DTU

Networked Embedded Systems

Week 12: Industrial Embedded Networks

Xenofon (Fontas) Fafoutis
Associate Professor
xefa@dtu.dk
www.compute.dtu.dk/~xefa

Requirements of (Industrial) Networked Embedded Systems

- Scalability
  - Supported number of embedded systems
- Throughput
  - Bytes received per second
- Reliability (Packet Delivery Ratio, PDR)
  - Number of packets received over packets sent
- Latency/Delay
  - Time interval from the time a packet is sent to the time packet received
- Jitter
  - Variability of latency/delay
- Time-sensitivity or determinism
  - Predictable/bounded latency and jitter
- Energy Efficiency and Consumption
  - All above need energy

Requirements of (Industrial) Networked Embedded Systems

- Scalability
  - Supported number of embedded systems
- Throughput
  - Bytes received per second
- Reliability (Packet Delivery Ratio, PDR)
  - Number of packets received over packets sent
- Latency/Delay
  - Time interval from the time a packet is sent to the time packet received
- Jitter
  - Variability of latency/delay
- Time-sensitivity or determinism
  - Predictable/bounded latency and jitter
- Energy Efficiency and Consumption
  - All above need energy

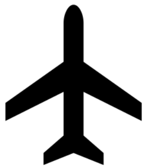
Trade-offs: There is no solution that optimises all; we need figure out what we can afford to sacrifice

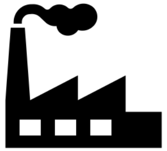
Industrial Embedded Networks

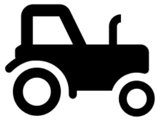
- Industrial Networks carry vital and often safety critical data
  - Tend to prioritise reliability and determinism over throughput and energy efficiency
  - Best-effort data may co-exist (e.g. vehicle sensor data vs entertainment)

- Common features
  - Schedule-based communication (avoid contention-based protocols)
  - Time synchronisation
  - Traffic prioritisation
  - Redundancy
  - Interference mitigation

- Examples
  - TSCH
  - TSN







Industrial Wireless Networks

- The 6TiSCH protocol stack
- A collection of IEEE/IETF standards
- Aiming at industrial wireless networks that require high reliability and deterministic delay/jitter
- Main components
  - RPL
  - IPv6
  - 6top
  - IEEE 802.15.4 TSCH

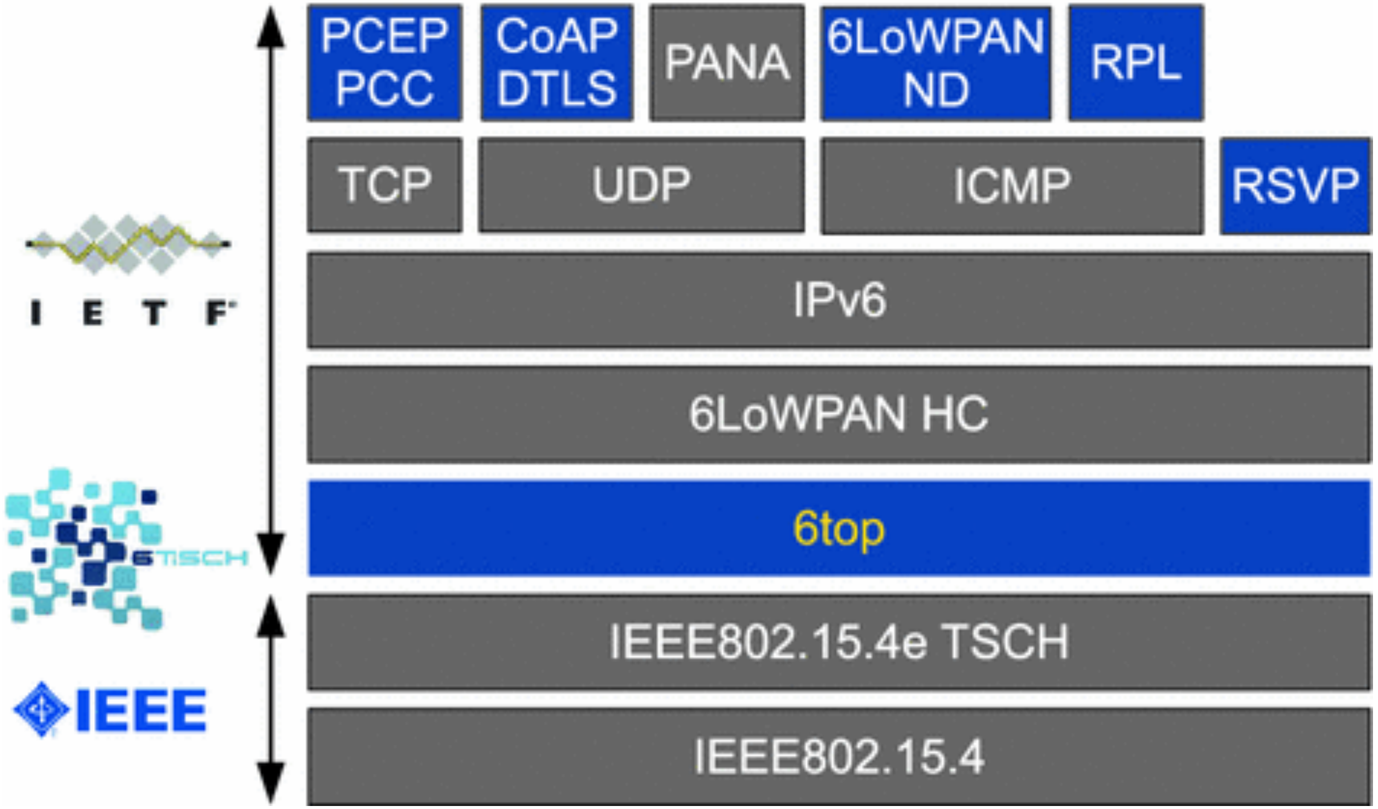


Image source: https://doi.org/10.1007/978-3-319-04223-7_5

IEEE 802.15.4 PHY

- A low-power wireless standard for Low-Rate Wireless Personal Area Networks (LR-WPANs)
  - Supports two ISM Bands (2.4 GHz, sub-GHz)
  - 250 kbps data rate @ 2.4 GHz
  - 127-byte packets
  - 16 channels @ 2.4 GHz
    (+ 1 channel @ 868 MHz in Europe)
  - Supports encryption/authentication

- Used in smart home/city/* wireless networks (Thread, Zigbee)

- Used in industrial wireless networks (6TiSCH)

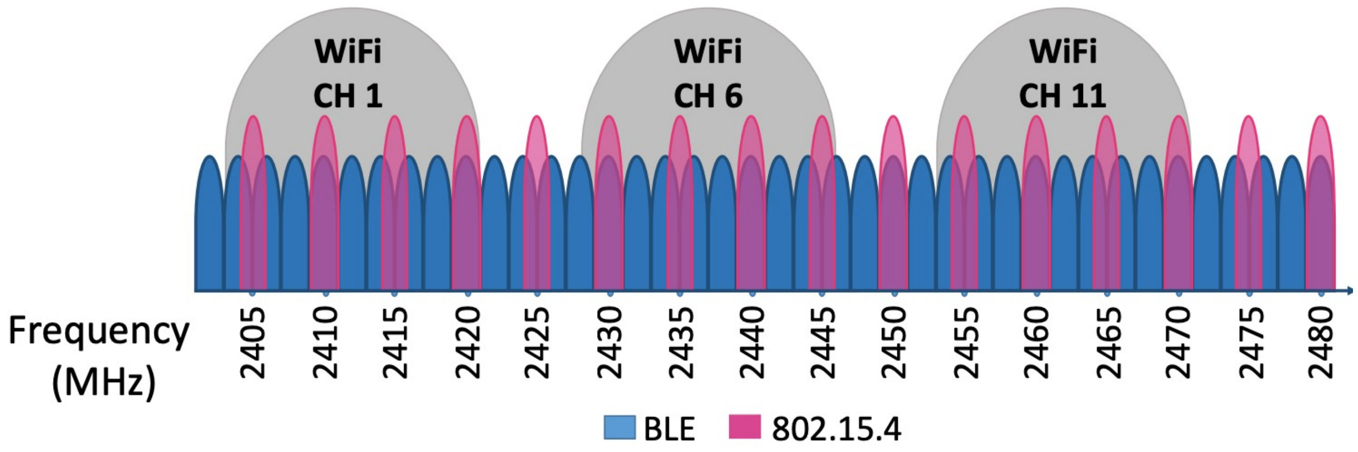


Image source: https://doi.org/10.1109/PIMRC.2017.8292262

IEEE 802.15.4 MAC

- Traditional IEEE 802.15.4-2011 MAC
  - Based on two classes of devices (asymmetric resources)
  - Full-Function Devices (FFD): Coordinator, frame forwarder
  - Reduced-Function Devices (RFD): Simple, energy-preserving
  - Supports contention-based (CSMA/CA) and contention-free (GTS) communication

- IEEE 802.15.4e MAC Enhancements
  - Enhanced MAC protocols for industrial applications
  - DSME (Deterministic and Synchronous Multi-channel Extension)
  - LLDN (Low Latency Deterministic Network)
  - TSCH (Time Slotted Channel Hopping)

IEEE 802.15.4 TSCH

- TSCH (Time-Slotted, Channel Hopping)
  - A MAC protocol based on the IEEE 802.15.4 PHY

- TSCH supports
  - Multi-hop networks (line, tree, mesh) topologies
  - Radio duty cycling in all devices

- TSCH provides
  - Very high reliability (99.99%+ PDR)
  - Interference avoidance
  - Predictable delay/jitter/energy consumption
  - Time synchronisation (10ms)

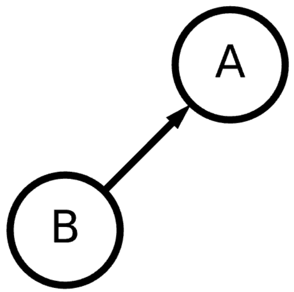
TSCH Mechanics

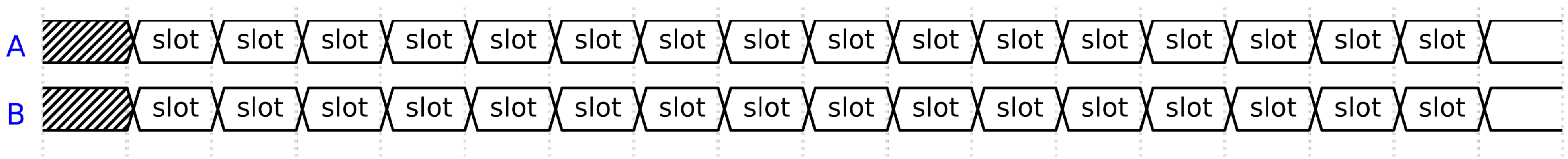
- A combination of TDMA and FDMA
- Time-Slotted: Synchronous schedule-based channel access
  - Predictable channel access, possible to eliminate collisions
- Channel Hopping: Use of multiple frequency channel in a rotating fashion
  - Resilience to external interference
- TSCH traces its roots to older industrial wireless standards
  - Time Synchronized Mesh Protocol (TSMP, 2006) by Dust Networks (proprietary)
  - WirelessHART (2007) by the HART Communication Foundation
  - ISA100.11a (2009) by the International Society of Automation (ISA)

TSCH: Timeslots and Time Synchronisation

- Network-wide Time Synchronisation
  - All devices in a TSCH network are time synchronised with each other
  - Relative time synchronisation based on the implicit synchronisation technique

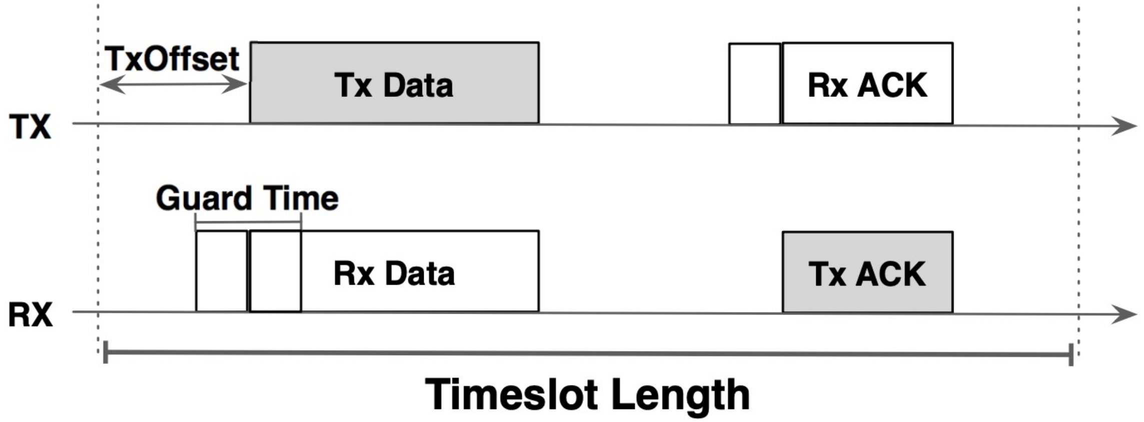
- Time is split into timeslots
  - Each slot is long enough to support:
    - Transmission of a frame of maximum size (~4 ms)
    - An acknowledgement (~0.35 ms)
    - The guard time (~2 ms)
    - Time required to switch from TX to RX mode, encryption/decryption
  - The duration of the timeslot is not imposed by the standard
    - Typical slot size is 10 ms
    - Some older radios are slow at switching from TX to RX mode and need 15ms





TSCH: Timeslot

- A timeslot defines a transmission opportunity
  - An actual frame transmission may not happen if there is nothing to transmit!
- The sender initiates the frame transmission at *TxOffset* after the beginning of the timeslot



- The receiver listens to the channel for the time defined by the *Guard Time*
  - The guard time is equally spaced around the expected transmission time to account for both positive and negative drift
  - If a preamble is captured within the guard time, the receiver stays on to capture the full frame
  - Otherwise, the receiver goes to sleep
- After a frame transmission, sender and receiver swap the modes of their radios for the ACK

Image source: https://doi.org/10.1109/WF-IoT.2016.7845475

TSCH: Guard Time

- The guard time allows for a certain degree of synchronisation error
  - Periodic synchronisation is required

- Longer Guard Time
  - More robust to synchronisation errors
  - Less frequent synchronisation required
  - More idle listening, more energy consumption
  - Occupy the channel, bigger slots
  - Fewer slots per second, less data

- Ideally as short as possible, but long enough to maintain robust synchronisation

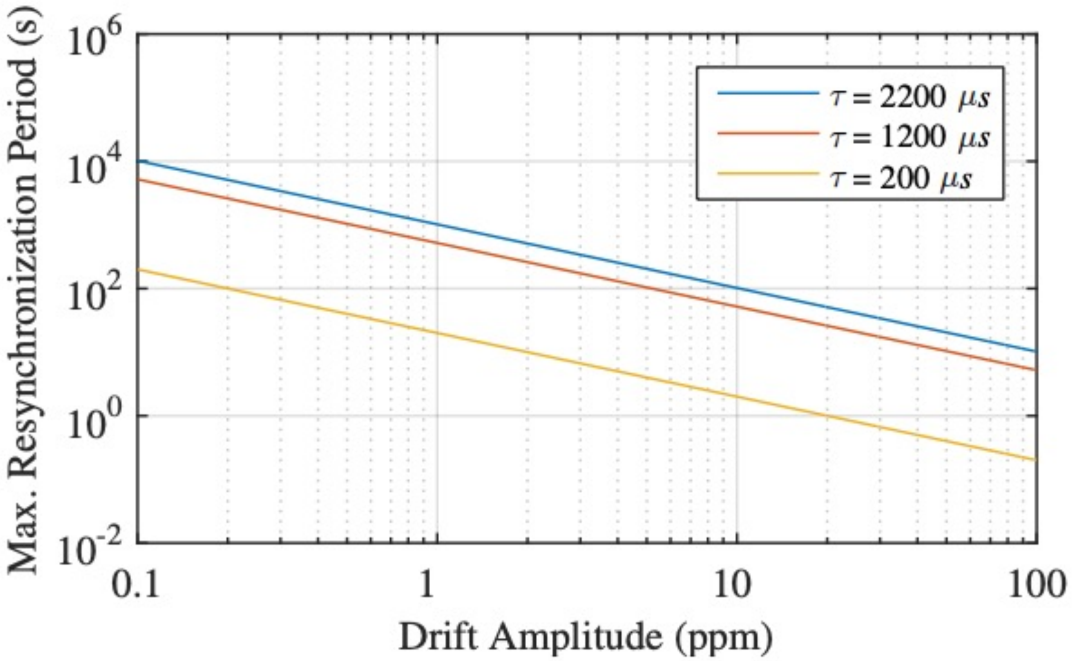
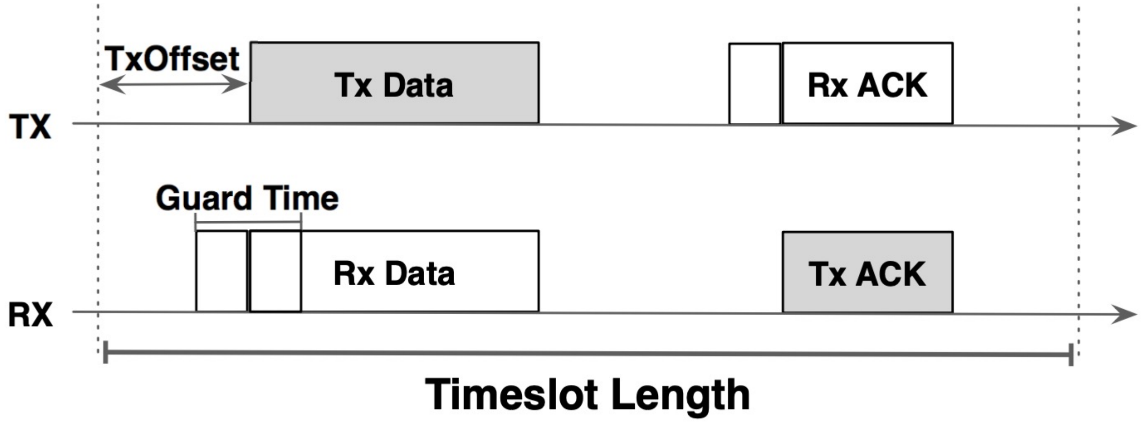


Image source: https://doi.org/10.1109/LCN.2016.042

TSCH: Frame-Based and ACK-Based Synchronisation

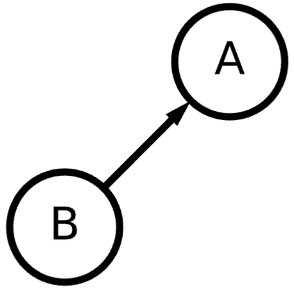


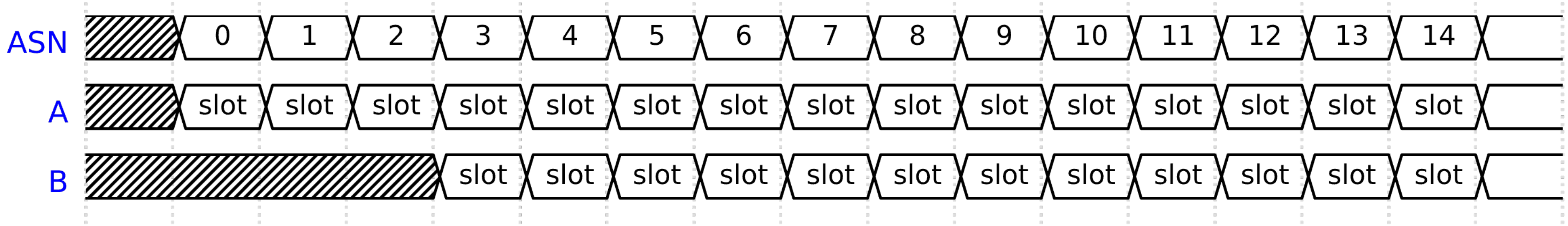
- TSCH uses implicit synchronisation with a neighbour on each frame transmissions
- The receiver calculates the difference between the expected and actual time of frame arrival
- In frame-based synchronisation, the receiver uses this offset to synchronise to the clock of the sender
- In ACK-based synchronisation, the receiver adds this offset in the acknowledgement frame and the sender uses it to synchronise to the clock of the receiver
- In the absence of data, devices need to exchange an empty *Keep-Alive* frame to re-synchronise
  - Significant overhead in applications that transmit very infrequently, e.g. smart metering

Image source: https://doi.org/10.1109/WF-IoT.2016.7845475

TSCH: Absolute Slot Number

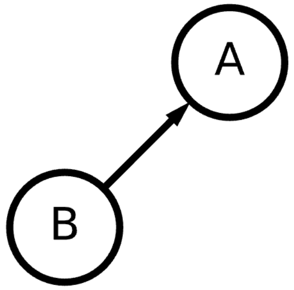
- A number that counts slots since the formation of the network
  - 5 bytes so that it can increment for hundreds of years without wrapping
- ASN Synchronisation
  - ASN is initialised to 0 by the device that forms the network
  - Devices learn the current value of ASN when they join the network
  - Since they are synchronised, all devices know the current value of ASN at any time



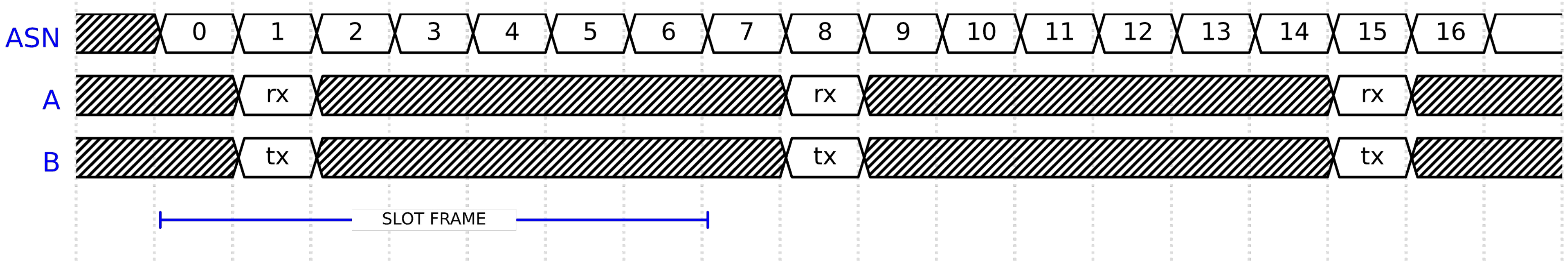


TSCH: Slot frame and Schedule

- Time slots are organised in a slot frame
  - A slot frame is a continuously repeating pattern of slots
  - Slot frame size (not defined by the standard, tailored to the application)
  - [slot offset] = [ASN] % [slot frame size]

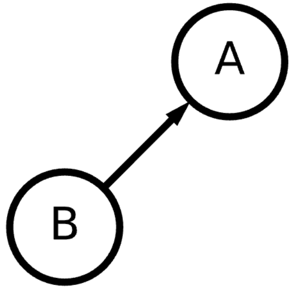


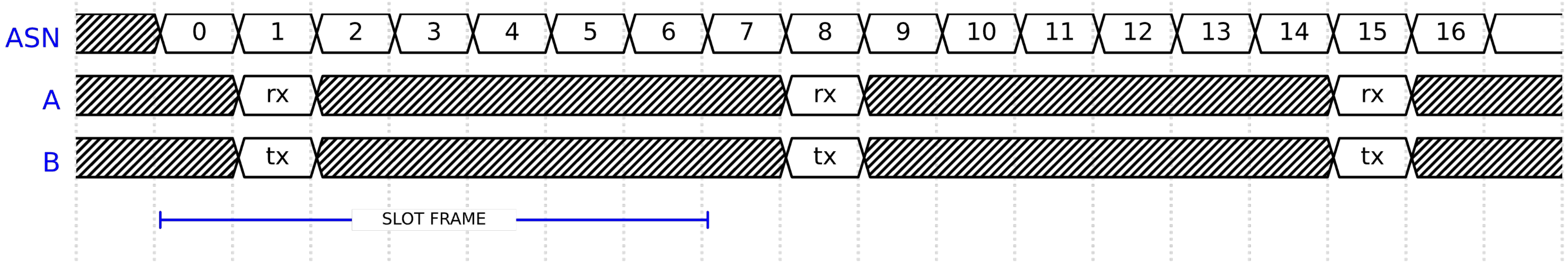
- Communication is based on a schedule, for example:
  - Slot frame size = 7
  - B transits to A in slot offset = 1



TSCH: The Schedule Controls Several Performance Metrics

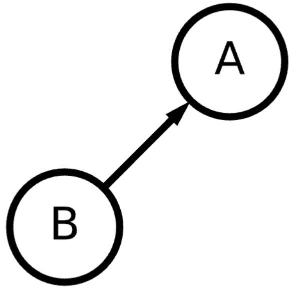
- Assuming timeslot size 10 ms and frame size 7…
- Link Capacity: 100 / 7 = 14.28 packets per second
- Energy Consumption: 1 / 7 = 14.28% radio duty cycle
- Latency: up to 7 x 10 ms = 70 ms

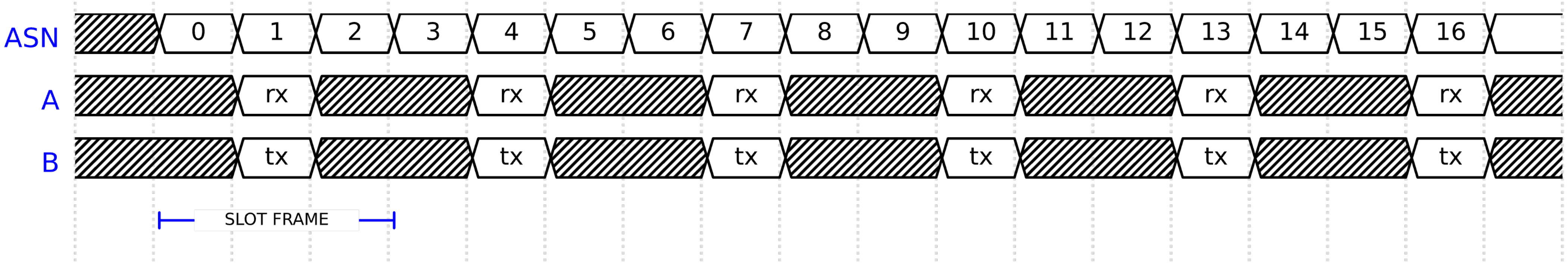




TSCH: Slot Frame Size

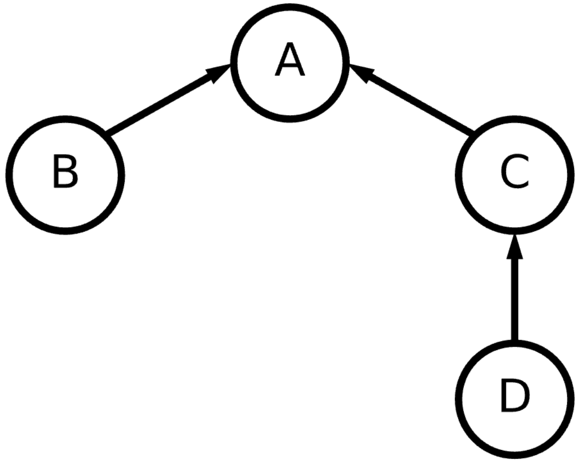
- Defines the number of idle slots in a frame
- Shorter slot frame size
  - More transmission opportunities -> higher capacity for data
  - More re-transmission opportunities -> higher reliability
  - Shorter average and worst-case latency
  - More unused slots -> worse energy-efficiency
  - Less room for other devices -> worse scalability

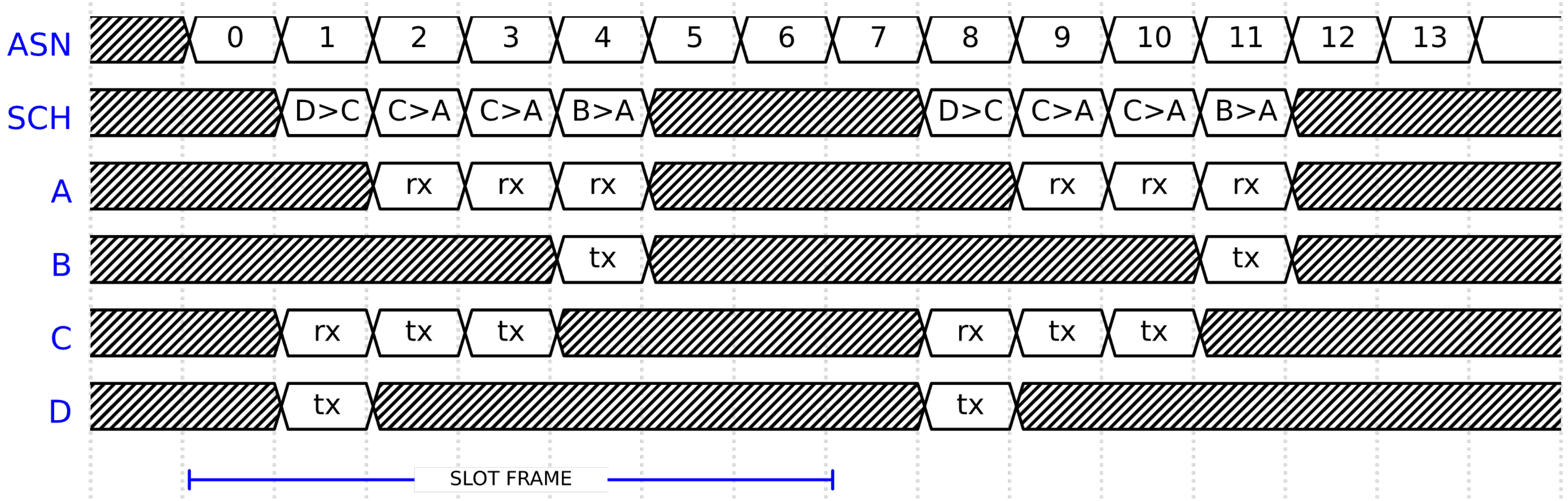




TSCH Schedule: Dedicated Slots

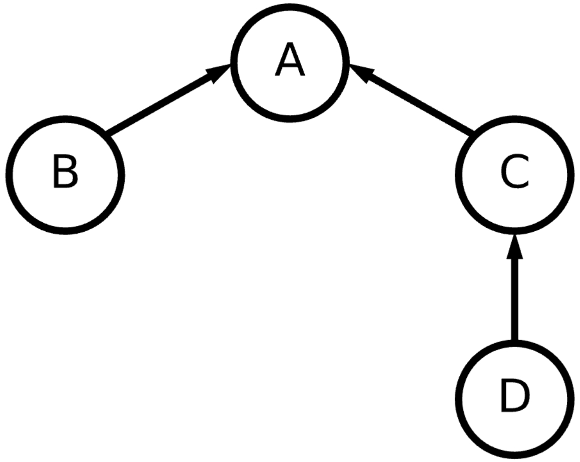
- In each slot, a device can transmit (Tx), receive (Rx), or sleep (idle)
- Dedicated slots (Contention-free)
  - Slot dedicated to a specific link
  - One assigned transmitter -> no collisions
  - Example: B>A, means B transmits (Tx) and A receives (Rx)

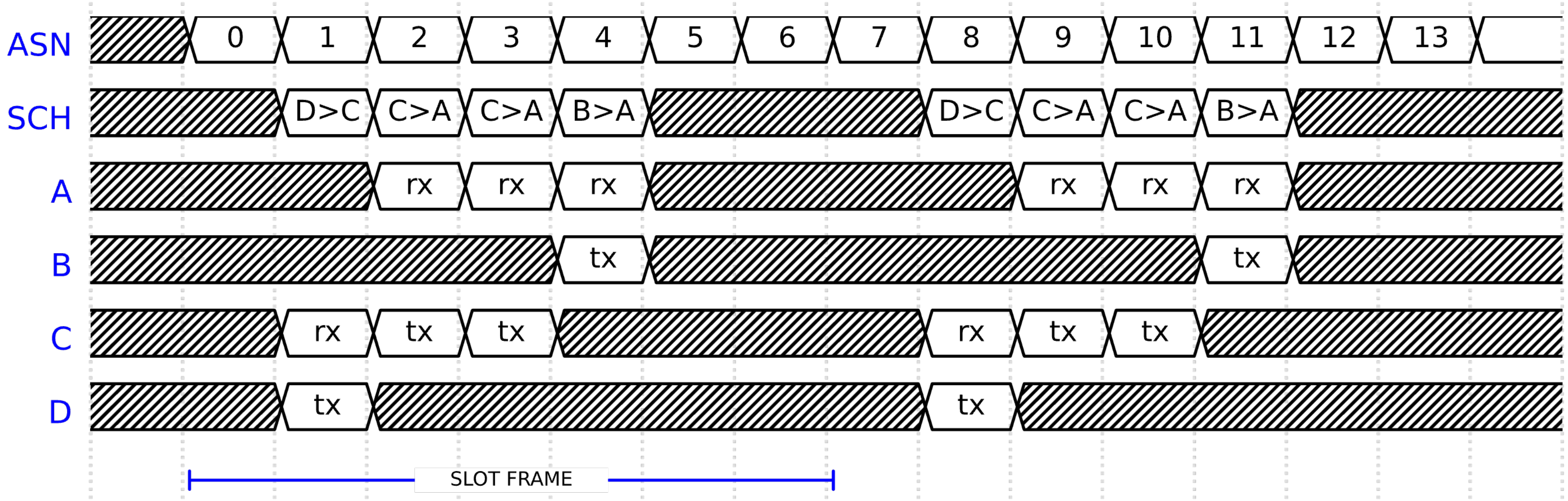




TSCH Schedule: How many slots?

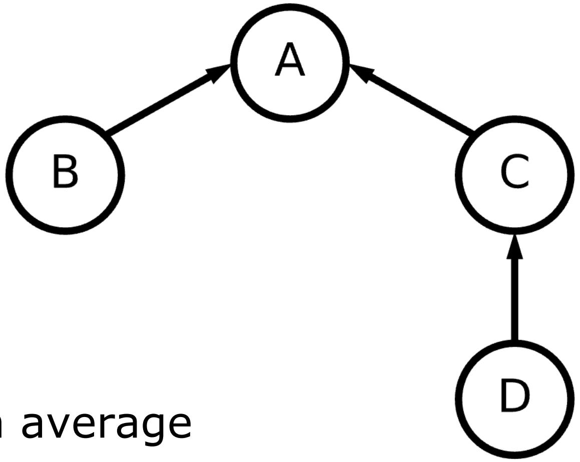
- Why did I allocate 2 slots per frame for link C>A?
- How many slots per frame I need generally?

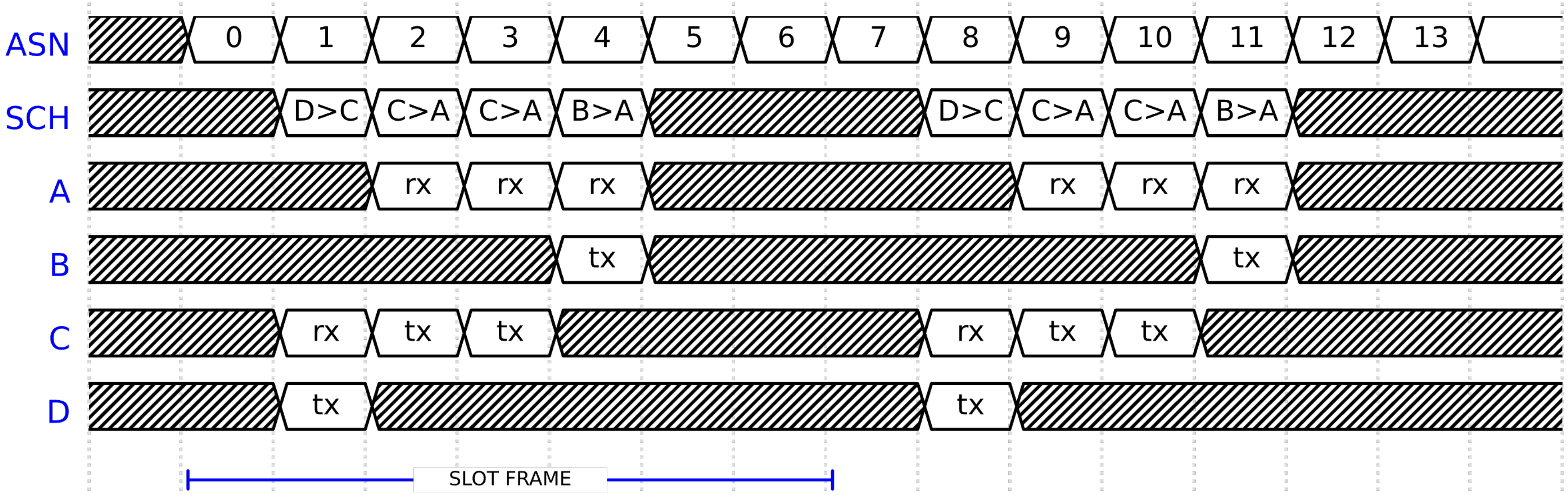




TSCH Schedule: How many slots?

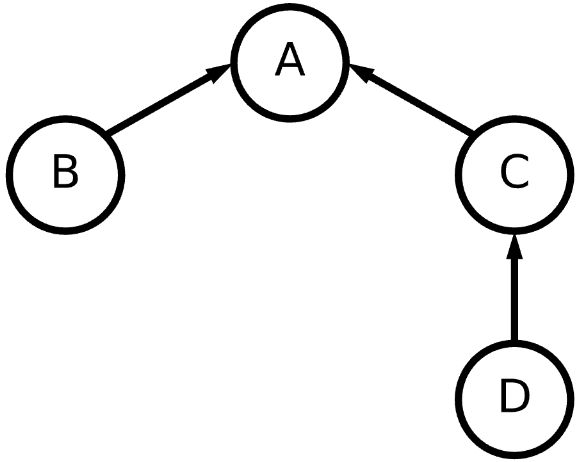
- Slots in the schedule should be able to have capacity for:
  - Packets generation rate by the transmitter
  - Packets forwarding rate by the transmitter
  - Retransmissions (ETX, Expected Transmission Count)
    - ETX = 1/p where p is packet reception probability
    - Example: if p=20%, I have to retransmit each packet 5 times on average

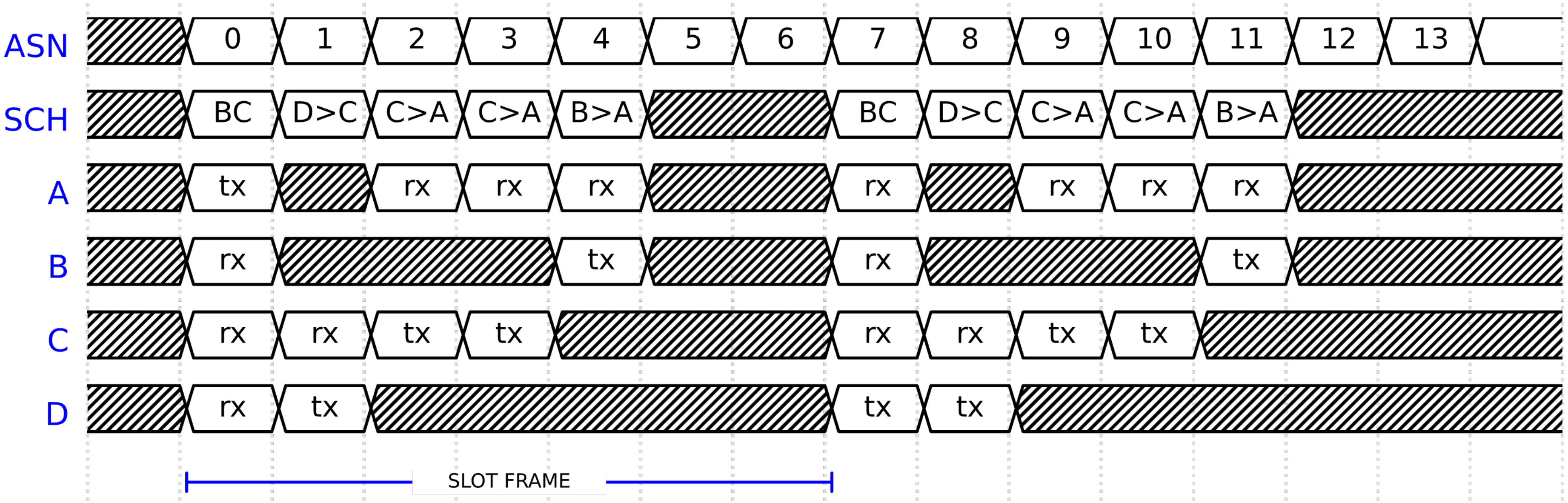




TSCH Schedule: Broadcast Slots

- Broadcast slots (every node active)
  - If I have something to broadcast, I transmit
  - If I have nothing to broadcast, I listen/receive
  - Typically, the first slot of the frame
  - Collisions may happen
  - Transmitters cannot receive broadcasts of others





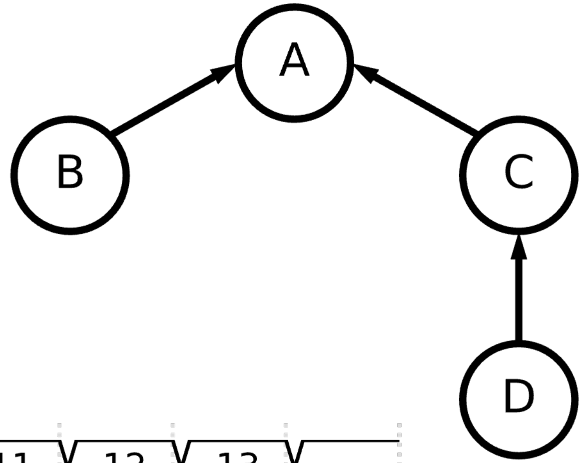
TSCH: Slots Are Limited

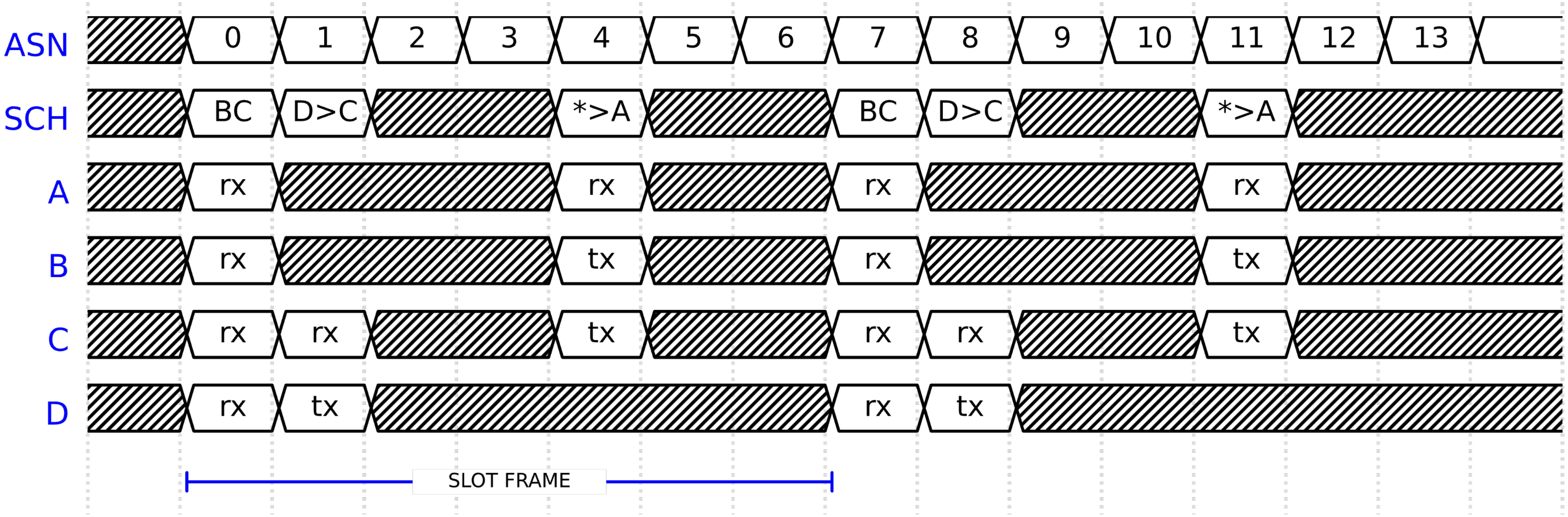
- Assuming a time slot of 10 ms, there are only 100 slots per second
  - Permit for maximum 100 packets per second

- What can do if we run out of slots, and we want to support more devices, traffic or retransmissions?

TSCH Schedule: Shared Slots

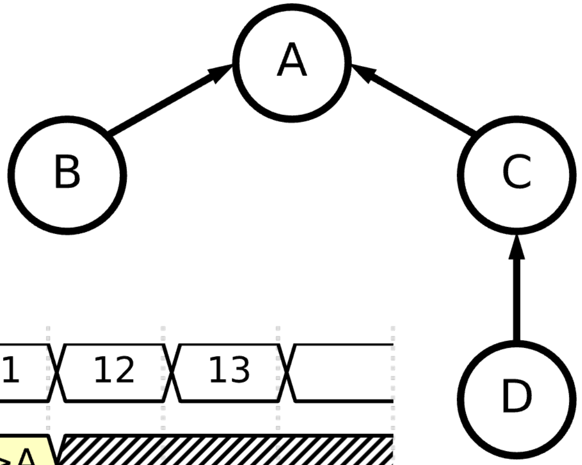
- Shared slots (Contention-based)
  - Slot assigned to multiple transmitters
  - Collisions are possible, need CSMA/CA

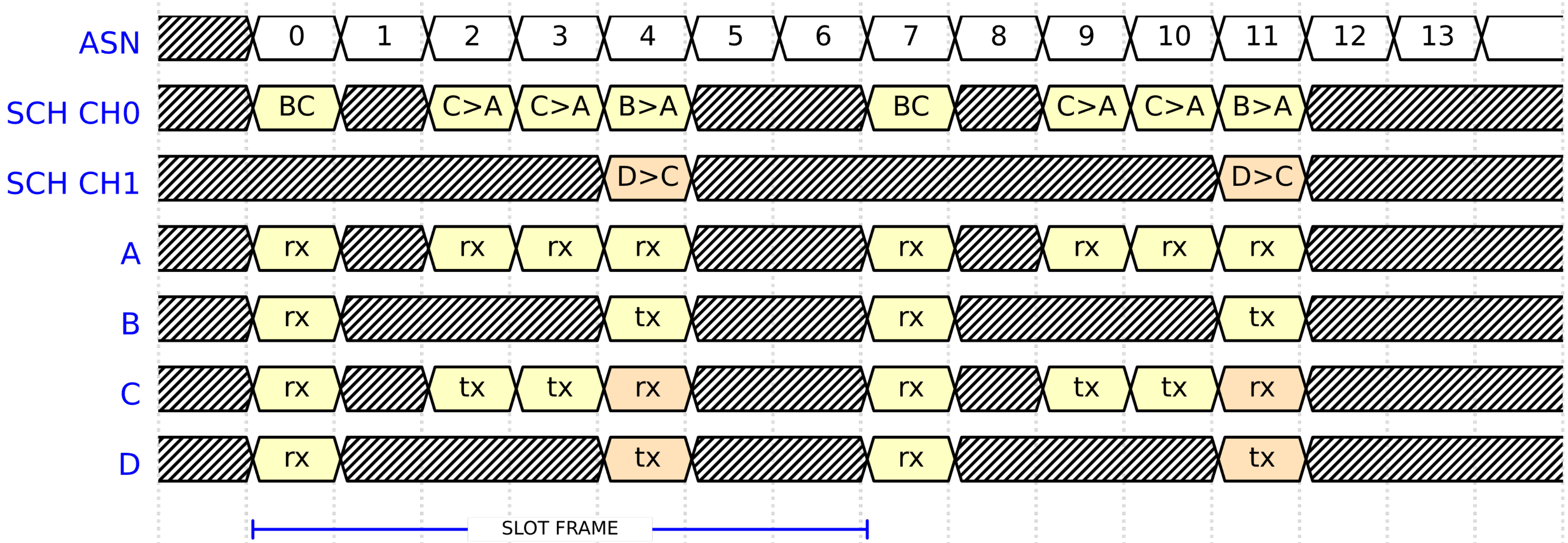




TSCH Schedule: Multiple Channels

- Parallel transmissions are possible in different channels
  - A transmitter and receiver can only tune to one specific channel





Some Channels are better than others

- IEEE 802.15.4 use retransmissions to combat channel errors

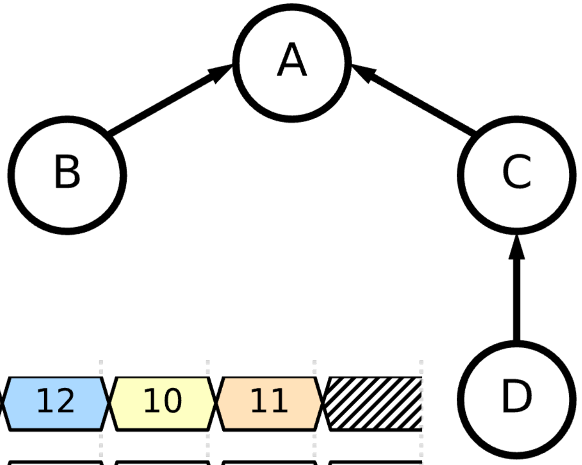
- Interference and fading errors are correlated in time
  - If a channel experiences a lot of interference now, it is very likely to experience a lot of interference in the next frame

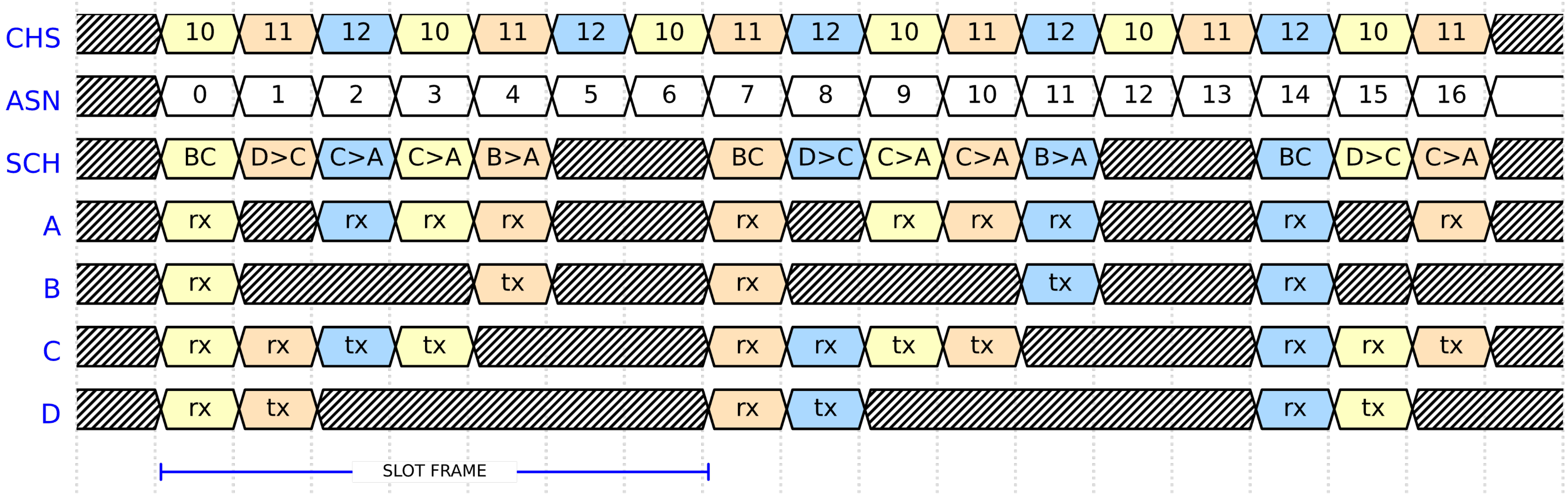
- Yet, interference and fading of different channels are often uncorrelated
  - If a channel experiences a lot of interference now, it is very likely that another channel will not be affected by the same source of in the next frame

- Idea: Change channels for each retransmission to enhance reliability

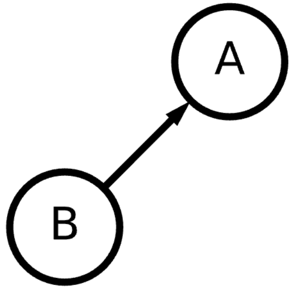
TSCH: Channel Hopping

- Channels change following a pre-agreed pseudo-random order
- All nodes agree on a Channel Hopping Sequence (CHS), e.g. 10-11-12
- Channel = CHS[index], where index = ASN mod len(CHS)

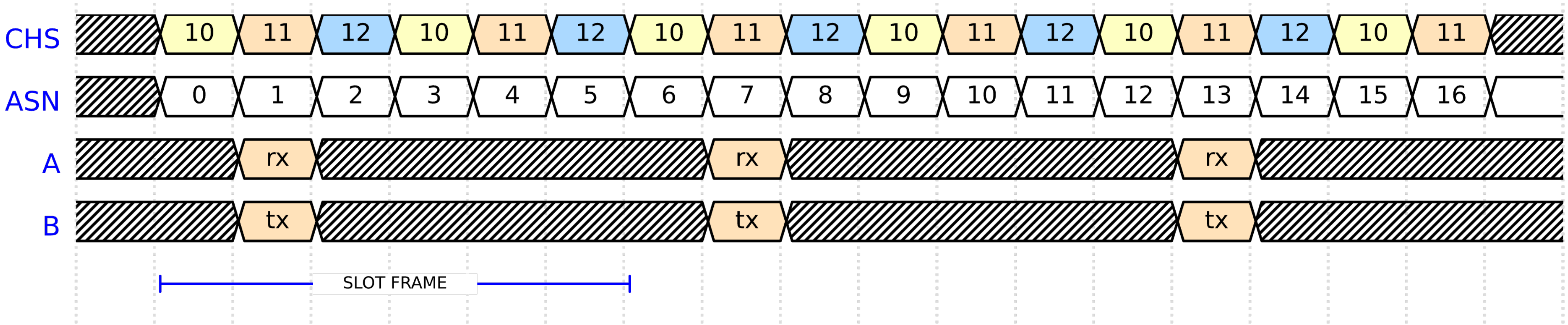




Slot Frame Size vs Channel Hopping Sequence Size

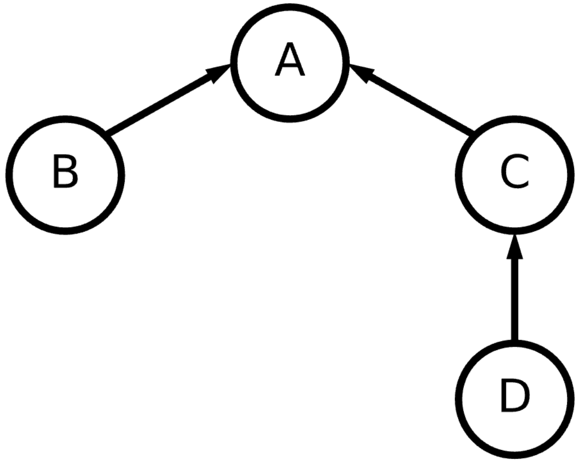


- The Slot Frame Size and CHS size must be relatively prime
  - Their highest common factor should be 1
- Otherwise, there is no channel hopping!
- Example: frame size is 6 and CHS size is 3



The TSCH Schedule

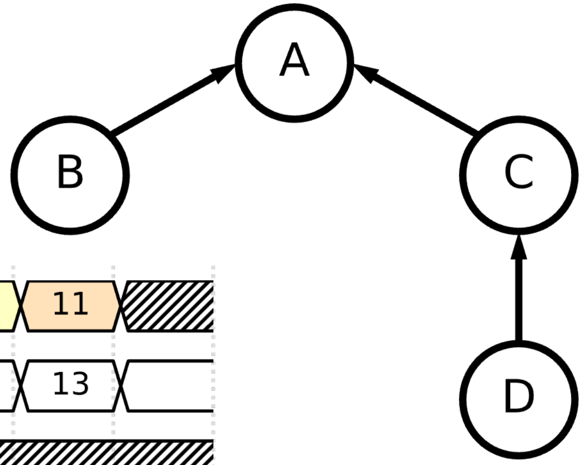
- A N-by-M table where N is the slot frame size and M is the CHS size
  - Each column represents a slot offset (SO)
  - Each row represents a channel offset (CHO)
- Channel = CHS[index], where index = (ASN + CHO) mod len(CHS)

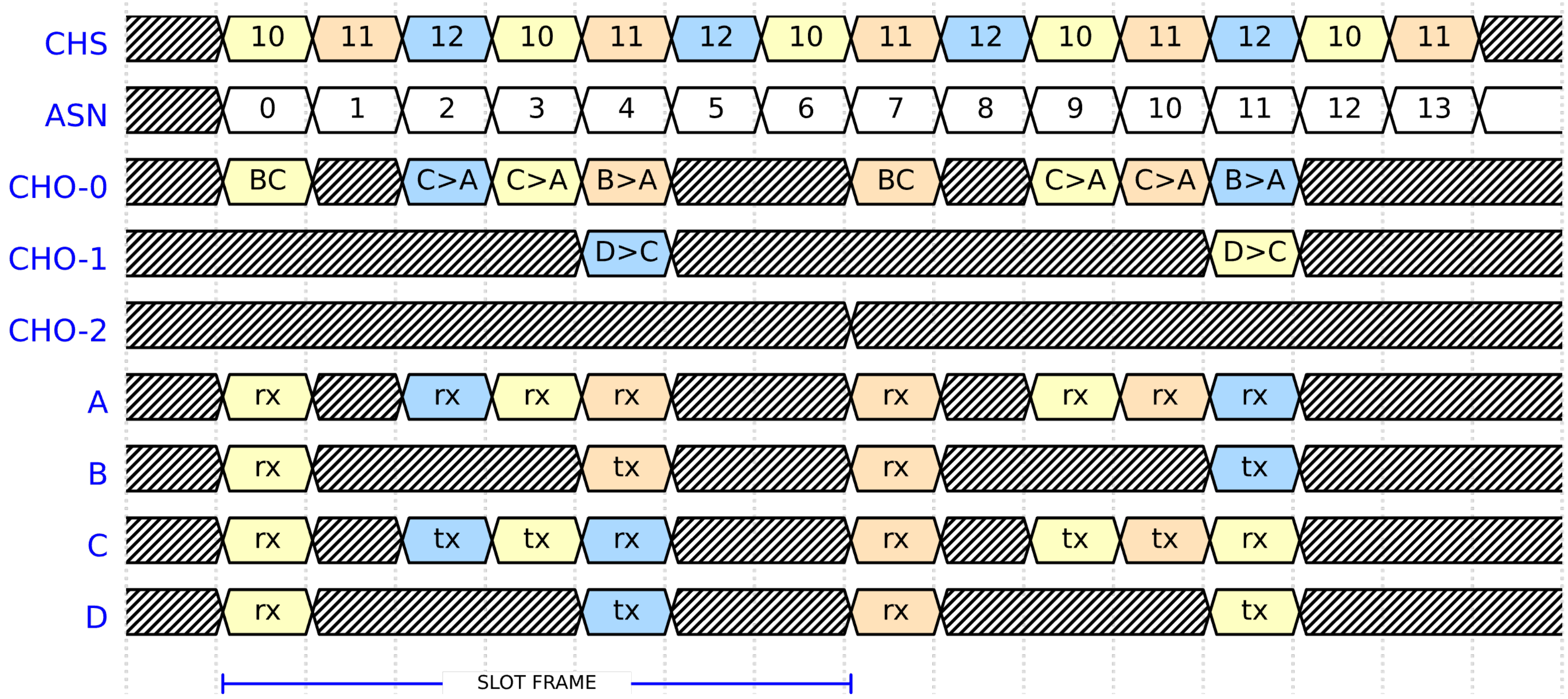


CHO \ SO	0	1	2	3	4	5	6
0	BC		C > A	C > A	B > A		
1					D > C		
2							

TSCH Schedule

- Channel = CHS[index], where index = (ASN + CHO) mod len(CHS)





Channel Selection

- Consider a channel with a lot of interference
  - Using as the only single channel is very bad
  - Using it as part of the CHS is better, but inefficient
- How can we select which channels to use?
  - Some channels are more busy than others
  - This quality of the channels changes over time
- Adaptive Channel Selection
  - Measure the quality of channels
  - Update metrics with statistics
  - Select the best channels (blacklist/whitelist)
  - Distribute changes to the channel hopping sequence

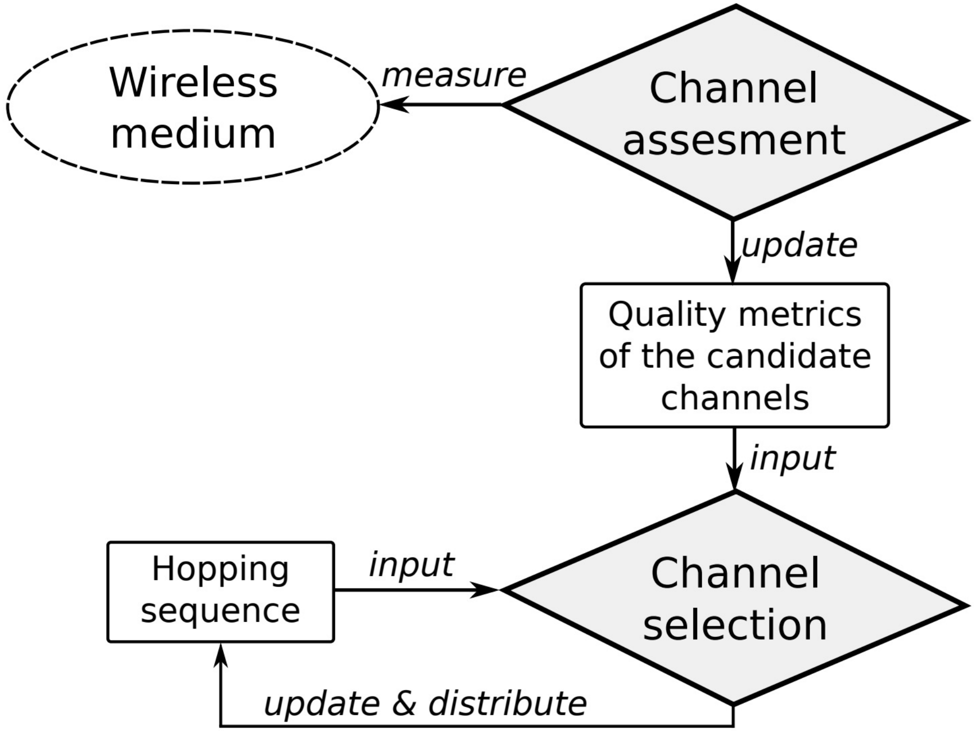
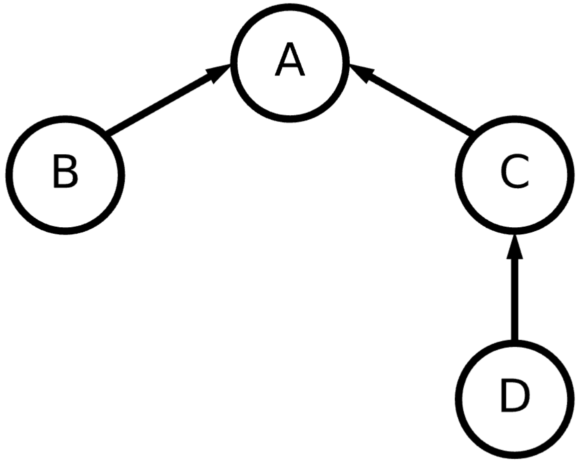


Image source: https://doi.org/10.1109/GIOTS.2017.8016246

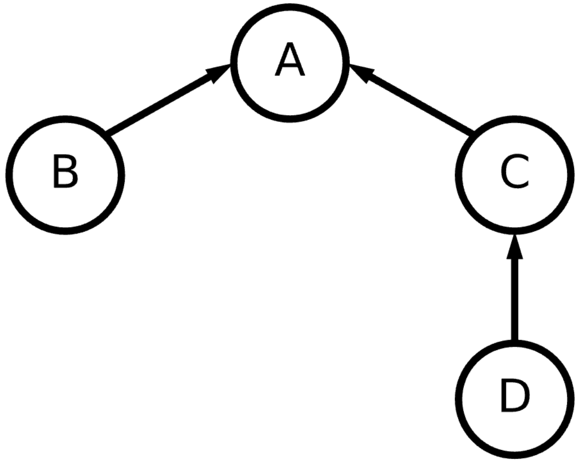
TSCH Scheduler

- A TSCH Scheduler is an algorithm that determines the TSCH schedule
- The Scheduler is not defined by the standard (flexible)
- Schedules are tailored to the use case
- Types of TSCH Scheduling
  - Static Scheduling
  - Dynamic Scheduling
    - Centralised Scheduling
    - Distributed Scheduling
    - Autonomous Scheduling



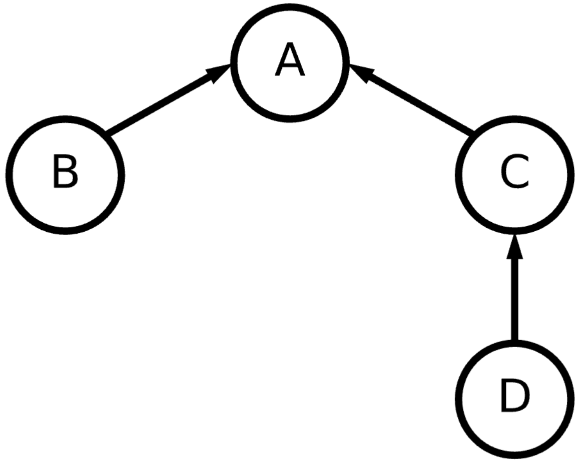
Static Scheduling

- Schedule is hardcoded on the firmware of the devices
- A static schedule can be handcrafted or algorithmically derived
- Makes sense only in relatively static TSCH networks
  - No. of devices, topology, traffic patterns, expected retransmissions



CHO \ SO	0	1	2	3	4	5	6
0	BC		C > A	C > A	B > A		
1					D > C		
2							

Dynamic Scheduling



- A minimal schedule with shared slots is defined
  - Hardcoded or installed when joining the network

- Dedicated slots are allocated dynamically

- Centralised Scheduling
  - The root node collects information about the nodes via these shared slots
  - Having the global picture of the network, it allocates dedicated slots to specific links
  - Such decisions can be determined using machine learning or reinforcement learning

- Distributed Scheduling
  - Neighbouring nodes exchange information and agree on which slots to use between them

IETF Minimal Schedule and 6top

- Minimal Schedule
  - One broadcast slot in offset (0,0)
  - The slot frame size and channel sequence size is undetermined
  - Hardcoded or installed when joining the network

CHO \ SO	0	1	2	3	4	5	…
0	BC						
1							
…							

THE COMMANDS SUPPORTED BY THE 6TOP PROTOCOL (6P)

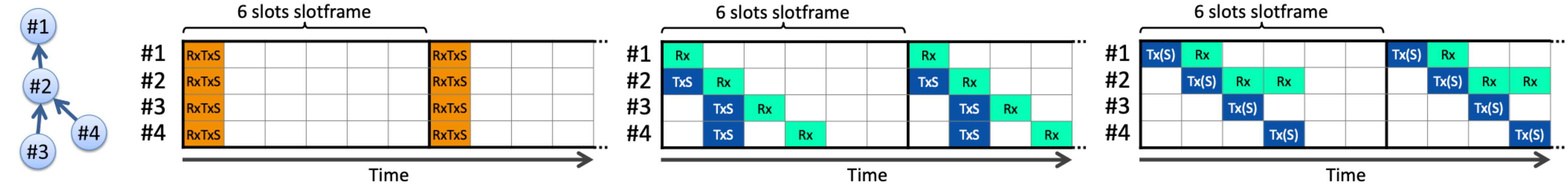
Command	Code	Description
ADD	1	Add cell(s) between the two neighbors. The CellOptions bitmap indicates the type of cell(s) to add.
DELETE	2	Delete cell(s) from the schedule.
RELOCATE	3	Relocate cell(s) in the schedule. Used to handle schedule collisions.
COUNT	4	Count the cells with a particular CellOptions.
LIST	5	List the cells with a particular CellOptions.
SIGNAL	6	Placeholder for SF-specific commands.
CLEAR	7	Clears all cells between the two neighbors. Possibly used to handle schedule inconsistencies.

- 6top (6TiSCH Operation Sublayer Protocol)
  - A protocol to exchange messages for distributed scheduling

Image source: https://doi.org/10.1109/COMST.2019.2939407

Autonomous Scheduling

- Each node derives and changes its schedule autonomously
  - No need to exchange messages
- Shared slots are used for the routing protocol to determine parent nodes
  - Nodes autonomously determine when to transmit/receive using routing information
  - Devices hash the Node ID or MAC address (of sender or receiver) modulo frame size to determine which slot to use
- Orchestra is a widely used autonomous scheduler (albeit not a standard)



(a) Topology (b) Common Shared Slot (c) Receiver-based Shared Slot (d) Sender-based (Shared) Slot

Image source: https://doi.org/10.1145/2809695.2809714

Joining a TSCH Network

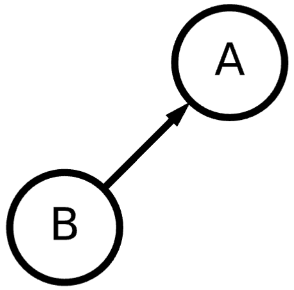
- How does a new device joins a TSCH network?

- A new device that wants to join a TSCH network:
  - Does not know the schedule (unless static scheduling is used)
  - Does not know the current ASN
  - Does not know when the beginning of a frame/slot is (not in sync)

- Enhanced Beacon (EB)
  - Devices of the TSCH network periodically broadcast an EB to advertise the network
  - EB includes the current ASN and (part of) the schedule

- The joining device scans the wireless medium for an EB but without knowing the time and channel of the transmission

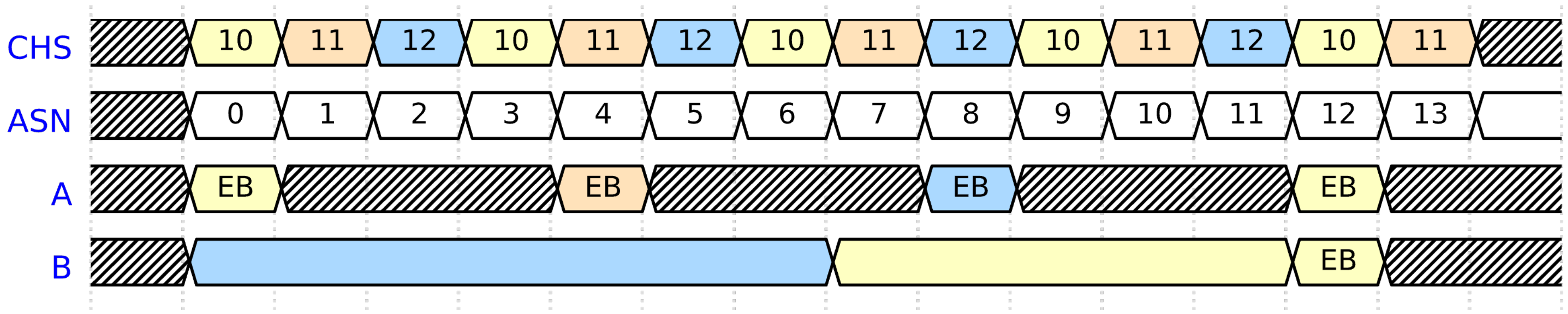
Searching for an EB packet



- The joining node scans sequentially all the channels until it receives an EB
  - If the CHS is fixed, the joining node needs to search only those channels
  - Otherwise, it needs to search all 16 channels

- Upon the reception of the first EB, the joining node keeps scanning for a potentially better parent until a timeout or a maximum number of candidate parents is reached

- The joining process is notoriously slow and inefficient
  - But often considered insignificant in static TSCH networks as it ideally happens just once



Industrial Wired Networks

- IEEE 802.1Q
  - Supports Virtual LANs (VLAN) over Ethernet (IEEE 802.3)
  - VLAN Tagging with 8 priority classes

- Time-Sensitive Networking (TSN)
  - A set of extensions on top of IEEE 802.1Q

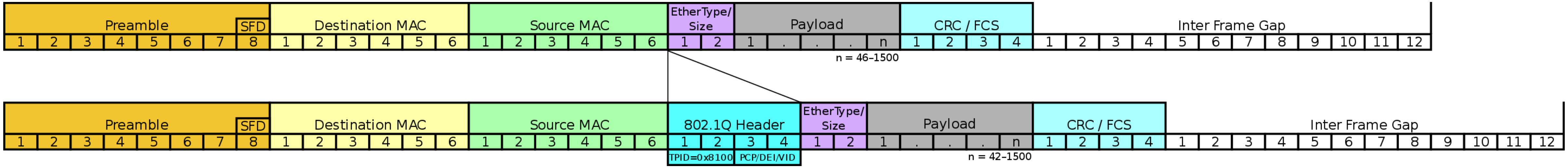


Image source: Wikipedia

Time Sensitive Networking (TSN)

- IEEE 802.1AS Timing and Synchronization for Time-Sensitive Applications
  - Precise time synchronisation based on PTP

- IEEE 802.1Qbv Enhancements to Traffic Scheduling: Time-Aware Shaper (TAS)
  - Synchronised TDMA-based medium access
  - Time is organised in repeating cycles of time slices
  - Time slices can be allocated to specific VLAN priorities for exclusive access
  - Time-critical traffic can be separated from non-critical background traffic

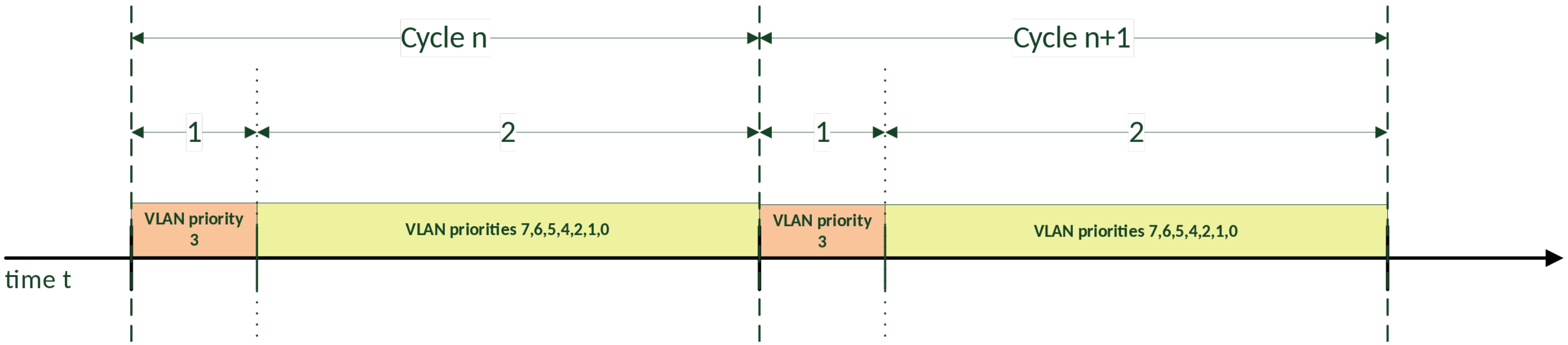


Image source: Wikipedia