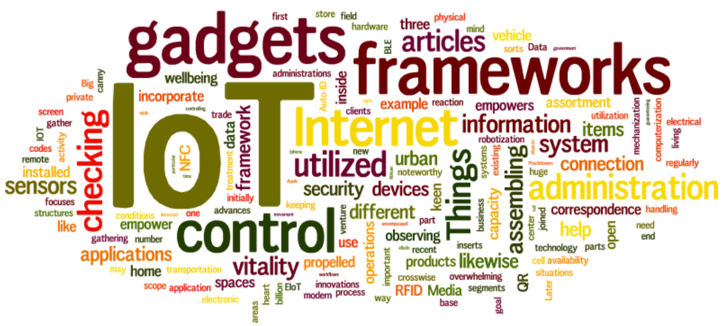
CS578: Internet of Things

IEEE 802.15.4e

IEEE 802.15.4e Standard: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6185525
Article: “IEEE 802.15.4e: A survey” https://www.sciencedirect.com/science/article/pii/S0140366416301980



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“The best among you is the one who doesn’t harm others with his tongue and hands.” – **Muhammad**

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.
  - complex synchronization and beacon scheduling in BE mode for multihop
  - Consume large energy

- So, IEEE 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 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 modes

- Time Slotted Channel Hopping (**TSCH**)
  - Industrial automation and process control
  - Delay sensitive applications

- Deterministic and Synchronous Multi-channel Extension (**DSME**)
  - Industrial and commercial applications
  - Non-delay tolerant and delay tolerant applications

- Low Latency Deterministic Network (**LLDN**)
  - For single hop and single-channel networks
  - Star topology
  - Provides very low latency

Cont..

- Asynchronous multi-channel adaptation (**AMCA**)
  - For large network such as smart utility networks, infrastructure monitoring
  - 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)
  - Operate in very low duty cycle (<= 1%)
  - Appearing always on to the upper layers
  - Intended for applications that can trade latency for energy efficiency
- Information Elements (IE)
  - Mechanism to exchange information at the MAC sublayer
- Enhanced Beacons (EB)
  - Extension of the 802.15.4 beacon frames
  - 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

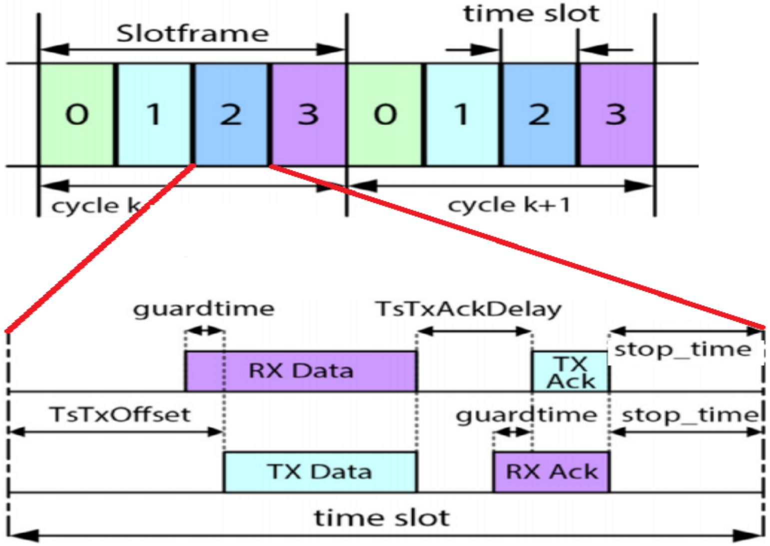
- Time slotted access
  - Increase throughput by eliminating collision among competing nodes
  - Predictable and bounded latency

- 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 / multipath interference
    - ✓ 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

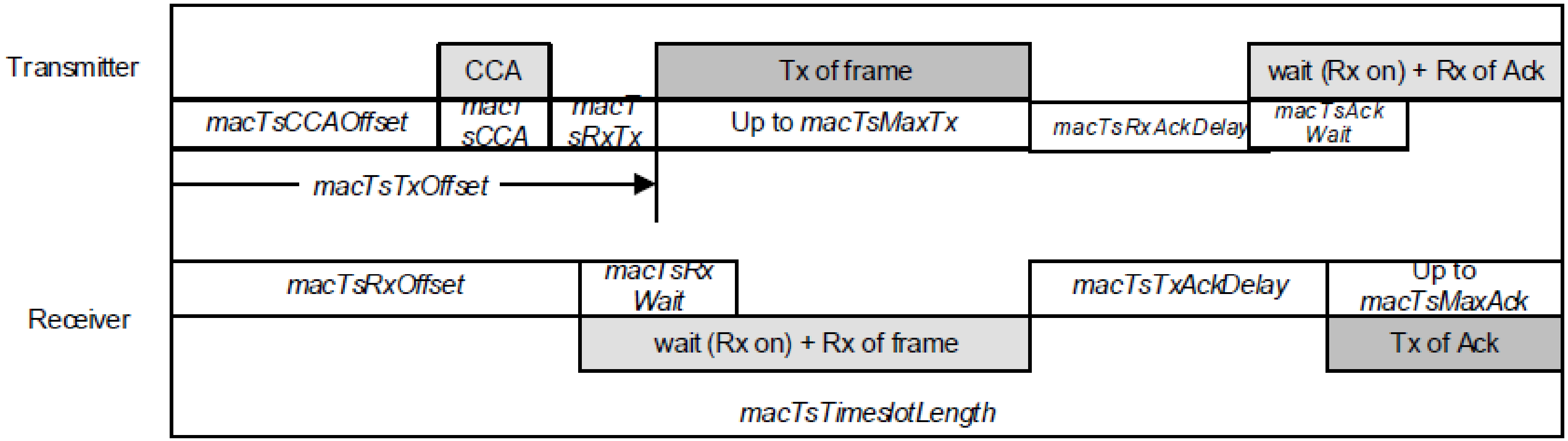


Figure 22b—Timeslot diagram of acknowledged transmission

Synchronization

- 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

- Nodes synchronize on a periodic slotframe

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

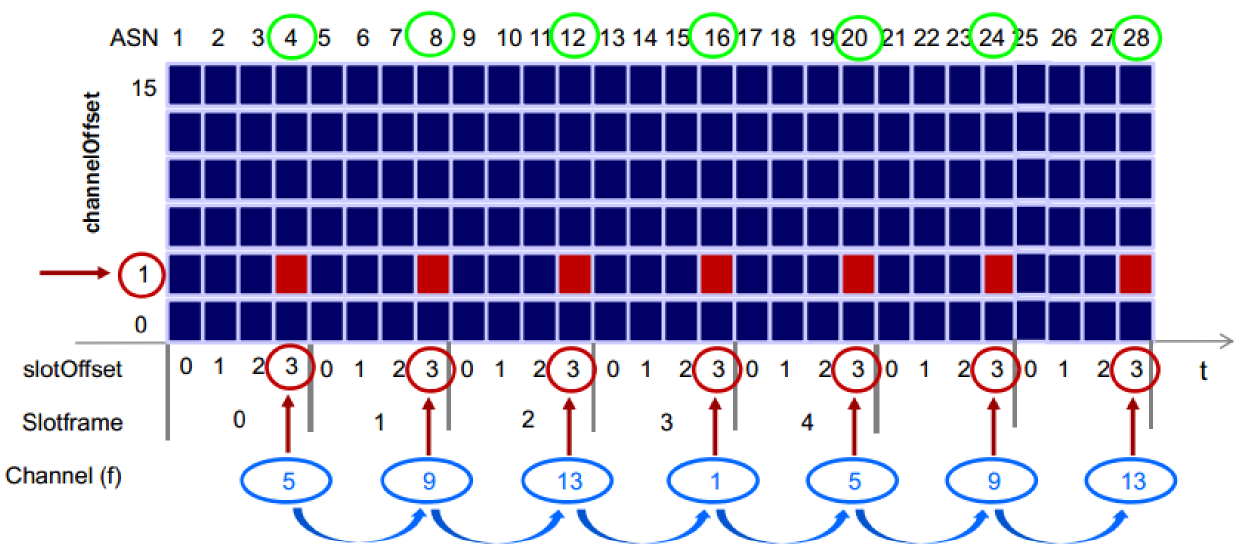
- Nodes need to periodically re-synchronize
  - Frame-based synchronization
  - ACK-based synchronization

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

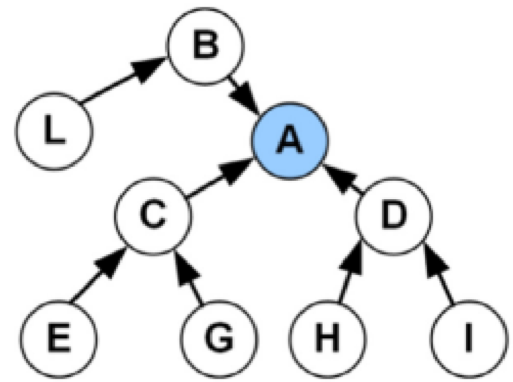


- Max. no. of available channel =16
- Each channel is identified by a *channelOffset*
- Channel could be blacklisted because of low quality

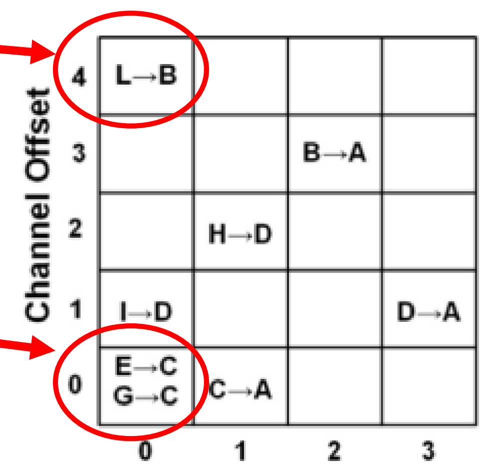
Link and Schedule

- **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

IEEE 802.15.4 default CSMA/CA **v/s** TSCH CSMA/CA algorithm

	802.15.4 CSMA/CA	TSCH CSMA/CA
Backoff Mechanism	transmitting node waits for a random backoff time before trying to transmit	backoff mechanism is activated only after the node has experienced a collision. By default no backoff
Backoff unit duration	320µs (~20 symbol duration)	corresponds to a slot duration (~10ms)
Clear Channel Assessment (CCA)	each node performs CCA to check the channel state, before performing transmission	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	If the sender consecutively found channel busy for *macMaxCSMABackoffs* times	only if it reaches the maximum number of retransmissions i.e., *macMaxFrameRetries*

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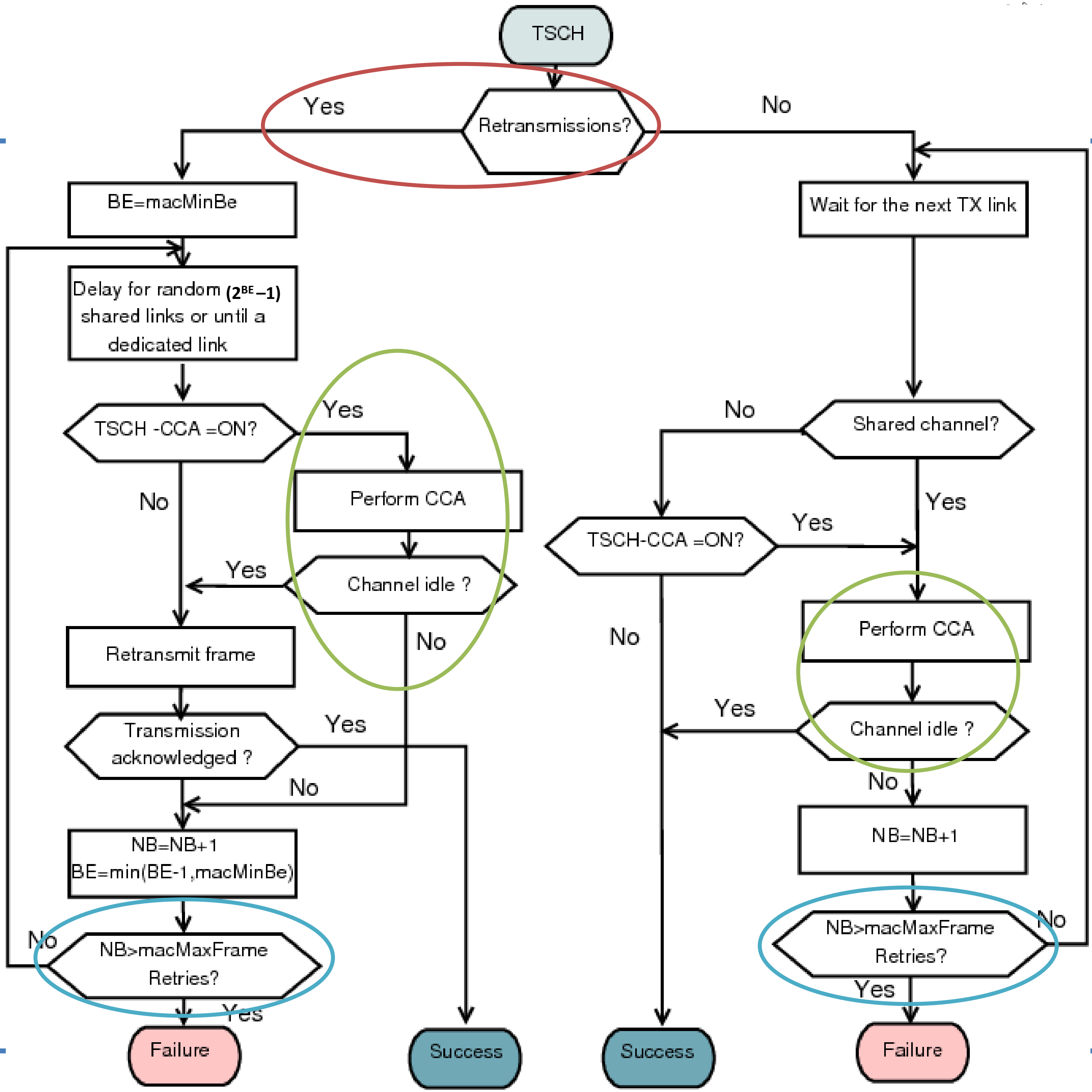
Generally retransmission in TSCH is not allowed.

It is handled by link scheduling

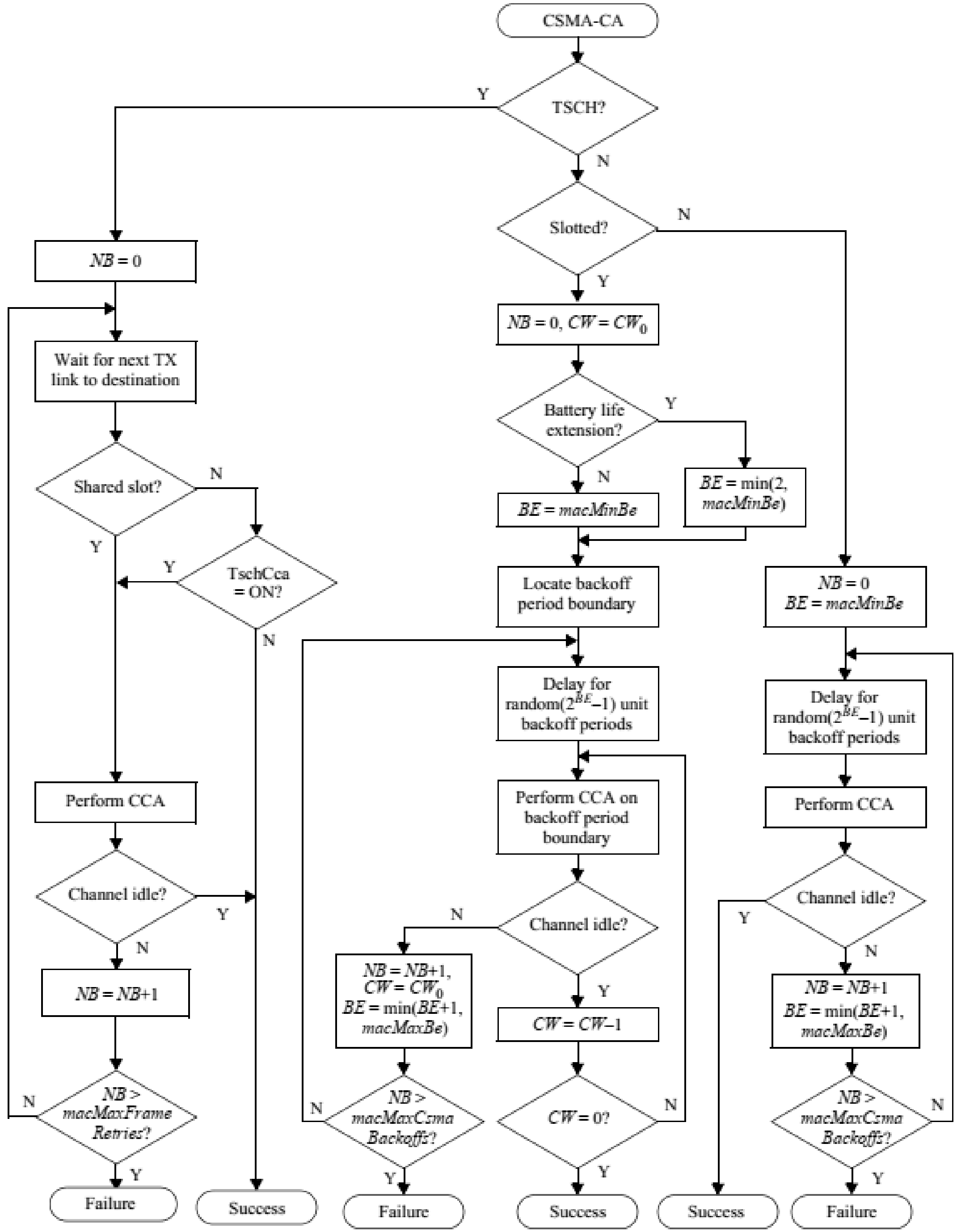
CSMA/CA used **in shared link** to avoid repeated collisions.

In **dedicated link**, no chance of collision.



TSCH CSMA/CA

See the IEEE 802.15.4 – 2015 standard to get this flowchart



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

A. Kalita and M. Khatua, "6TiSCH – IPv6 Enabled Open Stack IoT Network Formation: A Review", ***ACM Transactions on Internet of Things***, Volume 3, Issue 3, Article No. 24, pp. 1-36, 2022.

TSCH Link scheduling

- Assignment of unique link to node for data transmission

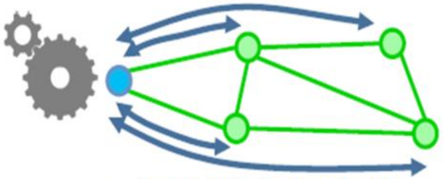
- It is challenging in dynamic network
  - Node join / leave in between
  - Traffic rate changes in between

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

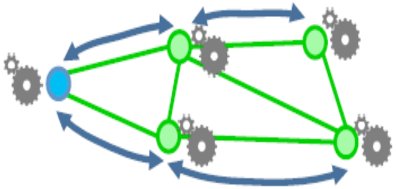
- Existing multi-channel scheduling schemes are not suitable for TSCH networks
  - They do not allow per-packet channel hopping
  - Not for resource-constrained nodes
  - They are not efficient in terms of channel utilization

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



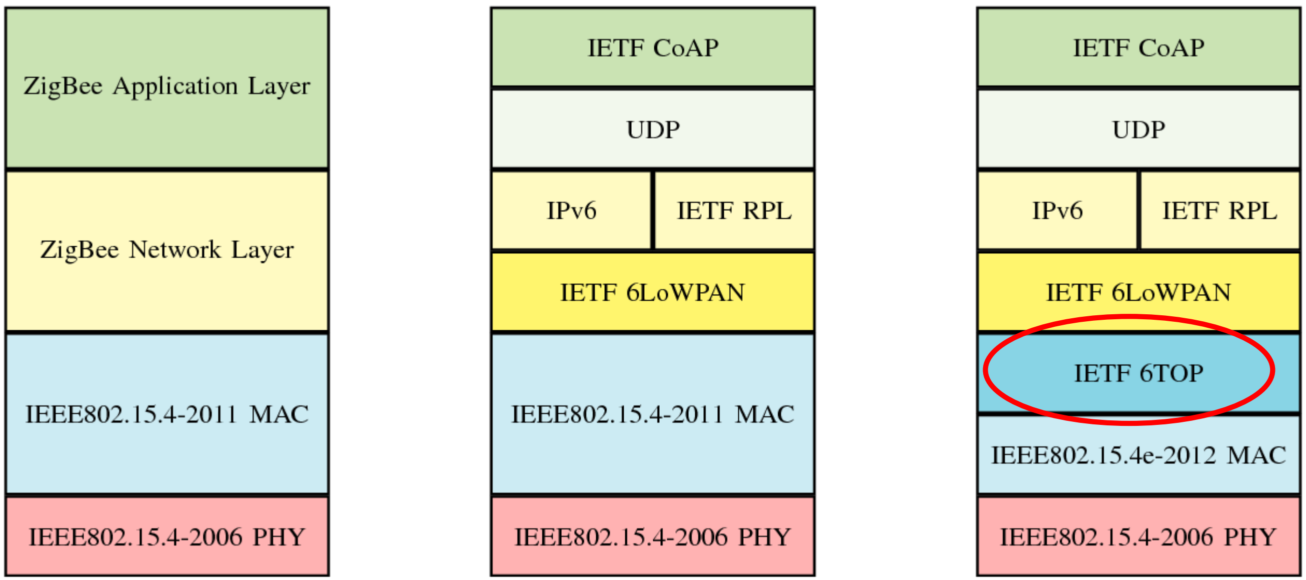
- ➢ **Autonomous Scheduling**
  - No negotiation is used to create the TSCH schedule
  - Only used information from routing protocol (RPL)
  - Nodes autonomously calculate their cell usage plan based on the RPL structure.
    - ✓ Does not require any central coordinator, negotiation, signaling or any path reservation

TSCH: Open Issues

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

6TiSCH Network

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



(a) ZigBee stack. (b) ZigBeeIP stack. (c) 6TiSCH stack.

A new sublayer, called 6top
- Works on top of TSCH
- Build and manage TSCH schedule
  - add/delete links/cells
- 6top also collects connectivity information
  - Monitors the performance of cells

Survey Article: “IETF 6TiSCH: A Tutorial” https://ieeexplore.ieee.org/document/8823863

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

- 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

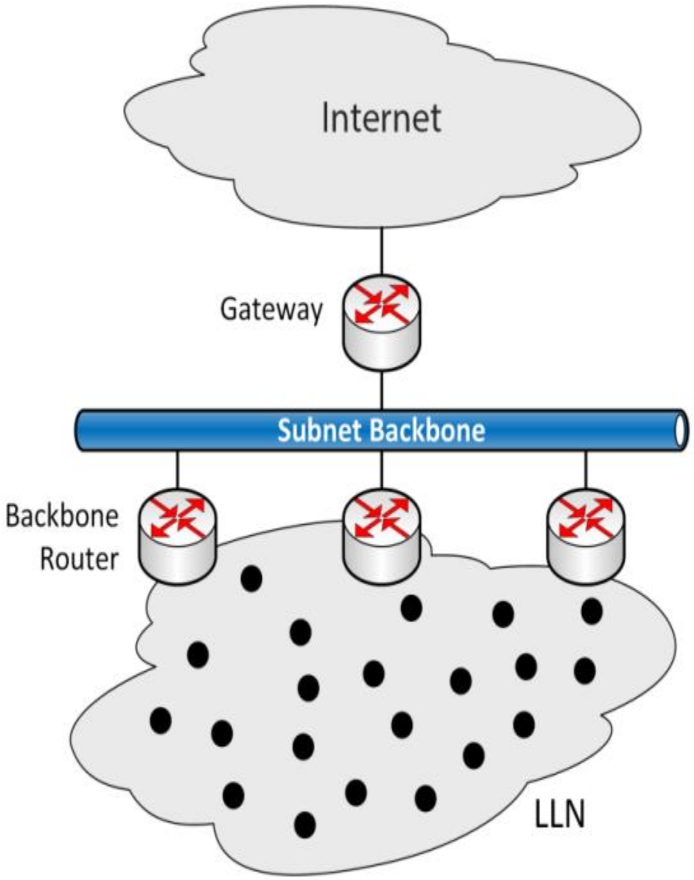


Fig. 6TiSCH Architecture

RFC 9030: An Architecture for IPv6 over the Time-Slotted Channel Hopping Mode of IEEE 802.15.4 (6TiSCH)

6TiSCH Protocol Stack

Application (CoAP)	**RFC8613**	(2019)	*object security extension to CoAP*	
	RFC7252	(2014)	*base CoAP specification*	
Routing (RPL)	**RFC6554**	(2012)	*header format for routing header*	
	RFC6553	(2012)	*header format for RPL option*	
	RFC6552	(2012)	*Objective Function, RPL algorithm*	
	RFC6550	(2012)	*base RPL specification*	
Adaptation (6LoWPAN)	**RFC8505**	(2018)	neighbor discovery and registration	
	RFC8138	(2017)	*routing header* compression	
	RFC8025	(2016)	*mechanism for extending 6LoWPAN*	
	RFC6282	(2011)	*updated base 6LoWPAN* specification	
	RFC4944	(2007)	*base 6LoWPAN specification*	
Scheduling (6TiSCH)	**draft-ietf-6tisch-msf**	(WIP)	*distributed scheduling algorithm*	**RFC 9033**
	RFC8480	(2018)	*6P, distributed scheduling protocol*	
	RFC8137	(2017)	*container for 6P*	
	draft-ietf-6tisch-minimal-security	(WIP)	*security framework for 6TiSCH*	**RFC 9031**
	RFC8180	(2017)	*minimal 6TiSCH*	
Physical layer	**IEEE802.15.4**	(2015)	*2.4 GHz, 50-200 m range, 250 kbps, 127 byte frames*	

Source: Xavier Vilajosana et al., "IETF 6TiSCH: A Tutorial" *IEEE Communications Surveys & Tutorials*, 22(1), 2020, pp. 595– 615.

Lessons Learned

- ✓ Limitations of IEEE 802.15.4
- ✓ IEEE 802.15.4e
  - ✓ MAC Modes
  - ✓ Functional Enhancements
- ✓ IEEE 802.15.4 TSCH
  - Functionalities
  - TSCH CSMA/CA
  - Network Formation
  - Link Scheduling
- ✓ Introduction to 6TiSCH Networks

Thanks!