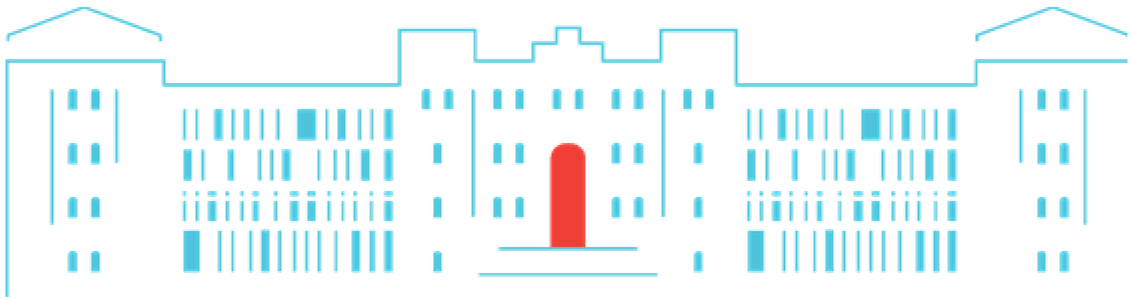
Introduction to IEEE 802.15.4

ComNets

TUHH
Institute of Communication Networks



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Course Contents

Online lectures

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- Lecture 2 – IEEE 802.15.4
- Lecture 3 – IETF 6TiSCH

Physical Meeting 13th to 17th of April

- Lecture 4 – Theoretical Analysis
- Cooja Simulations and Experiments
- Industrial visit and a talk
- Team Presentations on self learned material
- Lecture 5 – Research Project Results

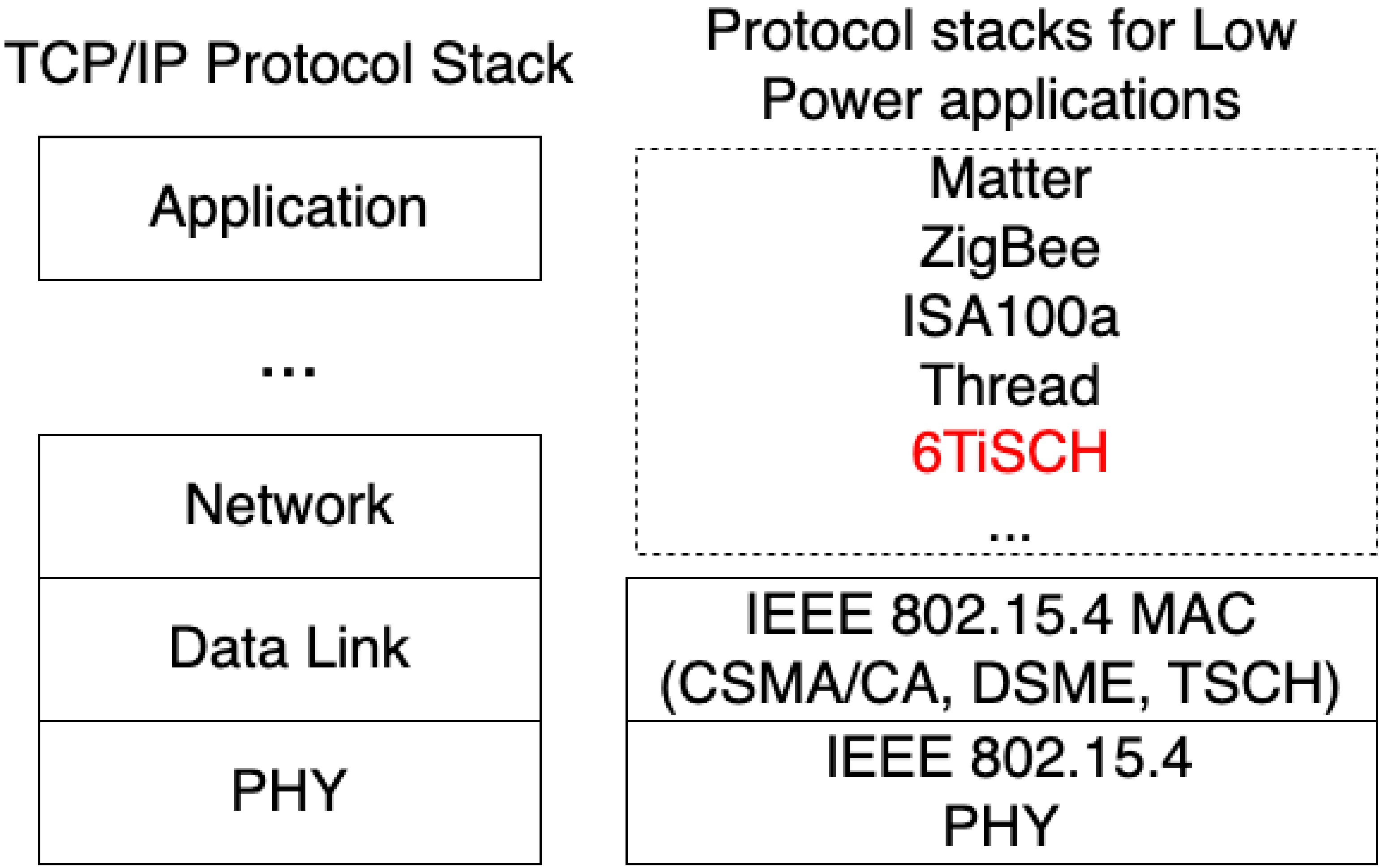
More details on our padlet,
https://tuhh.padlet.org/c00zIl01/enabling-industry-4-0-j88rkh1i3j7rzmv3

Wireless Communication for Deterministic Networks

- 2006: Dust Networks Time Sync Mesh Protocol (TSMP)
- 2008: WirelessHART
  - TDMA with fixed time slots
  - Vendor-driven
- 2011: ISA 100.11a
  - TDMA (variable time slots) + CSMA
- 2012: **IEEE 802.15.4 TSCH** (Time Slotted Channel Hopping) mode
  - Configurable TDMA – predictable latency, avoids idle listening and extends device lifetime
  - Channel hopping - improves the reliability in the presence of narrowband interference

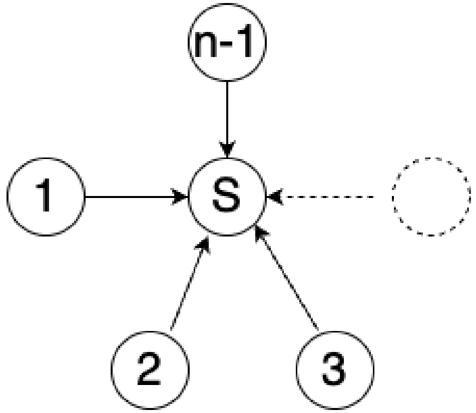
Any other wireless protocols that you heard about for industry 4.0?

Protocol Stack for Industry 4.0 Applications

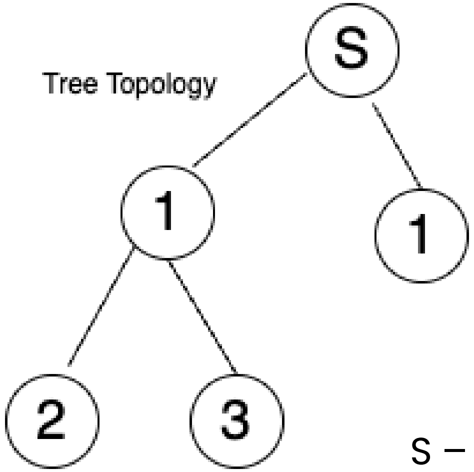


Types of MAC - IEEE 802.15.4

- CSMA/CA – Carrier Sense Multiple Access / Collision Avoidance
  - No guaranteed access
- DSME - Deterministic and Synchronous Multichannel Extension
  - TDMA slots with periodic CSMA/CA access for slot negotiation, broadcast traffic
- TSCH – Time Slotted Channel Hopping
  - TDMA combined with FDMA, scheduled communication *cells* (shared or dedicated)



Star Topology

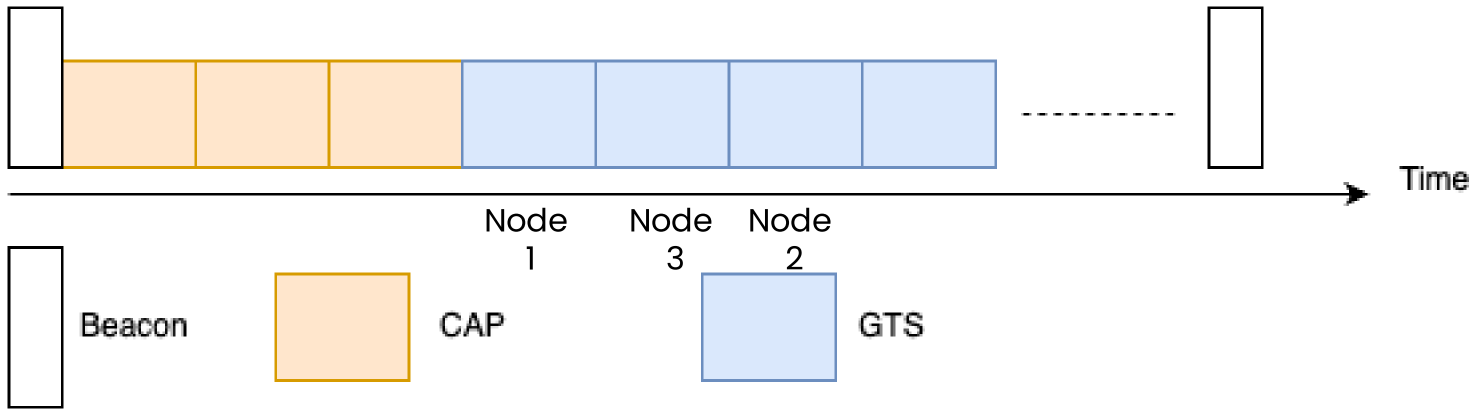


S – Sink/ Root/ Gateway/ PAN Coordinator

802.15.4 MAC Modes - DSME

DSME (Deterministic and Synchronous Multi-Channel Extension)

- Uses **beacon-enabled mode** with **multi-channel communication**.
- Supports **two phases**:
  - **CAP (Contention Access Period):** Nodes compete for access using CSMA/CA.
  - **CFP (Contention-Free Period):** Time slots are allocated for deterministic access.



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IEEE 802.15.4 TSCH Mode

These slides were prepared using the following references:

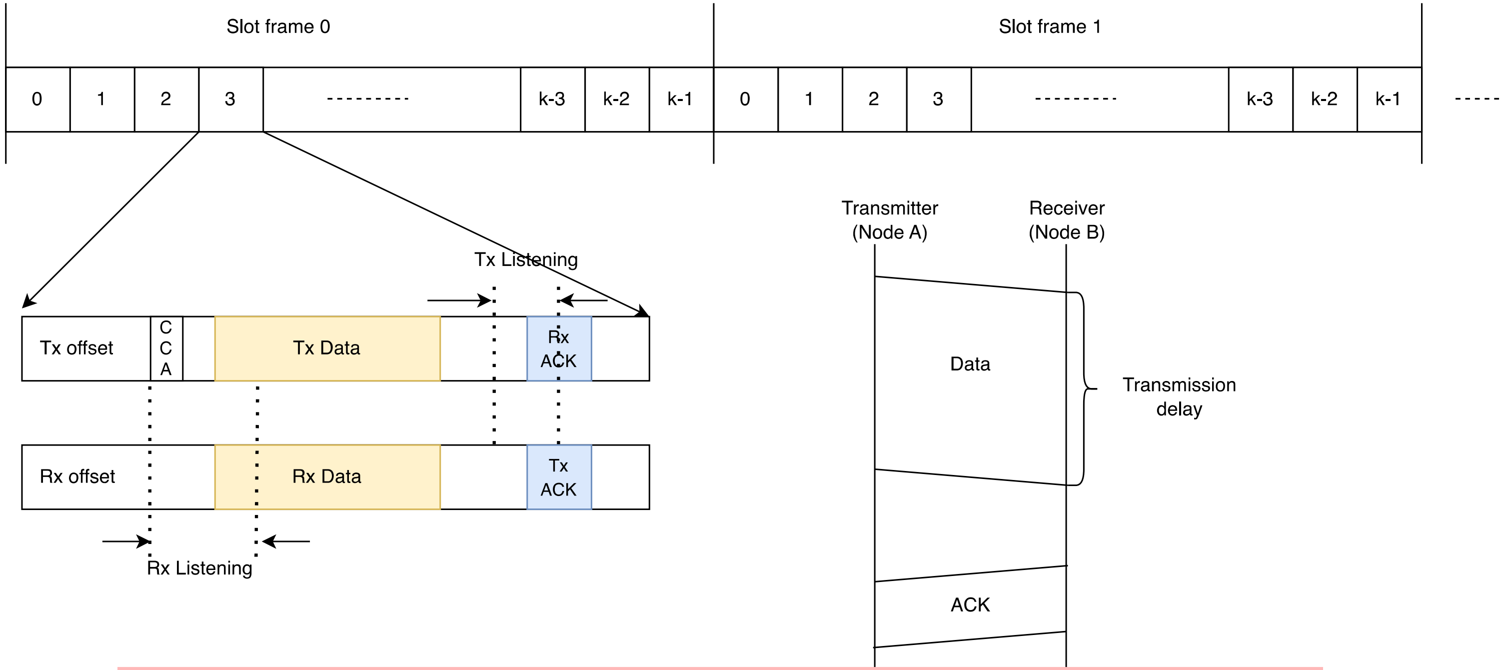
[1] IEEE standards for Low-Rate Wireless Networks, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9144691

[2] Appendix A of RFC 7554 - TSCH Protocol Highlights, https://datatracker.ietf.org/doc/html/rfc7554#page-15

[3] RFC 8480 - 6TiSCH Operation Sublayer (6top) Protocol (6P), https://datatracker.ietf.org/doc/html/rfc8480

IEEE 802.15.4 TSCH Mode

- Slotframe consists of k time slots
  - Structure repeats over time
- A pair of nodes communicate within a time slot
  - Actions that are performed are **transmit**, **receive**, or **sleep**



Any factors that impact the duration of a timeslot?

Time Slot Duration

- Example: IEEE 802.15.4 in 2.4 GHz frequency band
  - Max Transmission delay ~ 4 ms (127 bytes @ 250 kbps)
  - a shorter ACK takes about 1 ms

=> 10ms slot (a typical duration)

  - leaves 5 ms for radio turnaround, packet processing and security operations

Slotframe

- Continuously repeats over time
- Multiple slotframes are possible (sorted by priority)
  - Control, application traffic, etc.
  - Resulting schedule is a superposition
- Slotframe size depends on the application needs (from 10 to 1000 of time slots)
  - Shorter vs. longer slotframes?
    - Data transmission rate vs. power consumption

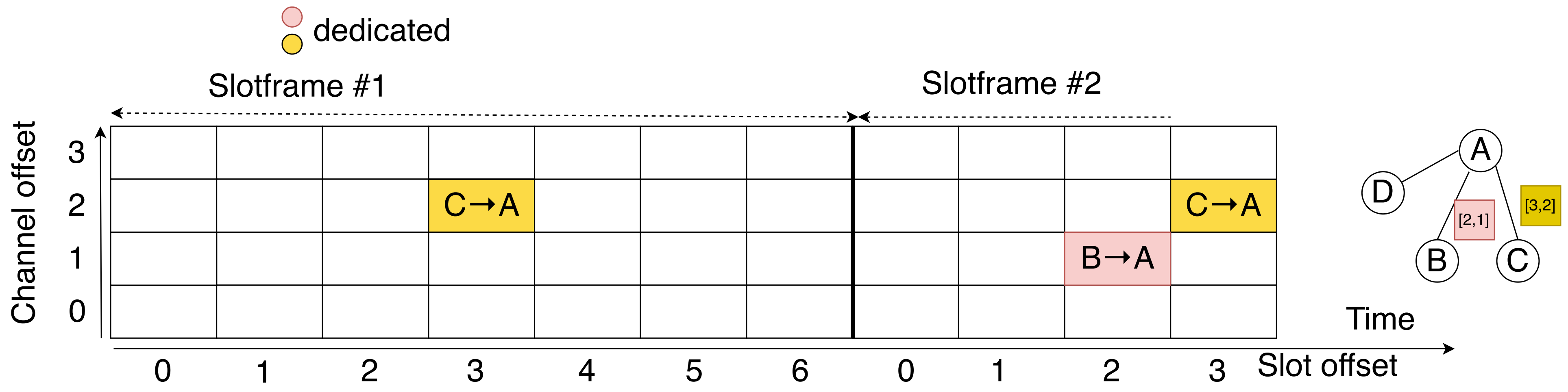
```
                  | 0    1    2    3    4  | 0    1    2    3    4  |
                  +------------------------+------------------------+
     Slotframe 0  |    |    |    |    |    |    |    |    |    |    |
    5 slots long  | EB |    |    |    |    | EB |    |    |    |    |
(Minimal 6TiSCH)  |    |    |    |    |    |    |    |    |    |    |
                  +------------------------+------------------------+
                  | 0    1    2    3    4    5    6    7    8    9  |
                  +-------------------------------------------------+
     Slotframe 1  |    |    |    |    |    |    |    |    |    |    |
   10 slots long  |    |A->B|    |    |    |    |    |    |B->A|    |
            (6P)  |    |    |    |    |    |    |    |    |    |    |
                  +-------------------------------------------------+
```

Figure 1. 2-Slotframe Structure when using 6P alongside the Minimal 6TiSCH Configuration[1]

1.

Channel Offset vs. Slot Offset

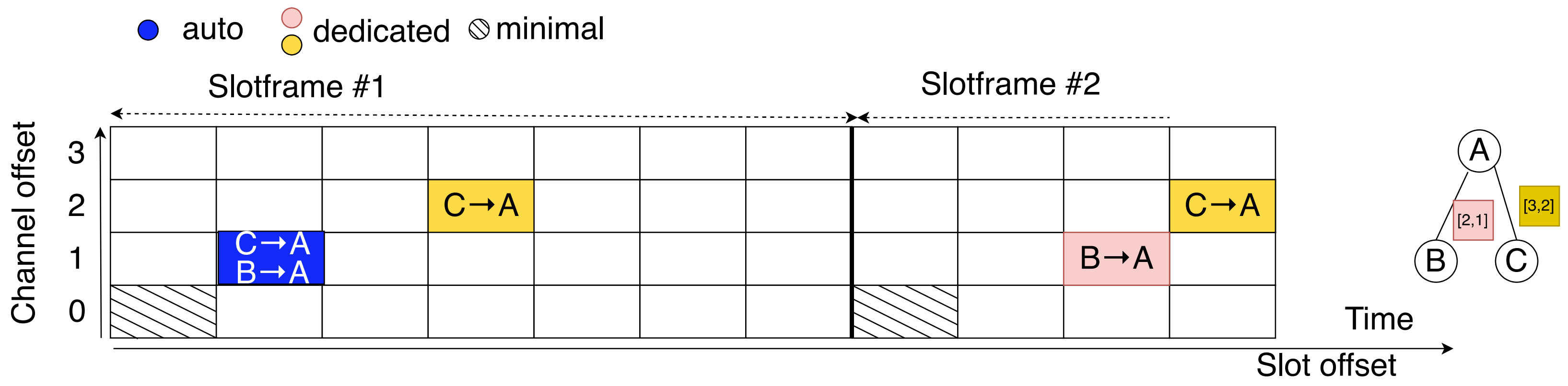
[slotOffset, channelOffset] is called a *cell*, either transmit (TX), receive (RX) or both.



1. **C uses cell [3,2] to communicate with A. Does node C use the same channel every slotframe?**
2. **How to support broadcast traffic (e.g. routing information)?**
3. **How to negotiate/install a dedicated cell between two nodes?**

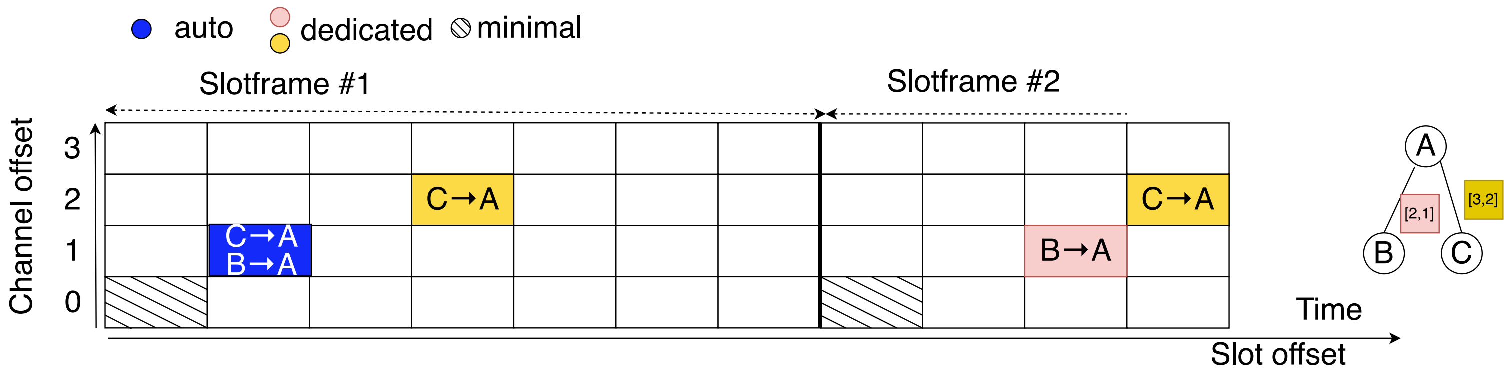
TSCH Cells

- **Dedicated**
  - Contention-free
  - Communication between a *single* pair of nodes
  - Either transmit or receive mode
- **Shared**
  - Contention-based (Slotted ALOHA)
  - Communication from/to *multiple* nodes
    - **Auto cell** among neighbors
    - **Minimal cell** [0, 0] is for everything - broadcast traffic (beacons, routing) and joining the network



Auto Cell

- Enables shared communication between neighbors
- Maintained autonomously by each node without negotiation
  - Auto RX Cell: [slotOffset, channelOffset] computed as a hash of the 64-bit Extended Unique Identifier (EUI-64) of the node itself
  - Auto TX Cell: [slotOffset,channelOffset] computed as a hash of EUI-64 destination address (MAC) in the unicast frame to be transmitted



  - Example implementation of the hash function see RFC 9033 (Appendix A).[2]

2. https://datatracker.ietf.org/doc/html/rfc9033#name-example-implementation-of-t

Channel Hopping

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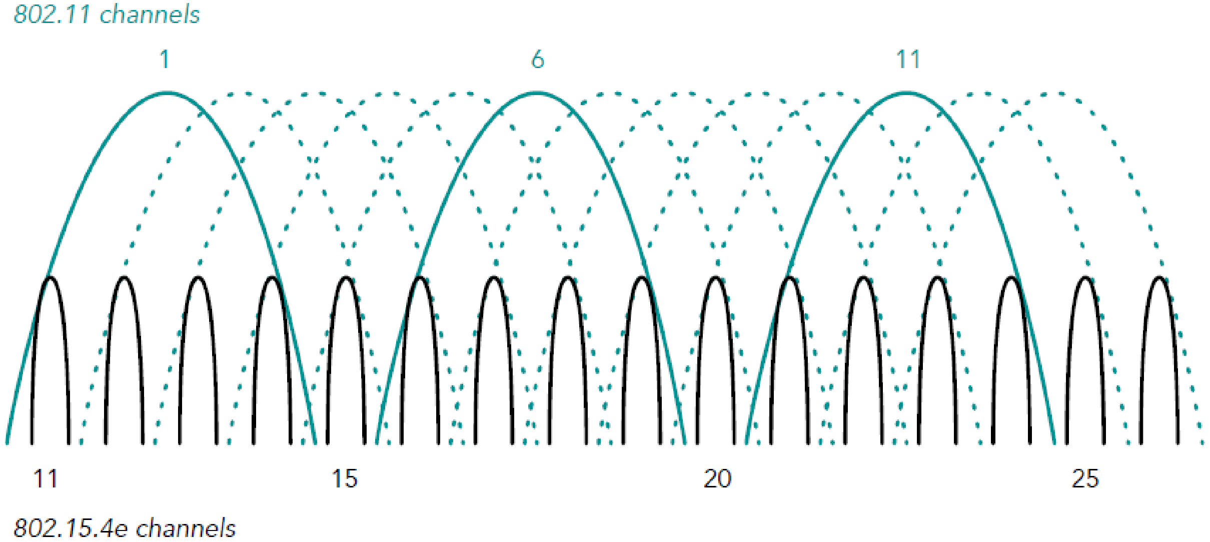
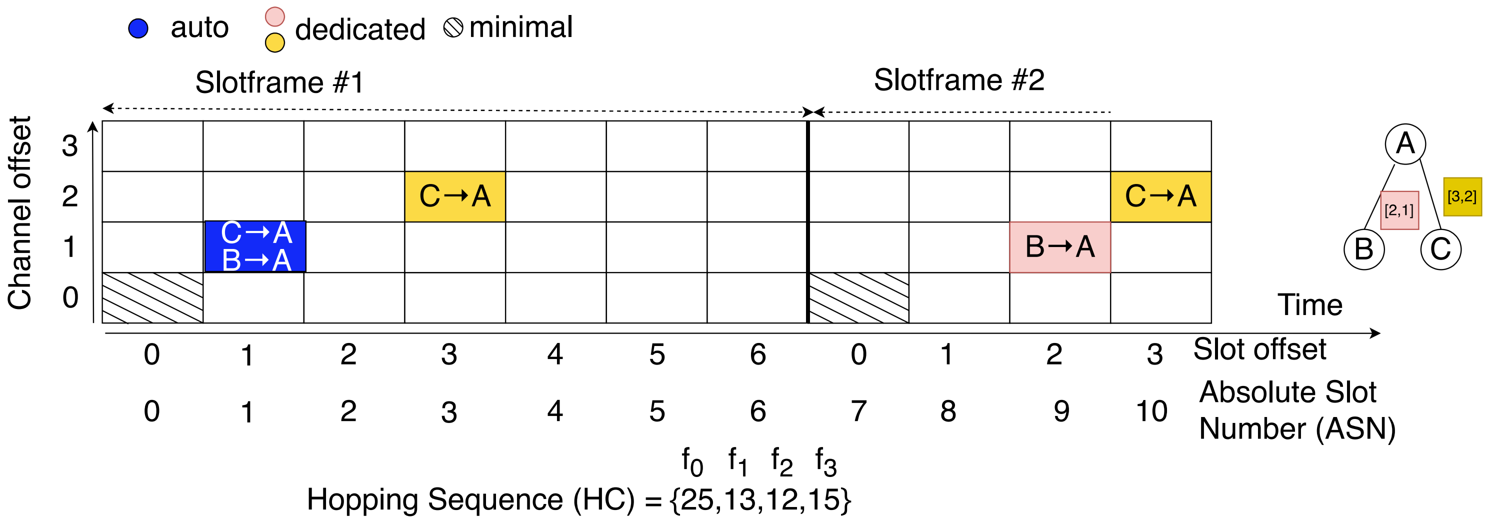
- Hopping Sequence (HS) is a configurable, unordered list of channels to be used for communication
  - Advertised via Enhanced Beacons (EBs) on the minimal cell
  - IEEE 802.15.4 has 16 Channels (11 to 26)



Channel Hopping

- C has a transmit cell to node A on a channel offset 2, translated by both nodes into a frequency f



$$f = HC\left[(ASN + channelOffset) \bmod |HC|\right]$$

- When a new network is created, the *ASN* is initialized to 0 and increments throughout the network lifetime

Which channels are used for data transmission from C to A in slotframe #1 and slotframe #2?

Channel Hopping contd.

- For a given cell
  - same channel offset, but with different ASN
  - this results in different frequency from the HC
- How to ensure all frequencies from the HC are used?
  - HC and slotframe lengths are coprime
- Time Synchronization among nodes is crucial (out of the scope of this lecture)

Is TSCH channel hopping robust enough?

Blind Channel Hopping

- Mainly designed to work in a **distributed** manner with a very simple algorithm
- Compared to Cellular networks
  - Full control is done by the base station (**centralized** approach)
    - Channels are monitored continuously
    - Dynamic reallocation of cells

TSCH Open Issues

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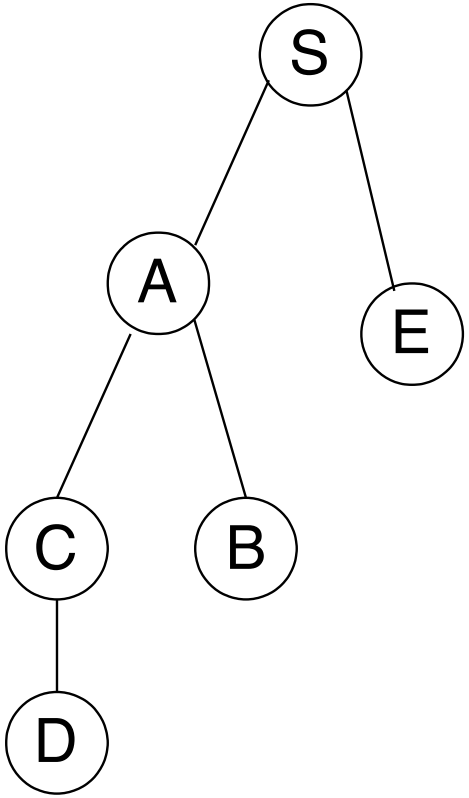
- Scheduling: trade off between throughput, delay and power consumption
    - Centralized vs. distributed
    - Time slot length, slotframe size
    - Spectrum sensing and blacklisting of channels
    - Number of cells per link
        - Avoiding internal collisions
        - Adaptive cell allocation (traffic monitoring)
- Synchronization
- Scalability
- Deployment
- …

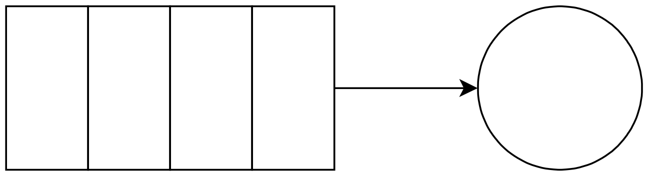
End-to-End Delay

- Transmission
- Propagation
- Processing
- Queuing



Queue Model

- Single server
- Unlimited buffer
- Arrival rate λ in packets per slotframe (pkt/sf)
  - Periodic arrivals
- Service rate μ in cells per slotframe



Are these scenarios valid?

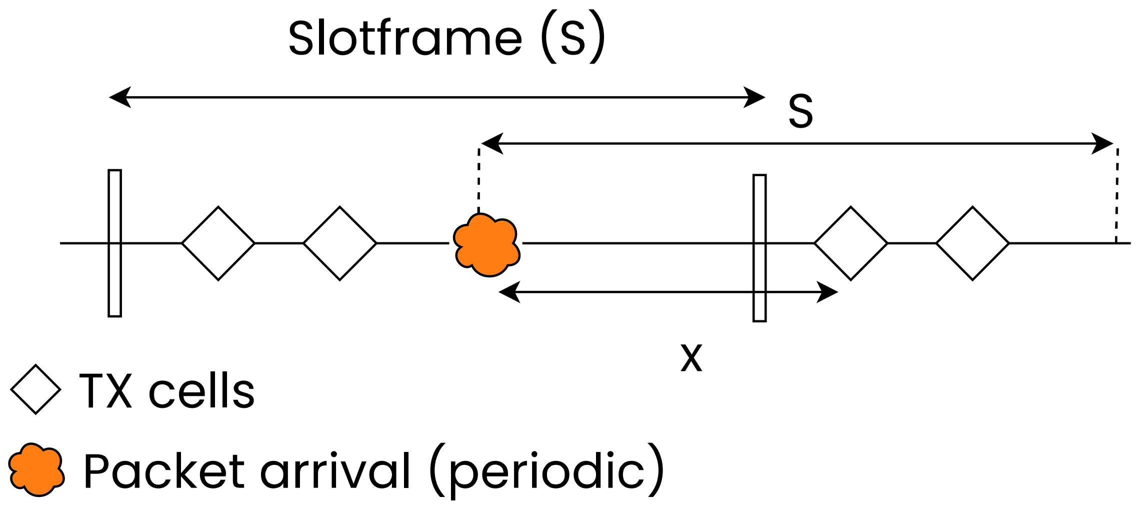
- $\boldsymbol{\lambda = 1.3, \mu = 2}$
- $\boldsymbol{\lambda = 2.3, \mu = 2}$
- $\boldsymbol{\lambda = 1.3, \mu = 1.6}$

Service Time Modeling

- Packet arrives in an empty queue
- The Cumulative Distribution Function (CDF) of the service time is

$$F_W = (W < x) = 1 - \left(1 - \frac{x}{S}\right)^{\mu},$$

- S is the slotframe length in time slots
- $0 < W < S$



Run cell A1 of the Jupyter Notebook.