Principles of Wireless Sensor Networks

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Lecture 3

Wireless Channel

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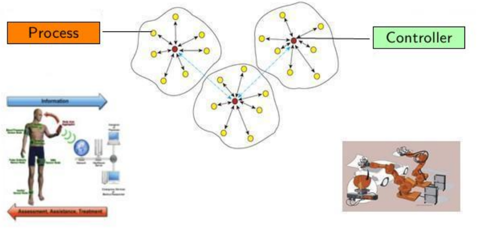
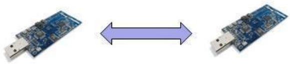
Where we are

- Application
- Presentation
- Session
- Transport
- Routing
- MAC
- Phy





- Suppose that a node has permission to transmit messages over wireless
- How the signals carrying the messages are treated by the wireless channel?

Today's learning goals

- What is the AWGN channel?
- How the channel attenuates (fades) the transmit power?
- What is the slow fading?
- What is the fast fading?

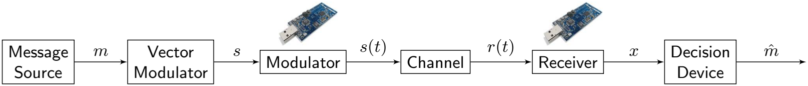
Outline

- Additive White Gaussian Noise channel
- The wireless channel fading models
- The Gilbert-Elliot model

Outline

- Additive White Gaussian noise channel
- The wireless channel fading models
  - Path-loss
  - Slow fading
  - Fast fading
- The Gilbert-Elliot model

Digital communications over wireless channels



m = source message, e.g., video, sounds, temperature

s = vector "quantized" source

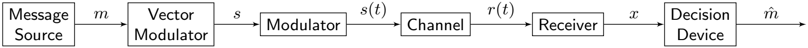
$s(t)$ = modulated signal transmitter over the wireless channel

$r(t)$ = received signal

x = demodulated signal

$\hat{m}$ = decoded signal

AWGN wireless channels



AWGN channel: the transmitted signal is received together with an Additive White Gaussian Noise

$$r\left(t\right) \triangleq s\left(t\right) + n_0\left(t\right)$$

$$n_0\left(t\right) \in N\left(0, \sigma^2 \triangleq \frac{N_0}{2T_s}\right)$$

Example: binary phase shift keying modulation

- To fix ideas, let us consider a basic modulation format: BPSK

$$s(t) \triangleq \begin{cases} \cos(2\pi f_c t) & \text{if bit 0,} \\ \cos(2\pi f_c t + \pi) = -\cos(2\pi f_c t) & \text{if bit 1.} \end{cases}$$

- $f_c =$ carrier frequency over which the signal is transmitted
- f_c is around 2.4GHz for many low data rate and low power WSNs
- The presence of AWGN noise can determine an erroneous detection of the signal. See next lecture

More real wireless channels

- In AWGN channels, the transmitted signal $s(t)$ is received corrupted by additive noise
- In real wireless channels it is also multiplicatively attenuated

$$r\left(t\right) \triangleq \sqrt{A} s\left(t\right) + n_0\left(t\right)$$

- The power of $s(t)$

$$P_t \triangleq \int_{t_0}^{t_0+T_s} s^2\left(t\right) dt$$

which, due to antennas and wireless channel, is attenuated by A

- The received power is

$$P_r \triangleq \int_{t_0}^{t_0+T_s} r^2\left(t\right) dt$$

- Let's see how P_r can be modeled

A little warning...

- The wireless channel behavior depends on the carrier frequency
- What we present below is for carrier frequencies around 2.4 GHz, the typical for low data rate WSNs

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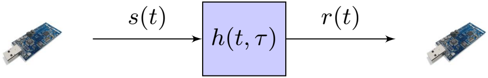
- Additive White Gaussian noise channel
- The wireless channel fading models
  - Path-loss
  - Slow fading
  - Fast fading
- The Gilbert-Elliot model

The wireless channel



- Communication channels are described by the impulse response

$$r\left(t\right) \triangleq s\left(t\right) \otimes h\left(t,\tau\right) = \int_{-\infty}^{+\infty} s\left(z\right) h\left(t,\tau - z\right) dz$$

$$P_t \triangleq \int_{t_0}^{t_0+T_s} s^2(t)dt$$ transmitted radio power over a time T_s

$$P_r \triangleq \int_{t_0}^{t_0+T_s} r^2\left(t\right) dt$$ received radio power (no additive noise)

The free space wireless channel

$$r(t) = \sqrt{A} s(t) + n_0(t)$$

$$P_r = P_t G_t(\theta_t, \psi_t) G_r(\theta_r, \psi_r) c = P_t A$$

$G(\theta_t, \psi_t)$	antenna gain
$c \triangleq \frac{\lambda^2}{(4\pi r)^2} \overline{\mathrm{PL}} \cdot z \cdot y$	channel attenuation
$\lambda \triangleq \frac{u}{f_c}$	wavelength
r	distance between transmitter and receiver

The carrier frequency affects the attenuations

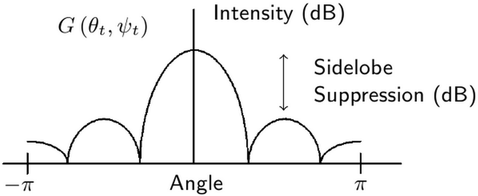
The antenna

- The antenna determines the attenuations of the transmitted signals
- Let's see how

Antennas

- Antennas are transducers to transmit and receive radio signals
- Variable currents within antenna conductors induce radiation of electromagnetic waves
- Efficiency of energy capture to a receiver depends on
  1. The antenna geometry
  2. How impedance is matched between the antenna and the medium and between the antenna and the electronics
- Due to the reciprocity between transmission and reception, an antenna that is efficient in transmission is also efficient in reception

Antenna's radiation diagram



- Antennas are designed for shaping the pattern of reception or transmission
- Transmit power may have increased gains in particular directions

Antenna's figure of merit

Efficiency: the fraction of input energy that is radiated. By reciprocity, the fraction of incident radiation that is captured

Gain: the ratio of the intensity in the pattern to that of an isotropic antenna

Beamwidth: the angle between the 3 dB of the main antenna lobe (set of angles with largest intensity)

Sidelobe suppression: the ratio of the peak intensity to the intensity of the largest sidelobe

The environment in which the antennas operate, the packaging of the radio receiver, and the presence of nearby conductive entities (e.g., people) can alter the antenna efficiency and beam pattern

The signal to noise ratio, SNR

- The antennas and wireless channel attenuates and distorts the transmitted radio power

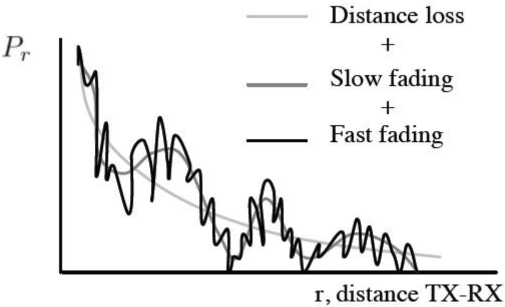
$$P_r \triangleq P_t G_t(\theta_t, \psi_t) G_r(\theta_r, \psi_r) \frac{\lambda^2}{(4\pi r)^2} \overline{\mathrm{PL}} \cdot y \cdot z$$

- The signal to noise ratio at the receiver is defined as

$$\mathrm{SNR} \triangleq \frac{P_r}{N_0}$$

- For a fixed SNR,
  1. Quadrupling the transmitted radio power doubles the range
  2. Decreasing the carrier frequency of two will double the range

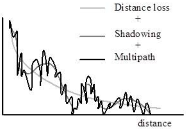
Channel attenuation vs distance



$$P_r \triangleq P_t G_t\left(\theta_t, \psi_t\right) G_r\left(\theta_r, \psi_r\right) \frac{\lambda^2}{(4\pi r)^2} \overline{\mathrm{PL}} \cdot z \cdot y$$

Path loss

$$P_r = P_t G_t(\theta_t, \psi_t) G_r(\theta_r, \psi_r) \frac{\lambda^2}{(4\pi r)^2}\overline{\mathrm{PL}} \cdot z \cdot y$$



- The path loss power depends on the distance transmitter receiver

$$\mathrm{PL} \triangleq \frac{\lambda^2}{(4\pi r)^2}\overline{\mathrm{PL}}$$

- The dB of the path loss power is often called Received Signal Strength (RSS) and provided by TelosB motes as RSSI, for indoor scenarios is

$$\mathrm{PL}_{\mathrm{dB}} \triangleq 10\log_{10}\mathrm{PL} = \mathrm{PL}(d_0) - 10 n_{\mathrm{SF}} \log\left(\frac{r}{r_0}\right) - \mathrm{FAF} - \sum_j \mathrm{PAF}_j$$

n_{SF}: path loss exponent

FAF: floor attenuation factor

PAF_j: path attenuation factor per obstacle within a room

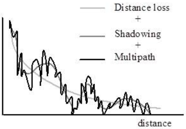
Typical figures of path loss

Material	Loss (dB)
Aluminum siding	20
Foil insulation	4
Concrete block wall	8-20
One floor	10-30
One floor and one wall	40-50
Right-angle corner in corridor	10-15

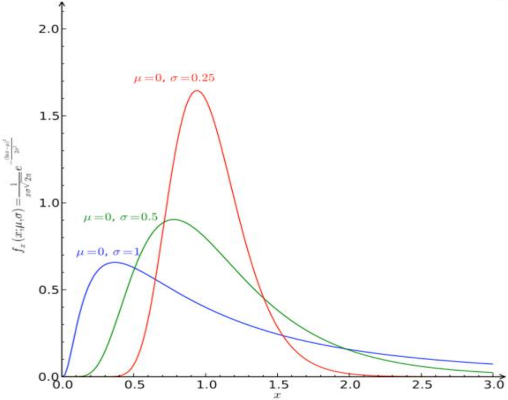
Typical losses for indoor obstructions [Pottie & Kaiser, 2005]

Shadow fading

$$P_r = P_t G_t(\theta_t, \psi_t) G_r(\theta_r, \psi_r) \frac{\lambda^2}{(4\pi r)^2} \overline{\mathrm{PL}} \cdot z \cdot y$$



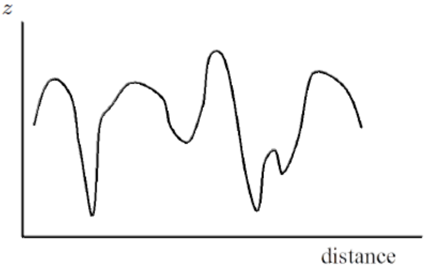
$$X \triangleq N(\mu, \sigma^2)$$
$$y \triangleq e^{\frac{x}{10}}$$



The shadow fading often follows a lognormal probability distribution function

The fast fading channel attenuation

$$P_r = P_t G_t(\theta_t, \psi_t) G_r(\theta_r, \psi_r) \frac{\lambda^2}{(4\pi r)^2} \overline{\mathrm{PL}} \cdot z \cdot y$$

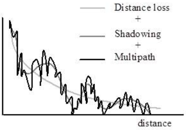


Intensity variations due to multipath fading [Pottie & Kaiser, 2005]

- Fast fading is due to multi-path propagation
- For physical reasons, the square root of the fast fading can follow some probability distributions, such as Rayleigh, Rice, Nakagami. . .

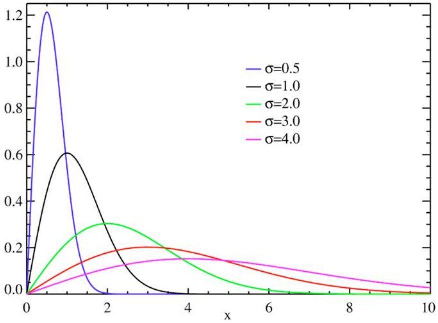
Rayleigh fast fading

$$P_r = P_t G_t(\theta_t, \psi_t) G_r(\theta_r, \psi_r) \frac{\lambda^2}{(4\pi r)^2} \overline{\mathrm{PL}} \cdot z \cdot y$$



$$x^2 \triangleq z$$

$$f(x) \triangleq \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}$$



- Fast fading may follow a Rayleigh distribution (if x is a Rayleigh random variable, z is an exponential random variable)

Multi-path Rayleigh fading

- The channel impulse response may spread the transmitted signal over time due to multiple reflectors

imaginary number

$$h(t,\tau) \triangleq \sqrt{G_t G_r \mathrm{PL} y} \sum_i \alpha_i(t)\, e^{j\theta_i(t)} \delta(\tau - \tau_i(t))$$

delay of path i

random variable with Rayleigh distribution

random variable with uniform distribution

$$\sqrt{z_i} \triangleq \left| \alpha_i(t)\, e^{j\theta_i(t)} \right| = \alpha_i(t)$$

Typical figures of fading

Environment	Distance exponent	Shadowing model	Multipath model
Free space	2	None	None
Urban cellular	2.7-3.5	Lognormal σ =8-9 dB	Rayleigh or Rice
Shadowed urban cellular	3-5	Lognormal σ =8-9 dB	Rayleigh
In building line of sight	1.6-1.8	None	Rice or lognormal
Obstructed in office building	4-6	Site-specific	Rayleigh or lognormal
Obstructed in factories	2-3	Site-specific	Lognormal
Satellite	2	Site-specific	Rice

Statistical model parameters [Pottie & Kaiser, 2005]

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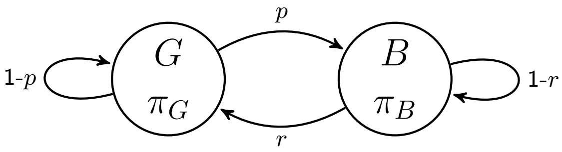
Gilbert-Elliot model

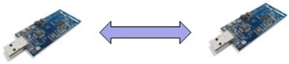
- It is a simple way to describe the behavior of the wireless channel in two states: Bad and Good



$$\pi_B + \pi_G = 1$$
$$\pi_G = (1-p)\,\pi_G + r\pi_B$$

- π_B probability of bad state
- π_G probability of good state
- p probability to go from the good state to the bad
- r probability to go from the bad state to the good

Conclusion



- We studied the wireless channel attenuates the transmit power
  - AWGN
  - Path loss
  - Slow fading
  - Fast fading

Next lecture

In the next lecture, we examine how bits of messages are transmitted over a channel. Moreover, we study the probability to successfully receive such messages over AWGN/fading channels