This lecture is being recorded

18-452/18-750
Wireless Networks and Applications
Lecture 20: PAN

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http://www.cs.cmu.edu/~prs/wirelessS22/

Outline

- **802.15 protocol overview**
- **Bluetooth**
- **Personal Area Networks – 802.15**
  - » **Applications and positioning**
  - » **Bluetooth**
  - » **High speed WPAN**
  - » **Zigbee**
  - » **Other**
- **UWB**

IEEE 802.15:
Personal Area Networks

- **Target deployment environment: communication of personal devices working together**
  - » **Short-range**
  - » **Low Power**
  - » **Low Cost**
  - » **Small numbers of devices**
- **Four groups of standards:**
  - » **IEEE 802.15.1 – "Bluetooth"**
  - » **IEEE 802.15.2 – Interoperability (e.g. Wifi)**
  - » **IEEE 802.15.3 – High data rate WPAN (WiMedia)**
  - » **IEEE 802.15.4 – Low data rate WPAN (ZigBee)**
  - » **IEEE 802.15.6 – Body Area Networking**
  - » **IEEE 802.15.7 – Visible Light Communication**

Some Common Themes

- **Master/slave notion**
  - » **Or basic node versus coordinator**

- **Use of "piconets"**
  - » **Small groups of devices managed by a master or coordinator**
  - » **Supports only small numbers of devices - scalability is not a concern**
  - » **These are typically not general networks (e.g., Ethernet)**

- **Support for QoS**
  - » **Want to support voice and other media**

- **But there are many variants in how this functionality is supported**

Bluetooth

- **Think USB, not Ethernet**
  - » **Cable replacement technology**
- **Originally defined as IEEE 802.15.1, but standard is now maintained by the Bluetooth Special Interest Group**
  - » **Created by Ericsson**
- **Some features:**
  - » **Up to 1-3 Mbps connections**
  - » **1600 hops per second FHSS**
  - » **Includes synchronous, asynchronous, voice connections**
  - » **Piconet routing**
- **Small, low-power, short-range, cheap, versatile radios**
- **Used as Internet connection, phone, or headset**
- **Master/slave configuration and scheduling**

Bluetooth Standards

- **Core specifications: defines the layers of the Bluetooth protocol architecture**
  - » **Radio - air interface, txpower, modulation, FH**
  - » **Baseband - power control, addressing, timing, connections..**
  - » **Link manager protocol (LMP) - link setup & mgmt, incl. authentication, encryption, …**
  - » **Logical link control and adaptation protocol (L2CAP) - adapts upper layer to baseband**
  - » **Service discovery protocol (SDP) – device info, services and characteristics.**

- **The standard is very big and complicated!**

Bluetooth "Profiles"

- **Profile specifications describe the use of BT in support of various applications**
  - » **Includes which parts of the core specification are mandatory, optional or not applicable**

- **Data and voice access points**
  - » **Real-time voice and data transmissions**

- **Cable replacement**
  - » **Eliminates need for cable attachments for connection**

Usage scenarios: Headset

Usage scenarios: Synchronization
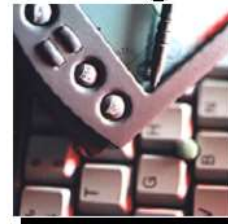
Some Example Profiles

- **Audio/video profile**
- **Fax profile**
- **Basic printing profile**
- **Serial port profile**
- **PAN profile**
- **Phone book access profile**
- **Headset profile**
- **LAN access profile**
- **Service discovery profile**
- **Cordless phone profile**

Frequency Hopping in Bluetooth

- **Provides resistance to interference and multipath effects**

- **Provides a form of multiple access among co-located devices in different piconets**

- **Total bandwidth divided into 79 1MHz physical channels**

- **FH occurs by jumping from one channel to another in pseudorandom sequence**

- **Hopping sequence shared with all devices on piconet**

 » **Remember that all communication is with the master, i.e., only one transmitter at any time**

Sharing the Channel

- **Bluetooth devices use time division duplex (TDD)**

- **Access technique is TDMA**

- **FH-TDD-TDMA**
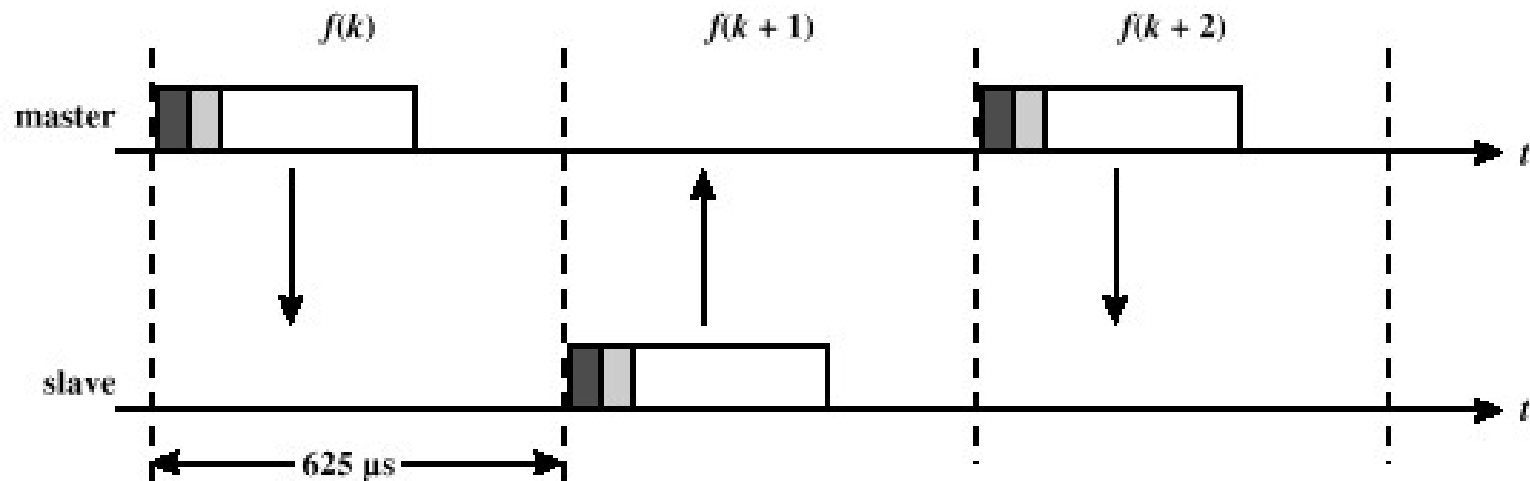
Piconets are Basis for Topology

- **Master with up to 7 active slaves**
  - » **Slaves only communicate with master**
  - » **Slaves must wait for permission from master**

- **Master picks radio parameters**
  - » **Channel, hopping sequence, timing, …**

- **Scatternets can be used to build larger networks**
  - » **A slave in one piconet can also be part of another piconet**
  - » **Either as a master or as a slave**
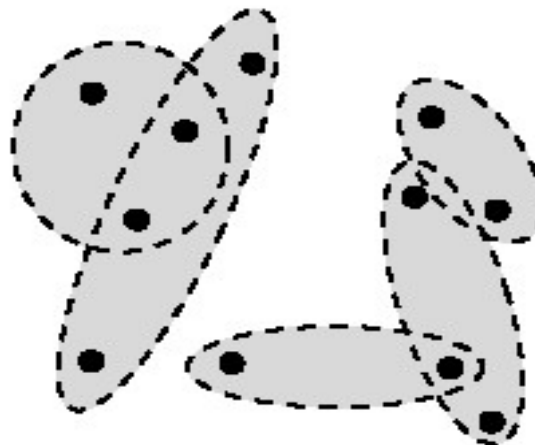 - » **If master, it can link the piconets**
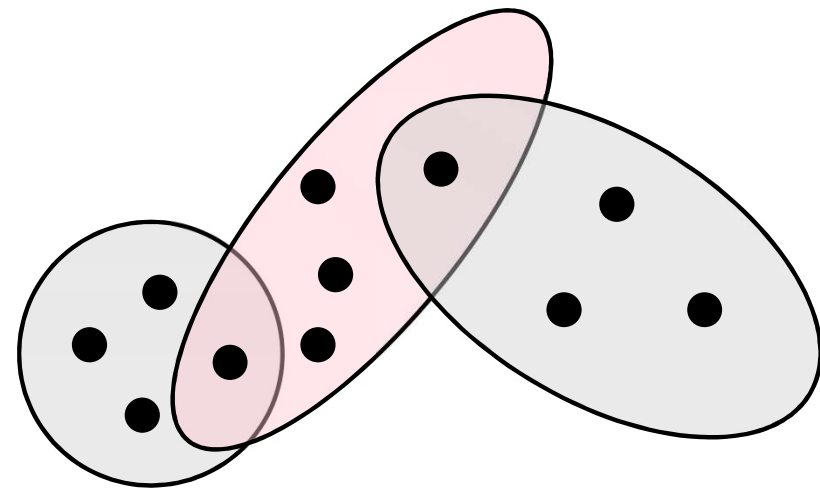
Wireless Network Configurations
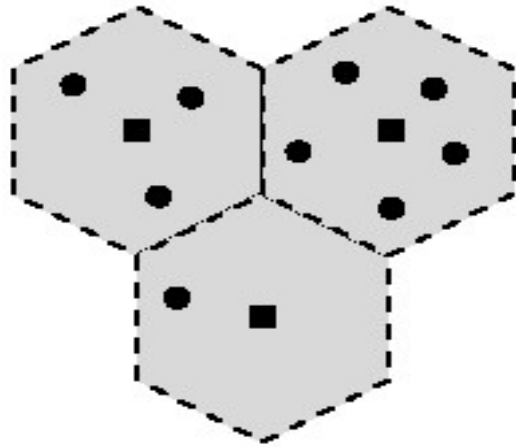
(a) Cellular system (squares represent stationary base stations)
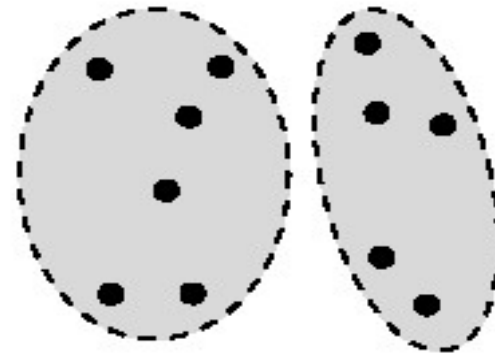
(b) Conventional ad hoc systems

(c) Scatternets

Bluetooth Piconet

- **A collection of devices connected via Bluetooth technology in a master-slave network**
  - » **Master functions as the piconet coordination (PNC)**
  - » **Can have a master and 1-7 slaves**

- **Joining of piconet involves three steps**
  - » **Master advertises its presence**
  - » **Slave can submit a join request (typically initiated by user)**
  - » **Master accepts request and establishes connection**

- **All Bluetooth devices are identical, but play a master or slave role when connecting**
  - » **Roles can be reversed**
  - » **Example: headsets connects as master to phone but then becomes slave**
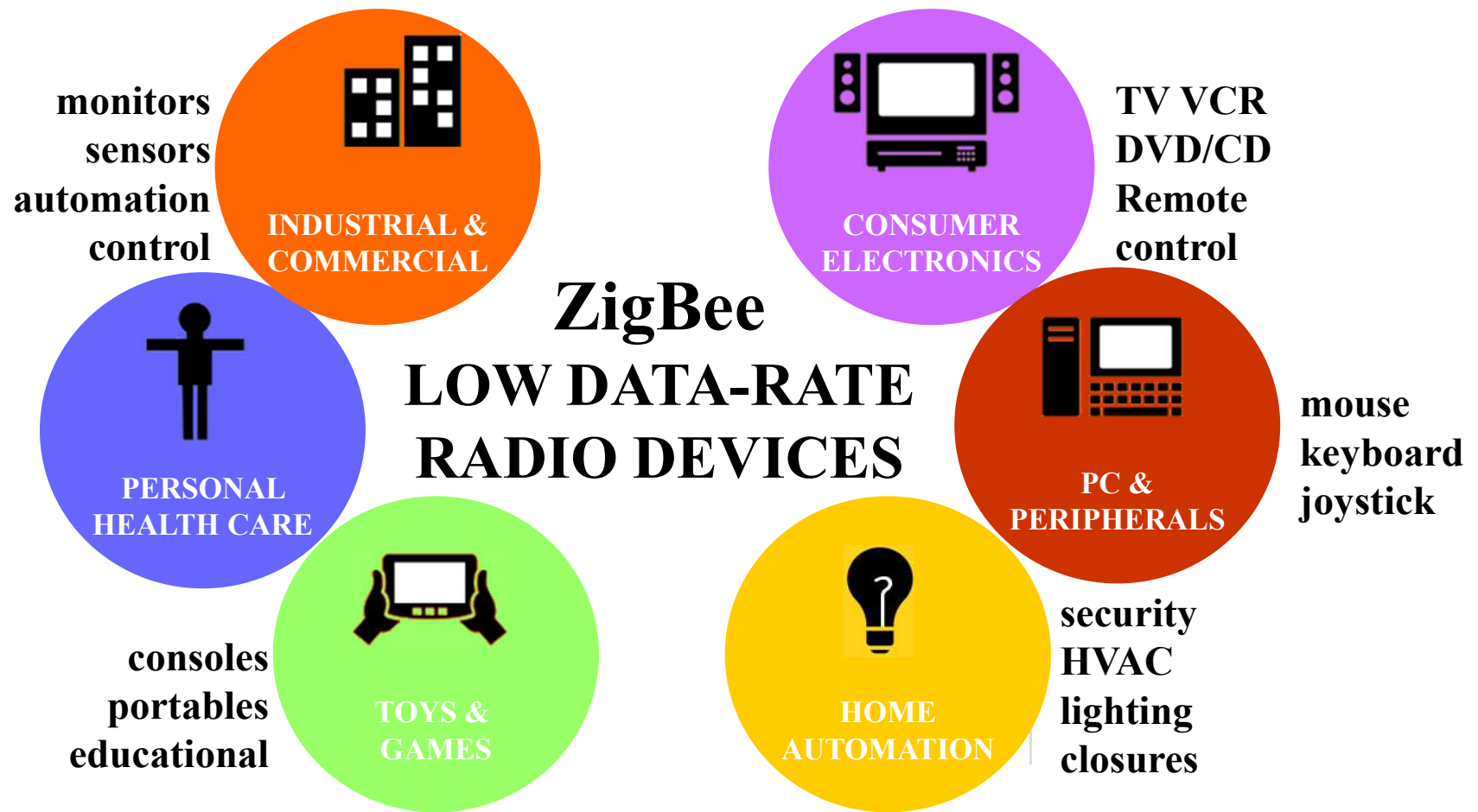
Configuring a Piconet

- **Needs two parameters:**
  - » Hopping pattern of the radio it wishes to connect.
  - » Phase within the pattern i.e. the clock offset of the hops.
  - » Effectively defines a channel that must be unique to the piconet – master must scan for other piconets first

- **The global ID defines the hopping pattern.**

- **The master shares its global ID and its clock offset with the other radios which become slaves.**

- **The global ID and the clock parameters are exchanged using a FHS (Frequency Hoping Synchronization) packet.**
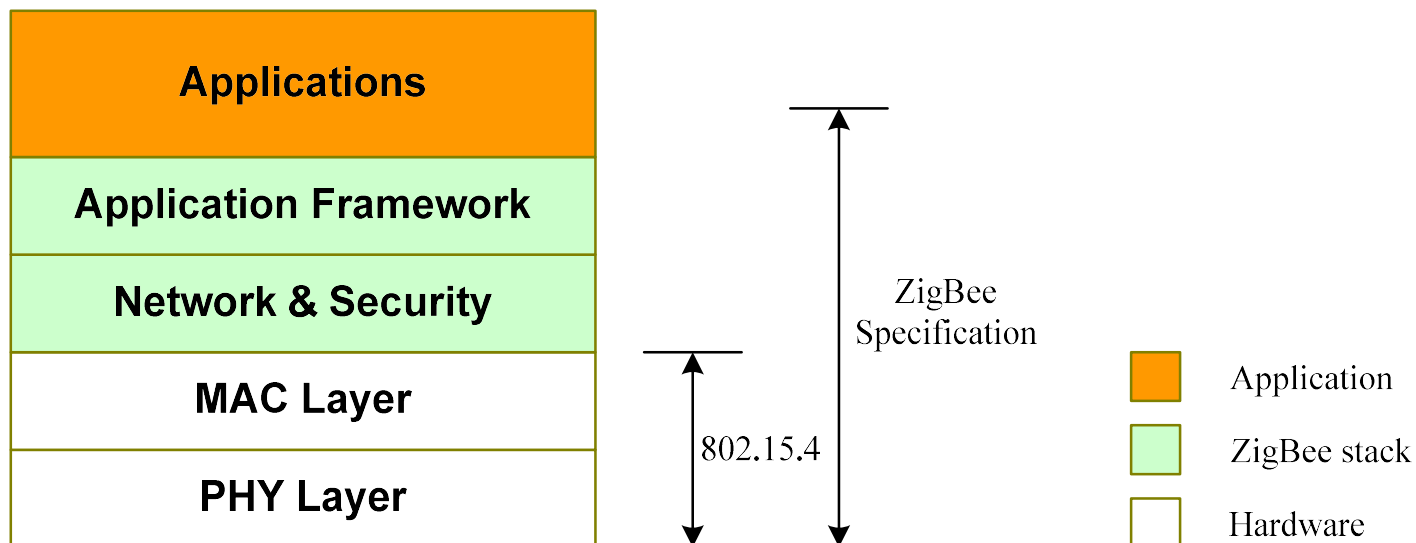
IEEE 802.15.4 - Overview

- **Low Rate WPAN (LR-WPAN)**
- **Simple and low cost**
- **Low power consumption**
  - » Years on lifetime using standard batteries
- **Mostly in sensor networks**
- **Data rates: 20-250 kbps**
- **Operates at multiple frequencies**
  - » 868 Mhz, 915 Mhz, 2.4 GHz
- **Blends elements from 802.15.3 and 802.11**
- **Many versions exist for difference application domains**

802.15.4 applications

monitors
sensors
automation
control

INDUSTRIAL & COMMERCIAL

TV VCR
DVD/CD
Remote
control

CONSUMER ELECTRONICS

ZigBee
LOW DATA-RATE
RADIO DEVICES

PERSONAL HEALTH CARE

mouse
keyboard
joystick

PC & PERIPHERALS

consoles
portables
educational

TOYS & GAMES

HOME AUTOMATION

security
HVAC
lighting
closures

Zigbee/802.15.4 architecture

- **ZigBee Alliance**
  - 45+ companies: semiconductor mfrs, IP providers, OEMs, etc.
  - Defining upper layers of protocol stack: from network to application, including application profiles
  - First profiles published mid 2003
- **IEEE 802.15.4 Working Group**
  - Defining lower layers of protocol stack: MAC and PHY
  - PHY based on DSSS – runs at 250 Kbps in 2.4 GHz band
  - Links are encrypted

Applications
Application Framework
Network & Security
MAC Layer
PHY Layer

ZigBee Specification

802.15.4

- ■ Application
- ■ ZigBee stack
- □ Hardware

802.15.4 devices

- **Full function device (FFD)**
  - Any topology
  - Network coordinator capable
  - Talks to any other device

- **Reduced function device (RFD)**
  - Limited to star topology
  - Cannot become a network coordinator
  - Talks only to a network coordinator
  - Very simple implementation

# Roles: What Functionality the Device Supports

- **Devices** (RFD or FFD)
  - » must be associated to a coordinator
- **Routers** (FFD)
  - » can operate in peer-to-peer mode and forward packets between devices
  - » Can be a PAN coordinator
- **PAN Coordinator** (FFD)
  - » The router responsible for managing the PAN

- **Coordinator**
  - » manages a list of associate devices
  - » devices need to associate and disassociate
  - » allocates short addresses
  - » beacon frames (in beacon mode)
  - » processes requests for fixed time slots

Example

https://www.eetimes.com/a-choice-for-a-zigbee-pan-coordinator/
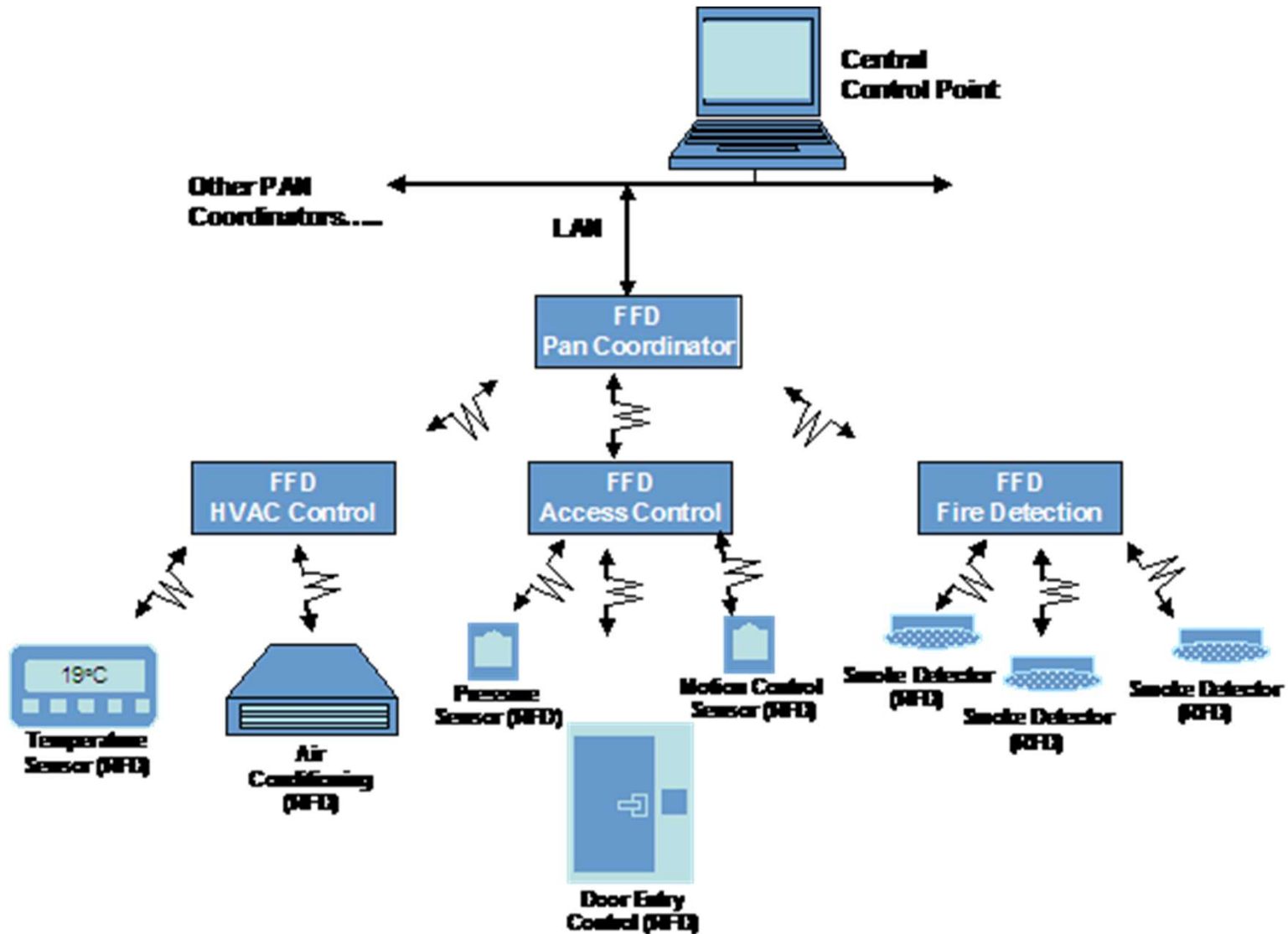
IEEE 802.15.4 - Star
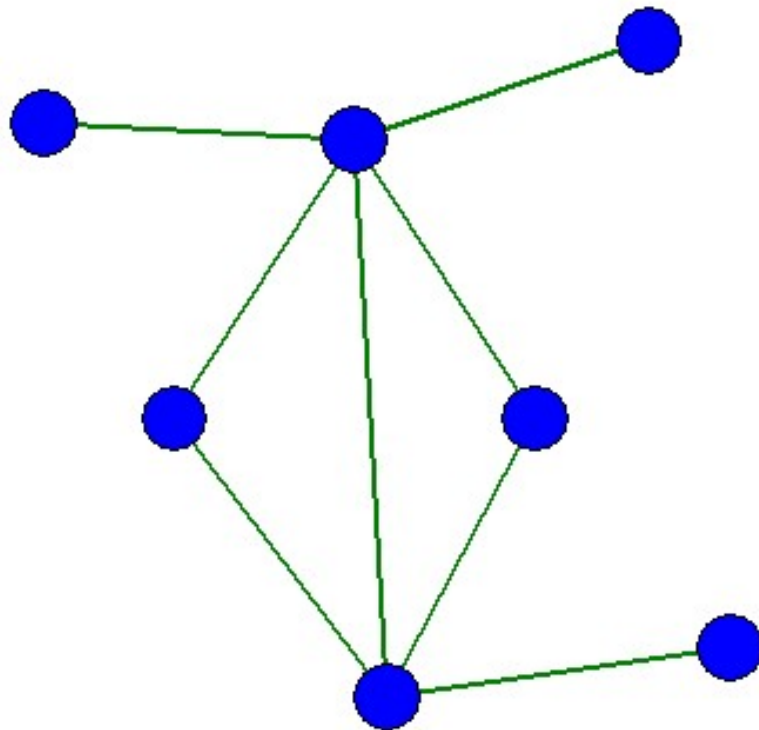

Star Topology

PAN Coordinator

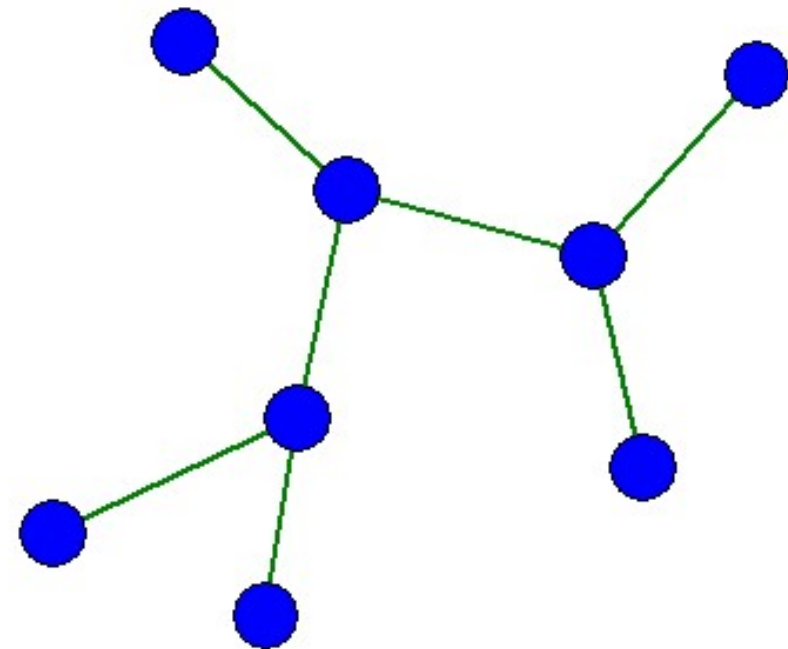Master/slave
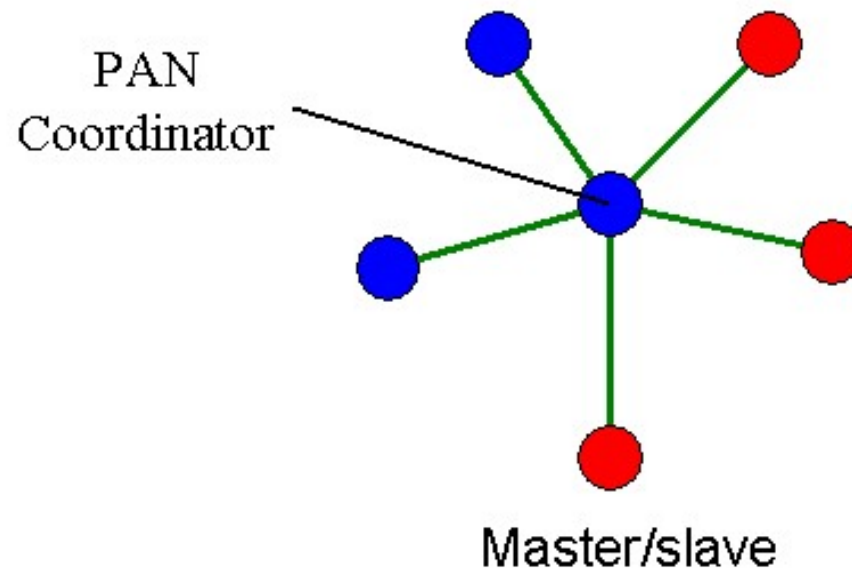
Full function device — Communications flow

Reduced function device

IEEE 802.15.4 – Peer-to-Peer

Peer-Peer Topology

Point to point
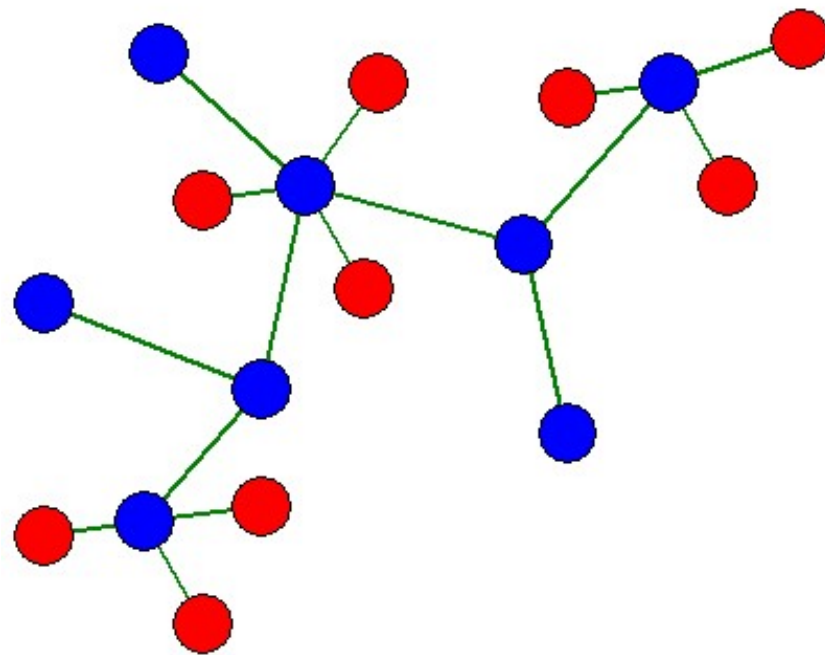
Cluster tree

● Full function device — Communications flow

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IEEE 802.15.4 - Combined

Combined Topology

Clustered stars - for example, cluster nodes exist between rooms of a hotel and each room has a star network for control.

- 🔵 Full function device
- 🔴 Reduced function device
- —— Communications flow

IEEE 802.15.4 - MAC

- **One PAN coordinator & multiple RFDs/FFDs**
  - » **Association/disassociation**
- **CSMA-CA channel access**
  - » **Reliable delivery of data**
- **Optional superframe structure with beacons**
- **AES-128 security**
- **QoS – 3 traffic types**
  - » **Periodic data: e.g. Sensor data**
  - » **Intermittent data: generated once a while, e.g. light switch traffic**
  - » **Repetitive low latency data: E.g. Mouse device traffic**

802.15.4 superframe structure

Beacon

Contention access period (CAP)	Guaranteed time slots (GTS)	
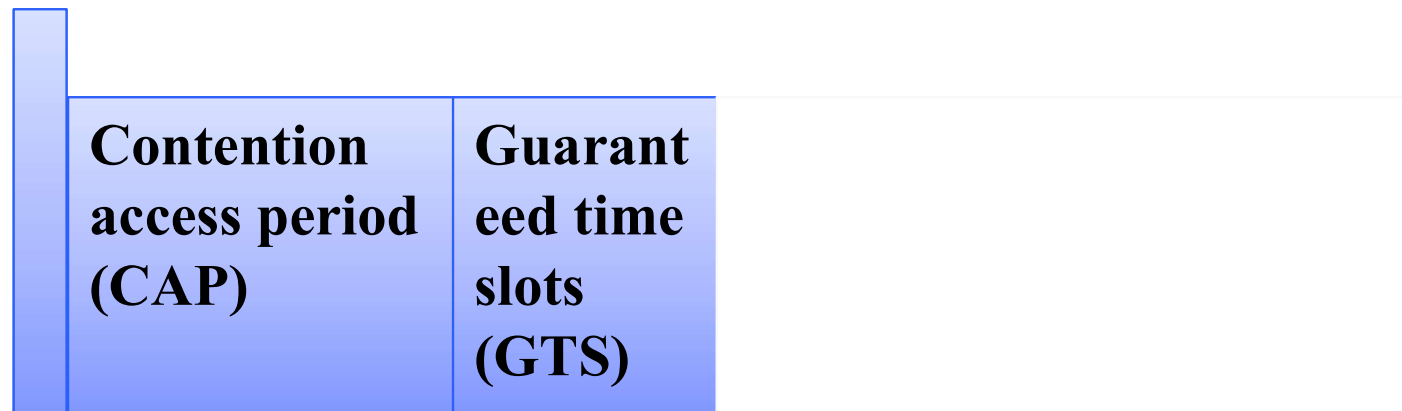
Active period   **Inactive period**

Outline

- **802.15 protocol overview**

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- **Personal Area Networks – 802.15**

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  - » **Bluetooth**

  - » **Zigbee**

  - » **Other**

- **UWB**

Low Power Technologies

- **Battery life times of years or even decades**
  - » **Ubiquitous deployment of sensors**
  - » **Internet of Things (IoT), automation, …**
  - » **Replacing batteries is labor intensive**
- **Example: Bluetooth Low Energy**
  - » **Not backwards compatible; deployed in some phones**
  - » **Profiles for healthcare, proximity sensing, alerts, keyboard/mice/.., ..**
  - » **2.4 GHz but simpler modulation schemes**

- **More on this in the next lecture**

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  - » **Other**

- **UWB**

Ultra WideBand

$$C = B \log_2(1 + \text{SNR})$$

- **Can achieve high throughputs with low SNR by using a high B**

- **Motivation is the 802.15.3a (high rate PAN) standards effort**
  - » Targets high speed, short distance communication

- **But where do I find this much spectrum?**

- **Use a transmit power that is low enough to so it will not affect other users**
  - » Can be used in most licensed frequency bands (with FCC permission, of course)

FCC UWB Rules

- **UWB technically defined as:**
  - » **Width of signal > 500 MHz, or** $B_f = 2\dfrac{f_H - f_L}{f_H + f_L} > 0.2$

- **Approved for 3.1 GHz to 10.6 GHz**

- **Power limit is -41.3 dBm/MHz**
  - » Note that the limit is not on the total signal but across the part of the spectrum that is used

- **Results in a frequency mask that must be satisfied**

- **Certain narrow bands must be filtered out**
  - » E.g. certain radio astronomy bands
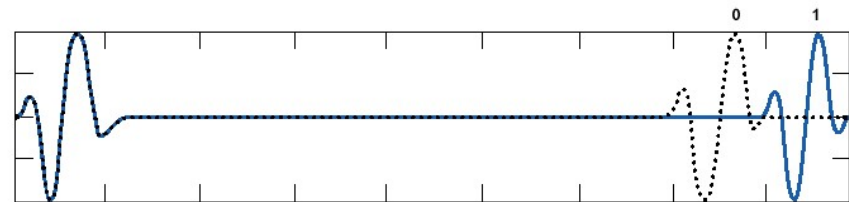 - » Depends on the country
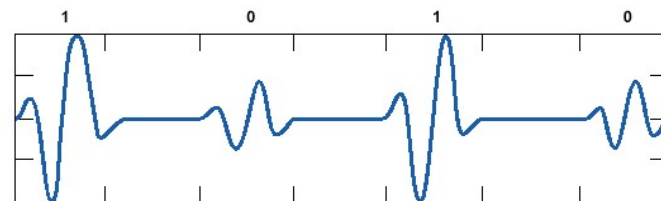
FCC Regulations

UWB Emission Limit [1]
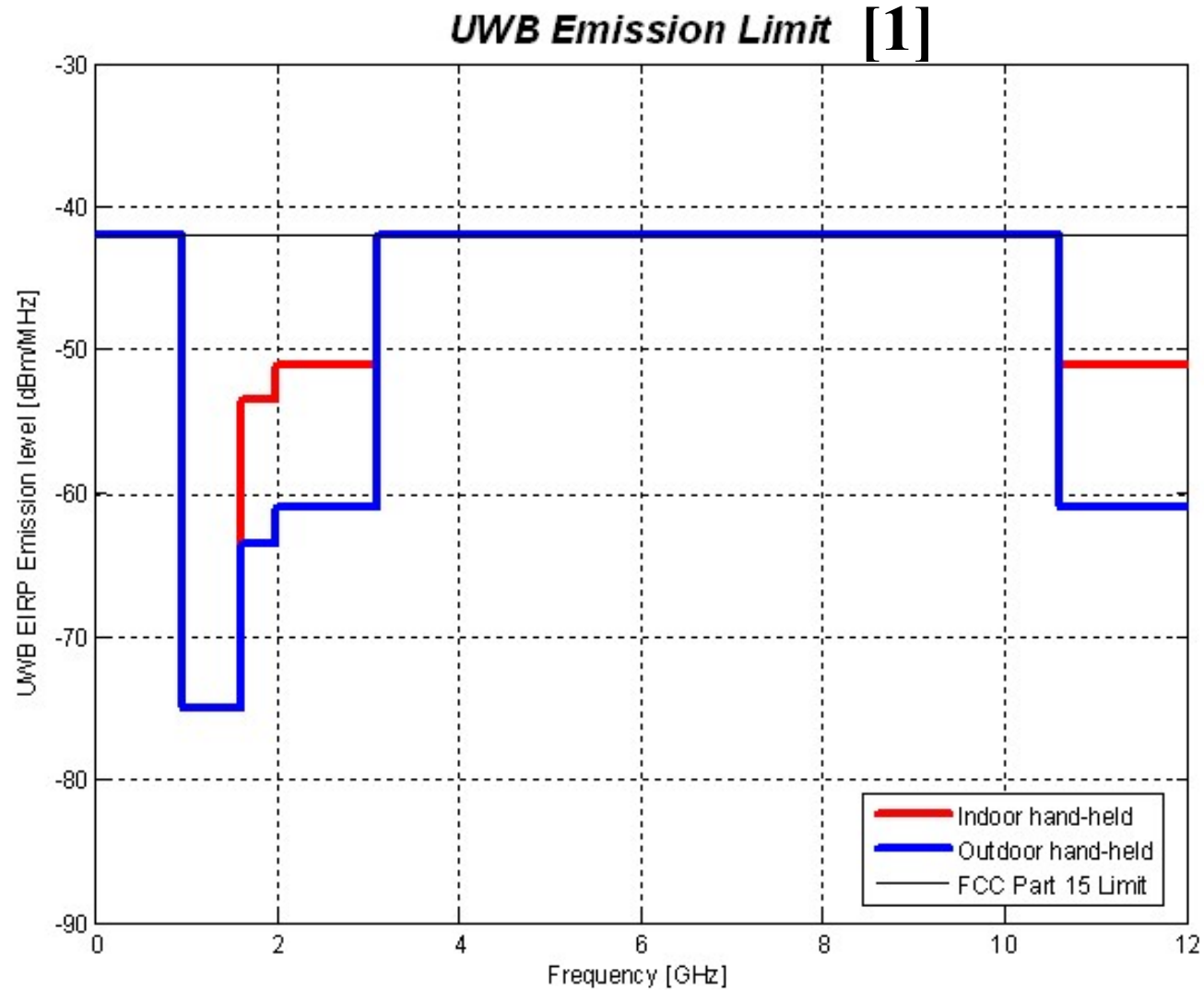
Example Technology: Basic Impulse Information Modulation

**Pulse length ~ 200ps; Energy concentrated in 2-6GHz band;
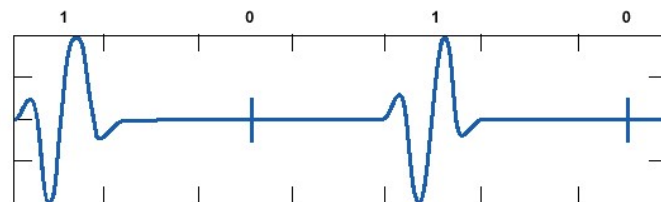Voltage swing ~100mV; Power ~ 10uW**
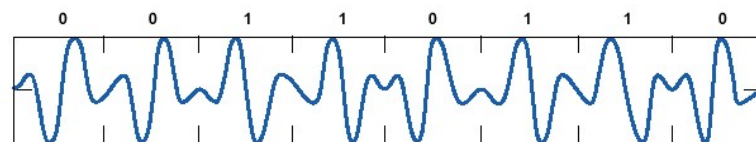
- **Pulse Position Modulation (PPM)**

- **Pulse Amplitude Modulation (PAM)**
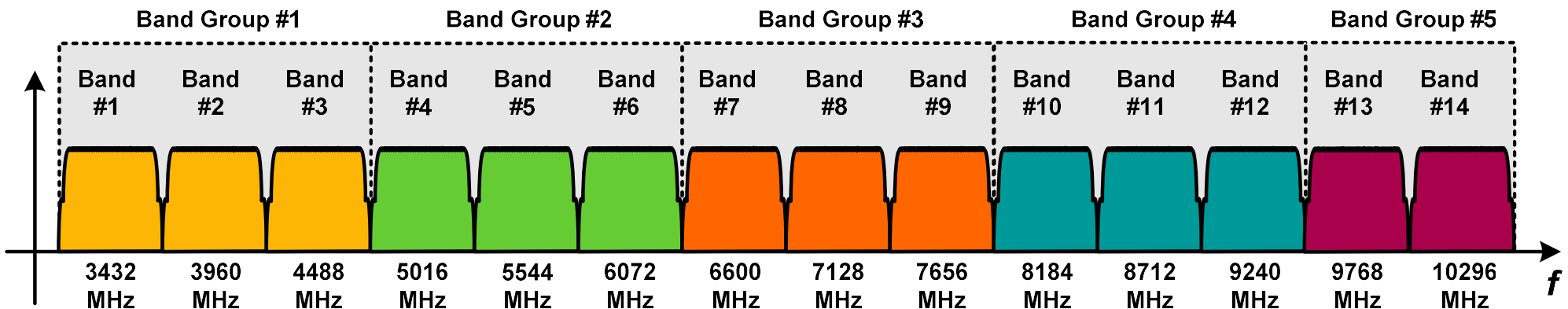
- **On-Off Keying (OOK)**

- **Bi-Phase Modulation (BPSK)**

Multi-band OFDM

- **Divide the spectrum into bands of 528 MHz.**

Band Group #1			Band Group #2			Band Group #3			Band Group #4			Band Group #5	
Band #1	Band #2	Band #3	Band #4	Band #5	Band #6	Band #7	Band #8	Band #9	Band #10	Band #11	Band #12	Band #13	Band #14
3432 MHz	3960 MHz	4488 MHz	5016 MHz	5544 MHz	6072 MHz	6600 MHz	7128 MHz	7656 MHz	8184 MHz	8712 MHz	9240 MHz	9768 MHz	10296 MHz

  - » Transmitter and receiver process smaller bandwidth signals.
  - » Can spread symbols across multiple bands (FH)
  - » Can avoid bands based on local regulations

- **Use of OFDM offer additional advantages**
  - » Proven technology that is known to be efficient
  - » Can selectively disable subcarriers to protect narrow band signals
  - » For example: 128 tones of 5.125 MHz

Discussion

- **UWB was included in 802.15 standards**
- **802.15.3a was going to be based on UWB but never materialized**
  - » Fight between two competing proposals
  - » Example on previous slide is one of them
- **Also added as 802.15.4a to the low power PAN group**
  - » Provides for 3 "narrower" bands
  - » Not clear it is used much