Physical Layer Characteristics

1 Physical characteristics of mobile wireless networks

1.1 Overview

As the name suggests, wireless systems operate by transmission through space rather than through wired connection. There are two major problems to be addressed in a wireless setting that do not arise in the wired case. The first is that the channel over which communication takes place is time varying. The second being interference between multiple users using a common communication medium. Therefore in wireless systems, we must combat not only noise but also time varying properties and interference. In general, wireless communication devices may be mobile (eg. cell phones, radio transceivers mounted on cars, aircrafts, etc) or stationary (eg. base stations of cellular networks).

In a wireless channel, signals are transmitted via electromagnetic radiations which are analog in nature. In practice, one could solve the Maxwell's equations for a given transmitted signal to find the electromagnetic field at the receiver[1]. The wavelength of electromagnetic radiations at any given frequency f is given by $\lambda = c/f$ where c is the velocity of light in air. Mobile devices and base stations communicate with each other using radio broadcasts which happen over the radio spectrum containing a finite bandwidth of available frequencies. Antennas couple the signals at the transmitter and the receiver into the communication medium (air) and vice versa respectively and their properties shall be discussed in the sections to follow.

1.2 Devices

Wireless communication devices may be small and in general have limited battery and memory capabilities.

Typical mobile and wireless devices, progressing from small to large/powerful are listed below:

- Sensors
- Embedded controllers
- Pagers
- Mobile phones
- PDAs

- Pocket computers
- Notebook/laptop

In the future one may expect to see a combination of wired and wireless networks where a single static wired device may control and coordinate with many small wireless devices in its vicinity.

1.3 Free Space, fixed transmitting and receiving antennas

In the far field[1], the electric and magnetic field are perpendicular to each other and to the direction of propagation. The electric field at any given distance $|r|$ in response to a transmitted signal $Aexp(2\pi ift)$ is given by

$$E(f,t,r) = \frac{g(\theta,\phi,f)Aexp(2\pi if(t-|r|/c)}{|r|}$$

where $(|r|,\theta,\phi)$ represents the spherical coordinates of the measured point in space, f is the frequency of the transmitted signal, A is the amplitude of the transmitted signal and $g(\theta,\phi,f)$ is the complex radiation pattern or the gain of the transmitting antenna. The above choice of the input and received signal representation is very general since any given finite energy transmitted signal can be decomposed into an infinite sum of such sinusoids using the fourier series expansion[2]. In most cases, the noise in Wireless Communication Systems is modelled as Additive White Gaussian Noise (AWGN) which is characterised by a flat power spectral density and whose amplitude is gaussian distributed with uniformly distributed phase between $[0,2\pi]$.

1.4 Antennas

Antennas couple electromagnetic energy from the transmitter into the space and vice-versa at the receiver. Antennas are divided into various types depending on their radiation or gain pattern as described below.

Isotropic Antennas:
Isotropic antennas radiate equal power in all directions. Such antennas are a theoretical construct and do not exist in practice

Dipole Antennas:

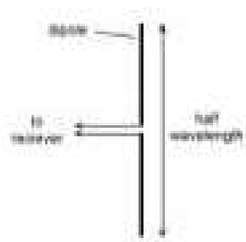

Figure 1: Halfwave dipole antenna

Dipole Antennas have a uniform radiation pattern in one plane, a directional radiation pattern in the other plane. Fig.2 shows the radiation pattern of a Halfwave dipole antenna where the dipole radiant energy is concentrated into a region that looks like a "donut", with the dipole placed vertically through the center of the "donut".

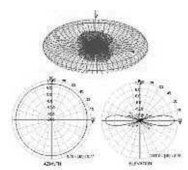

Figure 2: Radiation pattern of a halfwave dipole antenna

Many other types of antennas exist classified according to their radiation patterns such as Directional antennas(Eg. satellite dish), Antenna arrays and Smart antennas (antennas with adjustable radiation patterns), etc.

1.5 Signal propagation

An ideal representation of the signal propagation around an antenna is shown in Fig.3. The region around the antenna can be conceptually divided into three regions: the transmission region, the detection region and the interference region. However, in practice, one often finds bizarrely shaped polygons depending on the channel of propagation and surroundings.

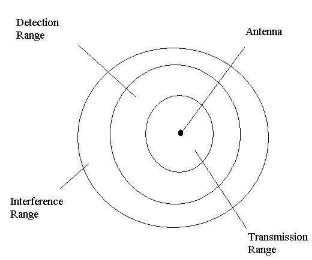

Figure 3: Signal Propagation around an Antenna

As the distance $|r|$ increases, the power per square meter in the free space wave goes down as $|r|^{-2}$. This is expected, since if we look at concentric spheres of increasing radius around the antenna, the total power radiated through the sphere remains constant. Also, receiver's power level is proportional to the receiver's antenna gain, transmitter's antenna gain and the path gain along the path from the transmitter to the receiver. Explicitly,

$$P_r = kP_tG_tG_r/|r|^2$$

Where, P_t and P_r are the power levels (in watts) at the transmitter and receiver respectively, G_t and G_r are the antenna gains at the transmitter and receiver respectively and k is the path gain in the direction of propagation. Expressed in decibels $P(dB) = 10log_{10}P$; therefore path-loss (in decibels)

$$= P(dB)_t - P(dB)_r = 10log(P_t/P_r)$$

$$= 20log|r| - 10log(kG_tG_r)$$

In practice, the unit power attenuates at $|r|^{-n}$, where $2 \le n \le 4$. Effects that cause higher degradation are:

- Blocking or shadowing by large obstacles.
- Reflection: Reflecting objects absorb some of the energy.
- Refraction, scattering and diffraction.
- Multi-path propagation: Multiple copies of the transmitted signal arrive at the receiver due to reflection of multiple surfaces and moving objects which causes a spread in the signal both in terms of the arrival (delay spread) and frequency (doppler shift).

Thus the received signal behavior is highly variable depending on antenna types, characteristics of the environment and the relative motion of the reflectors. Shown in Fig.4 is the two-ray ground propagation model which assumes the existence of a direct line of sight path and a reflected path from the ground plane. Such a model of the channel yields $P_r = kP_tG_tG_r/|r|^4$ and path-loss, $P(dB)_t - P(dB)_r = 10log(P_t/P_r) = 40log|r| - 10log(kG_tG_r)$.

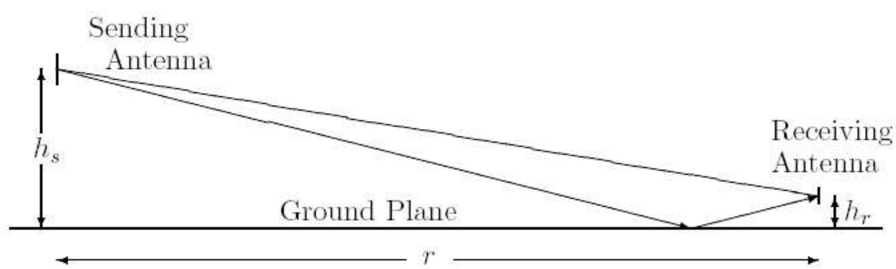

Figure 4: Two-ray propagation model [3]

1.6 Tasks of the physical layer

The principle task of the physical layer is to transmit streams of bits from the transmitter to the receiver with minimal bit errors. Both point-to-point and broadcast transmission techniques are used to transmit bits. This involves the following tasks; a) selection of the frequency bands for transmission; b) generation of the carrier frequency; c) detection and estimation of the transmitted bits d) modulation of the incoming discrete bit streams on the carrier to generate analog transmission signals followed by demodulation at the receiver; and e) Encryption and decryption techniques for data transmission. The next layer above the physical layer is the data link layer (or MAC layer) which is responsible for achieving more reliable local point-to-point and broadcast communication.

1.7 Techniques used within the physical layer

1.7.1 Modulation and Demodulation

Modulation and demodulation refer to the general technique of mapping the incoming discrete bit stream (0's and 1's) into analog signals used for transmission and vice versa. The most common modulation techniques used today include:

1. Amplitude Shift Keying (ASK) or Amplitude Modulation (AM): This technique uses different amplitude levels of the carrier signal to represent 0 and 1. However, AM is highly susceptible to noise as it can greatly effect the amplitude of the received signal. Hence, AM is very rarely used for wireless radio but is widely used in optical communication which has relatively low noise levels.
2. Frequency Shift Keying (FSK) or Frequency Modulation (FM): This technique uses two different carrier frequencies to represent 0's and 1's. FM is widely used in wireless communication due to its robustness to noise levels.
3. Phase Shift Keying (PSK): This technique adjusts the phase of the carrier signal to represent 0's and 1's but is also susceptible to noise levels.

1.7.2 Spread spectrum

Spread spectrum techniques spread the message signal over a wide range of frequencies thus making it robust to narrowband interference and reducing the power usage of the system.

1.7.3 Multiplexing

Multiplexing refers to a technique of channel utilization where multiple users communicate without interference with each other. The most commonly used multiplexing techniques include:

- Frequency Division Multiplexing (FDM): Simultaneous users using the same channel communicate using mutually exclusive set of frequencies thus avoiding interference with one other.
- Time Division Multiplexing (TDM): Simultaneous users using the same channel communicate in the same frequency band using mutually exclusive set of time slots thus avoiding interference with one other. This technique is extensively used in the MAC layer and requires precisely synchronized clocks. TDM offers flexibility in order to assign longer time slots to busy users or when used in combination with FDM is called as 'Frequency Hopping' which is used in GSM systems.

1.8 Some problematic scenarios in wireless networks

1.8.1 Hidden terminals

Consider three wireless nodes A, B and C as shown in Fig. 5. A and C can both reach B but A and C cannot detect each other. In such a case, both A and C start transmitting to B without knowledge of the existence of each other and as a result B receives a garbled version of the transmitted signal from A and C due to collision. One possible way to get around this problem is to have the range of detection much greater than the reception range (more than twice).

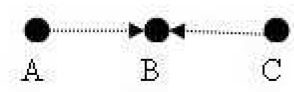

Figure 5: Hidden terminal problem

1.8.2 Exposed terminals

Consider wireless nodes A, B, C and D as shown in Fig. 6. Node B transmits to A, node C wants to send to node D. However, since C can hear B's transmission, it might decide not to transmit since the channel is busy whereas in reality C's message to D would not interfere with A and B's communication.

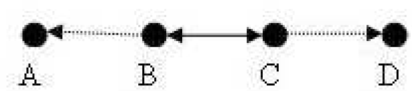

Figure 6: Exposed terminal problem

1.9 Cellular systems

Modern mobile communication systems use a base station, which covers a "cell" area divied into hexagons as shown in Fig. 7. The cell areas range from 10's of square meters in buildings to 10's of square kms in the countryside. "Cell" shapes vary, depending on the environment, weather, user load etc. Mobile devices within a given 'cell' communicate (only) to and from their respective base stations.

Advantages of using smaller cell size:

- Less power needed for the mobile devices and the base station to communicate to each other.
- More concurrent transmissions possible and has local interference only.

Disadvantages of using smaller cell size:

- Needs more base station infrastructure.
- More handovers.

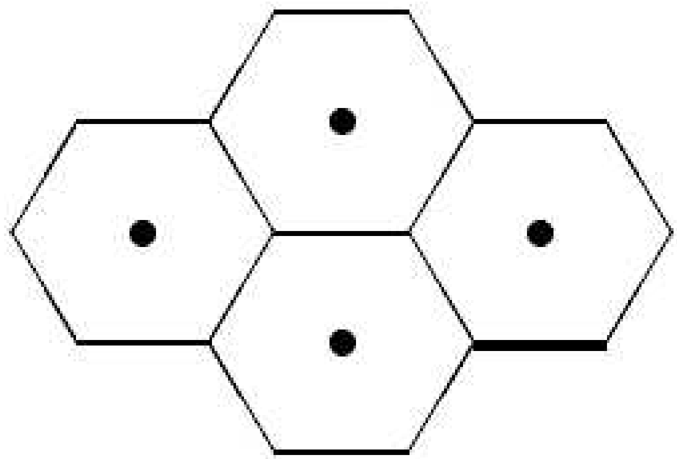

Figure 7: Simplified overview of a cellular network [3]

Typically, only a limited number of frequencies are available for usage. Therefore, to avoid interference nearby cells are grouped into clusters, where cells in the same cluster use different frequencies and cells in different clusters use the same set of frequencies.

1.10 Making wireless networks look like wired networks

One approach to programming wireless networks is to try to make them look like wired networks. The first step here would be to try to provide each nearby pair of nodes with a separate "reliable link" abstraction. However, it is complicated to understand the behavior of these links. Shannon's equation,

$$C = Blog_2(1 + S/N)$$

where C is the channel capacity, B is the bandwidth of the communication channel, S is signal strength at receiver and N is the noise level; gives a capacity bound for a single channel. However, interference among various channels prevents one from achieving this capacity on all the links simultaneously. Therefore, one must consider the capacity for the entire network and not individual links. The goal of many wireless network designers is to maximize the aggregate data delivery capacity of the network, while providing some kind of fairness measures. Understanding and achieving capacity bounds is a complicated optimization problem in itself and one also has to include the intricacies of motion and time varying nature of the channel to solve the problem comprehensively.

Other problems:

- Designing IP-like point-to-point routing services.
- Designing TCP-like reliable stream processing services.

Making wireless networks mimic wired networks may seem like a plausible solution to these problems, but one may find it worthwhile not to assume this. So we will consider this new setting ground up, starting from the physical layer.

1.11 References

[1] Balanis, C. A., "Antenna Theory: Analysis and Design", John Wiley & Sons, Inc., 1982.

[2] Proakis, John G., "Digital Communications", McGraw-Hill (1995).

[3] Gallager, R. G., "Chapter 9: Principles of Digital Communication (6.450)", Fall 2005, MIT.