ITCE 720A Autonomic Wireless Networking (Fall, 2009)

Mobile Communications

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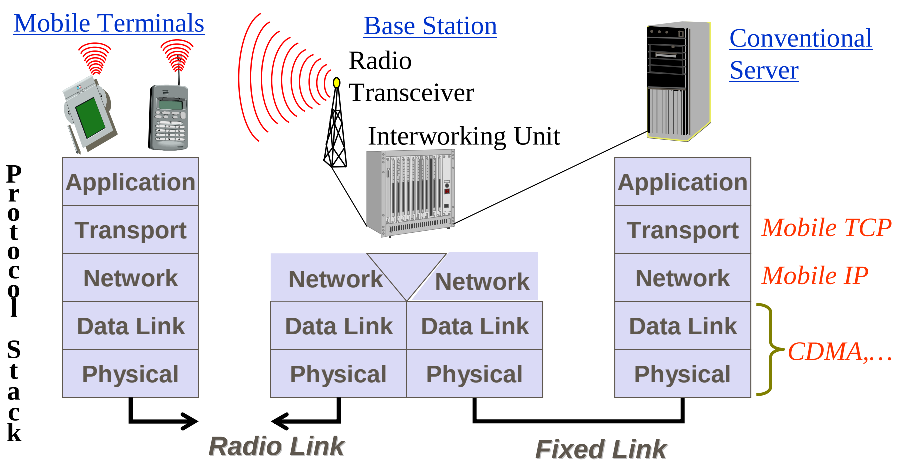
Simplified Reference Model



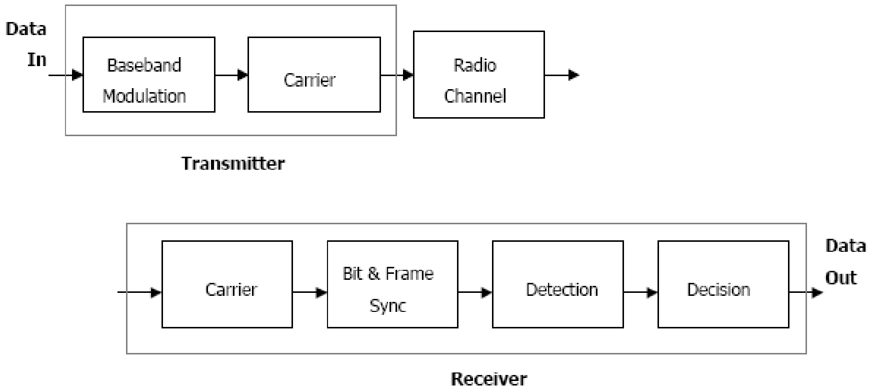
Wireless Radio Channel

- Time-varying impairments
  - medium is susceptible to noise, interference, blockage and multipath and these channel impediments are time-varying because of user movements
  - these characteristics impose fundamental limits on the range, data rate and reliability of communications over wireless links
  - these limits are determined by several factors
    - propagation environment
    - user mobility
  - e.g., a radio for an indoor user at walking speeds will typically support higher data rates with better reliability than an outdoor user channel that operates in the shadow of tall buildings and where the user moves at high speeds.

Limits of Wireless Channel

- Shannon defined the capacity limits for communication channels with additive white Gaussian noise.
- For a channel without shadowing, fading, or ISI, Shannon provided that the maximum possible data rate on a given channel of bandwidth B is:
  - R = B log2(1+SNR) bps
  - where SNR is the received signal to noise ratio
- Shannon's is a theoretical limit that cannot be achieved in practice

Digital Radio Communications



Modulator and demodulator components

Modulation and Demodumation

- Modulation
  - is the process of taking information from a message source (baseband) in a suitable manner for transmission
  - generally involves translating the baseband signal onto a radio carrier at frequencies that are very high compared to the baseband frequency
- Demodulation
  - is the process of extracting the baseband from the carrier so that it may be processed and interpreted by the receiver (e.g., symbols detected and extracted)

IEEE 802.11/a/b Physical layer

Table 14.4 IEEE 802.11 Physical Layer Specifications

(a) Direct sequence spread spectrum

Data rate	Chipping code length	Modulation	Symbol rate	Bits/symbol
1 Mbps	11 (Barker sequence)	DBPSK	1 Msps	1
2 Mbps	11 (Barker sequence)	DQPSK	1 Msps	2
5.5 Mbps	8 (CCK)	DBPSK	1.375 Msps	4
11 Mbps	8 (CCK)	DQPSK	1.375 Msps	8

(b) Frequency-hopping spread spectrum

Data rate	Modulation	Symbol rate	Bits/symbol
1 Mbps	Two-level GFSK	1 Msps	1
2 Mbps	Four-level GFSK	1 Msps	2

(c) Infrared

Data rate	Modulation	Symbol rate	Bits/symbol
1 Mbps	16-PPM	4 Msps	0.25
2 Mbps	4-PPM	4 Msps	0.5

(d) Orthogonal FDM

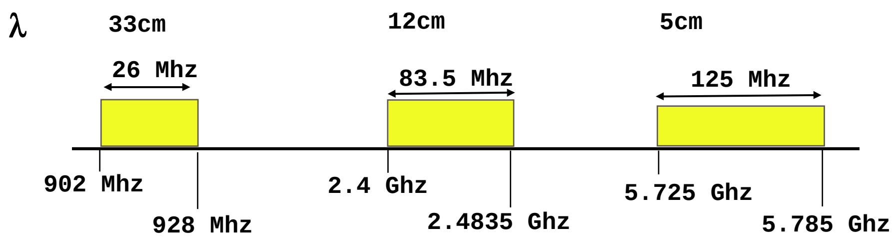
Data rate	Modulation	Coding rate	Coded bits per subcarrier	Code bits per OFDM symbol	Data bits per OFDM symbol
6 Mbps	BPSK	1/2	1	48	24
9 Mbps	BPSK	3/4	1	48	36
12 Mbps	QPSK	1/2	2	6	48
18 Mbps	QPSK	3/4	2	96	72
24 Mbps	16-QAM	1/2	4	192	96
36 Mbps	16-QAM	3/4	4	192	144
49 Mbps	64-QAM	2/3	6	288	192
54 Mbps	16-QAM	3/4	6	288	216

/

Why carrier?

- For example, voice range 300-3300Hz we must consider the fact that for effective signal radiation the length of the antenna must be proportional to the transmitted wave length
  - at 3 kHz at 3kbits/sec would imply an antenna of 100 Km!
  - By modulating the baseband on a 3GHz carrier the antenna would be 10 cm
- to ensure the orderly coexistence of multiple signals in a given spectral band
- to help reduce interference among users
- and for regulatory reasons

Cf. Unlicensed Radio Spectrum



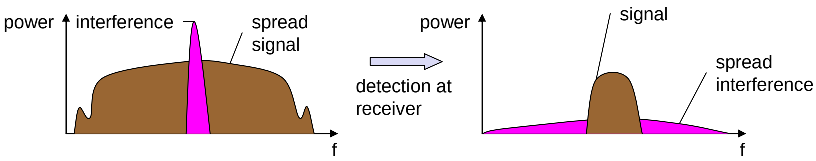
cordless phones baby monitors Wireless LANs	802.11 Bluetooth Microwave oven	unused

Why Spread Spectrum?

- Spread spectrum signals are distributed over a wide range of frequencies and then collected back at the receiver
  - These wideband signals are noise-like and hence difficult to detect or interfere with
- Initially adopted in military applications, for its resistance to jamming and difficulty of interception
  - Spreading spectrum makes signal appear as wideband (“white” noise) - less detectable and interceptable (stealth)
  - Spreading spectrum makes signal less vulnerable to hostile intentional interference (anti-jamming)
- More recently, adopted in commercial wireless communications

Spread Spectrum

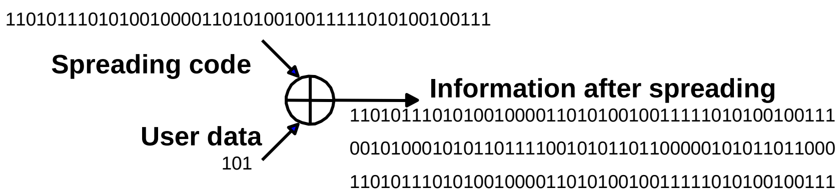
- Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code



protection against narrowband interference

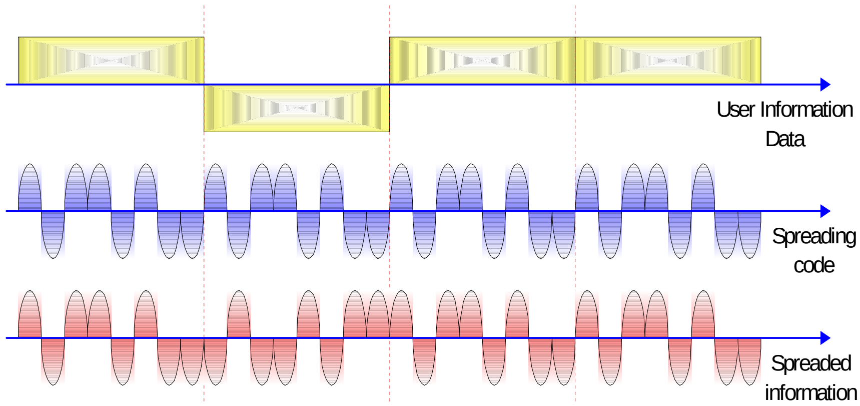
- Side effects:
  - coexistence of several signals without dynamic coordination
  - tap-proof

Direct Sequence Spread Spectrum (DSSS)



- Data signal is multiplied by a spreading code, and resulting signal occupies a much higher frequency band
- Spreading code is a pseudo-random sequence

DSSS Example



Andrew J. Viterbi

Multiple Access: CDMA

- Interference is unintentional from a multitude of other users
- Ideally choose each user's spreading code not to interfere with other users.
  Requires Orthogonal Sequences (Any 2 user codes differ in as many places as they agree)
- But requires perfect frequency and time synchronization
- Easily implemented in CDM (multiplexing) as in downlink from Base Station
- Very difficult in CDMA for multiple separate moving users as in uplink. Furthermore, multipath destroys orthogonality - renders impossible.
- So use very long (non-orthogonal) spreading codes for all users. Result is mutual interference which appears as white noise - just as in military application

Multiple Users is proportional to spreading factor

Signals

- physical representation of data
- function of time and location
- classification
  - continuous time/discrete time
  - continuous values/discrete values
  - analog signal = continuous time and continuous values
  - digital signal = discrete time and discrete values

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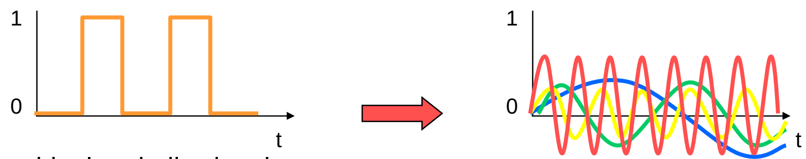
Fourier representation of periodic signals

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$



ideal periodic signal

real composition (based on harmonics)

- Digital signals (sequence of 0 & 1) need:
  - infinite frequencies for perfect transmission
  - modulation with a carrier signal for transmission

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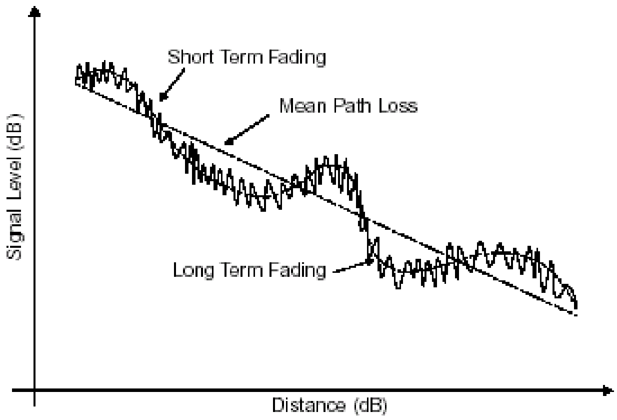
Signal Propagation Models

- Modeling the radio channel
  - has historically been one of the most difficult parts of the radio channel design and is typically done in a statistical fashion, based on measurements made specifically for an intended communication systems or spectrum allocation
- Foundation
  - predicting the average signal strength at a given distance from the transmitter
  - variability of the signal strength in close proximity to particular locations
- There is a need to be able to model:
  - **Path Loss**
  - **Multipath Propagation**

Signal Propagation: Fading

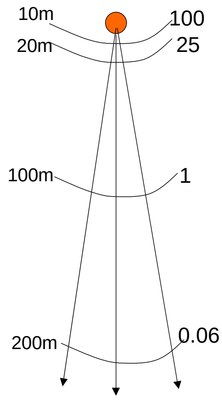
- Strength of the signal decreases with distance between transmitter and receiver: path loss
  - Usually assumed inversely proportional to distance to the power of 2.5 to 5
- Slow fading (shadowing) is caused by large obstructions between transmitter and receiver
- Fast fading is caused by scatterers in the vicinity of the transmitter

Signal Propagation: Fading



Transmitting Radio Signals

- **Free space model**
  - No matter exists between the sender and the receiver
  - Signal power is attenuated as $1/d^2$
- **Ground reflection model**
  - Signal power is attenuated as $1/d^4$
  - In short distance, free space model applies
  - Reference distance
    - 100 meters for outdoor low-gain antennas 1.5 meters above the ground place operating in 1-2GHZ band



Longer radio range requires much stronger power !!!

18.1 Free space model

The free space propagation model assumes the ideal propagation condition that there is only one clear line-of-sight path between the transmitter and receiver. H. T. Friis presented the following equation to calculate the received signal power in free space at distance d from the transmitter [12].

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \quad (18.1)$$

where P_t is the transmitted signal power. G_t and G_r are the antenna gains of the transmitter and the receiver respectively. $L(L \geq 1)$ is the system loss, and λ is the wavelength. It is common to select $G_t = G_r = 1$ and $L = 1$ in *ns* simulations.

18.2 Two-ray ground reflection model

A single line-of-sight path between two mobile nodes is seldom the only means of propation. The two-ray ground reflection model considers both the direct path and a ground reflection path. It is shown [29] that this model gives more accurate prediction at a long distance than the free space model. The received power at distance d is predicted by

$$P_r(d) = \frac{P_t G_t G_r {h_t}^2 {h_r}^2}{d^4 L} \quad (18.2)$$

where h_t and h_r are the heights of the transmit and receive antennas respectively. Note that the original equation in [29] assumes $L = 1$. To be consistent with the free space model, L is added here.

18.3 Shadowing model

The shadowing model consists of two parts. The first one is known as path loss model, which also predicts the mean received power at distance d, denoted by $\overline{P_r(d)}$. It uses a close-in distance d_0 as a reference. $\overline{P_r(d)}$ is computed relative to $P_r(d_0)$ as follows.

$$\frac{P_r(d_0)}{\overline{P_r(d)}} = \left(\frac{d}{d_0}\right)^\beta \quad (18.4)$$

β is called the path loss exponent, and is usually empirically determined by field measurement. From Eqn. (18.1) we know that $\beta = 2$ for free space propagation. Table 18.1 gives some typical values of β. Larger values correspond to more obstructions and hence faster decrease in average received power as distance becomes larger. $P_r(d_0)$ can be computed from Eqn. (18.1).

The path loss is usually measured in dB. So from Eqn. (18.4) we have

$$\left[\frac{\overline{P_r(d)}}{P_r(d_0)}\right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) \quad (18.5)$$

The second part of the shadowing model reflects the variation of the received power at certain distance. It is a log-normal random variable, that is, it is of Gaussian distribution if measured in dB. The overall shadowing model is represented by

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) + X_{dB} \quad (18.6)$$

where X_{dB} is a Gaussian random variable with zero mean and standard deviation σ_{dB}. σ_{dB} is called the shadowing deviation, and is also obtained by measurement. Table 18.2 shows some typical values of σ_{dB}. Eqn. (18.6) is also known as a log-normal shadowing model.

Environment		β
Outdoor	Free space	2
	Shadowed urban area	2.7 to 5
In building	Line-of-sight	1.6 to 1.8
	Obstructed	4 to 6

Table 18.1: Some typical values of path loss exponent β

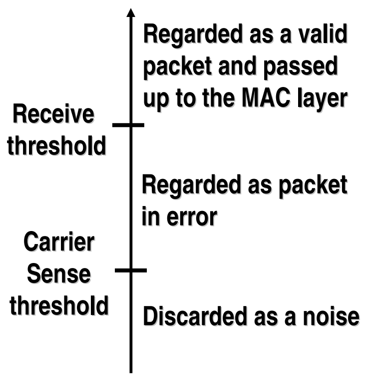
Environment	σ_{dB} (dB)
Outdoor	4 to 12
Office, hard partition	7
Office, soft partition	9.6
Factory, line-of-sight	3 to 6
Factory, obstructed	6.8

Table 18.2: Some typical values of shadowing deviation σ_{dB}

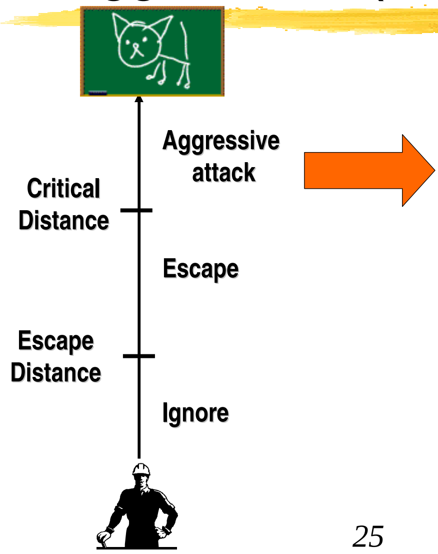
```
# first set values of shadowing model
Propagation/Shadowing set pathlossExp_ 2.0  ;# path loss exponent
Propagation/Shadowing set std_db_ 4.0       ;# shadowing deviation (dB)
Propagation/Shadowing set dist0_ 1.0        ;# reference distance (m)
Propagation/Shadowing set seed_ 0           ;# seed for RNG
```


Receiving Radio Signals

- The power level of a received packet is compared to two values

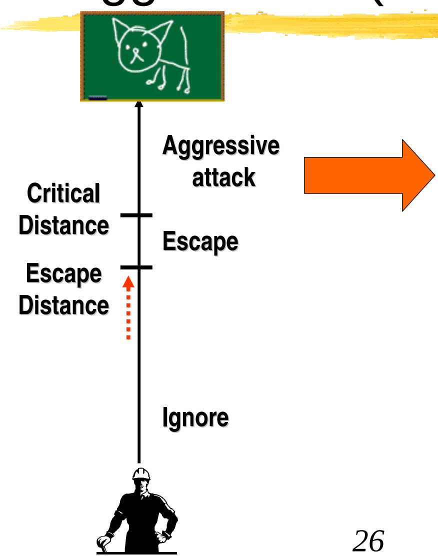


“On Aggression” (1971)



In the woods,
- A lion considers safer,
- In other words, the Escape distance becomes shorter

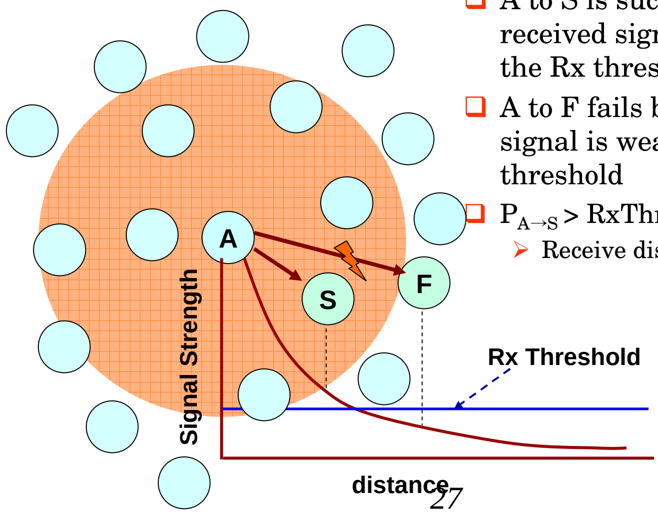
“On Aggression” (1971)



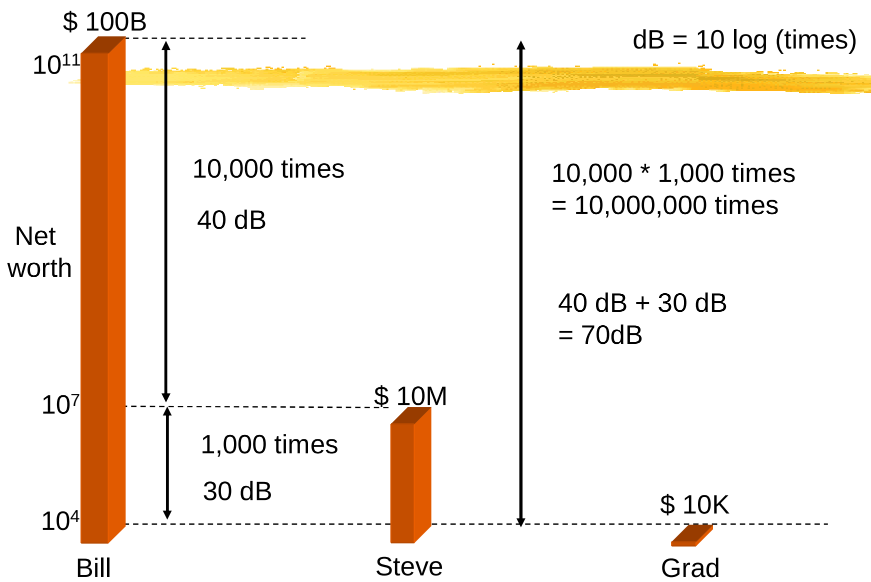
In the woods,
- A lion considers safer,
- In other words, the Escape distance becomes shorter
- A hunter approaches closer than possible
- The lion all of a sudden finds him within the Critical distance
- And it...

Receive Threshold

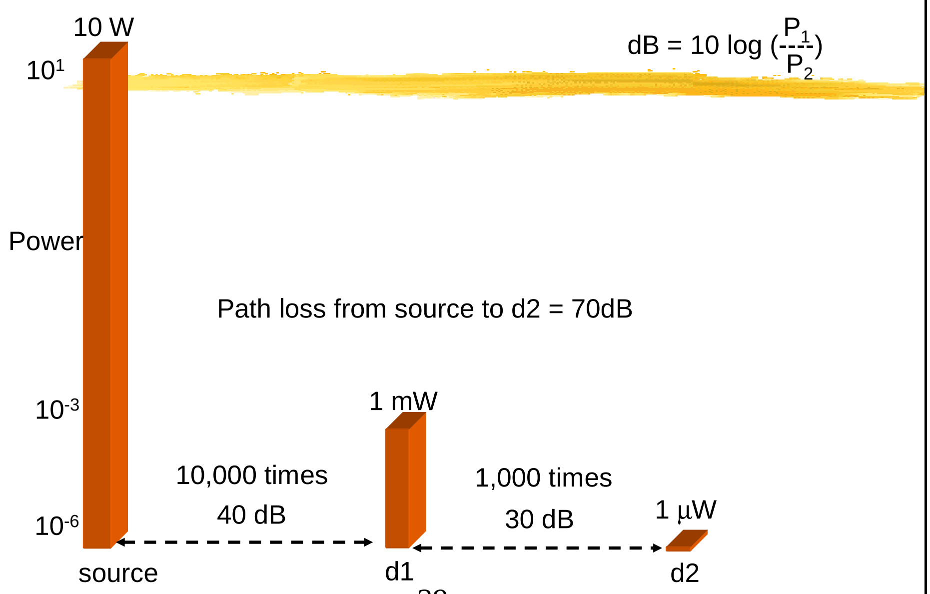
- A to S is successful because the received signal is stronger than the Rx threshold
- A to F fails because the received signal is weaker than the Rx threshold
- $P_{A \to S}$ > RxThreshold = -82 dBm
  - Receive distance (238m)



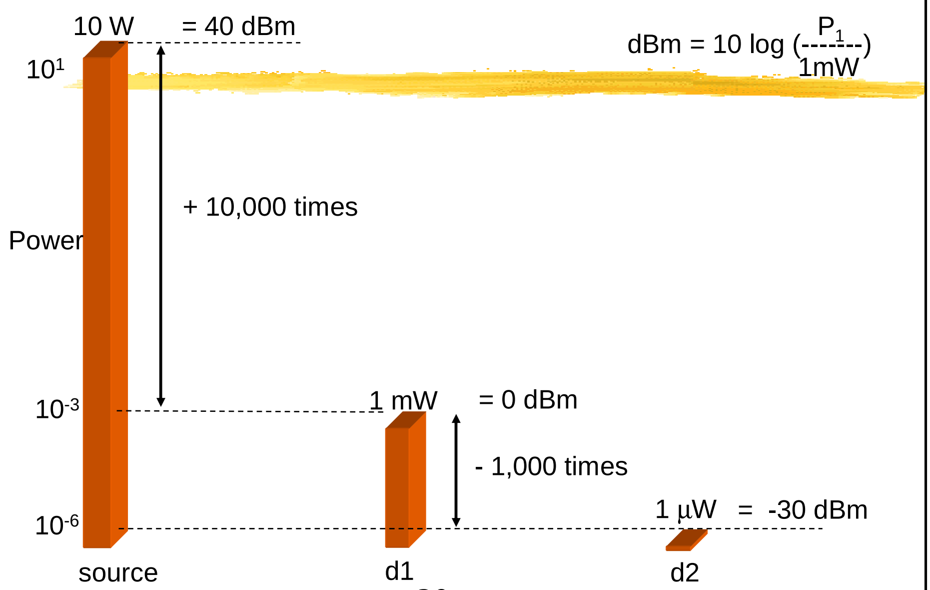
dB (relative measure)



Path loss in dB



dBm (absolute measure of power)



Let's Do the Math

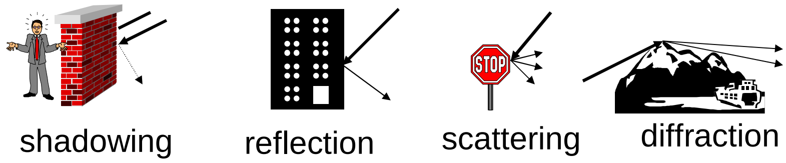
- In the 915 MHz WaveLAN radio hardware (free)
  - Transmit power (Pt) = 24.5 dBm = ??? Watts
  - Receive sensitivity = -64.5 dBm = ??? Watts
  - Receiving distance (Pr > Rth) = ??? m
    - $Pr(d) = Pt*GtGrht^2hr^2/(4\pi)^2Ld^2$
    - $Gt=Gr=1$, $L=1$, $\lambda = 3x10^8/915x10^6 = 0.328$

Let's Do the Math

- In the 915 MHz WaveLAN radio hardware (two-ray)
  - Transmit power (Pt) = 24.5 dBm = ??? Watts
  - Receive sensitivity (Rth) = -64.5 dBm = ??? Watts
  - Receiving distance (Pr > Rth) = ??? m
    - $Pr(d) = Pt*GtGr\lambda^2/Ld^4$
    - $Gt=Gr=1$, $ht=hr=1.5$, $L=1$
  - Carrier sense sensitivity (Cth)= -78dBm = ??? Watts
  - Carrier sense distance (Pr > Cth) = ??? m

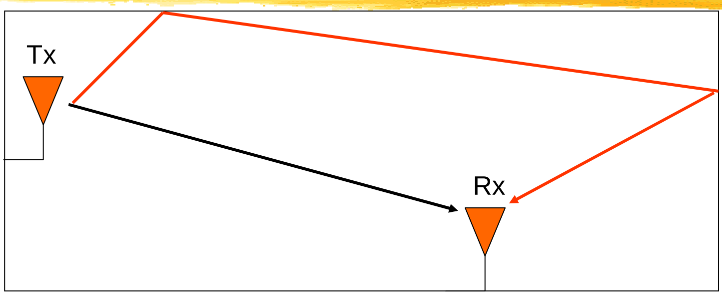
Signal Propagation: Others

- Receiving power additionally influenced by



- **Multipath propagation** : Signal can take many different paths between sender and receiver, which makes the correct comm. difficult

Signal Propagation: Multipath



Effects of multipath

- Fading
- Varying doppler shifts on different multipath signals
- Time dispersion (causing inter symbol interference)

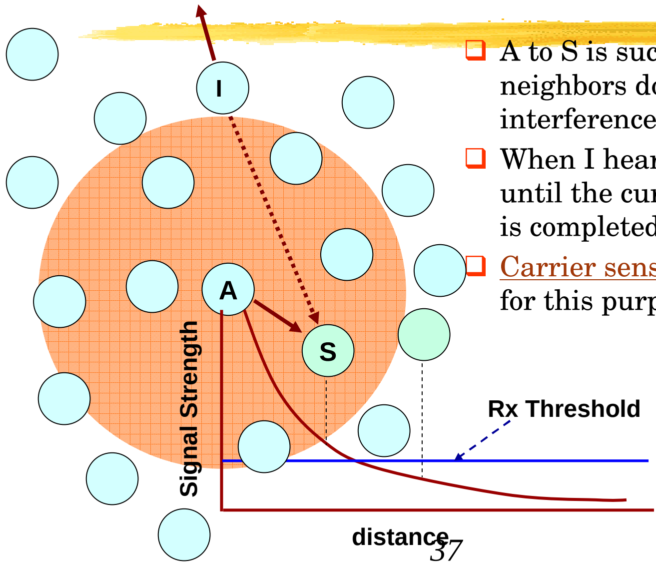
Physical Impairments: Noise

- Unwanted signals added to the message signal
- May be due to signals generated by natural phenomena such as lightning or man-made sources, including transmitting and receiving equipment as well as spark plugs in passing cars, wiring in thermostats, etc.
- Sometimes modeled in the aggregate as a random signal in which power is distributed uniformly across all frequencies (white noise)
- Signal-to-noise ratio (SNR) often used as a metric in the assessment of channel quality

Physical Impairments: Interference

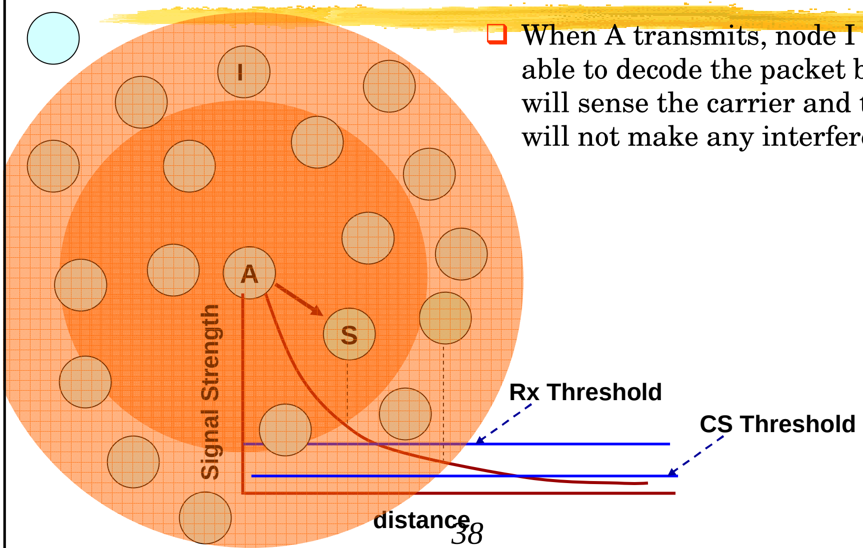
- Signals generated by communications devices operating at roughly the same frequencies may interfere with one another
  - Example: IEEE 802.11b and Bluetooth devices, microwave ovens, some cordless phones
  - CDMA systems (many of today's mobile wireless systems) are typically interference-constrained
- Signal to interference and noise ratio (SINR) is another metric used in assessment of channel quality

Capture/Carrier Sense Threshold



- A to S is successful only when its neighbors do not cause interference.
- When I hears something, I waits until the current communication is completed.
- Carrier sense threshold is used for this purpose

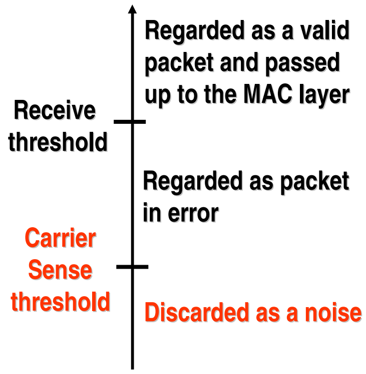
Capture/Carrier Sense Threshold



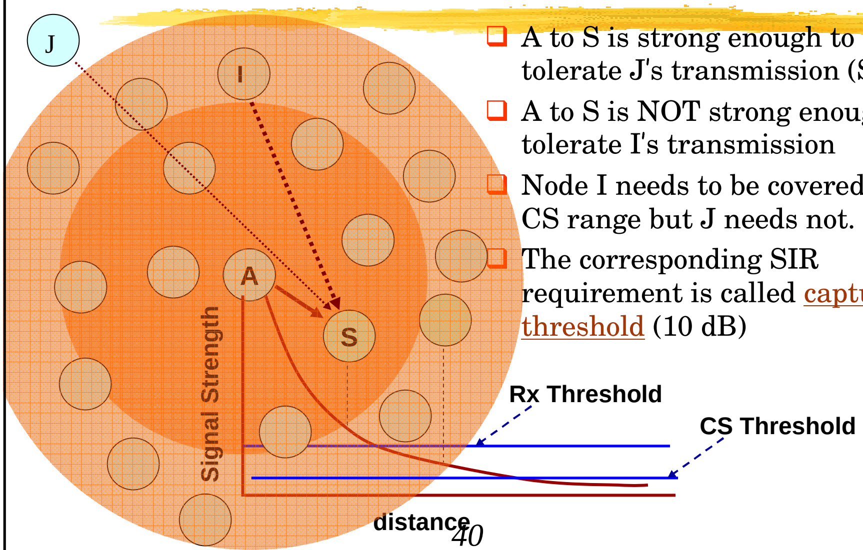
- When A transmits, node I is not able to decode the packet but it will sense the carrier and thus will not make any interference.

Receiving Radio Signals

- The power level of a received packet is compared to two values

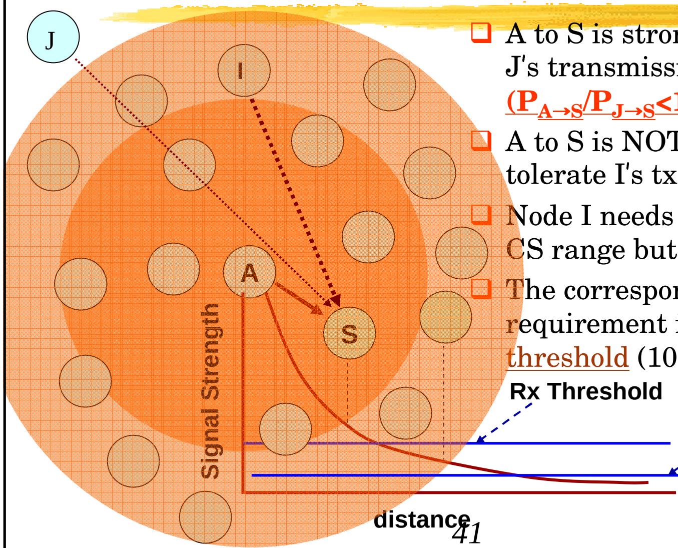


Determining Carrier Sense Threshold



- A to S is strong enough to tolerate J's transmission (SIR)
- A to S is NOT strong enough to tolerate I's transmission
- Node I needs to be covered in the CS range but J needs not.
- The corresponding SIR requirement is called capture threshold (10 dB)

Determining Carrier Sense Threshold



- A to S is strong enough to tolerate J's transmission (SIR) **($P_{A\to S}/P_{J\to S}$<10dB)**
- A to S is NOT strong enough to tolerate I's tx **($P_{A\to S}/P_{I\to S}$>10dB)**
- Node I needs to be covered in the CS range but J needs not.
- The corresponding SIR requirement is called capture threshold (10 dB)

Receiving Radio Signals

"signal capturing"

- The power level of a received packet is compared to two values

	Regarded as a valid packet and passed up to the MAC layer
Receive threshold	
	Regarded as packet in error
Carrier Sense threshold	
	Discarded as a noise

If the receiver receives one signal while receiving another (conflict),

- P(old)/P(new)>10dB, can still receive the old one (new packet is dropped)

- Otherwise, it is a "collision" and both packets are dropped

Reading

- Mandatory
  - "Tutorial on Basic Link Budget Analysis," Application Note, Intersil, 1998 (http://sss-mag.com/pdf/an9804.pdf)
  - Section 5 of "Understanding and Mitigating the Impact of RF Interference on 802.11 Networks," ACM SIGCOMM, 2007 (http://www.intel-research.net/Publications/Seattle/020520071626_397.pdf)

- Recommended
  - Propagation model embedded in a wireless network simulator (http://academic.csuohio.edu/yuc/mobile09/ns2-author.pdf)
  - Architecture and Evaluation of an Unplanned 802.11b Mesh Network (http://pdos.csail.mit.edu/papers/roofnet:mobicom05/roofnet-mobicom05.pdf)