b

UNIVERSITÄT
BERN

UNIVERSITÄT BERN

# Internet of Things

## VII. Medium Access Control

**Prof. Dr. Torsten Braun, Institut für Informatik**

Bern, 12.04.2021 – 19.04.2021

# Internet of Things: Medium Access Control

## Table of Contents

# 1. Wireless Sensor Network MAC Protocols

## 1. MAC Protocol Requirements

- Collision Avoidance
- Energy Efficiency
- Low complexity in terms of processing power and memory
- Latency
- Throughput
- Channel utilization
- Scalability and adaptivity to changes in
  - network size
  - node density
  - topology
- Fairness

UNIVERSITÄT BERN

# 1. Wireless Sensor Network MAC Protocols

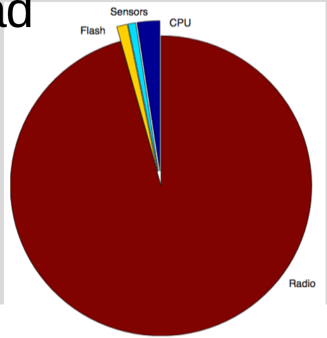
## 2.1 Sources of Energy Waste in MAC Protocols

| Operation | Telos |
|---|---|
| Minimum Voltage | 1.8V |
| Mote Standby (RTC on) | 5.1 $\mu$A |
| MCU Idle (DCO on) | 54.5 $\mu$A |
| MCU Active | 1.8 mA |
| MCU + Radio RX | 21.8 mA |
| MCU + Radio TX (0dBm) | 19.5 mA |
| MCU + Flash Read | 4.1 mA |
| MCU + Flash Write | 15.1 mA |
| MCU Wakeup | 6 $\mu$s |
| Radio Wakeup | 580 $\mu$s |

- Collisions and retransmissions
- Idle listening to channel in order to receive possible data
- Transmission and reception are similarly expensive, but much higher than active/idle CPU.

- Overhearing
  - occurs when nodes receive packets destined to other nodes.
  - can be dominant in scenarios with heavy load and high node density.
- Control packet overhead
- Over-emitting
  - transmission of a message when receiver is not ready

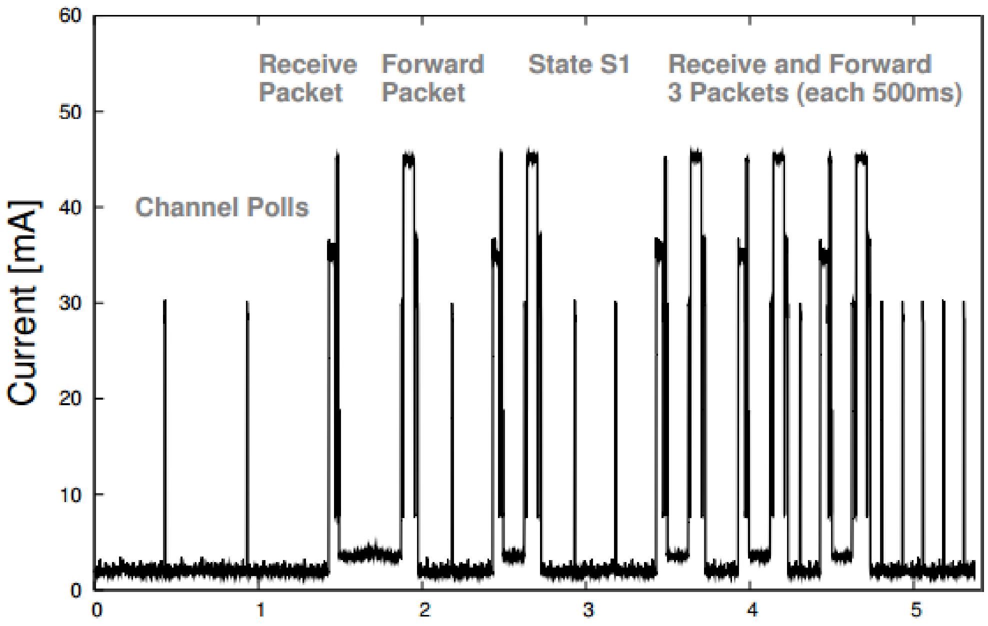
Example: TelosB



# 1. Wireless Sensor Network MAC Protocols

## 2.2 Sources of Energy Waste in MAC Protocols

- Self-developed duty-cycled MAC protocol
- Radio is most power-hungry component on board.
- Current is at 2 mA when radio is turned off and 45 mA when it is turned on.



# 1. Wireless Sensor Network MAC Protocols

## 3. MAC Protocol Classification

1. Scheduled protocols
   - Polling
     - Polling by central controller avoids energy waste caused by collisions but introduces polling overhead and delays
   - Multiplexing
     - Pre-allocation of channels based on time, frequency, or code multiplexing
     - Often: cluster formation required → limited scalability due to cluster head
2. Contention-based protocols
   - Sharing of channels and channel allocation on-demand
   - Problem: inefficient usage of energy in case of contention
3. Hybrid approaches
   - Combination of scheduled and contention-based protocols

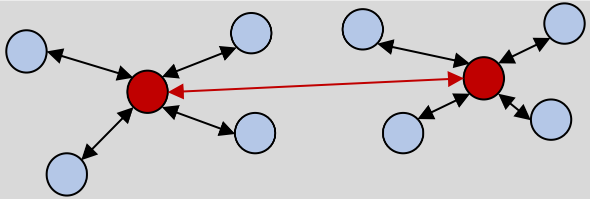
# 2. Scheduled Protocols

- Characteristics
  - Resources are scheduled to nodes or links.
- Advantages
  - Inherently collision-free

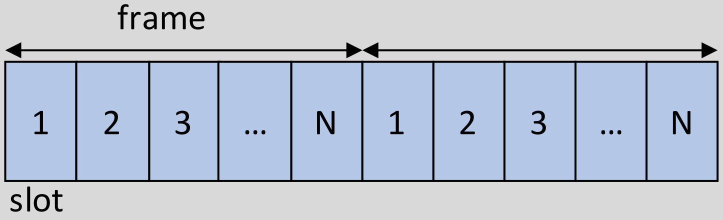
- Drawbacks: Scheduled protocols
  - are complex and costly to maintain.
  - require well synchronized nodes throughout the network.
  - have difficulties to adapt to changing topologies.

# 2. Scheduled Protocols

## 1. Scheduled Protocols based on Clusters



- Formation of clusters with cluster head acting as base station. often: TDMA
- Intra-cluster communication
  - Nodes can only communicate with cluster head.
- Inter-cluster communication
  - Higher power level for inter-cluster communication to interconnect cluster heads
  - Special time slots (TDMA), frequencies (FDMA) or codes (CDMA)




- Limited scalability and adaptivity to changes of number of nodes
  - Nodes join/leave cluster: overhead by frame length adaptation and slot assignment
  - Throughput limitation for static allocation
- Option
  - Dynamic slot assignment → signaling

# 2. Scheduled Protocols

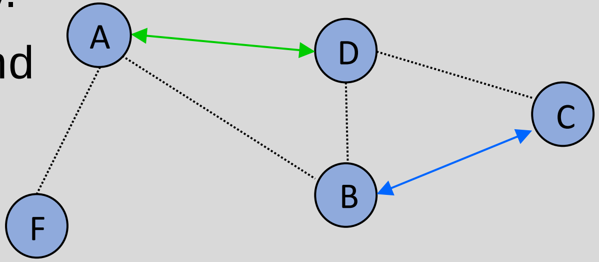
## 1.1 Low Energy Adaptive Clustering Hierarchy

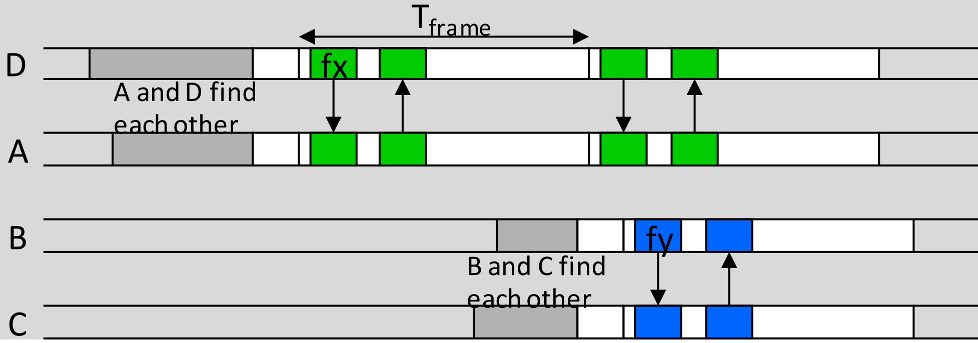
- Nodes
  - organize themselves into clusters with rotating cluster heads as local base stations.
  - are only active during their schedule and might transmit to cluster head.
- Cluster head
  - is permanently active.
  - calculates TDMA schedule for other nodes.
  - aggregates data and forwards data via other cluster heads to sink.
  - role is energy consuming and therefore rotated among nodes.
- Round = setup phase (cluster head election) + steady state phase (data transfer)
- Cluster head election
  - Each node elects itself as cluster head with a certain probability at the beginning of a round such that the expected number of cluster heads is k.
    Probability is lower for nodes with low energy level or if they have recently been a cluster head.
  - Announcement of cluster head status using CSMA/CA
  - Elected nodes wait for join request messages from nodes that select cluster head with strongest signal level.

# 2. Scheduled Protocols

## 2.1 Self-Organizing MAC for Sensor Networks

- Infrastructure building protocol that forms a flat topology.
- Nodes find each other on a fixed frequency (or code) and agree on a pair of time slots to send and receive data.
- Time slots are repeated periodically. Nodes wake up for these time slots. Time synchronization is required !
- Possibility of collisions is reduced by random selection of frequencies (codes).
- Subsequent growth of subnets towards connected network.

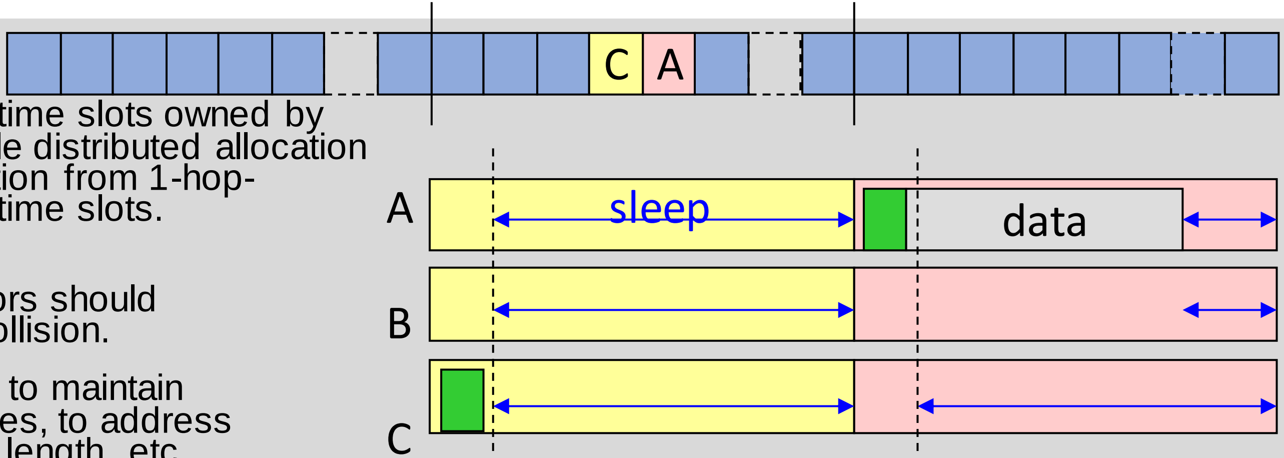


UNIVERSITÄT BERN

# 2. Scheduled Protocols

## 2.2 Lightweight MAC




- TDMA: Time is divided into time slots owned by various nodes using a simple distributed allocation algorithm based on information from 1-hop-neighbors. Spatial reuse of time slots.
- Nodes select free time slot.
  In case of collisions neighbors should inform nodes causing the collision.
- Control messages are used to maintain synchronization among nodes, to address destination, to indicate data length, etc.
- Problem:
  Nodes have to wake up at the beginning of each slot.
- Example: message from A to B

# 3. Contention-based Protocols

- Characteristics
  - Common channel shared by all nodes.
  - Resource allocation on demand
- Drawbacks
  - Risk of inefficient energy usage due to idle listening and collisions
- Advantages
  - Flexibility for topology changes
  - Peer-to-peer communication support
  - Fine-grained time synchronization is not required.
  - Scalability

UNIVERSITÄT BERN

# 3. Contention-based Protocols

## 1. Wakeup Radio

- Special low-power control channel to indicate upcoming transmission on separate data channel, e.g., PicoRadio
- Extension of CSMA into multi-channel CSMA
  - Channel = code, time slot, frequency, space
- Medium Access Control
  - A node randomly selects a channel and checks whether channel is busy.
  - If the node finds an idle channel it transmits the message.
    Otherwise, the node randomly selects another of the available channels.
  - If all channels are busy, the node sets a random timer for the checked channels and backs off.

- Nodes alternate between sleep and active mode
  → Wakeup required, here: paging
  - Dedicated wakeup radio channel consuming < 1 µW.
  - Destination ID is modulated into wakeup signal. Only destination will be waken up and informed about main radio channel it should tune to.

  → Low duty cycle of main radio, but susceptible to noise

UNIVERSITÄT BERN

# 3. Contention-based Protocols

## 2. Periodic Wakeup

– Receiving node periodically wakes up to receive packets from sending node and falls into sleep when no other node sends a packet.

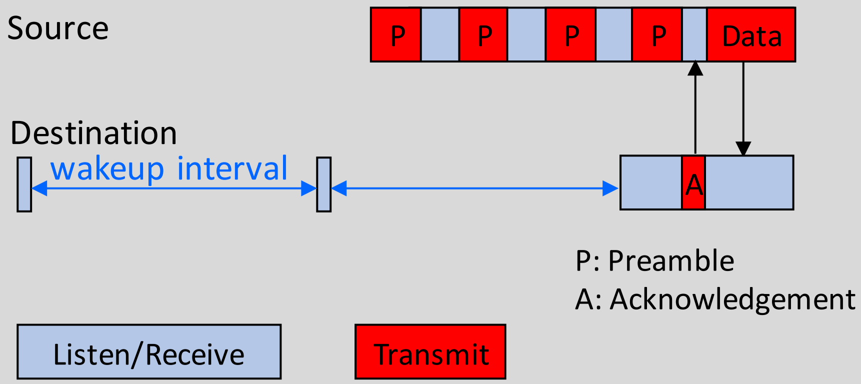
– Sending nodes need to know about duty / sleep cycles. Alternatives:
  1. Sending node sends frequent request packets (with receiver address) to be answered by the receiving node, e.g. X-MAC, BEAM, ContikiMAC. If start time is announced, receiving node can sleep until then.
  2. Sending node transmits long preamble (preamble length > sleep cycle), e.g., B-MAC, WiseMAC, MaxMAC
  3. Receiving node sends beacons at the beginning of its listen period, e.g., RI-MAC
  4. Synchronization of wakeup periods, e.g., S-MAC, T-MAC

– Problems: High delays due to periodic sleep, broadcasts

# 3. Contention-based Protocols

## 2.1.1 X-MAC

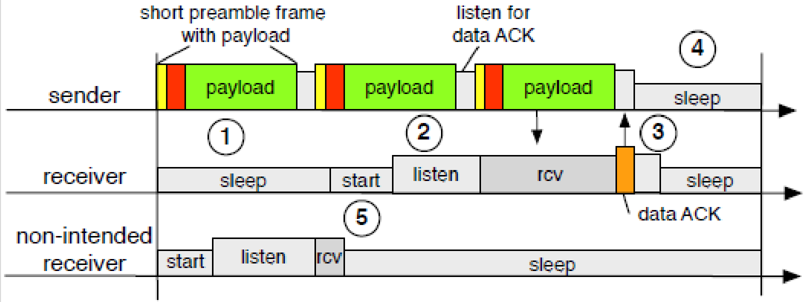
- Short preambles include address information to avoid overhearing.
- Receiver acknowledges receipt of preamble and listens to data packet.
- X-MAC can be implemented on any type of radio transceivers (bit/byte/packet-oriented).
- Alternative: transmit short data packets instead of short preambles

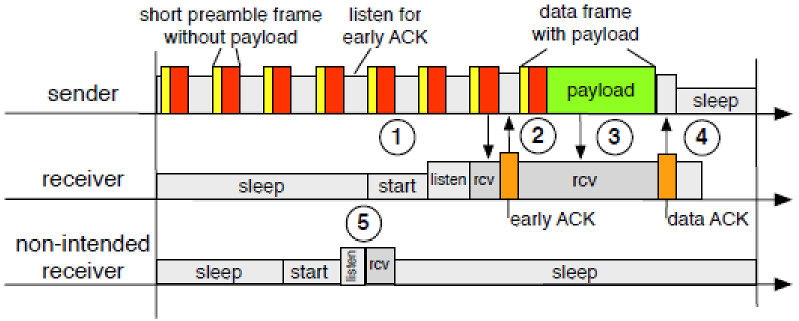


# 3. Contention-based Protocols

## 2.1.2 BEAM

- Transmission of long / short preambles with / without payload (< / > 40 bytes)
- Long preambles
  1. Periodic preambles including payload
  2. Reception of data
  3. ACK
  4. Sender stops transmission
  5. Early sleep for non-intended receivers
- Short preambles
  1. Periodic preambles
  2. Early ACK
  3. Data transmission
  4. ACK
  5. Early sleep for non-intended receivers



# 3. Contention-based Protocols

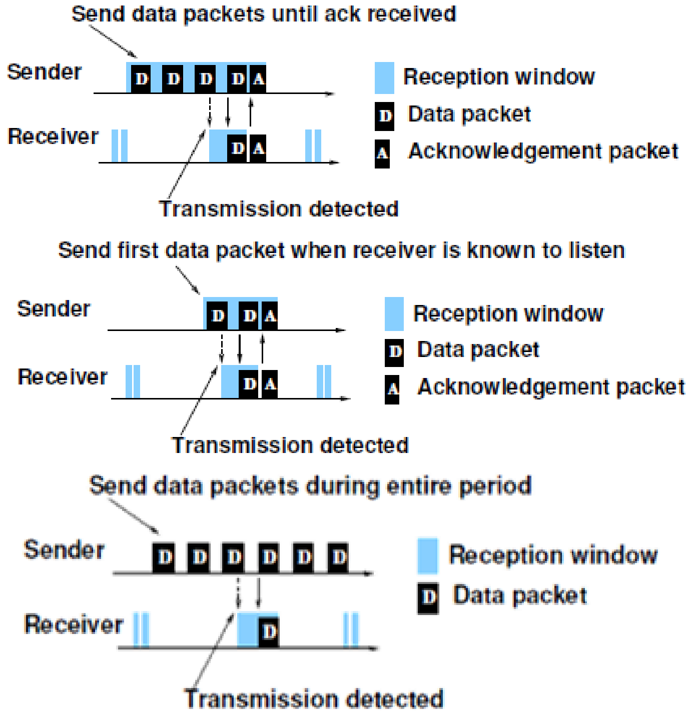
## 2.1.3 ContikiMAC

integrates concepts of

- B-MAC (low power listening)
- X-MAC (packetized preamble)
- BEAM / BoxMAC (data packets instead of preambles)
- WiseMAC (estimation of receiver wakeup)

Unicast

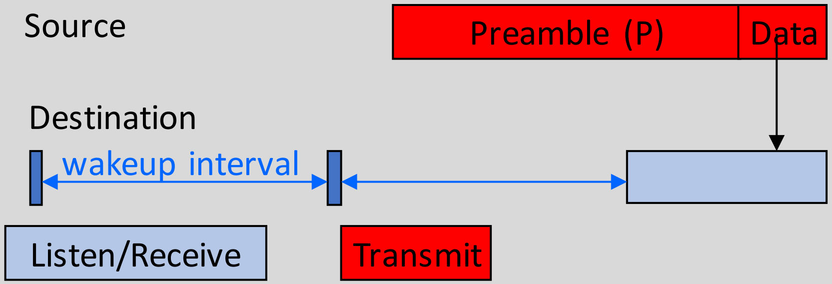
Broadcast



# 3. Contention-based Protocols

## 2.2.1 Berkeley-MAC (B-MAC)

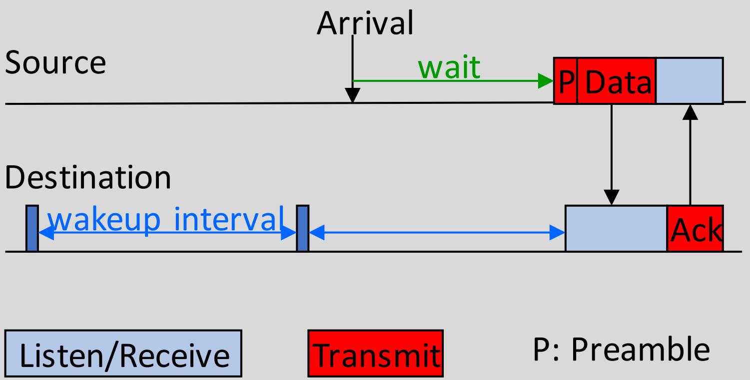
- Simple MAC protocol based on 2 functions
  1. Clear channel assignment and packet back-offs for channel arbitration
     - Noise estimation for detecting free channel
     - Transmission of long preambles
  2. Low power listening
     - Periodic wakeups for channel sampling based on noise estimation
- Optional mechanisms like RTS/CTS above B-MAC



# 3. Contention-based Protocols

## 2.2.2.1 WiseMAC

- Single-channel CSMA based protocol
- Sender sends a preamble prior to the data packet.
- All nodes sample the medium (signal strength measurement) with the same sampling period for activity, but sampling is not synchronized.
- Node discovering a busy medium continues to listen, receives packet, and becomes idle again.
- Long preambles are avoided by learning about each other node's sampling schedule: Nodes piggy-back sampling schedule in acknowledgement packets.



# 3. Contention-based Protocols

## 2.2.2.2 WiseMAC: Calculation of Preamble Period

- $T_w$: sampling period
- Time 0: Sender learns about schedule.
- θ: frequency tolerance
- L: Time of desired transmission
- 2·θ·L: time shift between 2 clocks
- Sending node must send preamble 2·θ·L before and 2·θ·L after assumed wakeup time.
- Required preamble length:
  $T_p = \min(4 \cdot \theta \cdot L, T_w)$

# 3. Contention-based Protocols

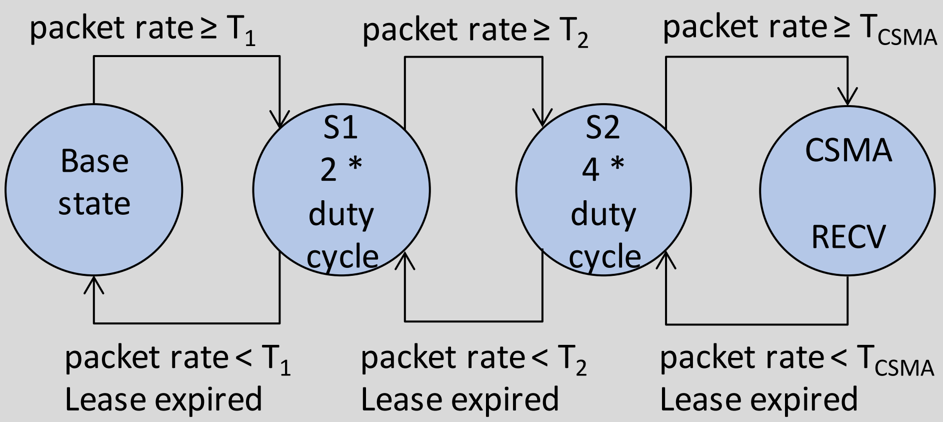
## 2.2.3.1 Maximally Traffic-Adaptive and Energy-Efficient MAC

– based on sampling of preambles, cf. WiseMAC

– Additional wakeups for higher rates of received packets (measurement by sliding window)

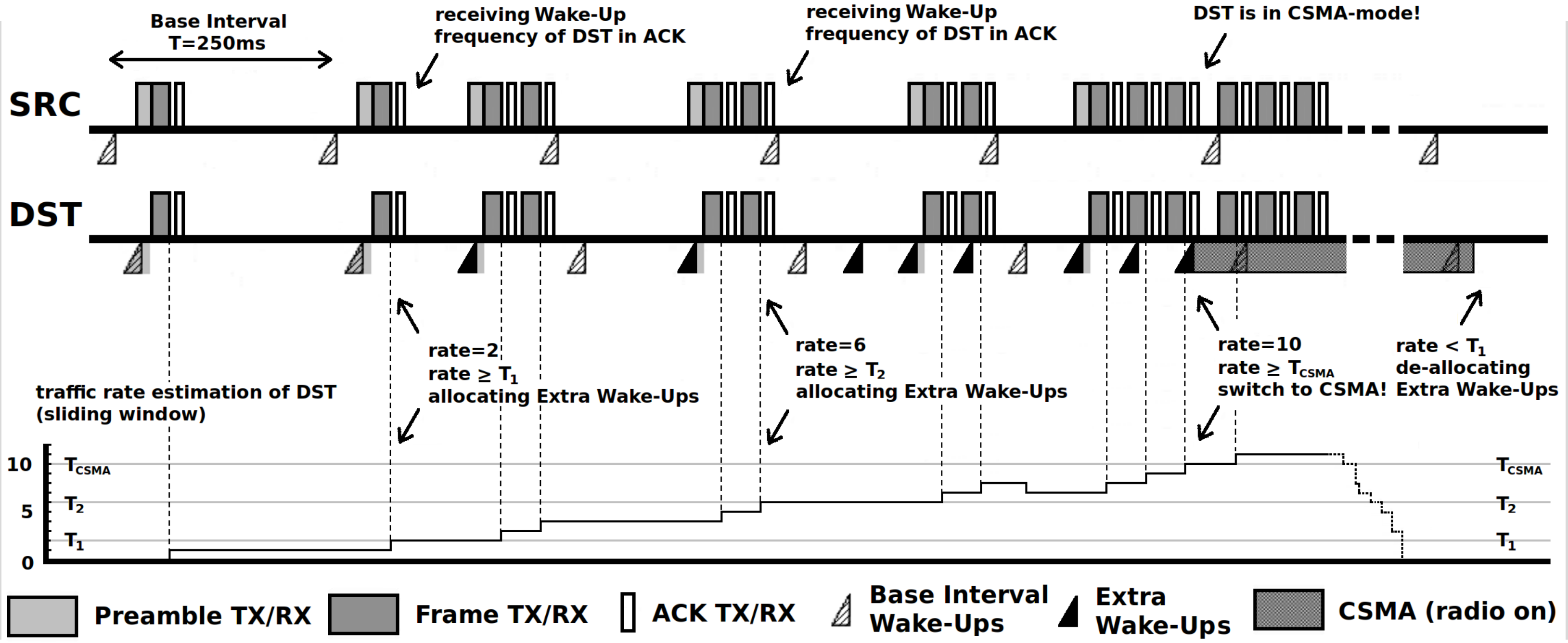
– State transitions if thresholds $T_1$, $T_2$, $T_{CSMA}$ are exceeded.

– Indication of lease times in acknowledgements



# 3. Contention-based Protocols

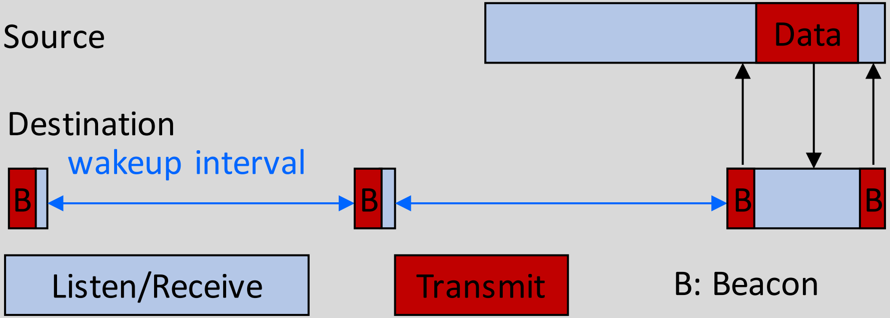
## 2.2.3.2 MaxMAC



# 3. Contention-based Protocols

## 2.3 Receiver-Initiated MAC

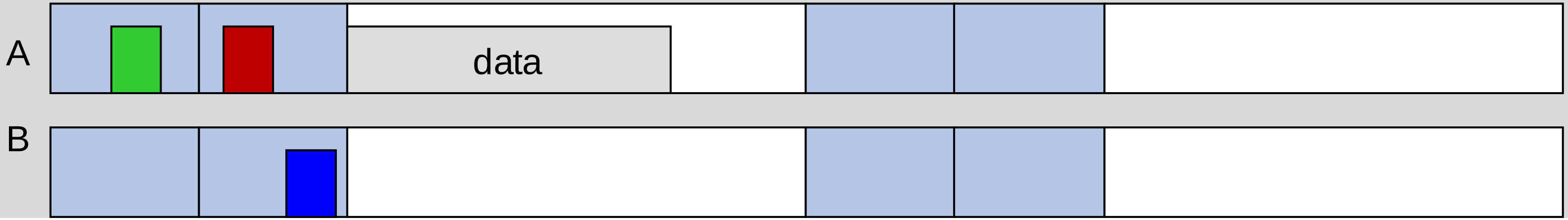
- Source becomes active, remains silent, but listens to destination's beacon.
- After beacon reception, data is transmitted
- Another beacon acknowledges data reception.



# 3. Contention-based Protocols

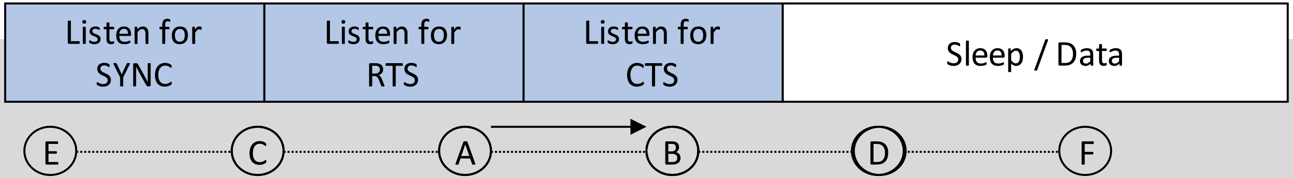
## 2.4.1.1 Sensor MAC

- Each node has alternating sleep and listen states.
  - Sleep: Node turns off its radio and sets a wakeup timer.
  - Listen: Node listens whether other nodes want to talk with it.
- Coordinated Sleeping and Synchronization
  - Each node selects its own listen/sleep schedule.
  - Neighbor nodes synchronize by periodic SYNC broadcasts describing the nodes' schedule.
- Collision avoidance similar to IEEE 802.11: RTS / CTS



# 3. Contention-based Protocols

## 2.4.1.2 S-MAC: Collision Avoidance & Data Exchange




- IEEE 802.11 like contention protocol
  - Physical carrier sense:
    Listening to carrier on physical layer
  - Virtual carrier sense:
    Duration field in each packet indicates remaining transmission time. Initialization of a timer.
  - Broadcast packets are sent without RTS / CTS.
  - Unicast packets follow RTS / CTS / DATA / ACK scheme.

- Nodes use their normal sleep time for packet exchange.
- Message Passing: Multiple fragments of a message can be sent in a burst, but with only one preceding RTS / CTS pair.
- Nodes might go into sleep state after receiving RTS / CTS, e.g., C,D.

# 3. Contention-based Protocols

## 2.4.1.3 S-MAC: Coordinated Sleeping

Initially, each node selects a sleep / listen schedule.


Procedure

1. A node listens for a certain time (> synchronization period).
2. If the node receives a schedule from another node it follows that schedule.
   Otherwise it selects its own schedule.
   The selected schedule is broadcast in a SYNC message following normal medium contention procedures.
3. A node might receive a different schedule after announcing its own schedule.
   – If the node does not have other neighbors it discards its schedule and takes over the new one.
   – If the node shares schedules with other neighbors it adopts both (or more) schedules.
     This is an exception and should appear mainly at nodes at the border of two synchronization areas.

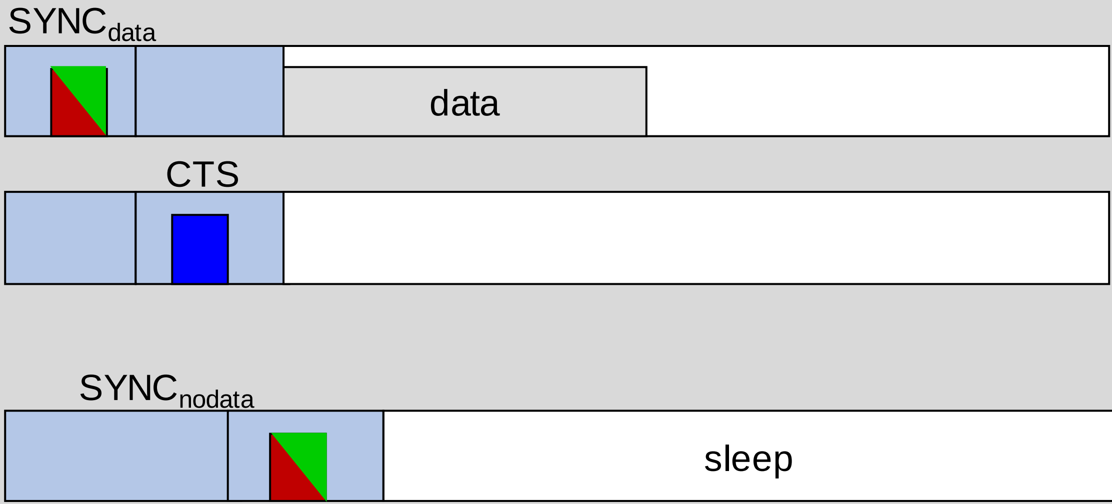
# 3. Contention-based Protocols

## 2.4.2 Traffic Aware Energy Efficient MAC

Optimization of S-MAC by combining SYNC and RTS, cases:

1. There is at least 1 sender.

2. There is no sender.



# 4. Industry Standards

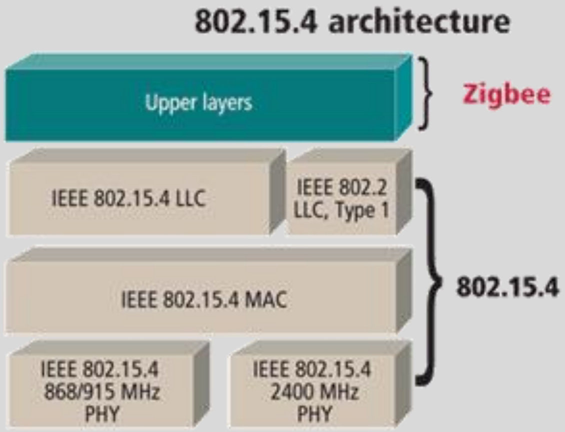
Large number of standardization bodies with different roadmaps

# 4. Industry Standards

## 1. IEEE 802.15.4e Low-Rate Wireless Personal Area Networks

- IEEE 802.15.4 specifies
  - Wireless Medium Access Control
  - Physical Layer

  for Low-Rate Wireless Personal Area Networks
- Contiki OS only uses 802.15.4 PHY layer from radio hardware. Using 802.15.4 radios does not imply using their MAC.
- Standard is the basis for the ZigBee, ISA100.11a, and WirelessHART specifications.



b UNIVERSITÄT BERN

# 4. Industry Standards

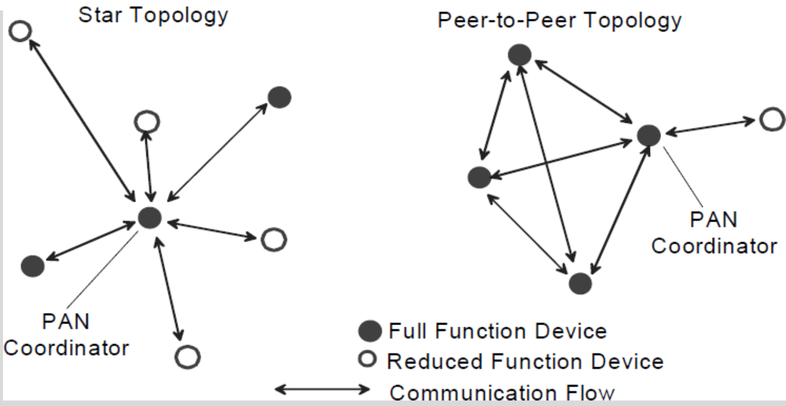
## 1.1 IEEE 802.15.4e Characteristics

- Over-the-air data rates of 250 kbps, 100kbps, 40 kbps, and 20 kbps
- Star or peer-to-peer operation
- Unique 64-bit extended address or allocated 16-bit short address
- Optional allocation of Guaranteed Time Slots
- Carrier sense multiple access with collision avoidance (CSMA/CA) or Aloha channel access
- Fully acknowledged protocol for transfer reliability
- Low power consumption
- Energy Detection
- Link Quality Indication for received packets
- Physical Layer frequencies
  - 868–868.6 MHz, 902–928 MHz, 2400–2483.5 MHz
  - 314–316 MHz, 430–434 MHz, 779–787 MHz band for LR-WPAN systems in China
  - 950–956 MHz in Japan

# 4. Industry Standards

## 1.2 IEEE 802.15.4e Device Types

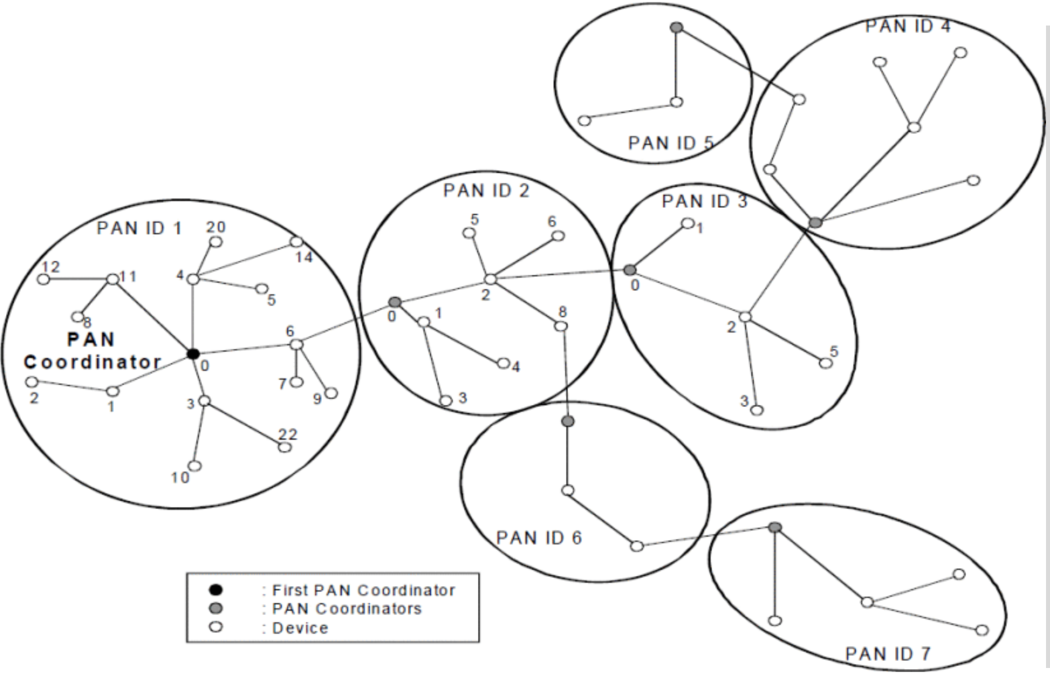
- Device types participating in an IEEE 802.15.4 network
  - Full-Function Device
  - Reduced-Function Device
- FFD can operate in three modes serving as a
  - Personal Area Network coordinator,
  - coordinator (provides synchronization services),
  - or device.
- FFD can talk to RFDs or other FFDs, while an RFD can talk only to an FFD.



UNIVERSITÄT BERN

# 4. Industry Standards

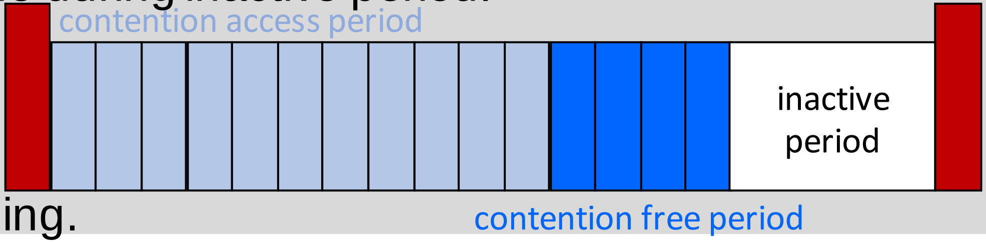
## 1.3 IEEE 802.15.4e Clusters



# 4. Industry Standards

## 1.4 IEEE 802.15.4e Slot Structure

- Coordinator defines optional super-frame structure with 16 equally sized slots.
- Beacons synchronize devices.
- Slotted CSMA/CA protocol for contention access period
- Transactions shall be completed until next beacon.
- Super-frame may have active and inactive period.
  Coordinator may enter low power mode during inactive period.
- Coordinator may allocate up to 7 Guaranteed Time Slots in contention free period




- Non-beacon mode allows no duty cycling.

b UNIVERSITÄT BERN

# 4. Industry Standards

## 1.5 IEEE 802.15.4e Low-Energy Mechanisms

Low-energy mechanisms are provided to reduce energy consumption by allowing devices to communicate while maintaining low duty cycles.

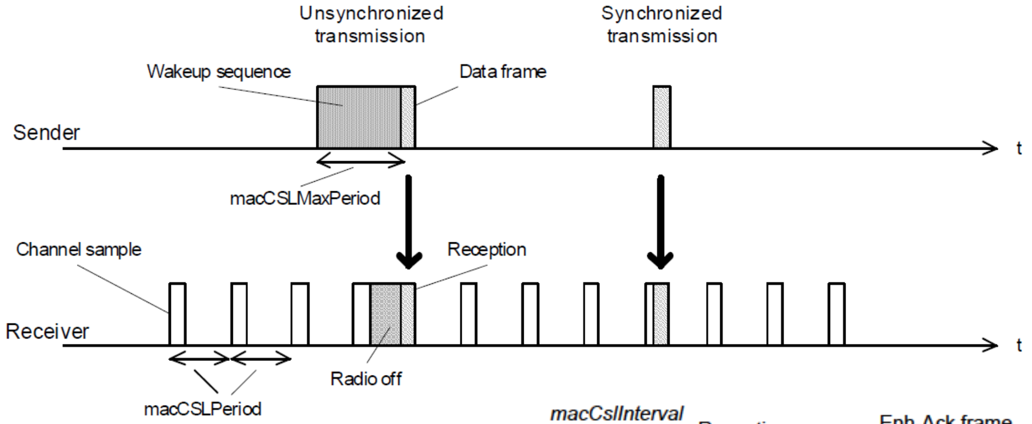
– Coordinated Sampled Listening

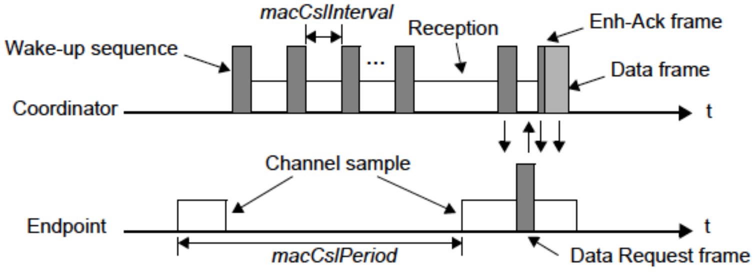
– Receiver Initiated Transmission

# 4. Industry Standards

## 1.5.1 IEEE 802.15.4e Coordinated Sampled Listening

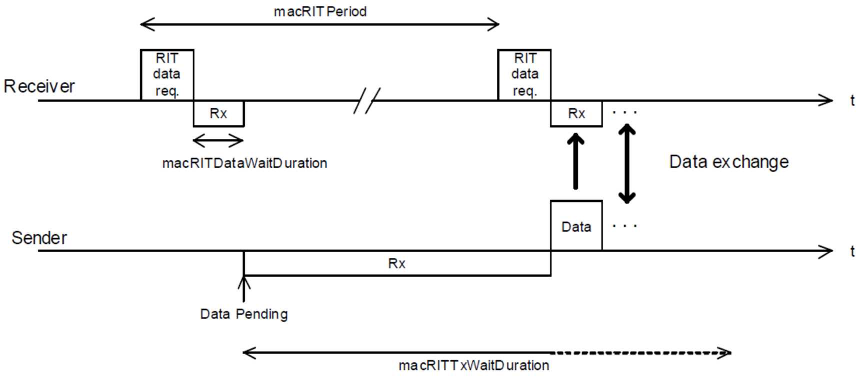
- allows receiving devices to periodically sample the channel(s) for incoming transmissions at low duty cycles.
- Receiving device and transmitting device are coordinated to reduce transmitting overhead.



# 4. Industry Standards

## 1.5.2 IEEE 802.15.4e Receiver Initiated Transmission

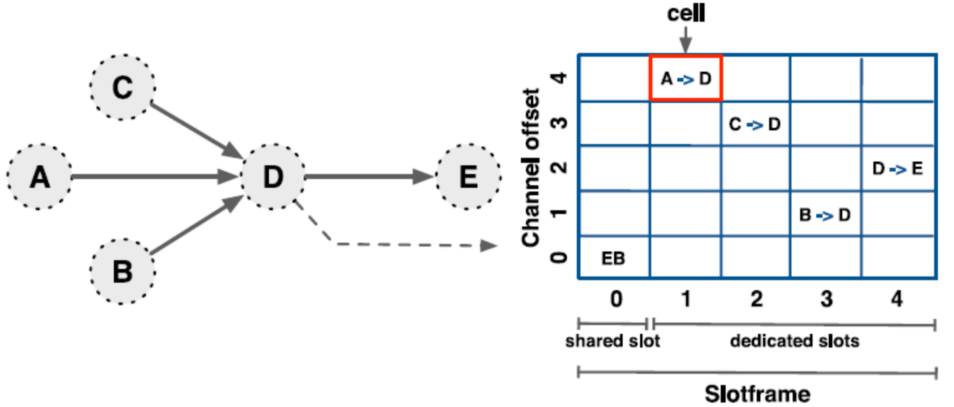



- allows receiving devices to periodically broadcast data request frames, and transmitting devices only transmit to a receiving device upon receiving a data request frame.
- is suitable for the following scenarios
  - Low data traffic rate and loose latency requirement, where a few seconds of latency is allowable by the application.
  - Local regulations restricting the duration of continuous radio transmissions, e.g., 950 MHz band in Japan

# 4. Industry Standards

## 1.6 IEEE 802.15.4e Timeslotted Channel Hopping

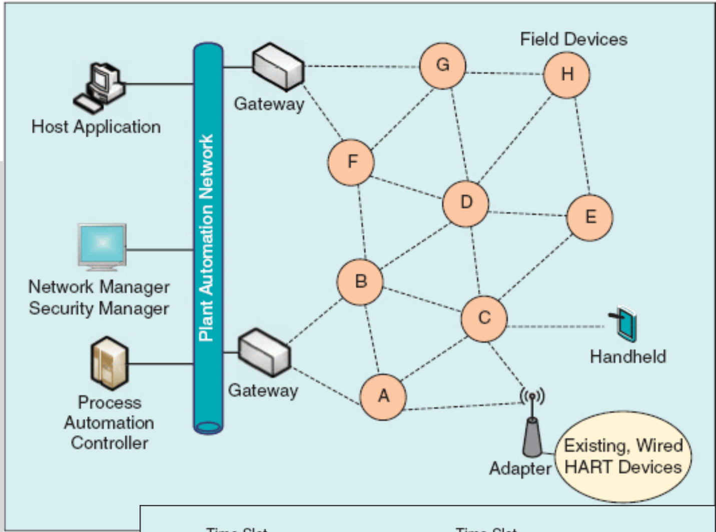
- TSCH uses time-division multiple access (TDMA) and frequency hopping spread spectrum (FHSS)
  - to achieve high network reliability,
  - reduce energy consumption, and
  - mitigate multipath fading and the impact of external interference.
- Time is sliced into timeslots of equal length, sufficient enough to transmit a data packet and to receive an acknowledgment.
- A set of timeslots constructs a slotframe that repeats perpetually.
- Absolute Sequence Number (ASN) is assigned to each timeslot to count the number of timeslots since the establishment of the TSCH network.
- frequency = f(ASN + channelOffset) % (number of available physical channels)

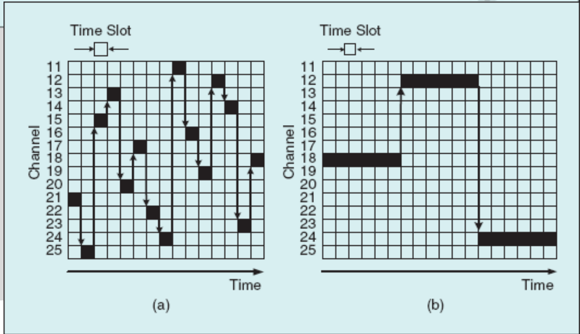


# 4. Industry Standards

## 2. Wireless HART

- Industry standard for industrial wireless sensor networks, ratified in 2010, also used in ISA 100.11a
- Based on IEEE 802.15.4 physical layer, but other layers of the stack such as data link (including MAC), network, transport, and application are new.
- Characteristics
  - TDMA MAC Layer with rigid time-synchronization needed across entire network
  - (Slow) frequency hopping and channel blacklisting
  - 10 ms slots provides sufficient time for 1 data / acknowledgement packet pair, combination of slots into super-frames
  - Unique network IDs and security keys assigned by security manager
  - Network manager for scheduling and routing in meshed networks



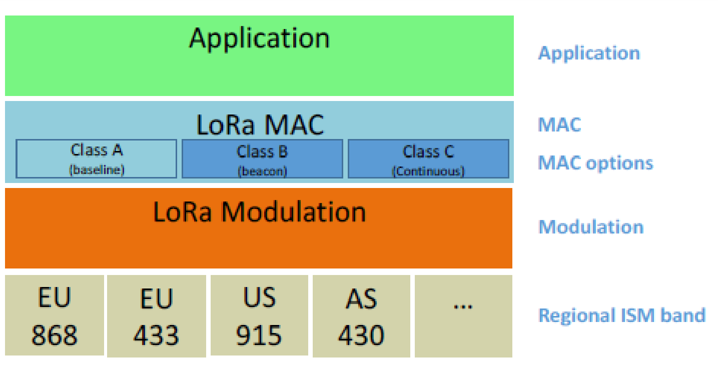



UNIVERSITÄT BERN

# 4. Industry Standards

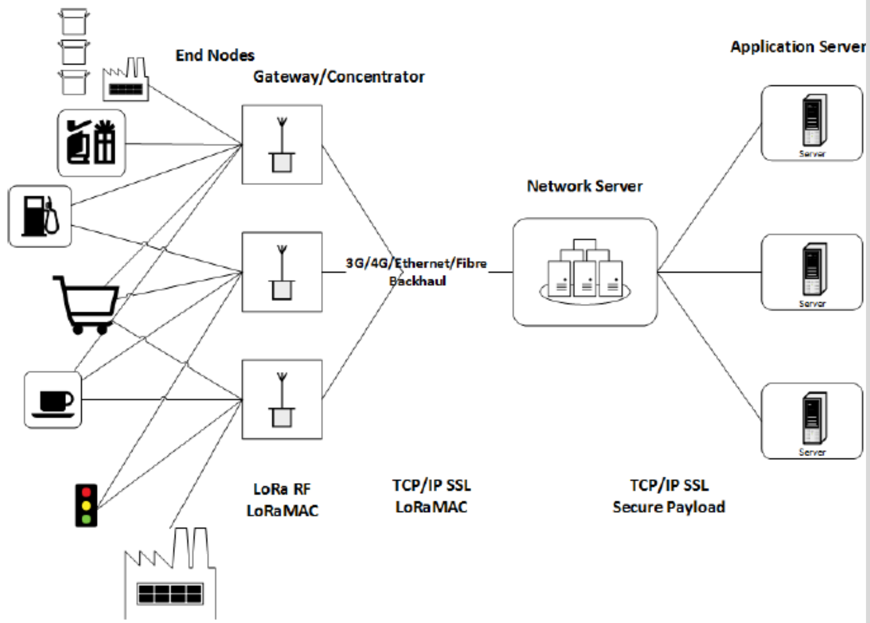
## 3. Long Range Wide Area Network

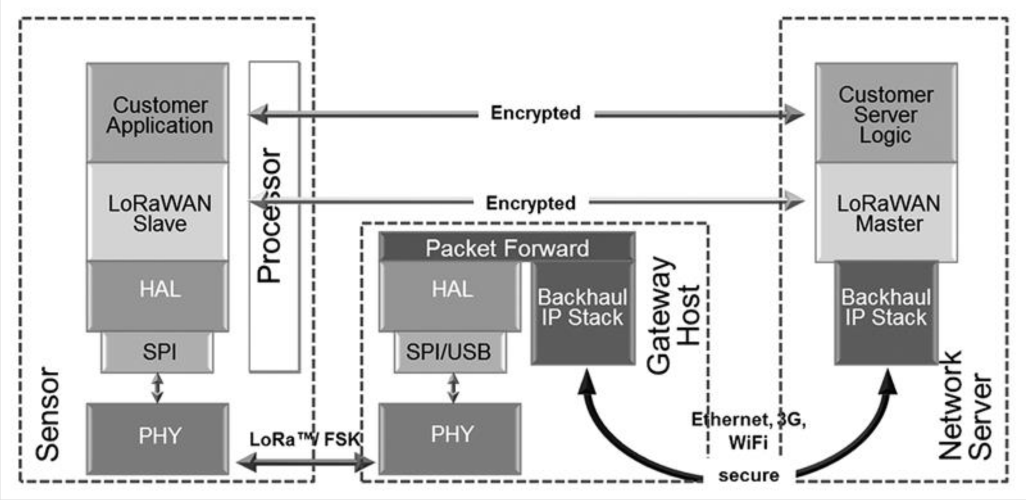
- Low Power Wide Area Network for battery operated things in regional, national or global network
- Secure bi-directional communication, mobility and localization services.
- Star-of-stars topology
- Gateways are
  - transparent bridges relaying messages between end-devices and central network server in backend
  - connected to the network server via standard IP connections.
- End-devices use single-hop wireless communication to one or many gateways.
- Support of multicast enabling software upgrade over the air or other mass distribution messages
- (Adaptive) data rates range from 0.3 kbps to 50 kbps, distances of multiple km
- LoRaWAN network server is managing the data rate and RF output for each end-device individually by an adaptive data rate scheme.
- Technology for The Things Network



# 4. Industry Standards

## 3.1 LoRaWAN Network Architecture

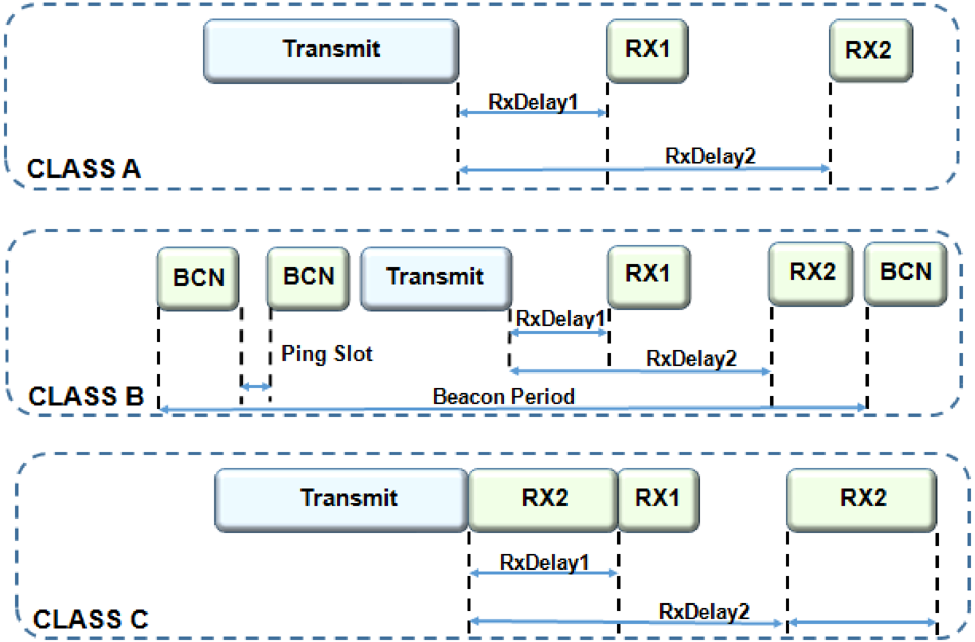


# 4. Industry Standards

# 3.2 LoRaWAN Device Classes

- Bi-directional end-devices (Class A, battery powered):
  - bi-directional communications, unicast messages only
  - Transmission slot scheduled by end-device is based on its own communication needs with a small variation based on a random time basis (Aloha type of protocol).
  - Device opens two receive windows, otherwise server has to wait until next scheduled uplink.
  - for applications that only require downlink communication from server shortly after end-device has sent an uplink transmission
- Bi-directional end-devices with scheduled receive slots (Class B, low latency, optional):
  - End-device receives time synchronized Beacon from gateway to open extra receive window (ping slot) at scheduled times.
  - Unicast and multicast messages
- Bi-directional end-devices with maximal receive slots (Class C, no latency, optional):
  - nearly continuously open receive windows, only closed when transmitting.
  - Unicast and multicast messages
  - more power but lowest latency for end-to-end communication.



# Thanks

# for Your Attention

**Prof. Dr. Torsten Braun, Institut für Informatik**

Bern, 12.04.2021 – 19.04.2021