18-452/18-750
Wireless Networks and Applications
Lecture 21: Sensor Networks

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http://www.cs.cmu.edu/~prs/wirelessS24/

Some Comments Surveys

- General outline generally looks like:
  - Background: why useful, challenges, design options, etc.
  - Discussion on the three papers:
    - What is the key idea – this should be clear (figures!)
    - Some sample results illustrating benefits
    - Do not use terminology specific to the paper!
  - Personal opinion on pros or cons (global or per paper)
  - But: outline depends on topic!!!
- Many students use the google templates, which as generally a disaster (24pt)
  - No slide numbers
  - Tiny font sizes (12pt) – You want to be bigger! (18pt)
  - 50%-80% of the slide is empty - Use the space wisely!

Outline

- Sensor networking overview
- Example technologies:
  - (Bluetooth Low Energy)
  - 802.15.4 and Zigbee
  - Cellular
  - Lora and Lorawan
  - Sigfox
  - UWB

Wireless Sensor Networks (WSN)

- Wireless sensors have limited compute, energy, memory, and bandwidth resources, but:
- Sensing capabilities → Can observe properties the physical world
- CPU and actuators → Can control some aspects of the physical world
- Small physical size → Can be embedded throughout the physical environment
- Basis for "Cyber physical" systems, "Internet of Things"

WSN Applications

- **Commercial Applications**
  - » Home automation: light/temperature control, …
  - » Precision agriculture (optimize watering schedule)
  - » Asset management (tracking freight movement/storage)
  - » Cold chain management: monitor temperature in fridges
  - » Reading residential water meters remotely, …
  - » Monitoring infrastructure (vibrations in bridges, …)
- **Monitoring tools supporting Scientific Research**
  - » Wild life Habitat monitoring projects Great Duck Island (UCB), James Reserve (UCLA), ZebraNet (Princeton.
  - » Building/Infrastructure structure (Earthquake impact)

Sensor Node Design: Low-cost

- **Hardware**
  - » Low-cost radio
  - » Low cost internal clock
  - » Limited storage and processing capabilities
  - » Not tamper-proof
  - » May have to withstand tough environmental conditions
- **Communication**
  - » Use unlicensed spectrum to reach a "gateway" that has internet connectivity
    - – Wired, WiFi, drive-by, cellular, …
  - » Relying on pay-per-use cellular infrastructure is much more challenging!

Network Design Focus: Power Management

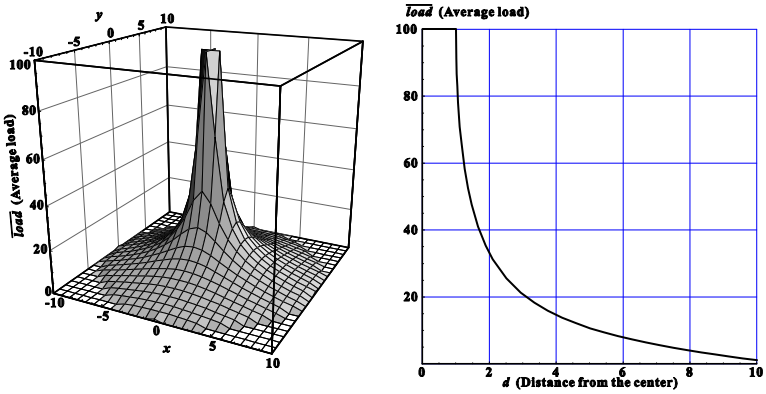
- Traditional metrics for network optimization: bandwidth, latency, economics ($$), …
- Wireless sensor networks: power efficiency
  - » Energy-efficient routing
  - » Load balancing to distribute power consumption
  - » In network aggregation to reduce traffic load
  - » Minimize up-time of sensors
- Requires new network technologies
  - » Routing algorithms (multi-hop sensor networks)
  - » Reduce traffic load based
  - » New MAC protocols

Load-balancing

- Assumption: in a multi-hop many-to-one sensor network, data collection follows a spanning tree.
  - » All data is collected on a single node
- Per-node power consumption for data transmission and reception grows exponentially from the leaves to the root of the tree
  - » Number of transmits and receives is the size of the subtree
- Consequence: the power sources of the nodes close to the sink deplete faster.
  - » They limit the network lifetime

Load balancing

- Power consumption increases at least linearly when nodes are closer to the sink
- Typical case is much worse



In-network Data Aggregation

- To mitigate cost of forwarding, compute relevant statistics along the way: *mean*, *max*, *min*, *median* etc.
- Forwarding nodes aggregate the data they receive with their own and send one message instead of relaying an exponentially growing number of messages
- Issues
  - » Location-based information (which nodes sent what) is lost
  - » Distributed computation of statistics
    - – *mean*: node needs to know both the mean values and the sizes of samples to aggregate correctly
    - – *median*: only an approximated computation is possible
- Especially useful in a query-based data collection system
  - » Queries regard a known subset of nodes
  - » Aggregation function can be specified

Today's Sensor Networks

- Push toward diverse set of low-power wireless technologies
  - » Differ in MAC, range, power, target bit rates, …
- New types of MAC technologies
  - » IEEE WiFi and PAN technologies: both WiFi and PAN
    - – Zigbee, Bluetooth Low Energy, 802.11ah
  - » Cellular: LTE-M, NB-IoT
  - » Industry-driven technologies LoRa, Sigfox, Z-Wave, …
- Many technologies use spread spectrum
  - » Protocols can be very simple, e.g., Aloha
  - » Packet encoding is very robust (redundancy)

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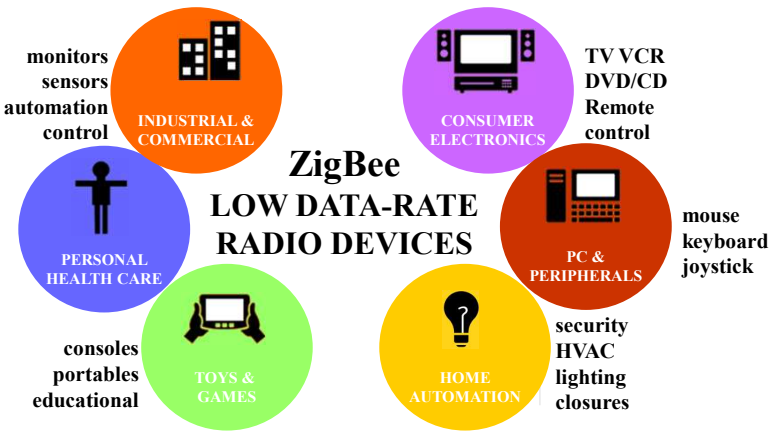
  - » UWB

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
- Many versions exist for difference application domains

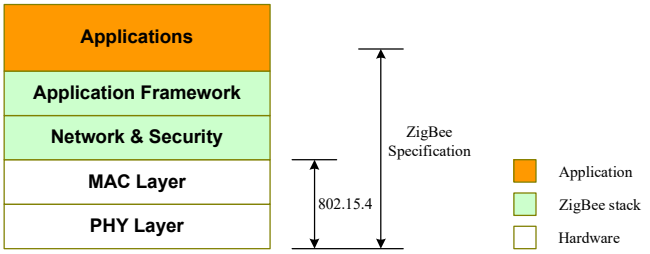
http://www.csie.nctu.edu.tw/~yctseng/WirelessNet06-02/zigbee-802-15-4.ppt

802.15.4 applications



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



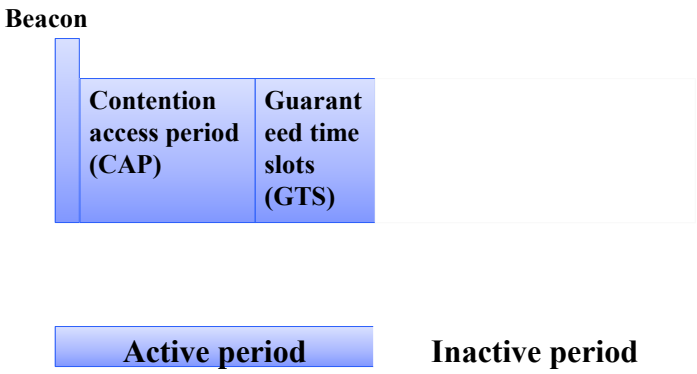
IEEE PAN - ZigBee

- **802.15.4 PHY layer is used by Zigbee (2003) and some non-IEEE protocols**
  - » **Defined for the 900 MHz and 2.4 GHz unlicensed bands**
- **Uses Direct Sequence Spread Spectrum**
- **MAC uses CSMA-CA**
- **Can create star and point-to-point topologies**
- **Targets low-bandwidth, relatively short range applications**
  - » **Up to 250 Kbps, range 10-100 m**
  - » **127 byte packets**

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



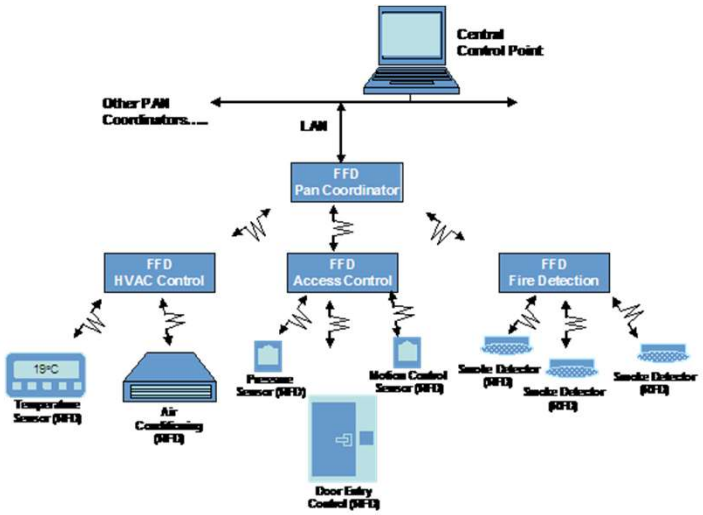
802.15.4 devices

- **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



Peter A. Steenkiste, CMU https://www.eetimes.com/a-choice-for-a-zigbee-pan-coordinator/ 21

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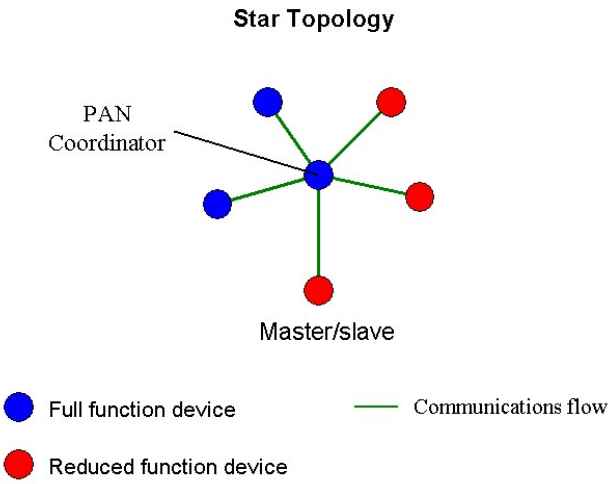
IEEE 802.15.4 - Star



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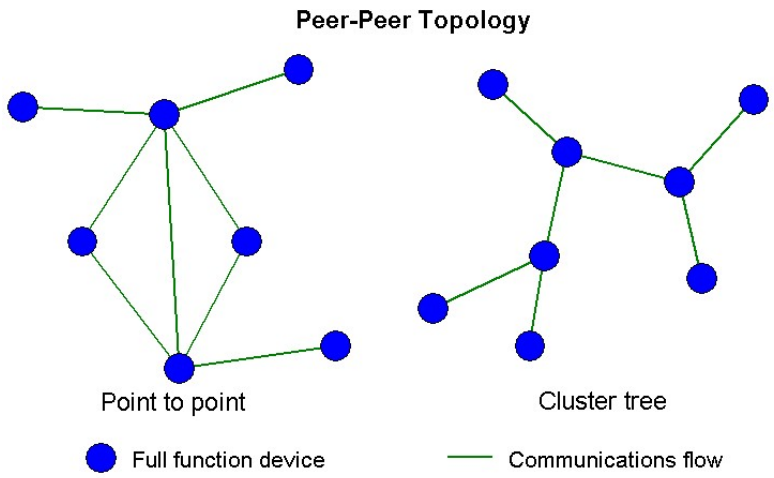
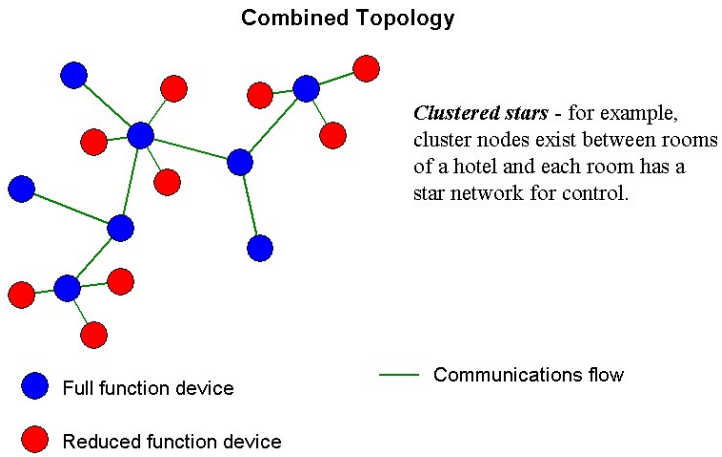
IEEE 802.15.4 – Peer-to-Peer



IEEE 802.15.4 - Combined

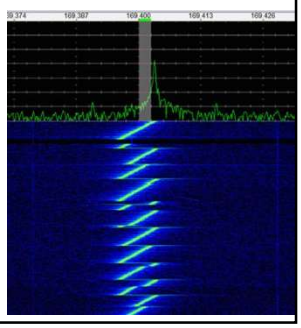


Low Power Cellular

- Started with LTE:
- Narrowband – IoT (NB-IoT) – 2016
  - » Focus on indoor coverage, low bitrates, dense deployments
  - » Two categories with different performance
  - » Uplink typically faster: 16-159 kbps vs 26-127 kbps
- LTE-M machine type communication - 2016
  - » Higher bandwidth including voice, mobility
  - » Lower latency but higher cost compared with NB-IoT
  - » Uplink 1-7 Mbps – Downlink 1-4 Mbps
- Both standards are defined by 3GPP
- Simple node design: single antenna, SISO
  - » Half duplex: always for NB-IoT, optional for LTE-M

LoRa Physical Layer

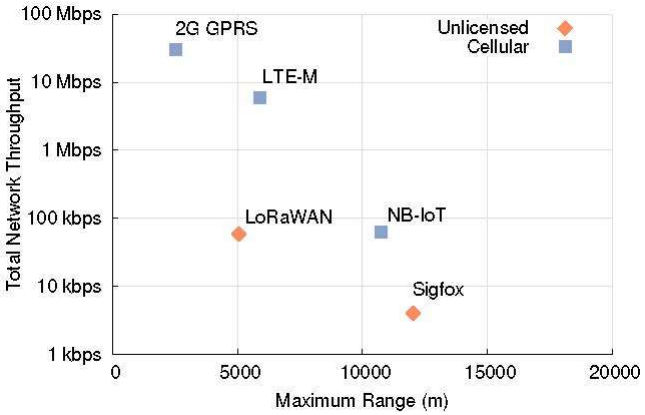
- Longer range to simplify deployment
  - » "Metropolitan" area – cite-wide sensor network
  - » Star topology, up to 10 km of range
- Based on spread spectrum across 125+ KHz band
  - » Chirp spread spectrum: change carrier frequency
  - » Very robust: spread spectrum
  - » Allows for reception of overlapping transmissions in many cases
  - » Supports multiple bit rates
  - » Devices report results to basestations
- Example protocol LoraWAN
  - » Very long range



SigFox

- Ultra-narrowband technology:
  - Transmits in 200 Hz in 200 KHz of sub-GHz spectrum
  - Low data rate 100s of bits/sec
  - Uses differential BPSK – phase modulation
- Based on Aloha protocol: transmitter picks a carrier frequency; receiver decodes full band
- Very basic protocol: small packets, no encryption, single bitrate
  - Payload is 12 bytes uplink, 8 bytes downlink
- Also uses a star topology
- Radios are cheaper than LoRaWAN
  - With roughly double the range

Comparison
Throughput versus Range

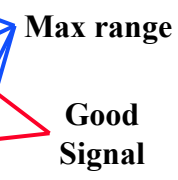


"Challenge: Unlicensed LPWANs Are not Yes the Path to Ubiquitous Connectivity", Branden Ghena et. al., ACM Mobicom'19

https://dl.acm.org/doi/10.1145/3300061.3345444

Power Efficiency

Network Technology	Average Power (uW) 84 Bytes Per 1 Hour	84 Bytes Per 4 Hours	200 Bytes Per 24 Hours	1000 Bytes Per 24 Hours
Sigfox (155 dB)	110	29	11	56
LoRaWAN (143 dB)	12	3.0	1.1	5.1
LTE-M (144 dB)	50	25	12	13
LTE-M (164 dB)	2200	620	150	440
NB-IoT (144 dB)	62	22	13	15
NB-IoT (164 dB)	1800	520	100	240



Outline

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

Ultra WideBand

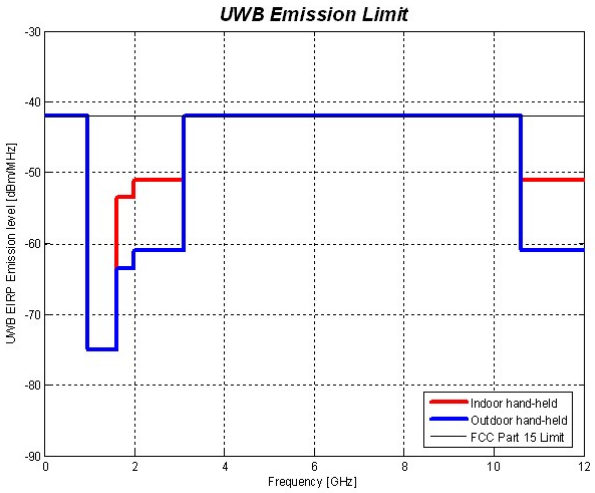
$$C = B\log_2(1+\mathrm{SNR})$$

- 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 $B_f = 2\frac{f_H - f_L}{f_H + f_L} > 0.2$
- 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

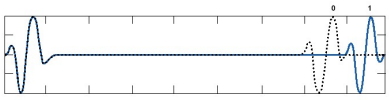
FCC Regulations



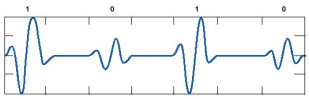
Example Technology: Basic Impulse Information Modulation

Pulse length ~ 200ps; Energy concentrated in 2-6GHz band; Voltage swing ~100mV; Power ~ 10uW

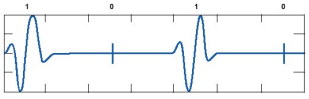
- **Pulse Position Modulation (PPM)**



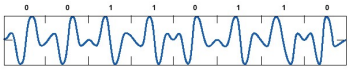
- **Pulse Amplitude Modulation (PAM)**



- **On-Off Keying (OOK)**

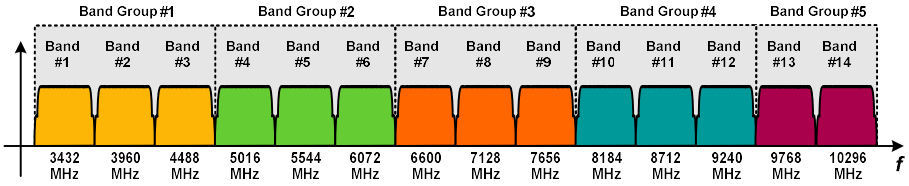


- **Bi-Phase Modulation (BPSK)**



Multi-band OFDM

- Divide the spectrum into bands of 528 MHz.



  - » 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
  - » 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 the proposals
- Also added as 802.15.4a to the low power PAN group
  - » Provides for 3 “narrower” bands
- Use of UWB
  - » Very useful for localization: high accuracy
    - – Inventory tracking, home automation, Apple airtags, ..
  - » UWB has limited use for (traditional) communication
    - – Exceptions: between cell phones (Airdrop), …