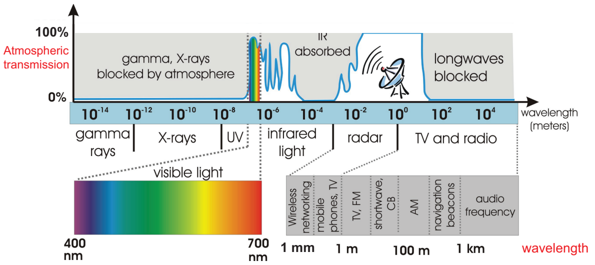

Figure TF20-1: The electromagnetic spectrum extends over a wide range of wavelengths—from gamma rays to radio waves. The atmosphere is transparent in the microwave and in selected windows in the visible and infrared.

where h is Planck's constant (6.6×10^{-34} J·s). In view of the direct link between E and f, we can refer to an EM particle (also called a ***photon***) either by its energy E or by the frequency f of its wave counterpart. The higher the frequency is, the higher is the energy carried by a photon, but also the shorter is its wavelength λ.

The Spectrum

In terms of the wavelength λ, the EM spectrum extends across many orders of magnitude (**Fig. TF20-1**), from the radio region on one end to the gamma-ray region on the other. The degree to which an EM wave is absorbed or scattered as it travels through a medium depends on the types of constituents present in that medium and their sizes relative to λ of the wave. For Earth's atmosphere, the composition and relative distributions of its gases are responsible for the near total opacity of the atmosphere to EM waves across most of the EM spectrum, except for narrow "windows" in the visible, infrared, and radio spectral regions (**Fig. TF20-1**). It is precisely because EM waves with these wavelengths can propagate well through the atmosphere that human sight, thermal infrared imaging, and radio communication are possible through the air.

1. Cosmic Rays: Emitted by the decay of the nuclei of unstable elements and by cosmic, high-energy sources in the universe, cosmic rays—which include gamma, beta, and alpha radiation—are highly energetic particles that can be dangerous to organisms and destructive to matter. Earth emits gamma rays of its own, but at very weak levels.

2. X-Rays: Slightly lower energy radiation falls into the X-ray region; this radiation is energetic enough to be dangerous to organisms in large doses, but small doses are safe. More importantly, their relatively high energy allows them to traverse much farther into solid objects than lower frequency radiation (such as visible light). This phenomenon allows for modern medical radiology, in which X-rays are used to measure the opacity of the medium between the X-ray source and the detector or film. Thankfully, Earth's atmosphere efficiently screens the surface from high-energy radiation, such as cosmic rays and X-rays.

3. Ultraviolet Rays: The atmosphere is only partially opaque to ultraviolet (UV) waves, which border the visible

Table TT20-1: Some examples of radio frequency communication channels and their frequency bands.

Communication modality	Band name	Frequencies
Medium wave AM radio (US)	MF	520 – 1610 kHz, broken into 10 kHz channels
FM radio (US)	VHF	88 – 108 MHz, broken into 100 – 200 kHz channels
GPS L1 and L2	UHF	1575.42 MHz (L1) and 1227.60 MHz (L2)
802.11g wifi	ISM	2.4 – 2.5 GHz, broken into 13 overlapping 22 MHz channels
Bluetooth®	ISM	2400 – 2483 MHz, broken into 1 MHz channels
802.15.4 – ZigBee (US)	UHF	902 – 928 MHz, broken into 30 channels
802.15.4 – ZigBee (Asia)	UHF	2.4 GHz, broken into 16 channels

spectrum on the short-wavelength side. UV radiation is both useful in modern technology and potentially harmful to living things in high doses. Among its many uses, UV radiation is used routinely in electronic fabrication technology for erasing programmable memory chips, polymer processing, and even as a curing ink and adhesive. While UV's potential danger to human skin is well recognized, it is for the same reasons that UV lamps are used to sterilize hospital and laboratory equipment.

4. Visible Light Rays: The wavelength range of visible light extends from about 380 nm (violet color) to 740 nm (red/brown color), although the exact range varies from one human to another. Some species can see well into the infrared (IR) or the UV, so the definition of *visible* is completely anthropocentric. It is no coincidence that evolution led to the development of sight organs that are sensitive to precisely that part of the spectrum where atmospheric absorption is very low. In the visible spectrum, blue light is more susceptible to scattering by atmospheric particles than the longer wavelengths, which is why the sky appears blue to us.

5. Infrared Rays: The infrared (IR) region, straddled in between the visible spectrum and the radio region, is particularly useful for thermal applications. When an object is heated, the added energy increases the vibrations of its molecules. These molecular vibrations, in turn, release electromagnetic radiation at many frequencies. Within the range of our thermal environment, the peak of the radiated spectrum is in the IR region. This feature has led to the development of IR detectors and cameras for both civilian and military thermal-imaging applications. Nightvision systems use IR detector arrays to image a scene when the intensity of visible-wavelength light is insufficient for standard cameras. This is because material objects emit IR energy even in pitch-black darkness. Conversely, IR energy can be used to heat an object, because a good radiator of IR is also a good absorber. Additionally, IR beams are used extensively in short-distance communication, such as in the remote control of most modern TV sets and garage door openers.

6. Radio Waves: The frequency range of the radio spectrum extends from essentially dc (or zero frequency) to $f = 1$ THz $= 10^{12}$ Hz. It is subdivided into many bands with formal designations (**Fig. TF20-1**) such as VHF (30 to 300 MHz) and UHF (300 to 3000 MHz), and some of those bands combine together to form bands commonly known by historic designations, such as the microwave band (300 MHz to 30 GHz). All major free-space communication systems operate at frequencies in the radio region, including wireless local area networks (LANs), cell phones, satellite communication, and television and radio transmissions (**Table TT20-1**). Because the radio spectrum is used so heavily, spectrum allocation is controlled (often sold) by various national and international agencies that set standards for what types of devices are permitted to operate, within what frequency bands, and at what maximum-power transmission levels. Cell phones, for example, are allowed to transmit and receive in the 2.11 to 2.2 GHz band and in the 1.885 to 2.025 GHz band. Radio waves are the range where the classic antenna-to-antenna transmission occurs.