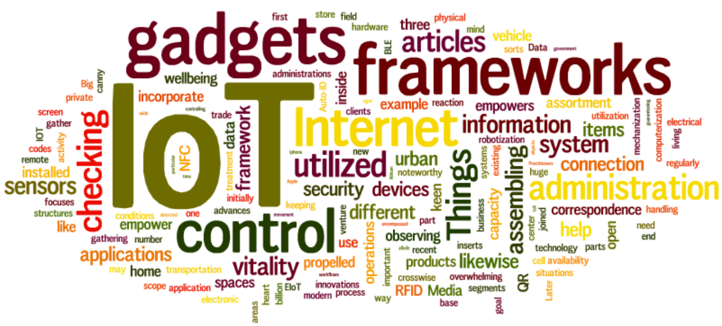
CS578: Internet of Things

IEEE 802.15.4e

Standard: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6471722
Survey Article: https://www.sciencedirect.com/science/article/pii/S0140366416301980



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Limitations of 802.15.4 MAC

- Unbounded latency
  - Both BE and Non-BE mode use CSMA-CA
  - No bound on maximum delay to reach destination
- Non-reliable communication
  - Very low delivery ratio due to the inefficiency of CSMA-CA
- No protection against interferences/multipath fading
  - Due to usage of single channel
- Powered relay nodes in multi-hop network
  - Relay nodes keep their radio active always.
  - Results in complex synchronization and beacon scheduling in BE mode
  - Consume large energy

- So, 802.15.4 is unsuitable for many critical scenarios
  - when applications have stringent requirements

Requirements of Critical Applications

- Timeliness
  - Deterministic latency for packet delivery
- Reliability
  - Wire-like reliability may be required, e.g., 99.9% or better
- Scalability
  - Large network size
- Energy Efficiency
  - Target battery lifetime: 5 years, or more

Introduction to 802.15.4e

- IEEE 802.15 Task Group 4e was created in 2008
    - To redesign the existing 802.15.4 MAC
- IEEE 802.15.4e MAC Enhancement Standard document approved in 2012
    - Contains idea from existing WirelessHART and ISA 100.11.a
        - Time slotted access
        - Shared and dedicated slots
        - Multi-channel communication
        - Frequency hopping
    - Introduce **five** MAC behaviour modes to support specific applications
    - General functional enhancements
        - Not tied to any specific application domain

MAC behaviour modes

- Time Slotted Channel Hopping (**TSCH**)
  - Industrial automation and process control
  - Non-delay tolerant applications
- Deterministic and Synchronous Multi-channel Extension (**DSME**)
  - Industrial and commercial applications
  - Non-delay tolerant and delay tolerant applications
- Low Latency Deterministic Network (**LLDN**)
  - Star network
  - For single hop and single-channel networks
  - Provides very low latency

Cont..

- Asynchronous multi-channel adaptation (**AMCA**)
  - For large network such as smart utility networks, infrastructure monitoring
  - In large network single, common channel is not appropriate
  - Used in non Beacon-Enabled PANs
  - Device selects best link quality channel as its designated listening channel
  - Sender node switch to receiver designated listening channel to transmit its data
  - Beacon or Hello packet is used to advertise node designated listening channel

- Radio Frequency Identification Blink (**BLINK**)
  - For Application like item/people identification, location and tracking
  - Node communicate without prior association
  - No ACK required
  - Aloha protocol is used to transmit BLINK packet by "transmit only" devices

General Functional Enhancements

These are not tied to any specific application domain:

- **Low Energy (LE)**
  - Intended for applications that can trade latency for energy efficiency
  - Operate in very low duty cycle (<= 1%)
  - Appearing always on to the upper layers
- **Information Elements (IE)**
  - Mechanism to exchange information at the MAC sublayer
- **Enhanced Beacons (EB)**
  - Extension of the 802.15.4 beacon frames
  - Provide greater flexibility
  - Allow to create application-specific frames, by including relevant IEs

Cont..

- Multi purpose Frame
  - MAC wise frame format, differentiate on Information Elements (IE)

- MAC Performance Metric
  - To provide feedback on channel quality to upper layers
  - IP protocol may implement dynamic fragmentation of datagrams depending on the channel conditions

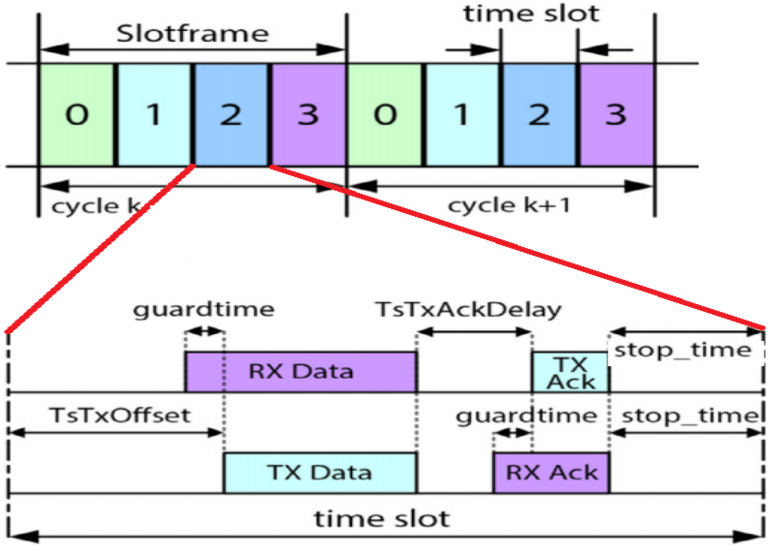
- Fast Association (FastA)
  - Allows a node to associate in a reduced amount of time
  - Critical application gives priority to latency over energy

TSCH Mode

- Topology independent
- Time slotted access
  - Increase throughput by eliminating collision among competing nodes
  - Predictable and bounded latency
- Multi-channel communication
  - More nodes exchange their frames at the same time
    - ✓ Increases network capacity
- Channel hopping
  - Mitigates the effects of interference and multi-path fading
    - ✓ Improve reliability

- So, **TSCH provides**
  - increased network capacity,
  - high reliability, and
  - predictable latency,
  - while maintaining very low duty cycles

Slotframe Structure



- TsTxOffset: Timeslot Transmission Offset
  = TsCCAOffset + TsCCA + TsRxTx

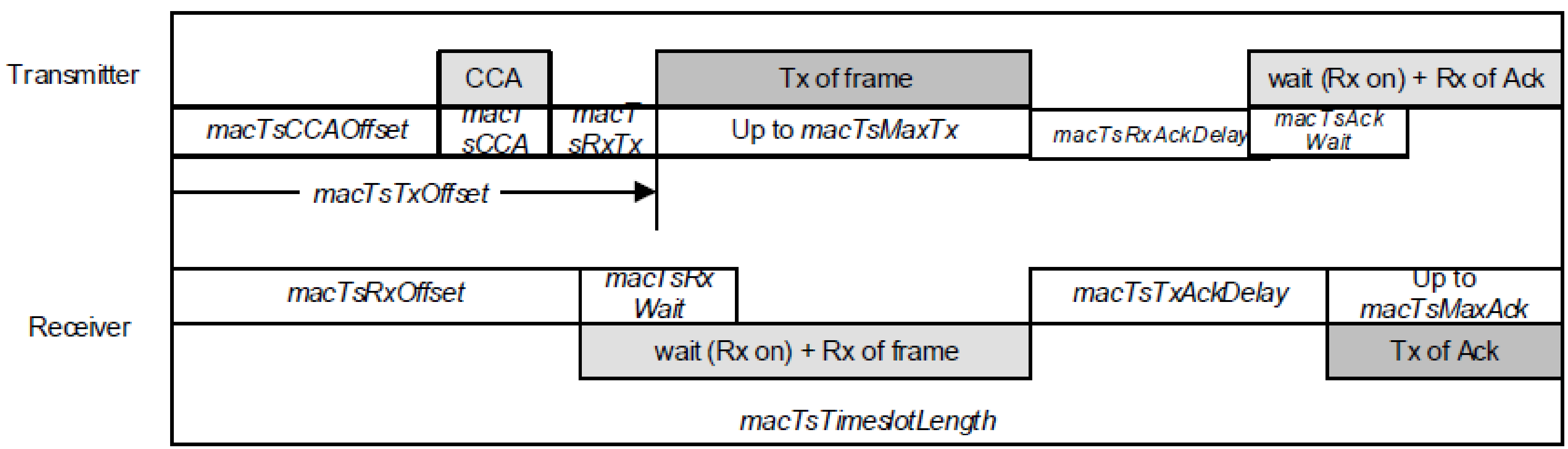


Figure 22b—Timeslot diagram of acknowledged transmission

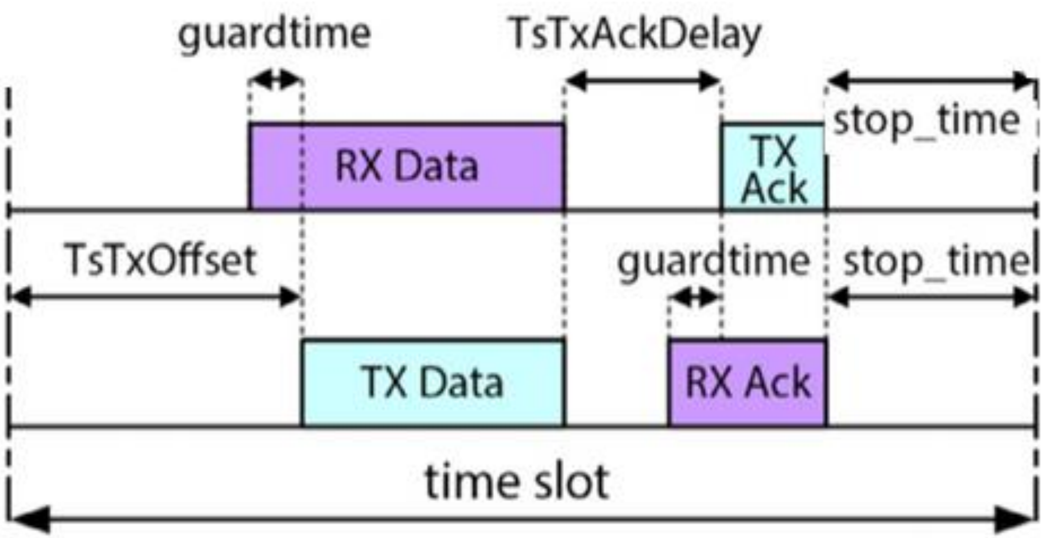
Synchronization

- Nodes synchronize on a periodic slotframe
- Slotframe consists of a number of timeslots
- A timeslot is long enough to send a data frame and receive its ACK
- In each slotframe, EB is broadcasted by PAN Coordinator or other FFDs
  - For network advertisement and synchronization
  - EB contains information of
    - ✓ Channel hopping, timeslot details and slotframe information for Synchronization
- A node can start sending its beacon only after getting a valid EB frame

Re-synchronization

- Clock drift occurs due to
  - Differences in manufacturing, temperature and supply voltage
    - ✓ Clocks of different nodes typically pulse at a slightly different frequency

- Nodes need to periodically re-synchronize
  - Frame-based synchronization
  - ACK-based synchronization

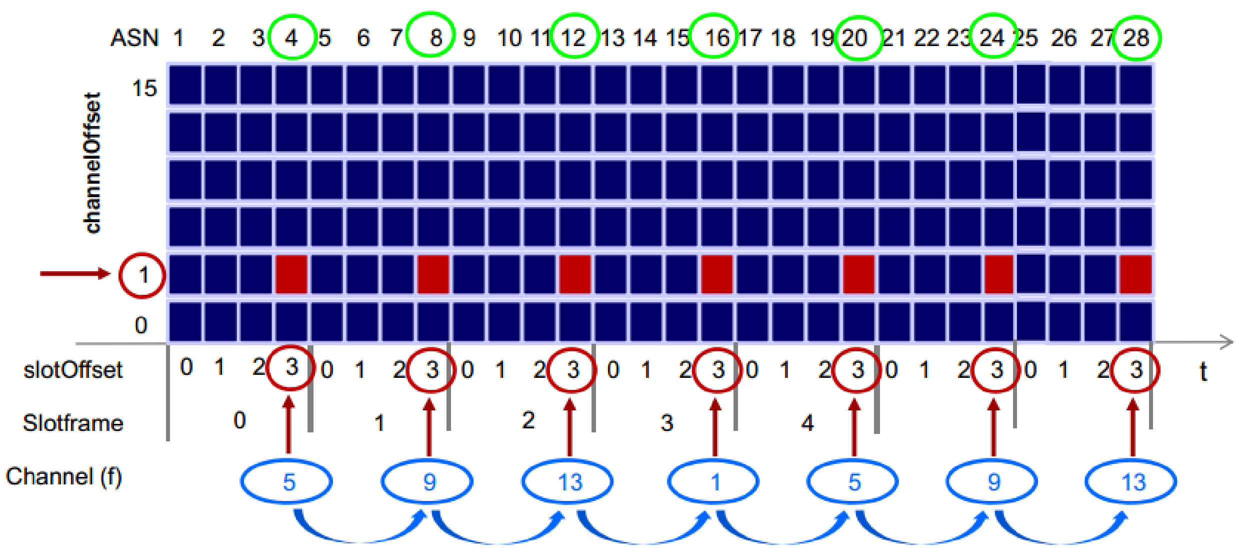


Channel Hopping

- The channel offset is translated in an operating frequency *f* using

$$f = F\{(ASN + chOf) \bmod n_{ch}\}; \qquad ASN = k \cdot S + t$$

  - ASN (absolute slot number) : total # of slots elapsed since the network was deployed
  - n_{ch} : number of physical channels presently available to consider
  - F is implemented as a look-up-table containing the set of available channels
  - k : count of slotframe cycle since the start of the network
  - S : slotframe size
  - t : timeslot in a slotframe

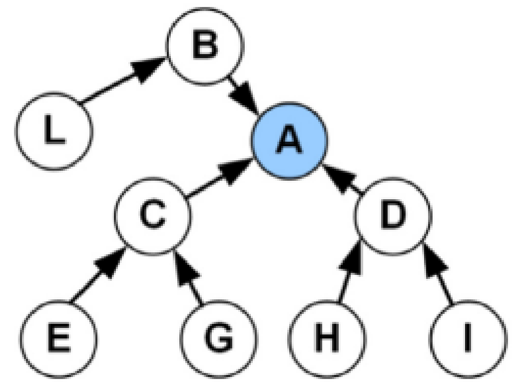


- Max. no. of available channel =16
- Each channel is identified by a *channelOffset*
- Channel could be blacklisted because of low quality

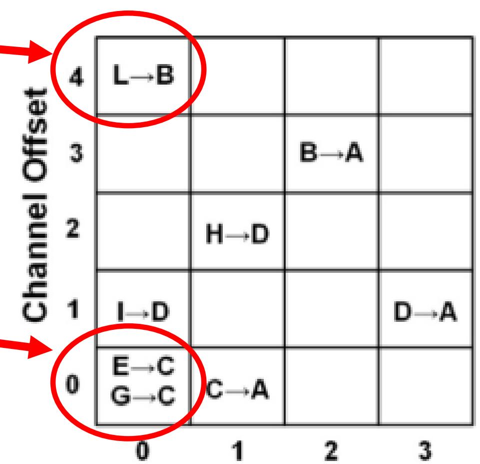
TSCH Mode: Link

- **Link**: Pairwise assignment of a directed communication between devices in a specific slot, with a given channel offset

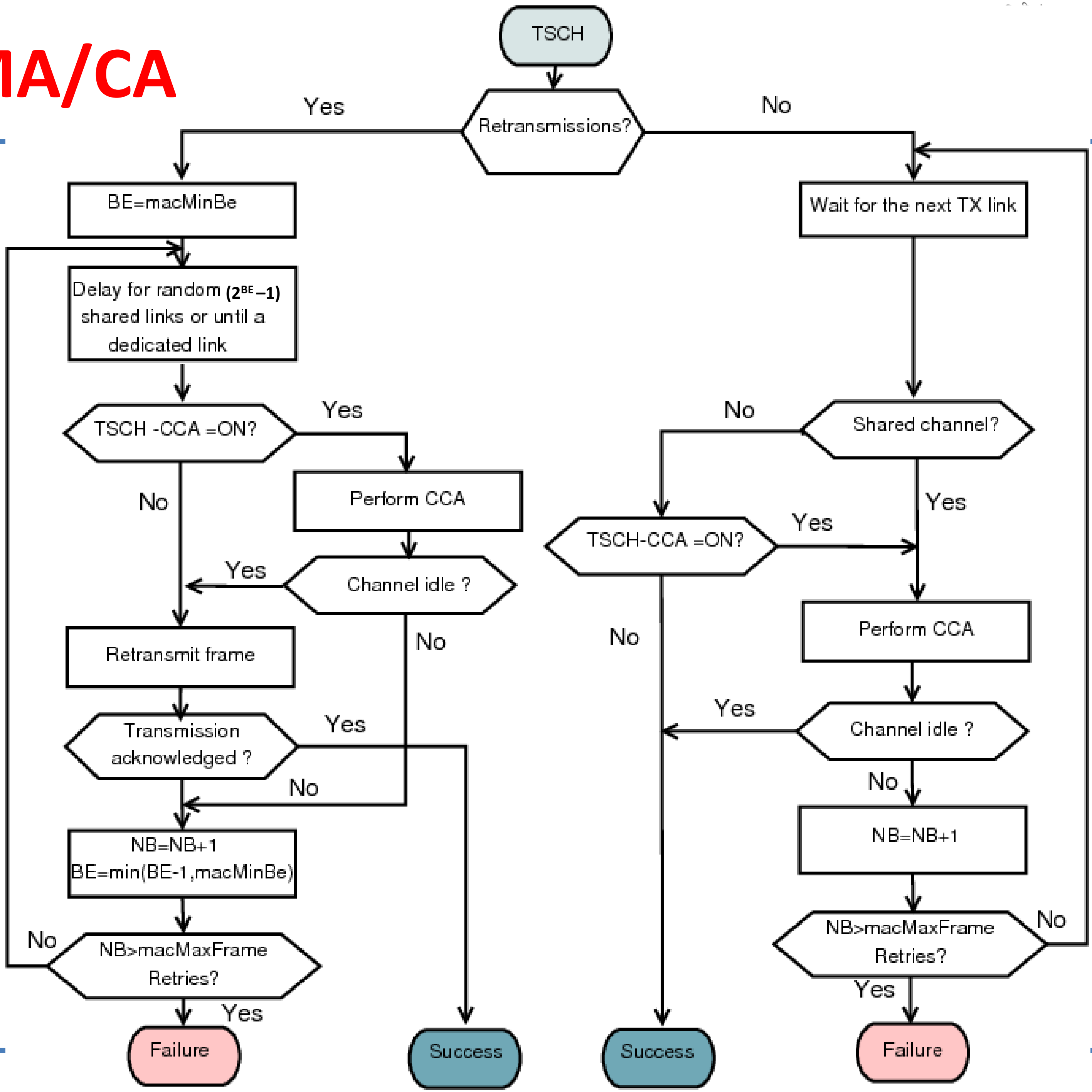
- Link is denoted by [*t, chOf*]
  - ***t*** is timeslot no. in the slotframe
  - ***chOf*** *is* channel offset



- Two types of Link
  - Dedicated links
    - ✓ Direct access
    - ✓ One transmitter – One receiver
    - ✓ Generally used for Data Packet
  - Shared links
    - ✓ TSCH CSMA-CA protocol
    - ✓ Multiple transmitters/receivers
    - ✓ Generally used for Control Packet



TSCH CSMA/CA



TSCH
Retransmission
Backoff Algorithm

CSMA-CA used **in shared link** to avoid repeated collisions.

In dedicated link, no chance of collision.

Cont…

- Original 802.15.4 CSMA-CA **v/s** TSCH CSMA-CA algorithm
  - Backoff mechanism
    - ✓ In 802.15.4 CSMA-CA, transmitting node waits for a random backoff time before trying to transmit it
    - ✓ In TSCH CSMA-CA, backoff mechanism is activated only after the node has experienced a collision
  - Backoff unit duration
    - ✓ In 802.15.4 CSMA-CA, backoff unit duration is 320µs
    - ✓ In TSCH CSMA-CA, backoff unit duration corresponds to a shared slot duration
  - Clear Channel Assessment (CCA)
    - ✓ In 802.15.4 CSMA-CA, each node performs a CCA to check the channel state, before performing transmission
    - ✓ In TSCH CSMA-CA, CCA is used to avoid the packet transmission if a strong external interference is detected. Internal collision is not possible due to TSCH.
  - Packet dropping
    - ✓ In 802.15.4 CSMA-CA, a packet is dropped after the sender found channel busy for *macMaxCSMABackoffs* consecutive times
    - ✓ In TSCH CSMA-CA, a packet is dropped only if it reaches the maximum number of retransmissions i.e., *macMaxFrameRetries*

Network Formation

- PAN coordinator starts the process of network formation by sending EB frame
  - Network advertisement

- EBs are special frames containing
  - Synchronization information
    - ✓ allows new devices to synchronize to the network
  - Channel hopping information
    - ✓ allows new devices to learn the channel hopping sequence
  - Timeslot information
    - ✓ describes when to expect a frame transmission and when to send an acknowledgment
  - Initial link and slotframe information
    - ✓ allows new devices to know:
      - when to listen for transmissions from the advertising device
      - when to transmit to the advertising device

Cont..

- A new node starts listening for EB on a certain frequency

- Upon receiving an EB
  - The MAC layer notifies the higher layer
  - The higher layer initializes the slotframe and links
    - ✓ Using information in the received EB message
  - Switches the device into TSCH mode
    - ✓ At this point the device is connected to the network
  - The device allocates communication resources
    - ✓ (i.e., slotframes and links)
  - and starts advertising, on its turn

- the 802.15.4e standard did not define the EB advertising policy.

Network Formation Goals

- Optimizing the network formation process
  - Synchronized communication schedule consumes less energy of nodes by reducing duty cycle
- Minimum Joining time
  - Devices must keep the radio ON during the joining phase
  - EBs should be sent frequently to reduce waiting time
- Minimize EB transmissions
  - Frequent EB transmission consumes more communication resources
  - Also Increases energy consumption at network and node level

TSCH : Link scheduling

- Assignment of unique link to node for data transmission

- Challenging in dynamic networks

- IEEE 802.15.4e standard does not specify how to derive an appropriate link schedule

- Existing multichannel scheduling schemes are not suitable for TSCH networks
  - They do not allow per-packet channel hopping
  - Not for resource-constrained nodes
  - They are not efficient in terms of channel utilization

Cont..

- Centralized Scheduling
  - Link schedule computed and distributed by a special node
    - ✓ Network coordinator
    - ✓ Based on information received by all the nodes of the network
    - ✓ Link schedule has to be re-computed and re-distributed every time a change in the operating conditions occurs
    - ✓ Not good for dynamic network and large scale network

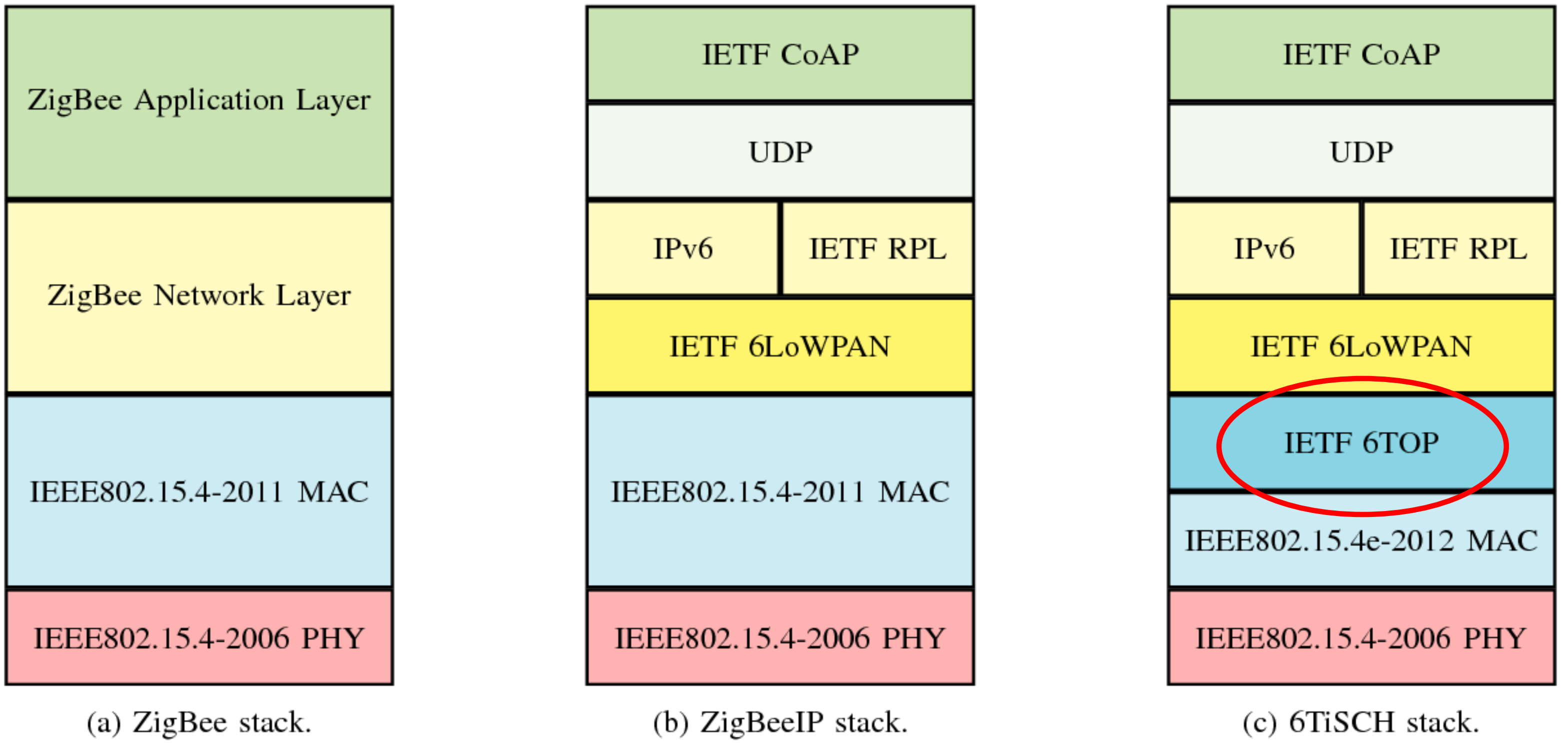
- Distributed Scheduling
  - Good choice for dynamic network and large scale network
  - Link schedule is computed autonomously by each node
    - ✓ Based on local, partial information exchanged with its neighbors
  - Limited Overhead
    - ✓ Suitable for energy-constrained nodes

TSCH: Open Issues

- Network Formation
  - Current solution inefficient for
    - Energy consumption
    - Mobile Objects
- Security
  - Selective Jamming (SJ) attacks
  - Secure Beacons and Different Frequency hopping sequence
- TSCH network synchronization
  - Energy consumption
- TSCH slot scheduling
  - Guaranteed QoS

6TiSCH Network

- 6TiSCH working group created by IETF
- **Goal**: integrate TSCH within the IoT protocol stack
  - To enable IPv6 over TSCH mode of IEEE 802.15.4e
  - Defining a new functional entity in charge of scheduling TSCH time slot



Need for 6TiSCH

- In 6TiSCH, the TSCH MAC mode is placed under an IPv6-enabled protocol stack:
  - IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN)
  - IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL), and
  - Constrained Application Protocol (CoAP)

- TSCH **does not** define
  - Policies to build and maintain the communication schedule
  - Mechanisms to match the schedule to the multi-hop paths maintained by RPL
  - Mechanisms to adapt the resources allocated between neighbor nodes to the data traffic flows
  - Techniques to allow differentiated treatment of packets
    - ✓ data packets & control packet

6TiSCH Architecture

- 6TiSCH WG considers low-power lossy-network (LLN)
- Allow more than 1000 nodes
- Nodes are in same IPv6 subnet
- 6LoWPAN Header compression (HC) is used to transmit packet
- Presence of high-speed backbone (e.g. WiFi mesh) to connect all nodes
- Constrained nodes are attached to backbone through backbone router (BBR)
- Backbone is connected to the Internet through a Gateway

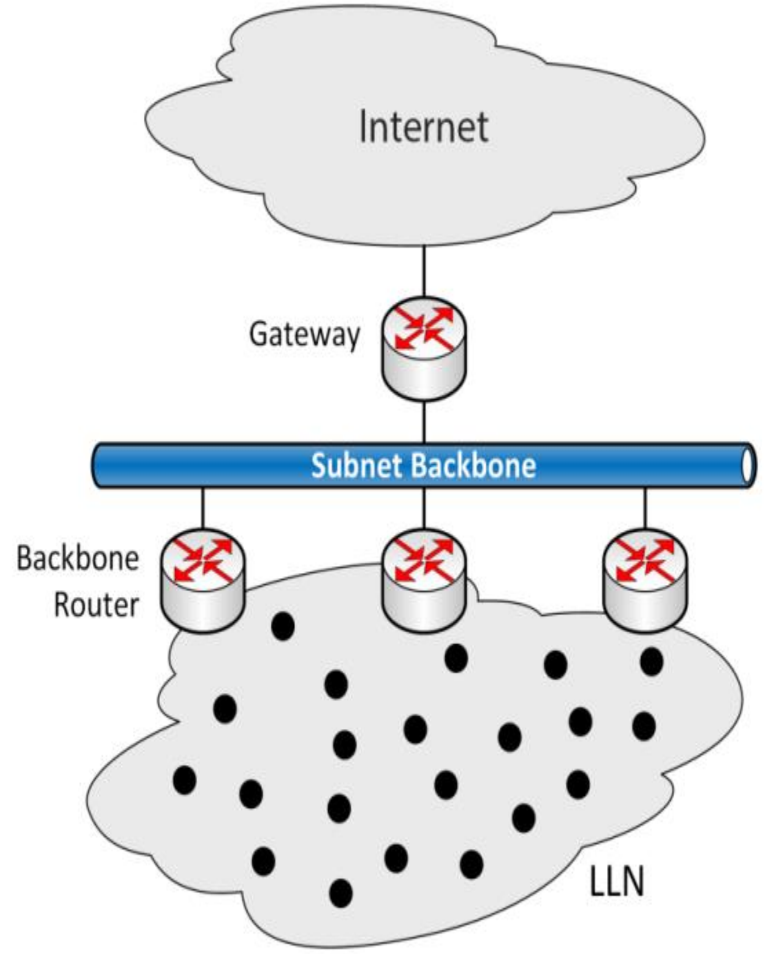


Fig. 6TiSCH Architecture

6TiSCH Protocol Stack

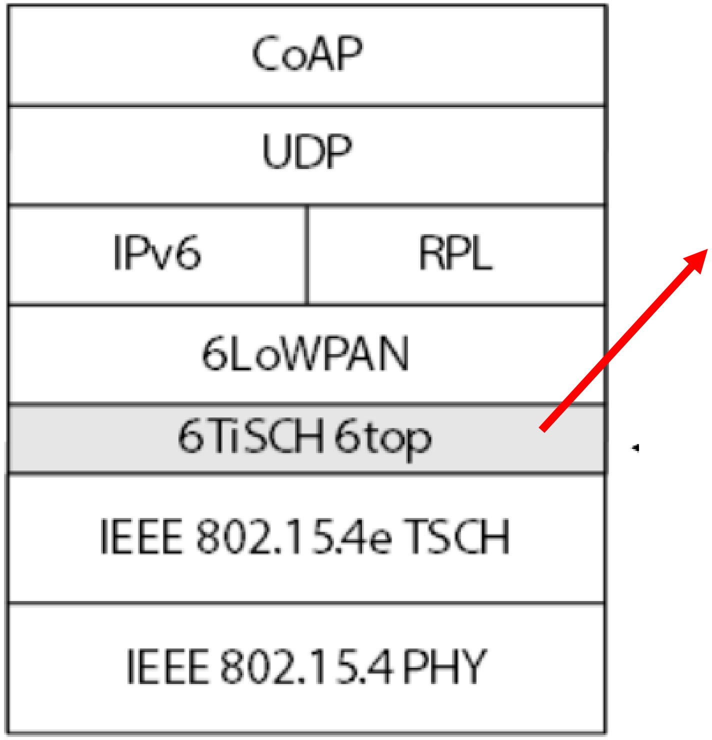


Fig. 6TiSCH Protocol Stack

- A new sublayer, called 6top defined by the 6TiSCH WG
  - Works on top of TSCH
  - Build and manage TSCH schedule
    - ✓ add/delete links/cells
  - 6top also collects connectivity information
    - ✓ Monitors the performance of cells
  - Both with centralized and distributed scheduling supported

6TiSCH Scheduling

- 6TiSCH considers three modes for building and maintaining the TSCH schedule

- 1. Minimal Scheduling **[RFC 8180]**
  - Default schedule
  - TSCH schedule is static, and either preconfigured or learnt by a node at joining time
  - Used during network bootstrap, or when a better schedule is not available

- 2. Centralized Scheduling
  - A central entity called Path Computation Element (PCE) collects network state information and traffic requirements
  - It builds and install the schedule in the network

- 3. Distributed Scheduling
  - Nodes agree on a common distributed schedule by using distributed multi-hop scheduling protocols and neighbor-to-neighbor scheduling negotiation
    - Reservation phase & negotiation phase

Thanks!