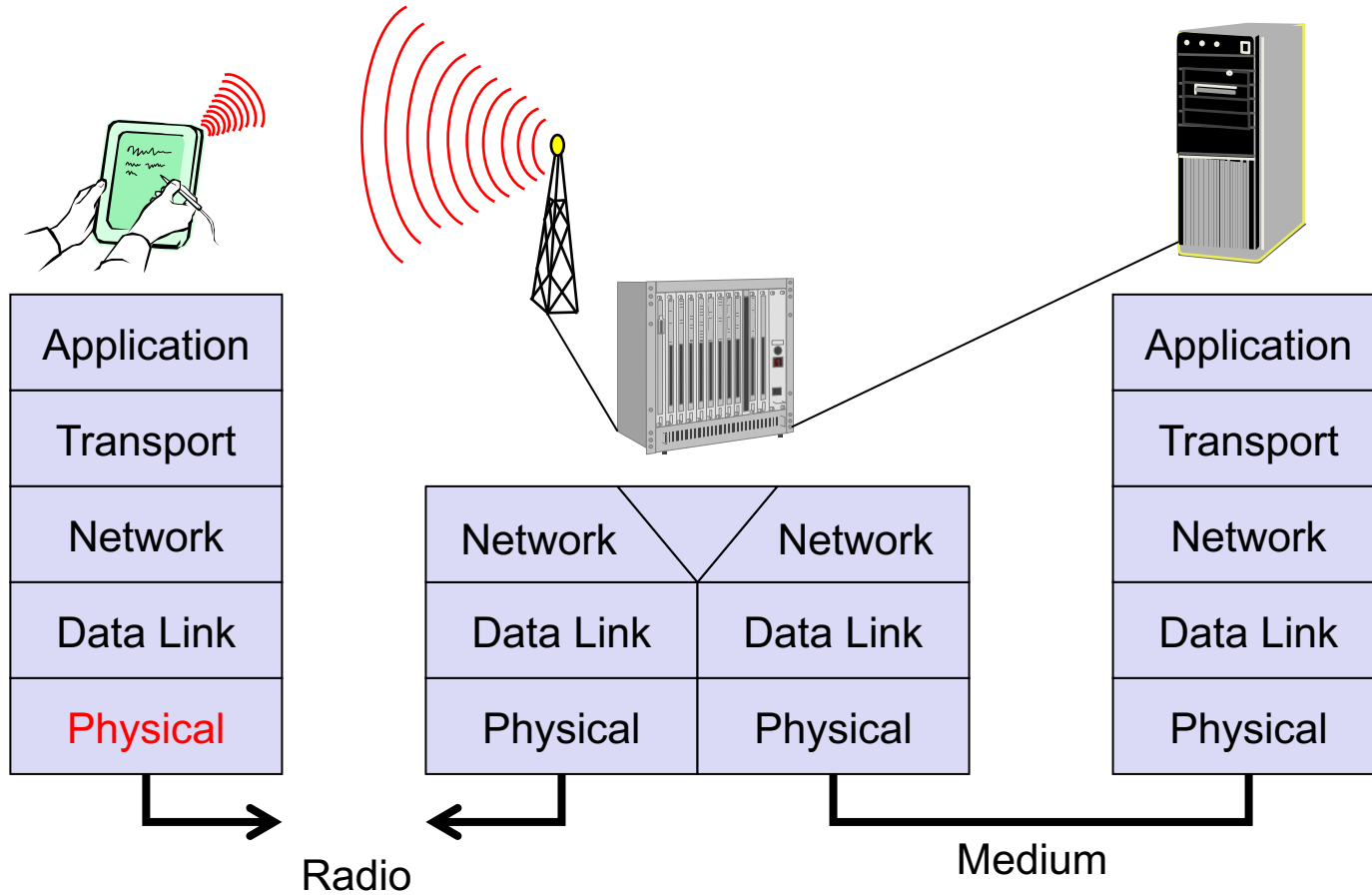


Wireless Sensor Networks

Wireless Transmission Fundamentals (Physical Layer)

Facultatea de Automatică și Calculatoare
Universitatea Politehnica București

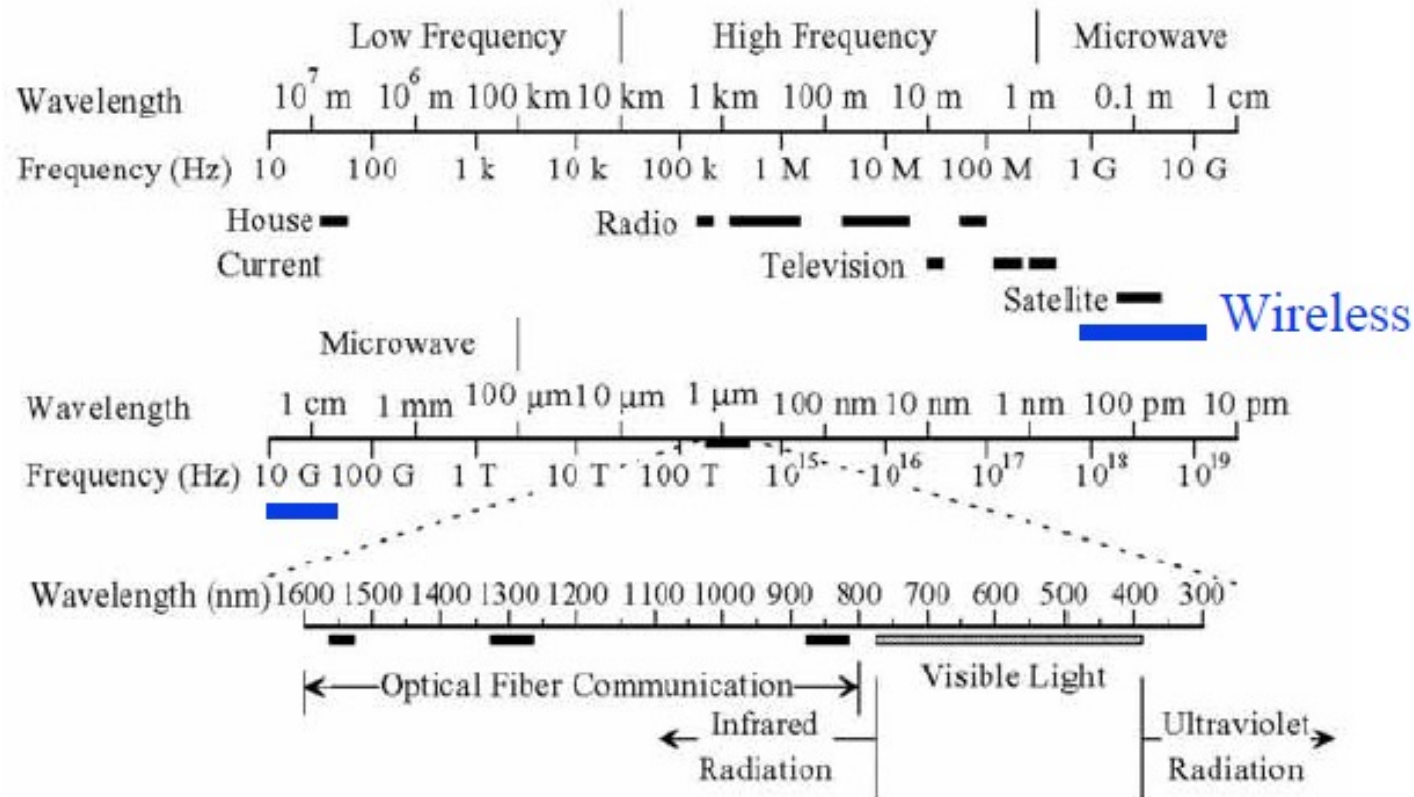
The Layered Reference Model



- RF introduction
- Wireless Terminology
- Antennas and signal propagation
 - How do antennas work
 - Propagation properties of RF signals
- Modulation and channel capacity

Electromagnetic Spectrum

- Wireless communication uses 100 kHz to 60 GHz



Frequencies are Assigned and Regulated

	Europe	USA	Japan
Cellular Phones	GSM 450 - 457, 479 - 486/460 - 467, 489 - 496, 890 - 915/935 - 960, 1710 - 1785/1805 - 1880 UMTS (FDD) 1920 - 1980, 2110 - 2190 UMTS (TDD) 1900 - 1920, 2020 - 2025	AMPS , TDMA , CDMA 824 - 849, 869 - 894 TDMA , CDMA , GSM 1850 - 1910, 1930 - 1990	PDC 810 - 826, 940 - 956, 1429 - 1465, 1477 - 1513
Cordless Phones	CT1+ 885 - 887, 930 - 932 CT2 864 - 868 DECT 1880 - 1900	PACS 1850 - 1910, 1930 - 1990 PACS -UB 1910 - 1930	PHS 1895 - 1918 JCT 254 - 380
Wireless LANs	IEEE 802.11 2400 - 2483 HIPERLAN 2 5150 - 5350, 5470 - 5725	902 - 928 IEEE 802.11 2400 - 2483 5150 - 5350, 5725 - 5825	IEEE 802.11 2471 - 2497 5150 - 5250
Others	RF - Control 27, 128, 418, 433, 868	RF - Control 315, 915	RF - Control 426, 868

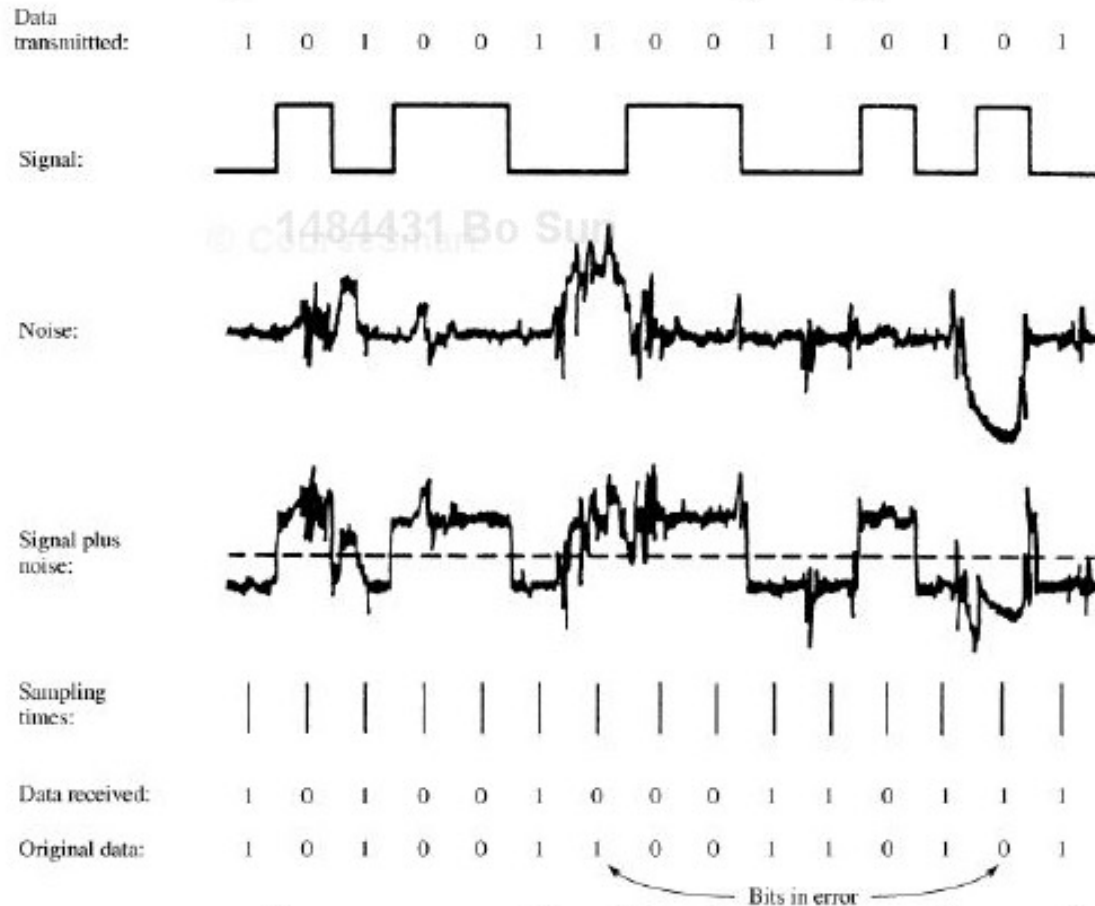
US operator: <http://wireless.fcc.gov/uls>

Some Basic Concepts

- RSSI
- dbm
- Noise floor: see wikipedia
- CCA thresholding algorithms
- Duty cycle
- LPL

Signal Transmission

Figure 2.9. Effect of Noise on a Digital Signal



Ref: Fig. 2.9 of “Wireless Communications and Networks” by William Stallings

Packet Reception and Transmission

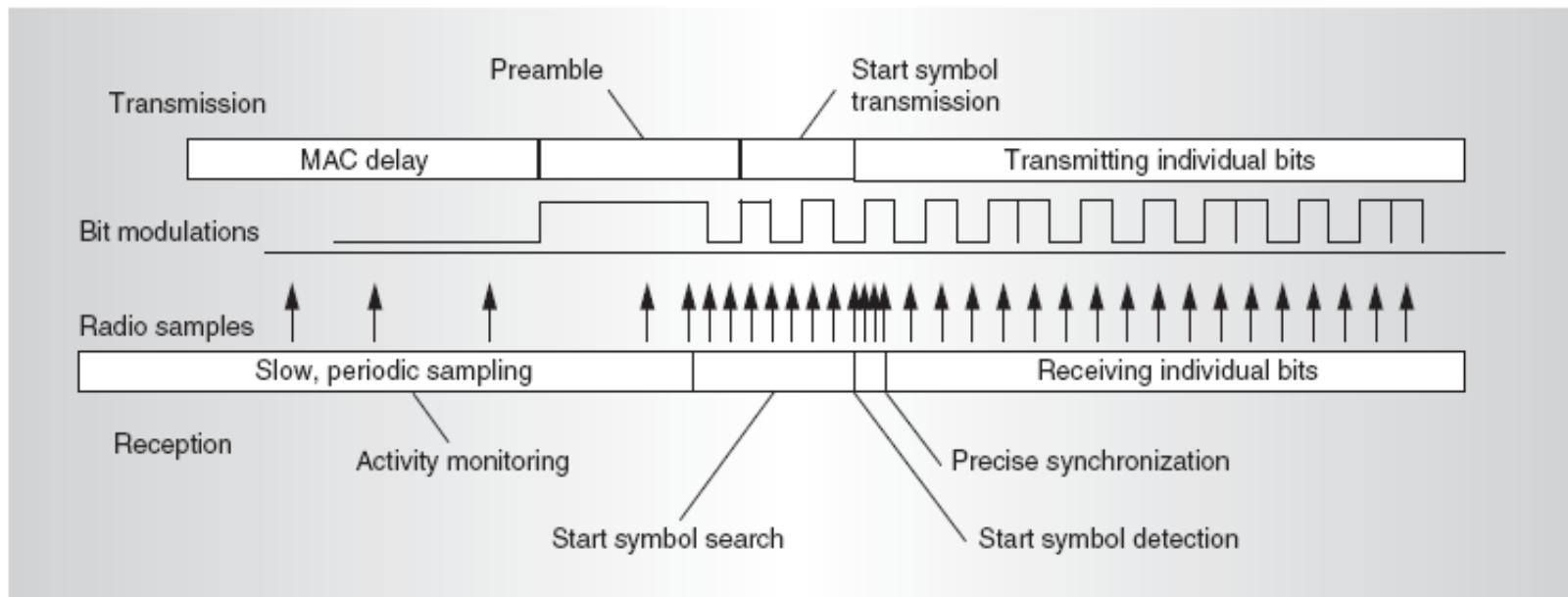


Figure 5. Anatomy of packet reception and transmission. For reception, slow sampling detects arrival of a 10-kilobits-per-second (Kbps) start signal. The receiver must determine the packet's precise timing to synchronize for the 50-Kbps data payload. Data sample timing for the entire packet is based on the initial synchronization. For transmission, after a short random delay, the preamble, then a start symbol, and then the data are sent.

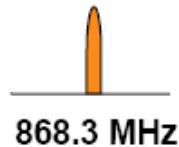
- An electromagnetic signal
 - A function of time
 - Also a function of frequency
 - The signal consists of components of different frequencies

802.15.4 Physical Layer

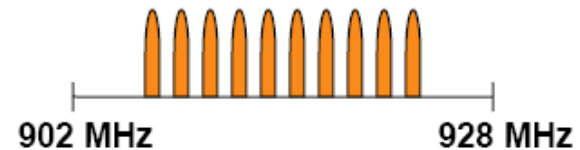
Operating Frequency Bands

868MHz/915MHz
PHY

Channel 0

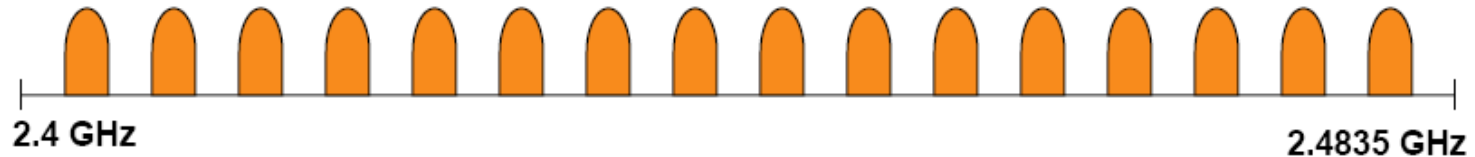


Channels 1-10



2.4 GHz
PHY

Channels 11-26



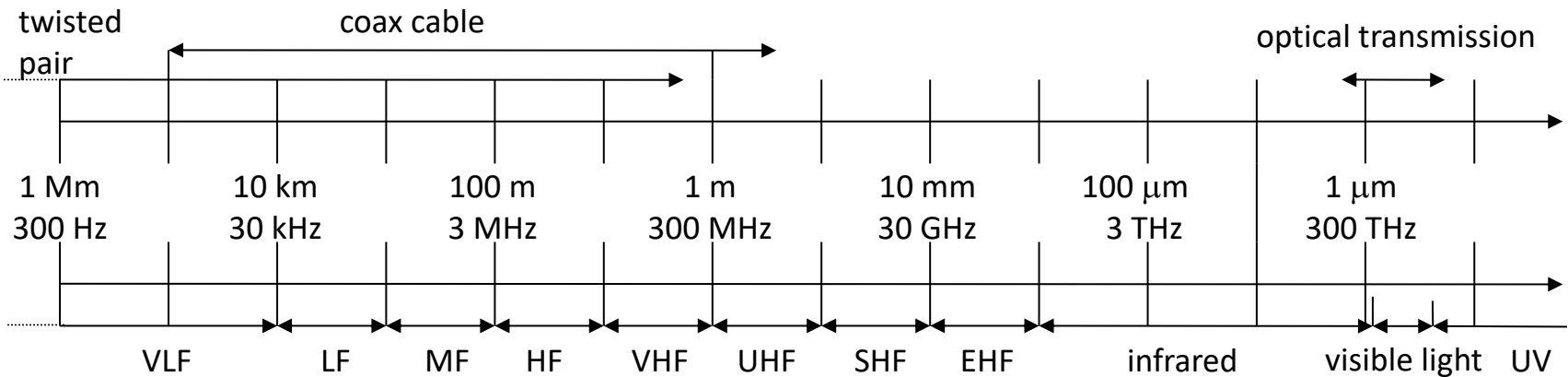
Spectrum and Bandwidth: Shannon Channel Capacity

The maximum number of bits that can be transmitted per second by a physical channel is:

$$W \log_2 \left(1 + \frac{S}{N} \right)$$

where W is the frequency range of the channel, and S/N is the signal noise ratio, assuming Gaussian noise

Frequencies for Communications



VLF = Very Low Frequency

LF = Low Frequency

MF = Medium Frequency

HF = High Frequency

VHF = Very High Frequency

UHF = Ultra High Frequency

SHF = Super High Frequency

EHF = Extra High Frequency

UV = Ultraviolet Light

Frequency and wave length:

$$\lambda = c/f$$

wave length λ , speed of light $c \cong 3 \times 10^8 \text{m/s}$, frequency f

Why Not Send Digital Signal in Wireless Communications?

voice



Transmitter

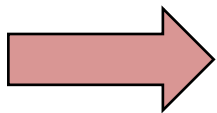


20-20KHz

Antenna:
size \sim wavelength

At 3 KHz,

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{3 \times 10^3} = 100km$$

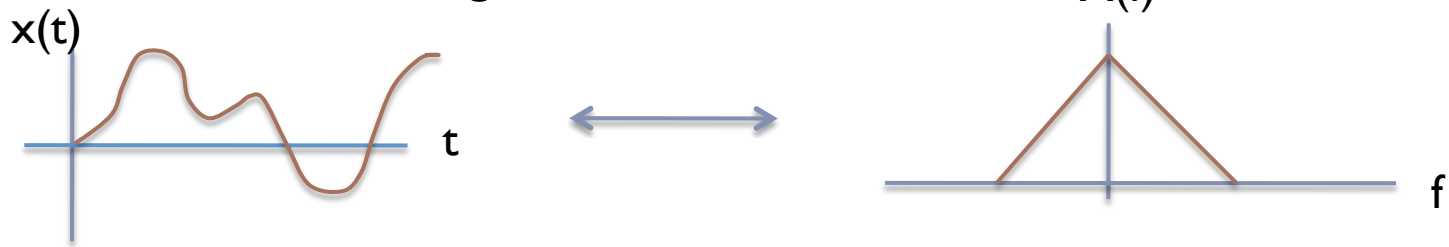


Antenna too large!
Use modulation to transfer to
higher frequency

Basic Concepts of Modulation

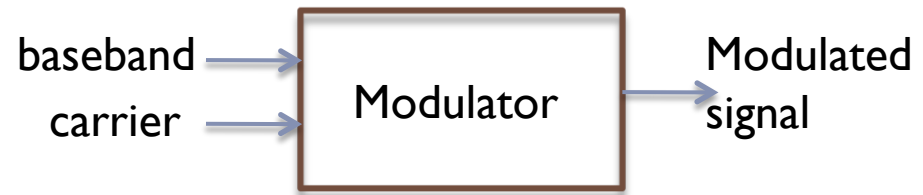
□ The information source

- Typically a low frequency signal
- Referred to as baseband signal



□ Carrier

- A higher frequency sinusoid
- Example $\cos(2\pi 10000t)$



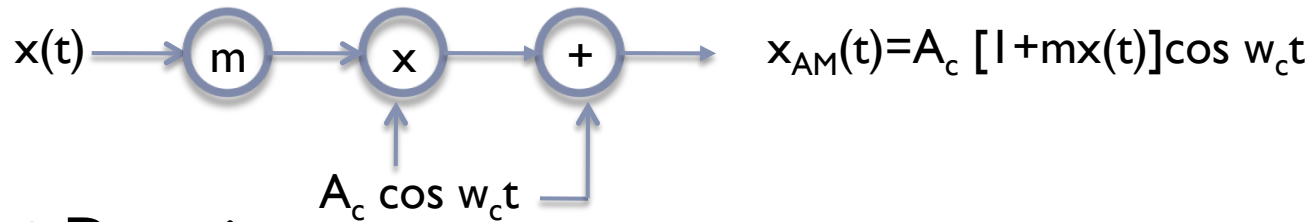
□ Modulated signal

- Some parameter of the carrier (amplitude, frequency, phase) is varied in accordance with the baseband signal

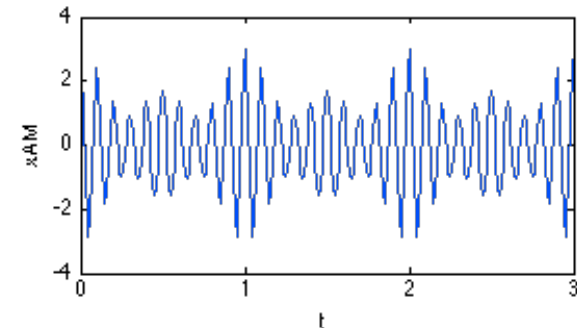
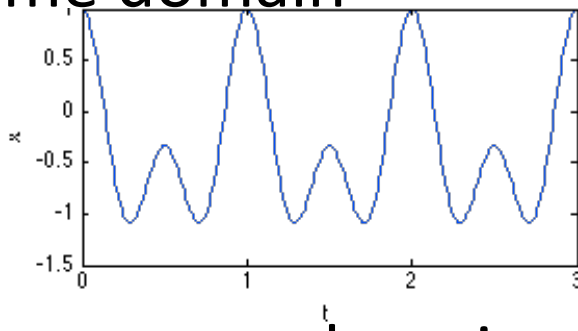
- Analog modulation
 - Amplitude modulation (AM)
 - Frequency modulation (FM)
 - Double and signal sideband: DSB, SSB
- Digital modulation
 - Amplitude shift keying (ASK)
 - Frequency shift keying: FSK
 - Phase shift keying: BPSK, QPSK, MSK
 - Quadrature amplitude modulation (QAM)

Example: Amplitude Modulation (AM)

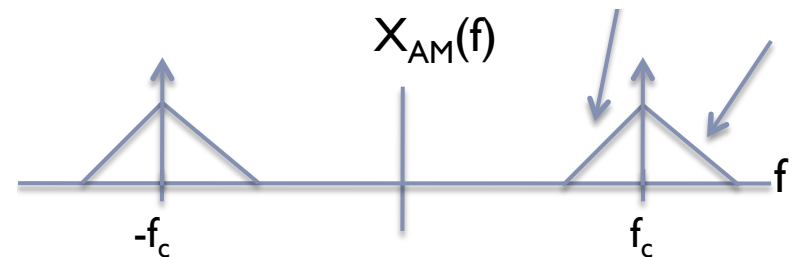
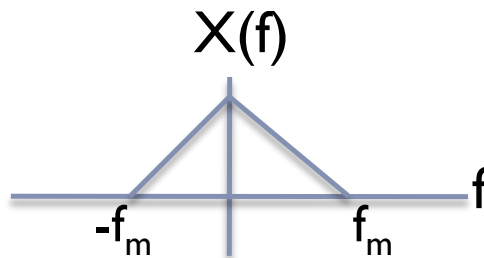
- Block diagram



- Time domain



- Frequency domain



- Decibel (dB). Ratio of two powers

$$\text{Ratio of } P_1 \text{ to } P_2 \text{ in dB} = 10 \log_{10} \left(\frac{P_1}{P_2} \right)$$

- dBm. The reference power is in mW
- SNR. Signal-to-Noise Ratio. Power, expressed in dB
- Attenuation. Power loss (dB)
- CDMA. Code Division Multiple Access
- Simplex communication. One direction at a time
- Duplex communication . Transmit and receive simultaneously
- FCC. Federal Communications Commission
- Antenna gain. How much more power the antenna received compared to reference (half wave). Expressed in dB
- MAC. Medium/Media Access Control

- Circuit Switched. Dedicated (virtual) link between parties. Connection held even when no data transmitted.
- Packet Data. Split information into packets and route independently through network. Use of spectrum only when data are transmitted.
- Spread Spectrum. A wideband modulation which imparts noise-like characteristics to an RF signal.
- Frequency-hopping and Direct Sequence Examples of Spread Spectrum
- TDMA. Time-Division Multiple Access
- FDMA. Frequency Division Multiplex Access

BER and Effective Channel Capacity

- Analog vs. Digital links
- BER – Bit Error Rate increases as SNR decreases
 - Error detection and correction mechanisms
 - Repeated transmission
 - Reduce channel capacity

Radio Propagation Mechanisms

- Free Space
- Reflection
 - Wave impinges on large (compared to wavelength) objects.
- Diffraction
 - Waves bends around obstacle (no LOS)
- Scattering
 - Objects much smaller than wavelength

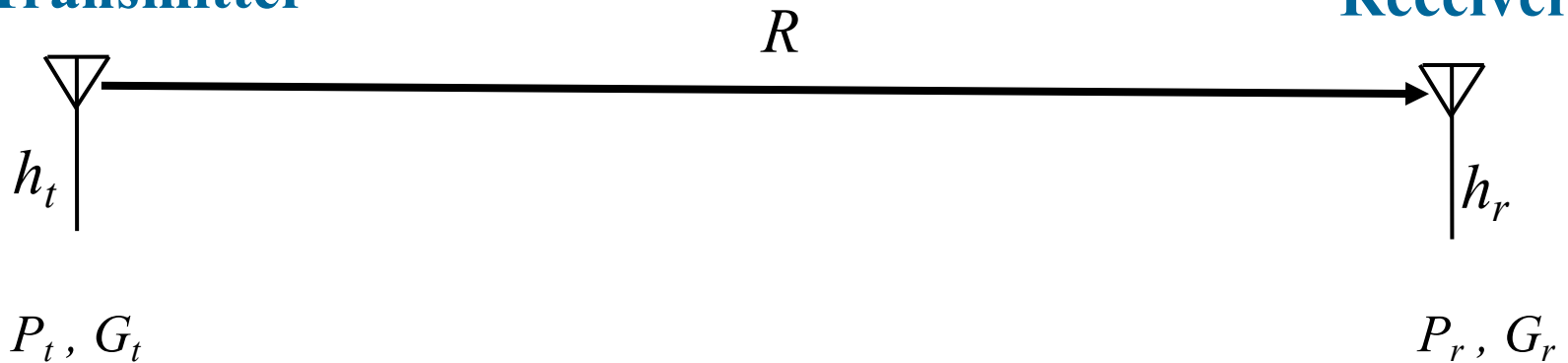
- Simple (but useful) models exist for
 - Free Space
 - Common geometries (flat, curved earth, wall)
- Radio propagation in many real environments is complex
 - Multipath propagation
 - Shadowing
 - Attenuation
- Environment changes => fluctuations in received power

Radio Propagation

- Free space model

Transmitter

Receiver



$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$

Free-Space Isotropic Signal Propagation

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

- P_r : received power
- P_t : transmitted power
- G_r, G_t : receiver and transmitter antenna gain
- λ ($=c/f$): wave length

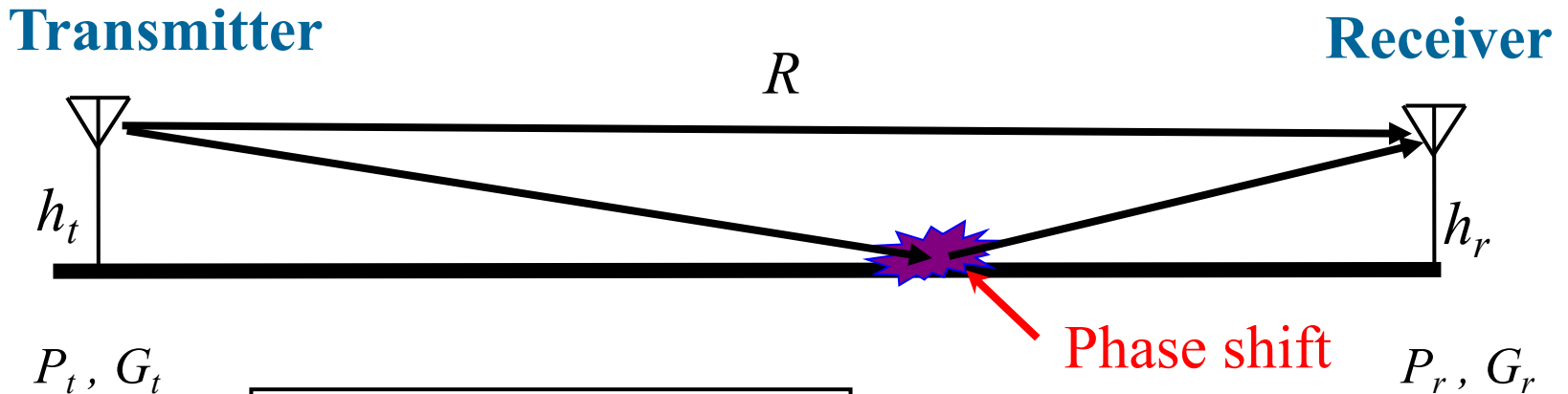
- In free space, receiving power proportional to $1/d^2$ (d = distance between transmitter and receiver)
- Suppose transmitted signal is x , received signal $y = h x$, where h is proportional to $1/d^2$
- Loss depends on the frequency: Higher loss with higher frequency
- Loss increase quickly with distance (d^2)

Sometime we write path loss in log scale:

$$L_p = 10 \log(P_t) - 10 \log(P_r)$$

Radio Propagation

- Two-beam/ray ground *reflection* model, large R

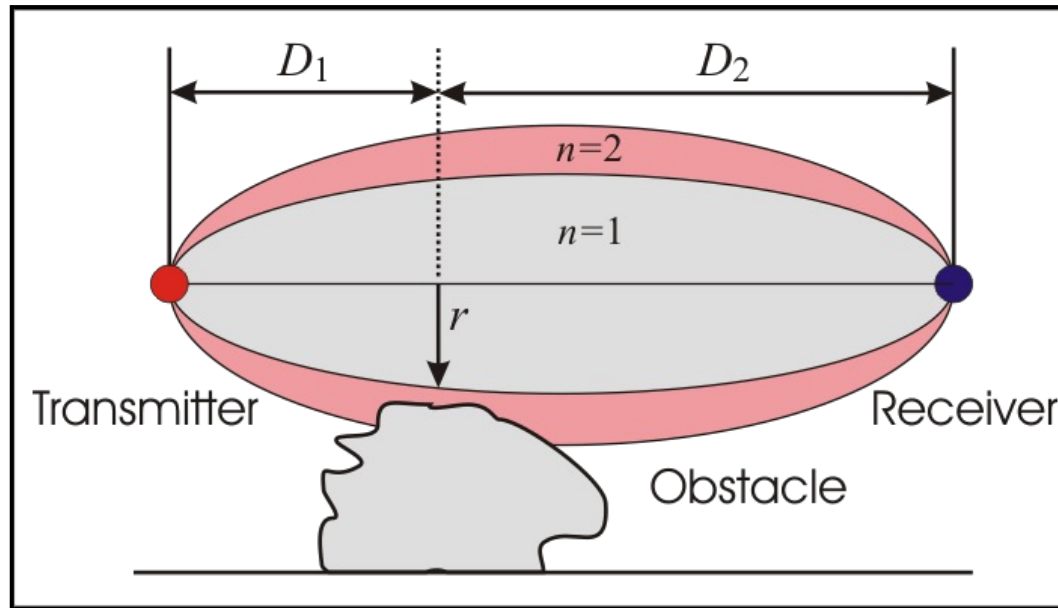


$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{R^4}$$

- The “breakpoint” distance R at which the model changes from $1/R^2$ to $1/R^4$ is $\approx 4\pi h_t h_r / \lambda$

Fresnel Zone and LOS

- Diffraction



$$F_n = \sqrt{\frac{n\lambda D_1 D_2}{D_1 + D_2}}$$

Consistent Units

60% rule-of-thumb

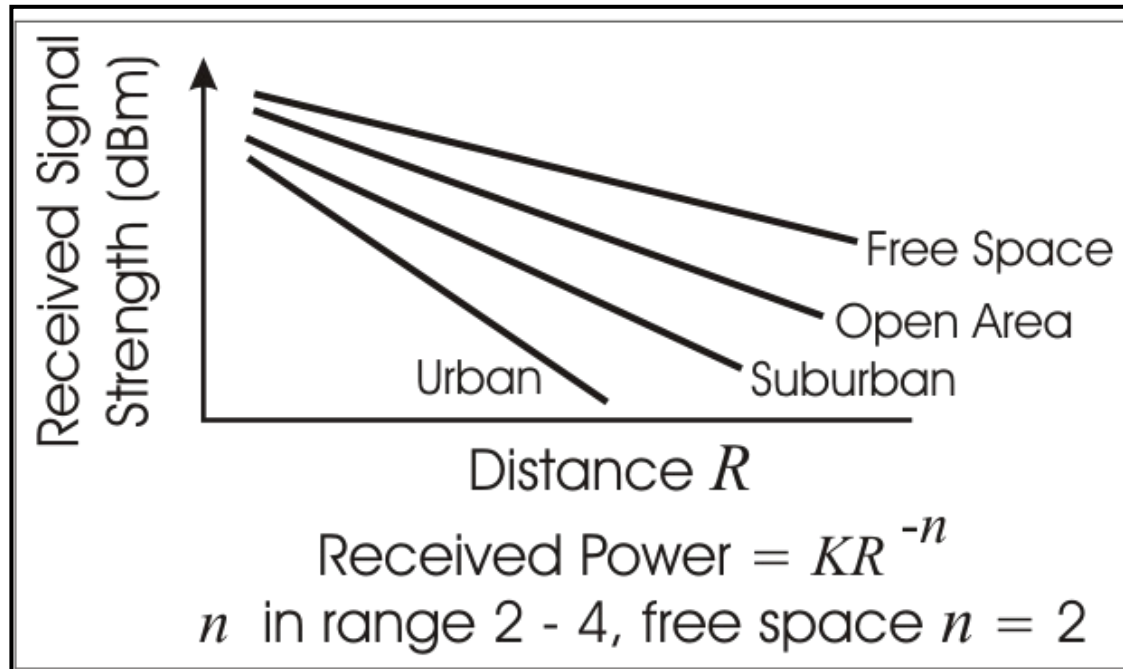
Example

- A 1-km 2.4 GHz link has two antennas that are 2 m above the ground. Do we have LOS?

$$\begin{aligned} F_n &= \sqrt{\frac{n\lambda D_1 D_2}{D_1 + D_2}} \\ &= \sqrt{\frac{1 \times 0.125 \times 500 \times 500}{500 + 500}} \\ &= 5.59 \text{ m} \end{aligned}$$

60% of this is 3.3 m, so we don't have clearance.
Answer is "NO"

- Why need model?
- Hybrid models (physics and empirical)



This graph does not reflect temporal changes

- Signal decays much faster
- Coverage contained by walls (waveguides)
- Very complicated dynamic (people move) attenuation and multipath

$$\text{Path Loss} = \text{Unit Loss} + 10n\log(R) = kF + lW$$

- Unit Loss = power loss @ 1 m (say 30 dB)
- n = power delay index
- R
- k = # of floors, F = # of floors
- l = # of walls, W = loss per wall

Indoor Propagation

$$\text{Path Loss} = \text{Unit Loss} + 10n\log(R) = kF + lW$$

Building	Freq (MHz)	n	Sigma (dB)
Retail Store	914	2.2	8.7
Grocery Store	914	1.8	5.2
Office	1500	3.0	7.0
Textile Factory	1300	2.0	3.0
Home	900	3.0	7.0

- dB (Decibel)
 - Express relative differences in signal strength
 - $\text{dB} = 10 \log_{10} (p1/p2)$
 - $\text{dB} = 0$: no attenuation. $p1 = p2$
 - 1 dB attenuation: 0.79 of the input power survives:
 $10 * \log_{10}(1/0.79)$
 - 3 dB attenuation: 0.5 of the input power survives:
 $10 * \log_{10}(1/0.5)$
 - 10 dB attenuation: 0.1 of the input power survives:
 $10 * \log_{10}(1/0.1)$
- <http://en.wikipedia.org/wiki/Decibel>
- <http://www.sss-mag.com/db.html>

- Attenuation = $10 \log_{10} (P_{in}/P_{out})$ decibel
- Attenuation = $20 \log_{10} (V_{in}/V_{out})$ decibel

- **Example 1: $P_{in} = 10 \text{ mW}$, $P_{out} = 5 \text{ mW}$**
 - Attenuation = $10 \log_{10} (10/5) = 10 \log_{10} 2 = 3 \text{ dB}$

- **Example 2: $P_{in} = 100 \text{ mW}$, $P_{out} = 1 \text{ mW}$**
 - Attenuation = $10 \log_{10} (100/1) = 10 \log_{10} 100 = 20 \text{ dB}$

Shadowing

- Signal strength loss after passing through obstacles
- Some sample numbers

Signal attenuation of 2.4 GHz through	dB
Window in brick wall	2
Metal frame, glass wall into building	6
Office wall	6
Metal door in office wall	6
Cinder wall	4
Metal door in brick wall	12.4
Brick wall next to metal door	3

i.e. reduces to $\frac{1}{4}$ of signal
 $10 \log(1/4) = -6.02$

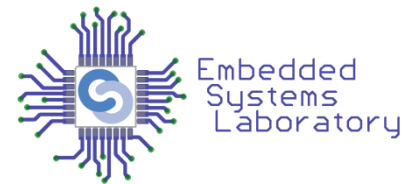
- The referenced quantity is one milliwatt(mW)
- $\text{dBm} = 10 \log_{10} (p1/1\text{mW})$
- 0 dBm: p1 is 1 mW
- -80 dBm: p1 is $10^{-11}\text{W} = 10\text{pW}$

- <http://en.wikipedia.org/wiki/DBm>

Received Signal Strength Indicator (RSSI)

- The strength of a received RF signal
- Many current platforms provide hardware indicator
 - CC2420, the radio chip of MicaZ and TelosB, provides RSSI indicator and LQI (Link Quality Indicator)

LQI (Link Quality Indicator)



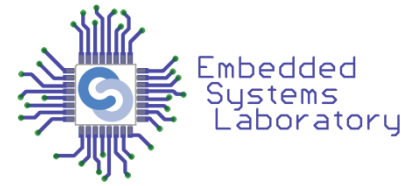
- A measure of chip error rate
- Error rate
 - The rate at which errors occur
 - Error
 - 0 is transmitted while 1 is received
 - 1 is transmitted while 0 is received

- The measure of the signal created from the sum of all the noise sources and unwanted signals

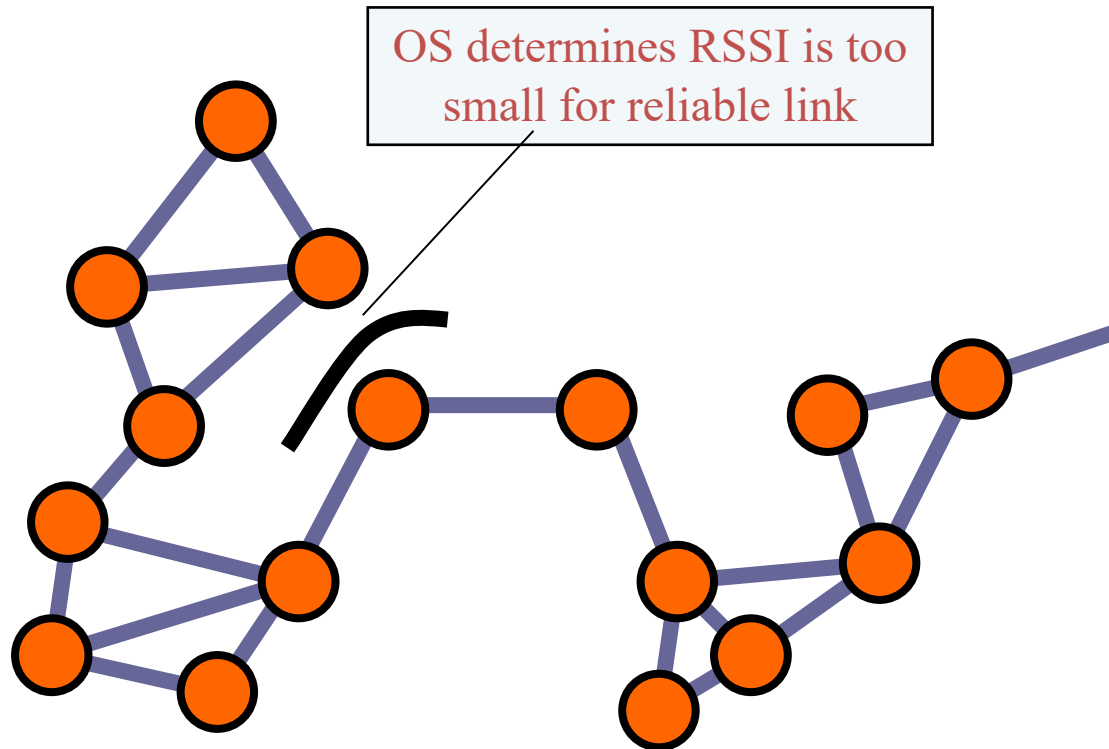
Signal Noise Ratio (SNR)

- The ratio of the power in a signal to the power contained in the noise that is present
- Typically measured at the receiver
- Take CC2420 as the example:
 - Noise Floor: the RSSI register from the CC2420 chip when not receiving a packet
 - For example -98dBm
 - The strength field from the received packet: RSSI of the received packet

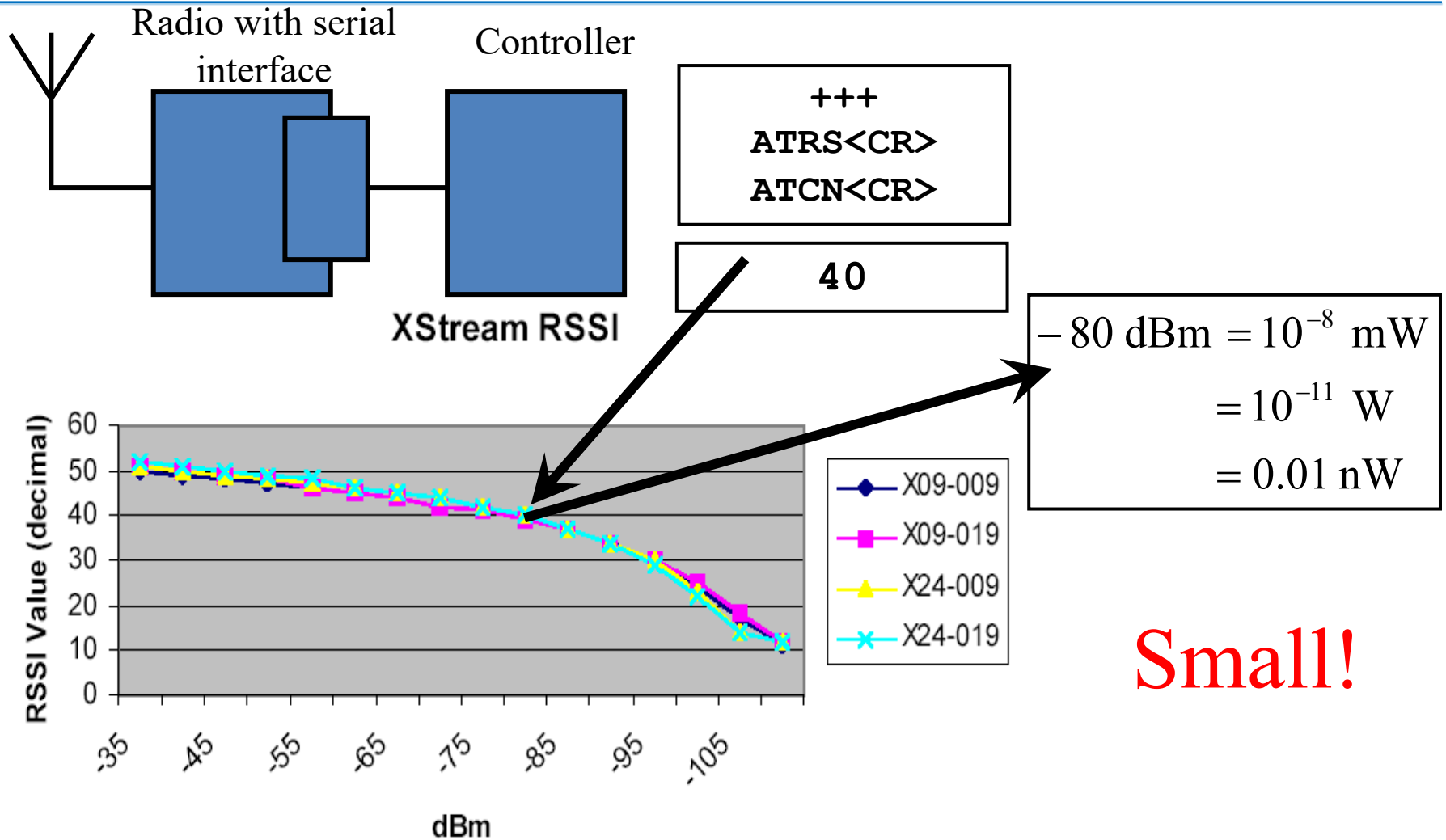
Received Signal Strength Indicator (RSSI)



- Measure of received signal strength of radio
- Indicator of link quality
- Radio can be interrogated for RSSI
- On-board Software use RSSI
- Typically a number 23, 19, etc.
- Consult manufacturer for mapping to power level dBm



RSSI



What is an Antenna

- Conductor that carries an electrical signal and radiates an RF signal.
 - The RF signal “is a copy of” the electrical signal in the conductor
- Also the inverse process: RF signals are “captured” by the antenna and create an electrical signal in the conductor.
 - This signal can be interpreted (i.e. decoded)
- Efficiency of the antenna depends on its size, relative to the wavelength of the signal.
 - e.g. half a wavelength



Types of Antennas

- Antenna is a point source that radiates with the same power level in all directions – omni-directional or isotropic
 - An antenna that transmits equally in all directions (isotropic)
 - Shape of the conductor tends to create a specific radiation pattern
- Common shape is a straight conductor
- Shaper antennas can be used to direct the energy in a certain direction
 - Well-know case: a parabolic antenna



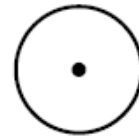
A parabolic antenna



Omni-Directional



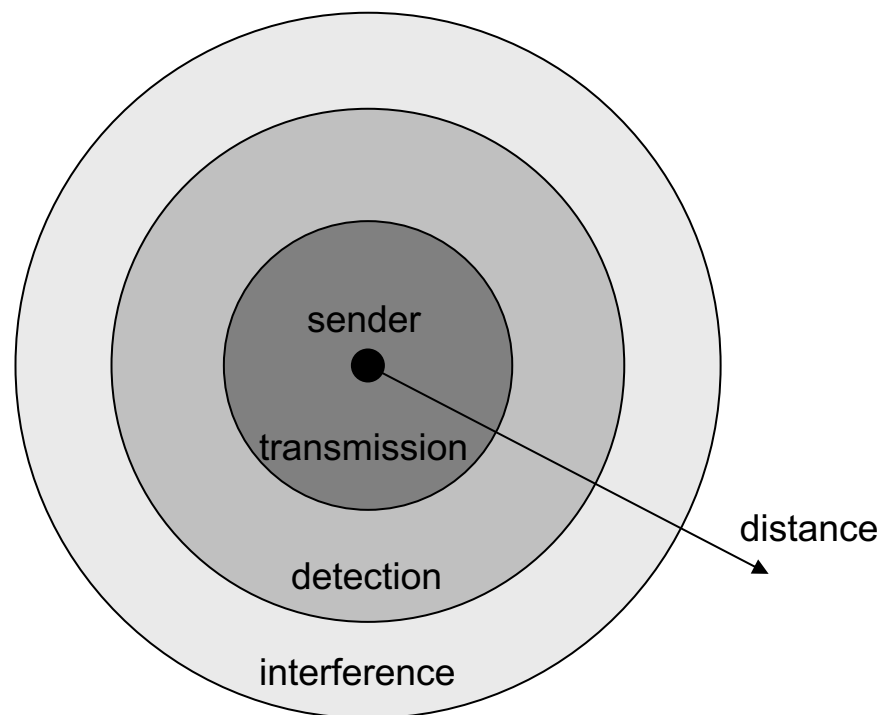
Directional



Isotropic

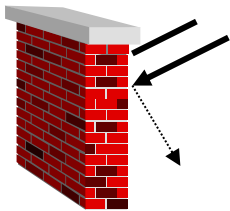
Signal Propagation Ranges

- Transmission range
 - communication possible
 - low error rate
- Detection range
 - detection of the signal possible
 - no communication possible
- Interference range
 - signal may not be detected
 - signal adds to the background noise

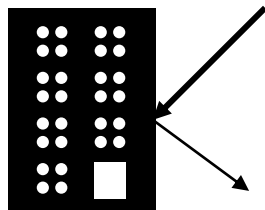


Signal propagation

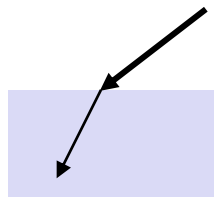
- Propagation in free space always like light (straight line)
- Receiving power proportional to $1/d^2$ in vacuum – much more in real environments
(d = distance between sender and receiver)
- Receiving power additionally influenced by fading (frequency dependent)
- Shadowing
- Reflection at large obstacles
- Refraction depending on the density of a medium
- Scattering at small obstacles
- Diffraction at edges



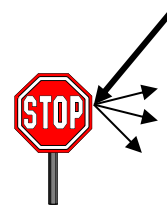
shadowing



reflection



refraction



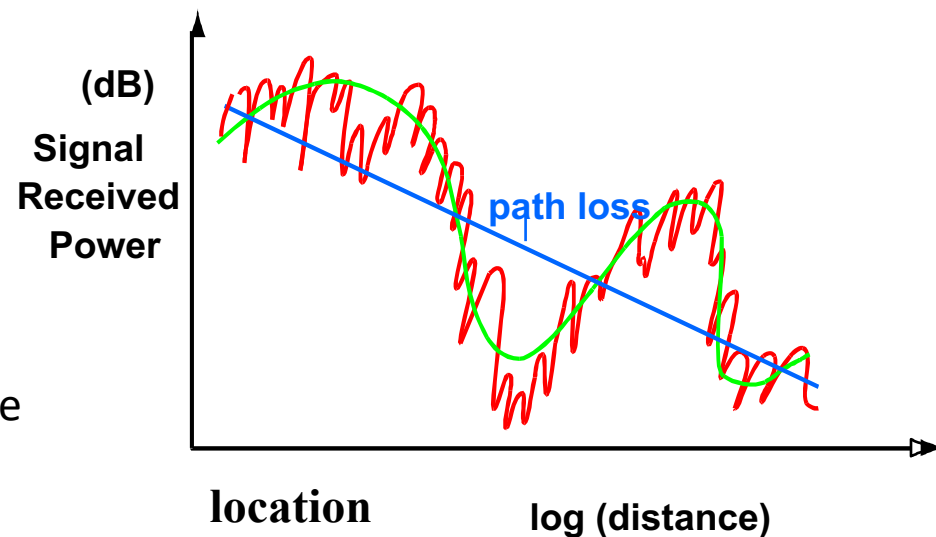
scattering



diffraction

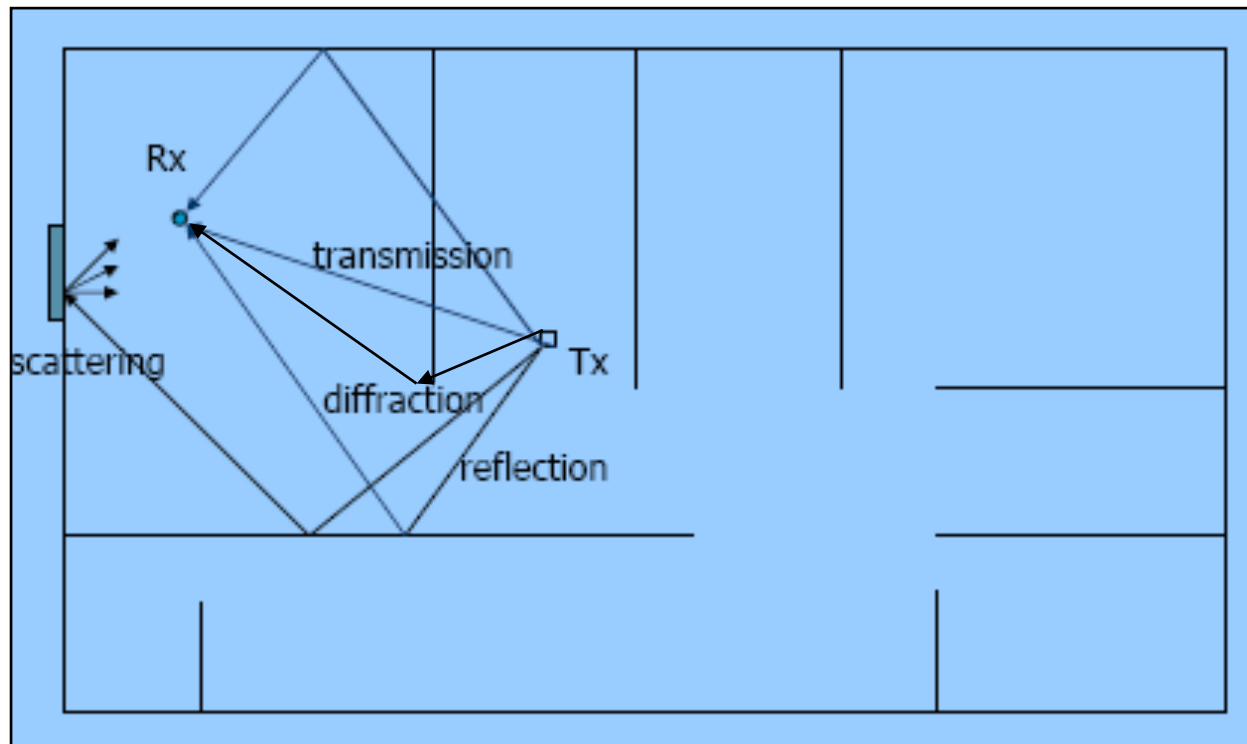
Propagation Degrades RF Signal

- Attenuation in free space
 - Signal gets weaker as it travels over longer distance
 - Free space loss- Signal spreads out
 - Refraction and absorption in the atmosphere
- Obstacle can weaken signal through absorption or reflection.
 - Part of the signal is re-directed.
- Multiple path effects
 - Multiple copies of the signal interfere with each other
- Mobility
 - Moving receiver causes another form of self interference
 - Node moves $\frac{1}{2}$ wavelength cause big change in signal strength



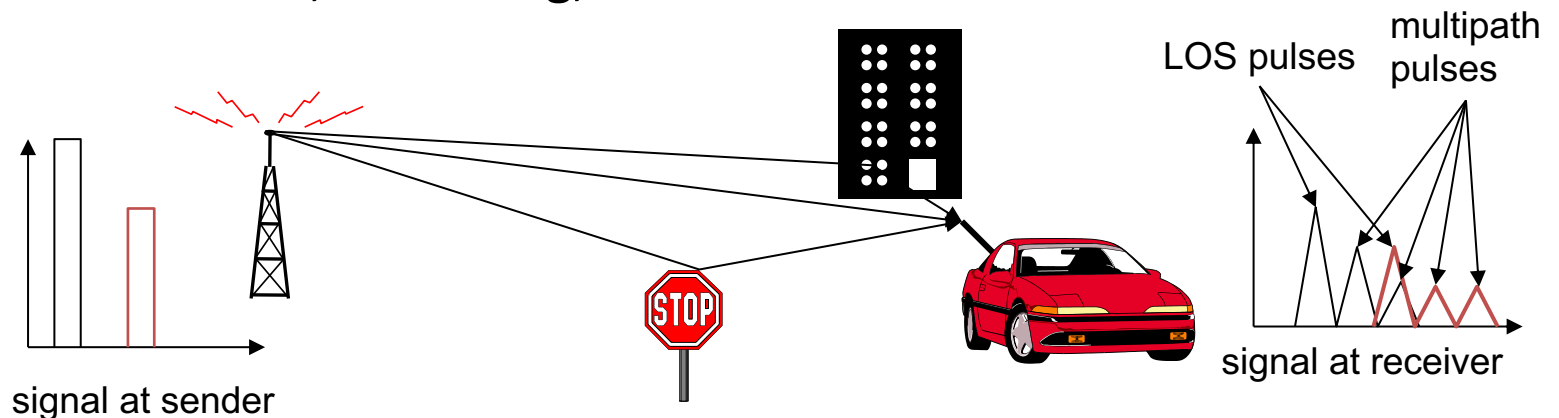
Multipath

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



Multipath propagation

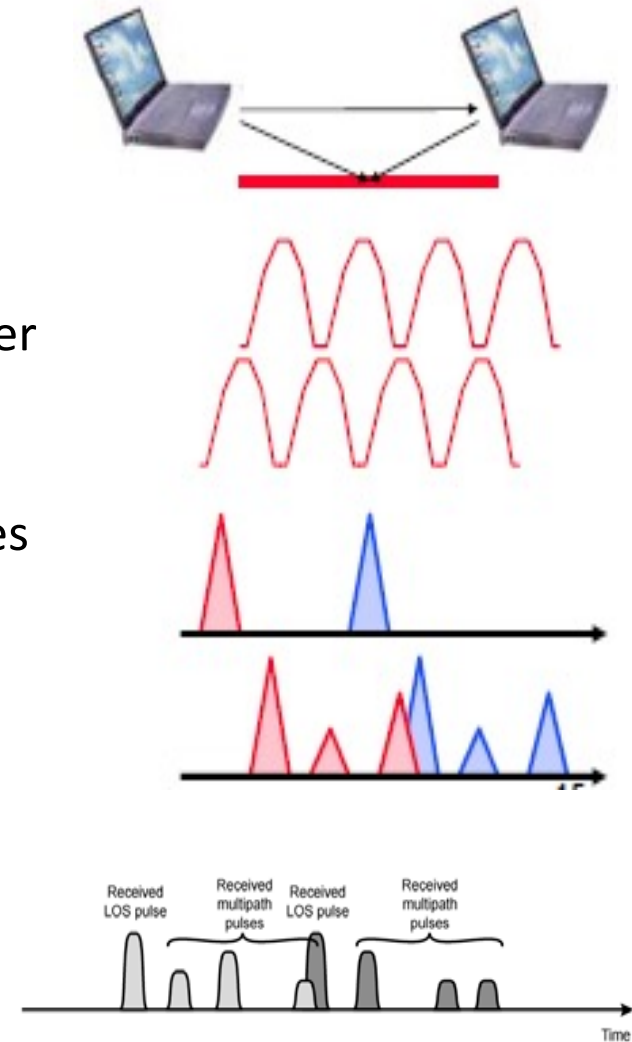
- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



- Time dispersion: signal is dispersed over time
 - interference with “neighbor” symbols, Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted
 - distorted signal depending on the phases of the different parts

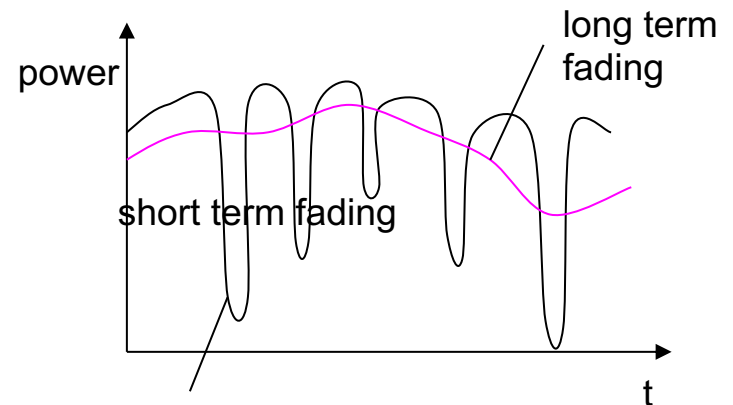
Multipath Effects

- Receiver receives multiple copies of the signal, each following a different path
- Copies can either strengthen or weaken each other
 - Depends on whether they are in or out of phase
- Small changes in location can result in big changes in signal strength
- Larger difference in path length can cause intersymbol interference (ISI)
 - More significant for higher bit rates (shorter bit times)



Effects of mobility

- **Channel characteristics change over time and location**
 - signal paths change
 - different delay variations of different signal parts
 - different phases of signal parts
 - quick changes in the power received (short term fading)
- **Fading: time variation of the received signal strength caused by changes in the transmission medium or paths.**
 - Rain, moving objects, moving sender/receiver, ...
- **Additional changes in**
 - distance to sender
 - obstacles further away
 - slow changes in the average power received (long term fading)



Radio Irregularity

- Spherical radio range is not valid
- When an electromagnetic signal propagate, the signal may be
 - Diffracted
 - Reflected
 - Scattered
- Radio irregularity and variations in packet loss in different directions

- Anisotropic Signal Strength: Different path losses in different directions

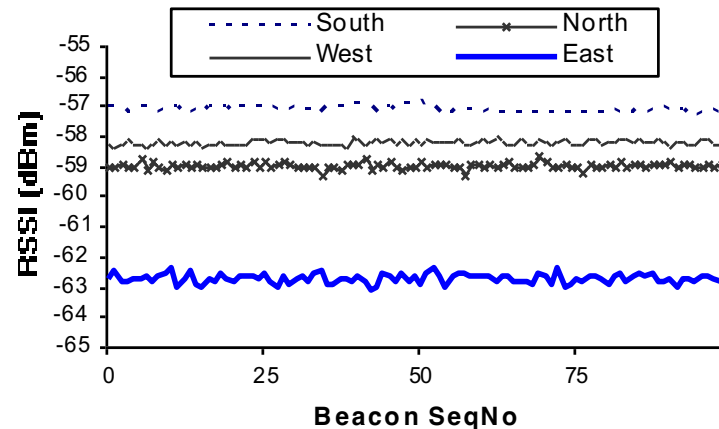


Figure 1: Signal Strength over Time in Four Directions

- Anisotropic Packet Loss Ratio: Packet Reception Ratio (PRR) varies in different directions

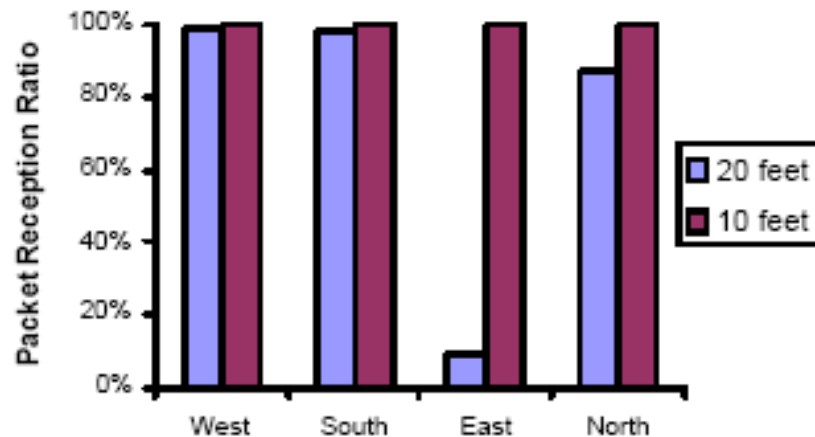


Fig. 3. Anisotropic Packet Reception

Radio Signal Property

- Anisotropic Radio Range: The communication range of a mote is not uniform

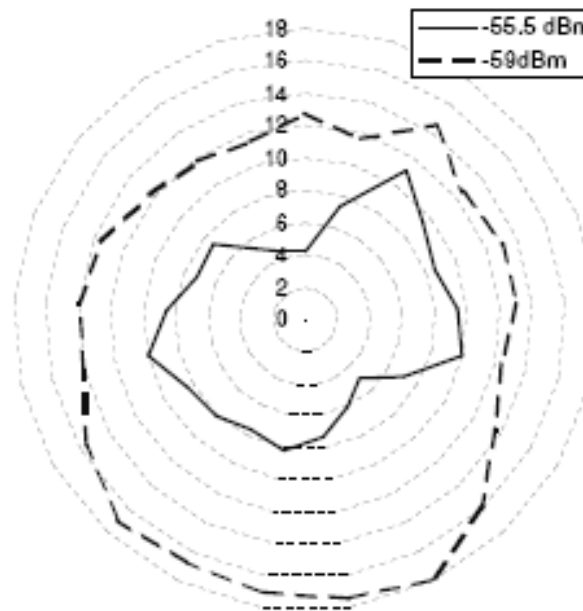


Fig. 4. Anisotropic Range

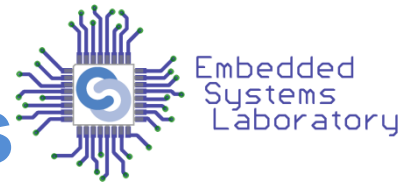
Radio and Medium Access Control

Radio Properties

Medium Access Control (MAC)

- A radio channel cannot be accessed simultaneously by two or more nodes that are in a radio interference range
 - Nodes may transmit at the same time on the same channel
- Medium Access Control
 - On top of Physical layer
 - Control access to the radio channel

MAC Protocol Requirements

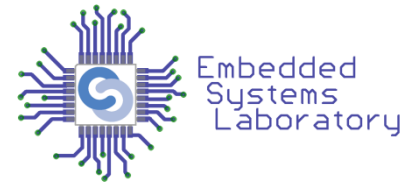


- Energy Efficiency
 - Sources of energy waste
 - Collision, Idle Listening, Overhearing, and Control Packet Overhead
- Effective collision avoidance
 - When and how the node can access the medium and send its data
- Efficient channel utilization at low and high data rates
 - Reflects how well the entire bandwidth of the channel is utilized in communications
- Tolerant to changing RF/Networking conditions
- Scalable to large number of nodes

Ref: [MAC_2] Section I, II

Two Basic Classes of MAC Protocol

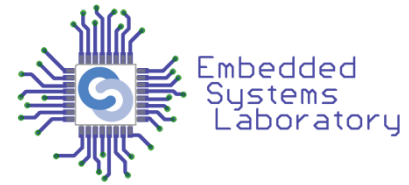
– Slotted and Sampling



- Slotted Protocols
 - Nodes divides time into slots
 - Radio can be in receive mode, transmit mode, or powered off mode
 - Communication is synchronized
 - Data transfers occur in “slots”
 - TDMA, IEEE 802.15.4, S-MAC, T-MAC, etc.
- Also Ref: J. Polastre Dissertation – Section 2.4:
<http://www.polastre.com/papers/polastre-thesis-final.pdf>

Two Basic Classes of MAC Protocol

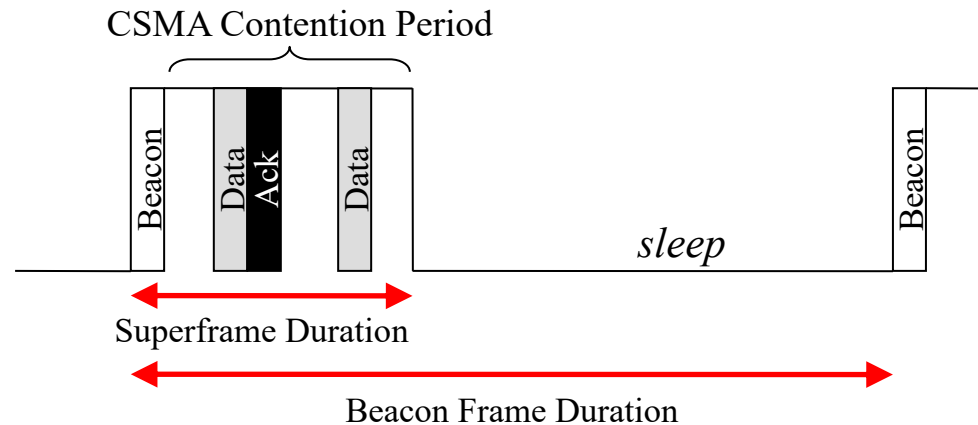
– Slotted and Sampling



- Sampling Protocols
 - Nodes periodically wake up, and only start receiving data if they detect channel activity
 - Communication is unsynchronized
 - Data transfer wakes up receiver
 - Must send long, expensive messages to wake up neighbors
 - B-MAC, Preamble sampling, LPL, etc.

Slotted Protocol Example: 802.15.4

- Each node beacons on its own schedule
- Other nodes synchronize with the received Beacons



IEEE 802.15.4 Superframe

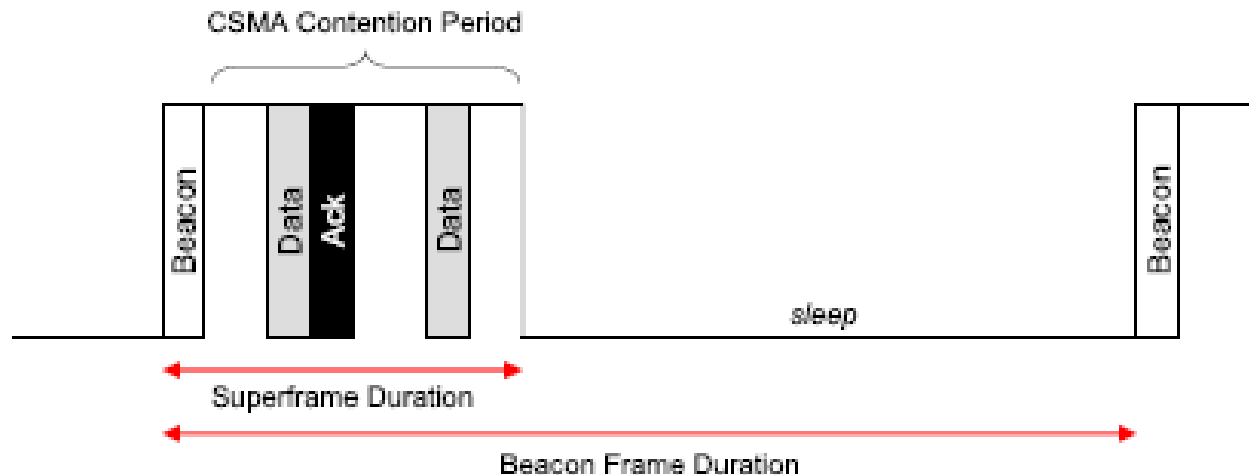
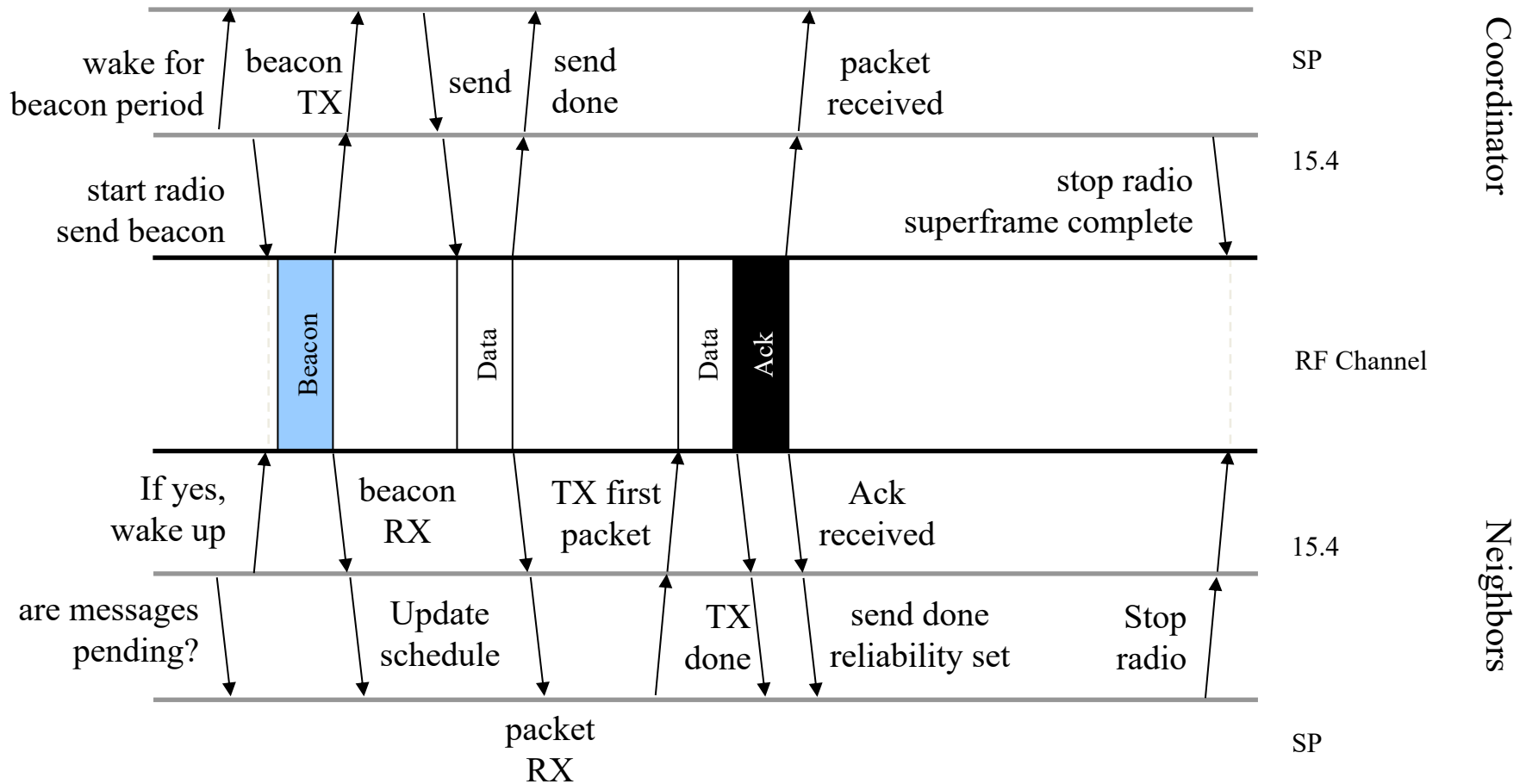
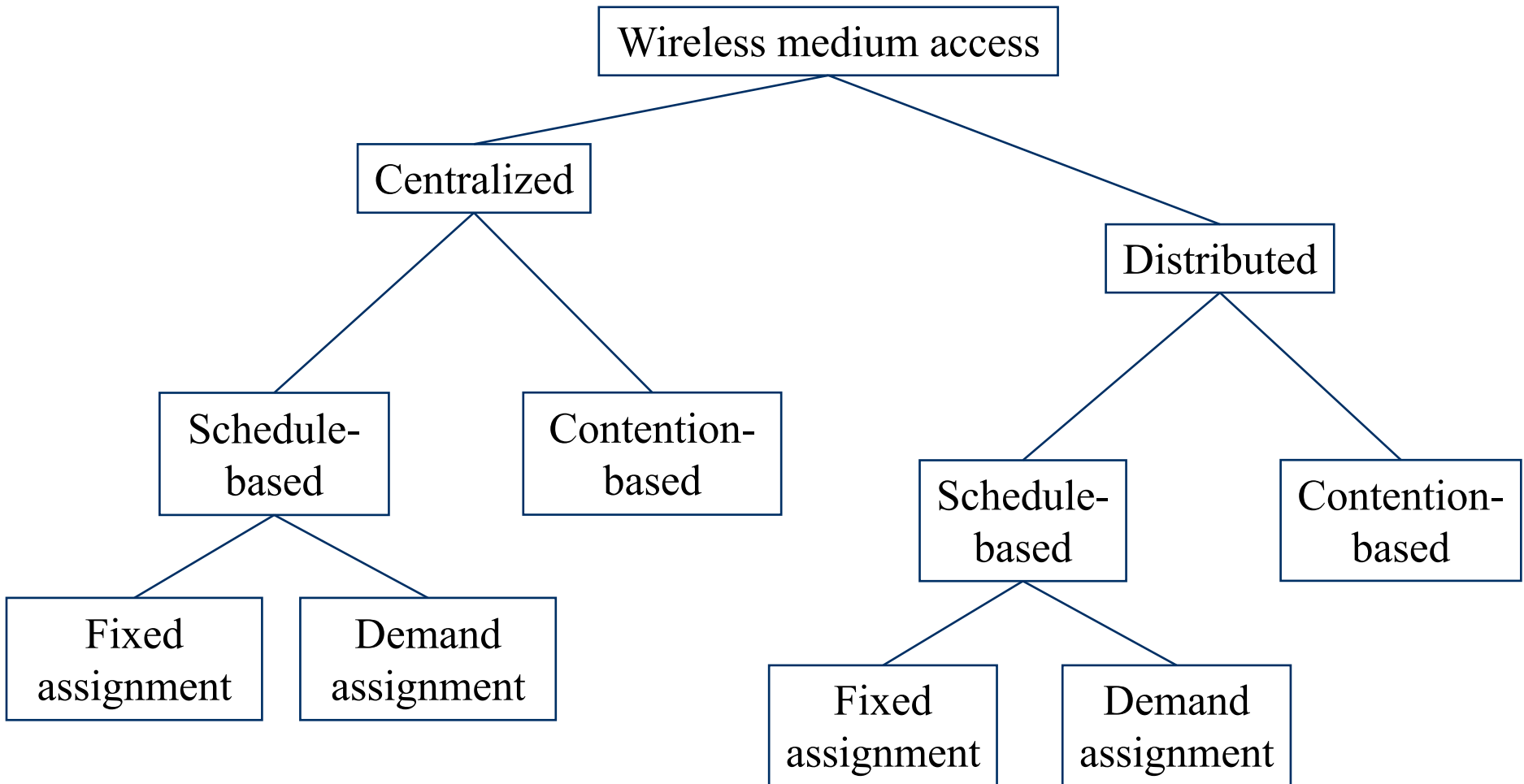


Figure 6: An IEEE 802.15.4 superframe consists of a MAC beacon message followed by a CSMA contention period for other traffic. The duty cycle is bounded by superframe to beacon frame ratio.

Using 802.15.4



Main MAC Protocols



- TDMA divides the channel into N time slots

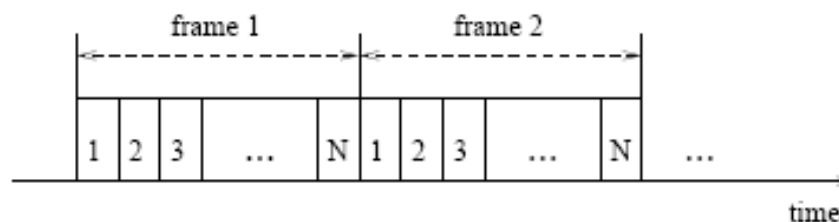


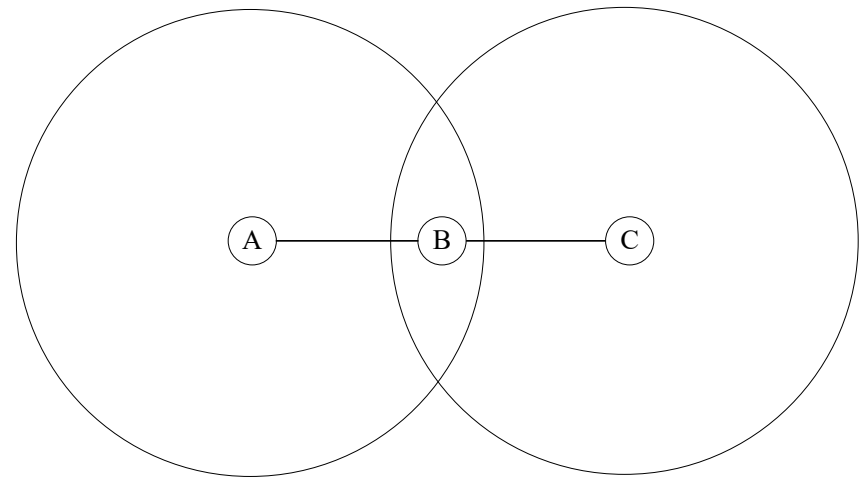
Fig. 1. TDMA divides the channel into N time slots.

- A common channel is shared by all nodes and it is allocated on-demand
- A contention mechanism is employed
- Advantages over scheduled protocols
 - Scale more easily
 - More flexible as topologies change
 - No requirement to form communication clusters
 - Do not require fine-grained time synchronization
- Disadvantage
 - Inefficient usage of energy
 - Node listen at all times
 - Collisions and contention for the media

- Listening before transmitting
- Listening (Carrier Sense)
 - To detect if the medium is busy
- Hidden Terminal Problem

Hidden Terminal Problem

- Node A and C cannot hear each other
- Transmission by node A and C can collide at node B
- On collision, both transmissions are lost
- Node A and C are hidden from each other



- CA
 - Collision Avoidance: to address the hidden terminal problem
- Basic mechanism
 - Establish a brief handshake between a sender and a receiver before transmission
 - The transmission between a sender and a receiver follows RTS-CTS-DATA-ACK

- Idea: Have a central station control when a node may access the medium
 - Example: Polling, centralized computation of TDMA schedules
 - Advantage: Simple, quite efficient (e.g., no collisions), burdens the central station
 - Not directly feasible for non-trivial wireless network sizes
 - But: Can be quite useful when network is somehow divided into smaller groups
 - Clusters, in each cluster medium access can be controlled centrally – compare Bluetooth piconets, for example
- ! Usually, distributed medium access is considered

Schedule- vs. Contention-based MACs

- *Schedule-based* MAC
 - A *schedule* exists, regulating which participant may use which resource at which time (TDMA component)
 - Typical resource: frequency band in a given physical space (with a given code, CDMA)
 - Schedule can be *fixed* or computed *on demand*
 - Usually: mixed – difference fixed/on demand is one of time scales
 - Usually, collisions, overhearing, idle listening no issues
 - Needed: time synchronization!

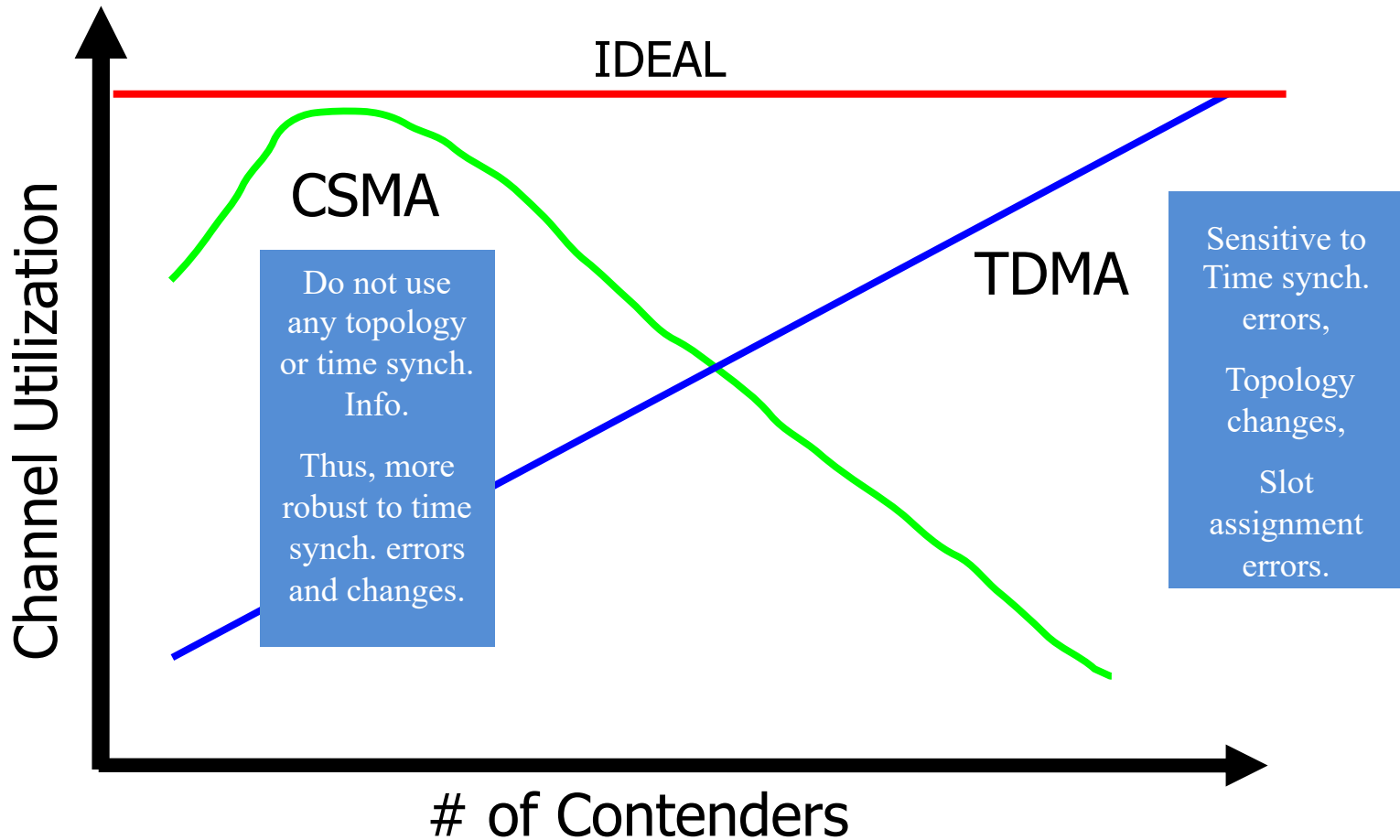
Schedule- vs. Contention-based MACs

- ***Contention-based*** protocols
 - Risk of colliding packets is deliberately taken
 - Hope: coordination overhead can be saved, resulting in overall improved efficiency
 - Mechanisms to handle/reduce probability/impact of collisions required
 - Usually, ***randomization*** used somehow

- CSMA (Carrier Sense Multiple Access)
 - Advantage:
 - No clock synchronization required
 - No global topology information required
 - Disadvantage
 - Hidden terminal problem: serious throughput degradation
 - RTS/CTS can alleviate hidden terminal problem, but incur high overhead

- TDMA (Time-division multiple access)
 - Advantage
 - Solve the hidden terminal problem without extra message overhead
 - Disadvantage
 - It is challenging to find an efficient time schedule
 - Need clock synchronization
 - High energy overhead
 - Handling dynamic topology change is expensive
 - Given low contention, TDMA gives much lower channel utilization and higher delay

Effective Throughput CSMA vs. TDMA



MAC Energy Usage

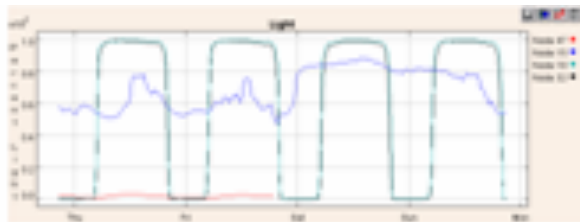
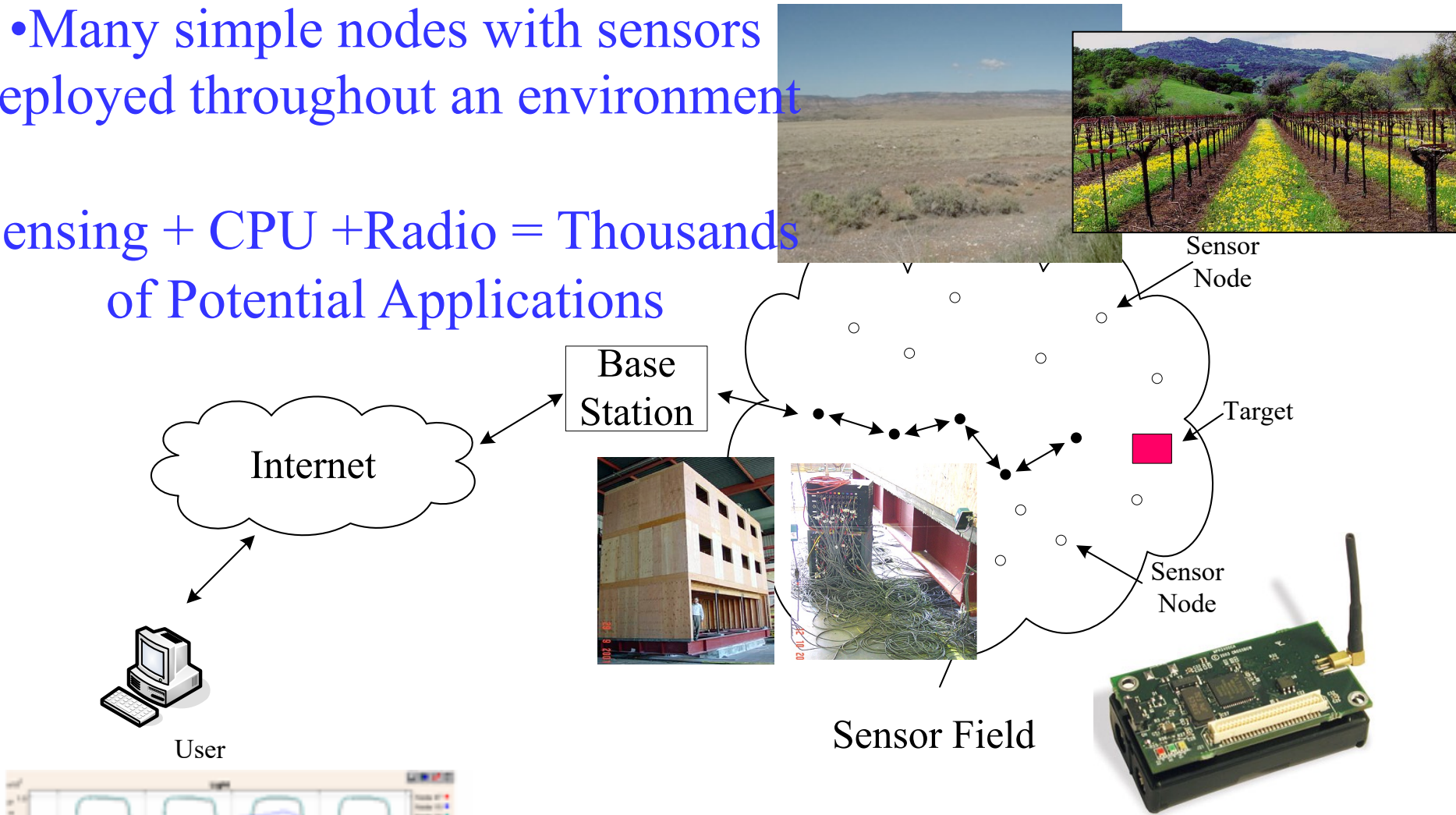
Four important sources of wasted energy in WSN:

- Idle Listening (required for all CSMA protocols)
- Overhearing (since RF is a broadcast medium)
- Collisions (Hidden Terminal Problem)
- Control Overhead (e.g. RTS/CTS or DATA/ACK)

Wireless Sensor Networks (WSNs)

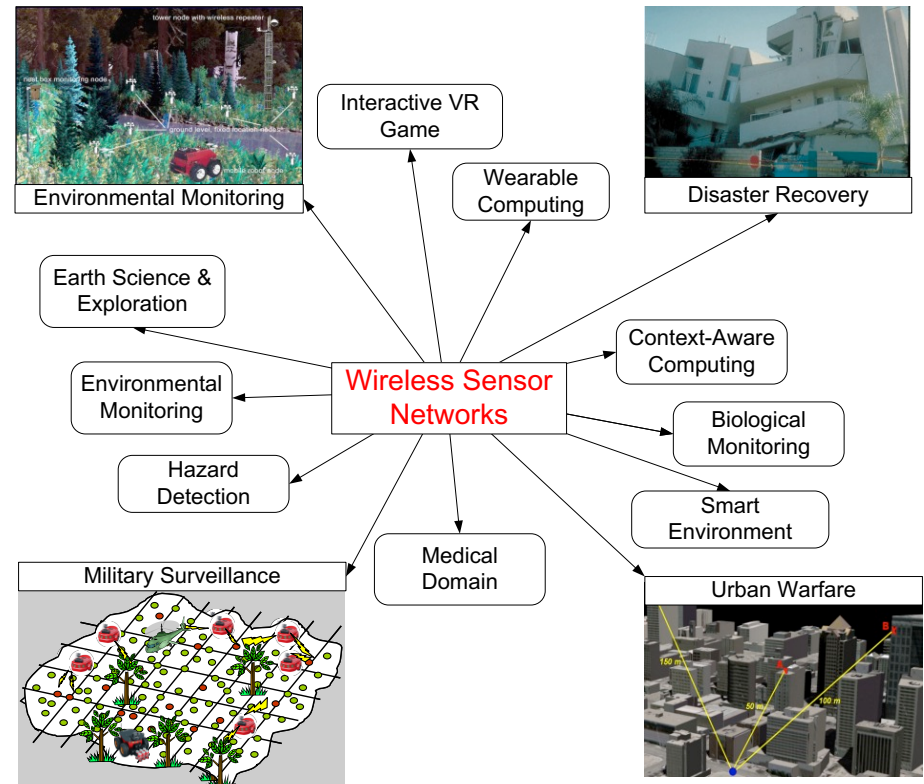
- Many simple nodes with sensors deployed throughout an environment

Sensing + CPU + Radio = Thousands of Potential Applications



WSN Applications

- Indoor/Outdoor Environmental Monitoring
 - Habitat Monitoring
 - Structural Monitoring
 - Precision Agriculture
- Triggered Events
 - Detection/Notification
- Military Applications
 - Battlefield Surveillance
- Health Monitoring



Some Existing Applications

- Create a macroscope
 - Deployed on Redwood Trees
 - Great Duck Island
 - Tracking zebra
 - Monitor volcanic eruptions

Operational Challenges of Wireless Sensor Networks

- Energy Efficiency
- Limited storage and computation
- Low bandwidth and high error rates
- Errors are common
 - Wireless communication
 - Noisy measurements
 - Node failure are expected
- Scalability to a large number of sensor nodes
- Survivability in harsh environments
- Experiments are time- and space-intensive

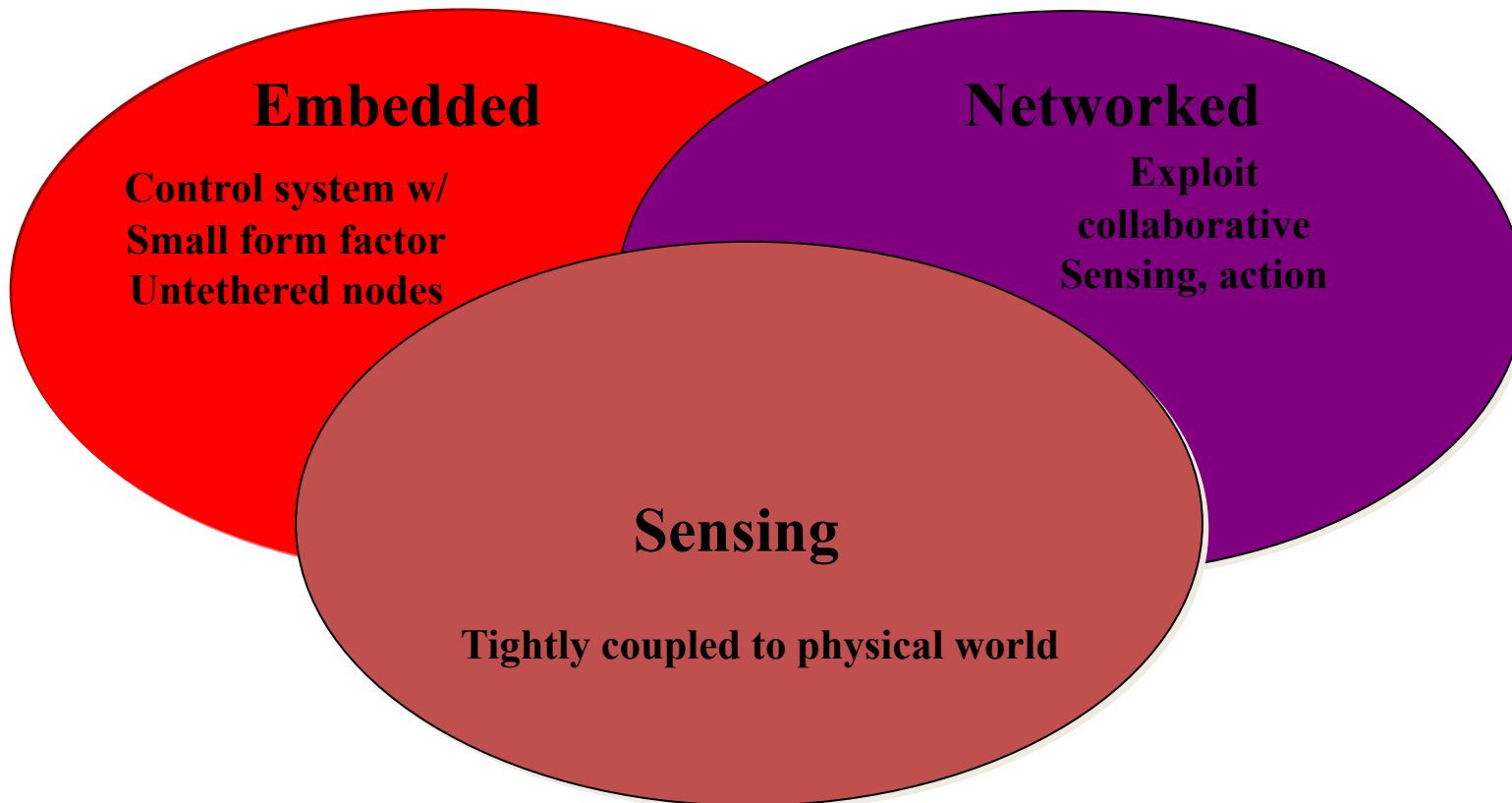
Characteristics of Wireless Sensor Networks

- Limited in
 - Energy
 - Computation
 - Storage
 - Transmission Range
 - Bandwidth
- Characteristics
 - Self-organize
 - Random Deployment
 - Cooperating
 - Local Computation

Enabling Technologies

Embed numerous distributed devices to monitor and interact with physical world

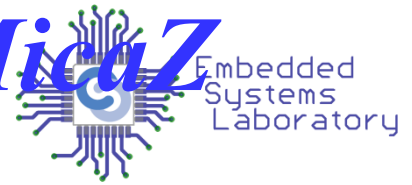
Network devices to coordinate and perform higher-level tasks



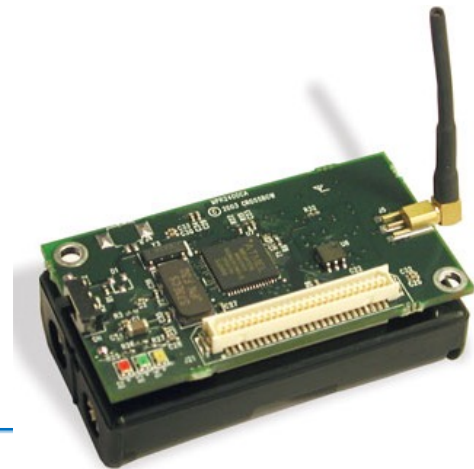
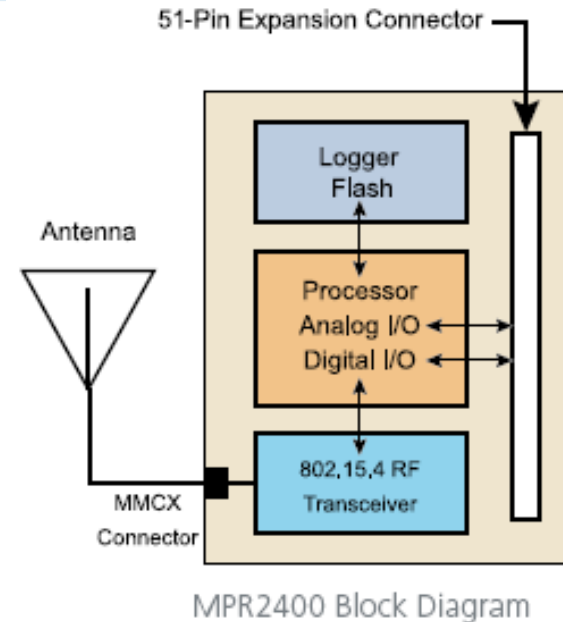
Exploit spatially and temporally dense, in situ, sensing and actuation

- Power, size, and cost constrained
 - Small memory
 - Slow clock cycles of microcontroller

One Example Sensor Node - *Micaz* Mote

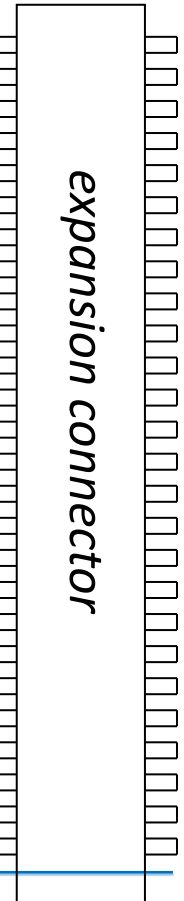


- Developed at UC Berkeley
- Fabricated by Crossbow Inc.
- Integrated Wireless Transceiver
- CPU
 - MPR2400, based on Atmega128L
 - 8MHz
- Memory
 - 4KB of primary memory (SRAM)
 - 128KB of program space (ROM)
 - 512KB Flash Memory
- Transmit Data Rate
 - 250kbps
- Transmission Range
 - Outdoor: 75m – 100m
 - Indoor: 20m - 30m

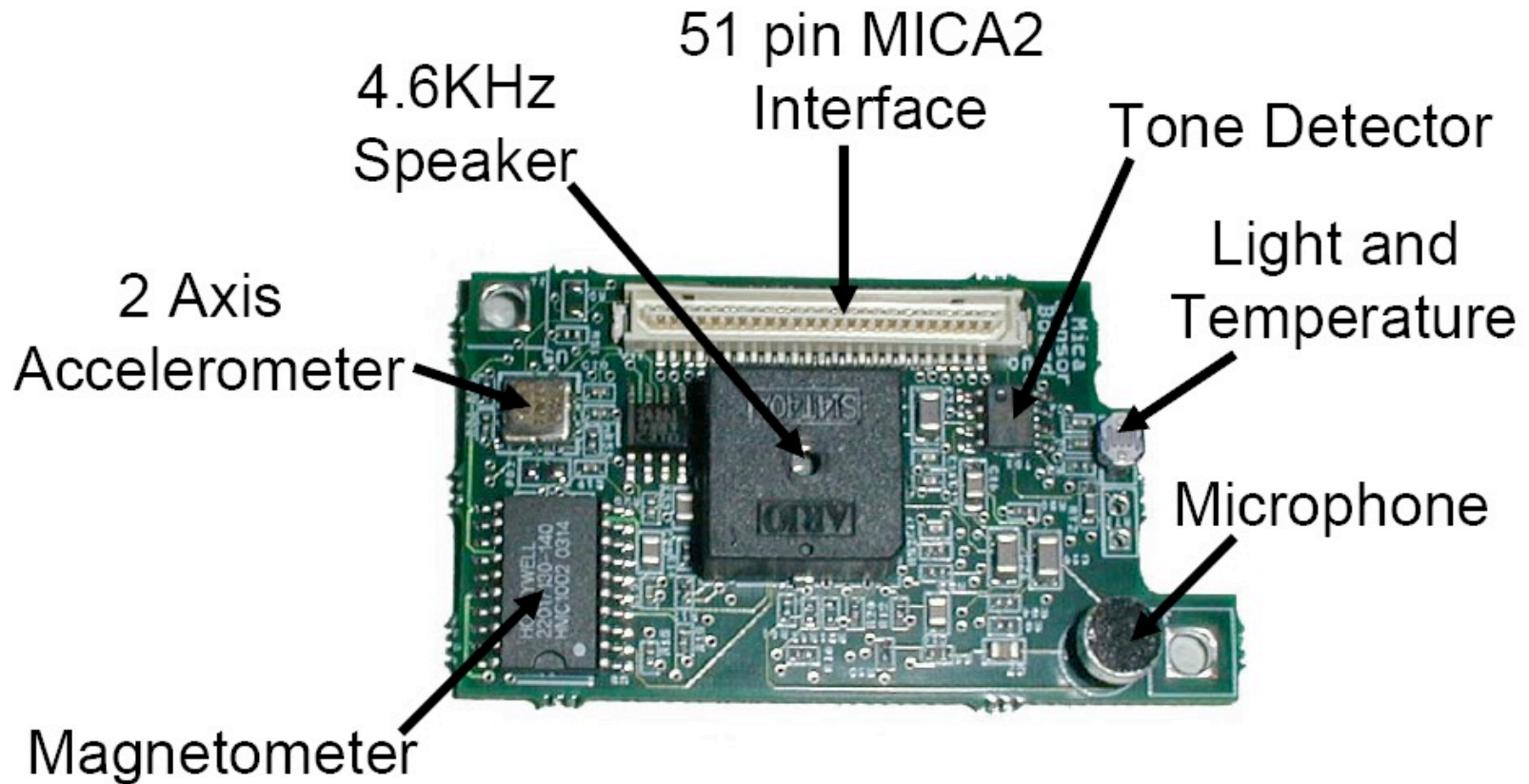


I/O Sub-System

- The I/O subsystem interface consists of a 51-pin expansion connector
 - eight analog lines,
 - eight power control lines,
 - three pulse-width-modulated lines,
 - two analog compare lines,
 - four external interrupt lines,
 - an I2C-bus from Philips Semiconductor,
 - an SPI bus,
 - a serial port,
 - a collection of lines dedicated to programming the microcontrollers.



One Example Sensor Board - MTS310



One More Example of Sensor Board



- MTS400/420

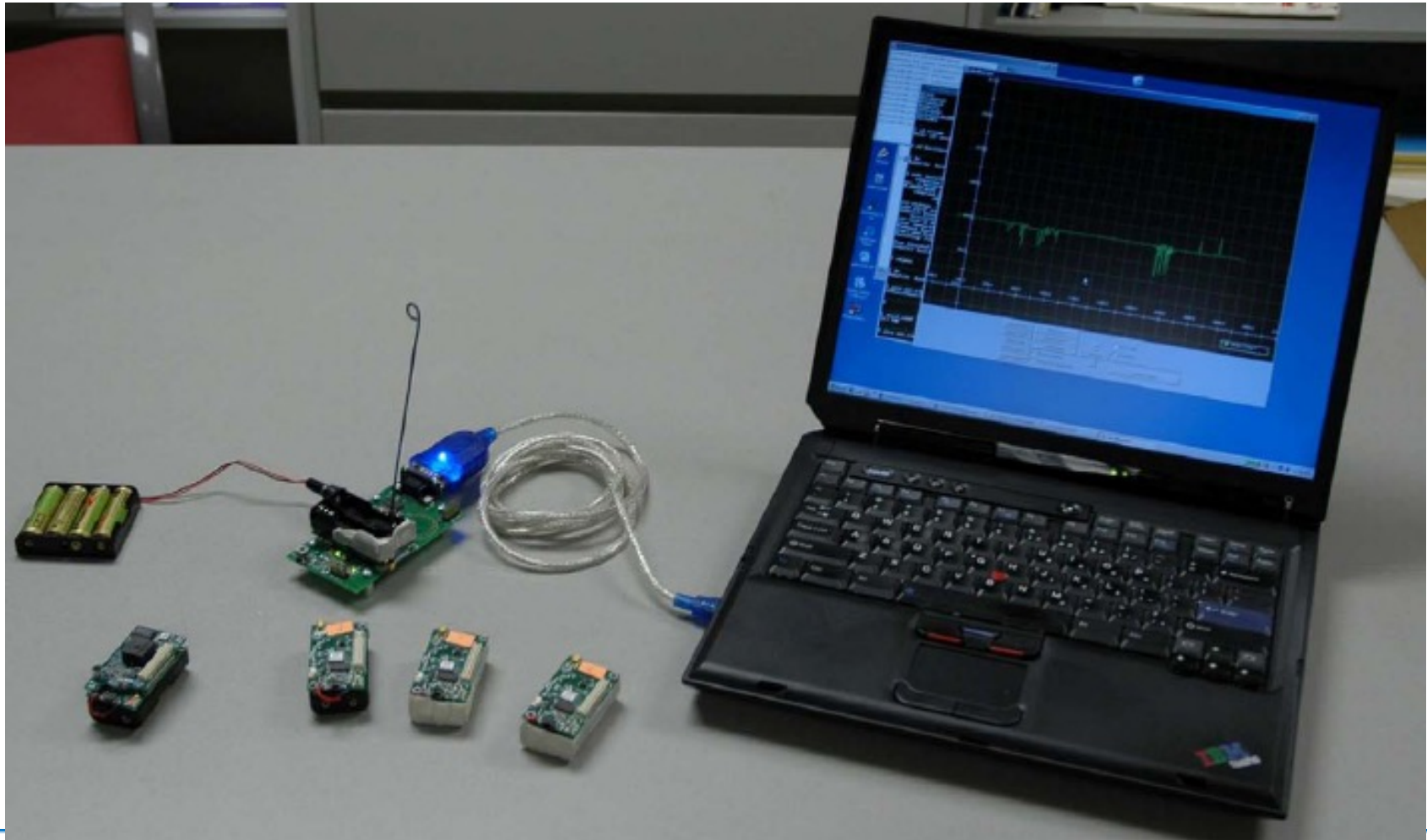
- Besides the functions of MTS 300, it mainly adds GPS functionality



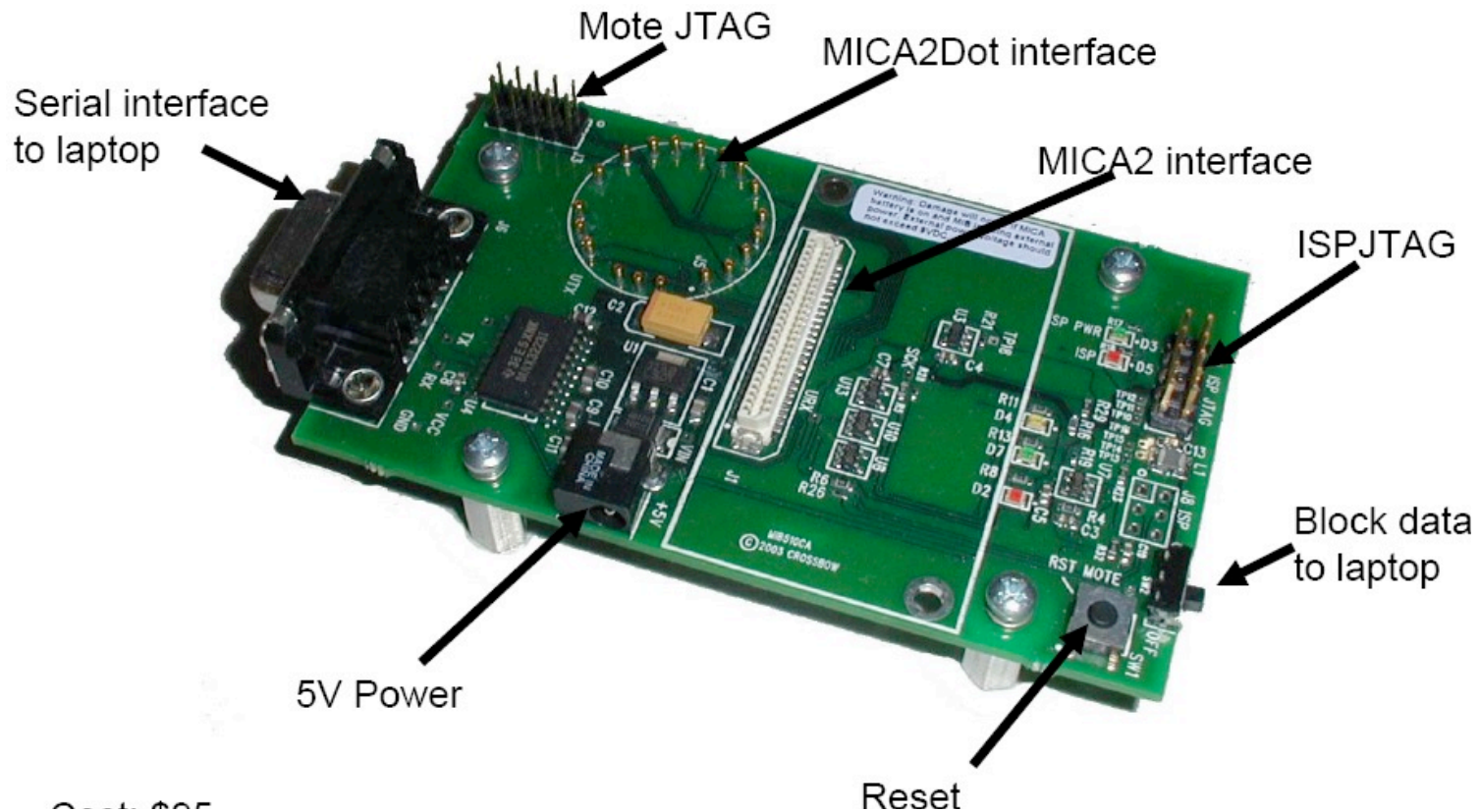
- Example GPS Reading

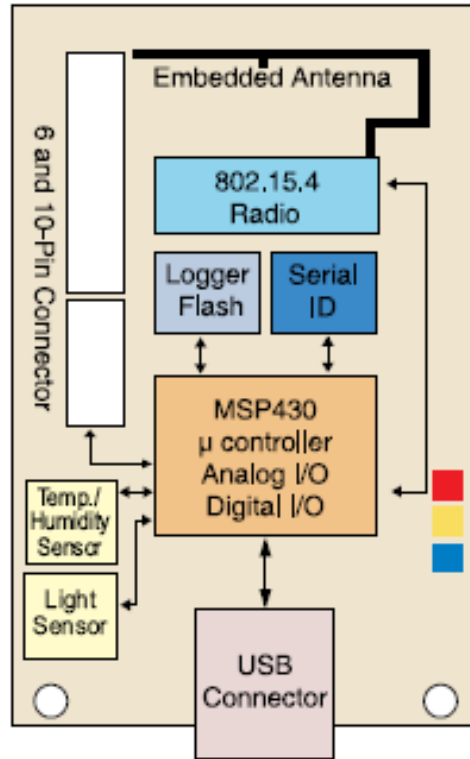
– http://firebug.sourceforge.net/gps_tests.htm

Hardware Setup Overview



Programming Board (MIB520)





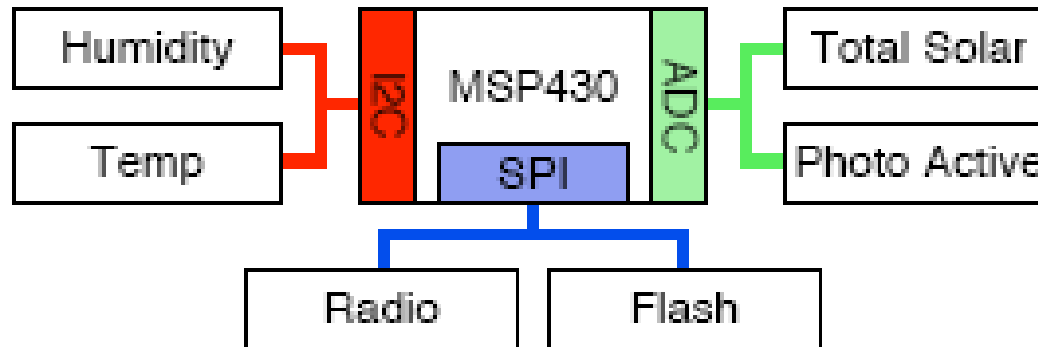


Figure 2: The application uses six peripherals: two SPI devices, two I2C sensors and two ADC sensors. The two I2C sensors are on the same chip (same I2C address), but require separate sensing command sequences.

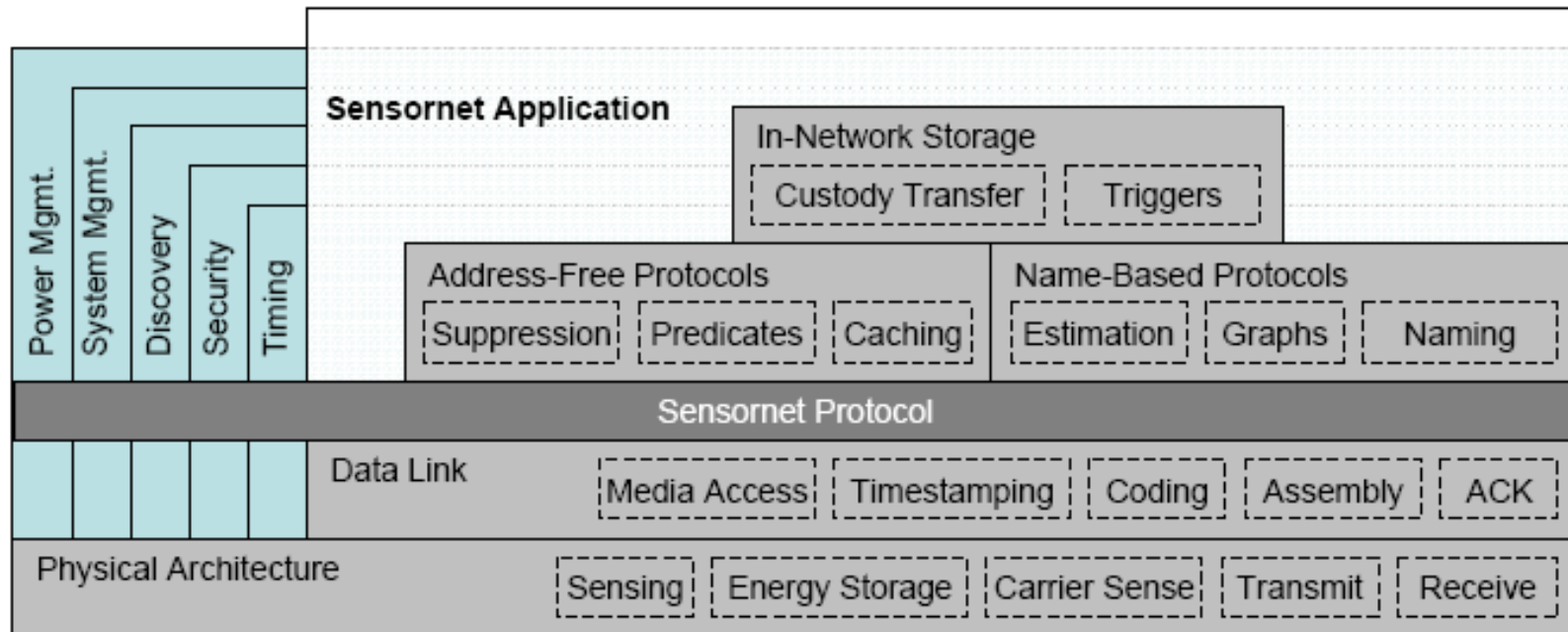
- [Energy_1]: Figure 2

Typical WSN Platforms

Platform	MCU	Buses	Radio	Flash
eyesIFX [11]	MSP430	UART/SPI/I2C0, UART/SPI/I2C1	TDA5250	at45db
ScatterWeb [24]	MSP430	UART/SPI0, UART/SPI1	TR1001	microchip 24xx64
imecCube [32]	MSP430	UART/SPI0, UART/SPI1	nRF2401	
Telos [21]	MSP430	UART/SPI/I2C0, UART/SPI/I2C1	CC2420	stm25p
WISAN [23]	MSP430	UART/SPI/I2C0, UART/SPI/I2C1	CC2420	
iMote2	PXA27X	UART0, UART1, SPI0, SPI1, I2C	CC2420	strataflash
micaZ [14]	Atmega128	UART0, UART1, SPI, I2C	CC2420	at45db
mica2 [33]	Atmega128	UART0, UART1, SPI, I2C	CC1000	at45db
BTnode [2]	Atmega128	UART0, UART1, SPI, I2C	ZV4002, CC1000	sst39
evb13192 [6]	HCS08	UART0, UART1, SPI, I2C	MC13192	

Functional Layer

Decomposition



- Ref: Fig. 1.1 of J. Polastre Dissertation:
<http://www.polastre.com/papers/polastre-thesis-final.pdf>

Architecture to Build WSN Applications

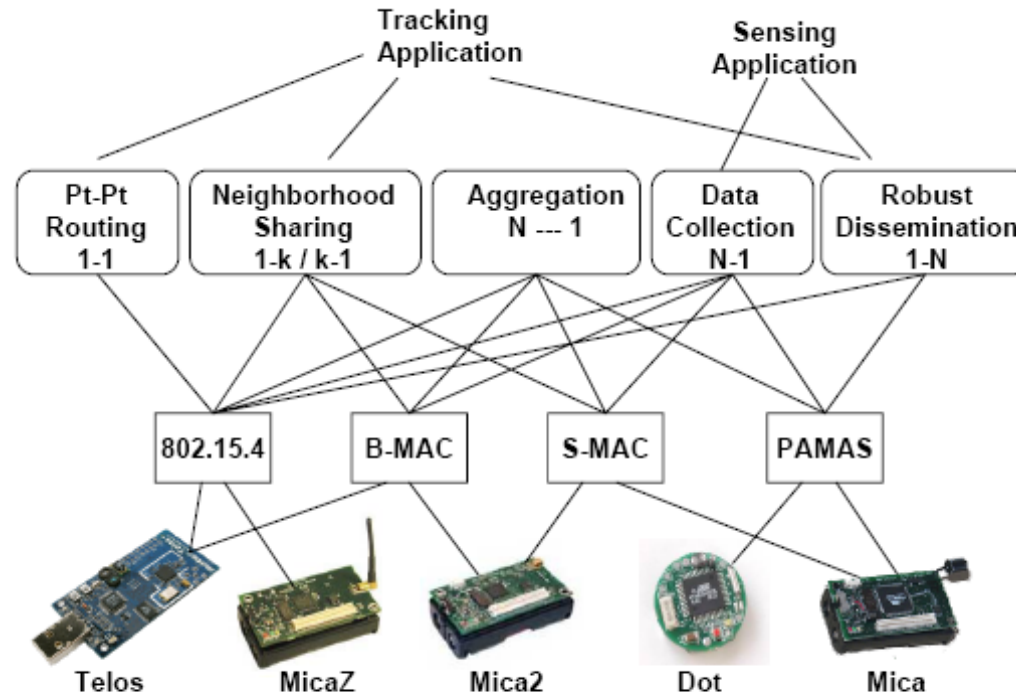


Figure 2.1: Current architecture for building sensornet applications. An application may choose a subset of network services that it requires. Those network protocols specify a set of link protocols that they support, which constrains the platforms available for application developers.

- Ref: Fig. 2.1 of J. Polastre Dissertation: