

Wireless Ad Hoc and Sensor Networks

Physical Layer

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Antennas

What is an antenna?

- An antenna is an electrical conductor used either for radiating or collecting electromagnetic energy
 - Transmission: electrical energy from the transmitter is converted to electromagnetic energy by the antenna and radiated into the surrounding environment
 - Reception: vice versa
- Antenna characteristics are essentially the same for sending or receiving.

Radiation

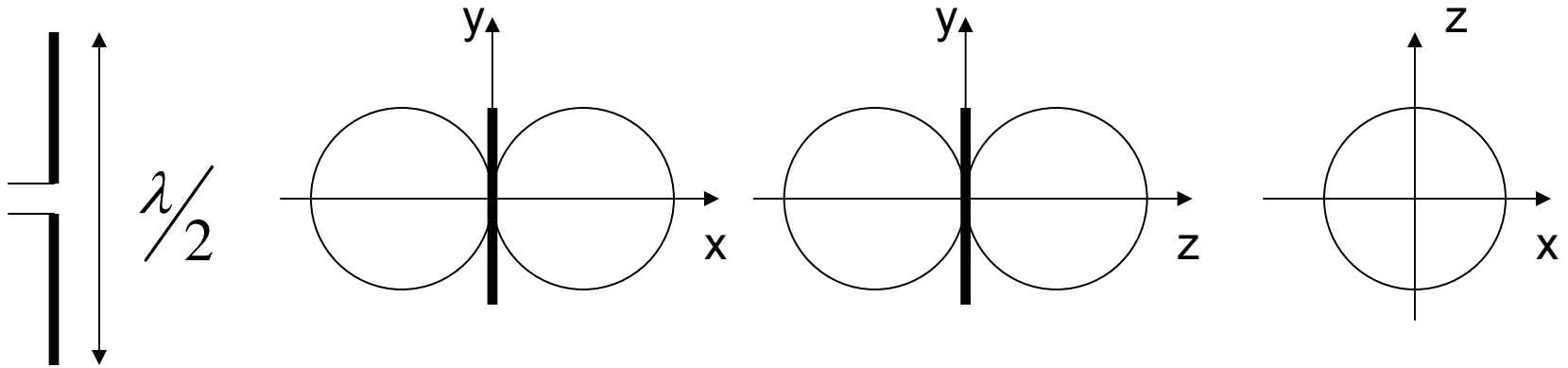
- **Radiation pattern**

- An antenna will radiate power in all directions
- Typically, it does not radiate equally in all directions
- The distance from the antenna to each point on the radiation pattern is proportional to the power radiated by the antenna in that direction

- **An 'isotropic antenna'**

- is an idealized antenna, represented by a point in space that radiates power in all directions equally
- Its radiation pattern is a sphere

Half-Wave Dipole Antenna



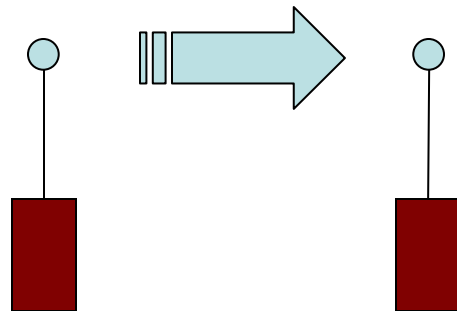
Directional antennas

- **‘Antenna Gain’**
 - Is a measure of directionality of an antenna
 - Is the power output in a particular direction compared to that produced by an equivalent isotropic antenna
 - The increased power in a given direction is at the expense of reduced power in the other directions

Propagation Modes

- **Ground wave propagation**
 - Follows the contour of the earth
 - Only for frequencies less than 2MHz
- **Sky Wave propagation**
 - Signal is bounced off the ionosphere (actually it is refraction) e.g. BBC & Voice of America
- **Line of sight propagation**
 - Neither ground wave nor sky wave modes work for frequencies above 30 MHz
 - Transmitter and receiver need to be 'effectively' in the line of sight (i.e. including reflection and refraction)

Digital Modulation and Detection



Simple Binary Modulation

- Two communicating nodes utilize a radio 'spectrum' of 'bandwidth' $2W$, centered at the carrier frequency f_c (assume $f_c \gg W$)
- Communication is achieved by 'modulating' a sequence of pulses by the source bit pattern
- The pulse $p(t)$ is chosen so that, when modulated, occupies the spectrum i.e. the spectrum of the baseband pulse is $(-W, W)$
- A new pulse is transmitted every T seconds. i.e. the pulse stream is

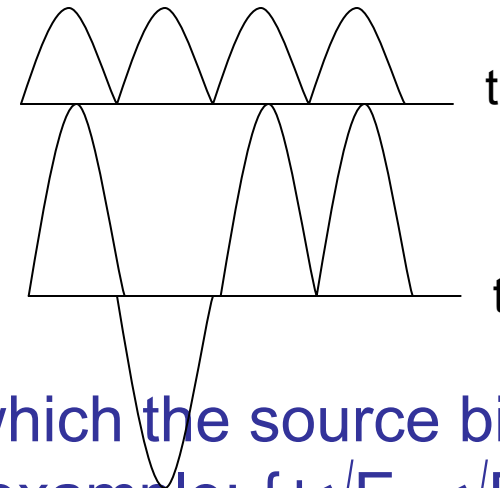
- $$\sum_{k=-\infty}^{\infty} p(t - kT)$$

Binary modulation example

- A very simple (amplitude) modulation technique
 - If source is 1, multiply the pulse by $+\sqrt{E}$
 - If source is -1, multiply the pulse by $-\sqrt{E}$
 - E.g. A sequence of bits 1011 is transmitted as $+\sqrt{E} p(t)$, $-\sqrt{E} p(t-T)$, $+\sqrt{E} p(t)$, $+\sqrt{E} p(t)$

$$\sum_{k=-\infty}^{\infty} p(t-kT)$$

$$\sum_{k=-\infty}^{\infty} C_k p(t-kT)$$



- In general, C_k is the symbol to which the source bits are mapped (symbol set in this example: $\{+\sqrt{E}, -\sqrt{E}\}$)
- Note: A set of four symbols would allow mapping two bits at a time.

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- The energy in each transmitted pulse is E (joules/symbol)
 - The symbol rate is $1/T$, so the transmitted signal power is E/T watts.
 - The baseband signal is then translated to the carrier frequency (by multiplying it with a sinusoid) and transmitted
 - At the receiver, the signal is translated back to the baseband. But the signal is also corrupted with (white Gaussian) noise with power spectral density $N_0/2$.

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- ‘Detection’: The receiver inspects each received pulse and determines which symbol it represents.
 - Each received pulse $C_k p(t)$ is multiplied by the pulse $p(t)$ and integrated (from 0 to T), yielding $C_k + \text{“noise”}$. Depending on the noise, the receiver may or may not decode correctly. In this example, the threshold for detection is 0.
 - The error probability for this channel is

- $$Q\left(\sqrt{\frac{2E}{N_0}}\right)$$

Higher Bit Rates

- From the previous example, higher bit rates could be achieved by:
 - Increasing the symbol rate (i.e. decrease T)
 - Nyquist criterion (to avoid aliasing): pulse rate must be less than $2W$.
 - Increase the number of possible symbols from 2 to $M > 2$ i.e. bit rate is $(\log M)/T$
 - How much can we “pack” while maintaining the same error probability per bit?

Channel Capacity

- The probability of error can be expressed as a function of the SNR at the receiver
- Because of physical limitations, it may not be possible to increase the SNR enough to meet the required BER.
- Channel coding is used to achieve lower BER with same power budget.
 - Map every set of k source bits into a code (i.e. symbol) of length $N > K$, thus introducing redundancy
 - The rate of the code is denoted by $R = K/N$
- **Reliable communication**
 - Reliable communication at a rate R bits/symbol means that one can design codes at that rate with arbitrarily small error probability
- **Channel Capacity**
 - The maximum data rate at which reliable communication is possible is called the capacity C of the channel.
 - For an AWGN channel, $C = \log(1 + \text{SNR})$ bits/s/Hz

Characteristics of Wireless Channels

Free Space Propagation (Path) Loss

- Radio signal strength decays as some power, α , called power-distance gradient or path-loss gradient
- Propagation loss increases with respect to both distance and frequency
 - Why PCS cellular coverage is worth than analog?
- $\alpha = 2$ in free-space
- The propagation delay is $d/c = 3d$ ns or 3 ns per meter traveled
- For an omnidirectional antenna that radiates at power P_t

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \quad \text{where } \lambda = \frac{c}{f}$$

Fading

- In urban (or non free-space) environments, two kinds of 'fading' may take place
 - Slow fading: due to the movement of obstacles or transmitter/receiver, causing slow variation in the signal strength
 - Fast Fading: due to multipath propagation

Shadow (slow) fading

- The received signal strength 'for the same distance' from the transmitter will be different – i.e. it will vary around the mean value given by the path-loss equation.
- It is called 'slow' because the variations are typically much slower with distance than another type of fading called fast fading
- Several measurements and simulations indicate that this variation can be expressed as a log-normal random variable
- It is typically compensated for by increasing the transmit power by an amount to guarantee a certain 'fading margin'

Multipath (fast) fading

- A signal may be received at the receiver through different 'paths'
- Each signal may have traveled different distances, hence arriving with different phase.
- Fast fading is the fluctuation of the signal amplitude because of the addition of signals arriving with different 'phases'
- The phase of the arriving paths change rapidly, causing fast fluctuations of the signal amplitude
- The distribution of the amplitude follows:
 - Rayleigh distribution: if all signals suffer nearly the same attenuation, but arrive with different phases
 - Ricean distribution: when there is a strong LOS signal component
- Mitigation:
 - Increasing signal power is not very helpful
 - Error control coding with interleaving
 - Diversity schemes
 - Directional Antennas (reducing the number of multiple paths)

Multipath Doppler Spectrum

- In addition to amplitude, it is important to know
 - Fade duration: For what duration of time a signal strength is below a particular value
 - Fading rate: How often the strength crosses a threshold value
- Several models of doppler spread exist [Pahlavan+]

Multipath Delay Spread

- If the multiple paths also introduce delays that are comparable to (or larger than) the symbol duration, the received waveform spreads into the neighboring symbols and produces ISI (irreducible error rates).
- Several models exist for multipath delay spread [Pahlavan95]
- Mitigation:
 - Equalization
 - Direct Sequence Spread Spectrum
 - Directional Antennas (reducing the multipath components)

Multiple users; Bits through networks

Multiple users

- **From a channel to a network:**
 - A wireless network comprises several transmitters and receivers sharing an assigned portion of the spectrum
- **Objective**
 - We would like to carry as much traffic as possible while keeping all transmissions within the assigned bandwidth (or keeping all transmission within the assigned transmit power constraints)

■ Interference

- In addition to AWGN, if a node receives signals from different transmitters over the same frequency band, there is a possibility of co-channel interference

■ Solution

- Allow several users to use the same spectrum at the same time:
 - Spatial re-use
 - Multiuser detection

$$\Psi_{i,j} = \frac{H_{i,j}P_i}{2WN_0 + \sum_{k=1}^M H_{k,j}P_k}$$

where

P_i = transmit power from i to j

$H_{i,j}$ = power attenuation from i to j

P_i = transmit power from other nodes to their receivers (not j)

$\Psi_{i,j}$ = Signal to Interference plus Noise Ratio (SIR)

This could be used to deliberately let several transmit/receive pairs to use the channel simultaneously.

■ Signal Orthogonalization

- In time (TDMA)
- In frequency (FDMA)
- In signal space (CDMA)

Interference or collision

- Typically difficult to design around SIR
- Worst case model
 - Whenever two transmissions in the same frequency band arrive at the receiver, neither can be detected; this is called a 'collision'
 - This assumption is usually made in the analysis of multiple access protocols, to simplify the analysis.
- More realistic models
 - A more optimistic model is the 'collision threshold' [KMK04, pp460]:
 - Decoding is possible if number of interferers is bounded by k
 - Another model uses a notion called the 'interference range' model
 - Only nodes within a certain distance from the receiver can potentially interfere.

References

- [KMK04] A. Kumar, D. Manjunath and J. Kuri, “Communication Networking: An Analytical Approach,” Elsevier, 2004.
- [PK02] K. Pahlavan, P. Krishnamurthy, “Principles of Wireless Networks,” Prentice Hall, November 2002.
- T.S. Rappaport, “Wireless Communications: Principles and Practice,” Prentice Hall, 2nd. Ed., 2001.