

Internet of Things (IoT)



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>

Dr. Manas Khatua

Associate Professor

Dept. of CSE, IIT Guwahati

E-mail: manaskhatua@iitg.ac.in

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

➤ 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** ($\leq 1\%$)
- 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

➤ 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

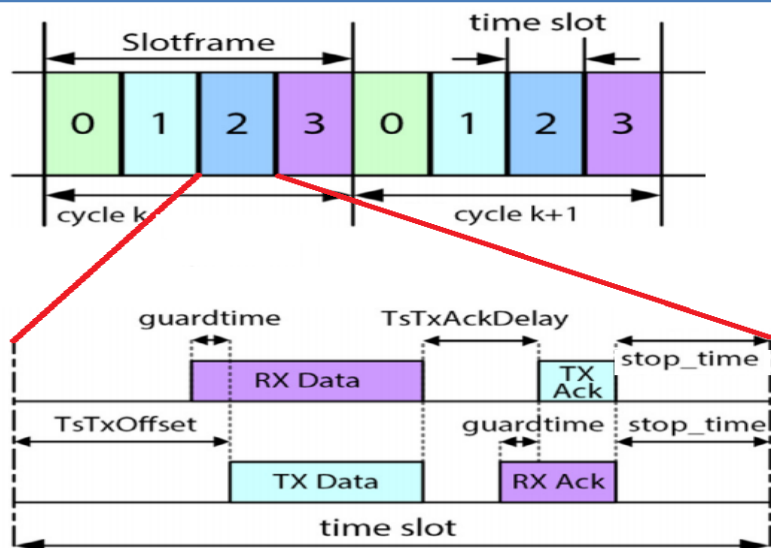
- More nodes exchange their frames at the same time
 - ✓ Increases network capacity

➤ Channel hopping

- Mitigates the effects of interference and multipath 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
 $= TsCCAOffset + TsCCA + TsRxTx$

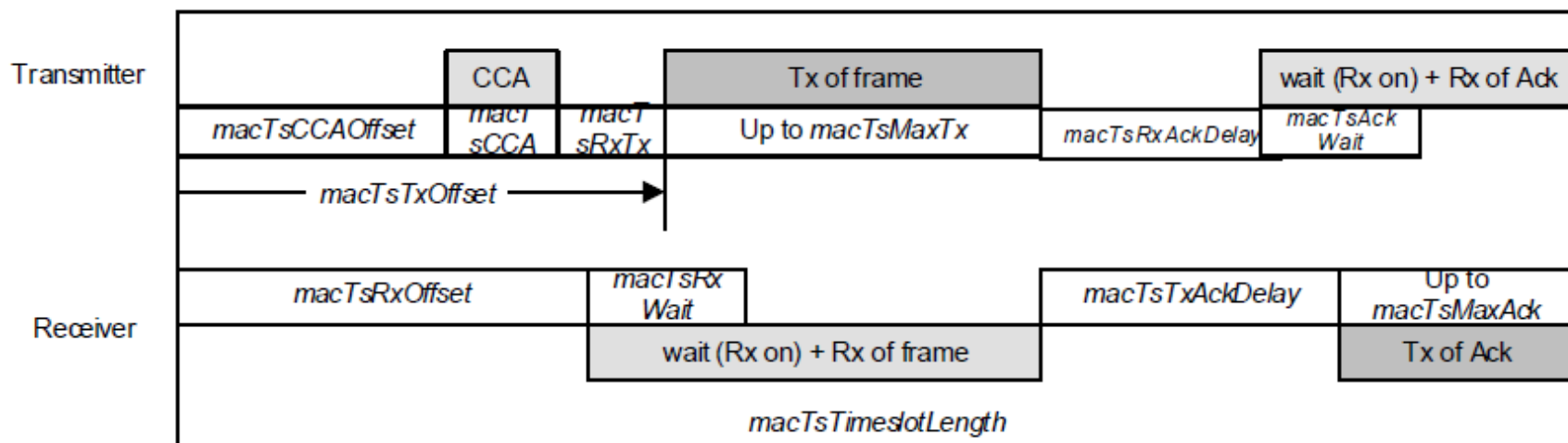


Figure 22b—Timeslot diagram of acknowledged transmission

Synchronization



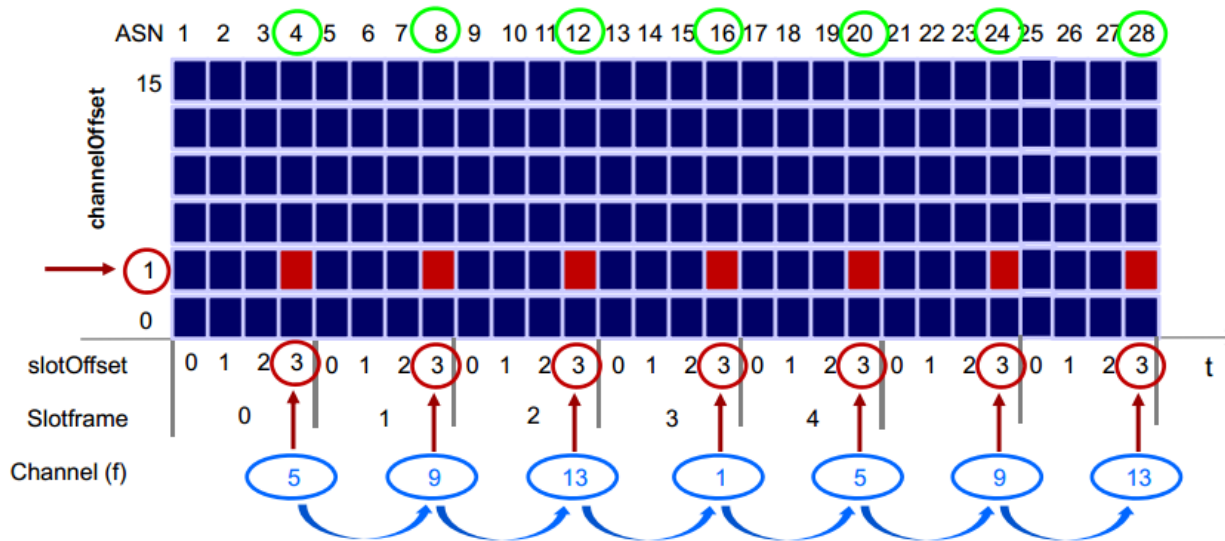
- In each slotframe, EB is **broadcasted** by PAN Coordinator or other FFDs
 - For **network advertisement** and **synchronization**
 - EB contains information of
 - ✓ Channel hopping, timeslot details, and slotframe information for Synchronization
- A node **can start** sending its beacon only after 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

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

- **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**

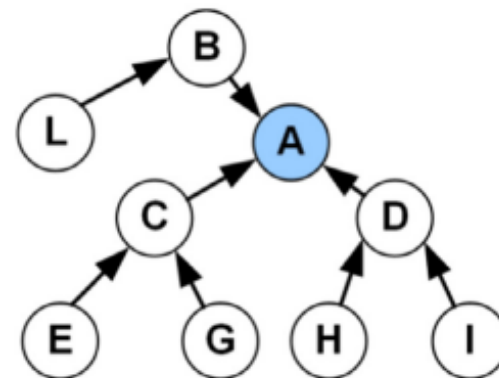
➤ Two types of Link

▪ **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



Channel Offset	4	L→B		
3			B→A	
2		H→D		
1	I→D			D→A
0	E→C G→C	C→A		
	0	1	2	3

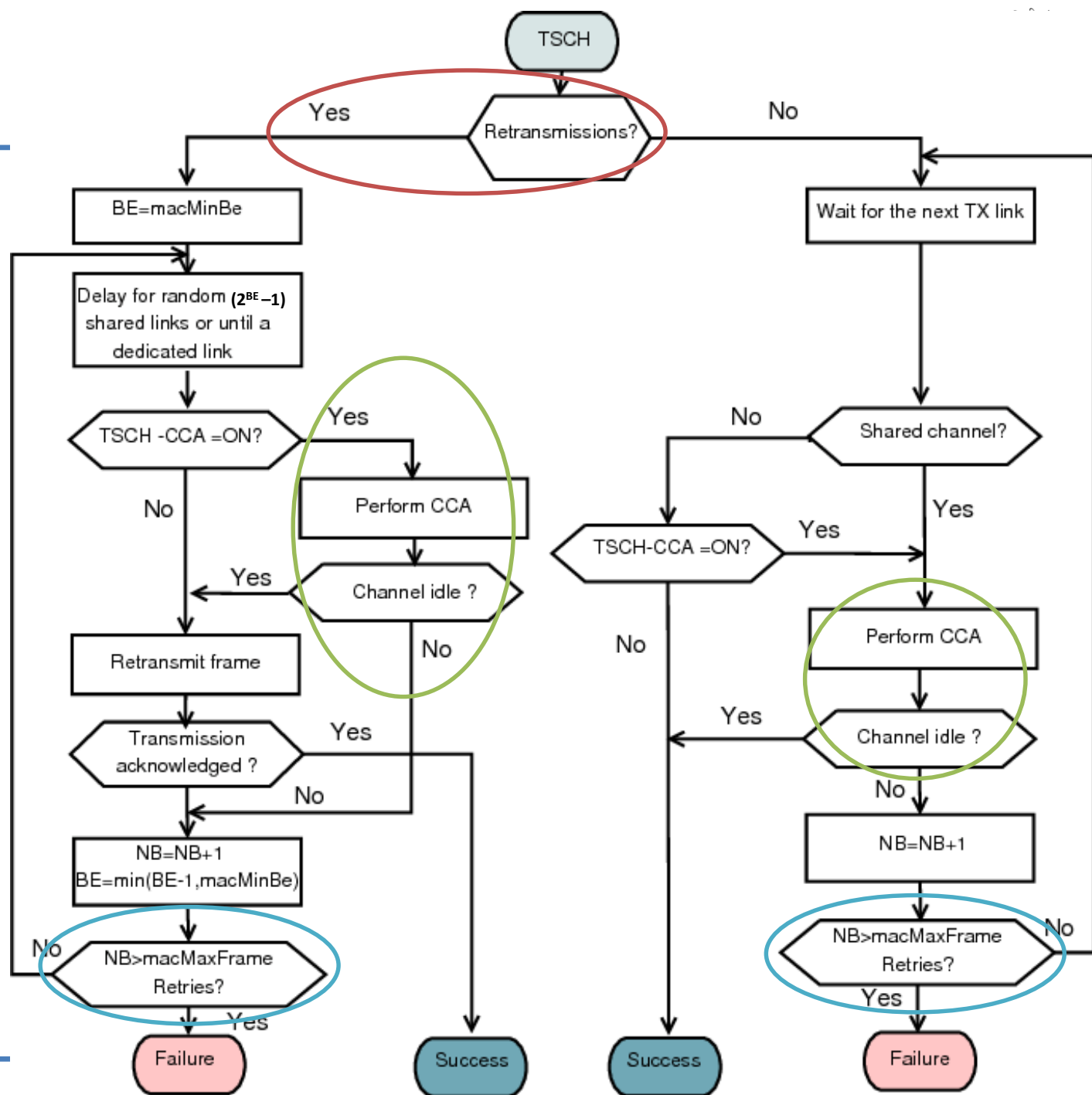
TSCH CSMA/CA



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

Cont...



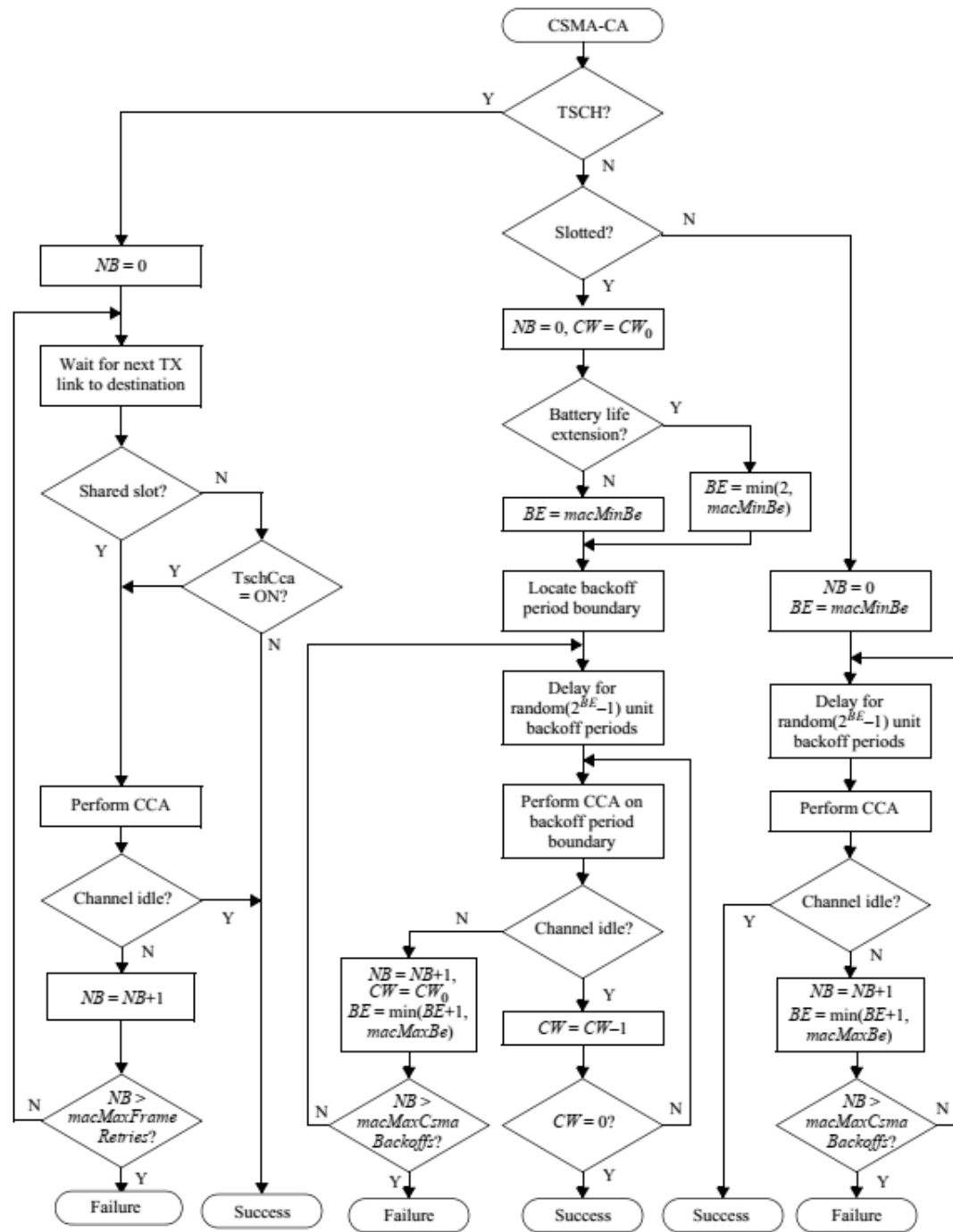
Generally **retransmission** in TSCH is not allowed. It is handled by link scheduling

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



TSCH Network Formation



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

- EBs are special frames containing
 - Synchronization information
 - ✓ allows new devices to synchronize to the network

 - 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

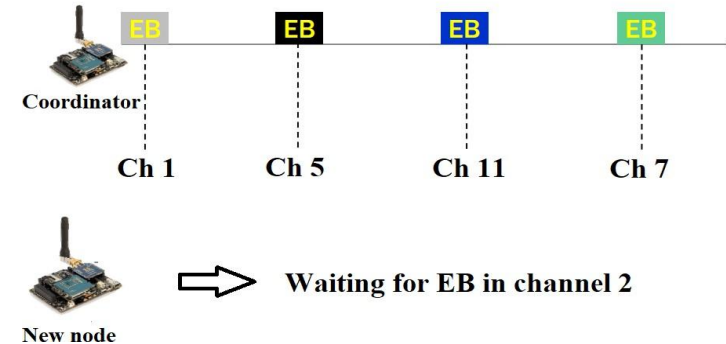
 - Channel hopping information
 - ✓ allows new devices to learn the channel hopping sequence

Cont..

➤ A new node **starts listening for EB** on a certain channel

➤ Upon receiving an EB

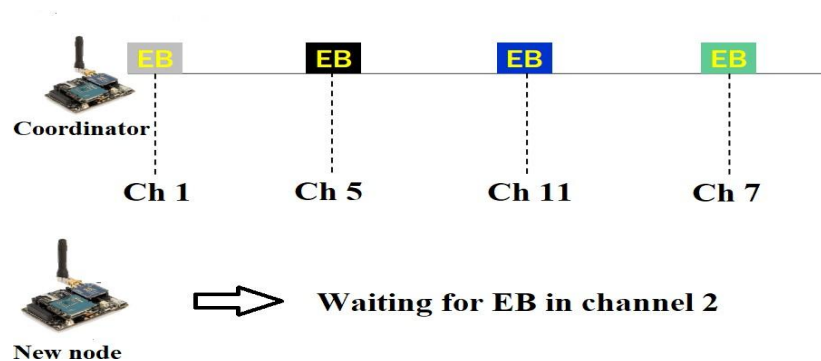
- The MAC layer notifies the higher layer
 - ✓ Using information in the received EB message
- **Switches** the device **into TSCH mode**
 - ✓ At this point the **device is connected to the network**
- The device allocates communication resources
 - ✓ (i.e., slotframes and links)
- The device starts advertising for further expansion



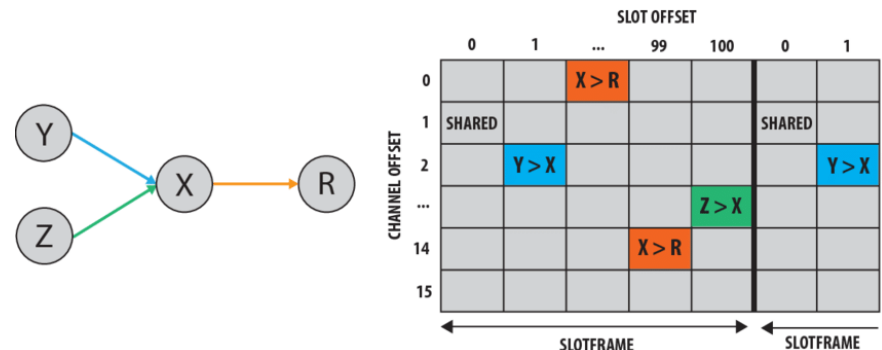
Note: The 802.15.4e standard did not define any **EB advertising policy**.

Why network formation is an issue?

- Channel hopping feature of TSCH
 - A pledge does not know in which channel transmission of control packets is happening



- Limited resource allocated for control packets
 - Only one shared cell in a slotframe



Network Formation Goals



- Optimizing the network formation process
 - Synchronized communication schedule consumes less energy of nodes by reducing duty cycle

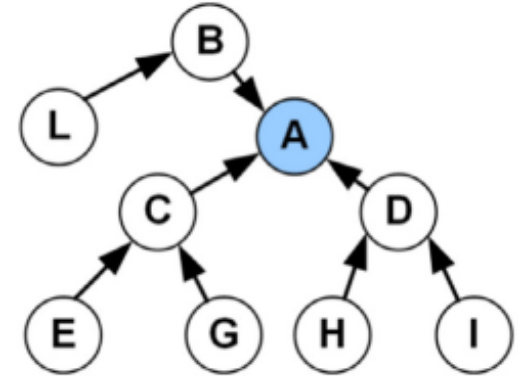
- Minimum Joining time
 - Devices must keep the radio ON during the joining phase
 - EBs should be sent frequently to reduce waiting time

- 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

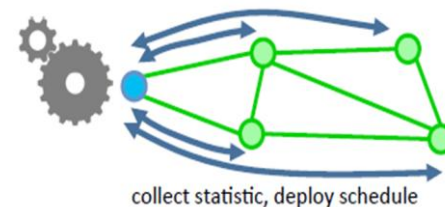


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Scheduling Approach

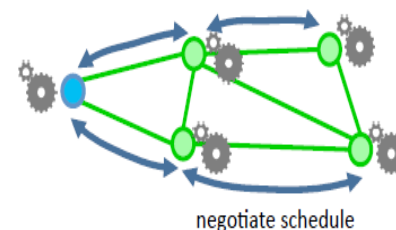
➤ Centralized Scheduling

- 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



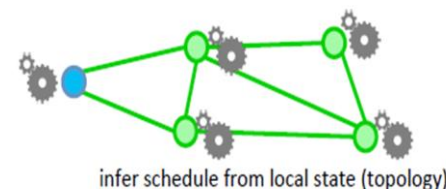
➤ Distributed Scheduling

- 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 TSCN 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



➤ 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

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

Thanks!

