Internet of Things
2017/2018

IoT (Wireless) Networks

Johan Lukkien

John Carpenter, 1982
• domains
  – home
  – mobile / outdoor (fields, ad-hoc)
  – office
  – industry
  – public (city)

• architecture, layered and deployment view
  – devices, things
  – functionality placement alternatives
  – data and control flow

• communication stack, protocols

• lifecycles
  – devices
  – services
  – applications

The IoT Architectural Framework, Design Issues and Application Domain, Gordana Gardas’evic et al.
Guiding questions

• What are IoT networks?

• What is the role of IP?

• What techniques are used in wireless communications?
  – techniques for media sharing
  – techniques for reducing energy use

• Which standards are considered?
Some IoT protocol stacks

The IoT Architectural Framework, Design Issues and Application Domain, Gordana Gardasˇevic et al.
Overview

- Physical organization
- IP
- The IEEE local area networks
- Techniques for medium sharing
- Techniques for energy reduction
- Wide area IoT-oriented initiatives
- Metrics
General architecture

Generic Physical organization

IEEE 802.16e  
(WiMAX)

3G, 4G

IEEE 802.3,  
(ethernet)

IEEE 802.11 (WiFi)

MN

AN

MN

MN

MN

MN

MN

MN

MN

MN

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MN

MN

MN

MN

AN

AN

IP-based network with wide-area coverage, wireless or wired and powerful servers

IoT infrastructure: static ambient nodes attaching to clusters in lowest layer

Moving clusters of nodes with sensing capability but often with limited resources

e.g. single person moving around with sensors

MN = mobile node / network

AN = ambient node / network

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TU/e Informatica, System Architecture and Networking
## Taxonomy

<table>
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<tr>
<th>Middle layer</th>
<th>Multi hop</th>
<th>Single hop (no hop)</th>
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</thead>
<tbody>
<tr>
<td>Bottom layer</td>
<td>(ambient infra structure)</td>
<td>(access points)</td>
</tr>
</tbody>
</table>

### Multi hop
- Most general case:
  - moving clusters through ambient infra structure
  - ad-hoc networks

### Single hop (no hop)
- Moving nodes connecting to ambient infra structure
- Moving nodes connecting to access points
## Examples

<table>
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<tr>
<th>Bottom layer</th>
<th>Middle layer</th>
<th>Multi hop</th>
<th>Single hop (no hop)</th>
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<tr>
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<td>Single hop (no hop)</td>
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<td></td>
</tr>
</tbody>
</table>

**Multi hop**
- vehicle to vehicle
- vehicle to infra structure
- user wearing cluster of sensors connected to phone

**Single hop (no hop)**
- vehicle to infra structure
- user wearing sensors connected to phone

**Middle layer**
- phone
- sensor in low power mesh network

**Bottom layer**
- laptop / wifi
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Layered protocols: OSI('83) reference model

- **Physical:**
  - sends bits on medium (i.e. standardizes the electrical, mechanical, and signalling interfaces)

- **MAC / Data link:**
  - manages medium access, detects and corrects errors in frames; deliver frames on one-hop medium

- **Network:**
  - send packets from sender to receiver machines using multihop routing

- **Transport:**
  - breaks messages into packets; delivery guarantees; multiplexing ports

Typical frame structure:
- Data link layer header
- Network layer header
- Transport layer header
- Session layer header
- Presentation layer header
- Application layer header
- Payload
- Data link layer trailer

Bits that actually appear on the network:

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29-Nov-17
The hour glass of IP

- The essence of IP, and its success
  - a unified protocol and naming (addressing) scheme to enable communication between any pair of devices
    - all ‘layer breaking’ or application knowledge is banned from lower layers until the transport layer
    - it is only about exchanging bits: semantics only at endpoints

- Recent standardization towards application protocols (HTTP, CoAP) standardizes application structures
Is IoT so much different?

• The essence of IoT
  – a unified protocol and naming (addressing) scheme to enable communication between any pair of devices things
  • … that contain embedded networked electronics, of course

• IP to every thing
IP to Every Thing?

• IP connectivity comes with hidden assumptions
  – endpoints are active, reachable
  – ... by IP packets

• Devices cannot always guarantee this
  – passive nodes, when there is no device to power wirelessly
  – battery-less nodes
  – duty cycling, or off-time planning
  – incapability to process IP

• Legacy may prevent IP to endpoints
  – existing networks, without capability to use IP

• Need technology to solve this (discussed later)
Example: which (IP) protocols occur in a lighting network?

- **Connectivity:**
  - 6LoWPAN (= adaptation for IP/802.15.4), UDP, TCP [sometimes]
  - RPL, RIP, MPL: routing, multicasting
  - DTLS: packet based security

- **Application**
  - **Trickle:** application protocol for dissemination to all devices in a network
  - **RESTful** style
    - REST plus HTTP methods
    - CoAP – constrained application protocol
  - **DNS-SD** using mDNS, or CoAP directory: for service discovery
  - M2M protocols, e.g. MQTT/TCP

Courtesy of Dee Denteneer
Example application: intelligent outdoor lighting

- Testbed in Achtse Barrier
  - specialized communication stack, 802.15.4 based
- ‘Real-time’, local behavior
  - light setting based on movement sensors
- Collect data about movements in the street
- Simulate lighting strategies using those data
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How do end points communicate?
Networking approaches

- Physical neighbors:
  - Shared medium or Point-to-point
- In case of physical separation
  - switching (layer 2)
  - connecting networks (layer 3)
  - ... multiple interfaces for some nodes
- Packet oriented
- Full connectivity by
  - (intelligent) flooding
    - send packet to everyone recursively
  - routing
    - series of hops
Wired or wireless

- Wired:
  - admits nodes to be powered through the network as well, e.g. Power over Ethernet (PoE)
  - no real need for very low resource devices (except power)
  - difficult to scale to large numbers
  - forbids mobility

- Wireless:
  - typical for really large numbers of devices…
  - … installed at difficult to reach locations
  - required for mobility
  - is an inherently unreliable medium
  - can still either be battery powered or connected to mains
<table>
<thead>
<tr>
<th></th>
<th>Wired</th>
<th>Wireless</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>Energy limitations will determine uptime, communication behavior and protocols. In principle, the wire could be used for power; and at least for waking up nodes</td>
<td>Energy limitations will determine uptime, communication behavior and protocols; nodes must manage their sleeping behavior; nodes can be mobile</td>
</tr>
<tr>
<td>Mains</td>
<td>No real need for low resources except cost and energy; this class captures ‘regular’ office/home infrastructure devices</td>
<td>Wireless is there for convenience (absence of other infra - outdoors) and for connecting to mobile wireless nodes; powerful wireless protocols can be used, always on</td>
</tr>
<tr>
<td>Name</td>
<td>Description</td>
<td>Note</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------------------------------------------</td>
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</tr>
<tr>
<td>IEEE 802.1</td>
<td>Higher Layer LAN Protocols (Bridging)</td>
<td>active</td>
</tr>
<tr>
<td>IEEE 802.2</td>
<td>LLC</td>
<td>disbanded</td>
</tr>
<tr>
<td>IEEE 802.3</td>
<td>Ethernet</td>
<td>active</td>
</tr>
<tr>
<td>IEEE 802.4</td>
<td>Token bus</td>
<td>disbanded</td>
</tr>
<tr>
<td>IEEE 802.5</td>
<td>Token ring MAC layer</td>
<td>disbanded</td>
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<tr>
<td>IEEE 802.6</td>
<td>MANs (QDB)</td>
<td>disbanded</td>
</tr>
<tr>
<td>IEEE 802.7</td>
<td>Broadband LAN using Coaxial Cable</td>
<td>disbanded</td>
</tr>
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<td>IEEE 802.8</td>
<td>Fiber Optic TAG</td>
<td>disbanded</td>
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<tr>
<td>IEEE 802.9</td>
<td>Integrated Services LAN (ISLAN or isoEthernet)</td>
<td>disbanded</td>
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<tr>
<td>IEEE 802.10</td>
<td>Interoperable LAN Security</td>
<td>disbanded</td>
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<tr>
<td>IEEE 802.11</td>
<td>Wireless LAN (WLAN) &amp; Mesh (Wi-Fi certification)</td>
<td>active</td>
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<tr>
<td>IEEE 802.12</td>
<td>100BaseVG</td>
<td>disbanded</td>
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<tr>
<td>IEEE 802.14</td>
<td>Cable modems</td>
<td>disbanded</td>
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<tr>
<td>IEEE 802.15</td>
<td>Wireless PAN</td>
<td>active</td>
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<tr>
<td>IEEE 802.15.1</td>
<td>Bluetooth certification</td>
<td>active</td>
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<tr>
<td>IEEE 802.15.2</td>
<td>IEEE 802.15 and IEEE 802.11 coexistence</td>
<td></td>
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<tr>
<td>IEEE 802.15.3</td>
<td>High-Rate wireless PAN (e.g., UWB, etc.)</td>
<td></td>
</tr>
<tr>
<td>IEEE 802.15.4</td>
<td>Low-Rate wireless PAN (e.g., ZigBee, WirelessHART, MIWI, etc.)</td>
<td>active</td>
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<tr>
<td>IEEE 802.15.5</td>
<td>Mesh networking for WPAN</td>
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<td>IEEE 802.15.6</td>
<td>Body area network</td>
<td>active</td>
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<td>IEEE 802.16</td>
<td>Broadband Wireless Access (WiMAX certification)</td>
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<tr>
<td>IEEE 802.16.1</td>
<td>Local Multipoint Distribution Service</td>
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<td>IEEE 802.16.2</td>
<td>Coexistence wireless access</td>
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<td>IEEE 802.17</td>
<td>Resilient packet ring</td>
<td>hibernating</td>
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<td>IEEE 802.18</td>
<td>Radio Regulatory TAG</td>
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<td>IEEE 802.19</td>
<td>Coexistence TAG</td>
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<tr>
<td>IEEE 802.20</td>
<td>Mobile Broadband Wireless Access</td>
<td>hibernating</td>
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<td>IEEE 802.21</td>
<td>Media Independent Handoff</td>
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<tr>
<td>IEEE 802.22</td>
<td>Wireless Regional Area Network</td>
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<tr>
<td>IEEE 802.23</td>
<td>Emergency Services Working Group</td>
<td></td>
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<tr>
<td>IEEE 802.24</td>
<td>Smart Grid TAG</td>
<td>New (November, 2012)</td>
</tr>
<tr>
<td>IEEE 802.25</td>
<td>Omni-Range Area Network</td>
<td></td>
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</tbody>
</table>
The LANs

- Taken from Wikipedia (Nov. 2017)
- Important for IoT:
  - the 3 group (ethernet, PoE)
  - the 11 group (‘WiFi’)
  - the 15 group (wireless PAN)
- Within IEEE 802.15
  - 1x: Bluetooth, BT LE
  - 4x: PHY/MAC layer for ZigBee, 6LoWPAN, Thread, WirelessHART, MiWi ContikiMAC, 6Tisch
• **IEEE 802.11a**: 54 Mbit/s, 5 GHz standard (1999, shipping products in 2000)
• **IEEE 802.11b**: Enhancements to 802.11 to support 5.5 Mbit/s and 11 Mbit/s
• **IEEE 802.11c**: Bridge operation procedures; included in the IEEE 802.1D-2004 standard
• **IEEE 802.11d**: International (country-to-country) roaming extensions (2001)
• **IEEE 802.11e**: Enhancements: QoS, including packet bursting (2005)
• **IEEE 802.11g**: 54 Mbit/s, 2.4 GHz standard (backwards compatible with b) (2003)
• **IEEE 802.11h**: Spectrum Managed 802.11a (5 GHz) for European compatibility (2005)
• **IEEE 802.11i**: Enhanced security (2004)
• **IEEE 802.11j**: Extensions for Japan (2004)
• **IEEE 802.11-2007**: A new release of the standard that includes amendments
• **IEEE 802.11k**: Radio resource measurement enhancements (2008)
• **IEEE 802.11n**: Higher-throughput improvements using MIMO (multiple-input multiple-output) (2008)
• **IEEE 802.11r**: Fast BSS transition (FT) (2008)
• **IEEE 802.11s**: Mesh Networking, Extended Service Set (ESS) (July 2011)
• **IEEE 802.11t**: Wireless Performance Prediction (WPP)—test methods and performance metrics

Within IEEE 802.11 LANs:
- **11p**: ITS
- **11e**: QoS
- **11s**: meshing
- **11ah**: low power, low interference (HaLow)

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**802.11ah** [edit]

Main article: [IEEE 802.11ah](https://en.wikipedia.org/wiki/802.11ah)

IEEE 802.11ah defines a WLAN system operating at sub-1 GHz license-exempt bands, with final approval slated for September 2016. Due to the favorable propagation characteristics of the low frequency spectra, 802.11ah can provide improved transmission range compared with the conventional 802.11 WLANs operating in the 2.4 GHz and 5 GHz bands. 802.11ah can be used for various purposes including large scale sensor networks, extended range hotspot, and outdoor Wi-Fi for cellular traffic offloading, whereas the available bandwidth is relatively narrow. The protocol intends consumption to be competitive with low power Bluetooth, at a much wider range.
Overview

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- **Techniques for medium sharing**
- Techniques for energy reduction
- Wide area IoT-oriented initiatives
- Metrics
Shared medium

- A shared medium can be a wire or bus, but also a wireless connection
  - standards must address this sharing, avoiding destructive interference
  - wired: typically, bus protocols

- Wireless communication is intrinsically subject to errors
  - received signal is the energy collected over time
  - can always be disturbed by an external party (a different protocol family in same frequency), or by another neighbor than the sender
  - quality depends on environment properties (e.g. reflections)

- Wireless communication is energy-hungry, particularly when compared to the energy used by embedded processors

- Standards must address the unreliability, sharing and energy use
What techniques are applied for wireless?

- **FDMA:** multiple channels (frequency division multiple access)
  - channel hopping with synchronization
    - e.g. 802.15.1 (Bluetooth), 6tisch,
  - cell formation / independent domains
    - e.g. 3/4G, IEEE 802.11 (WiFi)

- **TDMA:** division in timeslots (time division multiple access)
  - timeslots with schedules, time synchronization
    - e.g. WirelessHART, DECT, IEEE 802.15.4 in superframe mode
  - in combination with cell formation

- **Master-Slave**
  - e.g. an access point as master
  - beacon-based signaling
    - e.g. IEEE 802.11 (WiFi), Bluetooth, IEEE 802.15.4

- **CSMA:** ‘try before you cry’ (carrier sense multiple access)
  - Clear Channel Assessment: Aloha
    - with collision avoidance, detection or resolution
      - e.g. IEEE 802.15.4 (ZigBee): random distribution of retries
    - with priority
      - e.g. IEEE 802.11e (WiFi + QoS)

- **CDMA** (code division multiple access, as in 4G)
  - concurrent access of the medium with coded packets
  - admits decoding even with interference

- **Regulation**
  - duty cycle restrictions (e.g. 1% per station)
  - frequency assignment
FDMA (FDM)

- Use FDMA for several independent point-to-point channels
- Use FDMA for increasing reliability, e.g.,
  - isolation to a quiet channel
  - multiple transceivers
  - frequency hopping, avoiding crowded frequencies (6tisch, Bluetooth)
    - together with timeslots (TDMA)
  - OFDM: coding using multiple frequencies
CSMA/CD

- CSMA/CD: (fully distributed) protocol for sharing a wired medium, using the following algorithm:
  - sense carrier, wait until it is ready (i.e., free)
  - transmit and monitor for collision
    - upon collision: transmit jam signal until minimum frame size (time) has been reached
    - update counters and check for maximum retransmit
    - backoff random time (dependent on # collisions)
    - continue with sensing carrier
  - complete transmission

- Used in (shared medium) ethernet (which is obsolete)
CSMA/CR

- CSMA/CR: (fully distributed) protocol for sharing a wired medium, using the following algorithm:
  - sense carrier, wait until it is ready
  - transmit and monitor for detecting a collision.
    - upon collision: priority-based choice which station continues
    - upon loss (low priority): resume sensing carrier
    - upon win (high priority): continue transmission
  - complete transmission

- Used in CAN (in-vehicle bus)
  Millions of deployments.

Figure 1. The ISO 11898 standard CAN bus configuration scheme
CSMA/CA

• CSMA/CA: (fully distributed) protocol for sharing a (wireless) medium, using the following algorithm:
  – sense carrier
  – when active: back-off for a random period and retry
    • for a given maximum number of trials
  – when not active: send message; wait for ack
    • ack received: ok
    • no ack received: transmission failed (e.g. collision), retry (up to maximum)

• Collisions: are due to unfortunate timing or to hidden nodes
  – In wireless networks, collisions cannot be detected by the sending node (major difference with wired)
  – discovered by absence of ACK

• Back-off time: increases with number of retries
CSMA: Hidden stations, unicast and broadcast

- Wireless communication has a limited range
  - collisions can occur between nodes in the same range (NN)
  - or two nodes that cannot see each other disturb a third one (HN)

- In case of unicast:
  - sender warns its neighbors using an RTS signal
  - receiver responds, and warns its neighbors by responding with CTS
  - confirm receipt using an ACK (with immediate feedback)

- In case of broadcast this does not work (neither ACK nor CTS)
  - don’t know the receivers, in general
Beacons

• Beacons are periodic packet broadcasts
  – beacons enforce a globally slotted structure of the medium access
    • “superframe”, “beacon interval”
  – the beacon sender has the role of ‘master’ of the medium (during the superframe)
  – the beacon describes the structure of the period until the next beacon, and how nodes have to behave in that period
    • from overhearing a beacon a node understands next beacon time, when it is (allowed) to transmit and which protocol to use, when to change frequency
  – clock synchronization is required, and the beacon may be used for this

from IEEE 802.15.4
IEEE 802.15.4 beacons

- **CAP**: contention access period
  - CSMA/CA
- **CFP**: contention free period (assigned slots)
  - GTS: Guaranteed Time Slot
- **BI**: Beacon Interval
  - 16 equal time slots
- **SD**: Superframe duration
  - shorter than BI to admit duty cycling, or the superframe of another station

Figure 6-1—An example of the superframe structure
Example: IEEE 802.11

- IEEE 802.11 MAC protocols are generally CSMA/CA

- Original IEEE 802.11 MAC:
  - infrastructure mode vs ad-hoc mode
    - infrastructure: all communication via an access point
  - Distributed Coordination Function + RTS/CTS
    - just CSMA/CA
    - no prioritization
  - Point Coordination Function (in infrastructure mode only)
    - beaconing (access point is master)
    - Contention-free part of the superframe: AP polls the stations
    - Contention period: DCF
    - no further classing of stations or traffic
IEEE 802.11e

- QoS extensions to IEEE 802.11
  - TXOP: (transmission opportunity) contention-free period (CFP) to be given to stations
  - EDCA: Enhanced Distributed Channel Access
    - fully distributed *probabilistic* flow prioritization
    - access categories: settings of the MAC to be associated with a group of flows with the same characteristics
Initial waiting time

series of packets

- busy channel
- SIFS
- aSlotTime
- ... 
- ... 
- ... 
- MPDU (1)
- SIFS
- ACK
- ... 
- MPDU (r,q)
- SIFS
- ACK

Initial waiting time

current $CW_q$

$AIFS_q$

$CW_{min_q}$

$CW_{max_q}$

$TXOP_q$
EDCA

- Parameters for a backoff process in access control class $q$:
  - $AIFS_N_q$: initial wait time
  - $TXOPLimit_q$: max. #packets sent
    - 'arbitration inter frame space'
    - 'transmission opportunity limit'
  - $[0..CW_{min}, CW_q, CW_{max}]$: contention window
    - 'contention window minimum, current, maximum'
  - $RetryLimit_q$: #trials before giving up

- Further relevant parameters
  - $SIFS$: mandatory wait
  - $aSlotTime$: time unit
    - 'short inter frame space'

\[ AIFS = SIFS + AIFS_N \times aSlotTime \]
EDCA algorithm, very roughly

1. Select a number of backoff slots in variable \( bc \) uniformly from an interval
   - \([0..CW]\)
   - there is some debate if this backoff is there only after contention was observed
2. wait for the channel to be idle for AIFS; only then downcount \( bc \)
3. suspend this downcounting upon the media being active; upon resume wait AIFS first
4. when \( bc \) reaches 0
   - transmit frame
   - wait for ack
   - if this does not arrive, double the size of the interval and retry (exponential backoff)
5. after \( RetryLimit \) trials: drop the frame
6. after the first succesful frame: transmit available frames until \( TXOPLimit \) has been reached or frames run out
Effects of parameters

• During contention, the behavior of competing processes (hence, stations) becomes more synchronized

• A process with a lower AIFS:
  – gets to downcount its $bc$ more often

• A process with a lower CWMin / CWMax:
  – has its $bc$ reach 0 faster

• A process with a higher TXOP:
  – gets to send larger messages (more frames)

• Hence, there are two mechanisms:
  – gain control: even possible to define priorities in this way
  – retain control
TDMA (time division multiple access)

- Divide time into fixed periods (slots) and assign transmission slots to stations
  - typically, two-level hierarchy: slots and frames (group of slots)
    - admits slot-based interaction between stations within a frame
  - tricky with multiple cells (hidden nodes)
    - needs multiple frequencies
  - potentially wasteful as not all slots are used
- Requires time synchronization
- Requires a master for managing the assignment
- Both wired and wireless
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<th>Wireless</th>
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<td><strong>MA/CA</strong>: (pure) Aloha</td>
</tr>
<tr>
<td>CSMA/CD: coax ethernet</td>
<td><strong>CSMA/CA</strong>: Wifi, Zigbee</td>
</tr>
<tr>
<td>CSMA/CR: CAN</td>
<td><strong>TDMA</strong>: Wireless Hart</td>
</tr>
<tr>
<td>TDMA</td>
<td><strong>Master/Beaconing</strong>: Wifi, Zigbee</td>
</tr>
<tr>
<td>token passing: profibus</td>
<td><strong>FDMA + channel hopping</strong>: bluetooth</td>
</tr>
<tr>
<td>Master/Slave: ethercat</td>
<td>(low energy), 6tisch</td>
</tr>
<tr>
<td>(,profibus)</td>
<td><strong>CDMA</strong>: virtual point to point (4G), Chirp</td>
</tr>
<tr>
<td></td>
<td><strong>Spread Spectrum UWB</strong></td>
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<td><strong>Point to point</strong></td>
<td><strong>FDMA</strong></td>
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<tr>
<td>Switched ethernet: PoE</td>
<td><strong>Dedicated frequencies for long-haul</strong></td>
</tr>
<tr>
<td>Common way to set up</td>
<td><strong>transport</strong>: satellite</td>
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<td>larger networks using</td>
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<tr>
<td>switches and routers</td>
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Energy, in low capacity environment

• Radio communication is a major contributor to energy consumption
  – don’t use it 😊

• Applied techniques (combinations, need support at multiple layers)
  – asymmetry
    • low-power nodes are 1 hop away from well-powered infra
  – control the transmit / receive power
    • trade connectivity for energy
  – duty cycle
    • switch node or radio on and off periodically
  – demand driven
    • event driven control of radio (wakeup radio (IEEE 802.11ba), or push mode) with asymmetry
  – push / pull strategies
    • let the low power partner always be the one that takes initiative
  – trade power for range and throughput
    • special network technologies, special physical layers
Duty Cycling

- Strict interpretation: station switches on radio with a certain frequency and for a certain time
- Problem: how to meet each other
- Options:
  - strict time synchronization
    - energy expensive
  - sender initiated
    - send wakeup sufficiently often to guarantee reception
      - wakeup = packet or
      - wakeup = rendez-vous time
  - receiver initiated
    - switch transceiver on sufficiently long to guarantee meeting the sender
    - or enforce exchange: send receive request (similar as above)
  - asymmetry: one party always on (question: useful for both send and receive?)

Example for IEEE 802.15.4e CSL

- (CSL: Coordinated Sampled Listening)
- Broadcast:
  - transmit rendez-vous sufficiently often for all receivers to see it
- Unicast:
  - tune-in to the periodic behavior of the receiver to reduce overhead
  - include acknowledge

Asymmetry and event driven

• Consider a low-resource node:
  1. upon observing an event it wants to report it (push by node)
  2. it may need information for its work (pull by node)
  3. the environment of the node may want to send it information, updates or other (push by environment)
  4. the environment may want to have information from the node (pull by environment)

• Solutions:
  – 3,4: map to time driven behavior: align communication with periodic synchronization of the node with its environment
    • ‘keep alive’ plus handling pending request
    • inevitably, this introduces a delay, particularly for 4.
  – 1,2; provide always-on environment for demand driven radio control to reduce latency; can also map to time driven behavior of the node
Overview

• Physical organization
• IP
• The IEEE local area networks
• Techniques for medium sharing
• Techniques for energy reduction
• Wide area IoT-oriented initiatives
• Metrics
<table>
<thead>
<tr>
<th>Wired</th>
<th>Wireless</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outdoor</strong></td>
<td>No common infra structure available; some initiatives via light poles or other relatively dense infra</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Indoor</strong></td>
<td>Standard wired infra structure using UTP, fiber, switches, bridges and routers</td>
</tr>
</tbody>
</table>
Tradeoffs

- Typical tradeoffs are among communication range, data rate, transceiver power and spectrum usage.
- As a rule of thumb,
  - Increasing range decreases data rate (fix power, use modulation that can be demodulated farther away)
  - Increasing range increases power use (fix modulation and data rate)
  - Increasing power increases data rate (can go to higher modulation with the same error rate)
  - Increasing spectrum usage (spreading) increases range and decreases power
- Note: sketched dependencies are not automatic but require changes in encoding and modulation schemes.
- Outdoor IoT: long range, low data rate, low power
Long range: LoRaWAN

Picture from LoRa whitepaper on lora-alliance.org
Long range: LoRaWAN

- LoRaWAN (Long Range Wireless WAN), by LoRa Alliance
- topology:
  - star, IP-connected (L2, act as transparent bridge) gateways
  - single-hop wireless towards sensors
- physical layer:
  - CHIRP, spread spectrum, wideband (Semtech patent)
  - distinct frequencies
  - Aloha based MAC (just send)
- bitrate:
  - Adaptive Data Rate, managed by gateway, 0.3kbps ... 50kbps
  - trading range for bitrate
- device types
  - class A
    - one uplink, two downlink packets
    - device initiated, aloha-like
  - class B: add extra scheduled receive slots
  - class C: always on
- services
  - geolocation
  - Identification and security
    - Unique Network key (EUI64), ensure security on network level
    - Unique Application key (EUI64) ensure end to end security on application level
    - Device specific key (EUI128)
From link-labs site...

“Scalability, up to 120”

- “All gateways and nodes use the same channels for all transmissions.
- Time on air can be quite long. (up to 2 seconds)
- All uplink transmissions are uncoordinated (Pure Aloha)
- All gateway transmissions (Acknowledgement and downlink traffic) take the gateway “off the air,” unbeknownst to nodes trying to transmit.
- SX1301 based LoRa gateways have only 8 receiver modems to process simultaneous traffic.”

Improvements

- “Frequency Block Hopping
- Dynamic Transmit Power and Spreading Factor Selection
- Synchronous Uplink Slotting
- Variable Uplink/Downlink Time Boundary
- Compressed Acknowledgements
- Quality of Service
- Listen before talk”
LTE (4G), by 3GPP

- LTE IoT network: Integrated with the ‘normal’ 4G network
- LTE-M(TC)
  - machine type communication
  - end-point negotiated wakeup scheme
    - ‘extended discontinuous repetition’, DRX
  - small 1.4MHz assigned bandwidth fraction
    - simplifies receivers
- Narrowband LTE-MTC
  - further limit the bandwidth to 200KHz
    - 200kbps down/144kbps up
- NB-IoT
  - DSSS (direct-sequence spread spectrum)
  - less complex receivers
  - interferes with regular LTE, in principle
- Since October 2016, NB-IoT is actually deployed
New low power WAN: NB-FI

- WAVIoT: Narrowband Fidelity
  - starting at 8bps (!)

- Further similar issues as LoRa
  - trade range for data rate
  - has some APIs and protocols
  - some sample installations,

- Seems to make the standard error of implementing the entire OSI stack
  - rather than connecting to IP
<table>
<thead>
<tr>
<th>Technology</th>
<th>WAVIoT NB-Fi</th>
<th>Link Labs LoRa</th>
<th>Sigfox UNB</th>
<th>Ingenu RPMA</th>
<th>Nwave Weightless</th>
<th>LTE-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>868.8 MHz</td>
<td>868.8 MHz</td>
<td>868.8 MHz</td>
<td>2.4 GHz</td>
<td>868.8 MHz</td>
<td>1.8 - 2.7GHz</td>
</tr>
<tr>
<td>Max urban range with 99% reliability, m.</td>
<td>16 600</td>
<td>7 200</td>
<td>9 500</td>
<td>4 600</td>
<td>4 100</td>
<td>640</td>
</tr>
<tr>
<td>Maximum link budget, dBm</td>
<td>166</td>
<td>151</td>
<td>156</td>
<td>163</td>
<td>147</td>
<td>147</td>
</tr>
<tr>
<td>Node bandwidth</td>
<td>100 Hz</td>
<td>125 kHz</td>
<td>100 Hz</td>
<td>1 MHz</td>
<td>200 Hz</td>
<td>192 kHz</td>
</tr>
<tr>
<td>Spectrum efficiency</td>
<td>High</td>
<td>Very Low</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Gateway mode</td>
<td>Full Duplex</td>
<td>Half Duplex</td>
<td>Half Duplex</td>
<td>Half Duplex</td>
<td>Uplink Only</td>
<td>Full Duplex</td>
</tr>
<tr>
<td>Nodes per gateway</td>
<td>1 350 000</td>
<td>40 000</td>
<td>50 000</td>
<td>500 000+</td>
<td>50 000</td>
<td>20 000</td>
</tr>
<tr>
<td>Scalability</td>
<td>High</td>
<td>Very Low</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Simultaneous demodulation capacity</td>
<td>120 000</td>
<td>8</td>
<td>25</td>
<td>4 000</td>
<td>25</td>
<td>64</td>
</tr>
<tr>
<td>Security</td>
<td>XTEA 256 bit</td>
<td>32 bit</td>
<td>16 bit</td>
<td>AES 128 bit</td>
<td>No</td>
<td>128 - 256 bit</td>
</tr>
<tr>
<td>Minimum node cost, USD</td>
<td>$1.99</td>
<td>$29.00</td>
<td>$1.99</td>
<td>$5.00</td>
<td>$19.00</td>
<td>$5.00</td>
</tr>
<tr>
<td>Battery lifetime</td>
<td>10 years</td>
<td>10 years</td>
<td>10 years</td>
<td>10 years</td>
<td>10 years</td>
<td>5 years</td>
</tr>
<tr>
<td>Sector antennas</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Commercial Deployment</td>
<td>100+</td>
<td>100+</td>
<td>100+</td>
<td>30</td>
<td>10</td>
<td>N/A until 2020</td>
</tr>
<tr>
<td>First commercial project</td>
<td>2011</td>
<td>2014</td>
<td>2010</td>
<td>2010</td>
<td>2013</td>
<td>2020</td>
</tr>
</tbody>
</table>

Overview

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Metrics (which is how to judge all this)

- **throughput**
  - number of bytes per time unit
  - for a station: bytes per interval

- **latency or delay**
  - time difference in initiation of a transmission and the start of the receipt
  - consists of processing delay, transmission delay and queueing delay

- **jitter**
  - variations in timing, e.g. delay jitter, throughput jitter

- **fairness, ability to prioritize**
  - fairness: bound on delay in access to a transmission channel
  - or fair share in competition

- **overhead**

- **scalability**
  - as utilization
    - increasing the amount of communication
    - increasing # stations
    - e.g. CSMA/CA scales badly when increasing # stations while TDMA scales well
  - as dimensioning
    - LoRaWan can scale the number of gateways with the number of low-power nodes

- **predictability**

- **reliability**
  - e.g. resilience against interference

- **power**

- **range**
## Qualitative metrics

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Power</th>
<th>Resilience against interference</th>
<th>Predictability</th>
<th>Scalability (utilization)</th>
<th>Overhead</th>
<th>Prioritization</th>
<th>Fairness</th>
<th>Jitter</th>
<th>Latency</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDMA</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>-</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>TDMA</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>-</td>
<td>o/+(+)</td>
<td>-</td>
<td>-</td>
<td>o</td>
<td>+</td>
</tr>
<tr>
<td>CSMA/CA (+QoS)</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>-</td>
<td>+</td>
<td>o(+)+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>CDMA, spread spectrum</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Master / Slave</td>
<td>o</td>
<td>o</td>
<td>o/+(+)</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>-</td>
</tr>
<tr>
<td>Cell formation / domains</td>
<td>o</td>
<td>o</td>
<td>+</td>
<td>o</td>
<td>-</td>
<td>o</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Asymmetry</td>
<td>o</td>
<td>+</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Duty Cycling</td>
<td>o</td>
<td>+</td>
<td>o</td>
<td>o</td>
<td>+</td>
<td>o</td>
<td>-</td>
<td>o</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- **+**: improves (e.g. ‘Latency +’ means improves (reduces) Latency)
- **-**: makes worse
- **o**: no effect/not applicable
Guiding questions

• What are IoT networks?

• What is the role of IP?

• What techniques are used?
  – techniques for media sharing
  – techniques for reducing energy use

• Which standards are considered?