

Energy Autonomous Wireless Systems (EAWS)

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LESSON 3 – Wireless Communications for EAWS

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Slides adopted from Dr. Cyril Botteron

Course Objectives:

- To provide the essential knowledge required for understanding, selecting, designing, and implementing a wireless link in a low power system
- To provide an overview of the related challenges and design trade-off
- To provide an overview of the state-of-the-art

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1. *Wireless sensor network Basics*
2. *Physical layer Basics*
3. *(The wireless propagation channel)*
4. *Signal modulation and coding*
5. *Medium Access Control*

Part-2

1. *Wireless network standards*
2. *Case study on Radio Energy Consumption*

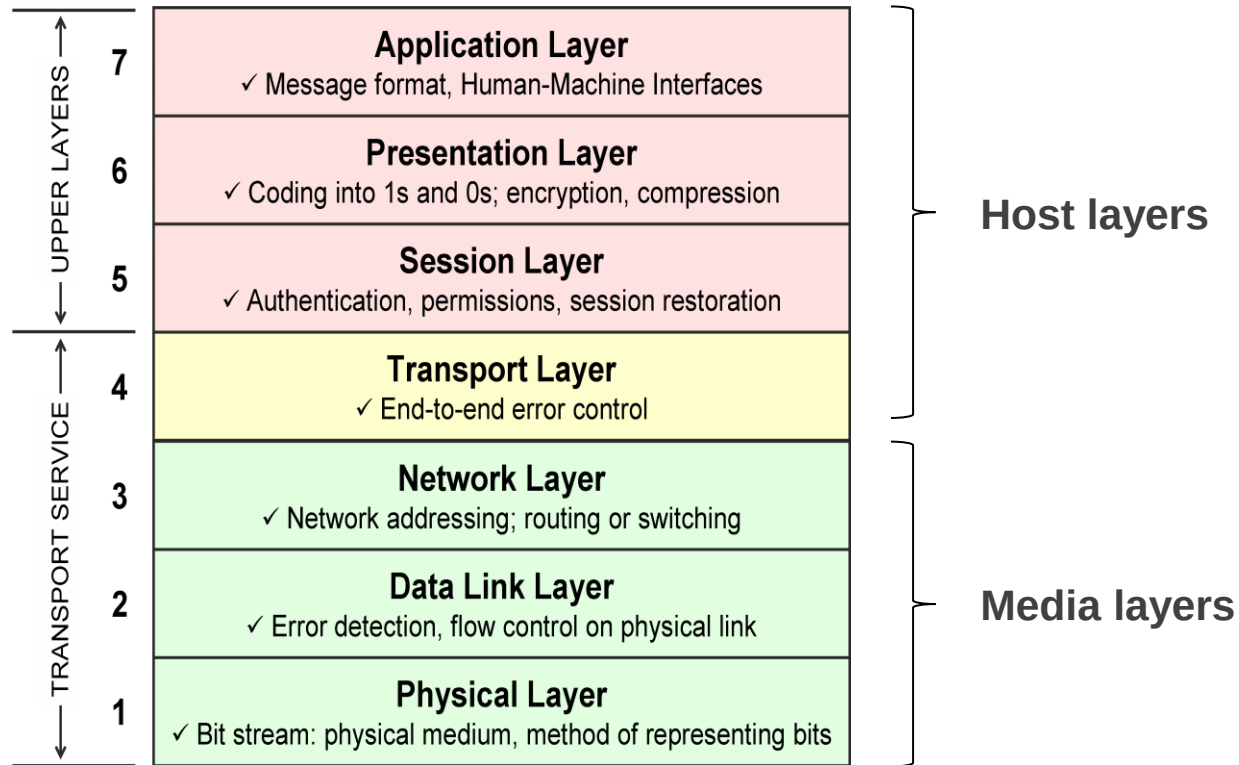
1. Wireless Sensor Network Basics

1.1 Definition

- [Wikipedia, Nov. 06, 2014]:
 - “A wireless sensor network (**WSN**) consists of **spatially distributed autonomous sensors** to **monitor physical or environmental conditions**, such as temperature, sound, vibration, pressure, motion or pollutants and to **cooperatively pass their data through the network to a main location.**”

1.2 Sub-layers

The Osi 7-layer model



Source: <http://www.telecommunications-tutorials.com/tutorial-OSI-7-layer-model.htm>

1.2 Sub-layers

- **Each layer is reasonably self-contained**
 - The tasks assigned to each layer can be implemented independently.
 - This enables the solutions offered by one layer to be updated without adversely affecting the other layers.
- **Upper layers deal with application issues**
 - Generally implemented only in software.
 - Closest to the end user.
- **The lower layers handle data transport issues**
 - Physical layer and MAC layer are implemented in hardware and software.
- **The lowest layer is the physical layer**
 - Closest to the physical network medium (the wires, for example)
 - Responsible for placing data on the medium.

WSN uses a simplified model of the 7-layer Open Systems Interconnection (OSI) Model

1.2 Sub-layers

Application layer

Network layer

- **Build complex networks with simple nodes (and bridge long distances)**

Media access control (MAC) layer

- **Efficiently share the common medium across different nodes (and nets)**

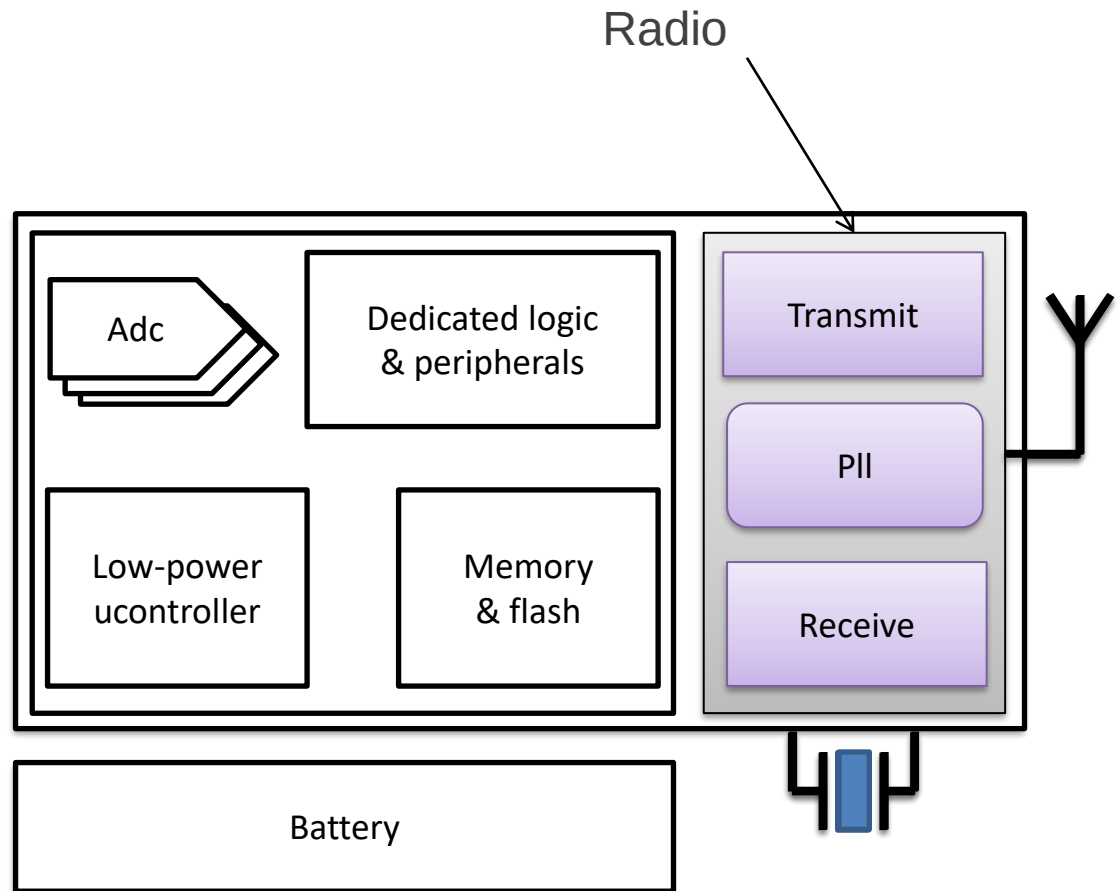
Physical layer

- **Transmitting data as reliable as possible in a hostile and noisy environment**

1.3 Physical layer

Main system components

- Sensors and actuators with digital interfaces
- A digital low power controller or microprocessor with memory
- An analog RF radio as air interface



In a low power system, the radio is one of the most power hungry parts!

1.3 Physical layer

- **Key requirements**

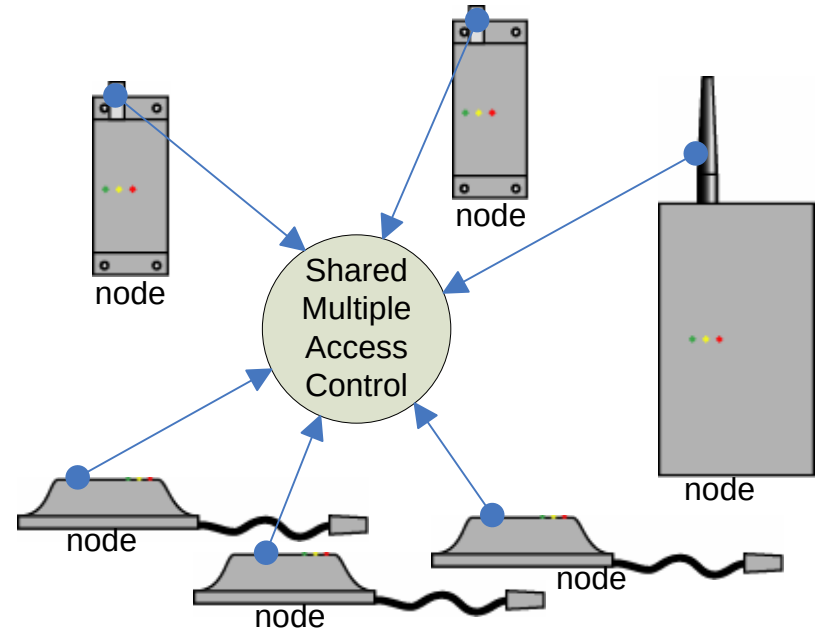
- Low cost
- Small form factor
- Low energy consumption
- Geolocation (e.g., fire sensor, temp. sensor, etc.)

- **Additional requirements**

- Robustness (in particular against wireless environment)
- Variable data rate
- Heterogeneous networking includes:
 - Reduced-Function Devices (RDF)
 - E.g., sensor end
 - Full-Function Devices (FFD)
 - E.g., coordinator, gateway

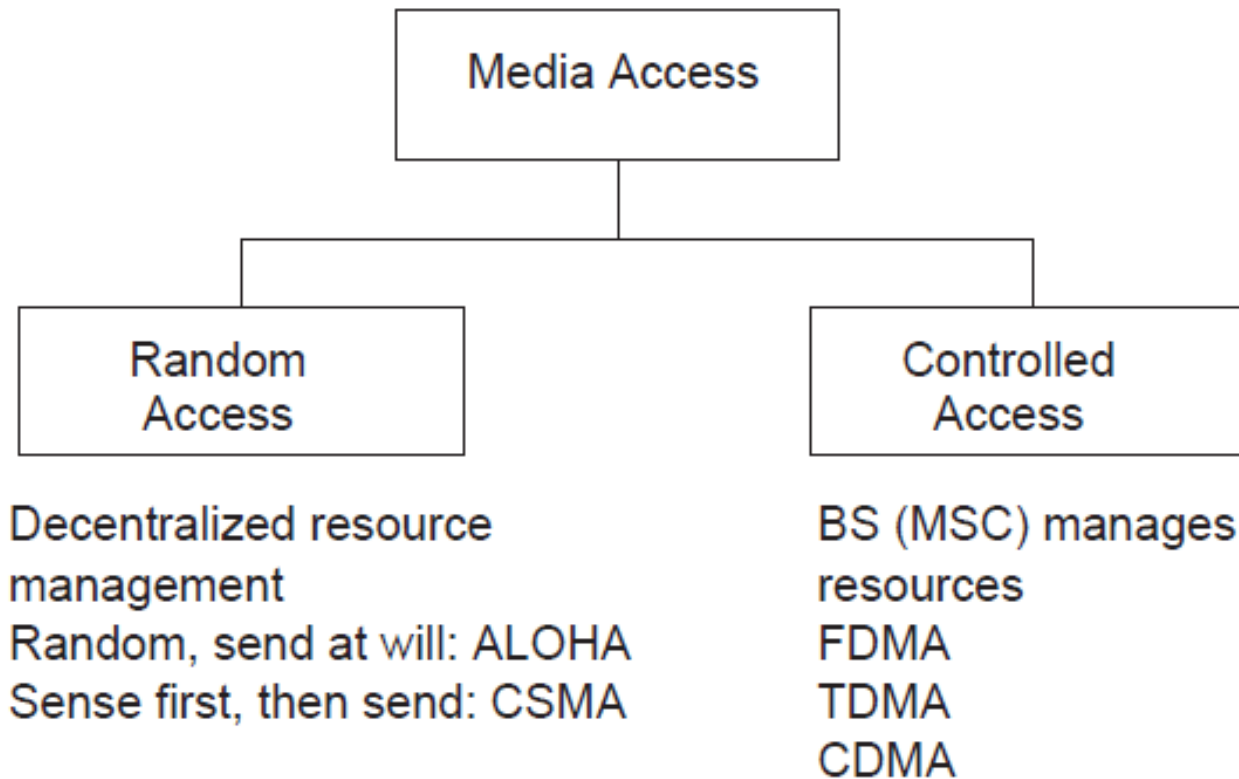
Multiple Access (MA) Techniques

- Each node is connected to a transceiver which communicates via a channel shared by other nodes.
- Transmission from any node is received by other nodes.
- For a large number of transceivers in a network, additional methods are required to ensure proper communication among multiple users.
- Such methods are called “Multiple Access Techniques”.



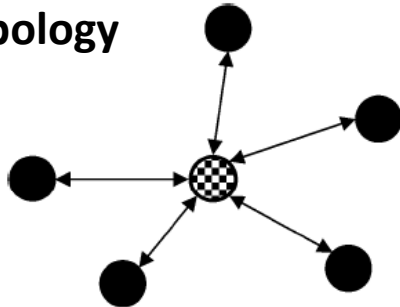
Source: [A. Boegli]

Multiple Access (MA) Techniques

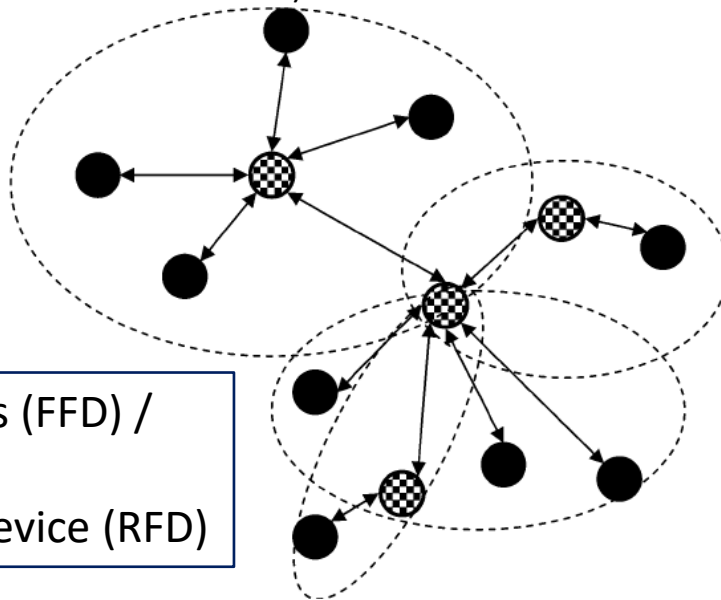


Network topologies

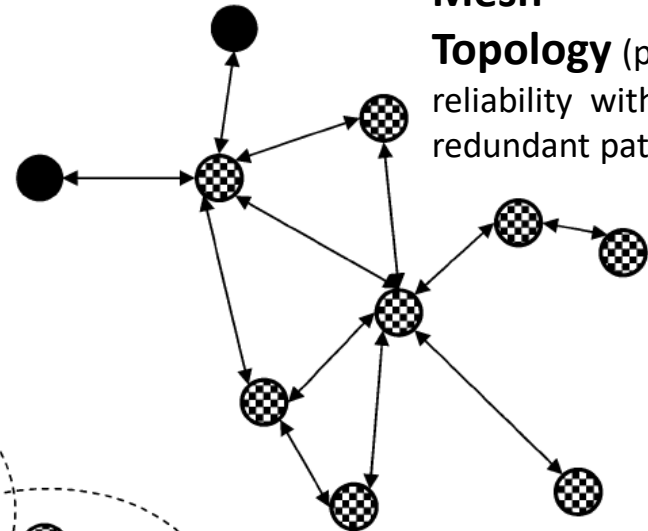
**Star
Topology**



Tree Topology
(amalgamation of star networks)



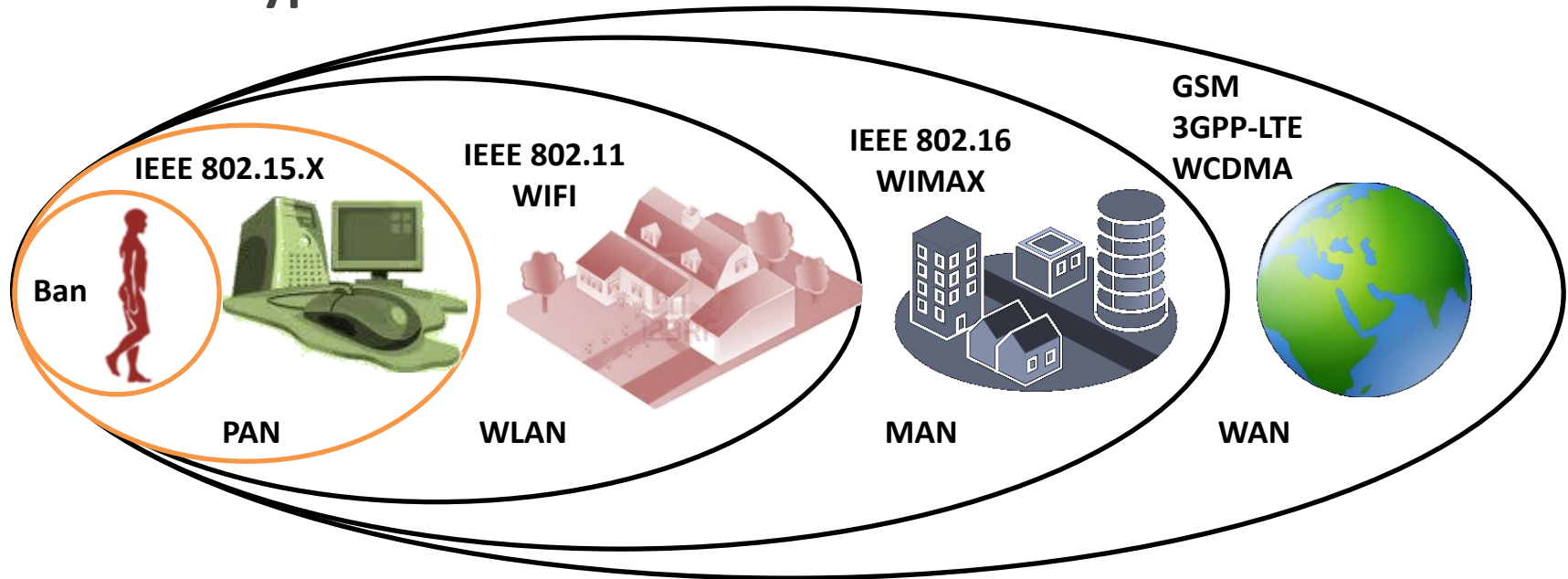
**Mesh
Topology** (provides
reliability with
redundant paths)



-  Full Function Devices (FFD) / Coordinator
-  Reduced Function Device (RFD)

Source: UWB Systems
for Wireless Sensor
Networks, Proceedings
of the IEEE, Vol. 97, No.
2, Feb. 2009

Network types

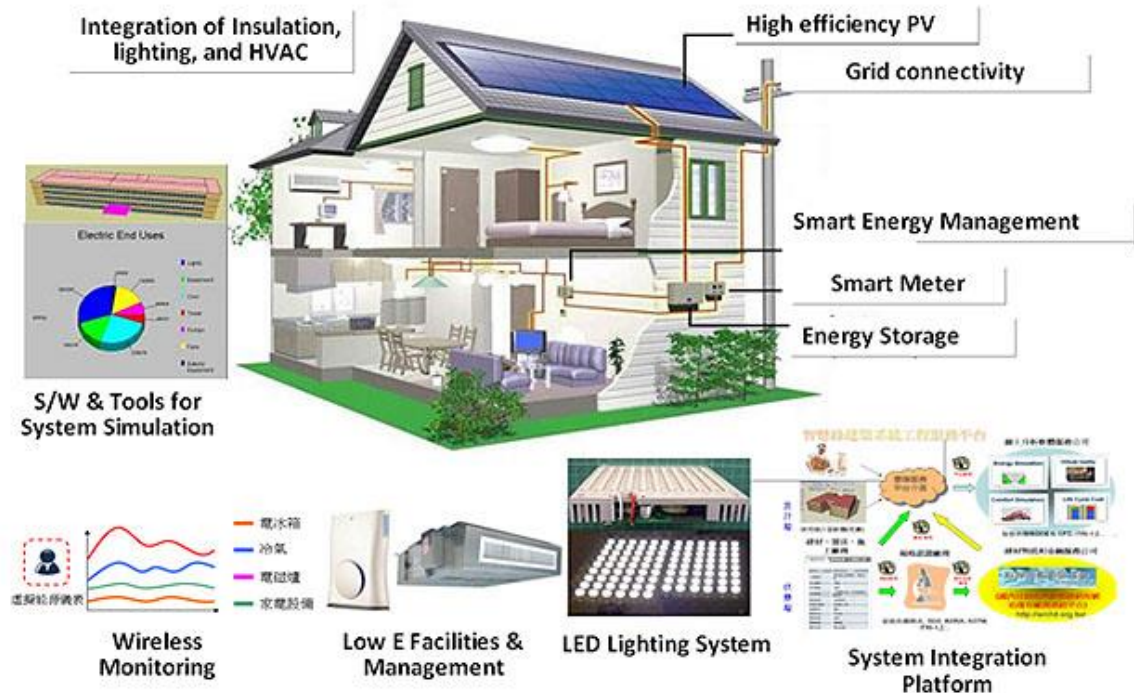


	Range	Data rates	Users
WAN	>10km	10 – 100 Mbps	Thousands
MAN	<10km	~100 Mbps	50-1000
LAN	<100m	100 Mbps – 1 Gbps	1-100
PAN	<10m	1 Mbps	<10-20
BAN	<2-5m	100 kbps	<10

1.6 Application layer

Home and commercial automation/security

- **Lighting**
 - On/off, dim (load control)
- **Heating, ventilation, air conditioning (HVAC)**
 - Thermostats, temperature sensors, etc.
- **Security/access control**
 - Door, window and motion sensors, entry monitoring, smoke detectors, etc.
- **Automated meter reading (amr)**



- **Industrial process control**
 - Monitoring of manufacturing flow and material handling
- **Asset management**
 - Monitoring / location of assets

Wearable medical body area networks

- In hospitals

- Networked wireless devices to maximize patient monitoring by reducing nurse to patient ratio
- Wireless devices include EKG, blood pressure, pulse oximetry, capnometry, infusion pumps and spirometry

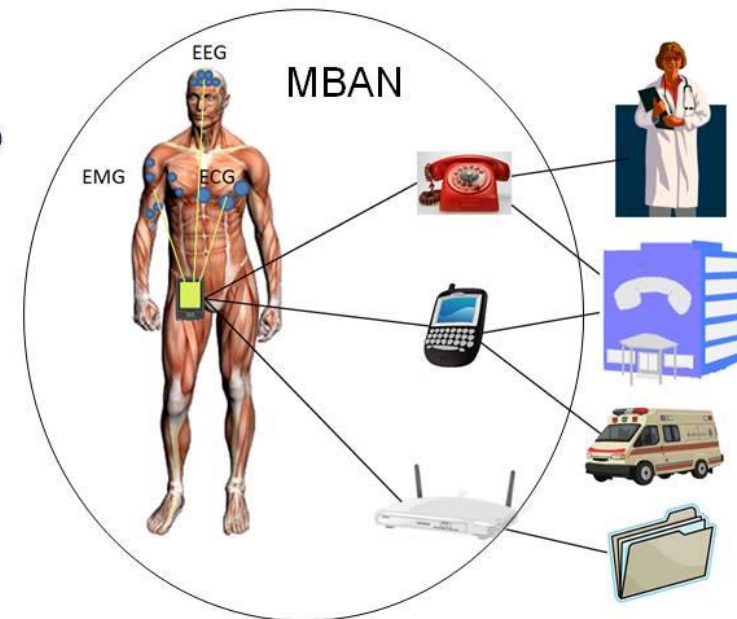
- Home care

- Telemetry for off-site diagnosis by collecting data of glucose levels, blood pressure, heart rate, etc. While patients are recovering at home

- Fitness

- Heart rate monitors for athletes

- **Bio-Medical**
 - EEG Electroencephalography
 - ECG Electrocardiogram
 - EMG Electromyography (muscular)
 - Blood pressure
 - Blood SpO2
 - Blood pH
 - Glucose sensor
 - Respiration
 - Temperature
 - Fall detection
- **Sports performance**
 - Distance
 - Speed
 - Posture (Body Position)
 - Sports training aid



1.6 Application layer

Example: wireless capsule endoscopy

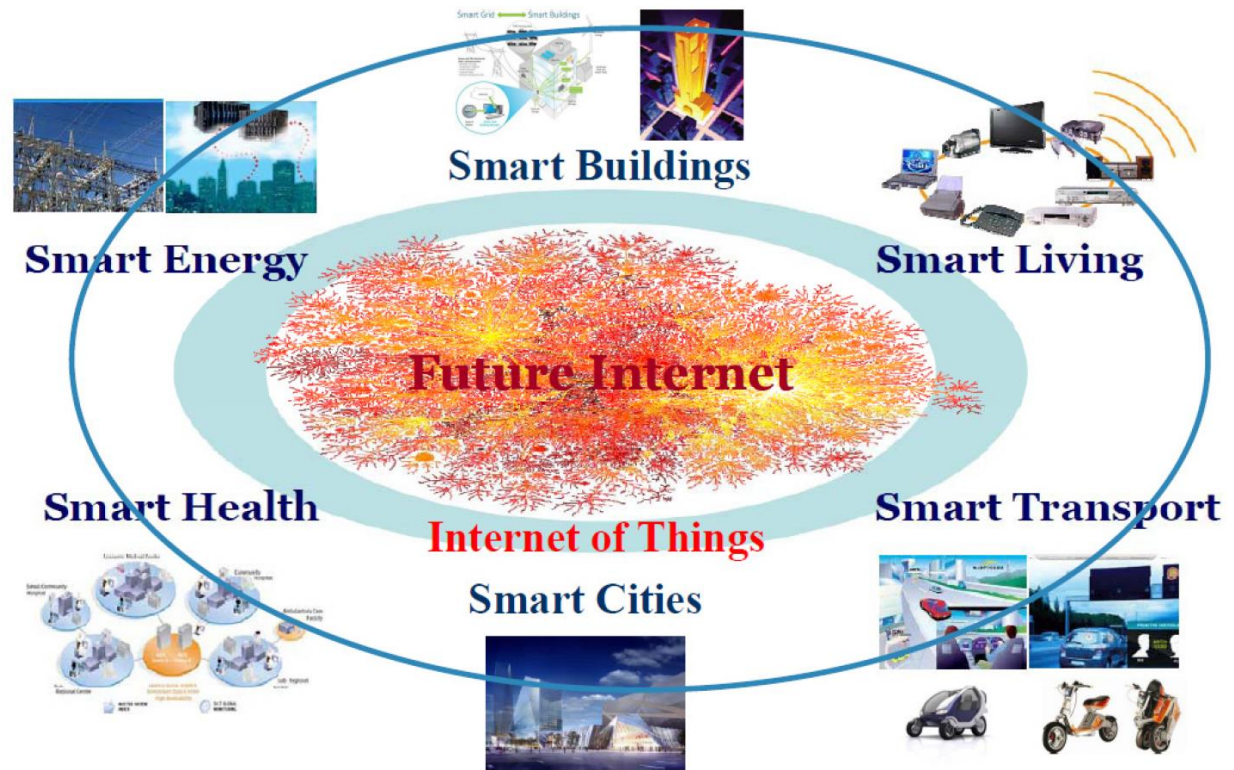


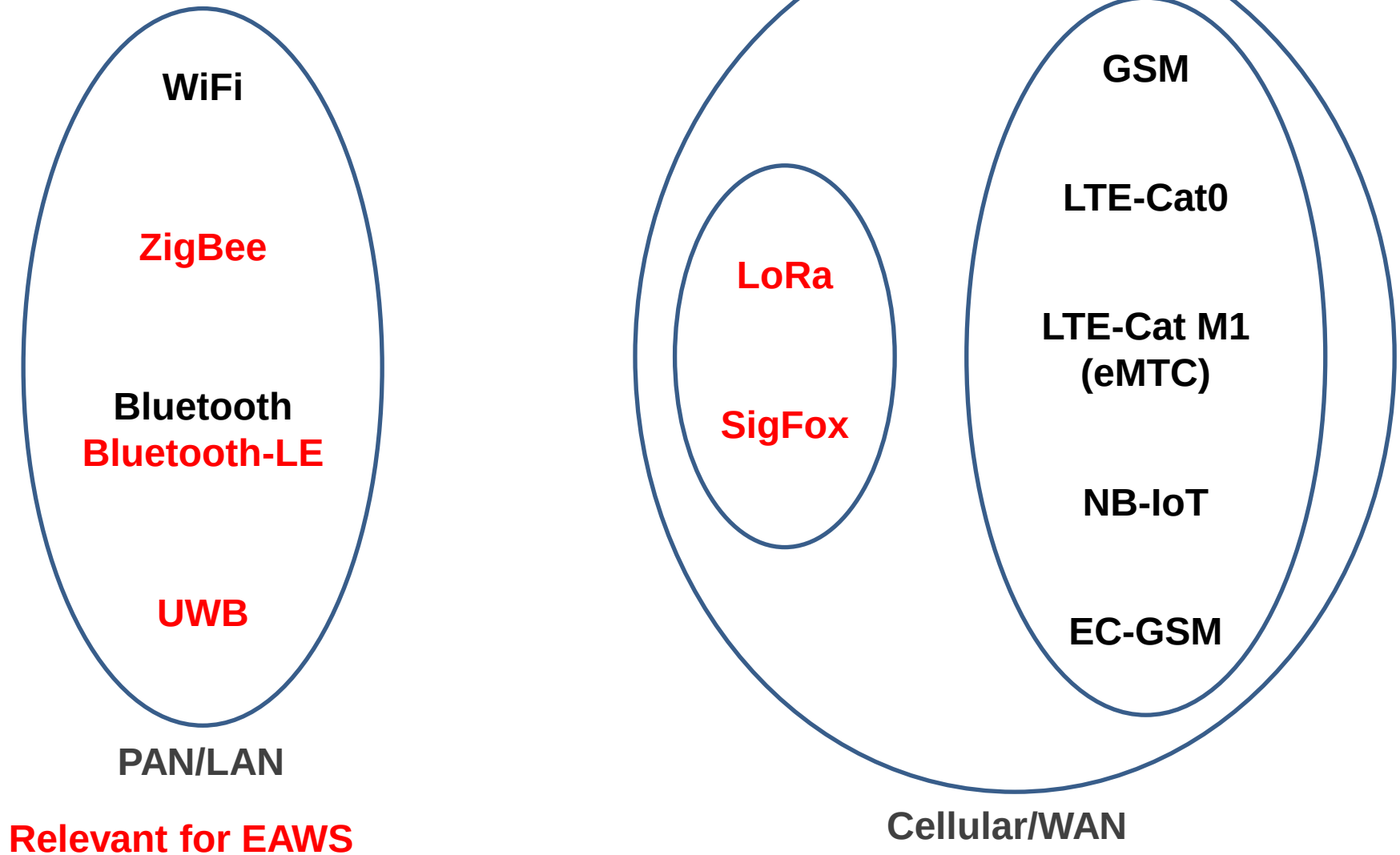
- **Wireless transmission of images to receiver box**
 - To visualize the gastrointestinal tract
 - Images are transmitted wirelessly outside of patient's body and received by the receiving box which is tied to patient's waist
- **4 main system components:**
 - Capsule endoscope
 - Data receiving box
 - Working station
 - Application software
- **Characteristics**
 - Pillcam SB is 11 × 26 mm
 - Weights less than 4 g
 - 6-8 hours autonomy

Internet Of Things (IoT):

“7 Trillion Wireless Devices Serving 7 Billion People By 2020 !”

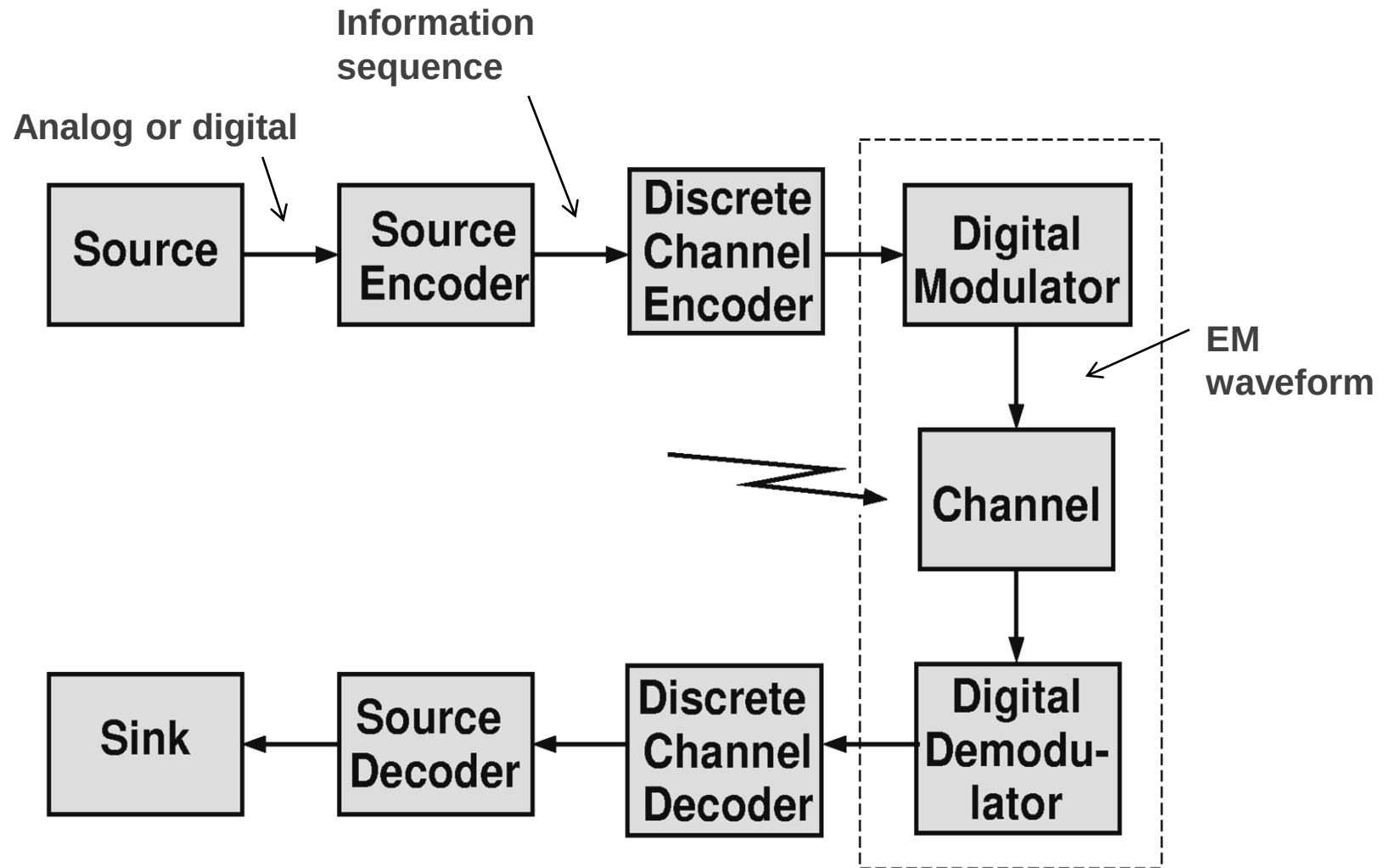
- Creation Of Smart Environments And Self-aware Things
- For Climate, Food, Energy, Mobility, Digital Society And Health Applications





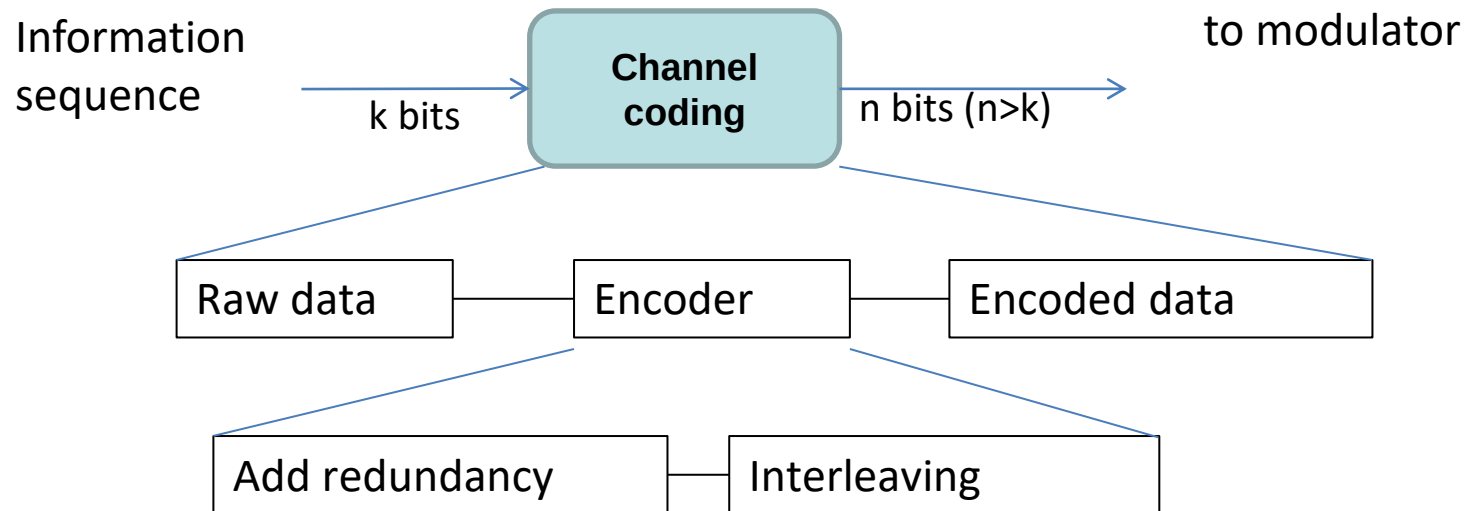
2. Physical Layer Basics

2.1 Basic elements of a communication system



2.2 Channel coding

Coding: used to protect (to a certain extent) the navigation data against the wireless channel errors



- **Basic idea:** fundamentally, error free transmission is always possible when the data-rate (bits/s) does not exceed the capacity of the channel (Shannon Limit)

$$C = B \cdot \log_2(1 + SNR)$$

where B is the bandwidth of the channel and SNR is the signal-to-noise ratio

- Caveat:
 - **Shannon capacity does not define how to encode data to achieve error free transmission**
 - **Error-free transmission only possible in the limit of infinitely large blocks of data**

- **Objective:** Minimize error probability for transmission at a given SNR
- **Forward Error Correction (FEC):**
 - Channel coding based on inserting redundancy in the transmit data
 - Redundancy allows the receiver to detect and possibly correct the transmission errors
 - **Block codes:** k information bits are encoded into n code bits
Hamming codes, Hadamard codes, Golay codes, cyclic codes, Base-Chaudhuri-Hocquenghem (BCH) codes, Reed-Solomon codes
 - **Convolutional codes:** a continuous sequence of information bits is mapped into a continuous sequence of encoder output bits Possible implementation with a finite state shift register and decoding using Viterbi algorithm (i.e., max likelihood decoding of conv. codes)
 - **Turbo codes:** nested or parallel convolutional codes allow coding gains much greater than all previous correcting codes allow wireless communication links performance to come very close to Shannon capacity bound at the cost of a high computational burden

**Difficulty in IoT: good codes require large blocks of data
while IoT data packets are usually small**

Channel Coding: ARQ

- **Objective:** Ensure 100% reliable transmission under all channel conditions
- **Automatic Repeat Request (ARQ):**
 - Channel coding techniques based on detection of errors followed by retransmission of erroneous data packers
 - **Transmitter:** Computes a Hash in form of a Cyclic Redundancy Check (CRC) from the original data to be transmitted and attaches the hash to the transmitted information (small overhead)
 - Size of the hash determines tradeoff between reliability (undetected errors) and **overhead**
 - **Receiver:** Re-computes the same hash based on the received data and compares to the transmitted CRC hash in the data packet. If the two match, the packet is acknowledged (ACK), if not, a NACK or no ACK is sent back
 - **Transmitter:** Repeats the packet if a NACK or no ACK is received

Difficulty in IoT: ARQ always requires a reverse channel to request re-transmission of faulty data packets



Real Systems Combine FEC and ARQ

- FEC and ARQ have their individual Pros and Cons:
 - FEC: Rate of the channel code (i.e., transmission rate) needs to be selected based on channel conditions to ensure a low (yet, never zero) error probability
 - ARQ: ensures 100% reliability, but can be inefficient for too many retransmissions
- Example
 - Consider the transmission of a data block (e.g., a file) comprising L bits
 - Bit-error probability (after decoding): P_e
 - Block error probability: probability that one or more bits in a block are corrupted

$$P_e(L) = 1 - (1 - P_e(1))^L$$

- Example: $P_e(1) = 10^{-6}$, with a file (block) size of 100k bytes ($L = 800'000$ bits)

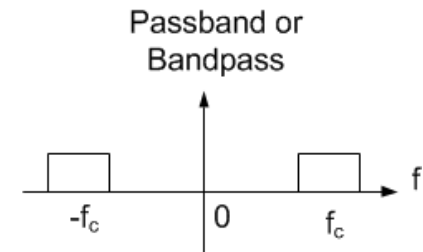
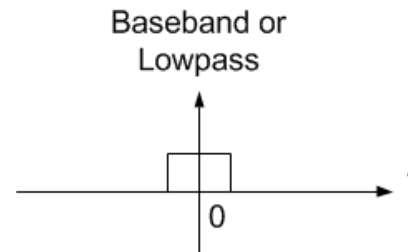
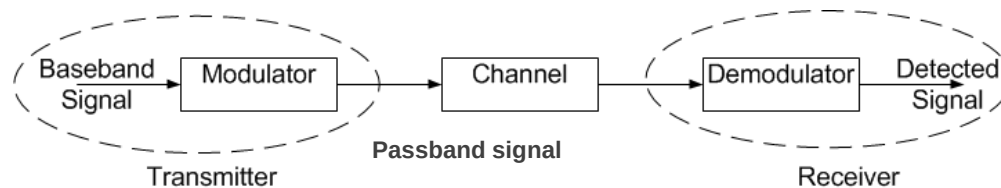
$$P_e(100 \text{ Kbytes}) = 1 - (1 - 10^{-6})^{800'000} = 0.55$$

FEC and ARQ are usually combined, where FEC rate is selected for a low error probability and ARQ then ensures 100% reliability

2.2 Channel modulation

Modulation converts a baseband signal to a passband counterpart

- Principle: Some characteristics (amplitude, phase or frequency) of a carrier wave (frequency f_c) are varied in accordance with an information bearing signal

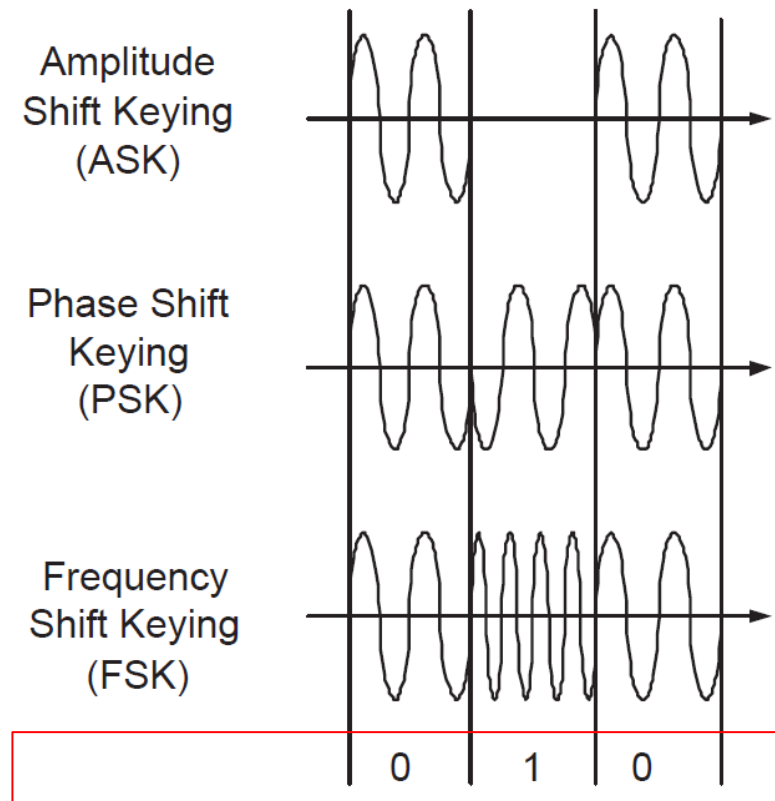


Objectives

- Multiple access** (allowing to share the medium (i.e., the EM spectrum) between different users)
- Minimize interference** to other users (e.g., ultra-wideband (UWB) communications)
- Robustness** against signal distortions and interferences
- Spectral efficiency** to provide high data rate with minimum bandwidth

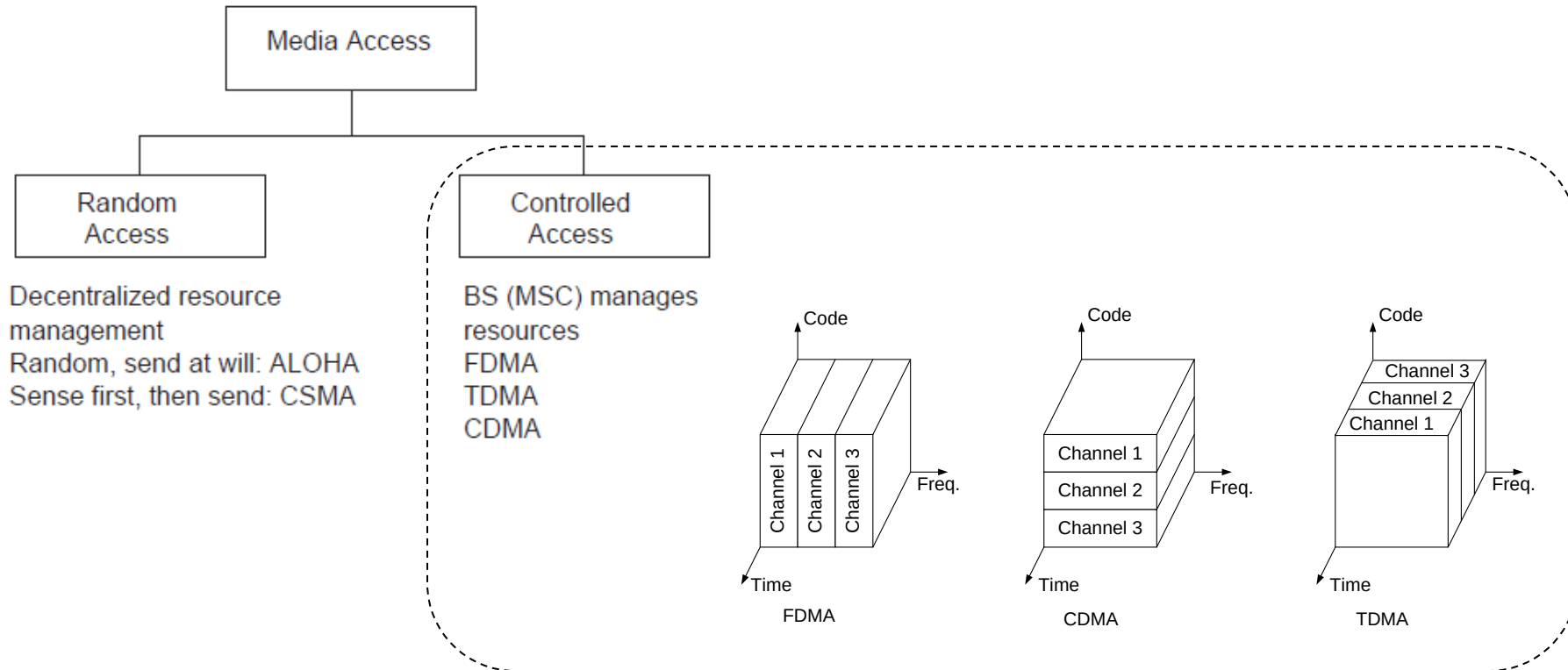
Some simple binary modulation techniques

- **OOK**: on/off Keying (OOK)
 - carrier is turned on and off to send 1 and 0
- **ASK**: amplitude shift keying
 - Carrier amplitude is varied between two (possibly antipodal) levels
- **FSK**: frequency shift keying
 - Two different frequencies indicate 1 or 0
 - Modulation index trades reliability vs. bandwidth occupancy
- **PSK**: phase shift keying
 - Two different carrier phases (e.g., 180° apart) indicate 1 or 0
 - Using a 180° shift corresponds to antipodal modulation



2.3 Channel modulation

Main multiplexing techniques (for MAC)



- **low power wireless sensor nodes often rely on random access to limit the overhead and complexity of the sensor** (no time or frequency synchronization requirements)

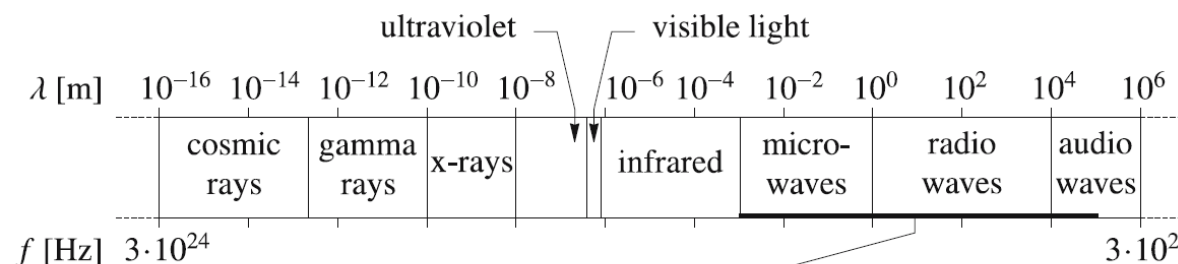
2.3 Channel modulation

Some important aspects for the choice of a modulator/demodulator

- **Quality and performance**
 - E.g., **prob. of bit error** of the output in the presence of various channel impairments (fading, multipath, interference, noise, timing jitter)
- **Price and complexity**
 - for mass-market applications, the cost and complexity of the receiver must be minimized
- **Power efficiency**
 - ability of a modulation technique to preserve the digital message at low power levels.
 - Often expressed as the minimum ratio E_b/N_0 required at the receiver input for obtaining a given bit error rate (BER)
- **Bandwidth or spectral efficiency:**
 - ability of a modulation scheme to accommodate data within a limited bandwidth.
 - Expressed as the ratio of throughput data rate R per Hz in a given bandwidth B

2.4 Channel propagation: electromagnetic waves

- EM spectrum



Notation	Wavelength λ	Frequency f
Extremely high frequency (EHF)	0.1–1 cm	300–30 GHz
Super high frequency (SHF)	1–10 cm	30–3 GHz
Ultra high frequency (UHF)	10–100 cm	3–0.3 GHz
Very high frequency (VHF)	1–10 m	300–30 MHz
High frequency (HF)	10–100 m	30–3 MHz
Medium frequency (MF)	0.1–1 km	3–0.3 MHz
Low frequency (LF)	1–10 km	300–30 kHz
Very low frequency (VLF)	10–100 km	30–3 kHz

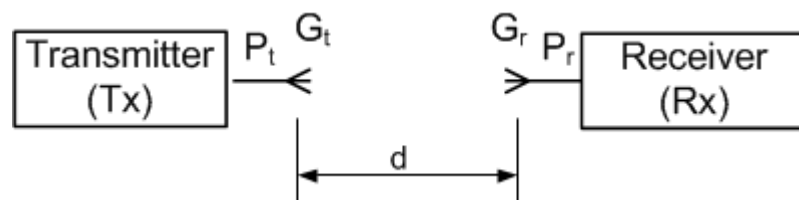
Band	f [GHz]
K	26.5–18
Ku	18–12.4
X	12.4–8
C	8–4
S	4–2
L	2–1

- Different systems and services use different bands of the electromagnetic spectrum, but its usage is strictly regulated by the International Telecommunication Union (ITU).
- The ISM (industrial, scientific and medical) bands are defined by the ITU-R in 5.138, 5.150, and 5.280 of the Radio Regulations. Individual countries' use of the bands designated in these sections may differ due to variations in national radio regulations.

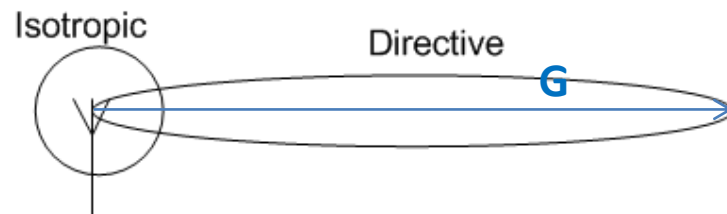
Source: Hofmann-Wellenhof 2008

2.4 Channel propagation: antenna concepts

- **Antennas:** In any wireless system, antennas are used at each end of the link as a mean of **coupling RF electrical power from a transmission line into RF electromagnetic waves in free space**, allowing a Tx to radiate and a Rx to capture incident electromagnetic power



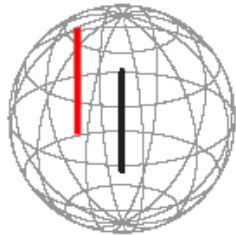
- **Isotropic antenna:** theoretical point source which radiates the same intensity of electromagnetic radiations in all directions
- **Real antenna:** a real antenna distributes the electromagnetic radiations non-uniformly through space, providing a gain in some directions as compared to an isotropic antenna.



– **An antenna does not amplify, but distributes energy through space !!!**

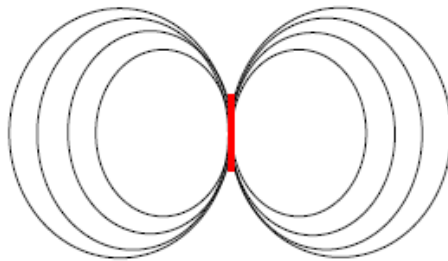
2.4 Channel propagation: antenna concepts

- **Effective isotropic radiated power (EIRP):** Amount of power that would be required with an isotropic antenna to produce the same power density that is achieved in the boresight direction of a directional antenna
 - **Power measurements are referenced to isotropic antenna (dBi)** as a theoretical model for comparison with all other antennas
 - Power measurements of a dipole antenna (dBd) = 2.14 dBi.

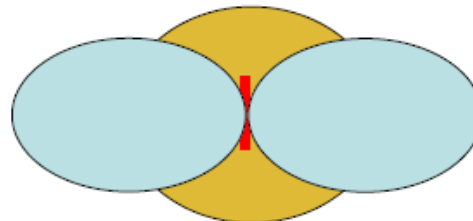
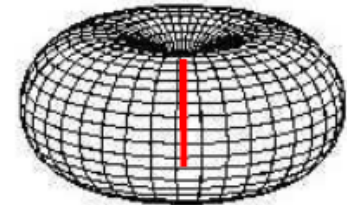


An Isotropic Antenna is a theoretical antenna that radiates a signal equally in all directions.

$$P_{\text{EIRP}} = P_t G_{\text{ant.}}$$



A Dipole Antenna is commonly used in wireless systems and can be modeled similarly to a doughnut



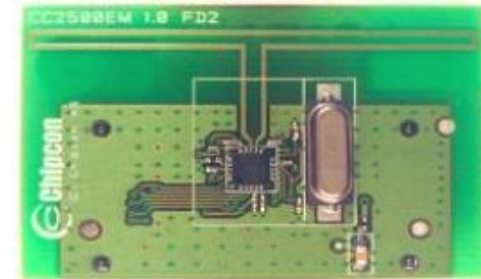
The Dipole represents a directional antenna with a further reach in the X&Y Plane (at the cost of a smaller reach in the Z plane) to the Isotropic.

Source:  TEXAS INSTRUMENTS

2.4 Channel propagation: antenna concepts

PCB antennas

- No extra cost development
- Requires more board area
- Size impacts at low frequencies and certain applications
- Good to high range
- Requires skilled resources and software



Whip antennas

- Cost from (starting~ \$1)
- Best for matching theoretical range
- Size not limiting application



Chip antennas

- Less expensive (below \$1)
- Lower range



Source:  TEXAS INSTRUMENTS

2.4 Channel propagation: antenna concepts

Lower frequency increases the antenna range

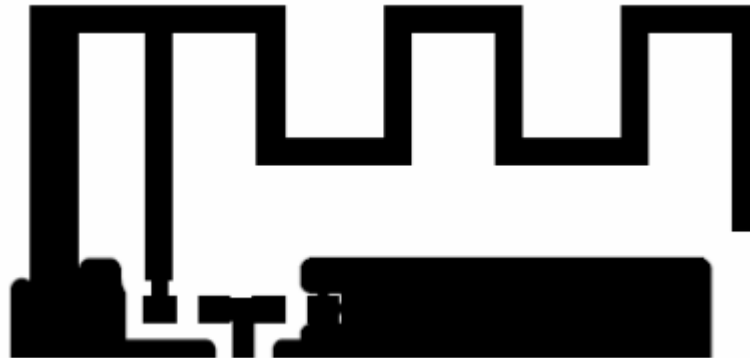
- Reducing the frequency by a factor of two doubles the range

However, lower frequency requires a larger antenna

- $\lambda/4$ at 433 MHz is 17.3 cm (6.81 in)
- $\lambda/4$ at 915 MHz is 8.2 cm (3.23 in)
- $\lambda/4$ at 2.4 GHz is 3.1 cm (1.22 in)

A **meandered** structure can be used to reduce the size

- $\lambda/4$ at 2.4 GHz

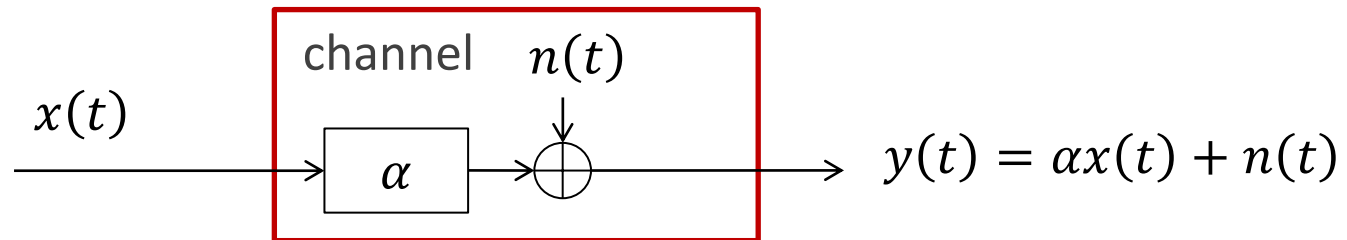


Source:  TEXAS
INSTRUMENTS

2.4 Channel propagation: AWGN channel

AWGN: additive white Gaussian noise

- **Additive:** noise (modeled as a random variable) $n(t)$ is added to the signal $s(t)$
- **White:** noise has uniform power spectral density (i.e., same power for all frequencies)
- **Gaussian:** noise samples have a normal distribution



- Signal attenuation is modeled implicitly by adjusting the signal (or the noise) power to obtain the desired signal-to-noise-ratio

Signal to Noise Ratio (SNR)

- SNR measures the average quality of the received signal as the *ratio between transmitted signal energy and energy of the additive noise term*

SNR for AWGN

$$SNR = \frac{\bar{P}}{P_{Noise}} = \frac{\mathcal{E}\{|\gamma x(t)|^2\}}{\mathcal{E}\{|n(t)|^2\}} = \frac{\gamma^2 \mathcal{E}\{|x(t)|^2\}}{\mathcal{E}\{|n(t)|^2\}}$$

- Transmitted power is measured in dBm

- Defined with reference to 1mW

$$P_{TX}[mW] = 10^{P_{TX}/10} \cdot 1mW$$

- Regulations limit the maximum transmitted power
- E.g., 2.4 GHz ISM band (Europe): 100 mW or 20 dBm

P[dBm]	P[mW]
-20 dBm	0.01 mW
-10 dBm	0.1 mW
0 dBm	1 mW
10 dBm	10 mW
20 dBm	100 mW

- The SNR is usually specified in dB

$$SNR [dB] = 10 \log_{10} \gamma^2 \frac{\mathcal{E}\{|x_k|^2\}}{\mathcal{E}\{|n(t)|^2\}} = P_{TX}[dB] - \text{Attn}[dB] - P_{Noise}[dB]$$

- SNR reflects ratios between received signal strength and the thermal noise power
- Using SNR instead of signal power helps to abstract away from absolute terms

2.4 Channel propagation: real channel

Important factors affecting the range

- **Antenna**
 - gain, sensitivity to body effects etc.
- **Sensitivity:**
 - Lowest input power with acceptable link quality (typically 1% PER)
- **Channel selectivity:**
 - How well a chip works in an environment with interference
- **Output power**
 - Limited by regulations (regions dependent)
- **Environment**
 - Line of sight, obstructions, reflections, **multi-path propagation**

Source:  TEXAS
INSTRUMENTS

2.4 Channel propagation: real channel

Free space scenario:

- The received power can be computed using **Friis Free-space transmission formula**

$$P_r(R) = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \propto \frac{1}{R^n} \text{ with } n = 2: \text{ the free space path loss exponent}$$

where

- P_t is the transmitted power, P_r is the received power
 - G_t is the transmitter antenna gain, G_r is the receiver antenna gain
 - R is the distance between transmitter and receiver, or the LOS range
 - $\lambda = c/f$ is the wavelength ($c \approx 3 \times 10^8$ m/s)
- It can also be expressed dB scale:

$$P_r(R) [\text{dB}] = P_t + G_t + G_r + 20 \log_{10} \frac{\lambda}{4\pi} - 20 \log R$$

- Achievable range:
$$R = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t G_r}{P_r}}$$

2.4 Channel propagation: real channel

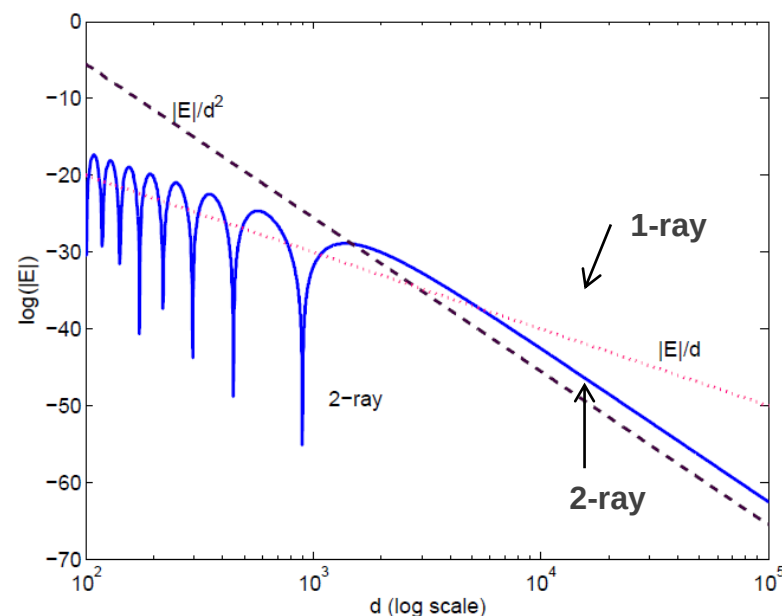
Real-world scenario – **large-scale fading**:

- **Large-scale**: mean signal strength variations over large distances
 - Averaged performed over dist of $5\text{-}40 \lambda$
- **The decrease in received power is faster than $1/R^2$, i.e., $n \geq 2$**
 - Reflections (e.g., from ground and ceiling) cause destructive interference with direct path signal and $n \geq 2$ (e.g., $n=4$ for a two-ray model)
- **Additional signal attenuation due to obstructions**
 - **Non-line-of-sight**: Typical path loss exponents: **$n = 3 \dots 7$**

Path Loss Exponents for Different Environments:

Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building LOS	1.6 to 1.8
In building obstructed	4 to 6
In factories obstructed	2 to 3

$$P_r(R) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2} \frac{1}{R^n}$$



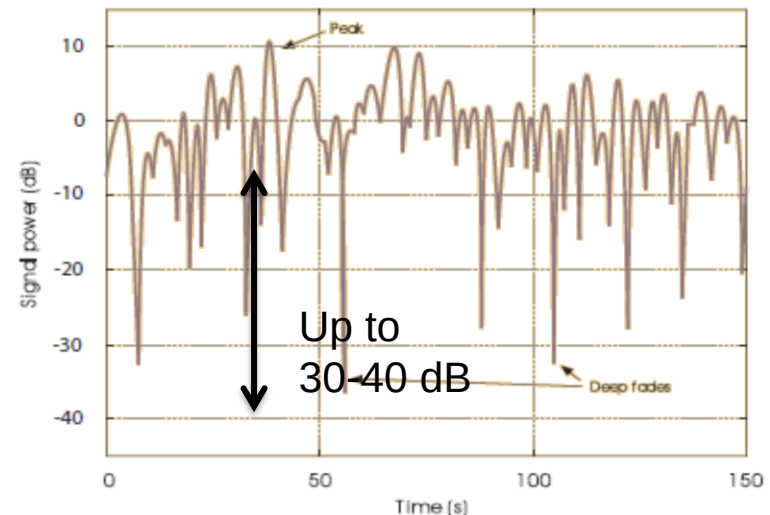
2.4 Channel propagation: real channel

Real-world scenario – **small-scale fading**:

- Small-scale: signal variations over short distance of a few wavelengths
- 3 most important effects of small-scale multipath propagation:
 - **Rapid (unpredictable) changes in signal strength (30-40 dB typical)**
 - **Random frequency modulation** due to varying Doppler shifts on different multipath signals
 - **Time dispersion (echoes)** caused by multipath delays
- Caused by interference between two or more versions of the transmitted signal (multipath waves) arriving at the receiver at slightly different times



Source: A. Burg



Increasing Reliability with Diversity

- When channel conditions change, transmissions (packets) may randomly be dropped due to poor (fading) channels



- Solution: **DIVERSITY** provides multiple alternate routes (copies) for the same information (packet/data)
 - If one copy is corrupted others still survive and arrive in tact
 - Each diversity branch exponentially reduces the risk of losing a packet

$$P_{loss}(\text{all } N \text{ copies}) \sim [P_{loss}(1 \text{ copy})]^N$$



Time diversity:

Packet repetitions exploit channel changes over time

Antenna diversity:

Multiple antennas experience different channels (if sufficiently far apart)

- Many different approaches to introduce diversity

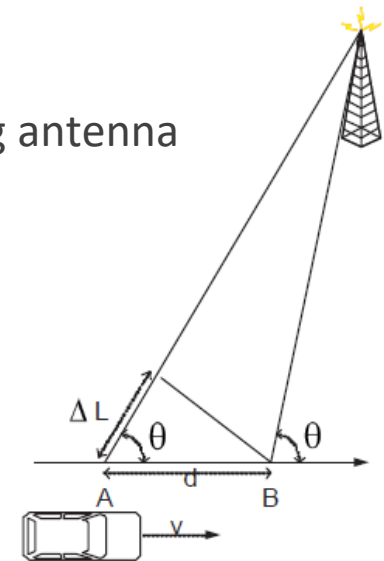
2.4 Channel propagation: real channel

Real-world scenario – Doppler shift

- Consider the phase change in the received signal at a moving antenna

$$f_D = \frac{1}{2\pi} \frac{\Delta\phi}{\Delta t} = \frac{v}{\lambda} \cos \theta$$

- Positive Doppler shift:
rx antenna moves towards tx antenna
- Negative Doppler shift:
rx antenna moves away from tx antenna



- Multipath components that arrive from different directions contribute to Doppler spreading of the received signal => increase of the signal bandwidth**



2.5 Receiver noise, noise figure, SNR, and BER

Noise:

- Any random interference unrelated to the signal of interest .
- Stochastic, not deterministic.
- Contribution of system noises:
 - sky, ground, galaxy, circuit, and medium.

Thermal noise:

- Thermally induced motion of electrons in conducting media.
- Present in any linear passive resistor (including radiation resistance of antennas, loudspeakers, microphones).
- Purely reactive components generate no thermal noise (i.e., only the real part of reactive components generate noise).
- Directly proportional to temperature T (unlike shot noise associated with direct current flow and present in diodes and transistors).
- From the central limit theorem (CLT), the thermal noise is **zero-mean Gaussian distributed**.

2.5 Receiver noise, noise figure, SNR, and BER

Thermal noise

- The 2-sided PSD of thermal noise in a resistor is [W/Hz]

$$S_n(f) = \frac{2h|f|}{\exp\left(\frac{h|f|}{kT}\right) - 1}$$

T : absolute temp. in Kelvin

k=1.38x10⁻²³ J/K: Boltzmann's constant

h=6.63x10⁻³⁴ Js: Planck's constant

– For $f \ll \frac{kT}{h} \approx 6 \times 10^{12}$, $\exp\left(\frac{h|f|}{kT}\right) \approx 1 + \frac{h|f|}{kT}$ and $S_n(f) \approx 2kT$

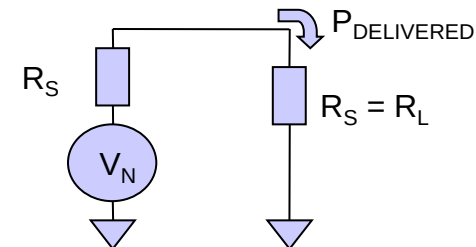
- For a resistor of R ohms in a frequency interval Δf , the mean-square voltage is: $\overline{v^2} = \overline{P}R = 2kT2\Delta fR = 4kTR\Delta f$

- The noise power delivered from an antenna is thus**

$$N_{av} = \frac{(v_N / 2)^2}{R} = kT\Delta f$$

- For antennas, the source of noise is the black-body radiation of the object at which the antenna is directed
 - Using $T = T_a = 290$ K as the temperature of the resistor modeling of the antenna is appropriate for terrestrial applications where the antenna is pointed at the horizon:

$$10\log_{10}(kT|_{T=T_a=290^\circ K}) = -203 \text{ dBW/Hz} = -174 \text{ dBm/Hz}$$



2.5 Receiver noise, noise figure, SNR, and BER

Practically, the noise added by the electronics must also be added to the noise from the input

=> concept of Noise factor (F) / Noise figure (NF)

- They relate to the contribution over the bandwidth of interest by the device itself to thermal noise at its output

- Noise factor is a measure of how much the SNF degrades as the signal passes through the system:

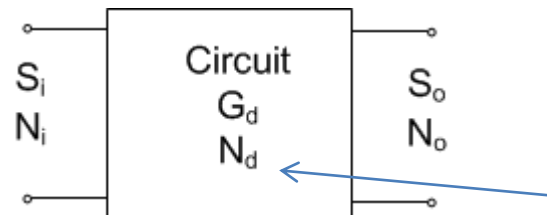
$$F = \frac{SNR_{in}}{SNR_{out}}$$

- Noise figure (NF) is expressed in dB as $NF = 10\log_{10}F$
- Assuming the above circuit, we have

- Signal at the output: $S_o = G_d S_i$
- Noise at the output: $N_o = G_d N_i + N_d$

$$F = \frac{SNR_{in}}{SNR_{out}} = \frac{N_o}{G_d N_i} = \frac{\text{tot av noise power due to device + source}}{\text{tot av output noise power due solely to source}} \geq 1$$

- If the device adds no noise, the minimum noise factor F is 1 (NF=0 dB)



N_d is the noise contribution of the device itself

2.5 Receiver noise, noise figure, SNR, and BER

Equivalent noise temperature T_e

- It is the temperature at which the source resistance R_s must be held so that the noise output from the circuit due to R_s equals the noise output of the circuit itself

- Available noise power at the device input : $N_s = kT\Delta f$

- Noise power contributed by the two-port device : $N_d = GkT_e\Delta f$

- Total output noise power :

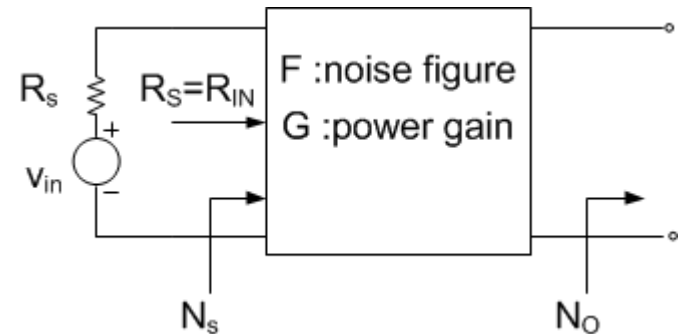
$$N_o = GN_s + N_d = Gk(T + T_e)\Delta f$$

- The noise factor of the device is thus :

$$F = \frac{N_o}{GN_s} = \frac{T + T_e}{T} \rightarrow T_e = T(F - 1) \quad \text{or} \quad F = 1 + \frac{T_e}{T}$$

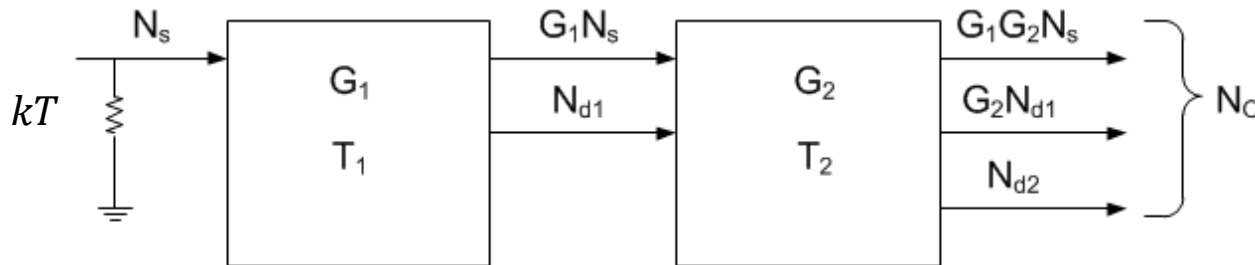
- Sometimes the noise power at the output is referred to the input, i.e.,:

$$N_{o/\text{ref.in}} = FkT\Delta f = k(T + T_e)\Delta f$$



2.5 Receiver noise, noise figure, SNR, and BER

Cascade connection of noisy networks:



Notes:

- T_o is the ambient temperature at which the networks are operating
- T_A may be different than T_o in the case of an antenna !

- We have: $N_s = kT\Delta f$, $N_{d1} = G_1 kT_1 \Delta f$, and $N_{d2} = G_2 kT_2 \Delta f$

- The overall noise N_o at the output can thus be written as:
$$N_o = G_1 G_2 k \left(T + T_1 + \frac{T_2}{G_1} \right) = G_1 G_2 k (T + T_e)$$

Generalization:

$$T_e = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \dots \quad \text{or} \quad F_e = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots$$

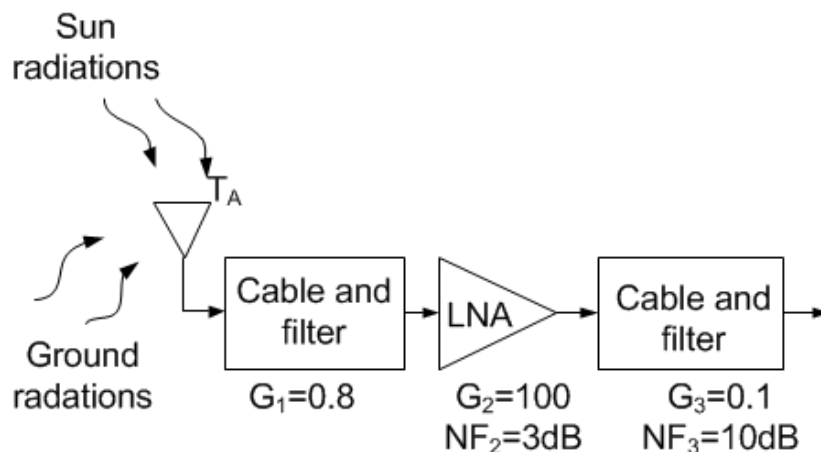
**Friis
formula for
noise**

Noise factors
and gains must
be expressed in
ratios, not dB!

- **The first stages in a cascade are the most critical!**
- **Noise temperature of next stage is divided by the gains of previous stages**
- The noise figure of a lossy circuit (passive devices such waveguides and passive filters) is equal to its loss, i.e., $F = L$

2.5 Receiver noise, noise figure, SNR, and BER

Example: Let us consider the following receiver front-end



Ambient temperature of the receiver: $T=290\text{ K}$

- The equivalent noise temperature of the front-end (not including antenna temp.) is:

$$F_e = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} = 2.6125$$

$$T_e = T(F - 1) = 467.625\text{ K}$$

- The noise power density at the output of the receiver, referred to the input, is :
 - For $T_A=290\text{ K}$

$$N_{o/\text{ref.in}} = 10 \log_{10} k(T_A + T_e) = -199.8\text{ dBW/Hz}$$

2.5 Receiver noise, noise figure, SNR, and BER

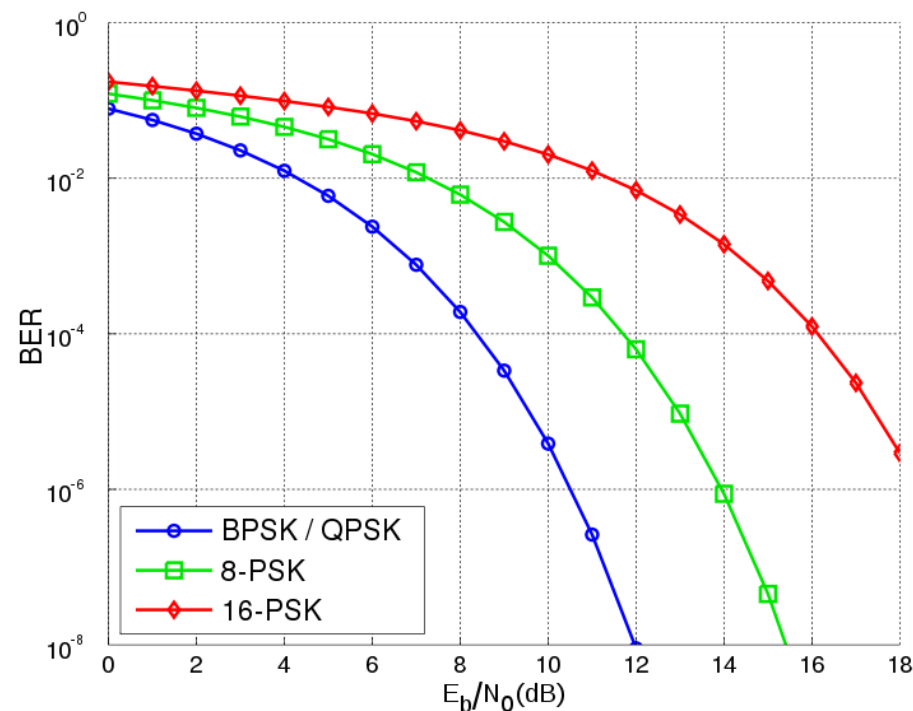
Communication systems are usually analyzed and compared in terms of their performance for different SNRs or E_b/N_o

Bit-error-rate (BER):

- Depends on the modulation scheme i.e., number of bits per symbol and the redundancy from coding

Packet-error-rate (PER):

- Correct transmission is detected on a packet-by-packet basis using a cyclic redundancy check (CRC)
- Packets with 1 or more errors are discarded completely
- $PER = 1 - (1 - P_b)^L$ for a packet with L bits



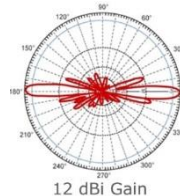
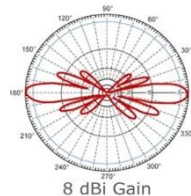
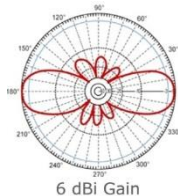
Source: A. Burg

2.6 Receiver link budget

- A Link budget ensures sufficient signal to noise ratio for reliable transmission
 - A receiver requires a certain minimum received signal strength to reliably recover the data (minimum sensitivity of the receiver)
 - **Receiver sensitivity P_{min} : minimum received signal level for a given bit error rate (BER)**
 - Need to related to PER in practice
 - Usually specified by the communication chip vendor
- A simple link budget verifies that requirement is met

$$P_{TX} + G_{TX} + G_{RX} - L(f, d) - M_F = P_{RX} > P_{min}$$

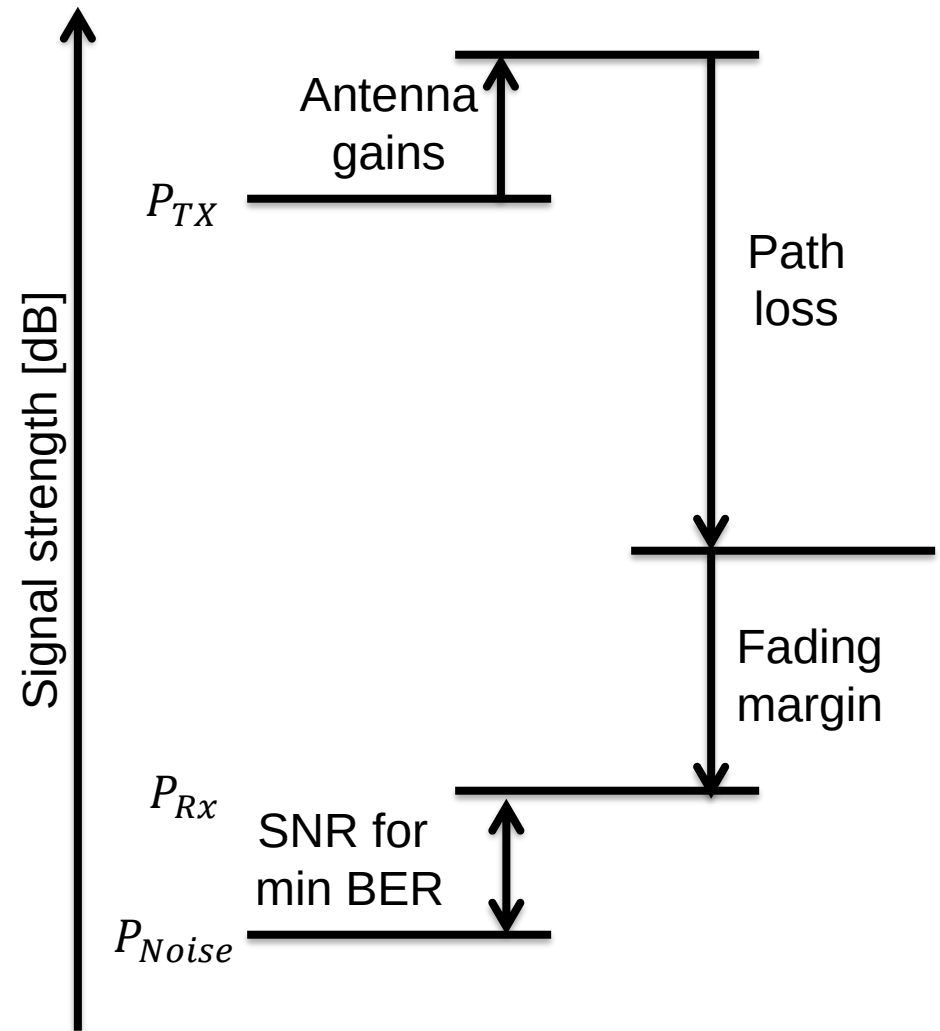
- **Output power P_{TX}** : power emitted into the antenna
- **Antenna gain G_{TX}, G_{RX}** : directivity of the antennas (omnidirectional = 0 dB)



- **Path loss $L(f, d)$** : average attenuation of the radio signal for a given distance
- **Fading margin M_F** : margin for (random) signal fluctuations (fading)

2.6 Receiver link budget

Graphical representation



Source: A. Burg

2.6 Receiver link budget

Example of a link budget for UWB communications

Parameter	Equation	Typical Value
<i>System Specifications</i>		
Channel data rate	f_b	100 kbps
Channel and signal bandwidth	B_T	1 GHz
Center frequency (arithmetic mean)	f_c	0.5 GHz
Maximum PSD	$\text{PSD}_{\max}$	-41.3 dBm/MHz
<i>Noise Power Density</i>		
Noise power density at antenna	kT	-173.8 dBm/Hz
RX Amplifier Noise Figure	NF	5 dB
Noise power density at detector	$\mathcal{N}_0 = kT + \text{NF}$	-168.8 dBm/Hz
<i>Signal Energy per bit</i>		
Average Transmit Power	$P_t = \text{PSD}_{\max} \cdot B_T$	-11.3 dBm
TX Antenna Gain	G_t	-3 dBm
Path Loss at 1 m	$L_1 = 20 \log_{10}(4\pi f_c/c)$	26.4 dB
RX Antenna Gain	G_r	-3 dBm
RX Power at 1 m	$P_r = P_t + G_t + G_r - L_1$	-43.7 dBm
RX Energy per bit at 1 m	$\mathcal{E}_b(1) = P_r - 10 \log_{10}(f_b)$	-93.7 dBm/Hz
$\mathcal{E}_b/\mathcal{N}_0$ at 1 m	$\mathcal{E}_b(1) - \mathcal{N}_0$	75.1 dB
<i>SNR per bit</i>		
Path Loss at d m	$L_2(d) = 10\gamma \log_{10}(d)$	$\gamma = 2.0$ $\gamma = 3.3$
$\mathcal{E}_b/\mathcal{N}_0$ at 2 m	$\mathcal{E}_b(1) - \mathcal{N}_0 - L_2(2)$	69.1 dB 65.2 dB
$\mathcal{E}_b/\mathcal{N}_0$ at 5 m	$\mathcal{E}_b(1) - \mathcal{N}_0 - L_2(5)$	61.1 dB 52.0 dB
$\mathcal{E}_b/\mathcal{N}_0$ at 10 m	$\mathcal{E}_b(1) - \mathcal{N}_0 - L_2(10)$	55.1 dB 42.1 dB
$\mathcal{E}_b/\mathcal{N}_0$ at 20 m	$\mathcal{E}_b(1) - \mathcal{N}_0 - L_2(20)$	49.1 dB 32.2 dB
$\mathcal{E}_b/\mathcal{N}_0$ at 50 m	$\mathcal{E}_b(1) - \mathcal{N}_0 - L_2(50)$	41.1 dB 19.0 dB
$\mathcal{E}_b/\mathcal{N}_0$ at 100 m	$\mathcal{E}_b(1) - \mathcal{N}_0 - L_2(100)$	35.1 dB 9.1 dB

System specifications are application dependent. The shown specs are taken from a local positioning system application scenario

Noise power density mainly coming from captured thermal noise and noise figure of first amplifier (low noise amplifier)

Signal energy per bit is computed by subtracting all the losses from the transmitted energy. Here, a reference distance of 1m is considered for calculating the path loss

SNR is considered for different communication ranges using a log-distance path loss model.

- A path loss exponent of 2 correspond to a free space propagation
- A path loss exponent of 3.3 corresponds to a worst case assumption for an indoor propagation channel

2.7 Spectrum regulations

The electromagnetic spectrum is a shared medium

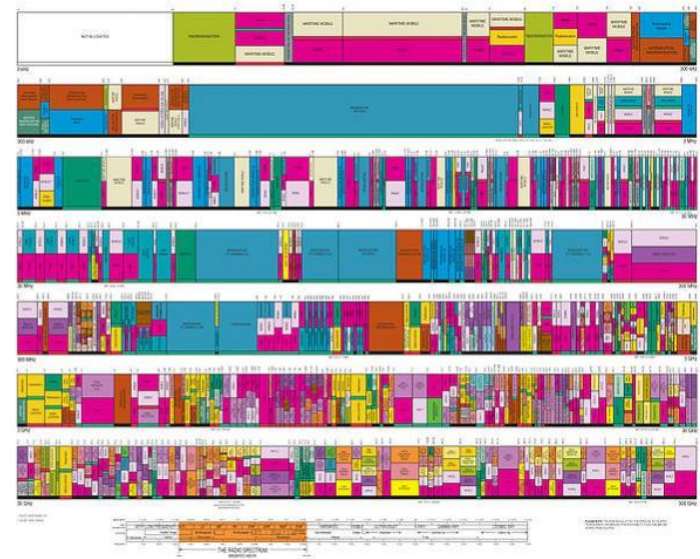
- Concurrent emissions at the same frequency interfere with each other
- Electronic devices cause emissions into the radio frequency bands
- Transmitted power determines the range of interference



Use of the EM spectrum is regulated on national and international level

- International regulating body: **ITU-R**
- Division into frequency bands assigned to services
- Bands can be **licensed** or **unlicensed**
- Licensed bands:
 - Services with a large coverage and signal power
 - TV, GSM, Satellite, ...

UNITED STATES FREQUENCY ALLOCATIONS THE RADIO SPECTRUM



2.7 Spectrum regulations

WLAN, WPAN, WBAN use unlicensed frequency bands

- Available for private or ad-hoc use
- **ISM : Industrial, Scientific, and Medical band**
 - Originally reserved internationally for non-commercial use of RF electromagnetic fields.
 - Today also used for license-free error-tolerant communications applications such as wireless LANs and Bluetooth.
- In Europe: **SRD: Short Range Devices**
- Used without license under certain conditions: **limited power, maximum bandwidth, and coexistence** (e.g., scan for and avoid radar)

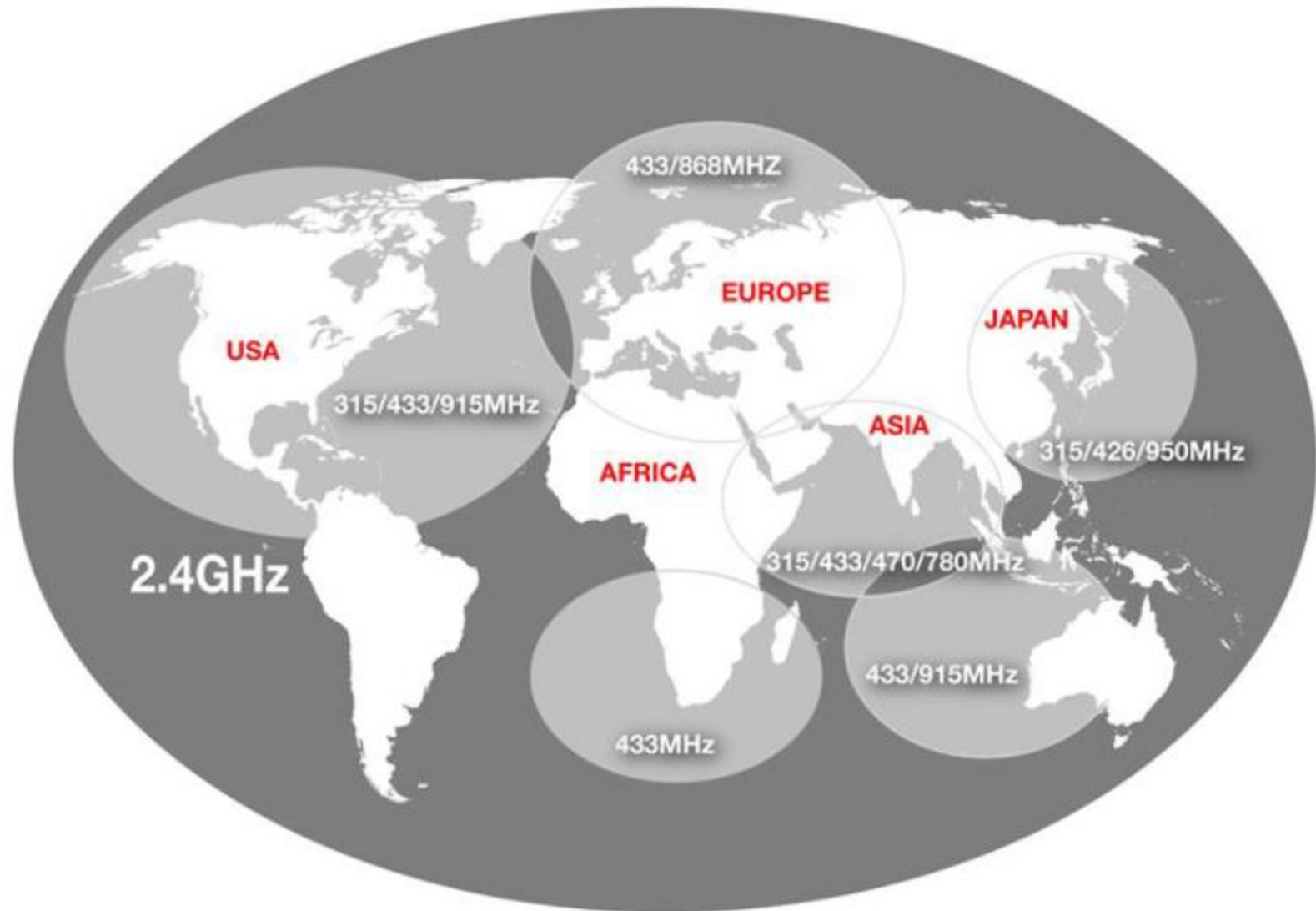
- Available bandwidth grows with frequency 😊
- Signal attenuation also grows with frequency ☹️

Frequency range		Region
13.553	13.567 MHz	World
26.957	27.283 MHz	World
40.660	40.700 MHz	World
433.050	434.790 MHz	Europe
902.000	928.000 MHz	US
2.400	2.500 GHz	World
5.725	5.875 GHz	World
24.000	24.250 GHz	World

$$P_r(R) = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \propto \lambda^2 \propto \frac{1}{f^2}$$

2.7 Spectrum regulations

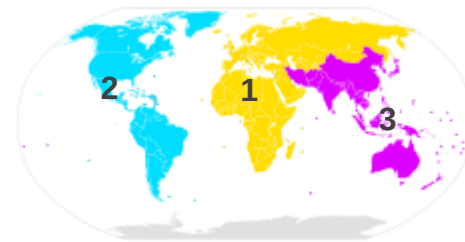
ISM/SRD frequency bands



2.7 Spectrum regulations

ISM bands defined by the ITU-R

Frequency range		Bandwidth	Center frequency	Availability
6.765 MHz	6.795 MHz	30 kHz	6.780 MHz	Subject to local acceptance
13.553 MHz	13.567 MHz	14 kHz	13.560 MHz	Worldwide
26.957 MHz	27.283 MHz	326 kHz	27.120 MHz	Worldwide
40.660 MHz	40.700 MHz	40 kHz	40.680 MHz	Worldwide
433.050 MHz	434.790 MHz	1.74 MHz	433.920 MHz	Region 1 only, subject to local acceptance (within the amateur radio 70 cm band)
902.000 MHz	928.000 MHz	26 MHz	915.000 MHz	Region 2 only (with some exceptions)
2.400 GHz	2.500 GHz	100 MHz	2.450 GHz	Worldwide
5.725 GHz	5.875 GHz	150 MHz	5.800 GHz	Worldwide
24.000 GHz	24.250 GHz	250 MHz	24.125 GHz	Worldwide
61.000 GHz	61.500 GHz	500 MHz	61.250 GHz	Subject to local acceptance
122.000 GHz	123.000 GHz	1 GHz	122.500 GHz	Subject to local acceptance
244.000 GHz	246.000 GHz	2 GHz	245.000 GHz	Subject to local acceptance



ITU regions

In Europe, the use of the ISM band is covered by short range device (SRD) regulations issued by the European commission, based on technical recommendations by CEPT and standards by ETSI.

Source: http://en.Wikipedia.Org/wiki/ism_band (oct 30, 2014)

- Regulations on the use of an ISM band often also include various restrictions such as
 - A constraint on the maximum radiated power
 - Constraints on equivalent isotropic radiated power (EIRP):
Total power that would be radiated an isotropic antenna that would provide the same power level in the direction of the maximum power of the antenna under consideration
 - Requirements to check for other signal sources in the same frequency band and to back off in the case of a collision (sometimes related to radar)
 - Maximum duty cycle for a single device

The 2400–2483.5 MHz ISM band

- **2.4 GHz Pros**

- Available for license-free operation in most countries
- Same solution for all markets without SW/HW alterations
- Large bandwidth available, allows many separate channels and high datarates
- 100% duty cycle is possible
- More compact antenna solution than below 1 GHz

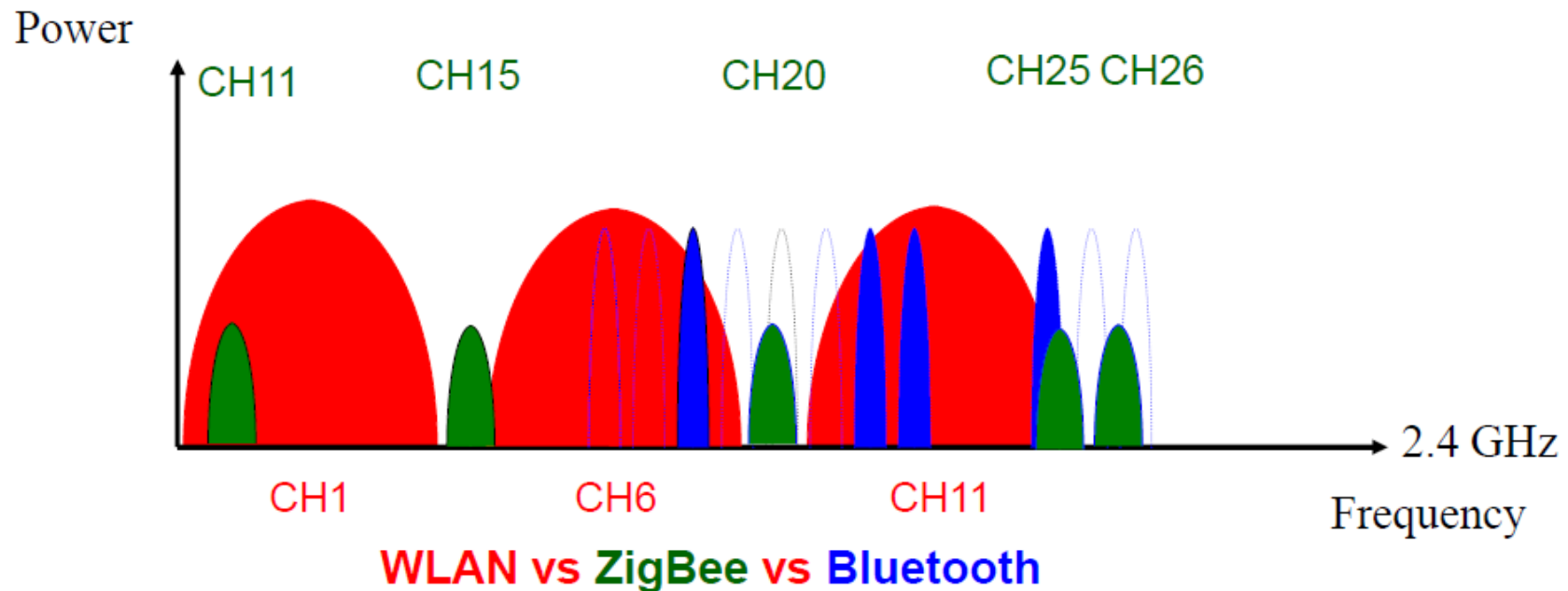
- **2.4 GHz Cons**

- Shorter range than a sub 1 GHz solution (with the same current consumption)
- Many possible interferers are present in the band

2.7 Spectrum regulations

The 2400–2483.5 MHz ISM band

- Due to the world-wide availability the 2.4GHz ISM band it is getting more crowded day by day.
- Devices such as Wi-Fi, Bluetooth, ZigBee, cordless phones, microwave ovens, wireless game pads, toys, PC peripherals, wireless audio devices and many more occupy the 2.4 GHz frequency band.



Source:  TEXAS INSTRUMENTS

2.7 Spectrum regulations

Sub 1 GHz ISM Band

902-928 MHz is the main frequency band in the US

- The 260-470 MHz range is also available, but with more limitations

The 902-928 MHz band is covered by FCC CFR 47, part 15

- Sharing of the bandwidth is done in the same way as for 2.4 GHz:
 - *Higher output power is allowed if you spread your transmitted power and don't occupy one channel all the time.* FCC CFR 47 part 15.247 covers wideband modulation
 - Frequency Hopping Spread Spectrum (FHSS) with **≥ 50 channels are allowed up to 1 W**, FHSS with **25-49 channels up to 0.25 W**
 - Direct Sequence Spread Spectrum (DSSS) and other digital modulation formats with **bandwidth above 500 kHz are allowed up to 1W**

FCC CFR 47 part 15.249

- **"Single channel systems" can only transmit with ~ 0.75 mW output power**

Source:  TEXAS
INSTRUMENTS

2.7 Spectrum regulations

Sub 1 GHz ISM Band

- **Sub 1GHz Pros**

- **Better range than 2.4 GHz** with the same output power and current consumption
- **Lower frequencies have better penetration** through concrete and steel (buildings and office environments) compared to 2.4 GHz

- **Sub 1GHz Cons**

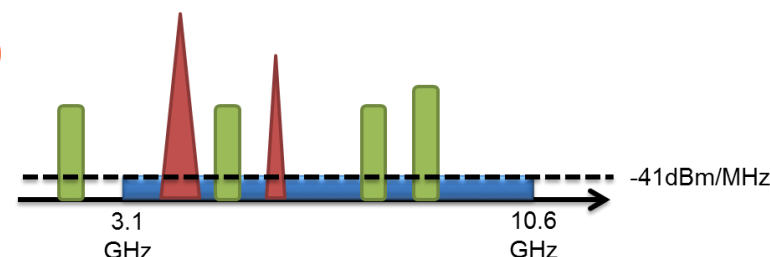
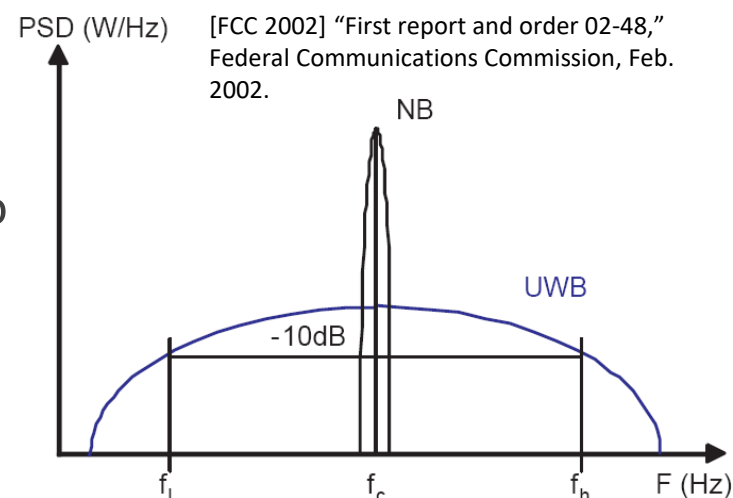
- **No worldwide solution possible.** Since different bands are used in different regions a custom solution has to be designed for each area
- Limitations vary a lot from region to region and getting a full overview is not an easy task
- **Duty cycle restrictions in some regions**

Source:  TEXAS
INSTRUMENTS

2.7 Spectrum regulations

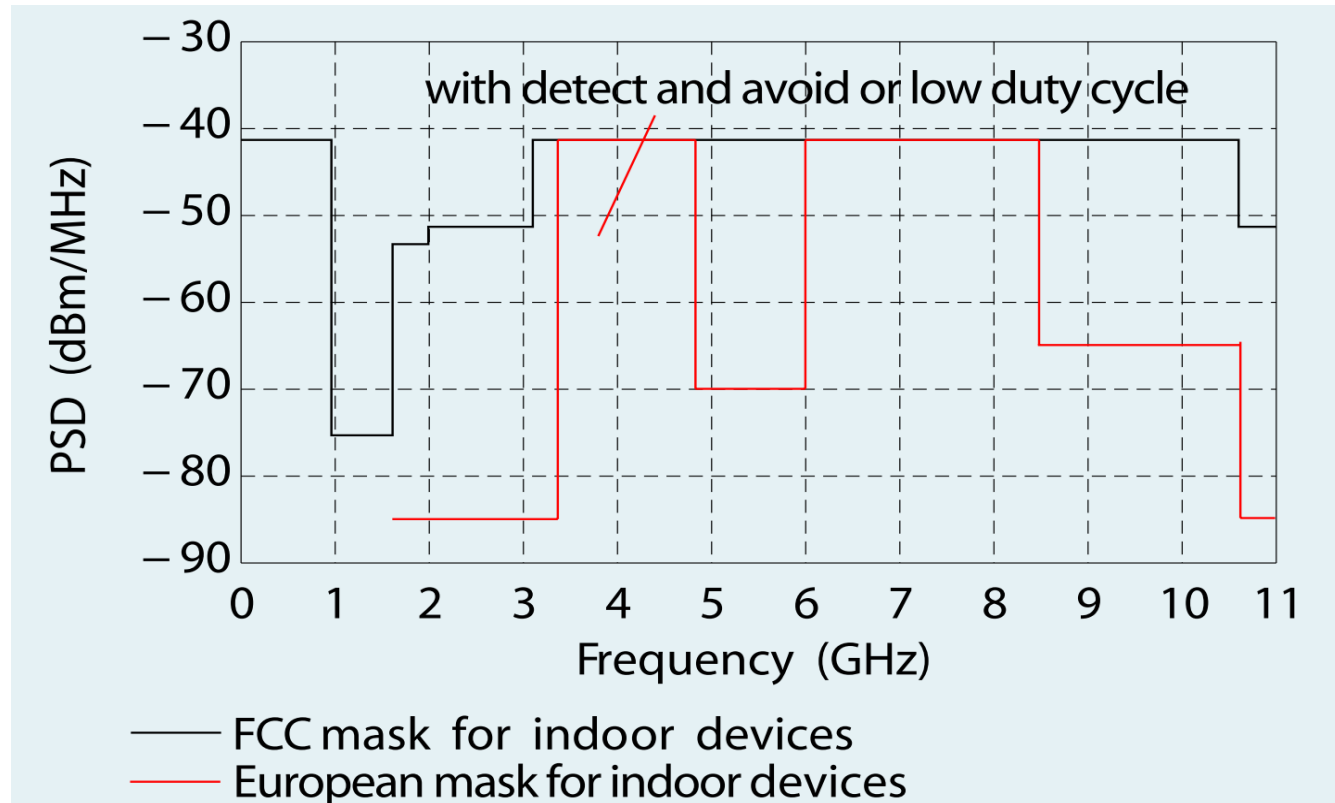
UWB radio spectrum regulations:

- [Wikipedia, August 8, 2011] “...radio technology that can be used at very low energy levels for short-range high-bandwidth communications by using a large portion of the radio spectrum”
- [US/FCC 2002]:
 - **Absolute BW** : $f_h - f_l > 500 \text{ MHz}$
 - Fractional BW : $\eta = 2 \frac{f_h - f_l}{f_h + f_l} \geq 20\%$
 - **Low transmit power density:**
 - 41.3dBm/MHz (within 3.1-10.6GHz)
 - i.e., 75 nW/MHz or 75 $\mu\text{W}/\text{GHz}$
 - Total: <1mW**



2.7 Spectrum regulations

UWB spectrum regulations in EU



[1]: 3.4 GHz – 4.8 GHz possible with **Detect and Avoid (DAA)**

[1]: 3.4 GHz – 4.8 GHz possible with **Low Duty Cycle (LDC)**

sources: ECC/DEC/(06)12 and
ECC/DEC/(06)04

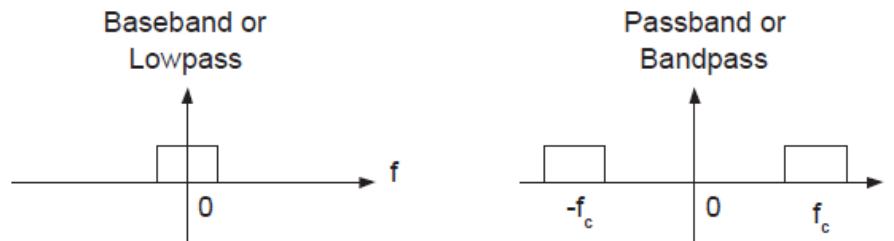
4. Signal modulation and coding

4. Signal modulation and coding

- 4.1 Signal modulation basics
- 4.2 Pulse shaping techniques
- 4.3 Optimum receivers in AWGN
- 4.4 Performance of digital modulation techniques in AWGN
- 4.5 Performance in slow flat fading channel
- 4.6 Performance in frequency selective channel

4.1 Signal modulation basics

- **Purpose of carrier modulation:**
 - **to transmit a data waveform** (a complex baseband or lowpass signal, as its frequency content is centered around 0 Hz) **in a portion of the EM spectrum** by **modulating some parameters** (e.g., amplitude, phase, frequency) **of a carrier**
- **After carrier modulation:**
 - the **baseband signal is translated at the carrier frequency** (called a bandpass signal as the frequency content is now centered around the carrier frequency)



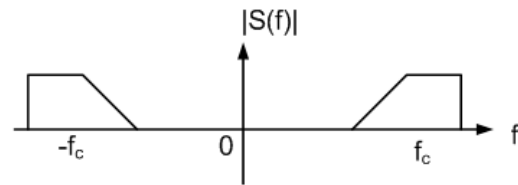
- Modulation **converts a baseband signal to a passband counterpart**

4.1 Signal modulation basics: complex baseband representation

- It is desirable to reduce all **bandpass signals and channels to equivalent lowpass signals and channels** so that the performance of various modulation and demodulation techniques can be calculated independently of the carrier frequencies and channel frequency bands.
- This is called the **lowpass or complex envelope representation**
- Definitions:
 - $s(t)$: **real bandpass signal**
 - $S(f)$: **spectrum** of the real bandpass signal $s(t)$. $S(f) = F\{s(t)\}$
 - $s_l(t)$: **complex envelope (lowpass representation) of the real signal $s(t)$**
 - $S_l(f)$: **lowpass spectrum** of the equivalent lowpass signal of $s(t)$
- In general, the lowpass signal $s_l(t)$ is complex-valued and can be expressed in terms of its **quadrature components $x(t)$ and $y(t)$** as

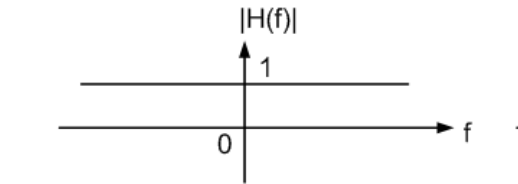
$$s_l(t) = x(t) + jy(t)$$

4.1 Signal modulation basics: complex baseband representation

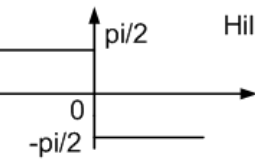


Real bandpass signal

The complex envelope of a real bandpass signal can be obtained by [Pro95]:

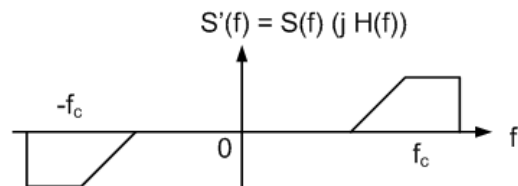


Phase H(f)

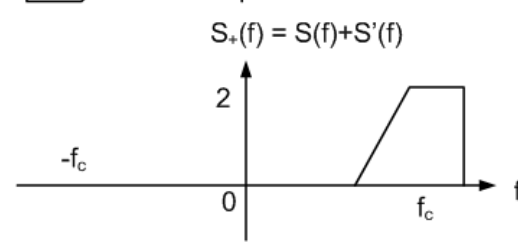


Hilbert transformer

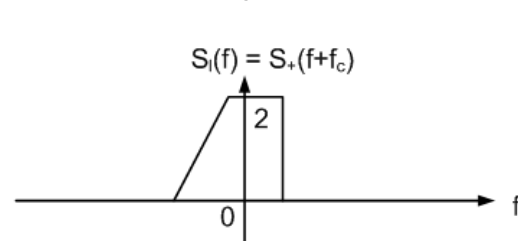
1) applying a Hilbert transform to the real bandpass signal



$S'(f) = S(f) (j H(f))$



$S_+(f) = S(f) + S'(f)$



$S_l(f) = S_+(f + f_c)$

Analytical signal or pre-envelope

Complex envelope of real bandpass signal

$$\begin{aligned}
 S_+(f) &= 2u(f)S(f) \\
 s_+(t) &= \int_{-\infty}^{\infty} S_+(f)e^{j2\pi ft} df \\
 &= F^{-1}[2u(f)] \circ F^{-1}[S(f)] \\
 &= \left(\delta(t) + \frac{j}{\pi t} \right) \circ s(t) \\
 &= s(t) + j \frac{1}{\pi t} \circ s(t) = s(t) + j \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{s(\tau)}{t - \tau} d\tau
 \end{aligned}$$

$\hat{s}(t)$ output of a Hilbert transformer
 $\circ$ denotes the convolution operator

2) adding its output to the signal to obtain the analytical signal $S_+(t)$

3) Operating a frequency translation equal to the carrier frequency

$$\begin{aligned}
 S_l(f) &= S_+(f + f_c) \\
 s_l(t) &= s_+(t)e^{-j2\pi f_c t} \\
 &= [s(t) + j\hat{s}(t)]e^{-j2\pi f_c t} \\
 \underbrace{[x(t) + jy(t)]}_{s_l(t)} e^{j2\pi f_c t} &= s(t) + j\hat{s}(t)
 \end{aligned}$$

Since $e^{j\phi} = \cos \phi + j \sin \phi$, we have $\hat{s}(t) = x(t) \sin 2\pi f_c t + y(t) \cos 2\pi f_c t$ and $s(t) = x(t) \cos 2\pi f_c t - y(t) \sin 2\pi f_c t = \text{Re} \{ \underbrace{[x(t) + jy(t)]}_{s_l(t)} e^{j2\pi f_c t} \}$

4.1 Signal modulation basics: complex baseband representation

- **Complex envelope of the real signal $s(t)$**

$$s_l(t) = x(t) + jy(t)$$

or equivalently using polar notations

$$s_l(t) = a(t)e^{j\theta(t)} \text{ where } a(t) = \sqrt{x^2(t) + y^2(t)} \text{ and } \theta(t) = \arctan \frac{y(t)}{x(t)}$$

- **Representation of a bandpass signal as a function of the lowpass signal:**

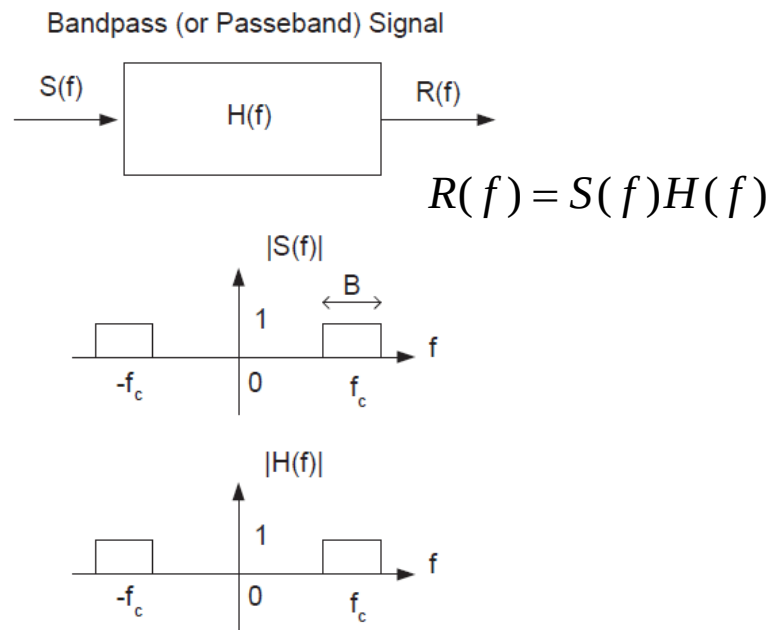
$$s(t) = \operatorname{Re}\{s_l(t)e^{j2\pi f_c t}\} = a(t) \cos[2\pi f_c(t) + \theta(t)] = x(t)\cos(2\pi f_c t) - y(t)\sin(2\pi f_c t)$$

- **Relationship between the spectrum** of the real bandpass signal (i.e., $S(f)$) and the equivalent lowpass (i.e., $S_l(f)$) :

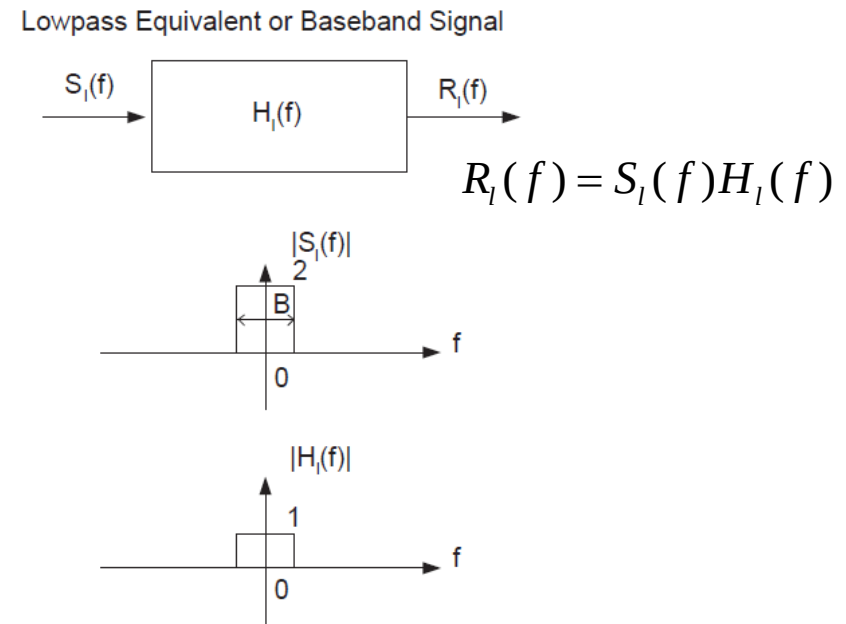
$$S(f) = \frac{1}{2}[S_l(f - f_c) + S_l^*(f + f_c)]$$

4.1 Signal modulation basics: complex baseband representation

- Response of a bandpass system to a bandpass signal



$$r(t) = s(t) \otimes h(t) = \int_{-\infty}^{\infty} s(t)h(t - \tau)d\tau$$



$$r_l(t) = s_l(t) \otimes h_l(t) = \int_{-\infty}^{\infty} s_l(t)h_l(t - \tau)d\tau$$

- These relationships allow us to ignore any frequency translation of bandpass systems to only deal with the transmission of equivalent lowpass signals through equivalent lowpass channels

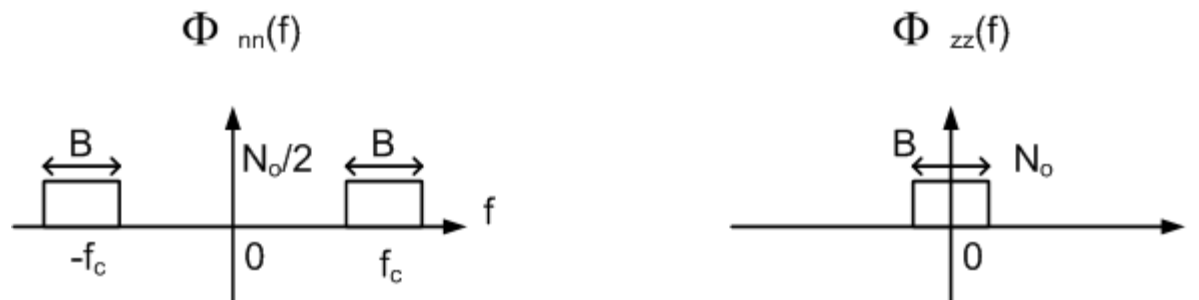
4.1 Signal modulation basics: complex baseband representation

- Representation of white noise:

- In problems concerned with the demodulation of narrowband signals, we assume that signals and noise at receiving terminals have passed through an ideal bandpass filter, having a passband that includes the spectrum of the signal but is much wider.
- Such a filter introduces negligible distortion on signal but eliminate noise frequency components outside of the passband
- Resulting noise is termed **bandpass white noise** and has the PSD and autocorrelation:

$$\Phi_{zz}(f) = \begin{cases} N_o & (|f| \leq \frac{1}{2}B) \\ 0 & (|f| > \frac{1}{2}B) \end{cases} \quad \phi_{zz}(\tau) = N_o \frac{\sin \pi B \tau}{\pi \tau}$$

- At the limit as $B \rightarrow \infty$, $\phi_{zz}(\tau) = N_o \delta(\tau)$



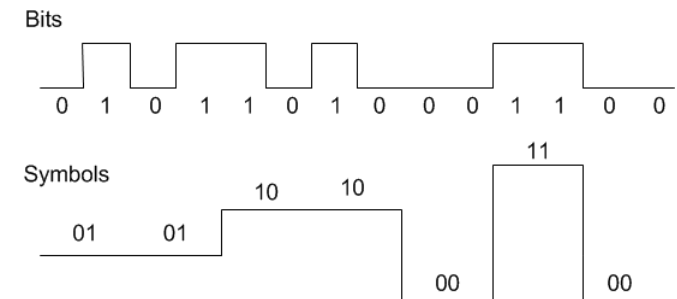
4.1 Signal modulation basics: binary vs. M-ary modulation

A **binary** digital modulated signal can be represented as a time sequence of bits or pulses, i.e., $x(t) = \sum_n b_n g(t - nT_b)$ where

- $b_n \in \{0,1\}$ or $b_n \in \{-1, +1\}$ is the bit value in the time interval $[nT_b, (n+1)T_b]$
- $g(t)$ is the pulse shape (e.g., a rectangle of length T_b or a Nyquist pulse)
- **Bit rate**: defines the rate at which information is passed (bits/s)

In **M-ary signaling**, b_n assumes M discrete levels and each transmitted level is called a symbol rather than a bit

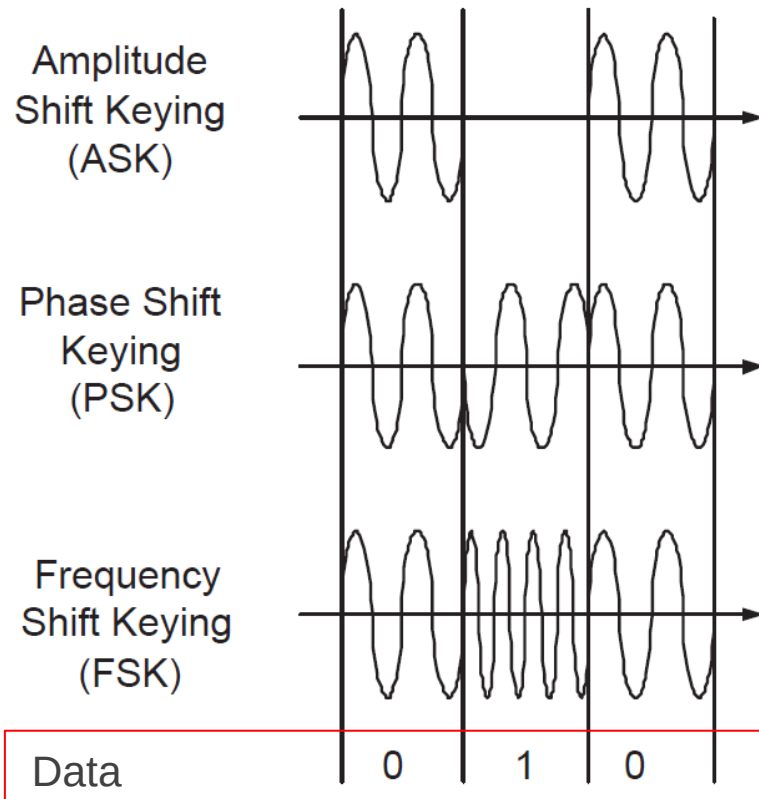
- Each symbol has $M = 2^N$ finite states and represents N bits of information, where $N = \log_2 M$ bits/symbol
- **Baud rate** (signaling rate): defines the number of symbols per second



$$\text{Symbol rate (baud rate)} = \frac{\text{bit rate}}{\text{number of bits transmitted per symbol}}$$

4.1 Signal modulation basics: binary vs. M-ary modulation

- **Examples of binary digital modulations**

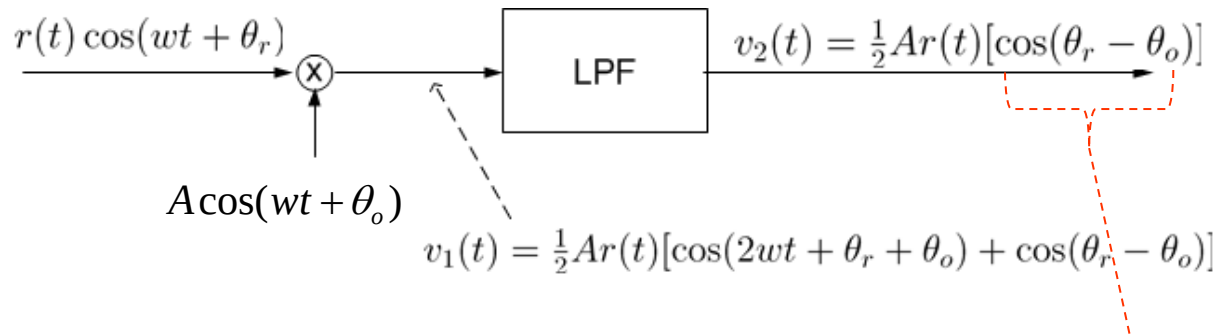


- ASK has poor performance, as it is heavily affected by noise and interference
- Binary Phase Shift Keying (BPSK) has better performance than ASK and FSK.
- Bandwidth occupancy of FSK is dependent on the spacing of the two frequencies.

- **These binary modulations can be expended to M-ary modulation, using multiple (i.e., M) amplitudes, phases, or frequencies**

4.1 Signal modulation basics: coherent vs non-coherent detection

Assume a receiver receives the waveform $r(t)\cos(\omega t + \theta_r)$ and must synthesize the waveform $A\cos(\omega t + \theta_o)$ for demodulation



- If the phase uncertainty between the two waveforms (i.e., $\theta_r - \theta_o$) is not resolved and is equal to an integer multiple of $\pi/2$, the output is zero!
- To avoid this case, the detector must synchronize with the phase of the received signal.
 - Detection schemes that require phase synchronization are called coherent
 - Coherent detectors are usually based on the matched filter concept and provide a lower BER than their non-coherent counterparts

4.1 Signal modulation basics: linear vs non-linear modulation

Linear modulations

- the transmitted signal can be represented as

$$s(t) = \text{Re}[Am(t)e^{j2\pi f_c t}] = A[m_Q(t)\cos(2\pi f_c t) - m_I(t)\sin(2\pi f_c t)]$$

where

- A is the amplitude
- f_c is the carrier frequency
- $m(t) = M_I(t) + jM_Q(t)$ is a complex envelope representation of the modulated signal
- The amplitude and phase of the carrier varies linearly with $m(t)$
 - In general, linear modulation schemes do not have a constant envelope
 - Linear modulations have good spectral efficiency, but require linear RF filter having poor power efficiency
- Linear modulation schemes include, e.g., BPSK, DPSK, QPSK, OQPSK, $\pi/4$ QPSK

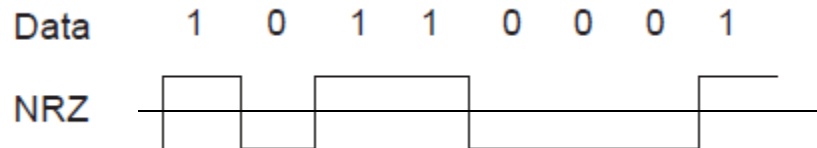
Nonlinear modulations

- the amplitude of the carrier is constant, regardless of the variation of the modulating signal
 - Power efficient Class C amplifiers can be used
 - Low out of band radiation (-60 dB to -70 dB) can be achieved
 - Can use simple receiver design
 - However, **non linear modulation schemes occupy a larger bandwidth than linear ones**
 - **Nonlinear modulation schemes include, e.g., FSK, MSK, GMSK**

4.1 Signal modulation basics: memoryless vs non-memoryless modul.

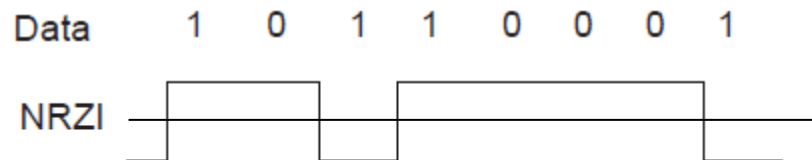
- **Memoryless modulation**: no inter-dependance between the signals transmitted in non-overlapping symbol intervals

- Example: non-return to zero modulation



- **Non-memoryless modulation**: signal dependence between the signals transmitted in different signal intervals is introduced

- Generally accomplished by encoding a data sequence at the input of the modulator by the means of a modulation code
- Example: non-return to zero inverted (output of NRZI = $b_k = a_k \oplus b_{k-1}$ (or-exclusive))



Input		XOR Output
A	B	
0	0	0
0	1	1
1	0	1
1	1	0

"One" is represented by a transition of the physical level.

"Zero" has no transition.

4.2 Pulse shaping techniques

Nyquist criterion for intersymbol interference (ISI) cancellation

- If the analog pulse is wider than the time between adjacent symbols, the outputs from adjacent symbols may overlap => ISI
- Idea: **Design a filter (Nyquist filter) such that the overall response of the communication system (including tx, channel, rx,) due to all symbols except the current one is zero at sampling instants, i.e.,**

$$h_{eff}(kT_s) = \begin{cases} 1 & k = 0 \\ 0 & k \neq 0 \end{cases}$$

- After sampling at instants kT_s

$$h_{eff}(t) \sum \delta(t - kT_s) = \delta(t)$$

- Taking the Fourier transform in both sides

$$H_{eff}(f) \circ \frac{1}{T_s} \sum \delta\left(f - \frac{k}{T_s}\right) = 1$$

$$\frac{1}{T_s} \sum H_{eff}\left(f - \frac{k}{T_s}\right) = 1$$

- That is, **the shifted replicas of $H_{eff}(f)$ must add up to a flat spectrum**

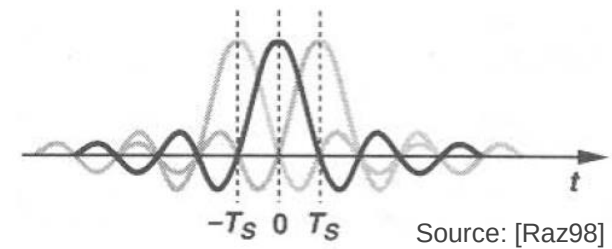


Figure 2.14 Pulse shape with no ISI.

Source: [Raz98]

4.2 Pulse shaping techniques

Nyquist pulse

- Sinc pulse

$$h_{eff}(t) = \frac{\sin(\pi t/T_s)}{\pi t/T_s} = \text{sinc}\left(\frac{\pi t}{T_s}\right)$$

- For zero ISI: $T_s = 1/2W$
=> this is the smallest value for T_s leading to the **Nyquist rate of $1/T_s = 2W$**

- Problems:

- **$h_{eff}(t)$ is noncausal ($h_{eff}(t)$ exists for $t < 0$)**
=> use delayed version and shifted sampling times
- **Complex filter difficult to approximate** (rectangular spectrum has sharp cutoffs)
- **The waveform decays slowly with time (slope of $1/t$ at each zero crossing)**
=> error in sampling will cause significant ISI (slope of $1/t^n$, $n = 2, 3, \dots$ is more desirable)

- **Solution: raised cosine pulse**

4.2 Pulse shaping techniques

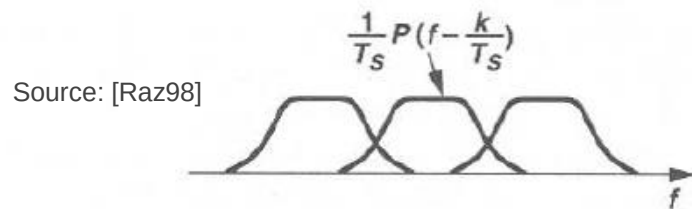
Raised cosine pulse

- Use $T_s > 1/2W \Rightarrow$ overlapping replicas of $H_{eff}(f)$ separated by $1/T$ to yield a flat spectrum:

$$h_{eff}(t) = \frac{\sin(\pi t/T_s)}{\pi t/T_s} \frac{\cos(\pi \alpha t/T_s)}{1 - 4\alpha^2 t^2/T_s^2}$$

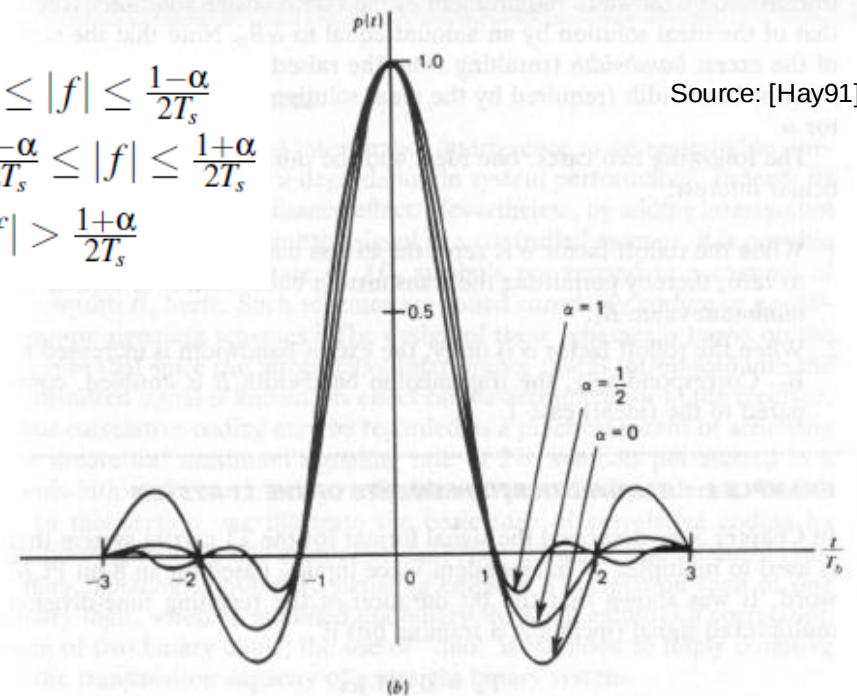
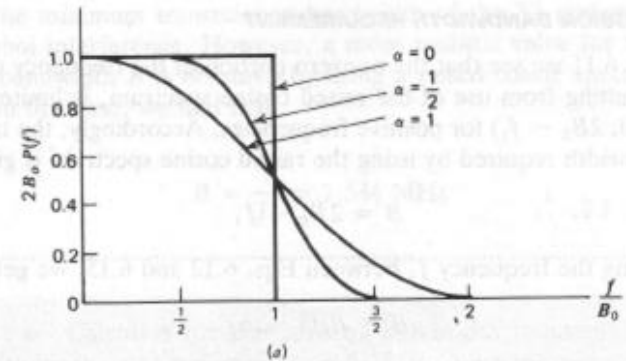
$$H_{eff}(f) = \begin{cases} T & 0 \leq |f| \leq \frac{1-\alpha}{2T_s} \\ \frac{T_s}{2} \left\{ 1 + \cos \left[\frac{\pi T_s}{\alpha} \left(|f| - \frac{1-\alpha}{2T_s} \right) \right] \right\} & \frac{1-\alpha}{2T_s} \leq |f| \leq \frac{1+\alpha}{2T_s} \\ 0 & |f| > \frac{1+\alpha}{2T_s} \end{cases}$$

where α is the rolloff factor ($0 < \alpha < 1$)



Source: [Raz98]

Figure 2.15 Nyquist's condition for the spectrum of a pulse shape that gives no ISI.



Source: [Hay91]

Figure 6.2 Responses for different rolloff factors. (a) Frequency response. (b) Time response.

4.2 Pulse shaping techniques

Raised cosine pulse

$$h_{eff}(t) = \frac{\sin(\pi t/T_s)}{\pi t/T_s} \frac{\cos(\pi \alpha t/T_s)}{1 - 4\alpha^2 t^2/T_s^2}$$

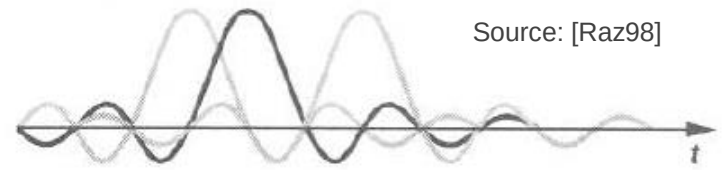


Figure 2.17 Raised-cosine filtering.

$$H_{eff}(f) = \begin{cases} T & 0 \leq |f| \leq \frac{1-\alpha}{2T_s} \\ \frac{T_s}{2} \left\{ 1 + \cos \left[\frac{\pi T_s}{\alpha} \left(|f| - \frac{1-\alpha}{2T_s} \right) \right] \right\} & \frac{1-\alpha}{2T_s} \leq |f| \leq \frac{1+\alpha}{2T_s} \\ 0 & |f| > \frac{1+\alpha}{2T_s} \end{cases}$$

- Faster decay than a sinc function
- $\alpha = 0$: $h_{eff}(t)$ reduces to a sinc function (zero excess bandwidth beyond Nyquist frequency of $1/(2T_s)$)
- $\alpha = 1$: excess bandwidth is 100% and symbol rate is $\frac{1}{T_s} = W$
- $H_{eff}(f)$ is similar to box spectrum but with smooth edges
- Trade-off in choice of α between decay rate in time domain and excess bandwidth in frequency domain (typical values are between 0.3 and 0.5)

4.3 Optimum receivers in AWGN

The optimum receiver can be decomposed into a pre-detection filter followed by a decision device

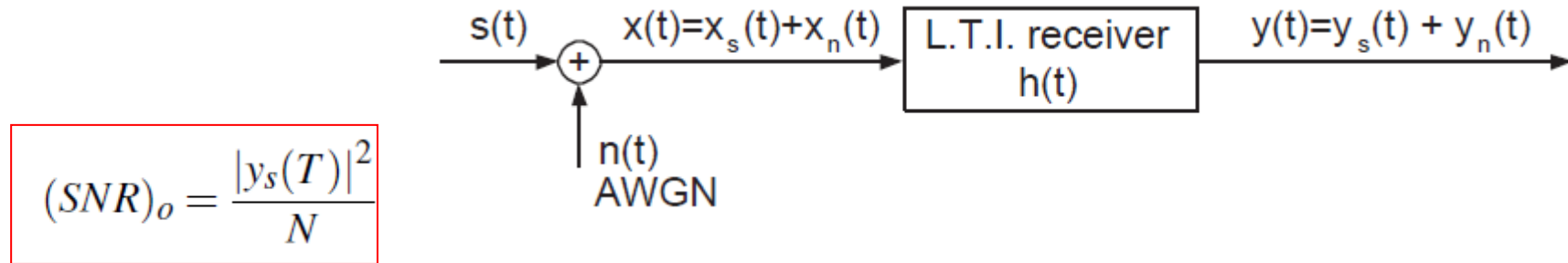
- Pre-detection filter enhances the strength of the signal relative to that of the noise
- Purpose of detection is to establish the presence or the absence of a signal in noise

Two main ideas:

- Maximization of the SNR at the output of the filter
 - Matched filter (MF) receiver
- Minimization of the probability of bit error at the output of the filter
 - Correlation receiver

4.3 Optimum receivers in AWGN: MF receiver

Goal: **maximization of SNR at the output of a filter $h(t)$** in presence of AWGN with PSD $N_o/2$ [Hay89]



- **Optimum matched filter:** $h(t) = s(T - t) \square \quad H(f) = X_s^*(f) e^{-j2\pi fT}$
 - Impulse response of the optimum filter $h(t)$ is a time-reversed and delayed version of the input signal $s(t)$.
- **Optimum SNR:** $SNR_{opt} = 2E_s / N_o$
 - Output SNR of a MF only depends on the ratio of the signal energy to the noise PSD at the filter input
 - All signals that have the same energy are equally effective using a matched filter!

4.3 Optimum receivers in AWGN: correlation receiver

Goal: minimization of the probability of bit error at the output of the filter [Hay89]

- The receiver must choose between hypothesis H_0 and hypothesis H_1 , corresponding to the transmission of a 0 or a 1, respectively, i.e.,

- $H_0: x(t) = s_0(t) + n(t)$
- $H_1: x(t) = s_1(t) + n(t)$

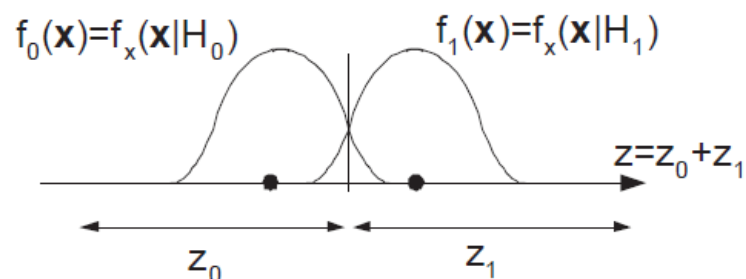
- The a-priori prob. are

- H_0 with prob. p
- H_1 with prob. q

- The conditional prob. are

- $f_0(\mathbf{x})$: cond. pdf of $\mathbf{x}$ given H_0 is true
- $f_1(\mathbf{x})$: cond. pdf of $\mathbf{x}$ given H_1 is true

- Solution: choose z_0 if $pf_0x > qf_1x$ and z_1 otherwise**
i.e., form the (log-)likelihood test



$$\begin{aligned} P_e &= p \int_{z_1=z-z_0} f_0(\mathbf{x}) d\mathbf{x} + q \int_{z_0} f_1(\mathbf{x}) d\mathbf{x} \\ &= p + \int_{z_0} [qf_1(\mathbf{x}) - pf_0(\mathbf{x})] d\mathbf{x} \end{aligned}$$

$$l(\mathbf{x}) = \frac{f_1(\mathbf{x})}{f_0(\mathbf{x})} \begin{matrix} >_{H_1} \\ <_{H_0} \end{matrix} \frac{p}{q}$$

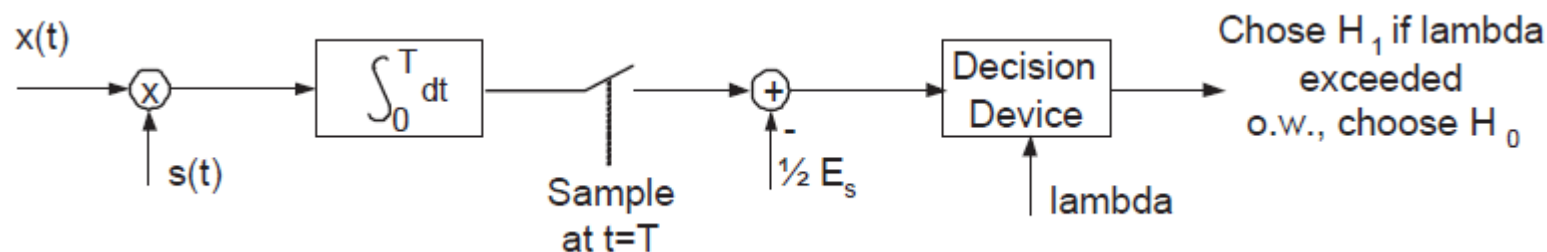
4.3 Optimum receivers in AWGN: correlation receiver

- For the AWGN case, this corresponds to test:

$$\int_0^T s(t)x(t)dt - E_s/2 \stackrel{H_1}{\underset{H_0}{><}} \lambda$$

where $E_s = \int_0^T s^2(t)dt$ and we defined the threshold λ as $\lambda = \frac{N_o}{2} \ln \left(\frac{p}{q} \right)$

- The above decision rule can be implemented using a **correlation receiver**:



- The correlation receiver output and the MF output are equivalent (only at time $t = T$)**

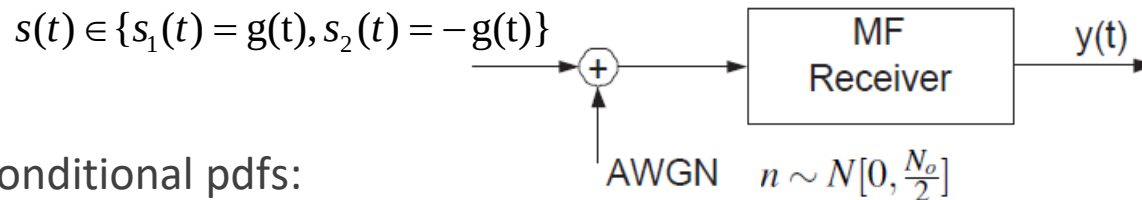
$$\int_0^T s(t)x(t)dt = - \int_T^0 s(T-\tau)x(T-\tau)d\tau = \int_0^T h_{opt}(t)x(T-\tau)d\tau$$

- The correlator becomes a simple integrator when $s(t)$ is rectangular
- For the case of unequal prior probabilities, it is necessary to know the prior probabilities as well as the noise PSD in order to calculate the threshold

4.4 Performance of digital modulation techniques in AWGN

Example: binary pulse modulation

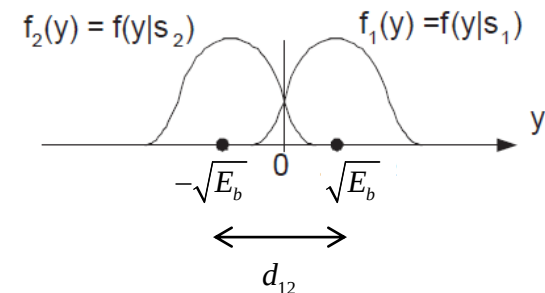
- Let us define $g(t)$: a pulse that is only non-zero in the time interval $0 \leq t \leq T_b$



- Conditional pdfs:

$$f(y|s_1) = \frac{1}{\sqrt{\pi N_o}} \exp \left\{ -\frac{(y - \sqrt{E_b})^2}{N_o} \right\}$$

$$f(y|s_2) = \frac{1}{\sqrt{\pi N_o}} \exp \left\{ -\frac{(y + \sqrt{E_b})^2}{N_o} \right\}$$



- P_e given s_1 was transmitted

$$\begin{aligned} P(e|s_1) &= \int_{-\infty}^0 f(y|s_1) dy = \frac{1}{\sqrt{\pi N_o}} \int_{-\infty}^0 \exp \left\{ -\frac{(y - \sqrt{E_b})^2}{N_o} \right\} dy = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{-\sqrt{2E_b}/N_o} e^{-x^2/2} dx = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{2E_b}/N_o}^{\infty} e^{-x^2/2} dx \\ &= Q \left(\sqrt{\frac{2E_b}{N_o}} \right) = P(e|s_2) \quad \text{where} \quad Q(x) \stackrel{\text{def}}{=} \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2} dt \stackrel{\text{def}}{=} \frac{1}{2} \operatorname{erfc} \left(\frac{x}{\sqrt{2}} \right), x \geq 0 \end{aligned}$$

- The average prob. of error assuming that $s_1(t)$ and $s_2(t)$ are equally likely is thus: $P_b = Q \left(\sqrt{\frac{2E_b}{N_o}} \right)$
 - P_b can also be expressed in terms of the minimum Euclidean distance between the two signals (here $d_{12} = 2\sqrt{E_b}$), hence

$$P_b = Q \left(\sqrt{\frac{d_{12}^2}{2N_o}} \right)$$

4.4 Performance of digital modulation techniques in AWGN

Probabilities of bit error rate for other modulations

- **On-off keying (OOK)**

$$P_b = Q\left(\sqrt{\frac{E_b}{N_o}}\right) \quad s_m(t) = \begin{cases} \operatorname{Re}[g(t)e^{j2\pi f_c t}] = g(t) \cos(2\pi f_c t) & m = 1 \\ 0 & m = 2 \end{cases}$$

- This form of amplitude modulation requires a **factor of 2 increase in energy** to achieve the same error prob. as antipodal signals

- **Quadrature phase shift keying (QPSK)**

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_o}}\right) \quad s_m(t) = \operatorname{Re}[g(t)e^{j\frac{\pi}{2}(m-1)}e^{j2\pi f_c t}], \quad m = 1, 2, \dots, 4, \quad 0 \leq t \leq T_s$$

- Identical error prob. as for BPSK
- Twice the spectrum efficiency as compared to BPSK
- QPSK can be viewed as 2xBPSK using two carriers that are in phase-quadrature

- **Offset Quadrature phase shift keying (QPSK)**

- Similar as QPSK but using different time alignment of even and odd bit stream to reduce the envelope variations (and the spectral regrowth)
- Can use more efficient nonlinear amplifiers at the transmitter which consume less
- Same performance as QPSK, but can not be detected with differential encoding (non-coherent decoding)

4.4 Performance of digital modulation techniques in AWGN

- **Binary orthogonal frequency shift keying (BFSK)**

$$P_b = Q\left(\sqrt{\frac{E_b}{N_o}}\right) \quad s_m(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + 2\pi m \Delta f t), m = \{1, 2\}, 0 \leq t \leq T$$

- where Δf denotes the frequency separation between adjacent signals. The min. separation to maintain orthogonality (leading to zero cross-correl. coeff.) is $\Delta f = \frac{1}{2T}$
- **Orthogonal signals require a factor of two increase in energy to achieve the same error probability as antipodal signals** (3 dB poorer than antipodal signals (due to a smaller min. distance between the constellation points))
- **BFSK is often used in low data rate applications (because of its simplicity in detection and its power efficiency)**
- Switching between two independent oscillators to generate a FSK signal (according to the data bits 0 and 1) results in a waveform that is discontinuous at the switching times
 - This type of FSK is called discontinuous FSK and may cause problems (spectral spreading and spurious transmission)

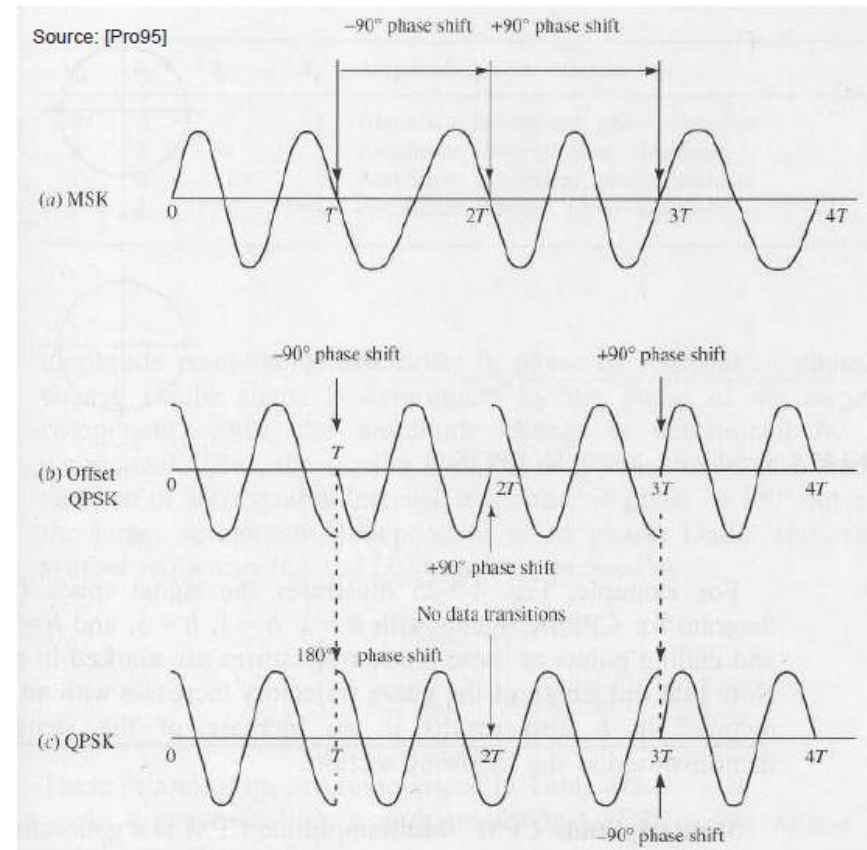
- **Binary Continuous Phase FSK (Binary CPFSK)**

- **Similar as BFSK but without waveform discontinuities**
 - Obtained by integrating the data bit waveform
- $$s_m(t) = \sqrt{\frac{2E_b}{T}} \cos\left(2\pi f_c t + \underbrace{2\pi h \int_{-\infty}^t d(\tau) d\tau}_{\phi(t)} + \phi_o\right)$$

4.4 Performance of digital modulation techniques in AWGN

- **Minimum shift keying**

- special form of continuous phase-frequency shift keying (CPFSK) in which the modulation index $h = \frac{1}{2}$
- The change in carrier frequency from symbol 1 to 2, or vice versa, is equal to half the bit rate, i.e., $\Delta f = |f_1 - f_2| = \frac{1}{2T}$ (min. separation to ensure orthogonality)
- MSK is attractive as it possesses
 - Constant envelope (phase continuity) $\Rightarrow$ can use nonlinear amplifiers
 - Spectral efficiency
 - Good BER performance (same as QPSK when coherently detected in AWGN)
 - Simple demodulation and synchronization circuits



- MSK can also be represented as a special form of OQPSK in which the pulse-shape is one-half cycle of a sinusoid

4.4 Performance of digital modulation techniques in AWGN

- **Gaussian Minimum shift keying**

- In MSK, the rectangular pulse used for QPSK was replaced with a half sinusoidal pulse, thus leading to better performance than QPSK and OQPSK

- **In GMSK, The pulse shape $g(t)$ is obtained by passing the baseband rectangular pulse through a filter having a Gaussian impulse response**

$$h(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{t^2}{2\sigma^2}}$$

- Gaussian filter generates a signal with low side lobes and narrower main lobe than the rectangular pulse
- For causality, a Gaussian-like shape is used
- The GMSK filter is completely defined from B, the -3 dB bandwidth of the premodulation Gaussian pulse-shaping filter, and T, the baseband symbol duration

- **Properties**

- **Excellent spectral efficiency** (less sidelobes as compared to MSK)
- **Excellent power efficiency** (constant envelope)
- **As the BT product decreases, the spectrum becomes narrower but ISI becomes more significant, especially below 0.5** (GMSK allows the modulating pulse to be wider than T_b , thus suffering from ISI)

- **The average prob. of error for coherent detection of GMSK is** $P_b = Q\left(\sqrt{\gamma \frac{2E_b}{N_o}}\right)$
where $\gamma \approx 0.68$ for GMSK with $BT = 0.25$

$\gamma \approx 0.85$ for simple MSK

Trade-off in M-ary signaling data transmission

- **M-ary PSK:**

- For M-ary PSK signals, the channel bandwidth is simply the bandwidth of the signal pulse $g(t)$
- Assume that $g(t)$ has duration T and bandwidth $W = 1/T$
- Since $T = \frac{k}{R} = \frac{\log_2 M}{R}$ (k bits per symbol and R is the bit rate),

$$W = \frac{1}{T} = \frac{R}{\log_2 M}$$

- The bandwidth efficiency is thus $\frac{R}{W} = \log_2 M$
- **The SNR per bit required to achieve a given BER increases as M increases at the cost of a decrease in the required channel bandwidth**

Trade-off in M-ary signaling data transmission

- **M-ary FSK:**

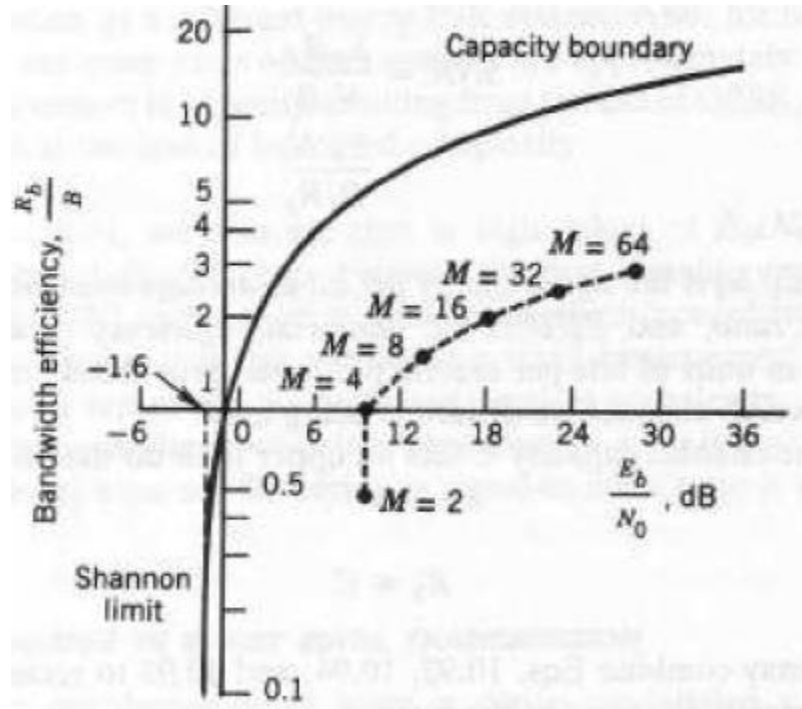
- For M-ary FSK signals, $M = 2^k$ orthogonal signals are constructed by means of orthogonal carriers with minimum frequency separation of $\frac{1}{2T}$ for orthogonality and

$$W = \frac{M}{2T} = \frac{M}{2(k/R)} = \frac{M}{2\log_2 M} R \text{ and } \frac{R}{W} = 2 \frac{\log_2 M}{M}$$

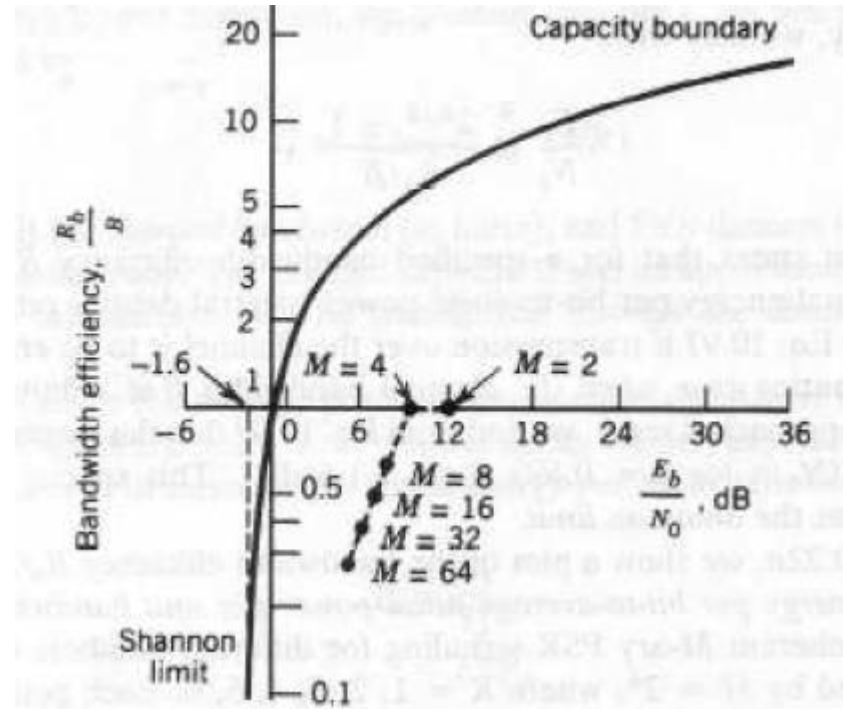
- In this case, the bandwidth increases as M increases and the bandwidth efficiency decreases
- **The SNR per bit required to achieve a given BER decreases as M increases at the cost of an increase in the required channel bandwidth**

4.4 Performance of digital modulation techniques in AWGN

Trade-off in M-ary signaling data transmission



M-ary PSK



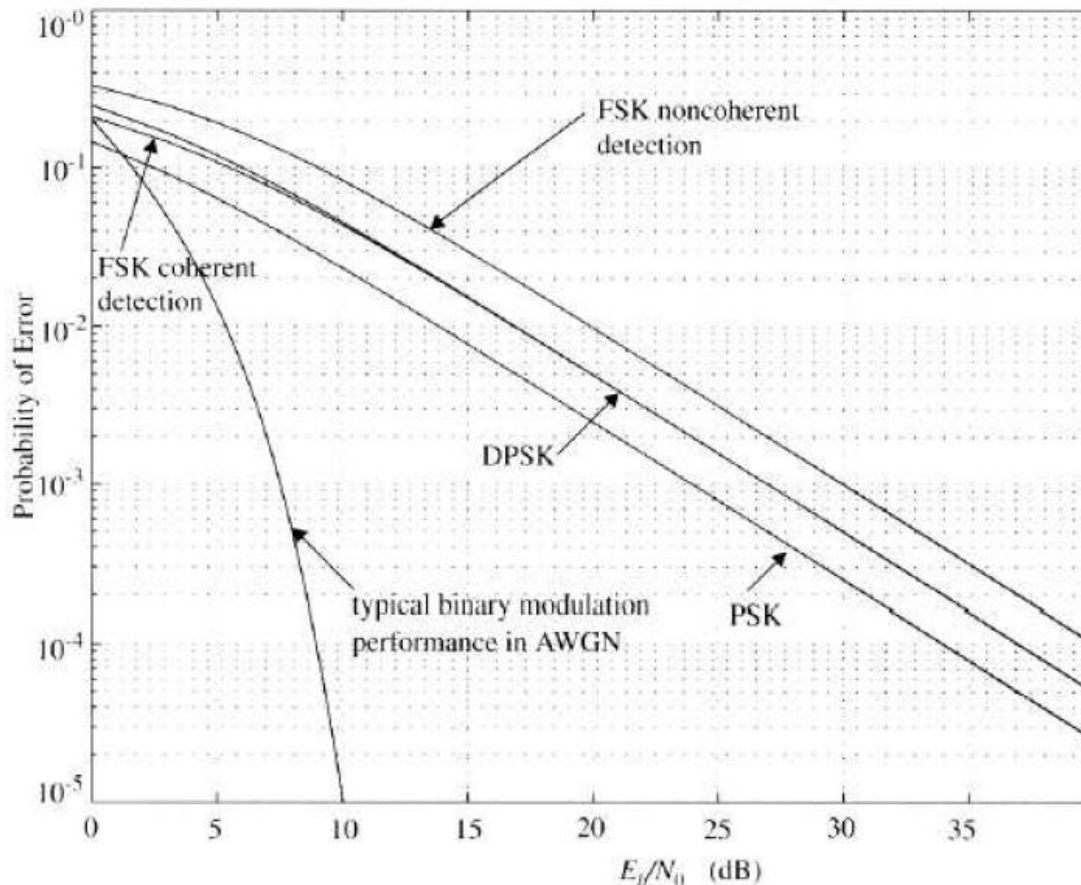
M-ary FSK

4.5 Performance in slow flat fading channel

- **Flat-fading** (frequency non-selective) channels:
 - The multipath components are not resolvable as $B \ll B_c = (\Delta f)_c$ and the channel appears as a single fading path
- **Slow** flat-fading
 - changes much slower than the applied modulation (i.e., $B \gg B_D$)
- The received equivalent low-pass signal in one signaling interval can be expressed as
$$r_l(t) = \alpha e^{-j\theta} s_l(t) + n(t), 0 \leq t \leq T$$
- For an arbitrary modulation for which the probability of error at a specific value of SNR $\gamma_b = \alpha^2 E_b / N_o$ is $P_e(\gamma_b)$, **the probability of error in a slow flat-fading channel can be evaluated as**
$$P_e = \int_0^\infty P_e(\gamma_b) p(\gamma_b) d\gamma_b$$
where
 - $p(\gamma_b)$ is the pdf of γ_b due to fading channel, i.e., chi-square for a Rayleigh fading channel
 - E_b and N_o represent the average energy per bit and noise power density in a non-fading AWGN channel, respectively (large scale propagation)

4.5 Performance in slow flat fading channel

Bit error rate of binary modulation schemes in a **Rayleigh flat fading channel** as compared to a typical curve in AWGN [Rap02]



Observation:

- The error rates decrease only inversely with SNR !
- In contrast, the decrease is exponential with SNR for a nonfading channel
- Operating at a BER of 10^{-3} to 10^{-6} requires roughly 20 to 50dB more than in nonfading AWGN channels !

Solution:

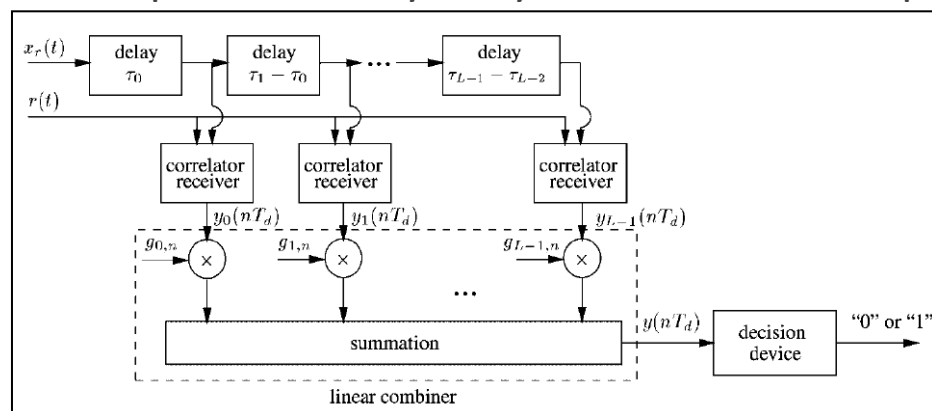
- => high transmit power necessary or use redundancy obtained by means of diversity techniques

4.5 Performance in slow flat fading channel

Slow flat fading channel mitigation:

use **diversity techniques** to provide the receiver with uncorrelated versions of the signal (E.g., time, frequency, spatial, or polarization diversity)

- **Use of error correction coding coupled with interleaving** (more efficient and powerful than repetition coding as instead of providing more signal energy it reduces the required E_b/N_o)
 - Addition of data bits in the message to allow for the recovery of the data in the event an instantaneous fade occurs in the channel
- **Use of FH/SS** (to compensate for the case when the user is moving slowly and happens to be in a spectral null)
- **Use of a Rake receiver** combined with DSSS or impulse-based UWB (combination of the multipath components delayed by more than one chip or one pulse)

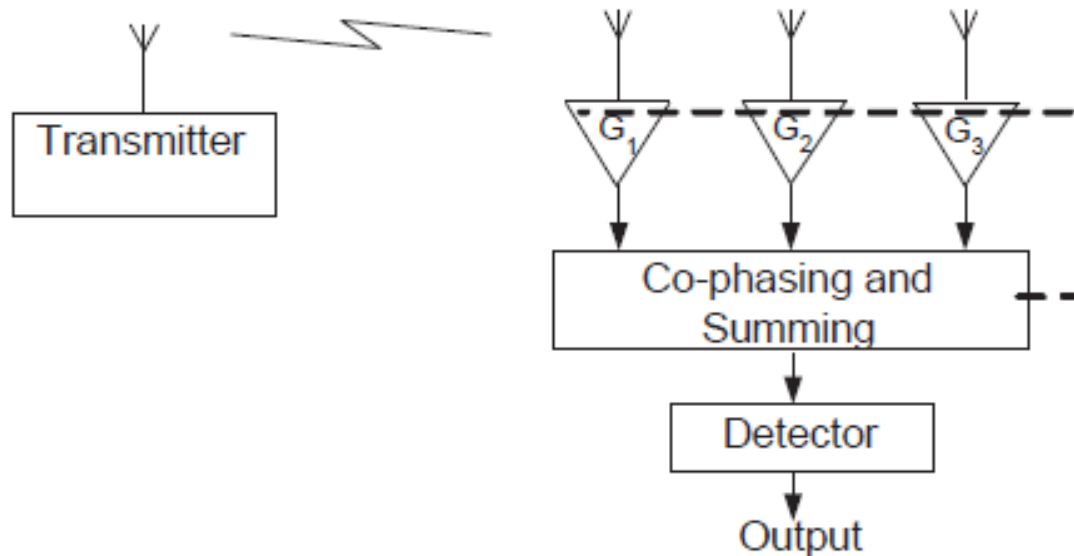


4.5 Performance in slow flat fading channel

Slow flat fading channel mitigation:

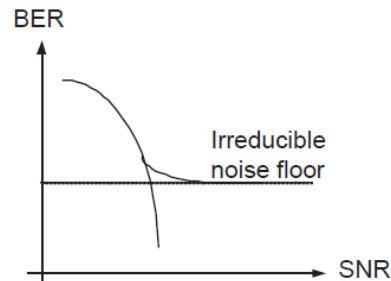
If M diversity branches are combined together using a maximum ratio combiner (MRC), the resulting mean SNR increases linearly with M

- Since the SNR for MRC is the sum of SNRs in each branch, it can produce an acceptable SNR even when none of the individual signals are themselves acceptable



4.6 Performance in frequency selective channel

- **Frequency selective channel:** $B \gg B_c = (\Delta f)_c$ or $T_S = \frac{1}{B} \ll \frac{1}{B_c} \approx 5\sigma_\tau$
 - Frequency selective channels cause severe signal distortions (multipath causes ISI)
 - The errors in a frequency selective channel tend to be bursty
- **The irreducible noise floor in a frequency selective channel is primarily caused by the errors due to intersymbol interferences.**
- This occurs when:
 - The main (undelayed) signal component is removed through multipath cancellation
 - The sampling time of the receiver is shifted as a result of delay spread



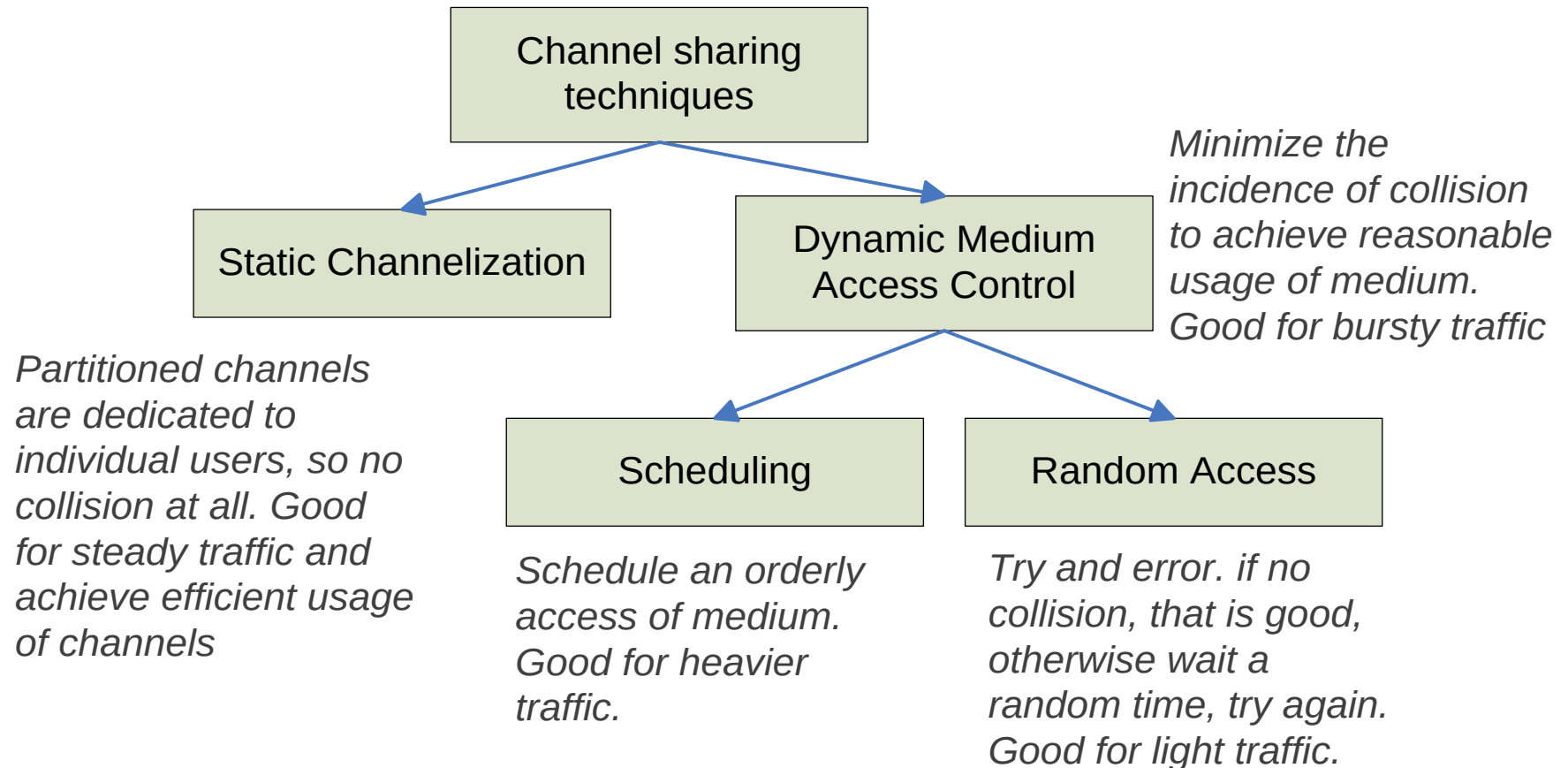
4.6 Performance in frequency selective channel

Frequency selective channel mitigation:

- **Equalization:** to equalize the ISI to gather the disperse symbol energy back together into its original time interval
 - E.g.: decision feedback equalizer (DFE), maximum likelihood sequence estimation (MLSE)
 - **Involves insertion of a filter to make the combination of channel and filter yield a flat response with linear phase**
 - An equalizer also provides diversity (as it gathers energy that otherwise would be lost)
 - The equalizer must be adaptive since the channel is generally unknown and time varying
- **Use of DS-SS** to reject ISI
 - The multipath components that are delayed by more than one chip are rejected:
- **Use of FH/SS** to avoid multipath losses by rapid changes in the transmitter frequency band
 - The interference is avoided by changing the receiver band position before the arrival of the multipath signal
 - The hopping rate must be at least equal to the symbol rate

5. Media access control algorithms

5.1 Introduction



Source: A. Boegli

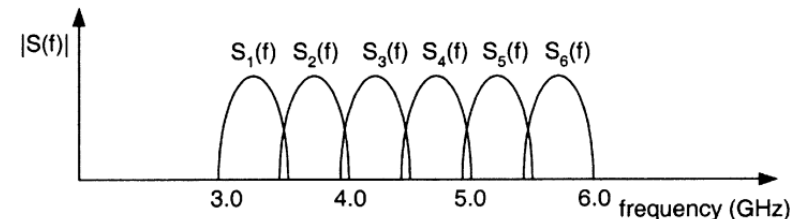
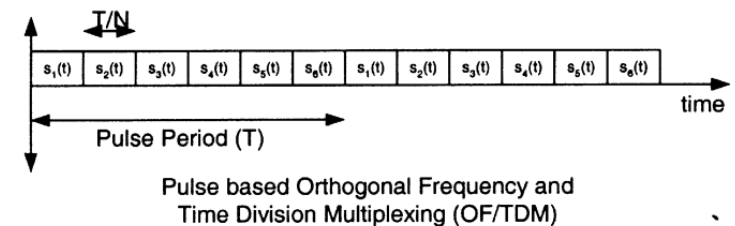
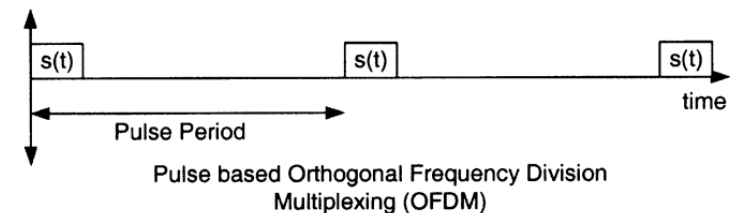
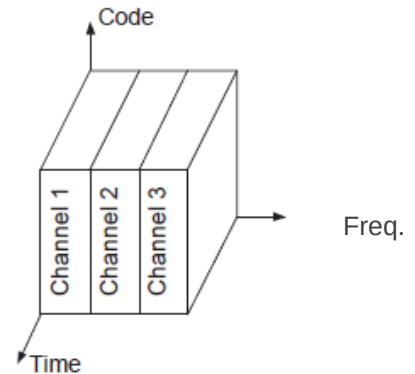
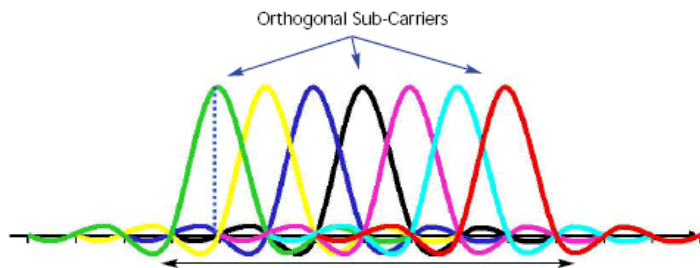
5.2 Channel-based multiple access

- **Frequency Division Multiple Access (FDMA)**

- May require guard bands between adjacent frequency bands

- **Orthogonal Frequency Division Multiplexing (OFDM)**

- Information is modulated onto a number of parallel subcarriers
- Subcarriers can be produced by DSP (FFT)
- Relatively high complexity and power consumption for WSN



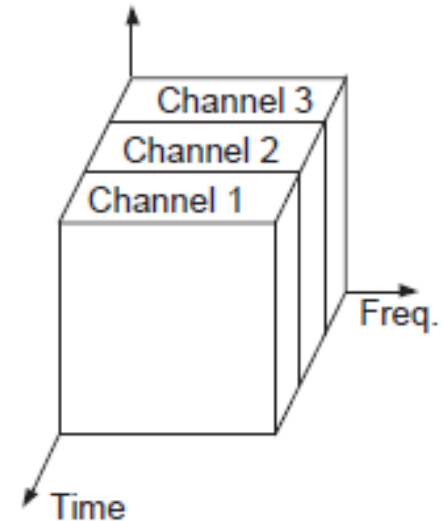
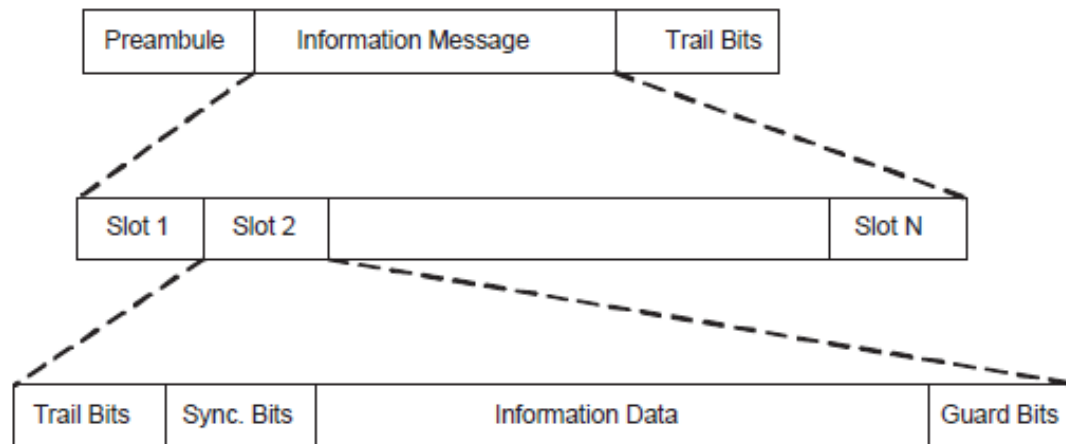
$s(t) = s_1(t) + s_2(t) + s_3(t) + s_4(t) + s_5(t) + s_6(t)$: Concatenated OFDM waveform
 $s_i(t)$: Sub-band waveform
 N : Number of sub-bands ($N=6$ in this example)

Source: Roy et al., "Ultrawideband Radio Design: The Promise of High-Speed, Short-Range Wireless Connectivity," PROCEEDINGS OF THE IEEE, VOL. 92, NO. 2, FEBRUARY 2004

5.2 Channel-based multiple access

- **Time Division Multiple Access (TDMA)**

- Centralized scheme
- **Time synchronization burdensome for large networks**

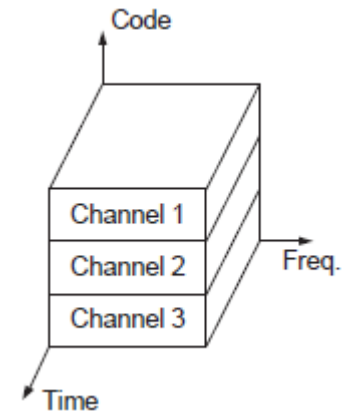
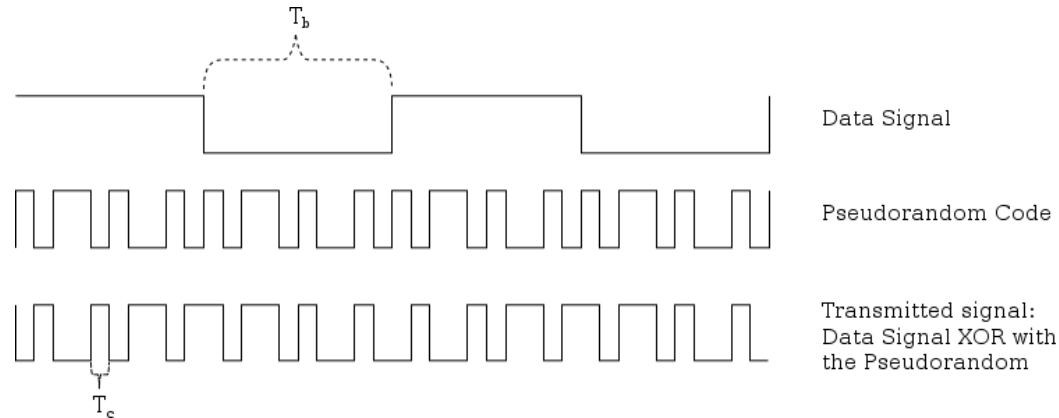


5.2 Channel-based multiple access

- Spread spectrum multiple access (SSMA)

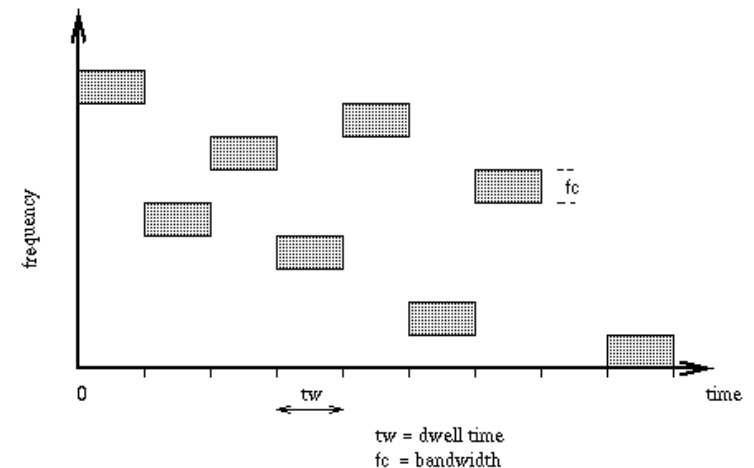
- Code Division MA (CDMA)

- Each bit is multiplied by a pseudo-noise spreading sequence



- Frequency Hopped MA (FHMA)

- Uses different carrier frequencies at different times
 - Slow FH
 - Fast FH



5.2 Channel-based multiple access

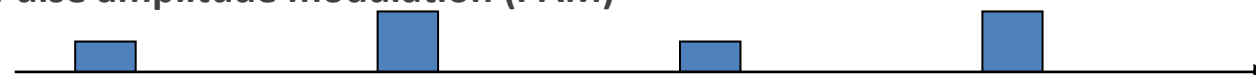
- **Time-hopping impulse radio (TH-IR)**

- Symbol => sequence of pulses with pseudorandom delays
- Example of binary modulations assuming a 0101 is transmitted

- Pulse position modulation (PPM)



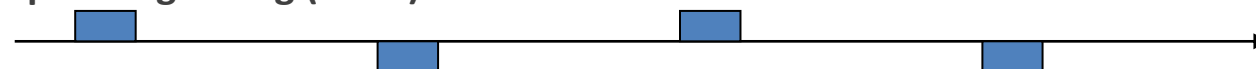
- Pulse amplitude modulation (PAM)



- On/Off keying (OOK)

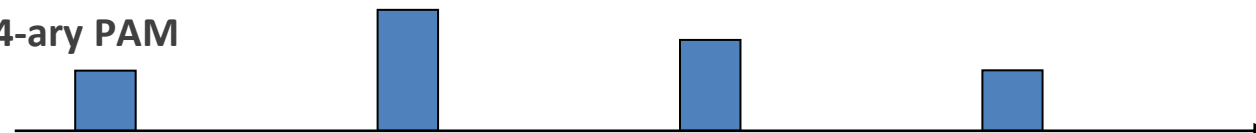


- Bipolar signalling (BPSK)



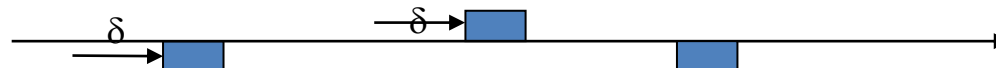
- M-ary modulation: Hyp: 01-11-10 (or 1-3-2) is transmitted

- 4-ary PAM



- Hybrid modulations are also possible: Hyp: 11-01-10 (or 3-1-2) is transmitted

- PPM + BPSK



Source: Roy et al., "Ultrawideband Radio Design: The Promise of High-Speed, Short-Range Wireless Connectivity," PROCEEDINGS OF THE IEEE, VOL. 92, NO. 2, FEBRUARY 2004

5.3 Packet-based multiple access

Idea: When a low duty cycle is used in a network, multiple communication links can exist simultaneously on the same channel with a small probability of collision

- **Pure ALOHA Protocol**

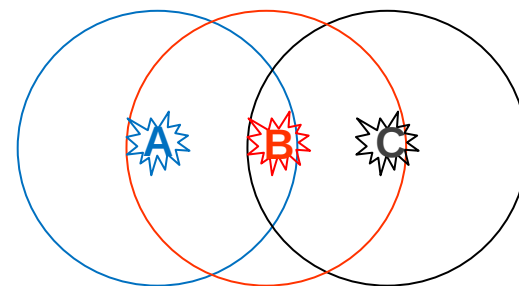
- A user transmits to another node whenever needed
 - After receiving a packet, the node transmits
 - ACK if successful transmission
 - NACK if collision occurred
 - After NACK, the user waits a random amount of time before re-transmitting the packet
- **Uncoordinated user access, very easy to implement**
- Drawback of ALOHA is that, when traffic is high, collisions are rapidly increases due to which degradation of network performance takes place
=> low spectral efficiency

- **Slotted Aloha**

- **Time is slotted** and a packet can only be transmitted at the beginning of one slot. **Collision of one packet with portion of another is avoided in this strategy**
- **Requires network synchronization!**

5.3 Packet-based multiple access

- Carrier Sense Multiple Access (CSMA)
 - Each node **verifies the absence of other traffic before transmitting** on a shared transmission medium
 - The advantage of a CSMA scheme over TDMA is that it is distributed.
 - However, CSMA suffers from some well known problems:
 - **Rely on ability of performing an accurate channel sensing** (not really suitable with UWB communications)
 - **“hidden terminal” problem**: A and C are hidden to each others. If A and C start sending packets at the same time, their signals will collide/interfere at B



5.3 Packet-based multiple access

- **Carrier Sense Multiple Access (CSMA)**

- **1-persistent CSMA:** nodes having a packet to send and finding the medium busy wait for the end of the current transmission (they persist!) and start sending with probability 1 as soon as the medium becomes idle.
 - Problem when more than one node is waiting at the same time for the medium to become idle: they all start sending at the same time
- **Non-persistent CSMA:** after receiving a negative acknowledgment, the node waits a random time before retransmission of the packet
- **p-persistent CSMA:** idea is to randomize the transmission attempts at the beginning of the idle period to avoid the probable collisions present with 1-persistent CSMA.
 - Probability that sender node sends data after sensing idle channel is p and probability that sender waits for specific time period before trying to transmit packet again is $1-p$.
 - P-persistent CSMA is a slotted CSMA protocol.
- **CSMA/CD:** CSMA with collision detection in which case transmission is immediately aborted

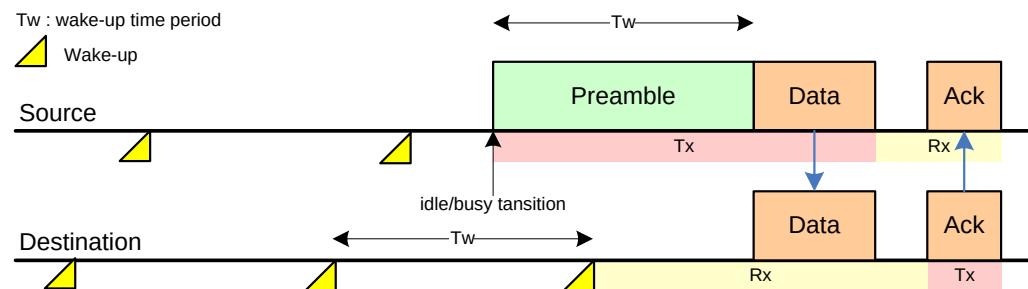
5.3 Packet-based multiple access

- Carrier Sense Multiple Access (CSMA)

- **Preamble sampling:**

- A node listens to the channel for a constant duration of time known as **sampling period independently**. If channel is listened as free, till next time slot appears, node goes back to sleep mode.
 - A sender node sends a long dummy packet, called preamble having size equal to sampling period in front of every data frame to avoid missing the neighbours wake up schedule.
 - After wake up, when node detects preamble, it continues to listen channel till valid data is received. By using an acknowledgement frame (ACK), the reception of valid message is confirmed.
 - A biggest disadvantage of preamble sampling is that all receivers have to receive the long preamble even if they are not addressed.

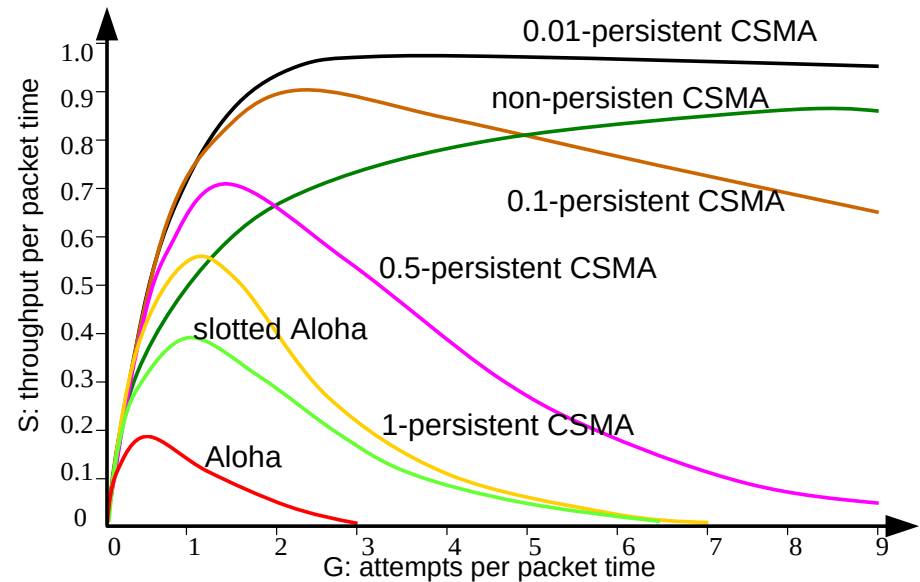
Non-persistent
CSMA with
preamble sampling



5.3 Packet-based multiple access

Aloha and CSMA throughput

- The amount of traffic transmitted with success is measured with the throughput S .
- The overall throughput of a protocol can be defined as the fraction of time when the channel carry a data message without collision.
- G is the attempt rate. It is the sum of the initial transmission attempts and the re-transmission attempts.



Source: A. Boegli

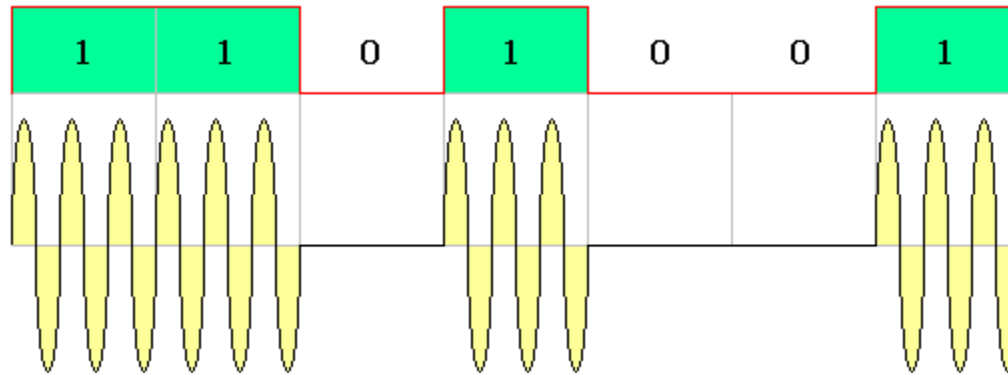
6. Wireless networks standards

6. Wireless networks standards

- 6.1 Proprietary OOK modulation
- 6.2 IEEE 802.15.x Standardization Activities
- 6.2 Bluetooth
- 6.3 IEEE 802.15.4 / ZigBee
- 6.4 Bluetooth vs. ZigBee
- 6.5 IEEE 802.15.4a
- 6.6 LoRa
- 6.7 SigFox

6.1 OOK RF Protocols

- Simple On/Off keying

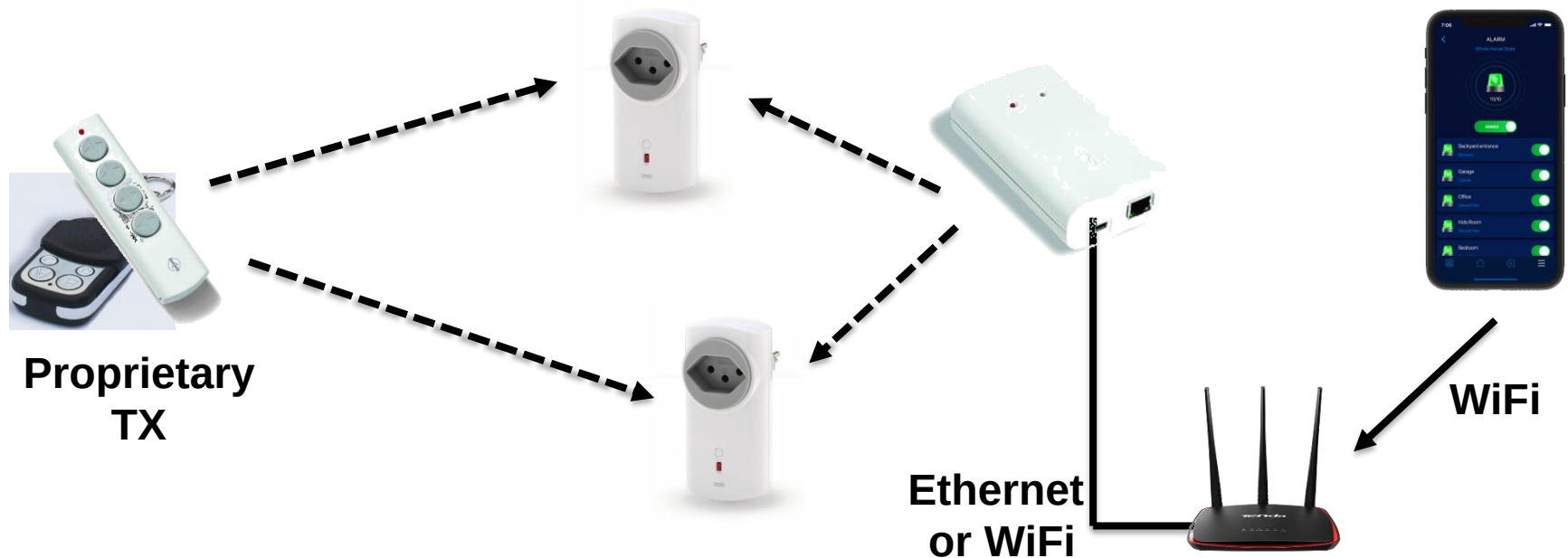


- Modulation and demodulation is super-simple
 - Ultra-low-cost hardware for both Tx and Rx
 - Can be built from discrete components
- No complex MAC protocol: ALOHA channel access
 - Rx needs to listen at all times (high power consumption)
 - Typically unidirectional with no acknowledgement



6.1 Home Automation Example (OOK)

- Frequently used in low-cost components (RC plugs)
- Proprietary PHY protocols:
 - no interoperability, but simplicity of the protocol allows development of custom drivers
 - **Requires a hub to connect to a network / smartphone**



6.1 Practical example: TI-CC1000

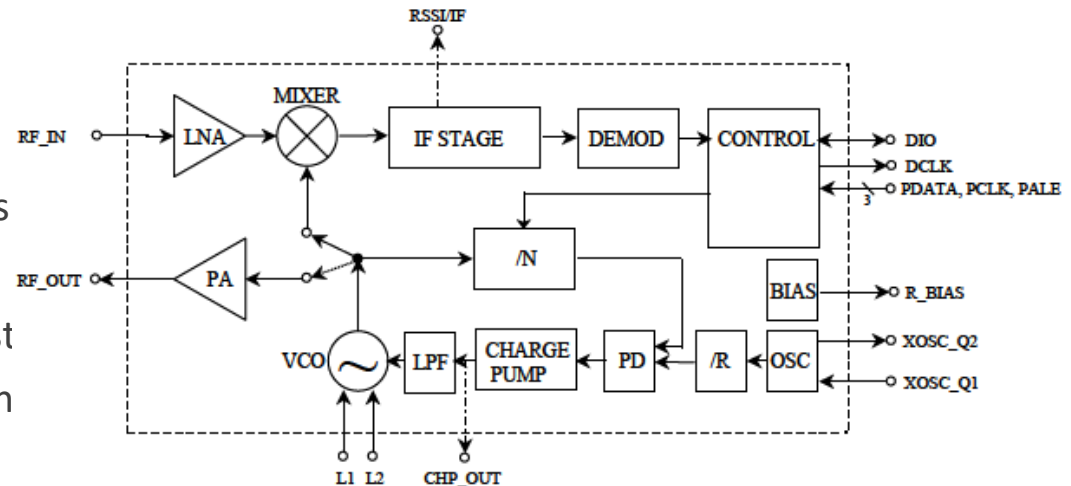
CC1000: Single Chip Very Low Power RF Transceiver

- **Combined transmitter and receiver** (=transceiver)
- **Comprises only the physical layer**
- RF frequency synthesis from a low-frequency reference quartz (3-16 MHz)
- **Frequency Shift Keying (FSK)** modulation up to 76.8 kbit/s
- Suitable for frequency hopping protocols
- Programmable output power **-20 to 10 dBm**
- **Received signal strength indicator (RSSI)**: detects presence of an RF signal and its strength
- Software-programmable **ISM/SRD** frequency bands: 315 / 433 / 868 and 915 MHz
- **Low supply voltage** (2.1 V to 3.6 V)
- Single port antenna connection



Applications:

- RKE – Two-way Remote Keyless
- Home automation
- Wireless alarm and security syst
- AMR – Automatic Meter Readin
- Low power telemetry



Wireless Personal Area Networks (WPAN)

- Replacement of wires
- Short distance with limited coverage
- Communication between battery-powered devices over a short range



Standardization is further split into subgroups, each addressing a different issue and different requirements with potentially different standards

- **802.15.1 : High-rate physical layer (Bluetooth)**
- 802.15.2 : Coexistence
- 802.15.3 : High-rate WPAN
- **802.15.4 : Low-rate WPAN (ZigBee)**
- 802.15.5 : Mesh Networking with 802.15.3 and 802.15.4
- 802.15.6 : WBAN (limited activity)
- 802.15.7 : Visible Light Communication



6.3 Bluetooth

- **1998** : Bluetooth special interests group (Ericsson, Nokia, IBM, Intel, Toshiba);
Today: > 8000 members

Objectives of the standardization

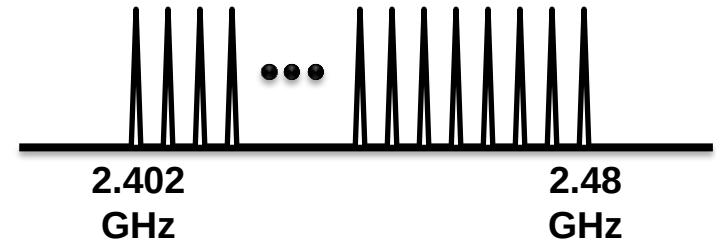
- Ad-hoc connectivity of devices
- Applications: connection between computers and peripherals, wearable microphones, synchronization between devices
- **Data and voice transmission** (real-time requirements!)
- Short range (WPAN) : approximately 10m
- Automatic association with associated near-by devices
- Maintain fixed connections over a longer period of time
- Security features: authentication and encryption

- 2001 : First consumer products based on Bluetooth v1.1
- **2003 : Bluetooth 1.2 corresponds to IEEE 802.15.1 (1 Mbit/s)**
- ...

6.3 Bluetooth : Physical Layer

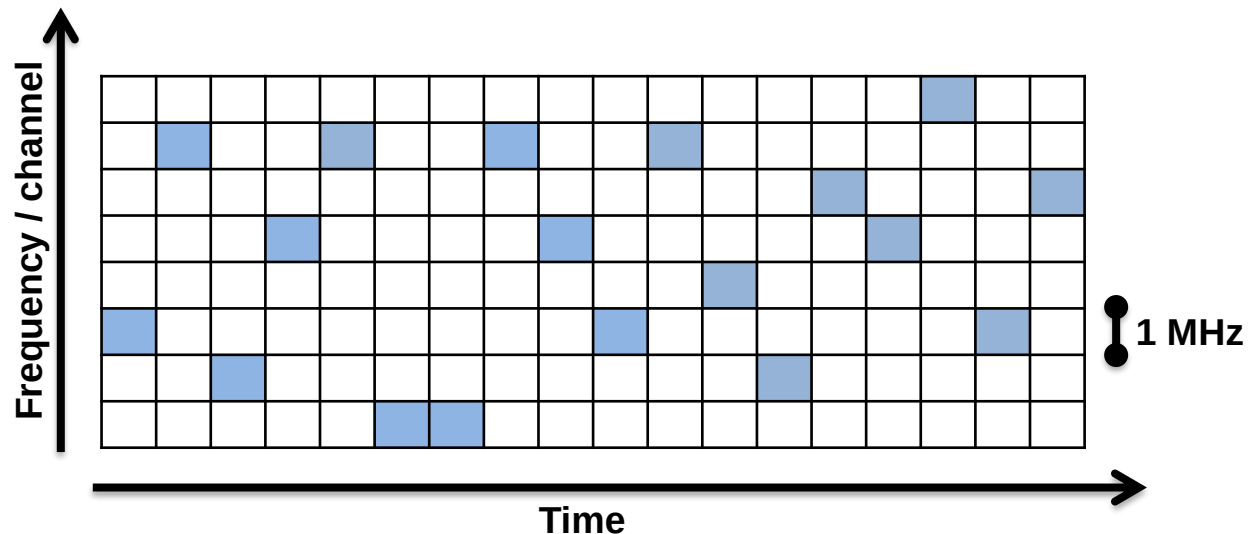
Bluetooth 1.2 PHY parameters

- Narrow band modulation : **GFSK (1 bit/s/Hz)**
- Uses the **2.4 GHz ISM band**
- Coexistence with WLAN and many others
- **79 narrow-band carriers** (bandwidth: 1 MHz)



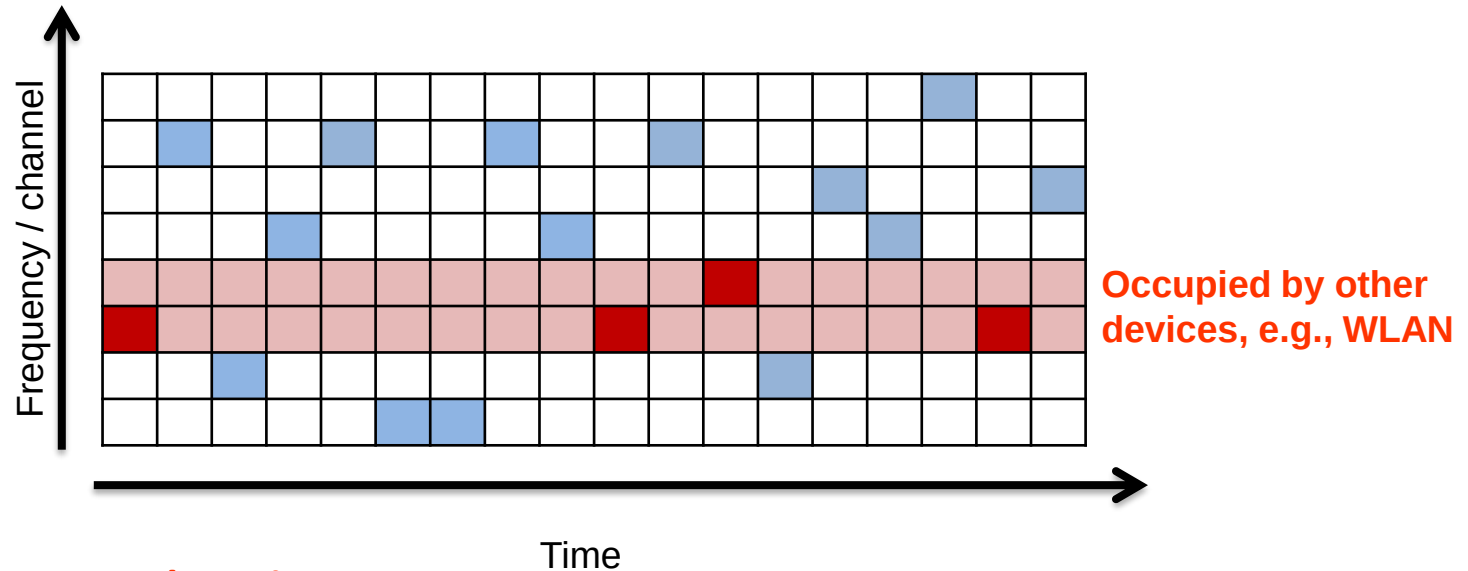
Frequency Hopping Spread Spectrum

- Communication is split into **time-slots** and **frequency-slots**
- **Carrier changes up to 1600 times per second (625 us per slot)**

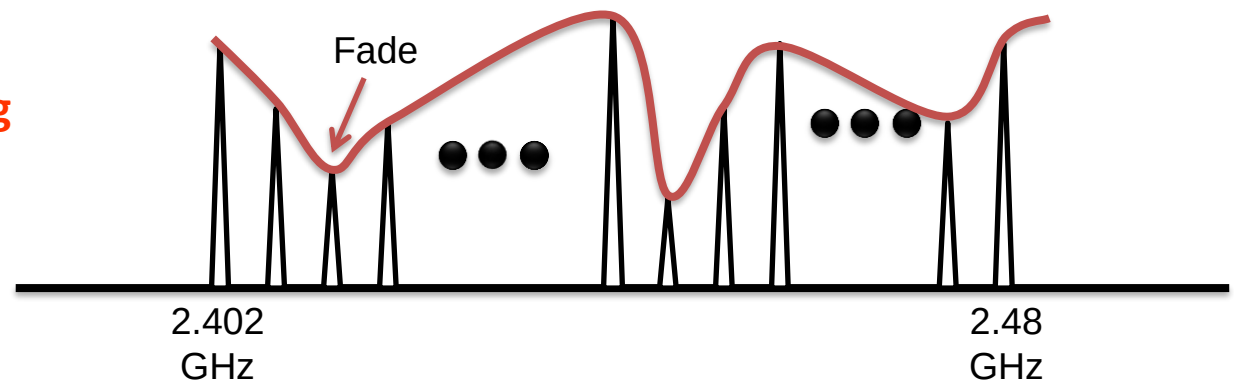


6.3 Bluetooth : Physical Layer

- Interference (from and to others) limited to short time periods



- Adaptive frequency hopping:**
detect and avoid carriers with interference
- Robustness against (frequency selective) fading**



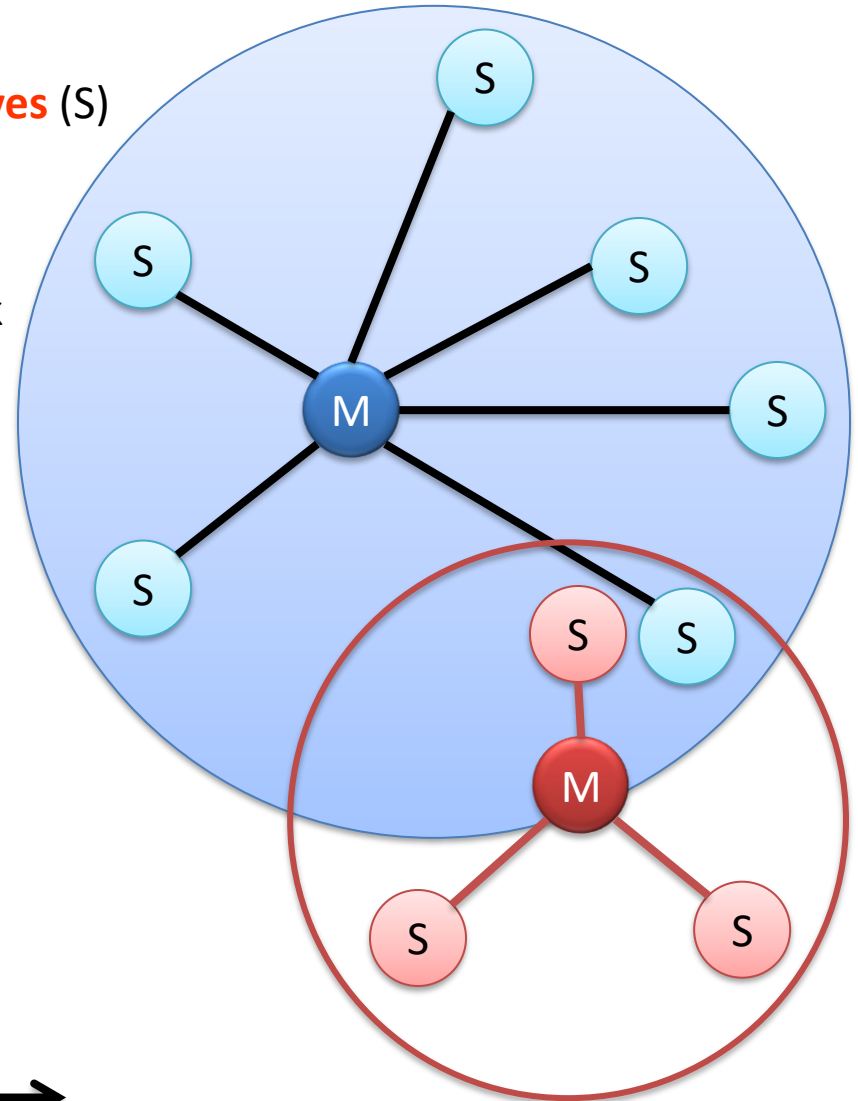
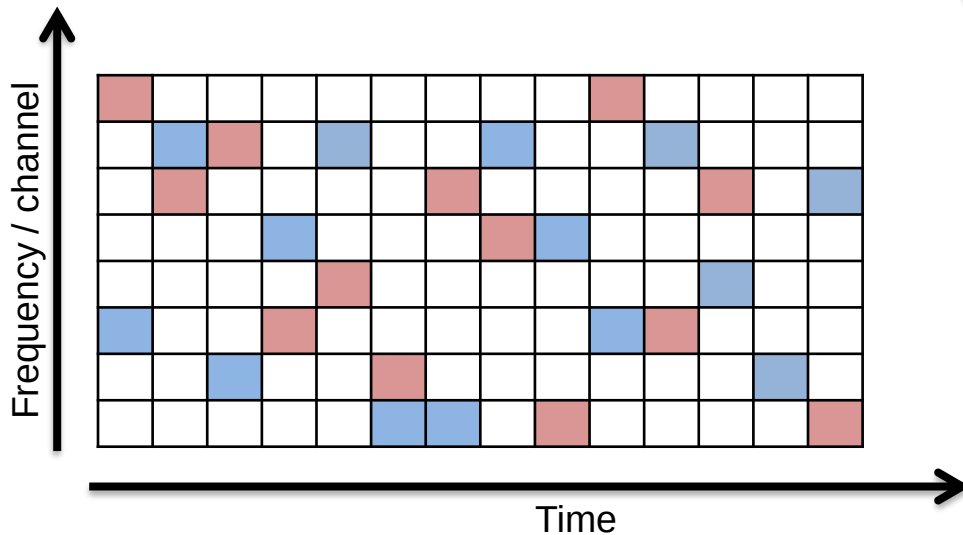
6.3 Bluetooth : MAC and Network Layer

Basic structure: Piconet

- 1 Master (M) communicates with **up to 7 Slaves (S)**
- Slaves communicate only with the master
- **Medium access is coordinated by the master**
- **Time division duplex (TDD):** Up and downlink alternate

Different hopping patterns separate piconets

- Unique 48-bit device ID of the master determines the hopping pattern



6.3 Bluetooth : MAC and Network Layer

Basic structure: Piconet

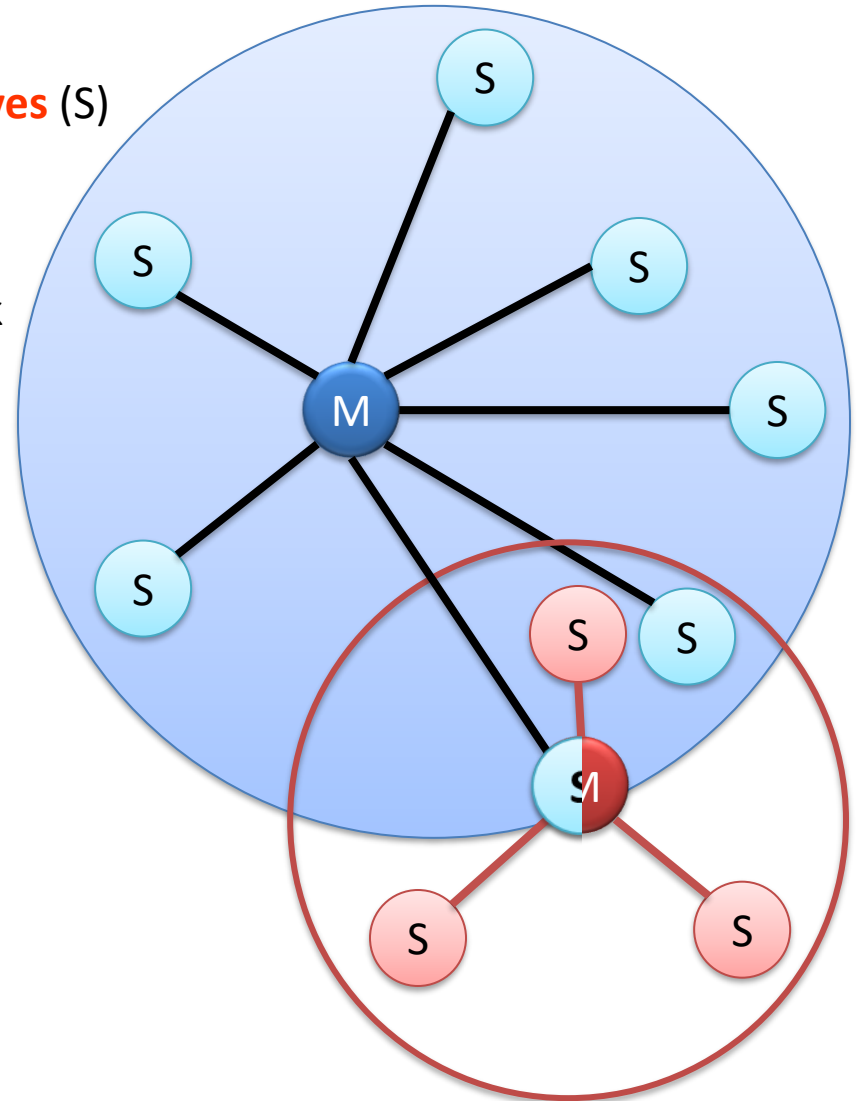
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- **Medium access is coordinated by the master**
- **Time division duplex (TDD):** Up and downlink alternate

Different hopping patterns separate piconets

- Unique 48-bit device ID of the master determines the hopping pattern

Connection between two piconets: Scatternet

- Single device is master in one net and slave in another net
- Roles alternate over time

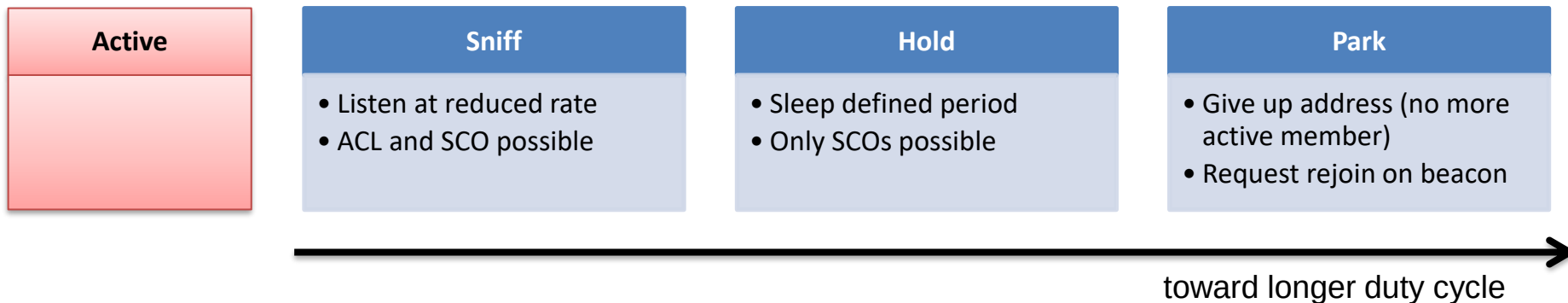


6.3 Bluetooth : Low Power Features/Modes

Bluetooth supports two main states: Standby and Connected

- **Standby**: No communication is possible. **Synchronization takes up to 3-6s**
- **Connected**: Synchronized with a master (3 low-power modes)

Low power operation: **increase duty cycle**



Bluetooth low energy: feature in Bluetooth 4.0

- Changes to the PHY and MAC layer
- Basic idea: **synchronized wakeup and high-speed data transfer in short bursts**
maximize sleep time

6.3 Bluetooth : Bluetooth Devices

- Transceivers are typically available as modules or highly integrated SoCs
- Receiver **sensitivity** (0.1% BER) typically **-80dBm to -86dBm** (standard specifies *-70dBm or better*) -> **rather poor!!**
- Three device-classes according to output power
- >5dBm output power (class 1): requires external PA (module)

Typical power consumption (class 2, 3.3V)

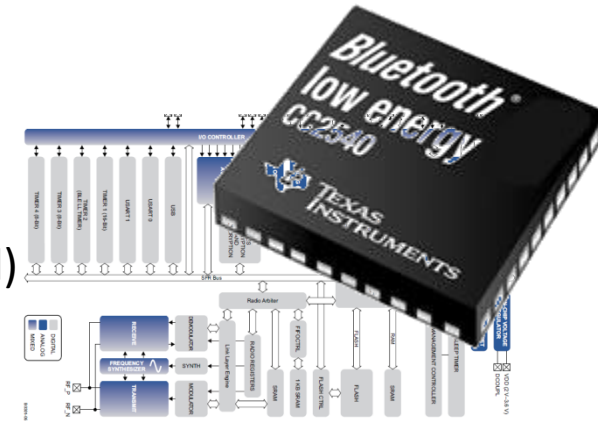
- Active 60 – 100mW (slave), master consumes less (no listening)
- Sniffing 10 – 25mW (duty cycle: depending on sniffing interval)
- Parked (1s beacon): 2-3 mW

	mW	dBm	Range
Class 1	100	20	~ 100m
Class 2	2.5	4	~ 10m
Class 3	1	0	~ 5m



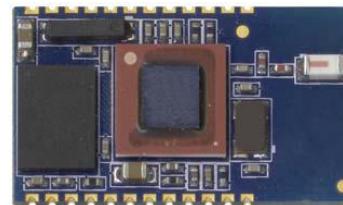
Bul-Tech BL-5A

Bluetooth 2.1 + EDR Module
28.5 x 16.5 x 2mm, >15 USD



TI CC-2540

Bluetooth 2.1 + EDR Module
6 x 6 mm, 3-6 USD



KC-21, 15 x 27 mm

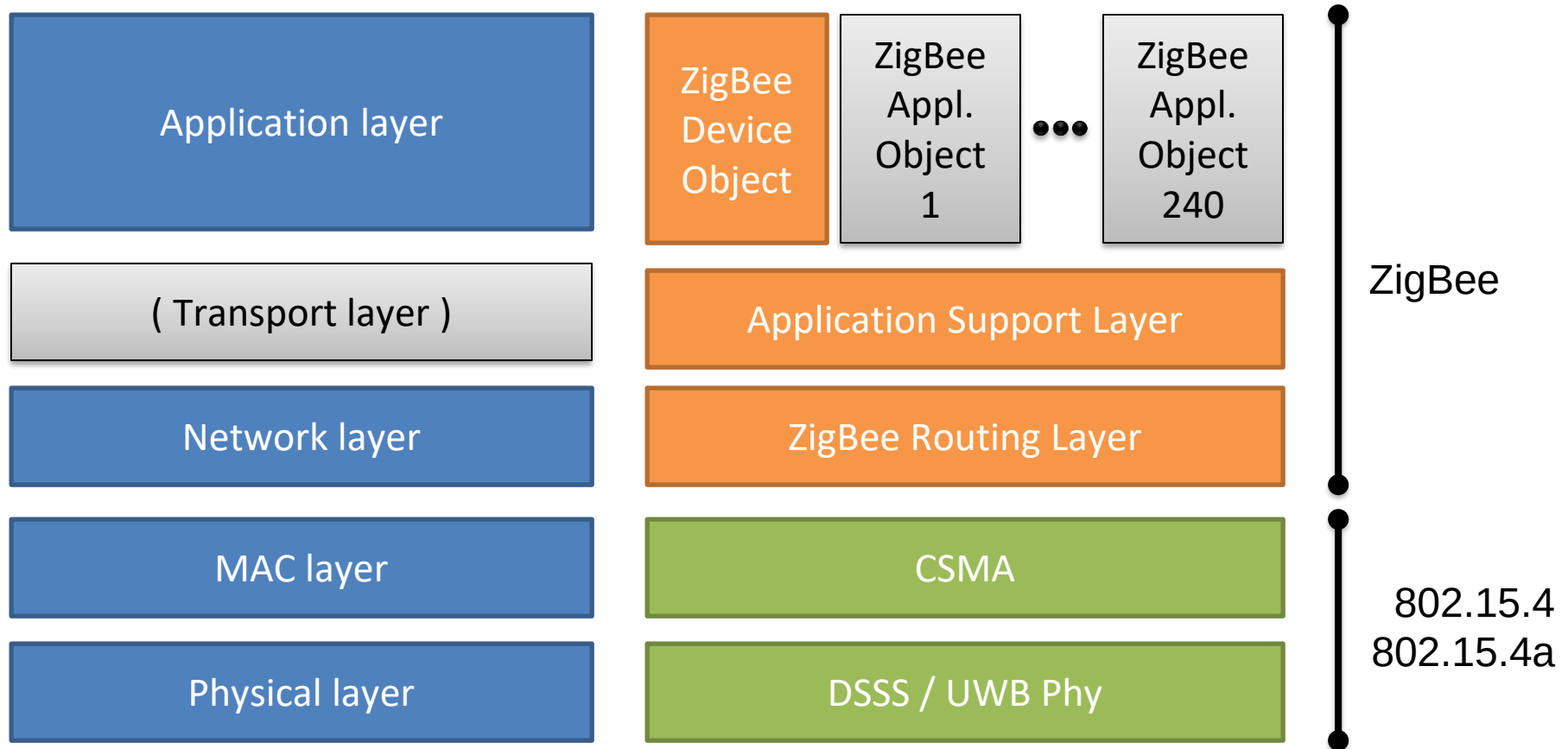
- **1998** : Start of the development of a low-power WPAN in IEEE 802.15.4

Objectives of the standardization

- Low cost and low-power mesh-network connectivity for sensors
 - Applications: control, automation and low data rate transmissions
 - **Simpler and less expensive than Bluetooth (*reduced-complexity protocol stack*)**
 - **Support larger networks (hundreds to thousands of sensor nodes)**
 - **Large coverage area with short-medium range (10-100m) links**
 - Flexibility to quickly join and leave a network
 - Security features: authentication and encryption
-
- **2002** : Foundation of the ZigBee Alliance as industry consortium
 - **2003** : Completion of the IEEE 802.15.4 standard (ratified Dec. 2004)
 - **2005** : ZigBee 1.0 specification publicly available

6.4 IEEE 802.15.4 / ZigBee

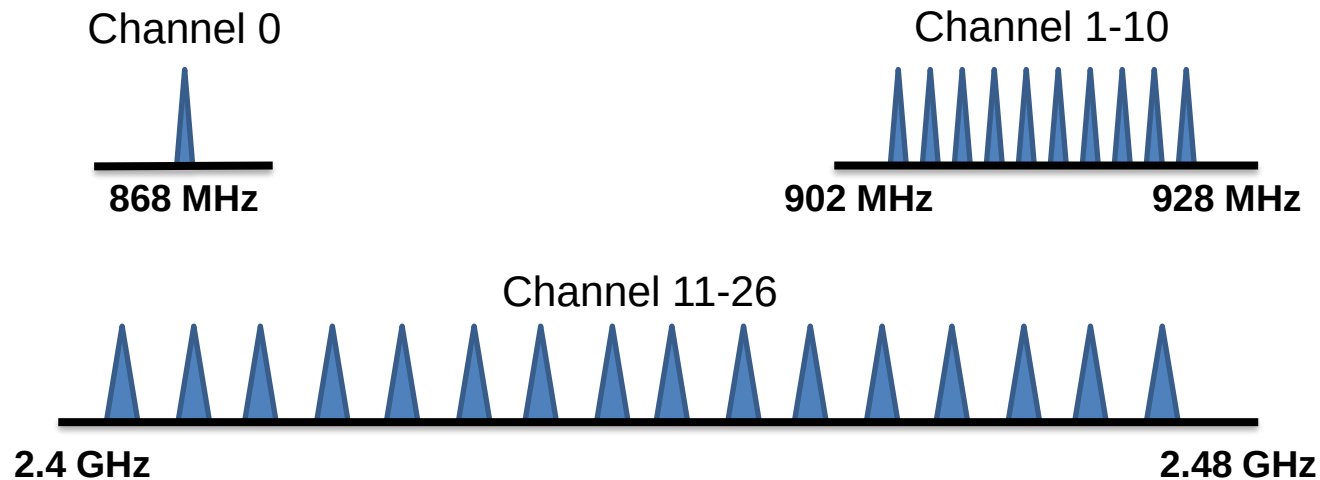
- Physical layer and MAC layer are based on IEEE 802.15.4 / IEEE 802.15.4a
- ZigBee adds the **network and security layers** and an **application framework**



6.4 802.15.4 Physical Layer

IEEE 802.15.4 PHY parameters

- Support for **3 unlicensed ISM frequency bands: 868 MHz, 915 MHz, 2.4 GHz**
- **Multiple channels in support parallel networks and avoid interference**
- Supported data rate depend on the frequency band

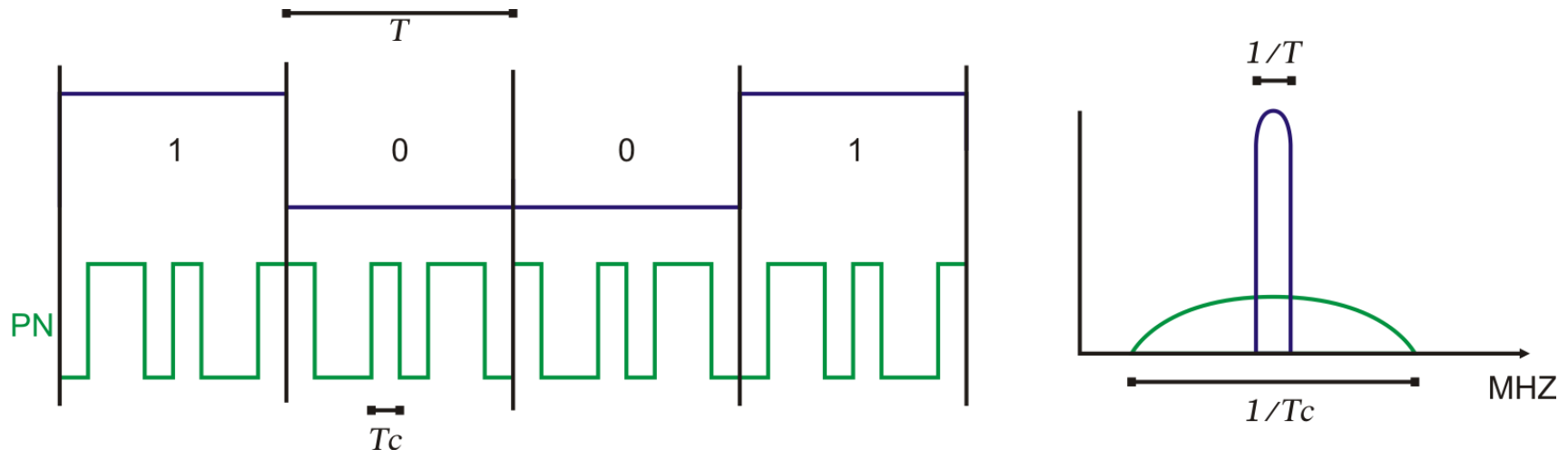


Frequency	Channels	Spacing	Datarate	Region
868-870 MHz	1		20 kbit/s	Europe
902-928 MHz	10	2 MHz	40 kbit/s	America
2.4 GHz	16	5 MHz	250 kbit/s	World

6.4 802.15.4 Physical Layer

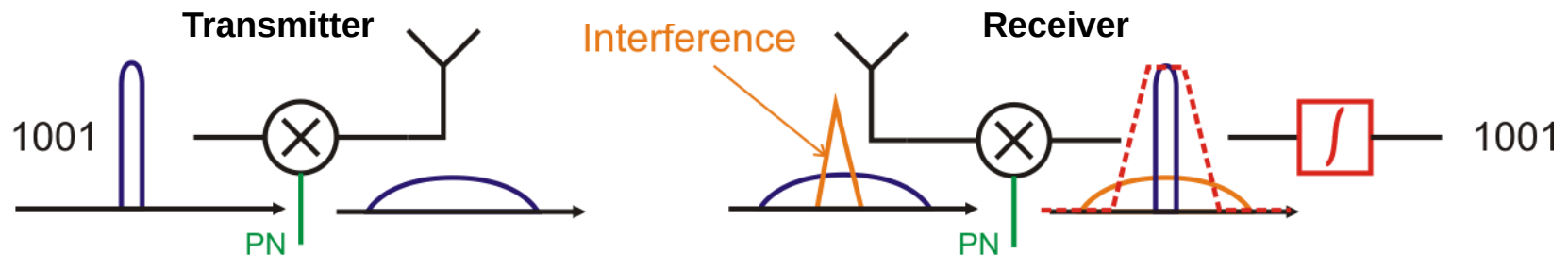
Direct Sequence Spread Spectrum (DSSS) Modulation

- Each symbol is represented by a (modulated) pseudo-noise (PN) sequence (chips)
- Chip-rate is higher than the symbol rate $\Rightarrow$ signal is spread in the frequency domain



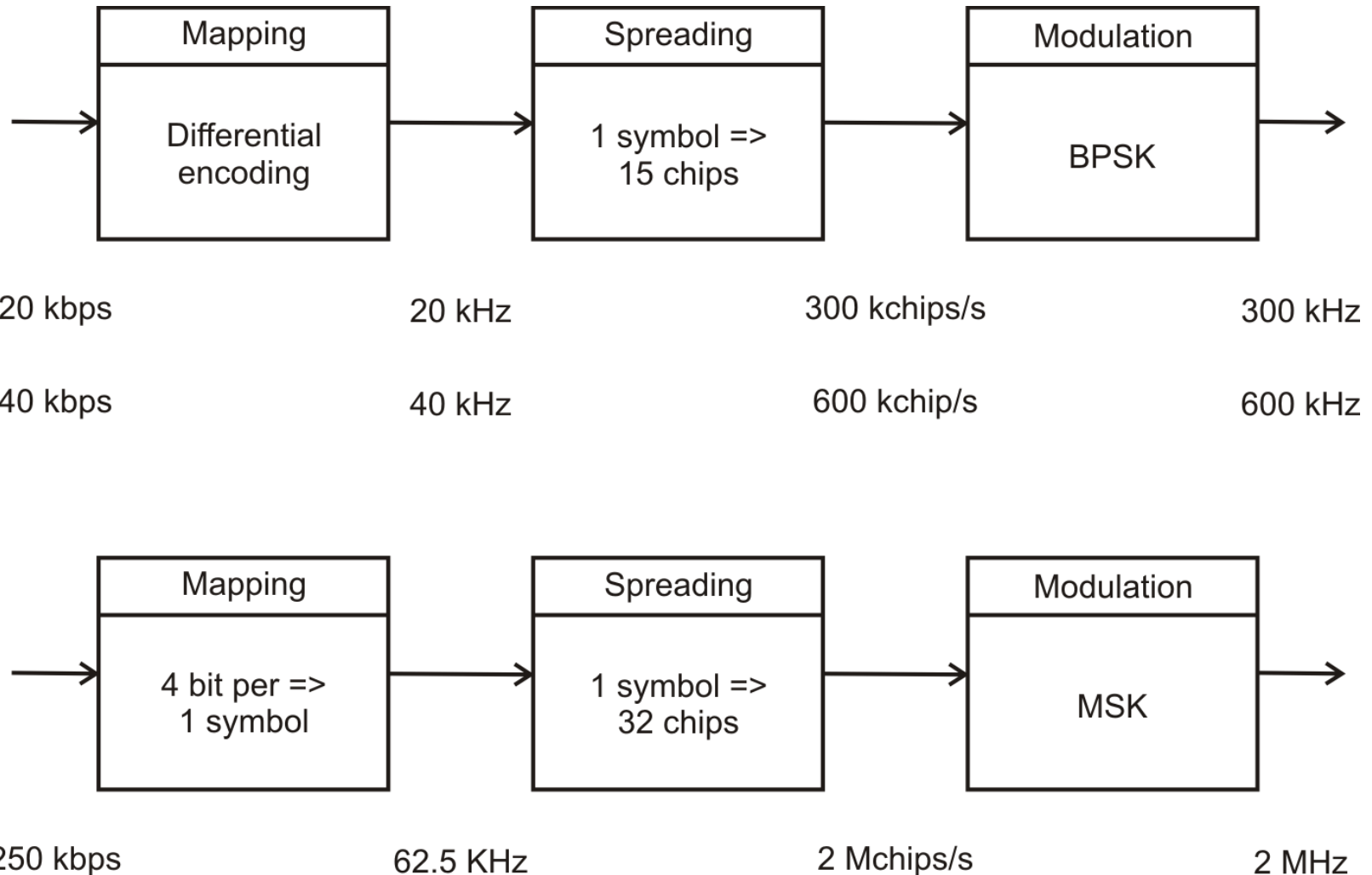
- Spectral efficiency (bits/s/Hz) is reduced

Reduces interference to and from other users in the same frequency band



6.4 802.15.4 Physical Layer

The details of the modulation scheme and the spreading depend on the frequency bands



6.4 ZigBee network topologies

Self organizing ad-hoc network with 3 different roles



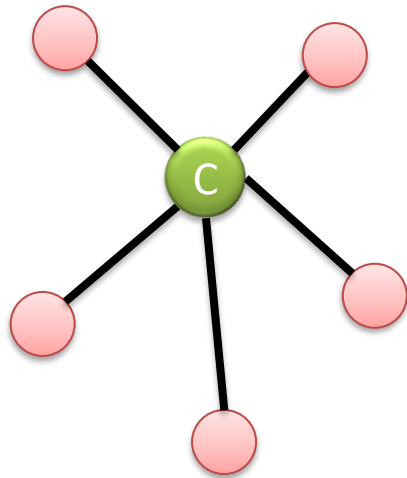
- **End device**: connects only to one and only one router
- **Router**: multiple connections to other routers and multiple end devices
- **Coordinator**: only one per network

6.4 ZigBee network topologies

Self organizing ad-hoc network with 3 different roles

▪ **Star**

- Simplest structure
- **A single coordinator connects to multiple endpoints**
- Reach is limited to the range of the coordinator



Star

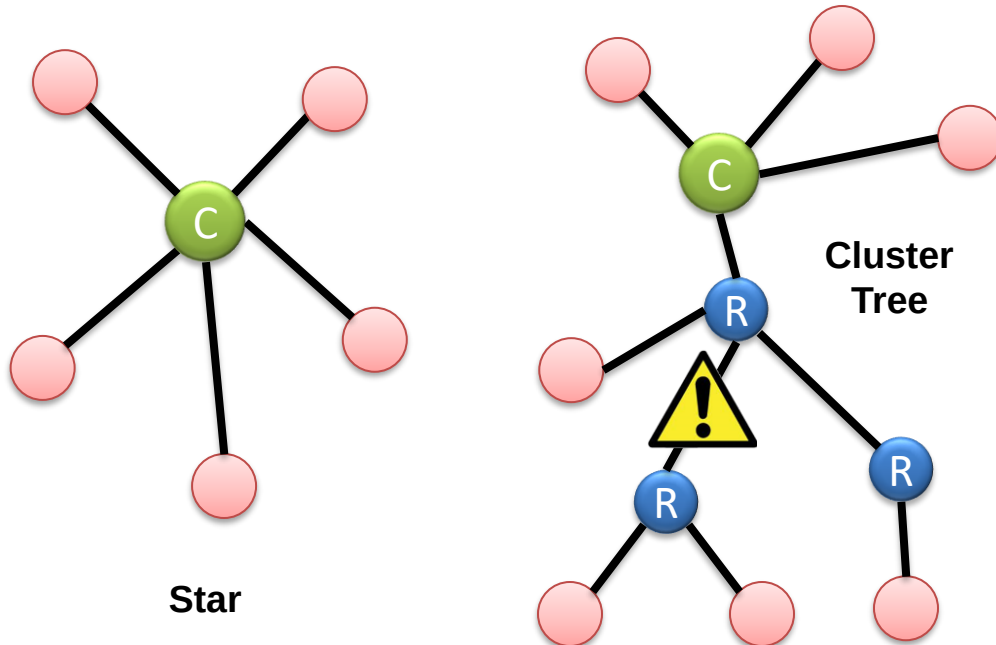
- **End device**: connects only to one and only one router
- **Router**: multiple connections to other routers and multiple end devices
- **Coordinator**: only one per network

6.4 ZigBee network topologies

Self organizing ad-hoc network with 3 different roles

- Star
- **Cluster Tree**
 - **Bridge long distances (beyond reach of the radio)**
 - Routers are connected to endpoints and to one other router
 - IEEE 802.15.4 has no provisions for routing (provided by Zigbee)
 - **Single point of failure!!**

- **End device**: connects only to one and only one router
- **Router**: multiple connections to other routers and multiple end devices
- **Coordinator**: only one per network

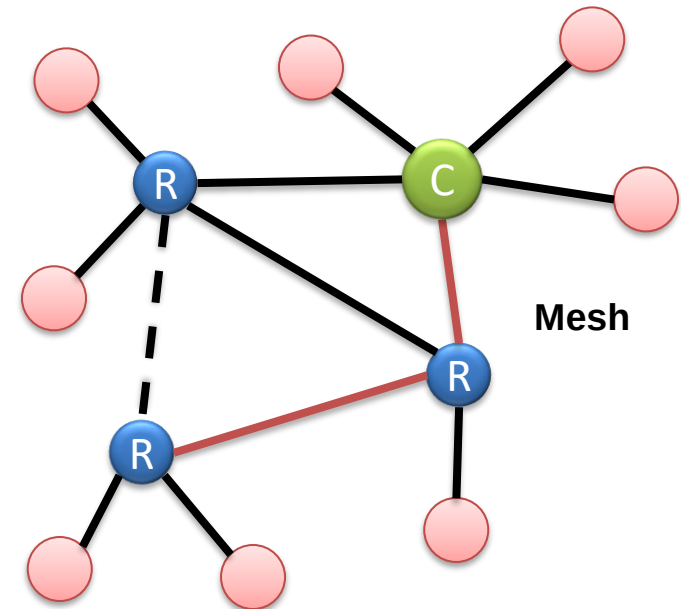
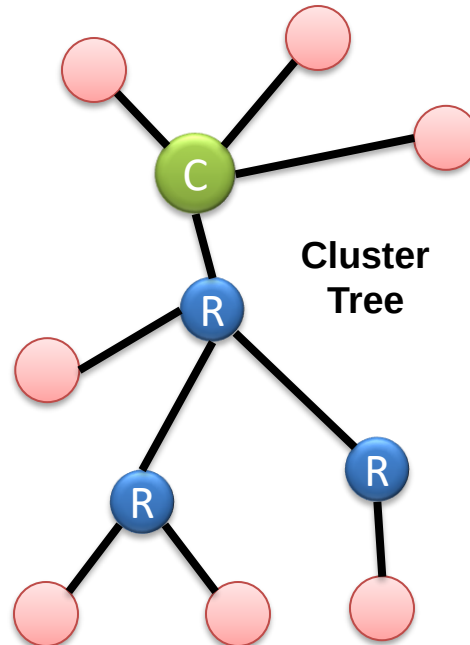
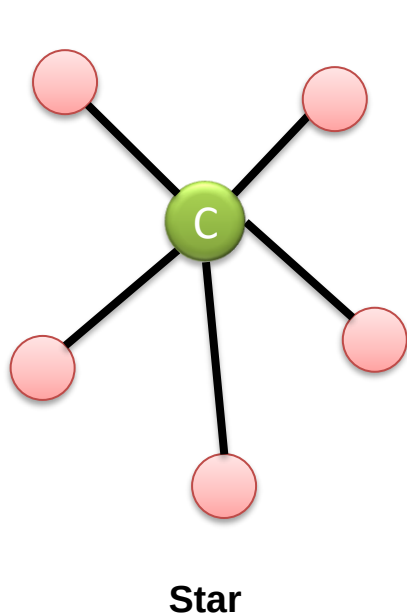


6.4 ZigBee network topologies

Self organizing ad-hoc network with 3 different roles

- Star
- Cluster Tree
- **Mesh Network**
 - **Routers connect to multiple other routers (and endpoints)**
 - Improved reliability (alternate routes)

- **End device**: connects only to one and only one router
- **Router**: multiple connections to other routers and multiple end devices
- **Coordinator**: only one per network



6.4 ZigBee network topologies

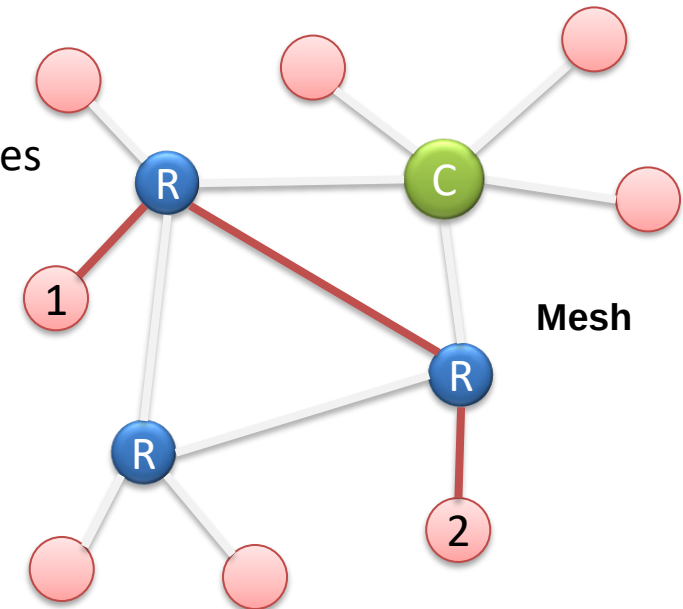
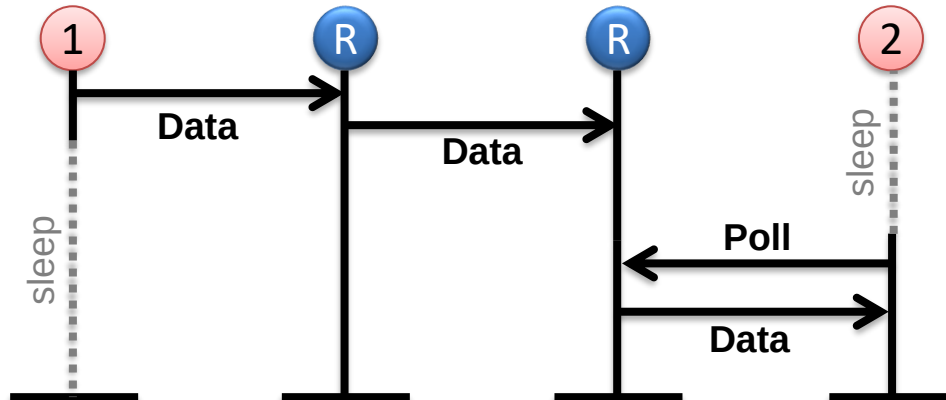
Self organizing ad-hoc network with 3 different roles

- Star
- Cluster Tree
- Mesh Network

Communication in the network

- **Coordinator** creates and manages the network
- **End devices** sleep most of the time and *always initiate the communication* by sending data or polling a router
- **Routers** buffer the traffic for their connected end devices

- **End device**: connects only to one and only one router
- **Router**: multiple connections to other routers and multiple end devices
- **Coordinator**: only one per network



6.4 802.15.4 / ZigBee Device Types

IEEE 802.15.4 and ZigBee know 2 types of devices

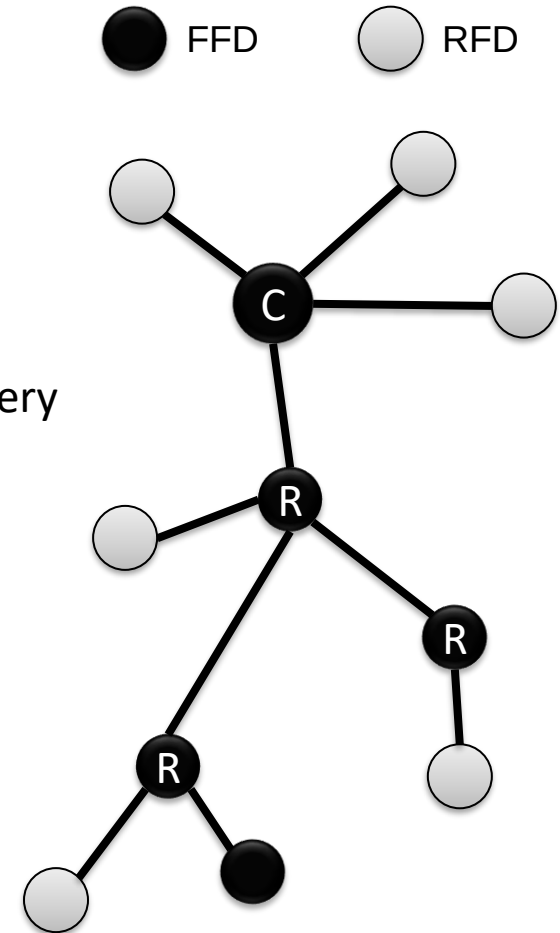
- Different in cost and power consumption

Full function device (FFD)

- Can act as router and as coordinator in a network
- Can also act as an end device
- Typically equipped with a power connection or a stronger battery
- Relatively complex protocol stack and need for more memory
- Code: 15-30k; RAM: 2.5k – 4k

Reduced function devices (RFD)

- Reduced protocol stack and less memory required
- Can only be leaves in the tree and can only talk to a router or to the coordinator
- Code: 6k; RAM: <2k



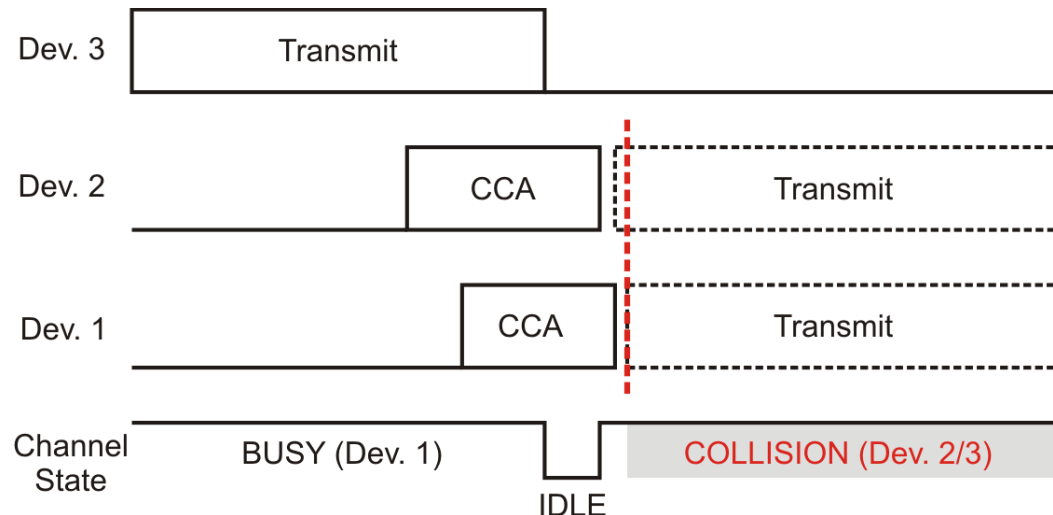
6.4 IEEE 802.15.4 Channel Access

Channel access

- Devices are not synchronized and have no assigned time slots
- Need other means to avoid collisions between devices

Carrier sense multiple access (CSMA)

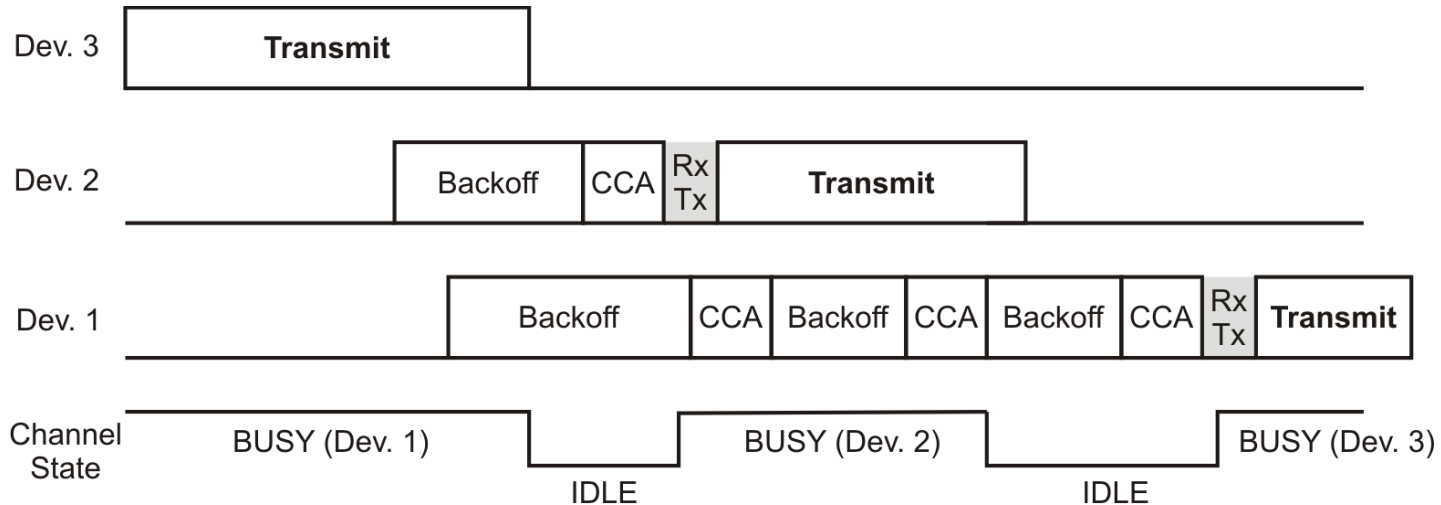
- Devices listen before sending : clear channel assessment (CCA)
- Send only if channel has been idle for a specified period
- **Collisions still occur frequently with multiple nodes due to delays**



6.4 IEEE 802.15.4 Channel Access

Carrier sense multiple access (CSMA) with collision avoidance (CA) : CSMA/CA

- Wait for a randomly chosen backoff interval before CCA



- If CCA fails, choose a new backoff time and try again
- For each attempt, the maximum length of the backoff interval increases exponentially



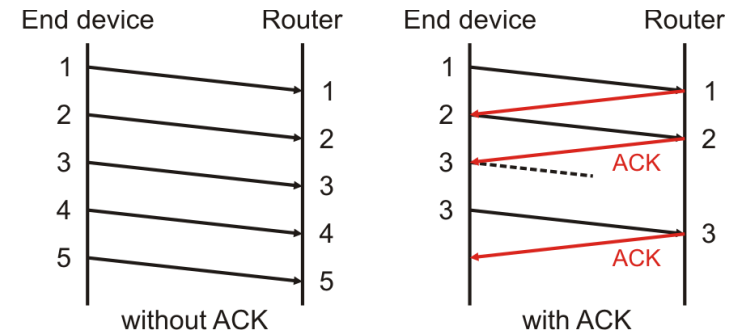
- Devices can sleep during backoff

- CCA requires power/energy for listening prior to transmission
- Random backoff introduces latency and reduces transmission rate

6.4 IEEE 802.15.4 Channel Access

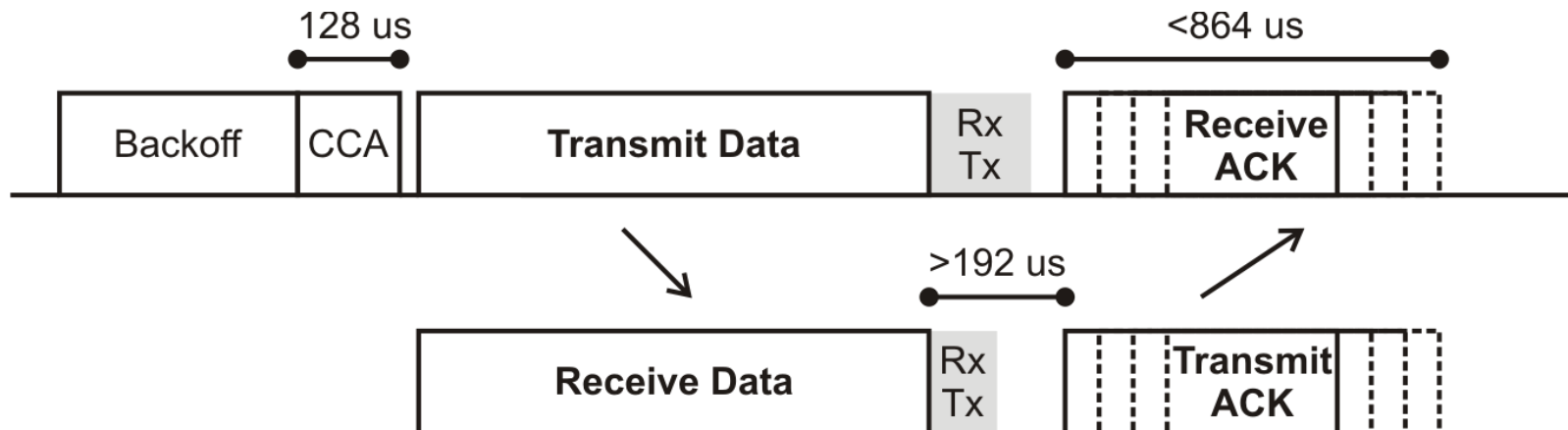
Data transfer between two nodes can be with or without acknowledge

- Competing for channel access to send a short ACK is inefficient
- A packet and its ACK should be a single, unbreakable entity to simplify packet management



ACK is sent without new CCA

- Receiver waits at least $T_{ack} = 192\mu s$ before sending the ACK (Rx/Tx and Tx/Rx turnaround)
- T_{ack} is short enough to prevent other devices from capturing the channel (in most cases!)



6.4 ZigBee Devices

- Transceivers are typically available as modules or highly integrated SoCs with MCU/ROM/flash/memory
- Receiver **sensitivity** (1% PER) typically **-90 to -100dBm**

Typical power consumption

- Standby: < 8uW
- Active: 60-120mW (@3V)



TI CC-2420/2430/2431
ZigBee Radio + MCU
6 x 6 mm, ~4-8 USD

M. Varchola, M. Drutarovsky,
“ZigBee Based Home Automation
Wireless Sensor Network,” Acta
Electronica Et Informatica, Vol. 7,
No. 4, 2007

	Vendor	Atmel	Ember		Freescale				Jennic		Microchip	Texas Instruments		
	ZigBee Chip	AT86 RF230	EM 250	EM 260	MC 13193	MC 13203	MC 13213	MC 13225	JN 5121	JN 5139	MRF 24J40	CC 2420	CC 2430	CC 2431
IEEE 802.15.4 Features	Sleep Current [uA]	0.1	1	1	1	1	1	NA	5	1.3	2	2	1	1
	RX Current [mA]	16	36	36	42	42	42	20	50	34	18	20	27	27
	TX Current [mA]	17	36	36	35	35	35	20	45	34	22	18	27	27
	RX Sensitivity [dBm]	-101	-98	-98	-92	-92	-92	NA	-90	-97	-91	-95	-92	-92
	TX Power [dBm]	+3	+5	+5	+4	+3	+3	NA	0	+3	+5	0	0	0
MCU Features	In Package		X	The ZigBee Coprocessor			X	X	X	X			X	X
	External	X			X	X					X	X		
	Core	AVR	XAP2b		HCS08	Coldfire	HCS08	ARM7	RISC	RISC	PIC	MSP430	x51	x51
	Bus Width [bits]	8	16		8	32	8	32	32	32	8	16	8	8
	RAM [kB]	8	5		4	~32	4	NA	to 96	to 96			8	8
	ROM [kB]	256	128		60	~256	60	NA	64	192			128	128
	Core Freq. [MHz]	16	12		20	50	40	26	16	16			32	32
ZB Stack	Availability	yes	yes	in ROM	yes	soon	yes	soon	yes	yes	yes	yes	yes	yes
	License Price				995 \$		995 \$				free	free	free	free
	Latest Version	PRO	2006	2006	2006	2006	2006	2006	2006	2006	2004	2006	2006	2006

6.5 Bluetooth vs. ZigBee

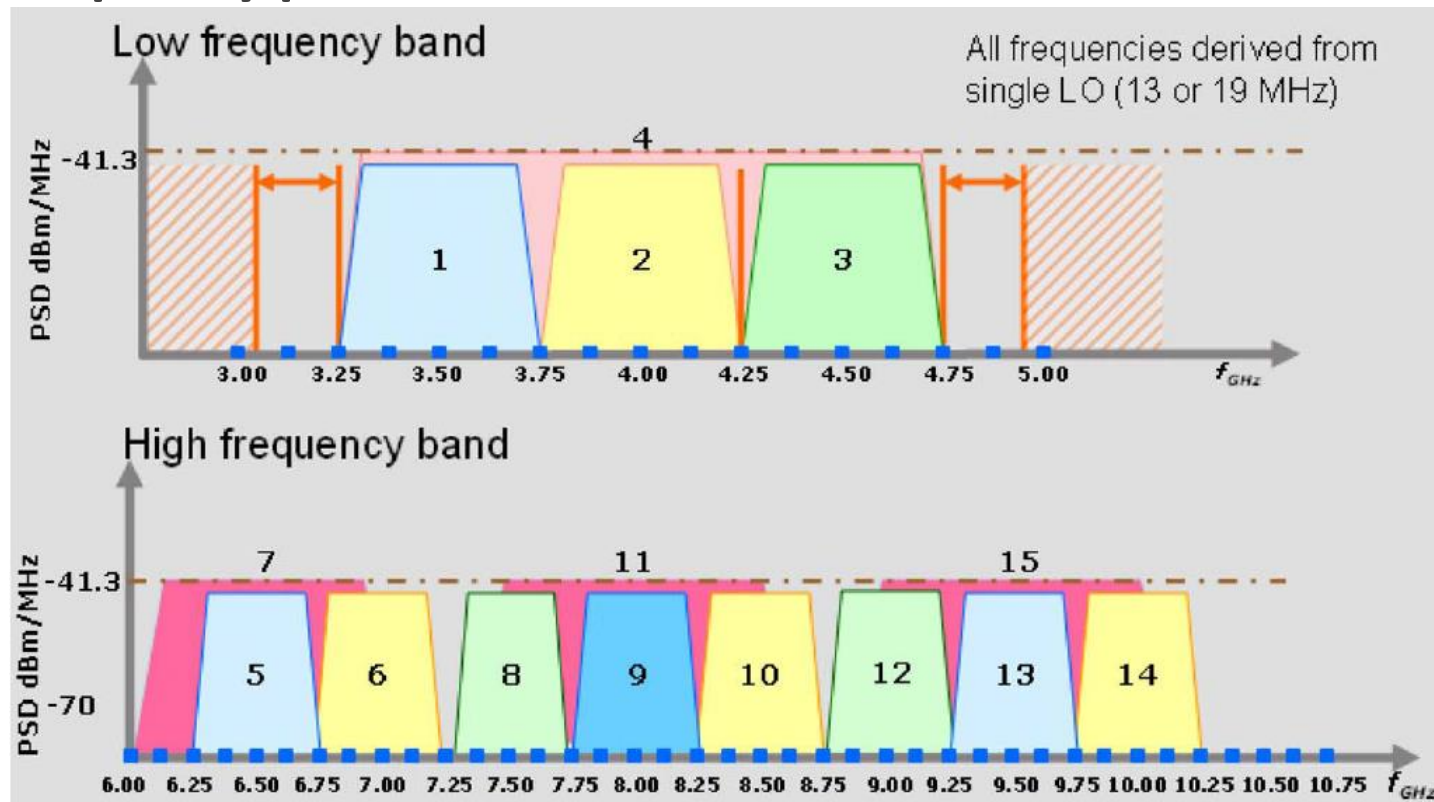
	Bluetooth	ZigBee
Aim	Connectivity of mobile devices	Control, automation, and low data rates
Traffic type	Streaming	Bursts
Protocol Stack Size	ROM: 140-200kB, RAM: 20-40 kB	ROM: 6 (RFD) – 28kB (FFD) / RAM: 1.5 (RFD) – 4kB (FFD)
Output power	0-20 dBm (typ. 1-2dBm)	0-20 dBm (typ. 1-2dBm)
Frequency bands	2.4GHz	2.4GHz, 868MHz, 915MHz.
Int. avoidance	Frequency Hopping	Channel selection, DSSS (ineffective)
Network join time	3-6 seconds	Order of 30ms
Network Topologies	Ad hoc, point to point and star	Ad hoc, Mesh and Star
Network Speed	1 Mbit/s.	250 kbit/s (@2.4 GHz)
Communication with end device	Initiated by Master	Initiated by end device

6.6 Practical example: 802.14.4a

- **802.14.4: Low-Rate Wireless Personal Area Networks (WPANs) supported by Zig-Bee alliance**
- **2004** : Initiation of the task group to amend IEEE 802.15.4
- **TG4a's Goal: providing a standard with high-precision ranging capability (1 m accuracy and better), high aggregate throughput, and ultra low power consumption (mainly due to low transmit power levels, typically under -10 dBm), as well as adding scalability to data rates, longer range, and lower cost**
- **Supported applications:**
 - Sensing and location mapping of disaster sites;
 - precision agriculture;
 - location-based routing and data collection;
 - location tracking of moving objects
- **One option of this standard is based on UWB transmission techniques, namely, TH-IR**
- **The other option makes use of chirp spread spectrum (CSS).**
- **On March 22, 2007, P802.15.4a was approved by the IEEE-SA Standards Board and was published in June 2007**

6.6 Practical example: 802.14.4a

- Frequency plan for UWB PHY



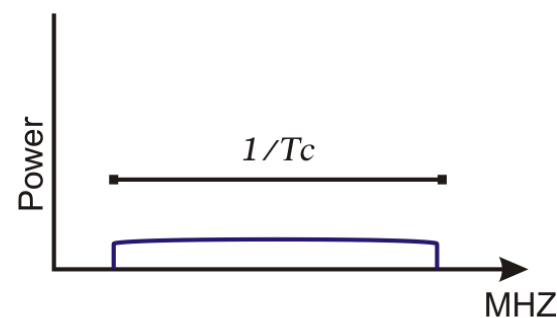
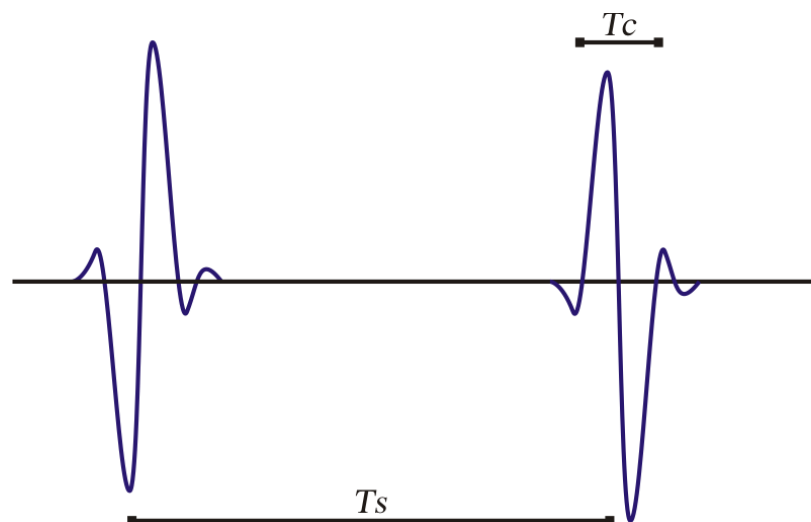
Source:
UWB
Systems
for
Wireless
Sensor
Networks,
Proceeding
s of the
IEEE, Vol.
97, No. 2,
Feb. 2009

- Sub-GHz band: channel 0 from 249.6-749.6MHz (not shown)
- Low band: channels {1-4} (4x 499.2 MHz BW)
- High band: channels {5:15} (8x 499.2 MHz BW +3 x 1331.1MHz BW)
- 5GHz ISM band is avoided

6.6 Practical example: 802.14.4a

IEEE 802.15.4a is based on **impulse radio (IR)**

- Spreading is achieved by sending only very short, high power pulses (2ns)
- From basic DSP we know that a short pulse has a wide spectrum



$$BW \approx 1/T_c \gg 1/T_s$$

- IEEE 802.15.4a chooses a **pulse duration of 2ns**, corresponding to **499.2 MHz bandwidth**

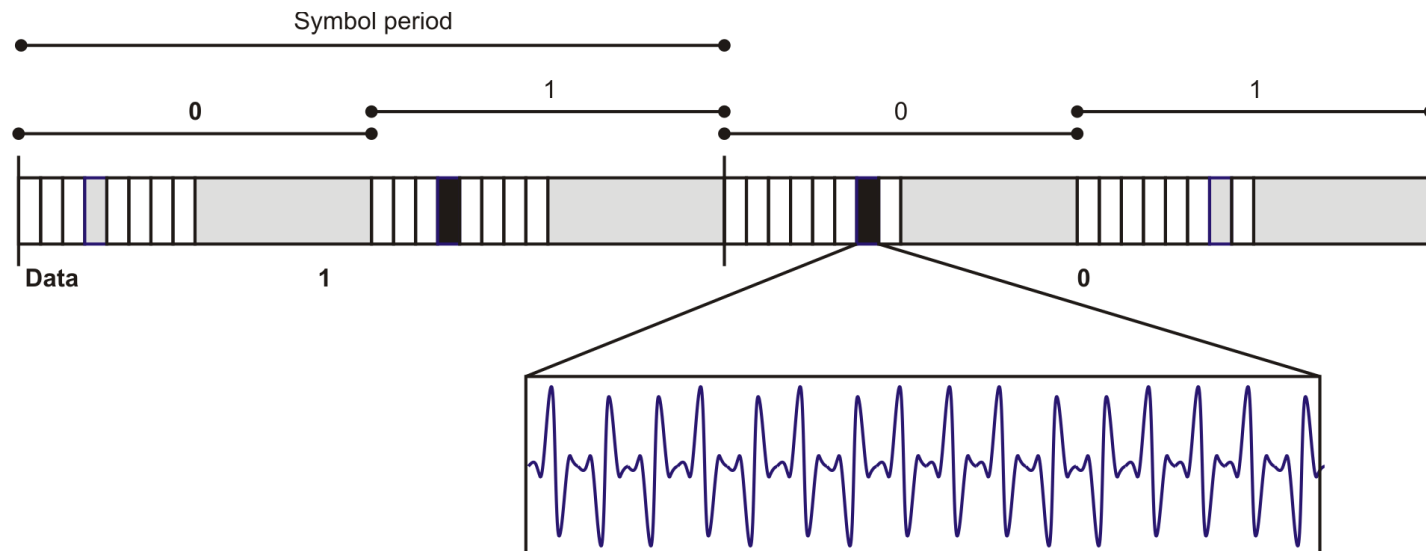
Implementation advantages

- Transmitter is only turned on for a very short time
- Linearity requirements for sending short pulses are very low (energy efficient design)

6.6 Practical example: 802.14.4a

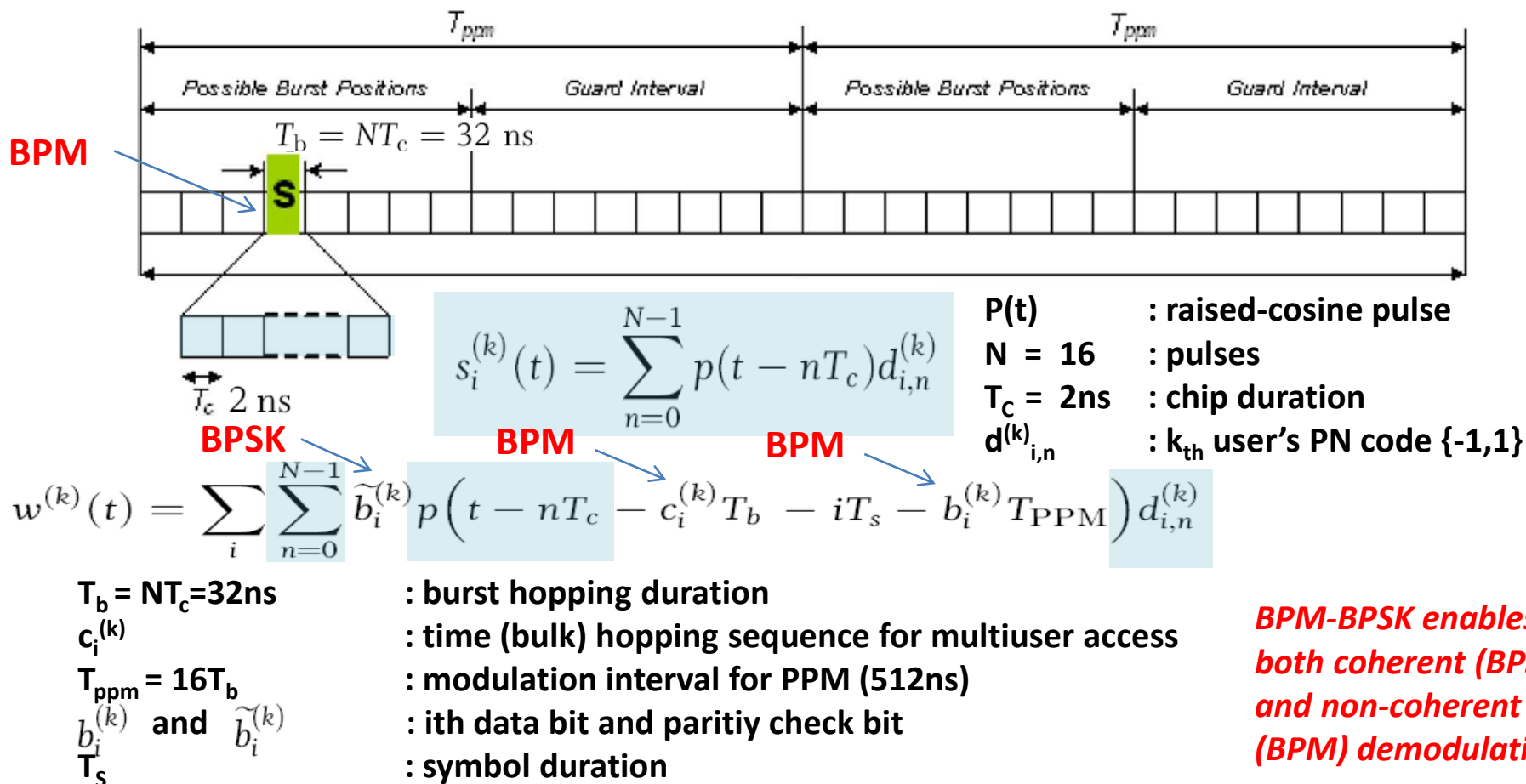
IEEE 802.15.4a employs **time hopping impulse radio (TH-IR)**

- Symbols are split into two parts: data is modulated by placing a PN-sequence burst in the 1st or 2nd half of a symbol period
- A burst corresponds to a sequence of 16 chips (each 2ns)
- In total 8 slots are available for sending the burst.
- Each user sends exactly one burst per symbol period
- User separation is performed by assigning different timeslots to different users



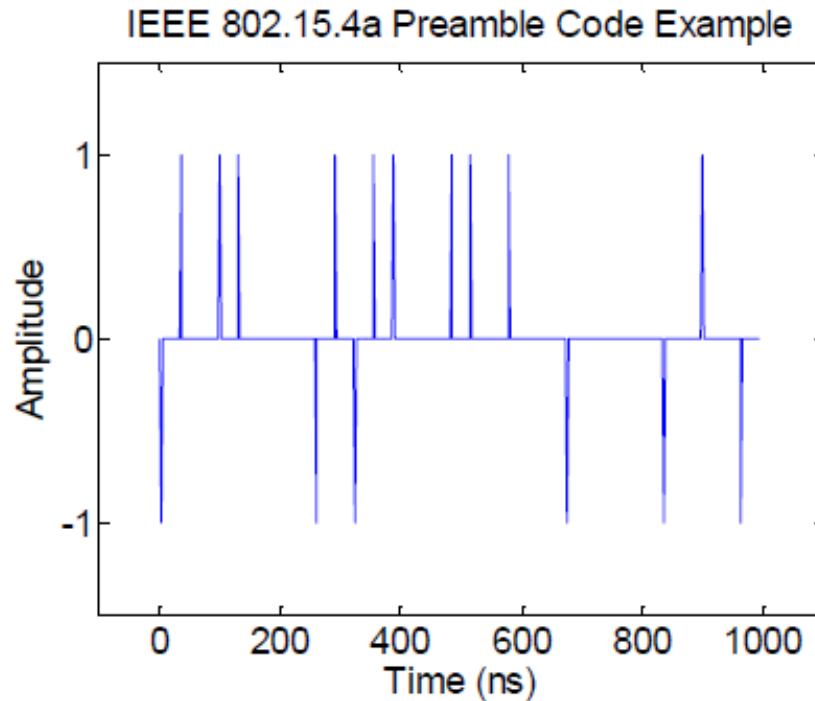
6.6 Practical example: 802.14.4a

- UWB PHY Symbol Structure (hybrid modulation and MA):
 - BPM-BPSK: Burst Position Modulation-Binary Phase Shift Keying.



6.6 Practical example: 802.14.4a

- Example of a preamble



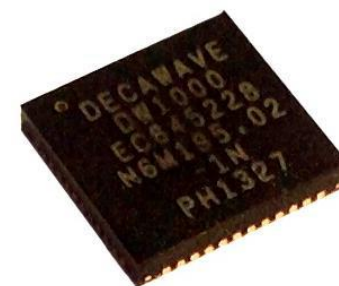
- Benefit of ternary code $\{0,1,-1\}$
 - Supports both coherent and non-coherent detection
 - Perfect autocorrelation allows ranging

Source: decaWave

6.6 Practical example: 802.14.4a

- **Example of commercial solution from decaWave:**

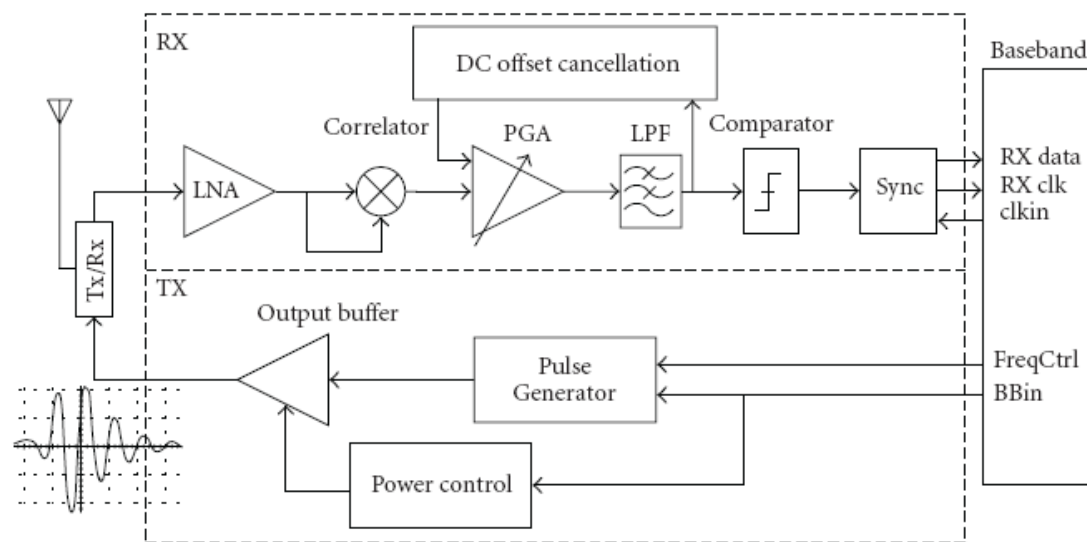
- single chip wireless transceiver based on ultra-wideband techniques compliant with the IEEE802.15.4-2011 standard
 - Excellent communications range of up to 300 m
 - Support high tag densities – up to 11,000 in a 20 m radius
 - Supports 110 kbit/s, 850 kbit/s & 6.8 Mbit/s data rates
 - 6 frequency bands supported with center frequencies from 3.5 GHz to 6.5 GHz
 - Transmit Power –14 dBm or –10 dBm
 - Preamble Length 64 μ s to 4 ms
 - Supports Packet Sizes up to 1023 bytes
- Power consumption:
 - Transmit mode from 31 mA*
 - Receive mode from 64 mA*
 - 2 μ A watchdog timer mode



6.6 Practical example: another UWB radio

- **impulse-based radio communication chip**

- Radio only turned on during pulse transmission and reception (**duty cycle**)
- Simpler architectures than for narrowband “tuned communications” are possible (**no DAC, PLL, PA**)



Source: Hia et al. “Experimental Characterization of a UWB Channel for Body Area Networks,” EURASIP Journal on Wireless Communications and Networking, 2011

		cc1101	cc1101	cc2500	This work
Frequency		433 MHz	868 MHz	2.4 GHz	3–5 GHz
Data rate		0.6~600 kbps	0.6~600 kbps	1.2~500 kbps	1~100 Mbps
Power consumption	TX	48 mW at 0 dBm	50.4 mW at 0 dBm	63.6 mW at 0 dBm	4.44 mW at –41.3 dBm/MHz
	RX	45~51.3 mW	43.8~50.7 mW	39.9~58.8 mW	13.2 mW
BER at RSSI		0.2% at –51 dBm	0.1% at –63 dBm	<0.1% at –64 dBm	1% at –50 dBm
Antenna size		Large	Medium	Small	Medium

6.6 Practical example: another UWB radio

UWB Energy Efficiency Advantage

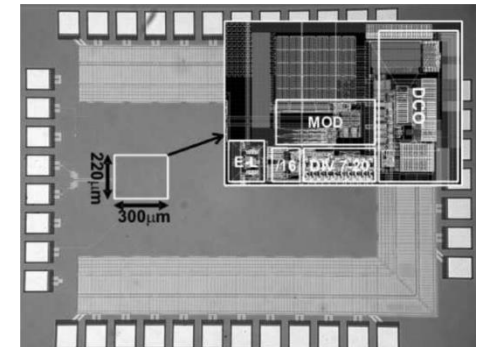
- UWB transmits data with a very low duty cycle (short bursts)
- Transmitter: pulse generation allows to duty cycle the transmitter
- Receiver: the most simple receiver can be realized with energy detection

Available devices:

- Research devices claim 1.4 nJ/bit in transmit mode

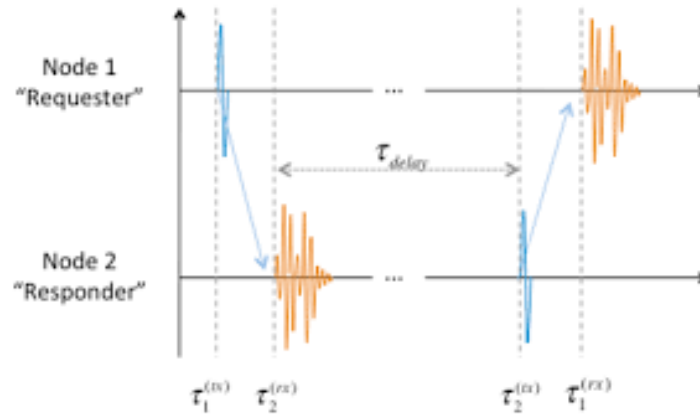
Ryckaert, J.; Van der Plas, G.; De Heyn, V.; Desset, C.; Van Poucke, B.; Craninckx, J.; , "A 0.65-to-1.4 nJ/Burst 3-to-10 GHz UWB All-Digital TX in 90 nm CMOS for IEEE 802.15.4a," *Solid-State Circuits, IEEE Journal of* , vol.42, no.12, pp.2860-2869, Dec. 2007

- Announcements of commercial devices specify 16mA @ 3V (480nJ/bit – 8nJ/bit) for transmit and ~34mA @ 3V for receive for 100kbps to 6 Mbps

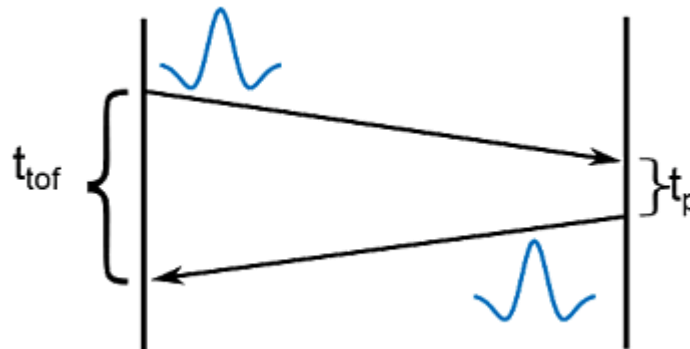


6.6 Practical example: 802.14.4a - RANGING

- Main idea: short pulses allow to precisely measure time of arrival



- With some protocol overhead, one can also compute the round-trip time, even in the absence of a common time reference



6.6 Prominent Practical examples: 802.14.4a

- UWB is gaining again popularity (mostly motivated by localization capabilities)



Apple iPhone 11



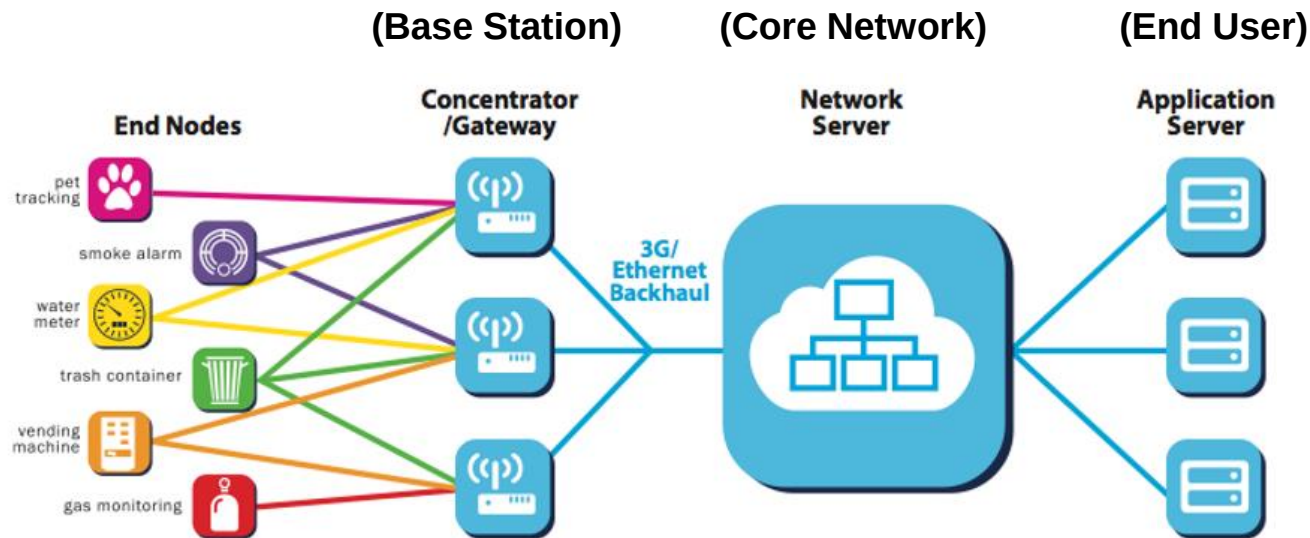
Car keys with ranging

- Alliance between multiple companies on different levels of the stack
- Multiple vendor offering based on cooperation between various companies offering services around a common open concept
- Technology was originally developed by Cycleo (Grenoble, France) and later acquired by *Semtech (Neuchatel, Switzerland)* in 2012
- Semtech broadly licenses the IP to other chip manufacturers
- LoRa Alliance provides a certification process for new products

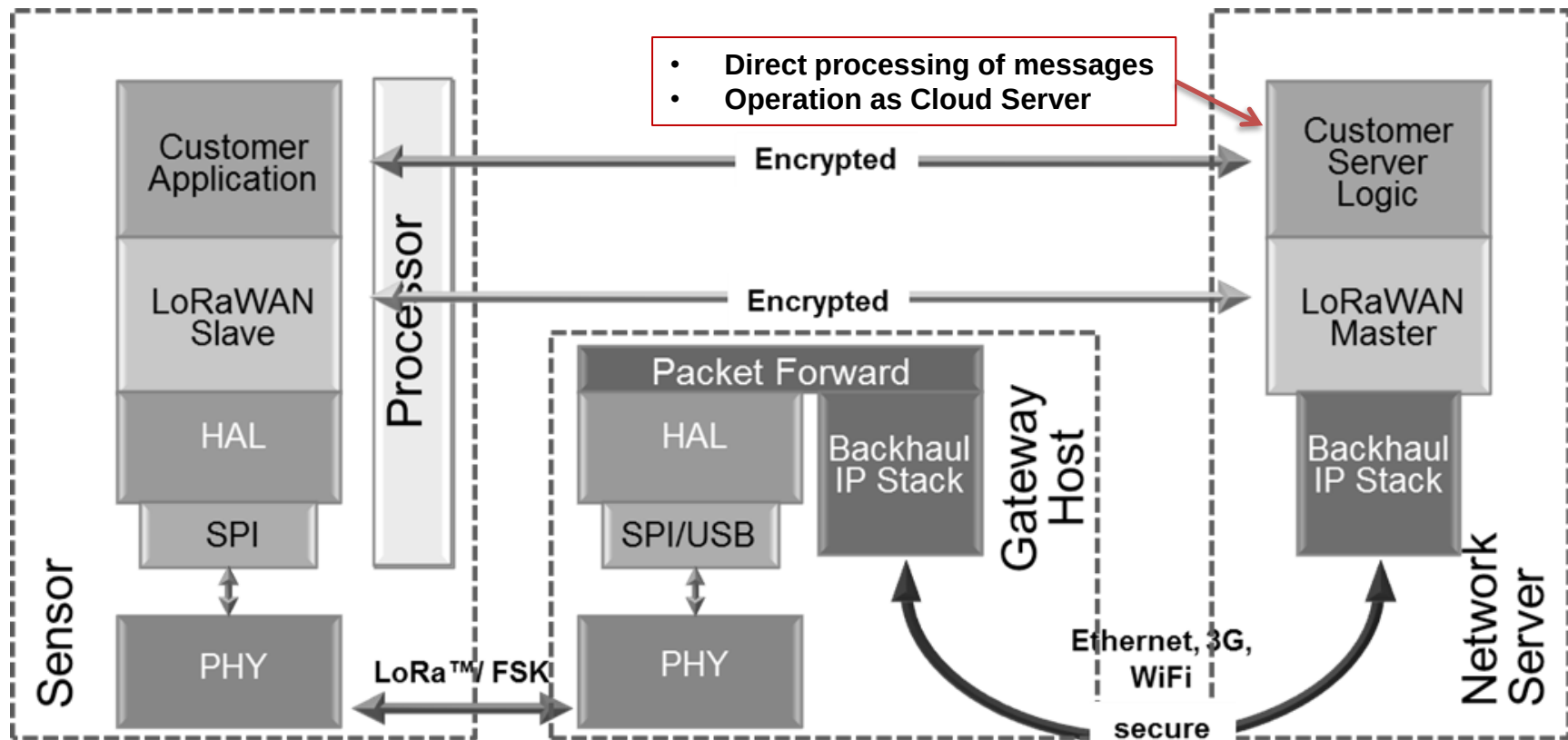
- Targets low data rates: 290 bps – 11 kbps (125 kHz), 1.16 kbps – 50 kbps (500 kHz)
 - Symmetric up and downlink
- Modulation provides multiple data rates using spread spectrum modulation
 - Robustness to interferers
 - Tradeoffs between data rate and range
 - Codes of different spreading factors are almost orthogonal
- Coverage per gateway: rural=5-10 km, urban=1-3 km
 - Multiple gateways extend coverage area and improve robustness (diversity)
 - Network server filters duplicate packets (received by multiple gateways)

6.7 The LoRa System Architecture

- **Gateways (Connectors):**
 - Receive and demodulate long-range wireless transmissions using LoRa PHY protocol and serve as interface between the wireless connection and a Network Server with almost no further intelligence
- **Network Server (intelligence):**
 - Collects receptions from multiple gateways (diversity), filters duplicate packets, schedules acknowledgements, controls data rates and checks security. They can process messages directly or act as Cloud Server to provide services to a further layer of customers (depending on the business model)



6.7 The LoRa System Stack

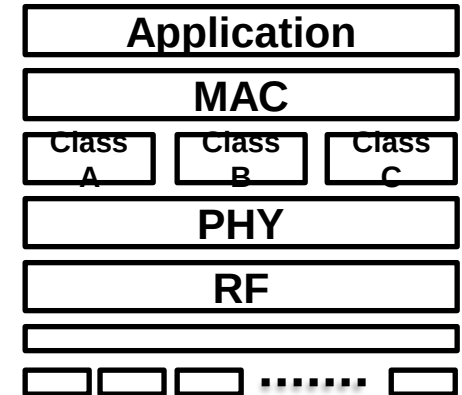


Source: <https://www.lora-alliance.org/What-Is-LoRa/Technology>

- Interface between Gateway and Network server is usually realized based on IP protocol
 - IP connection can be based on any wired or wireless technology (e.g., Ethernet, WiFi, or 3GPP)
- With LoRa, different business models may include or not Gateway Services

6.7 LoRa: RF and Physical Layer

- Typically used in ISM bands between 137 MHz to 1020 MHz (e.g., (169 MHz), 433 MHz, 868 MHz, and 915 MHz) to achieve long range
- Variable data rates up to a maximum of 11 kbps
- RF channel bandwidth of 125 kHz or 250 kHz
- Channel coding with different code rates (CR):
 $0=1$, $1=4/5$, $2=4/6$, $3=4/7$, $4=4/8$ (CR vs. channel coder rate)
 - Code rate of 1 is rarely used
- Proprietary LoRa Chip Spread Spectrum (CSS) modulation:
 linear FM signal conveys a binary Complementary Code Keying (CCK)
 signal with variable length of 2^{SF} chirps to convey SF bits
 - Advantages over conventional DSSS: insensitive to frequency offsets due to FSK
 - Spreading factors: $2^6, 2^7, 2^8, 2^9, 2^{10}, 2^{11}, 2^{12}$ (LoRa defines SF in log: 6,..., 12)

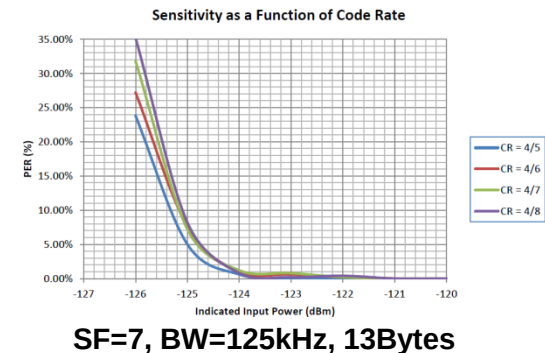


PHY Data Rate [bps]

$$R_b = SF \cdot \frac{4}{4 + CR} \cdot BW$$

Processing Gain / CR vs. Sensitivity Improvement

- Increasing SF by one increases sensitivity of 2.5 - 3dB
- Lower CR provide only a real advantage for high PERs



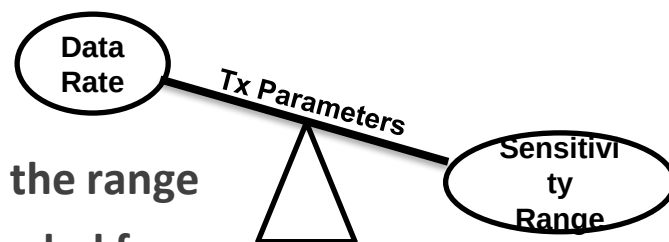
6.7 LoRa: RF and Physical Layer Sensitivity

- Doubling BW doubles data rate, but reduces sensitivity by 3 dB
- Example, based on Semtech SX1272 (860 – 1020 MHz)

Bandwidth	SF	Code rate	Bit rate (bps)	Sensitivity [dB]
125	6	4/5	9380	-122
125	12	4/5	293	-137
250	6	4/5	18750	-119
250	12	4/5	586	-134
500	6	4/5	37500	-116
500	12	4/5	1172	-131

- **Range:**

- In LOS scenario: 6 dB better sensitivity doubles the range
- Urban environment: 12 dB better sensitivity needed for doubling the range



6.7 LoRa: Multiple Access

- Different device classes provide tradeoff between power consumption and device capabilities (e.g., data rate and latency)

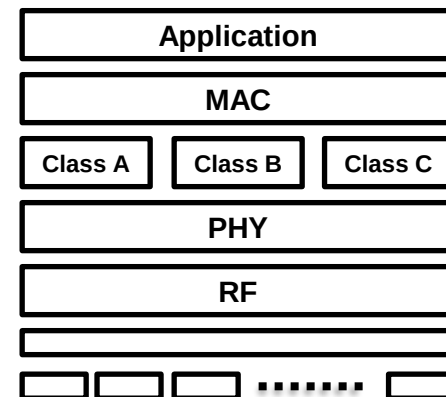
- Class A (battery): Bi-directional end-devices

Lowest power mode, where only the end-device can initiate a transmission. Downlink transmissions are pol-based and have to follow immediately to an uplink transmission within a very short time window. Uplink mostly used for ACK and for few rare downlink transmissions (costly since device needs to transmit first to receive a downlink transmission) that are not latency critical.

- Class B (battery): Bi-directional end-devices with scheduled receive slots

Periodically scheduled downlink transmissions enable downlink traffic without the need for a costly prior active poll on the uplink. End devices require a precise timer that is synchronized to the network server by periodic beacons.

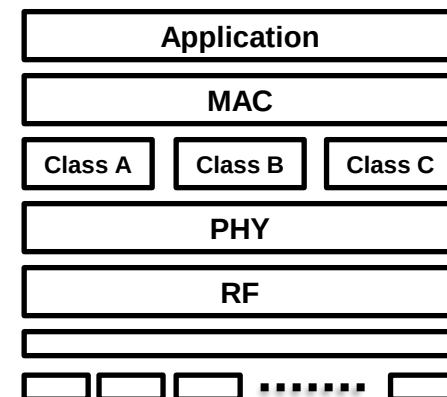
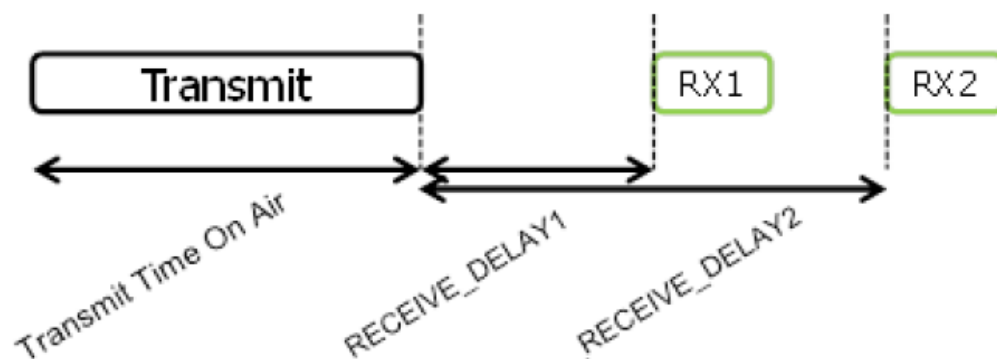
- Class C (mains): Bi-directional end-devices with maximal receive slots
End-device supports continuous reception of uplink traffic



6.7 LoRa: Multiple Access (Class A)

- **LoRa Class A based on the ALOHA protocol for multiple access**

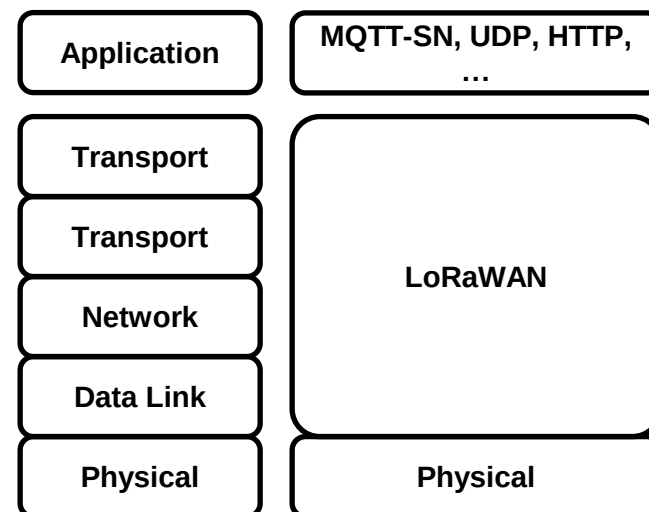
- Class A is the most frequently used type of devices with all communication initiated by end-user device with uplink msg.



- Orthogonality between spreading codes of different lengths allows collisions between devices that use different SFs
- Collisions are resolved by missing ACK and retransmissions with random transmission slots
- Target duty cycle of <1% and limited number of packets per day ensures low collision probability
- Typical ALOHA network capacity ~18% of its maximum
- Encryption and authentication using AES-128

6.7 LoRaWAN: The Network Layer

- **LoRaWAN:** open network standard for LoRa devices, maintained by the LoRa Alliance
 - It defines the communication protocol and system architecture for LoRa networks
- In the OSI reference model LoRaWAN spans from the Data Link Layer to the Session Layer
 - **Data link layer: loRaWAN manages channels, Data rates, and executes MAC commands**
 - Network layer: manages device addresses and selects gateways for downlink
 - **Transport layer: tracks frame counters and checks message integrity (and combines/selects uplink messages received from multiple gateways)**
 - Session layer: over-the-air-activation (OTAA) manages connection (and validation) of devices and the creation of new sessions (including security)
- loRaWAN does not dictate a binary payload format => compatible with different application layer protocols

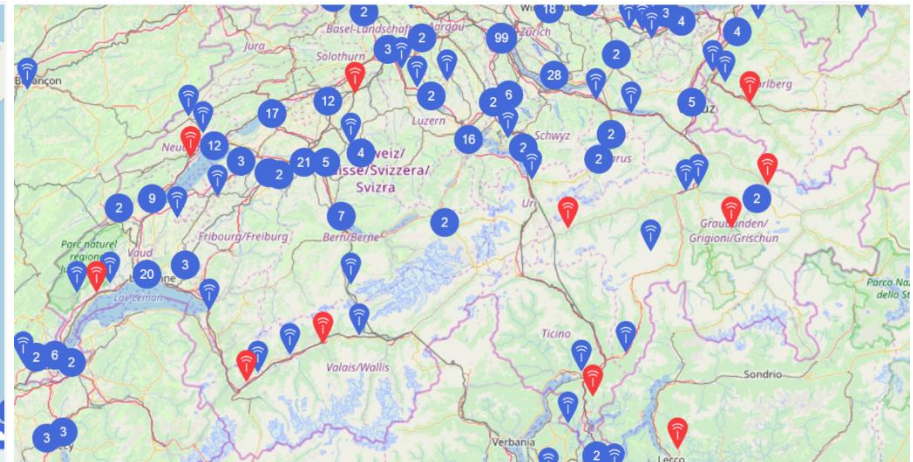


6.7 The Things Network (TTN): A Free Open Source LoRa Network

- Free Open LoRaWAN based community network
- Available network infrastructure includes
 - Various publicly accessible LoRaWAN gateways
 - LoRaWAN Network server
 - Basic application interfaces and bridges (MQTT, UDP, HTTP, ...)
- Users extend the network by adding their own gateways to cover holes in the network
 - Ready to use TTN gateway cost: 250 ~ 300 Euro



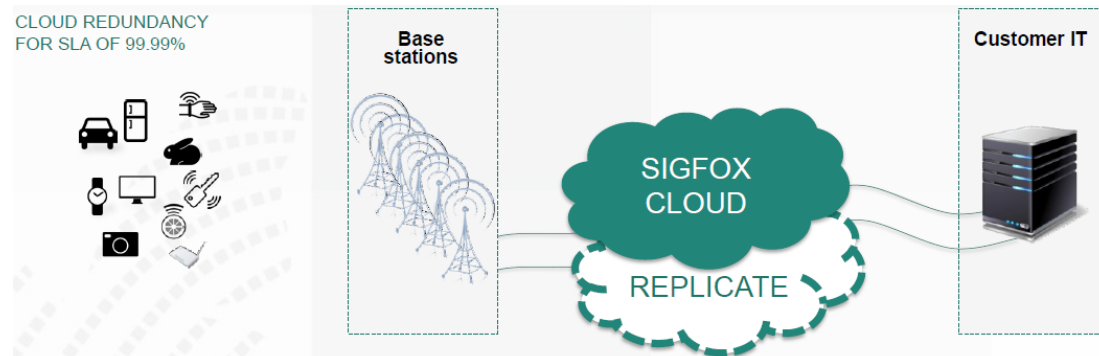
Worldwide availability



Good coverage in Switzerland

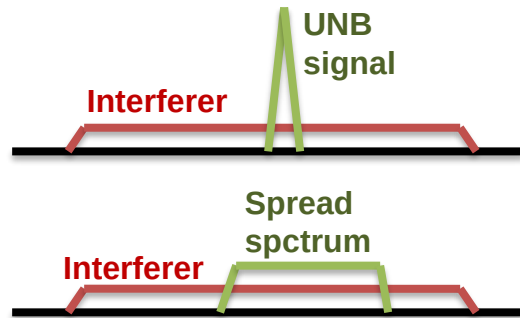
More information: <https://www.thethingsnetwork.org/>

- Proprietary turnkey solution offered by a single player: SIGFOX (France) founded in 2009
- SigFox offers the entire service chain (no licensing of IP)
- Targets ultra-low data rates: < 300 bps (uplink) and 8 bits/day (downlink)
 - Focused on uplink traffic only (reverse link for ACK)
- Number of up-link messages limited to 140 per day per device (4 downlink)
- Ultra short messages with maximum of 0,4,8, or 12 bytes/message
- Coverage per gateway: rural=15 km, urban=3-5 km
 - Multiple gateways extend coverage area and improve robustness (diversity)
- System architecture: similar to LoRa, but entirely owned by SigFox

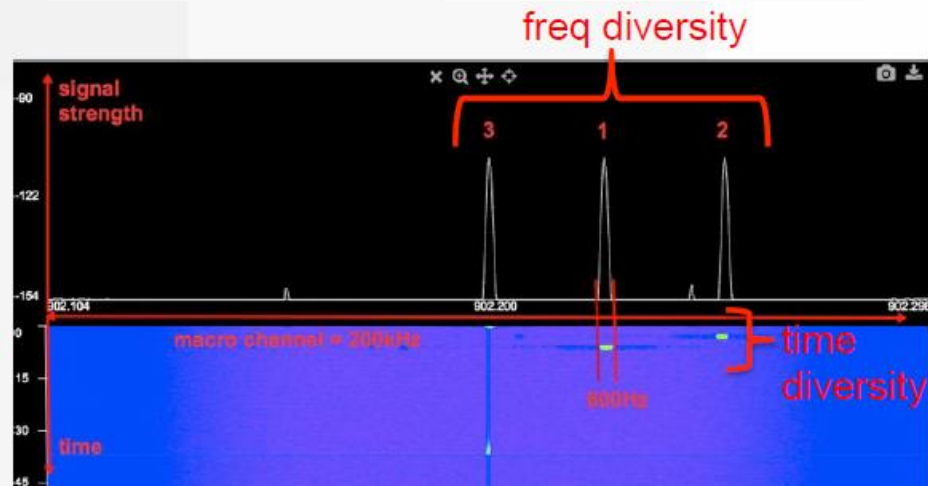
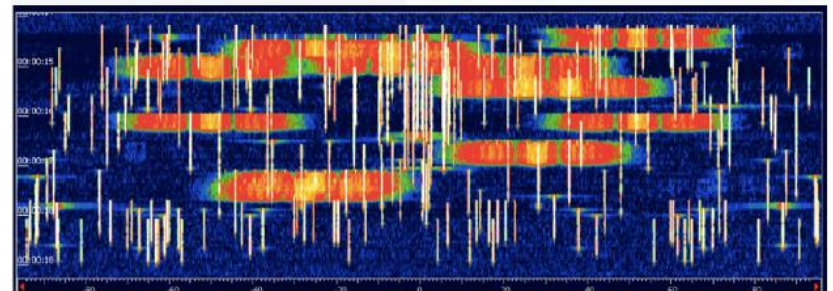


6.8 SigFox: Physical Layer

- Typically used in ISM bands (868 MHz, 902 MHz, and 920 MHz)
- Physical layer based on Ultra Narrow Band Band Differential BPS modulation (DBPSK)
 - Differential (non-coherent) modulation avoids the need for channel estimation
 - Baud rate ~ 100 Hz (600 Hz in the US)
 - Concentration of energy in a very small frequency band, but over a very long time): opposite concept to wideband modulation, but same idea to provide robustness to wideband interferers



- Packets are repeated three (3) times on different carriers for frequency and time diversity

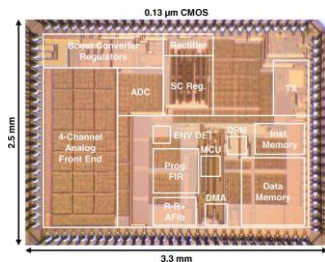
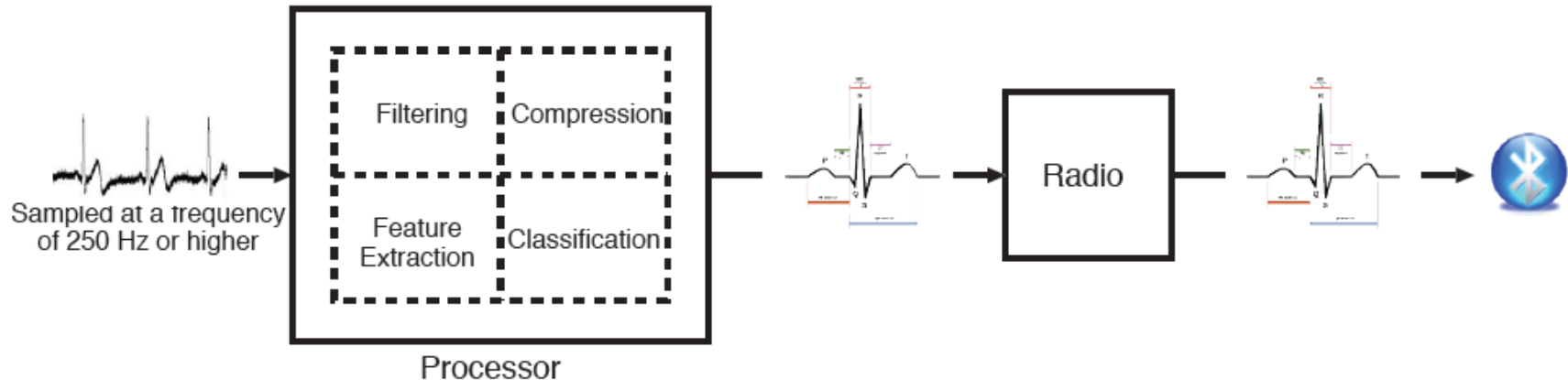


- **Medium access control**
 - All communication initiated by end-user device with an uplink message (Similar to Class A LoRa)
 - No signalling or negotiation between device and gateway
 - Randomization in time and frequency: device picks a random time- and frequency-slot (random FDMA) for any transmitted packet
 - User authentication based on SHA-256

7 Case study: energy consumption analysis and optimization of wireless transmission

Reducing the amount of data to be transmitted generally reduces radio interface power consumption, but requires

- reasonably efficient radio protocol (power-down between bursts)
- processing resources on the node to reduce data to the essence



Zhang (2012)



IMEC cardiac patch
(Yazicioglu, 2009)

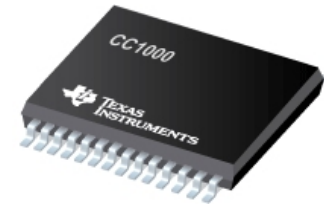


Holst Centre
(Masse, 2010-13)



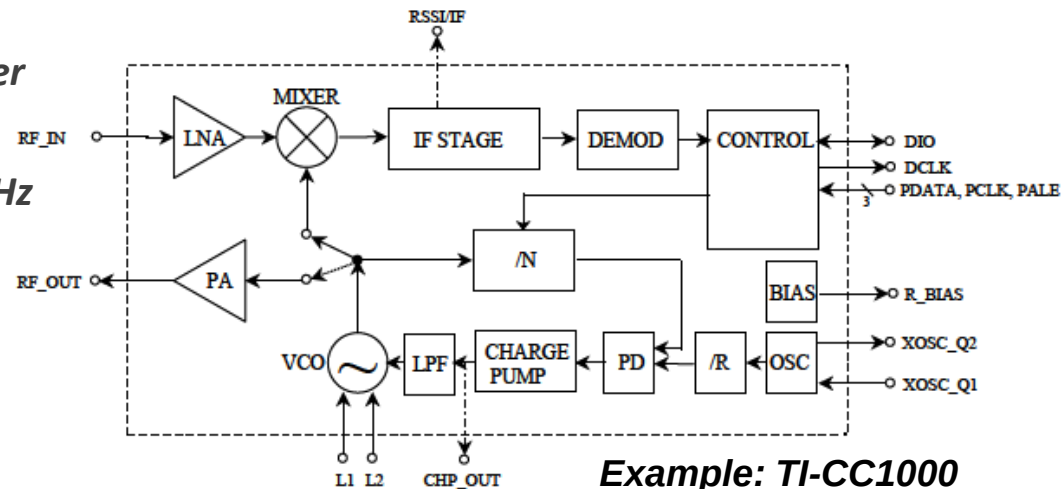
Shimmer
(shimmerresearch, 2010-13)

- Consider a system that comprises only the physical layer
- Simple RF radios are available as discrete components
 - TI, Analog Devices, Freescale, Microchip (often combined in SoCs with low power uControllers)
- A simple single-chip (UHF) transceiver
 - RF frequency synthesis from a low-frequency reference quartz (few MHz)
 - Modulation: alters the RF signal according to the data
 - Demodulation: analyzes the received signal to recover the data
 - Received signal strength indicator (RSSI): detects presence of an RF signal and its strength

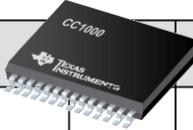


• Example: TI-CC1000

- *Combined transmitter and receiver*
- *Software-programmable freq. band: 315 / 433 / 868 and 915 MHz*
- FSK modulation up to 76.8 kbit/s
- Programmable output power

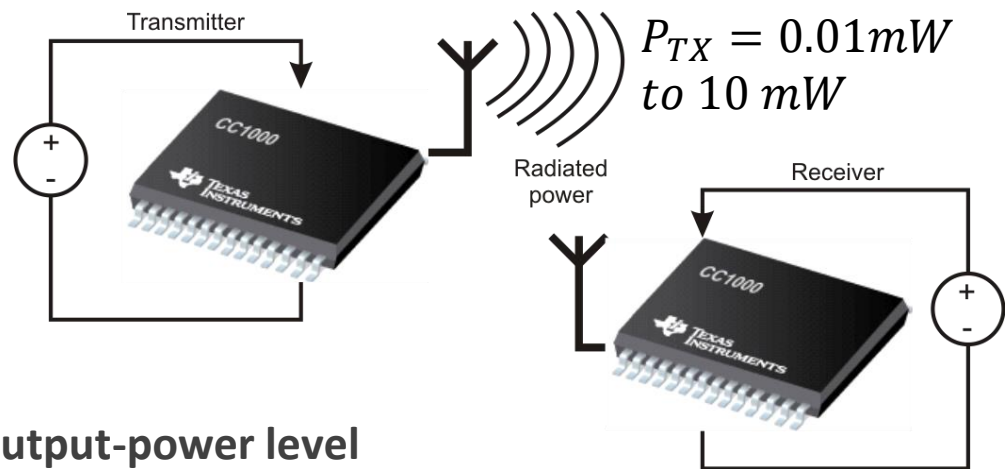


Example: TI-CC1000



Parameter	Typ.	Max.	Unit
Current Consumption, receive mode 433/868 MHz	7.4/9.6		mA
P=0.01mW (-20 dBm)	5.3/8.6		mA
P=0.3 mW (-5 dBm)	8.9/13.8		mA
P=1 mW (0 dBm)	10.4/16.5		mA
P=3 mW (5 dBm)	14.8/25.4		mA
P=10 mW (10 dBm)	26.7/NA		mA
Current Consumption, crystal osc.	30 80 105		μ A μ A μ A
Current Consumption, crystal osc. And bias	860		μ A
Current Consumption, crystal osc., bias and synthesiser, RX/TX	4/5 5/6		mA mA

- Transmitter W_{TX} :
 - 433 MHz: 16 – 80.1 mW
 - 868 MHz: 25.8 – 76.2 mW
- Receiver W_{RX} :
 - 433 MHz: 22.2 mW
 - 868 MHz: 28.6 mW



Transmitter

- Power consumption depends on the output-power level
- Radio output-power level P_{TX} is far below transmitter power consumption W_{TX}

Receiver

- Power consumption is comparable to the transmitter (at low power levels)

- For sensor node applications, power consumption is not the most relevant metric
 - Energy efficiency relates battery lifetime to the amount of data that can be transmitted
 - Energy efficiency is measured in Joules per (information) bit [J/bit] and depends on the active power consumption and the data rate

$$E \left[\frac{nJ}{bit} \right] = W_{Tx/Rx} \cdot T_{bit} = \frac{W_{Tx/Rx}}{f}$$

- Increasing the transmission rate f
 - improves energy efficiency, but also reduces radiated energy per information bit
 - Receiver: sensitivity drops for higher rates

Data rate [kBaud]	Separation [kHz]	433 MHz			868 MHz		
		NRZ mode	Manchester mode	UART mode	NRZ mode	Manchester mode	UART mode
0.6	64	-113	-114	-113	-110	-111	-110
1.2	64	-111	-112	-111	-108	-109	-108
2.4	64	-109	-110	-109	-106	-107	-106
4.8	64	-107	-108	-107	-104	-105	-104
9.6	64	-105	-106	-105	-102	-103	-102
19.2	64	-103	-104	-103	-100	-101	-100
38.4	64	-102	-103	-102	-98	-99	-98
76.8	64	-100	-101	-100	-97	-98	-97
Average current consumption		9.3 mA			11.8 mA		

toward higher
data rates
↓

↑
toward better
sensitivity

- Maintain a given signal to noise ratio as data rate f increases
 - Need to increase transmit power to maintain constant received energy per bit
 - From an information theoretic perspective we would expect

$$\frac{P_{RX}}{f} \equiv \text{const.} \Rightarrow P_{TX} \sim f \quad W_{TX} \sim P_{TX} \sim f$$

- “Luckily” reality is different: $P_{TX} < O(f)$ and $W_{TX} < O(P_{TX}) < O(f)$

Rate f	Duty cycle	Tx power	Sensitivity	Margin	Tx	Rx
4.8 kbit/s	1	-5 dBm	-107 dBm	102 dB	26.7 mW	22.2 mW
38.4 kbit/s	1/8	0 dBm	-102 dBm	102 dB	31.2 mW	22.2 mW

↓ 3x

↓ 1.2x

Overall improvement in energy efficiency with higher data rates

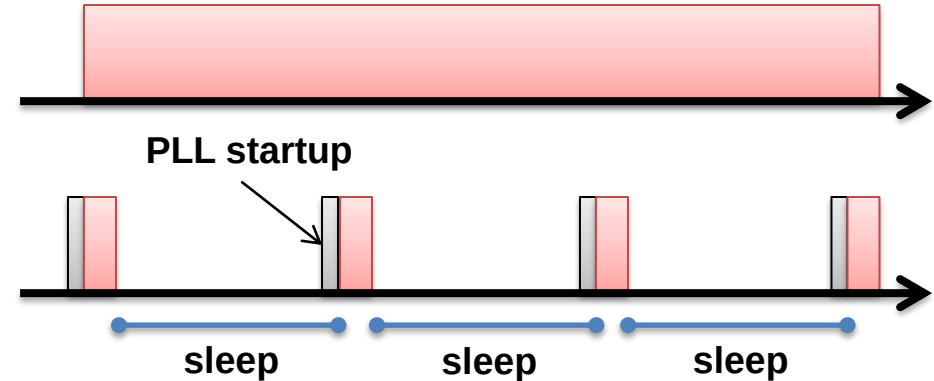
Rate f [kbps]	Tx energy efficiency	Rx energy efficiency
4.8 kbit/s	5.6 uJ/bit	4.6 uJ/bit
38.4 kbit/s	0.8 uJ/bit	0.6 uJ/bit

- Constant throughput requirement

- Higher rate allows to duty-cycle both transmitter and receiver
- Duty cycling is limited by the startup/locking time of the frequency synthesizer (typ: 0.1-1 ms)

Duty cycle	Rate f	Tx	Rx
1	4.8 kbit/s	26.7 mW	22.2 mW
1/8	38.4 kbit/s	3.9 mW	2.8 mW

$$L_{Burst}[bits] \gg T_{Startup} \cdot f$$



- Example: TI-CC1000

- $T_{Startup} = 250 \mu s$
- $f = 38.4 \text{ kbit/s}$

$$L_{Burst} \gg 10 \text{ bit}$$

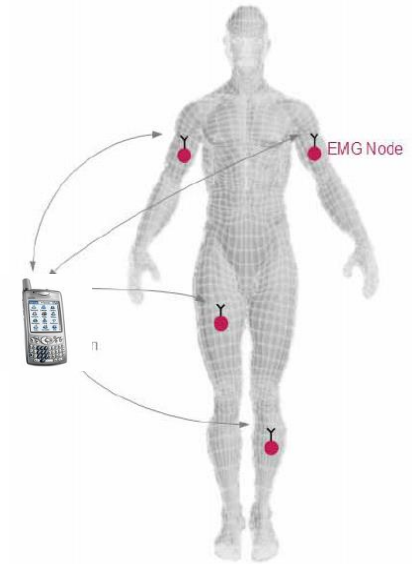
Parameter	Min.	Typ.	Unit	Condition / Note
PLL turn-on time, crystal oscillator on in power down mode		250	μs	Crystal oscillator running
Current Consumption, crystal osc. And bias		860	μA	
Current Consumption, crystal osc., bias and synthesiser, RX/TX		4/5 5/6	mA mA	< 500 MHz > 500 MHz



Sensor data is usually highly redundant (i.e., compressible)

- Data reduction through analysis and/or compression
- Requires computations (i.e., consumes power)
- Computations can often be done either after transmission on the central node *or* before transmission on the sensor node

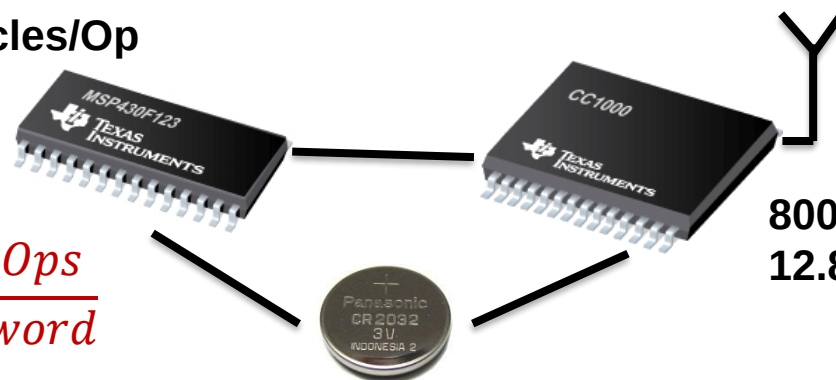
What is the cost of computation vs. the cost of transmission??



Example: MSP430 16-bit low-power uController with TI-CC1000 transceiver

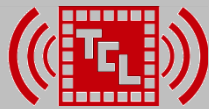
600 $\mu\text{W}/\text{MHz}$, 1-3 cycles/Op
200 pJ/Operation

$$\frac{12.8 \frac{\mu\text{J}}{\text{word}}}{200 \frac{\text{pJ}}{\text{Op}}} > 64'000 \frac{\text{Ops}}{\text{word}}$$



800 nJ/bit or
12.8 $\mu\text{J}/\text{word}$ (16-bit)

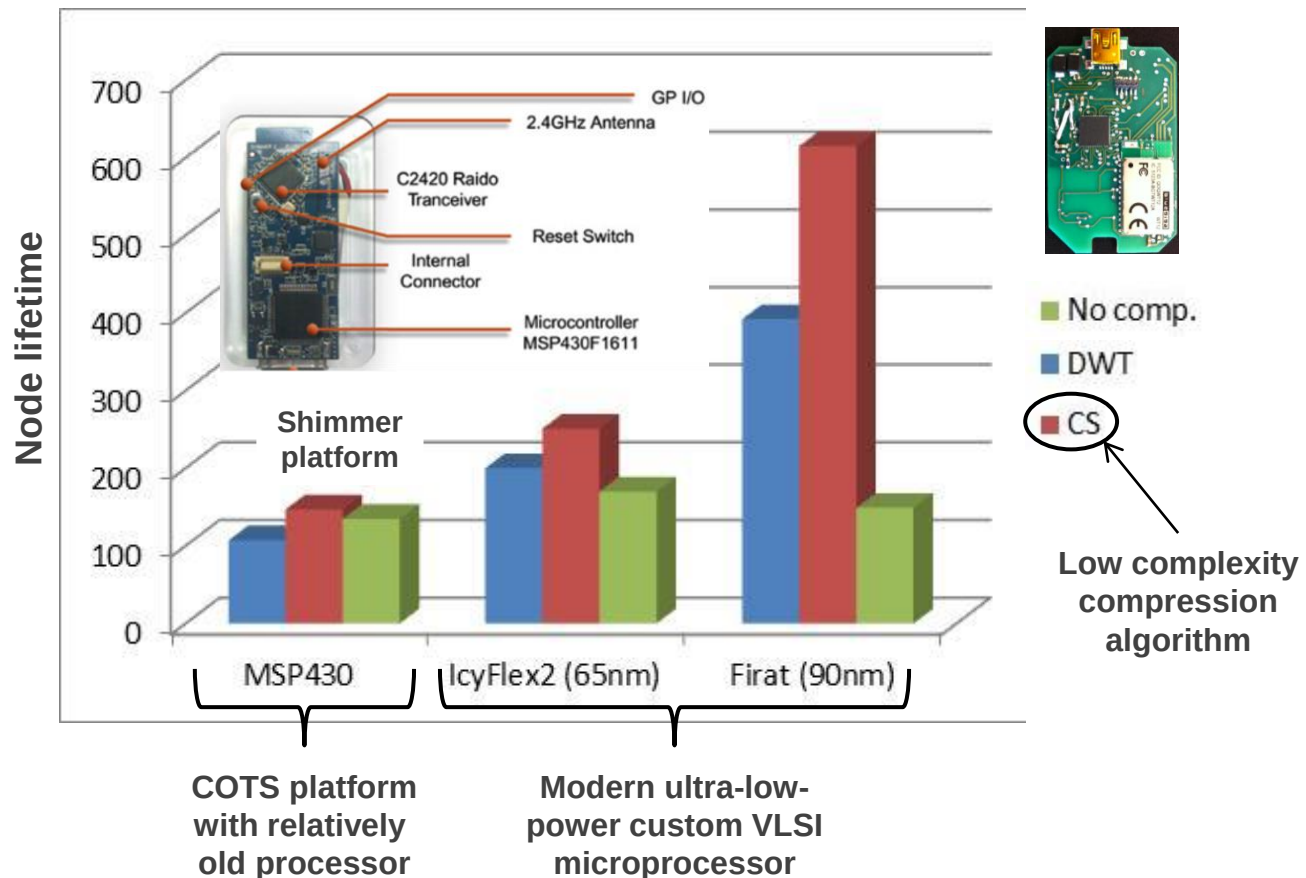
7 Lifetime extension from compression



Compression requires processing resources and consumes power

- Energy savings from reduced radio activity can get eaten up by
 - Poor energy efficiency of the embedded processor
 - Overly complex compression/analysis algorithms

- Burden shifts to more energy-efficient data processing



[Rincon et al., ITAB, 2011]

7 Summary

- Various technologies are available for communication in W(B)SNs
- Narrow band transceivers are simple to use and have little to no protocol overhead but data rates are low and channel access and network layers are undefined
- Standards such as Bluetooth and ZigBee are ready for complex network structures and higher data rates
- In low rate systems, higher data rates offer low power, if paired with low duty cycle operation
- For complex networks with low-complexity clients ZigBee has an advantage since it focuses on reducing power on the sensor side
- The advantage of Bluetooth are its higher data rates which can improve energy efficiency (shorter bursts), but duty cycles must be very long
- UWB (IEEE 802.15.4a) is a promising alternative

**This lesson was given in a previous edition of the EAWS
by Dr. Cyril Botteron**

Part of the slides of his presentation are reused in this lecture