

## 6.013(New) Lecture 1: Introduction to Wireless Communications

### A. Wireless communications are ubiquitous

This first section of 6.013(New), Electromagnetics and Applications, focuses on wireless communications, which can involve point-to-point communications, broadcasting (one point to many), or passive sensing of natural or man-made signals.

The original point-to-point wireless communications links for telephone and telegraph circuits sometimes were direct line-of-sight or diffracted paths and sometimes involved ionospheric reflections. They were largely superseded, initially by coaxial cables and multi-hop microwave links that were later supplemented by satellite links, and ultimately by optical fibers and cellular technology. Each technical advance markedly boosted capacity and generally increased reliability.

Most homes and offices are currently served by twisted pairs of wires, each conveying ~50 kbs - 1.5 Mbps, although coaxial cables, satellite links, and even wireless services are making inroads. All of these modalities will be addressed in 6.013(New). The most common wireless services currently include cell phones, wireless phones (within a home or office), walkie-talkies (dedicated mobile links), satellite links, microwave tower links, and many specialized variations for private or military use. In addition, optical or microwave line-of-sight links between buildings offer instant broadband connectivity for the “last mile” to the consumer, which accounts for a significant fraction of all installed plant cost. Weather generally restricts optical links to very short hops or to weather-independent optical fibers. Specialized medical devices, such as RF links to video cameras inside swallowed pills, are also being developed.

Broadcast services now include AM radio near 1 MHz, FM radio near 100 MHz and higher frequencies, TV in several bands between 50 and 600 MHz for local over-the-air service, and TV and radio delivered by satellite at many GHz. Shortwave radio below ~30 MHz also offers global international broadcasts dependent upon ionospheric conditions, and is widely used by radio hams for long-distance communications.

The intensities of thermal and non-thermal microwave radiation from the terrestrial atmosphere and surface can be passively sensed for meteorological and other geophysical purposes. For example, almost all objects radiate radio waves in proportion to their temperature, just as a bonfire radiates heat. More precisely, the power  $P$  [W] radiated by any blackbody (reflectivity = 0) into a transmission line at radio or microwave frequencies within a bandwidth  $B$  [Hz] is  $kTB$ , where  $T$  is the temperature of the radiator [ $^{\circ}\text{K}$ ] and  $k = 1.38 \times 10^{-23}$  [ $\text{JK}^{-1}$ ] is Boltzmann's constant. Similar passive sensors can monitor patients for medical purposes and artifacts of interest, such as motors, computers, or wildlife tracking devices.

Wireless services are so ubiquitous today that we may take them for granted, forgetting that a few generations ago the very concept would have been considered magic. Despite the wide range of services already in wide use, it is reasonable to assume that over the next few decades numerous other wireless technologies and services will be developed by today's engineering students.

## B. Communications requires power and energy

Even the best current radio receivers require a certain amount of energy per bit of information,  $E_b$ , whether that information is analog or digital. The current nominal state-of-the-art receivers require at least  $\sim 4 \times 10^{-20}$  Joules per bit of information, and so the power required at the receiver is simply  $E_b M$ , where  $M$  is the bit rate per second. The remarkably low values for  $E_b$  imply enormous data transfer rates are possible at very reasonable power levels that are easily achieved via wire or fibers, and that useful data rates are possible even via air links that are extremely weak.

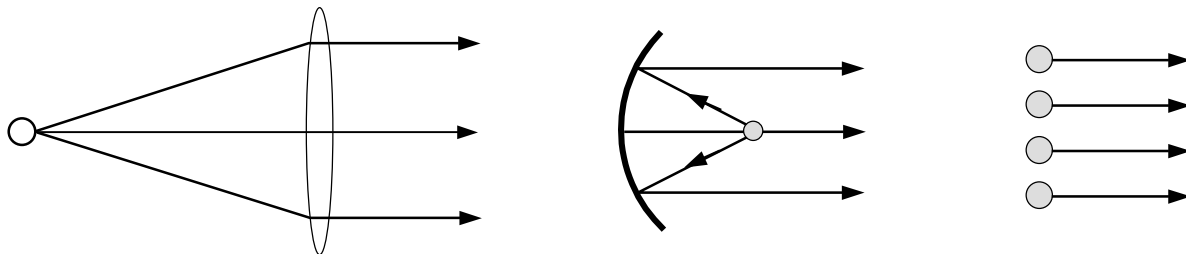
Although electromagnetic waves are slightly absorbed by losses in air, we shall ignore these for now and shall assume power is conserved as it propagates, even though it may weaken as it spreads out far from the transmitter. For example, a transmitter antenna radiating isotropically<sup>1</sup>  $P_R$  watts would produce a wave in direction  $\theta, \phi$  having  $P_r(\theta, \phi, r)$  [ $\text{Wm}^{-2}$ ] =  $P_R/4\pi r^2$  at distance  $r$  [m]. It follows that  $P_R = \int_{4\pi} P_r(\theta, \phi, r) r^2 \sin\theta \, d\theta \, d\phi$ . Most antennas are designed, however, to concentrate their power in desired directions, offering some “gain over isotropic”:

$$G(\theta, \phi) = P_r(\theta, \phi, r) / (P_R/4\pi r^2) \quad (1)$$

Antenna gain is a dimensionless quantity. The shapes of typical antenna gain patterns are suggested below.



Three standard approaches to concentrating electromagnetic waves are illustrated below: lenses, curved mirrors, and arrays.



Slide L1-5 has photographs of three examples. Throughout these notes references will be made to the lecture slides, where “L1-5” designates Slide 5 of Lecture 1. The upper illustration shows five microwave antennas operating near 1-cm wavelength that use bulbous lenses to focus the radio waves in a  $10^\circ$  beam. The middle illustration is of the National Radio Astronomy 300-ft parabolic radiotelescope (now dismantled) in Greenbank, West Virginia; its beamwidth was  $\sim \lambda/D \cong 0.2/100$  radians, or  $\sim 7$  arc minutes (the sun and moon have diameters of  $\sim 30$  arc minutes). The bottom illustration is of a multi-aperture optical interferometer that successfully measured the relative positions of two orbiting stars to  $\sim 100$  micro-arc-seconds

<sup>1</sup> Isotropic means equal in all directions, spherically.

through the terrestrial atmosphere (the Hubble space telescope achieves ~100 milli-arc-second resolution).

The receiving properties of antennas are commonly characterized by their “effective area”  $A(\theta, \phi)$  [ $\text{m}^2$ ], where the power received  $P_{\text{rec}}$  is simply the incident flux [ $\text{Wm}^{-2}$ ] from direction  $\theta, \phi$  times the antenna effective area for that same direction. That is,

$$P_{\text{rec}} = P_r(\theta, \phi)A(\theta, \phi) \text{ [W]} \quad (2)$$

We shall show later that there is, under most circumstances, a simple relation between the gain and effective area of an antenna: they have the exact same shape such that:

$$A(\theta, \phi) = G(\theta, \phi)\lambda^2/4\pi \text{ [m}^2\text{]} \quad (3)$$

With this simple definition we can now evaluate wireless communications links.

### C. Cell-phone example

In L1-6 a cellular phone example is presented, where we assume the user’s phone transmits 1 watt ( $P_R = 1$ ) isotropically (which is a reasonable approximation), and that at a range of 10 km we want an extra 40 dB at the receiver above the nominal threshold for detection (a factor of  $x = 10^4$ ). (Recall that 10 dB is a factor of ten [ $x = 10$ ], and 20 dB a factor of 100 [ $x = 100$ ], where  $\text{dB} = 10 \log_{10} x$ .) Therefore we expect  $P_r \text{ [Wm}^{-2}\text{]} = 10^4 P_R / 4\pi r^2 = 8 \times 10^{-14}$  at 10 km.. This corresponds at the base station to a received power  $P_{\text{rec}} = A(\theta, \phi)P_r(\theta, \phi) \text{ [W]}$ , where  $A = G\lambda^2/4\pi$ .

We might guess that the base station antenna in this example directed primarily toward the horizon, but not upward into the sky nor particularly downward (any user positioned downward is so nearby that leakage radiation suffices). A pattern like that illustrated in L1-6 is plausible, with  $G \cong 10$ . If this is a 900-MHz system, then the wavelength  $\lambda = c/f = 33.3$  cm, and we find  $A = 0.088 \text{ m}^2$ . It follows that  $P_{\text{rec}} = AP_r = 0.088 \times 8 \times 10^{-14} = 7.1 \times 10^{-15}$  watts =  $ME_b$ , where the data rate is  $M \text{ [bs}^{-1}\text{]}$  and we assume  $E_b = 4 \times 10^{-20}$ . Thus the received power here is enough to support a data rate of 176 kbps! The link in the reverse direction passes through the same two antennas and suffers the same  $1/4\pi r^2$  “path loss”, and since the base station transmitter can be much more powerful, this reverse link is traditionally stronger and more reliable.

The reason we don’t have cell phones with such high data rates is that they would require much greater bandwidths and spectrum utilization that is available today at reasonable cost. The required bandwidth is generally proportional to data rate for any given modulation scheme. To maximize the number of users served within any bandwidth allocation, the bandwidth allocated to each user is generally the minimum required to convey intelligible speech. Later we shall discuss tricks to boost “frequency reuse” of cellular phones that might permit these higher data rates.

The margin of 40 dB assumed in this example is arbitrary. Since it permits higher data rates than frequency allocations and economics now allow, we can send the data at slower rates consistent with speech (say 4.8-9.6 kbps) and obtain perhaps another 13 dB of margin ( $x = 176/9.6$ ), or a total of ~53 dB margin. This extra margin provides power to reflect or diffract around buildings, under bridges, and through windows and walls. The one-watt transmitter limit is consistent with reasonable battery weights and lifetimes and with the desire not to injure the user's head. The power density of radio waves [ $\text{Wm}^{-2}$ ] at the user's head produced by a 1-watt transmitter is on the same order as that from sunlight.

#### **D. Circuit properties of antennas**

Antennas must be connected to circuits and we therefore need to know their circuit properties. Fortunately Maxwell's equations are linear. Therefore antennas can be modeled by Thevenin equivalent circuits consisting of a "radiation resistance"  $R_r$ , a reactance  $X$ , and a Thevenin voltage source  $V_{Th}$ , all in series. The radiation resistance  $R_r$  corresponds to power "lost" by radiation rather than by dissipation that heats the structure. The power radiated  $P_R = \langle i^2(t) \rangle R_r$  watts, where  $\langle \bullet \rangle$  signifies "time average". The circuit illustrated in L1-7 shows how the Thevenin voltage is divided across the radiation resistance and the load resistance, which is made equal to maximize intercepted power. Note that the radiation resistance is generally the same whether the antenna is receiving or transmitting. It follows then that  $P_{rec} = \langle (V_{Th}/2)^2 \rangle / R_r$ . Later we shall see how to determine these equivalent circuit values.

Although we have now seen the basic equations necessary to compute communications links for ideal cases, we have yet to learn exactly what an electromagnetic wave is, how it propagates, how we launch and receive them and, in general, how we design wireless communications systems using such waves. Next, we shall extend this discussion briefly to optical communications links, which we shall also discuss at greater length later.