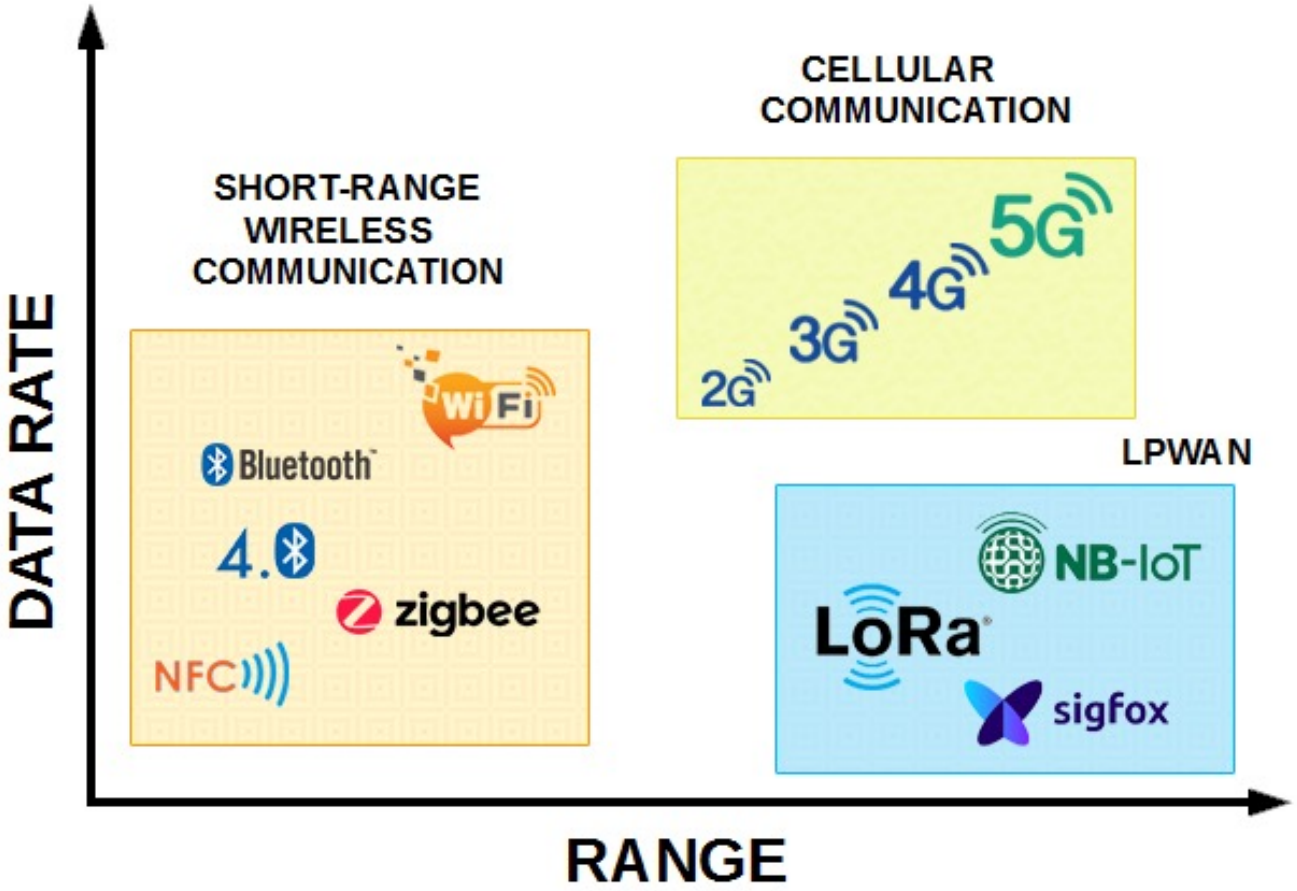
CSCE 438/838: Internet of Things

LoRa and LoRaWAN

Major Connectivity Standards

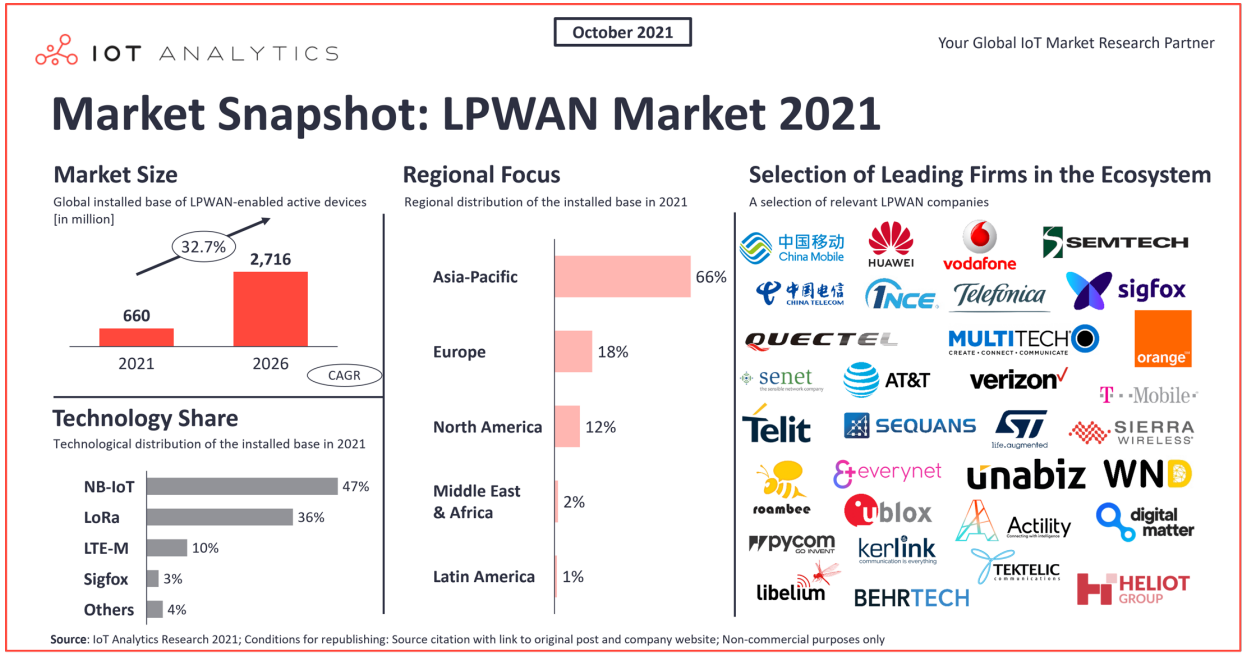


Source: Embien

LPWAN

- Low-power Wide-area Networks (LPWANs)
  - Relatively new wireless connectivity technologies
- Main Characteristics
  - Low-end IoT applications
  - Infrequent transmissions of small packets
  - Large number of devices
  - Wide area deployment
  - Long-term operation (several years)

LPWAN Market



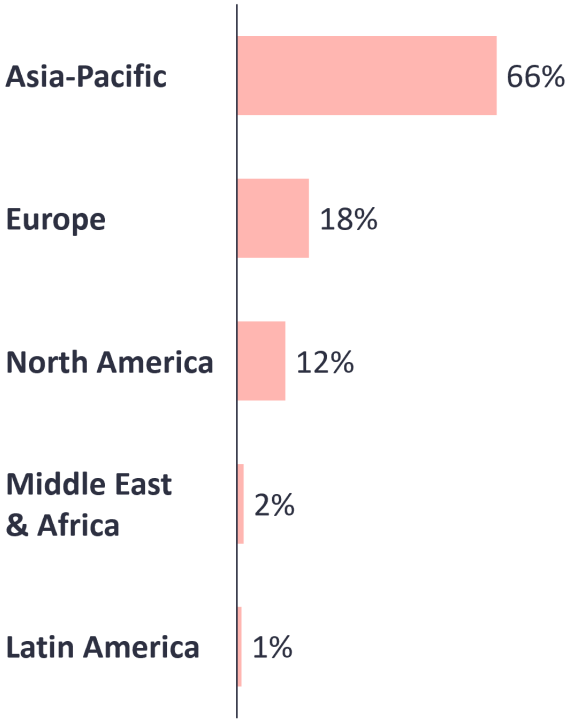
Source: https://iot-analytics.com/wp/wp-content/uploads/2021/10/LPWAN-Market-2021-min-1.png

Selection of Leading Firms in the Ecosystem

A selection of relevant LPWAN companies

Regional Focus

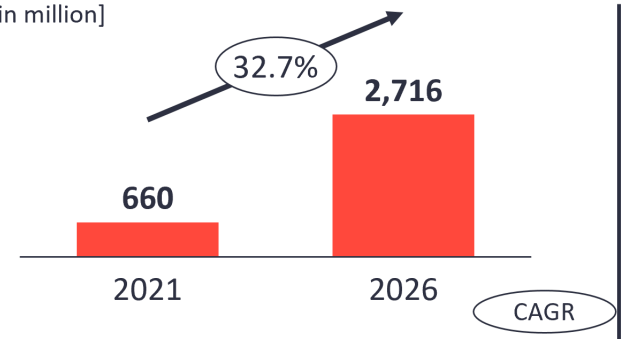
Regional distribution of the installed base in 2021



Source citation with link to original post and company website; N

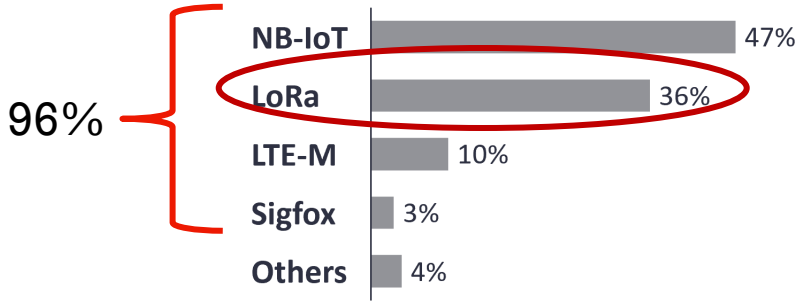
Market Size

Global installed base of LPWAN-enabled active devices [in million]

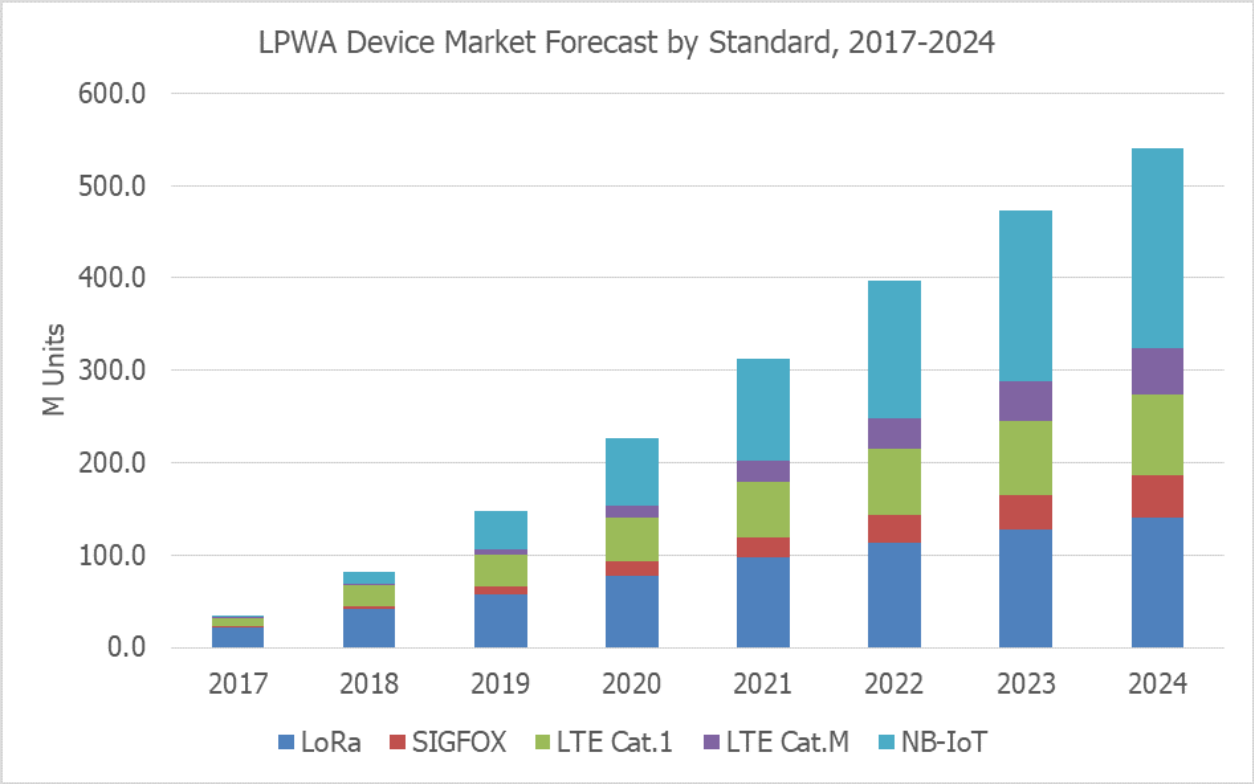


Technology Share

Technological distribution of the installed base in 2021



Source: IoT Analytics Research 2021; Conditions for republishing: ‹



Source: https://iotbusinessnews.com/2019/11/22/95154-lpwa-market-update-china-boosts-lpwa-market-development/

Future of LPWAN

- Cellular
  - eSIM/iSIM: Flexibility, device size, security
  - 5G
- Non-cellular
  - Multi-technology networks
  - Semtech ->
  - UnaBiz -> SigFox
- Satellite

Multi-technology LPWAN

Source: https://www.actility.com/unabiz-pr/

IOT ANALYTICS

August 2022

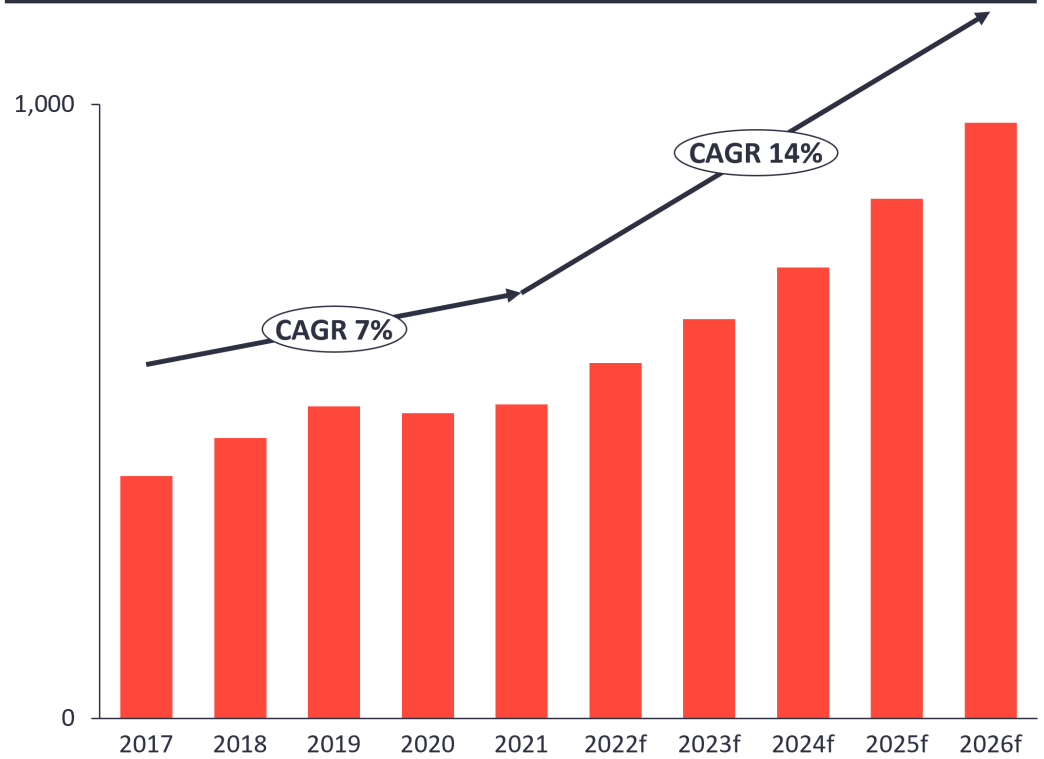
Your Global IoT Market Research Partner

Market Snapshot: Satellite IoT Market 2022 – 2026

Selection of satellite IoT network operators

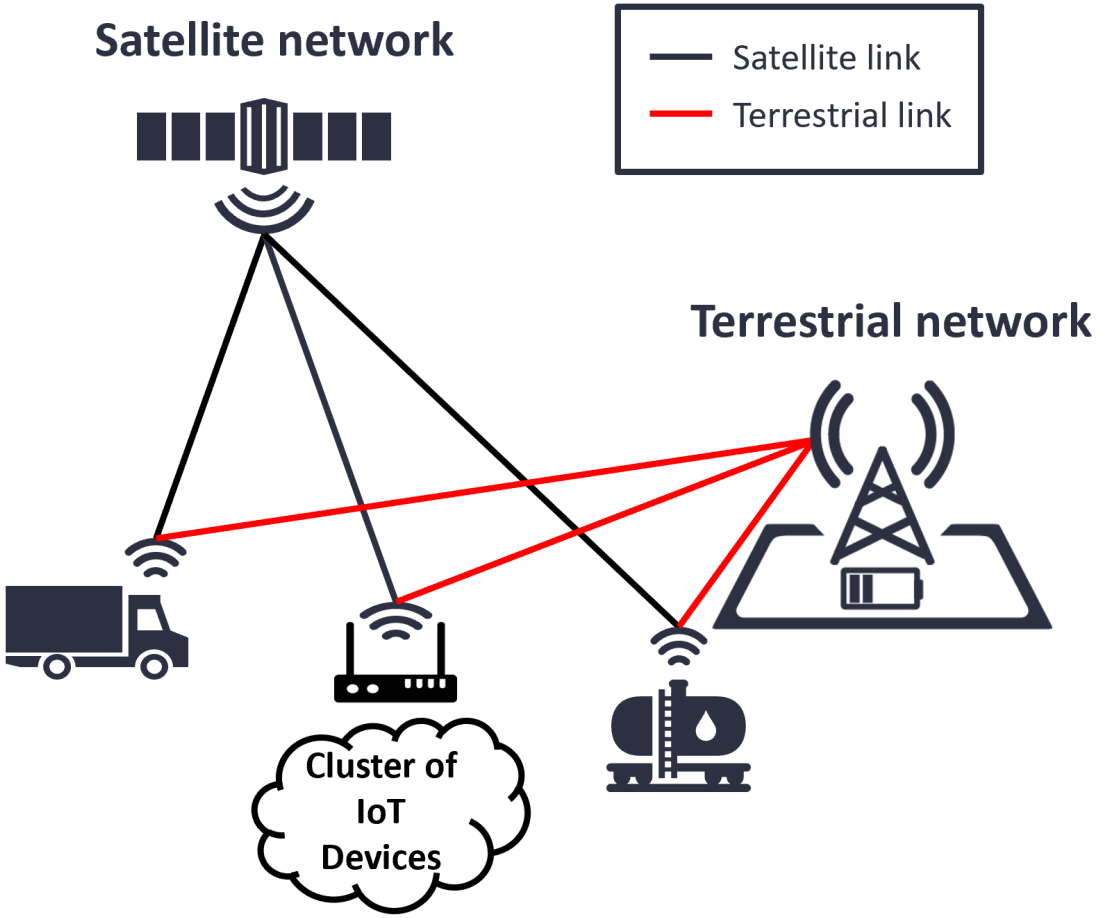
AsiaSat, HEAD Aerospace Group, ORBCOMM, kinéis, inmarsat, iridium, Myriota, THURAYA, EchoStar Mobile, SATELIOT, eutelsat, hiber, Viasat, SWARM, astrocast, FLEET, TELESAT, KEPLER, Lacuna space, SAT4M2M, INTELSAT, ligado networks, TOTUM, ingenu, eSAT GLOBAL, SAS, FOSSA, OQ TECHNOLOGY, hiSky, 银河航天 GALAXYSPACE, OMNISPACE, TELNET, KLEO, Globalstar, skylo, COMMSAT 九天微星, ROSCOSMOS, 国电高科, INNOVA SPACE, GEESPACE

Market Size (in $M)



Source: IoT Analytics Research 2022 – Satellite IoT Market Report 2022. We welcome republishing of images but ask for source citation with a link to the original post and company website.

Hybrid Terrestrial-Satellite



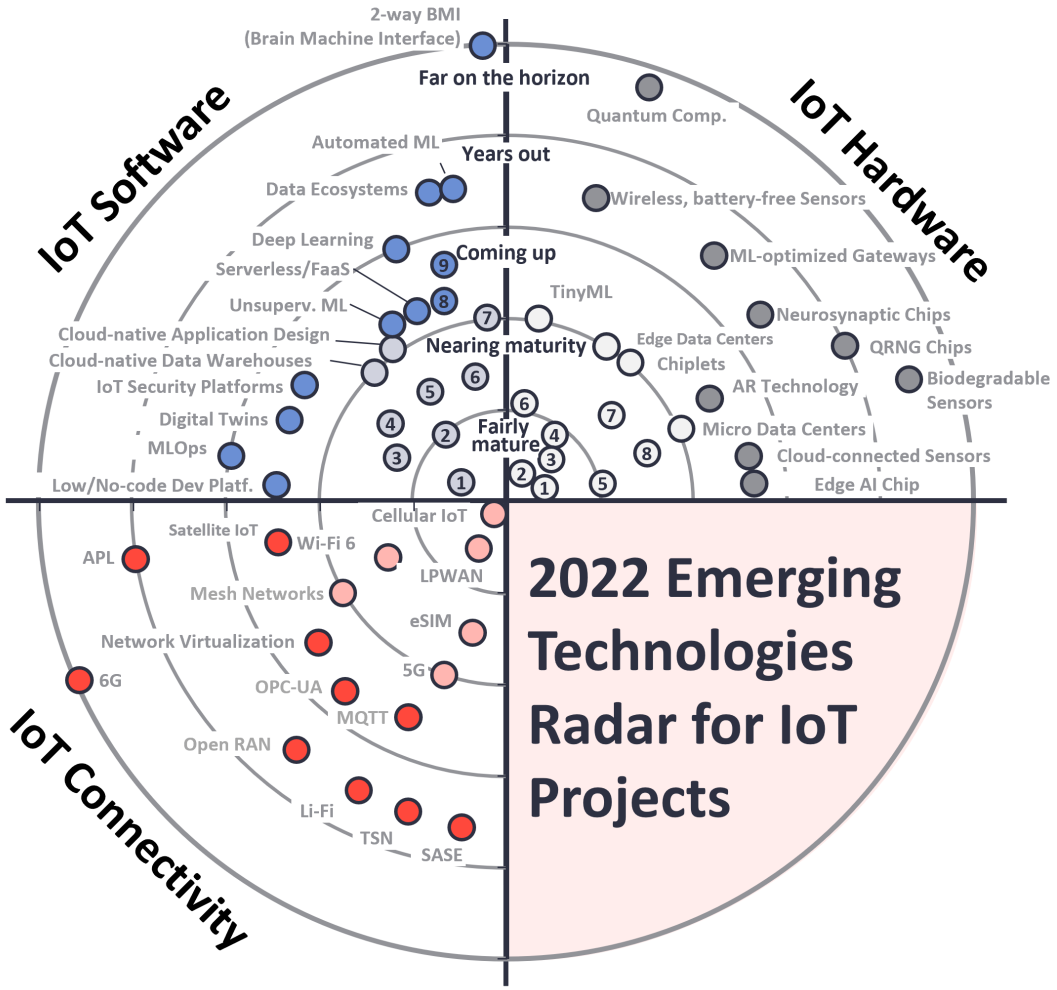
Source: https://iot-analytics.com/wp/wp-content/uploads/2022/08/Hybrid-terrestrial-satellite-mode-min.png

IOT ANALYTICS

April 2022

Your Global IoT Market Research Partner

Emerging IoT Technologies Radar 2022



1. Cloud Computing
2. IoT Platforms
3. Containers
4. Supervised ML
5. IoT-based Streaming Analytics
6. Edge AI
7. Real-time Databases
8. IoT Marketplace
9. Edge Data and App Platforms

1. CPUs
2. MCUs
3. GPUs
4. Security Chips
5. Edge Gateway
6. FPGA
7. ASICs
8. Intelligent Sensors

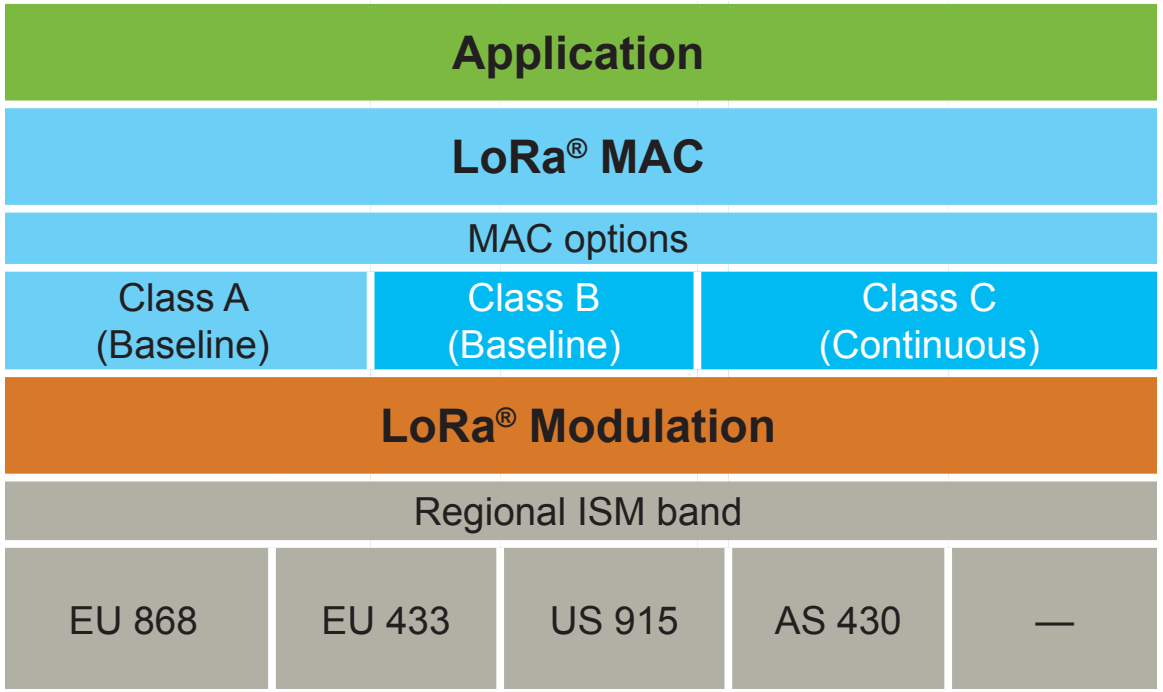
Disclaimer: The 2022 Emerging Technologies Radar for IoT projects represents the analyst view of the IoT Analytics' research team under the disclaimer that, depending on the context, the classification and perception of the project may be different in reality. IoT software refers to middleware, analytics, storage, platforms, and applications. The only relevant positioning of each topic is its distance to the center. The positioning on the axes plays no role.

Source: IoT Analytics Research—April 2022. We welcome republishing of images but ask for source citation with a link to the original post and company website.

LoRa + LoRaWAN

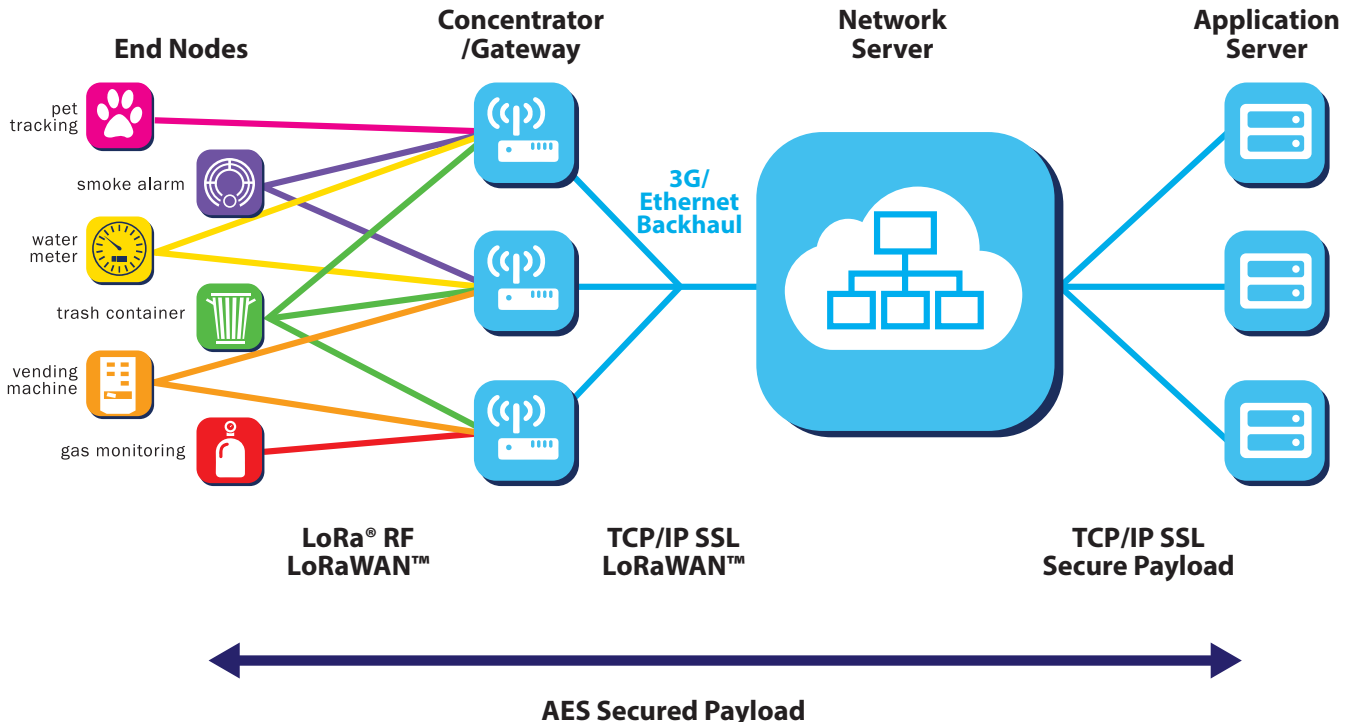
- LoRa – Long Range
  - Proprietary physical layer technology from Semtec
  - Based on chirp spread spectrum (CSS) modulation
  - Very low noise floor for enhanced coverage
- LoRaWAN
  - MAC and higher layer specifications
  - Open source
  - Allows third part implementation

LoRa + LoRaWAN



Source: LoRa Alliance

LoRa + LoRaWAN



Source: LoRa Alliance

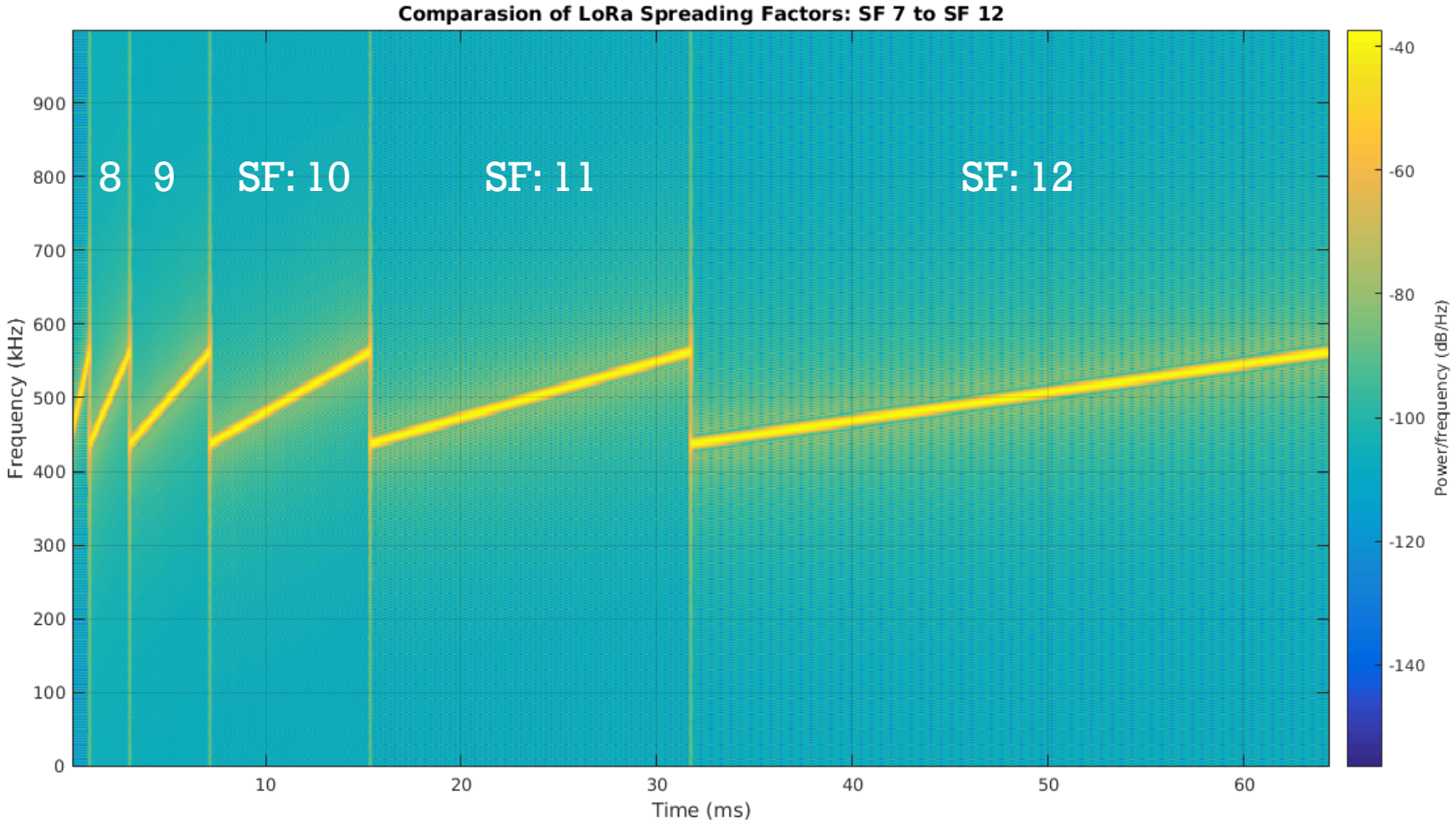
Chirp Spread Spectrum (CSS)

- LoRa uses CSS as the modulation scheme
- Operates on scalable bandwidth (125kHz, 250kHz, 500kHz)
- Spreads the signal to make it robust to interference
- Bit rate: 300bps – 37.5kbps
- CSS symbol

$$s(t) = e^{-j2\pi f(t)\,t}$$

- Spreading factor (S)
- Minimum frequency (f_{min})
- Maximum frequency (f_{max})
- Bandwidth ($B = f_{max} - f_{min}$)
- Input bit (f_0)

LoRa Waveform: Spreading Factor



Source: http://www.sghoslya.com

Chirp Spread Spectrum (CSS)

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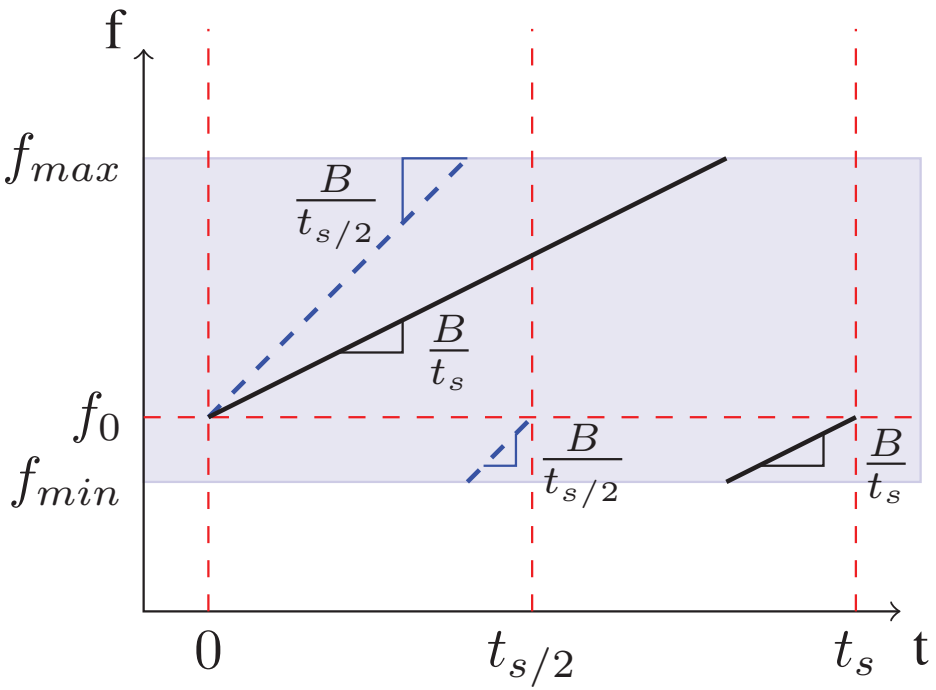
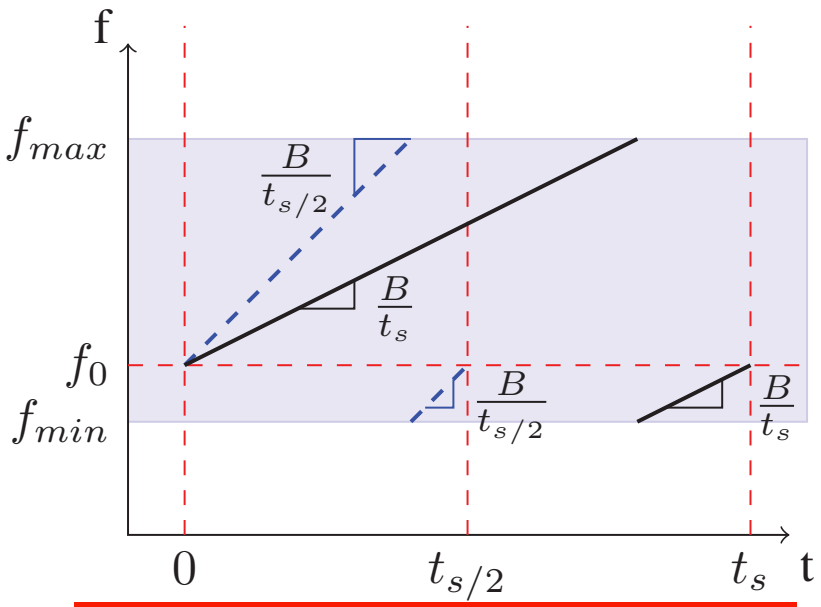


Spreading Factor

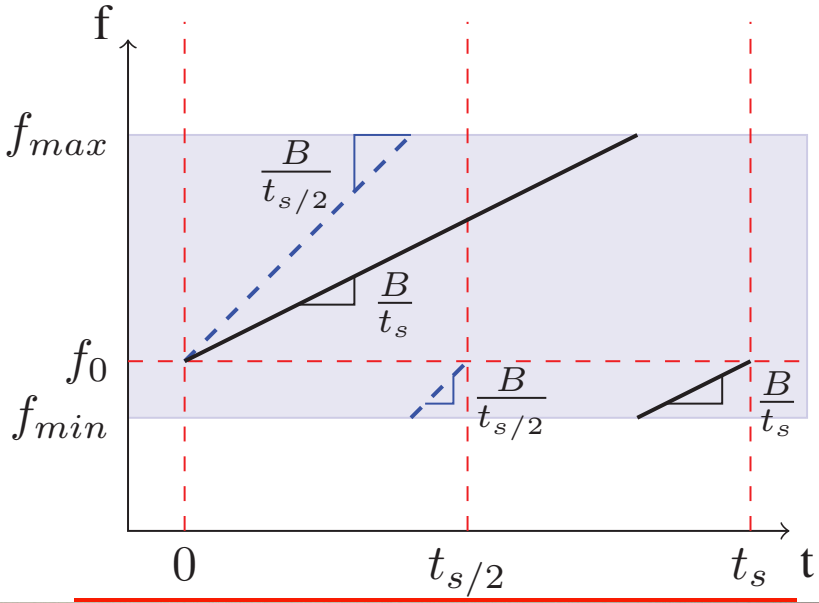
SF	BW (kHz)	Rate (bits/s)	Sensitivity
10	125	980	-132dBm
9	125	1,760	-129dBm
8	125	3,125	-126dBm
7	125	5,470	-123dBm
12	500	980	-129dBm
11	500	1,760	-128dBm
10	500	3,900	-125dBm
9	500	7,000	-122dBm
8	500	12,500	-119dBm
7	500	21,900	-116dBm

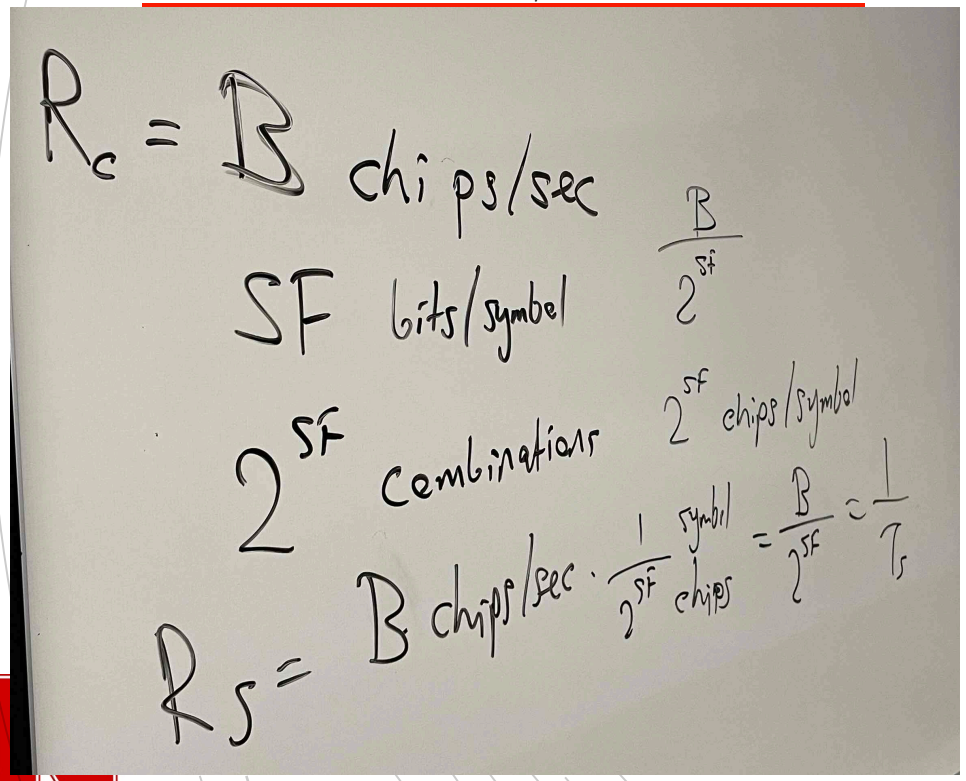
US 902-928 MHz LoRaWAN Spec



CSS Modulation

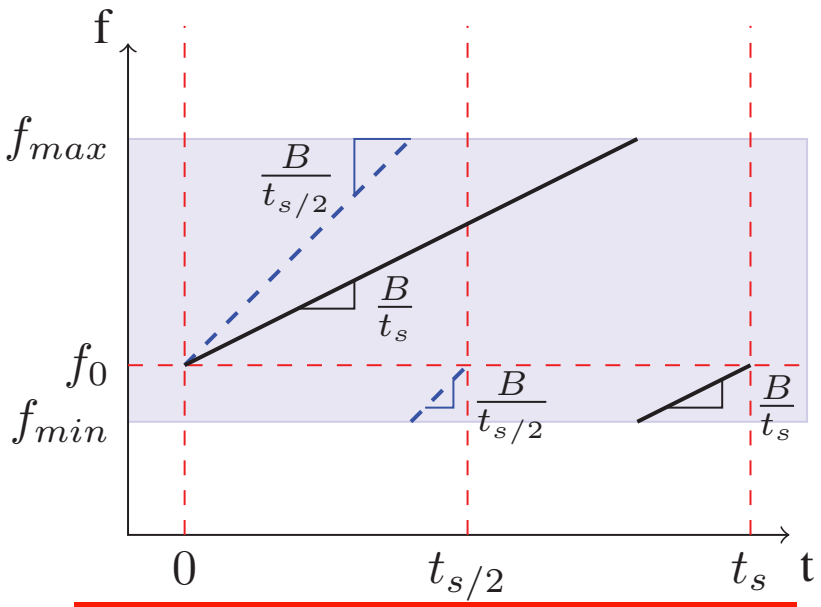
- Input bits determine the initial frequency f_0
- Depending on SF, there are 2^{SF} different initial frequencies (2^{SF} inputs)
- For a given input m, the signal chirps over all frequencies [f_{min}, f_{max}]
  - Starts from f_0 for m
  - Chirps up to f_{max}
  - Cycles back to f_{min}
  - Chirps up to f_0
- e.g., for m=0, start from f_{min}, chirp up to f_{max}





- Chip rate
  - R_c = B chips/sec
- SF binary bits create 2^{SF} combinations
- To send SF bits, we need 2^{SF} different waveforms
- These waveforms are generated by changing the initial frequency f_0 for a given set of bits (one of the 2^{SF} combinations)
- Therefore, we have 2^{SF} chips/symbol
- Symbol rate
  - Rs = B chips/sec * $1/2^{SF}$ symbols/chips

$$R_s = \frac{B}{2^{SF}} = \frac{1}{t_s}\ symbols/sec$$



CSS Modulation

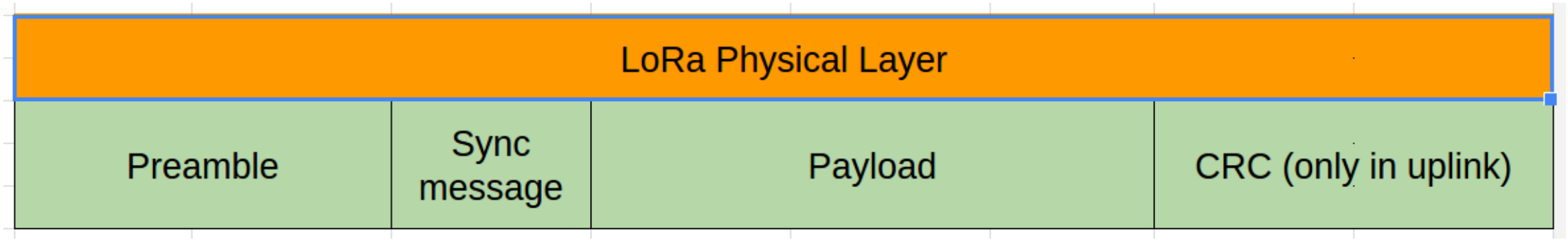
- Bits are modulated onto symbols based on the spreading factor
- Spreading factor (SF) determines
  - Modulation order, i.e., how many bits are mapped to a symbol (SF)
  - Symbol duration t_s

$$t_s = \frac{2^{SF}}{B} = \frac{2^{SF}}{f_{max} - f_{min}}$$

- Data rate R_b

$$R_b = \frac{SF}{t_s}$$

$$R_b = \frac{SF(f_{max} - f_{min})}{2^{SF}}$$



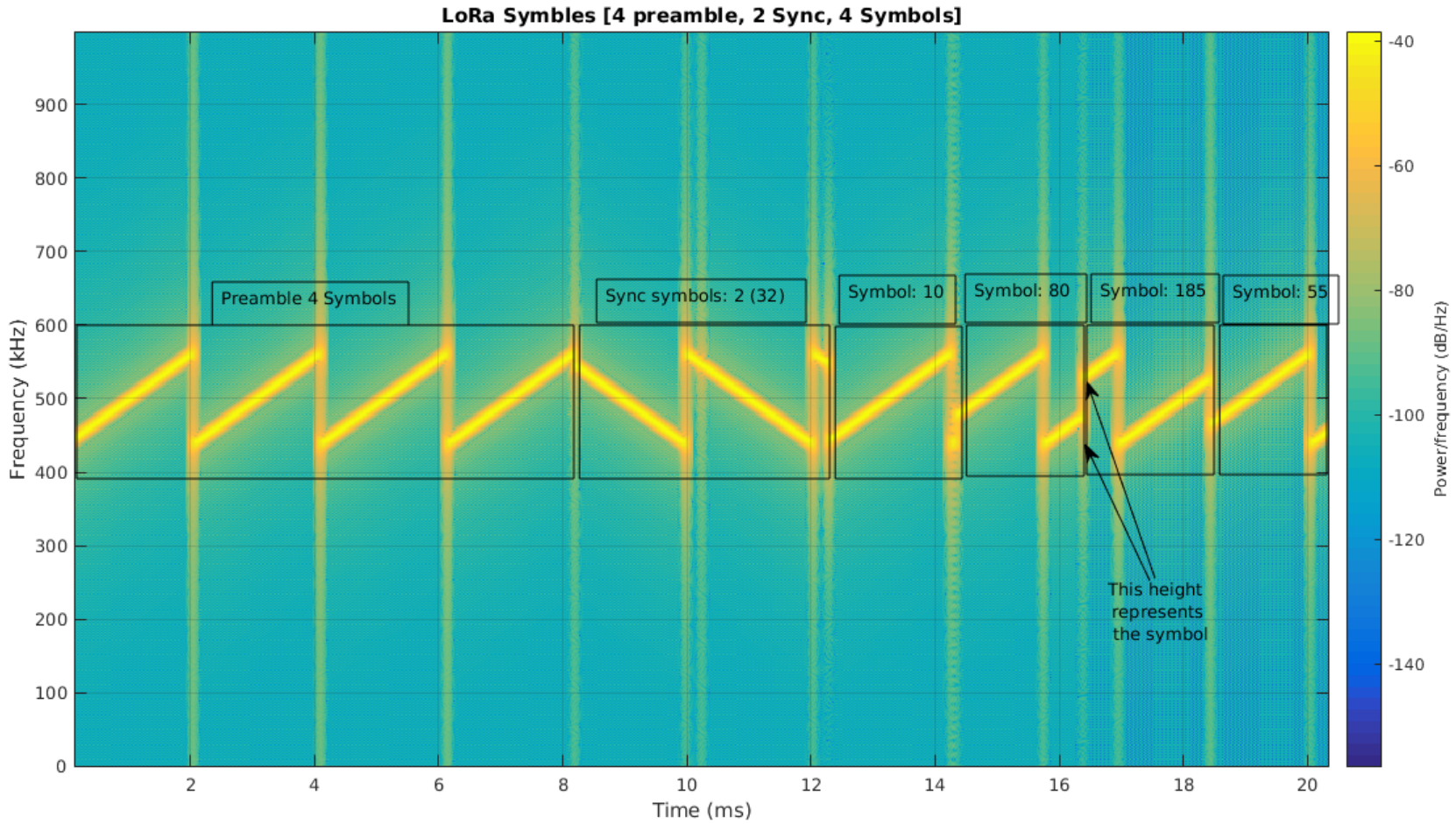
LoRa Packet

Source: LoRa Alliance

Example

- LoRa message with SF=8 at 125kHz
- 8 bits per symbol
- 2^8=256 levels
- 125kHz/256 = 488.3Hz step size
- Message
  - Preamble – 4 symbols (fixed, zeros)
  - Sync – 2 down chirp symbols
  - Payload – 4 symbols (10, 80, 185, 55)

Example

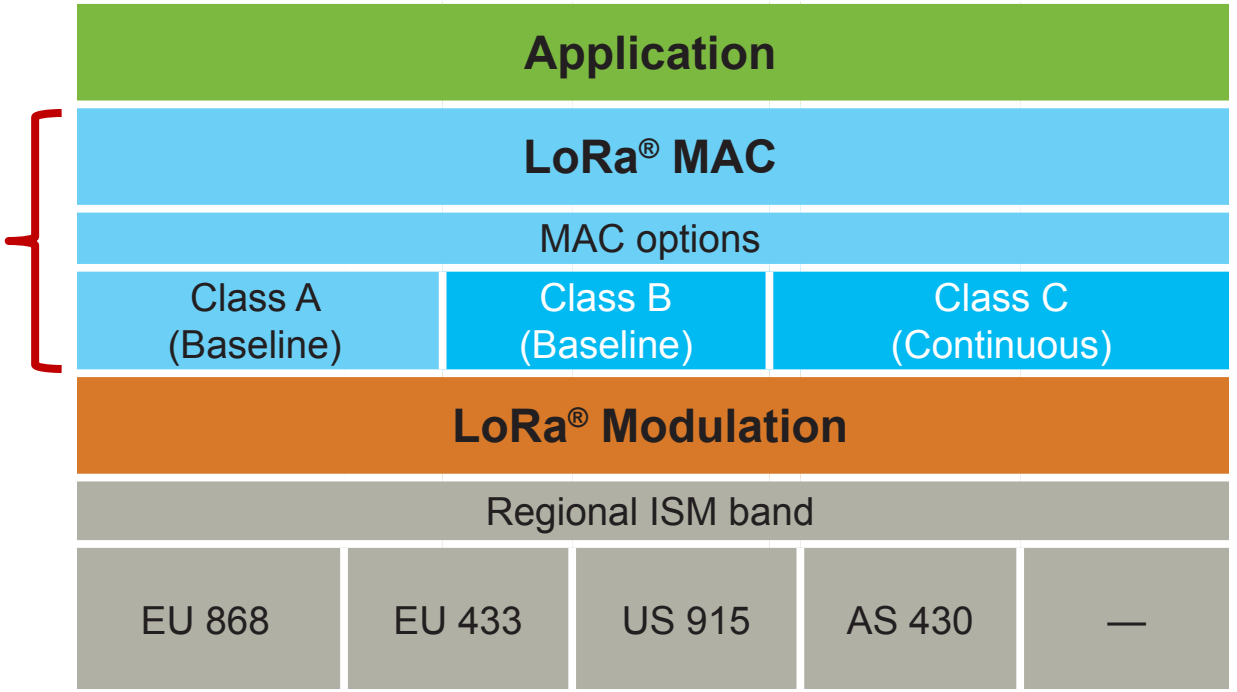


Source: http://www.sghoslya.com

LoRa Advantages

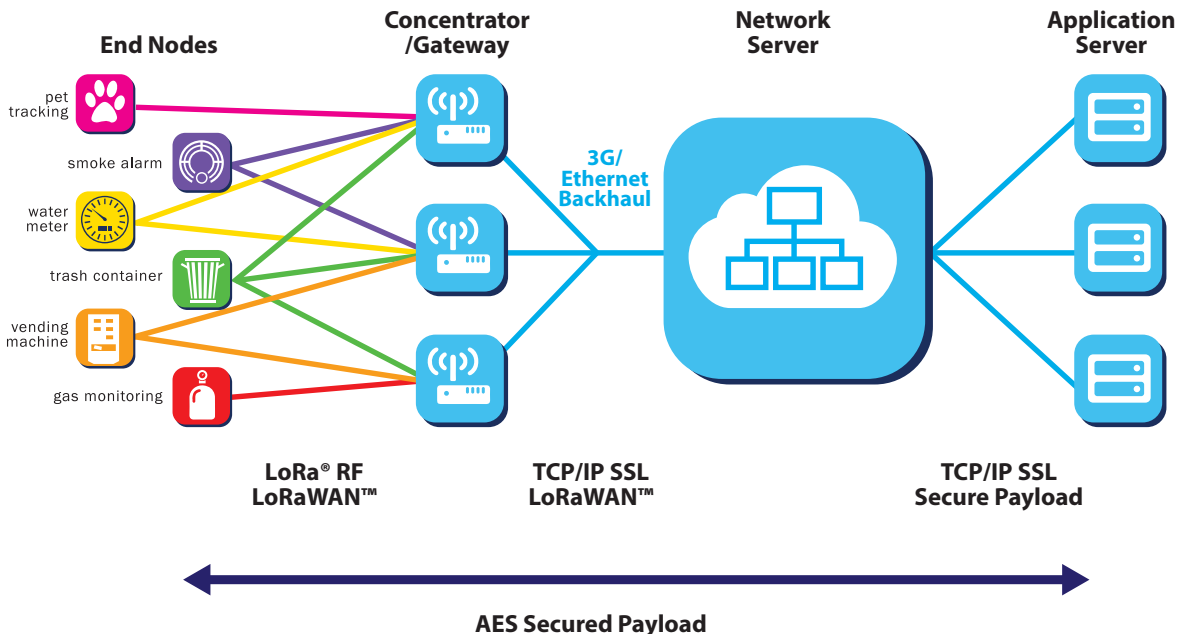
- Extremely low noise floor – large coverage for LPWAN
- Range, data rate, air time can be adapted by SF
- For a given BW, different symbols with different SF values are orthogonal
- Increased network density with parallel communications

LoRaWAN



Source: LoRa Alliance

LoRaWAN

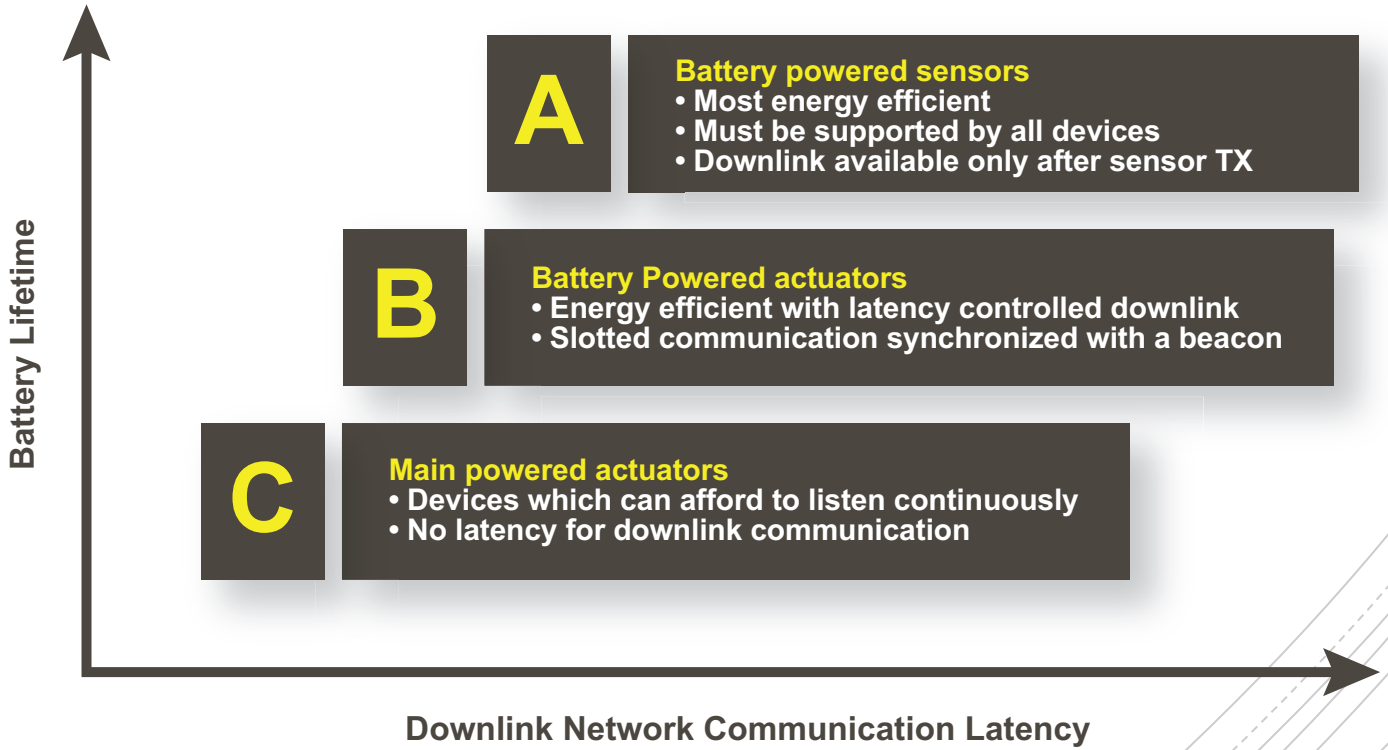


- LoRaWAN® L2 1.0.4 Specification (TS001-1.0.4)
- Star-of-stars topology
- Gateway<u>s</u> relay transmissions b/w end-devices and a central Network Server (NS)
  - End-device – Gateway: LoRa
  - Gateway – NS: Standard IP
- Majority traffic: Uplink (from end-device to NS)
- Medium Access Control (MAC)
  - Multiple frequencies (frequency hopping)
  - Multiple data rates (SF)
  - Over time (ALOHA or pings)

Source: LoRa Alliance

End-Devices

- Three device classes
- Support diverse applications



Source: LoRa Alliance

End-Devices

- Class A: Lowest-power end-device system
- Supported by all devices
- Allow bi-directional communications
- Uplink transmission is followed by two short downlink receive windows
- ALOHA-type protocol
- Downlink communication from the server only shortly after the uplink transmission

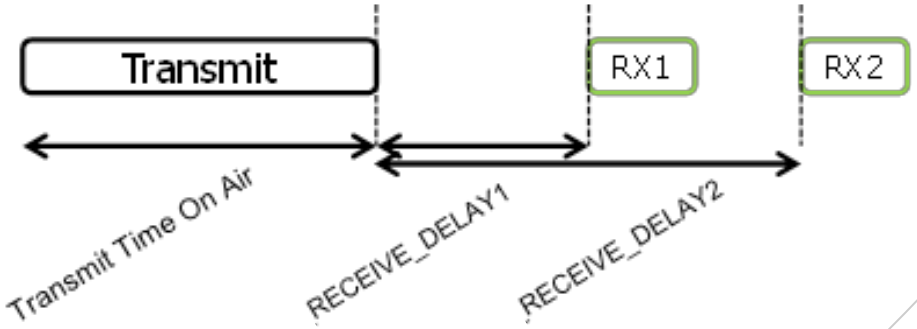
- Class B: Extra receive windows at scheduled times
- Time-synchronized beacon from the gateway

- Class C: Nearly continuously open receive windows
- Use more power (generally plugged in) but the lowest latency

Packets

- Uplink Packets: From end-devices to NS, relayed by one or many gateways
- Downlink Packets: From NS to one end device, through one or more gateways

End-device



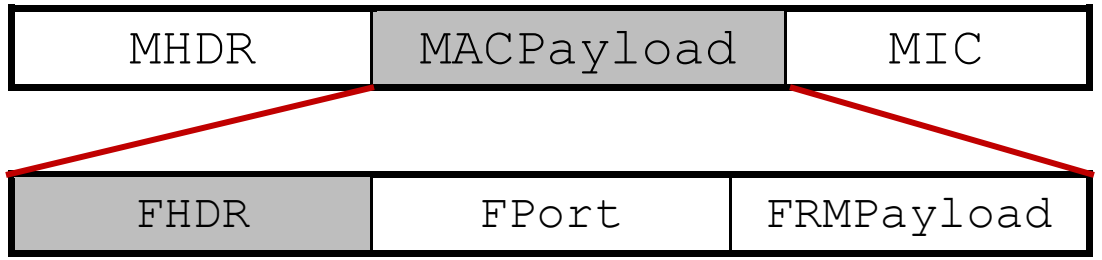
Source: LoRa Alliance

MHDR	MACPayload	MIC

Packets

- MAC Header (MHDR): Frame type (join, uplink, downlink, etc); frame format
- MAC Payload
- Message Integrity Code (MIC): Encryption

Source: LoRa Alliance

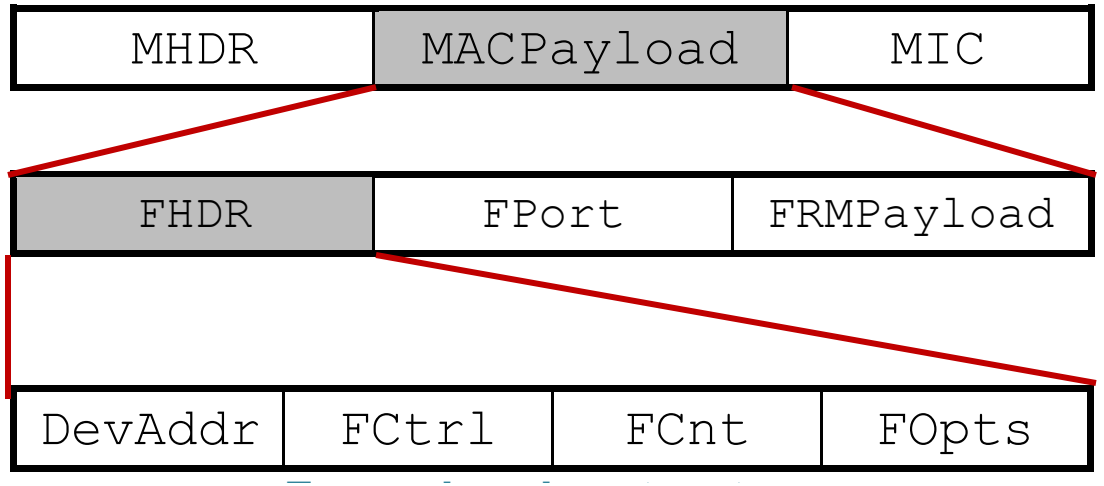


Packets

- MAC Payload:
- Frame Header (FHDR)
- Port field (FPort): Test protocol
- MAC payload encryption (FRMPayload): Payload is encrypted based on AES 128

Source: LoRa Alliance

Packets



- Frame Header (FHDR):
- End-device address (DevAddr)
- Frame control (FCtrl): For adaptive data-rate control, retransmissions, and multi-packet comm.
- Frame Counter (FCnt): Keeps track of uplink and downlink frame counters, specifies options length
- Frame Options (FOpts): Optional field

Size (octets)	4	1	2	0..15
FHDR	DevAddr	FCtrl	FCnt	FOpts

Source: LoRa Alliance

Adaptive Data-Rate (ADR) Control

Downlink

Bits	7	6	5	4	[3..0]
FCtrl	ADR	RFU	ACK	FPending	FOptsLen

Uplink

Bits	7	6	5	4	[3..0]
FCtrl	ADR	ADRACKReq	ACK	ClassB	FOptsLen

- NS can adapt number of retransmissions, data rate (SF), and transmit power of end-devices
- Uplink ADR bit
  - End-devices may allow NS to adopt these parameters
- Downlink ADR bit
  - Informs the end-user that NS can send ADR commands
- LoRaWAN leaves implementation of ADR to NS – active research area!

Source: LoRa Alliance

Retransmissions

Downlink

Bits	7	6	5	4	[3..0]
FCtrl	ADR	RFU	ACK	FPending	FOptsLen

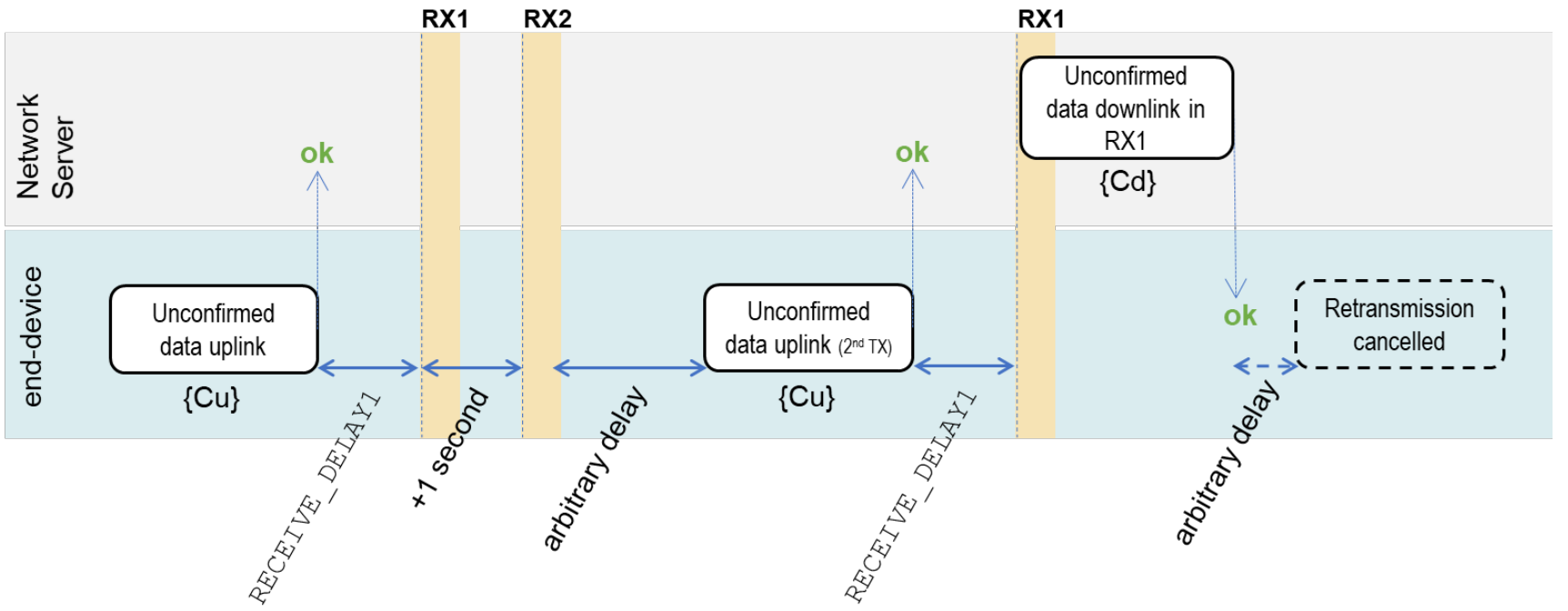
Uplink

Bits	7	6	5	4	[3..0]
FCtrl	ADR	ADRACKReq	ACK	ClassB	FOptsLen

- Packets are retransmitted based on packet type (unconfirmed or confirmed - FType)
- Unconfirmed data - Number of retransmissions can be adapted by NS (NbTrans)
- Confirmed data:
  - ACK is sent following the successful receipt of a packet
  - Can be explicit (empty ACK packet) or piggybacked in the next transmission

Source: LoRa Alliance

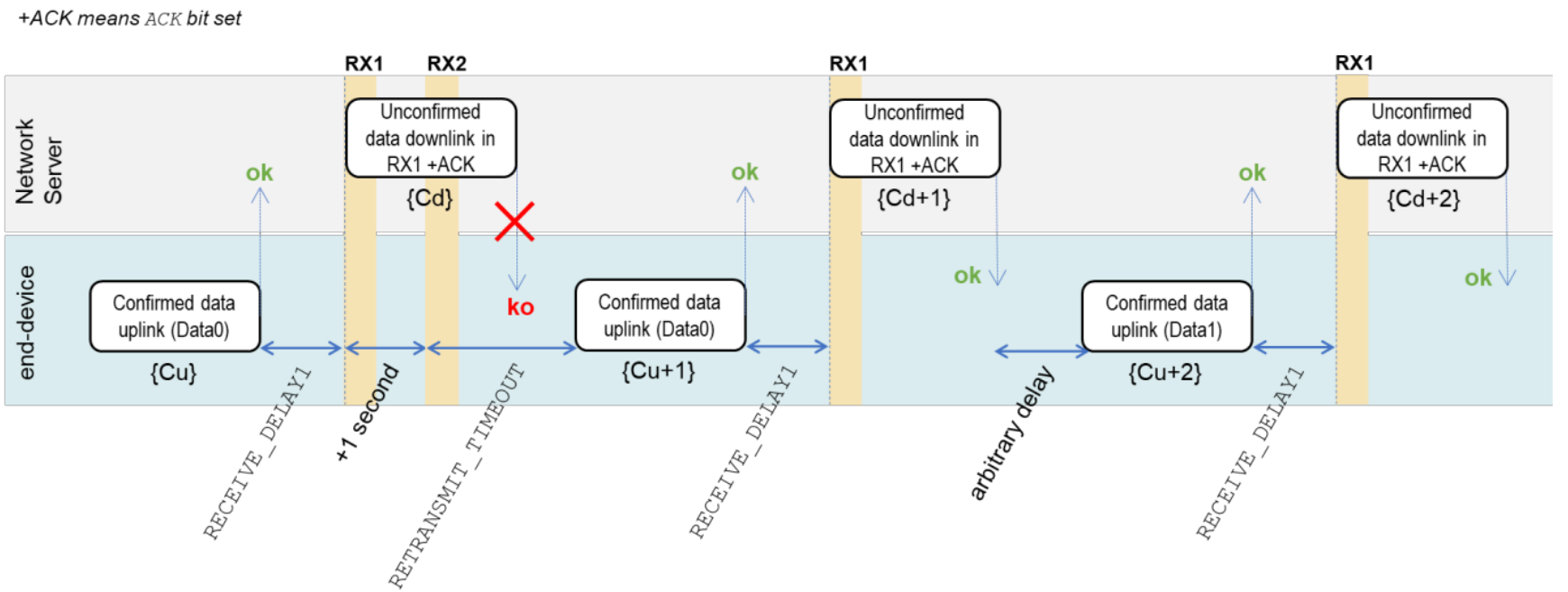
Unconfirmed Packets



- NbTrans = 3
- End-device retransmits the packet until it hears a downlink packet
- Assumes the packet is successfully received

Source: LoRa Alliance

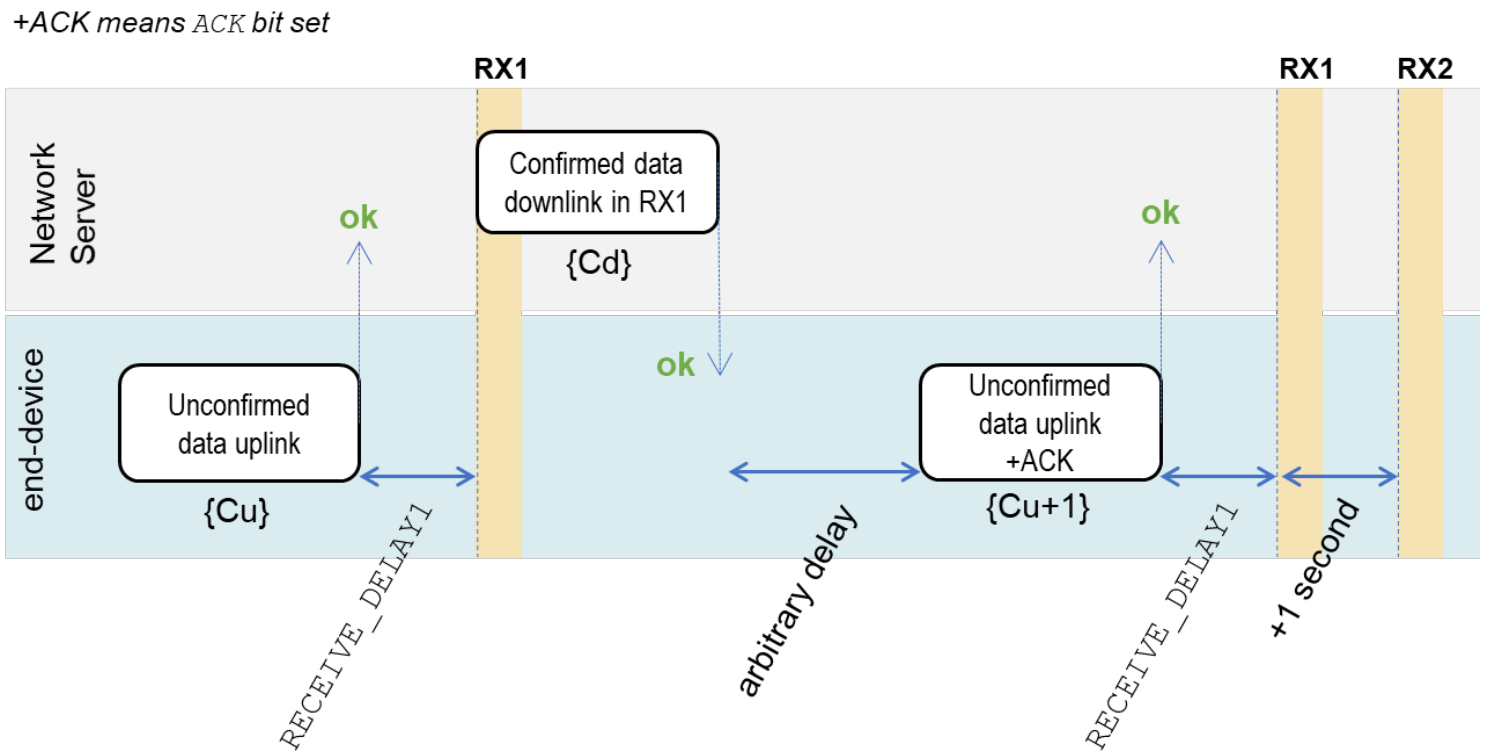
Confirmed Packets



- Uplink
- NS successfully receives Data0
- NS sets ACK bit in its packet and sends during RX1
- Downlik packet is lost
- End-user waits for RETRANSMIT_TIMEOUT sec and retransmits
- NS ACKs

Source: LoRa Alliance

Confirmed Packets



- Downlink
- Class B and Class C
- Upon receiving a downlink packet, end-device can send an ACK (explicit or piggybacked)

Source: LoRa Alliance

Multi-packet Communication

Downlink

Bits	7	6	5	4	[3..0]
FCtrl	ADR	RFU	ACK	FPending	FOptsLen

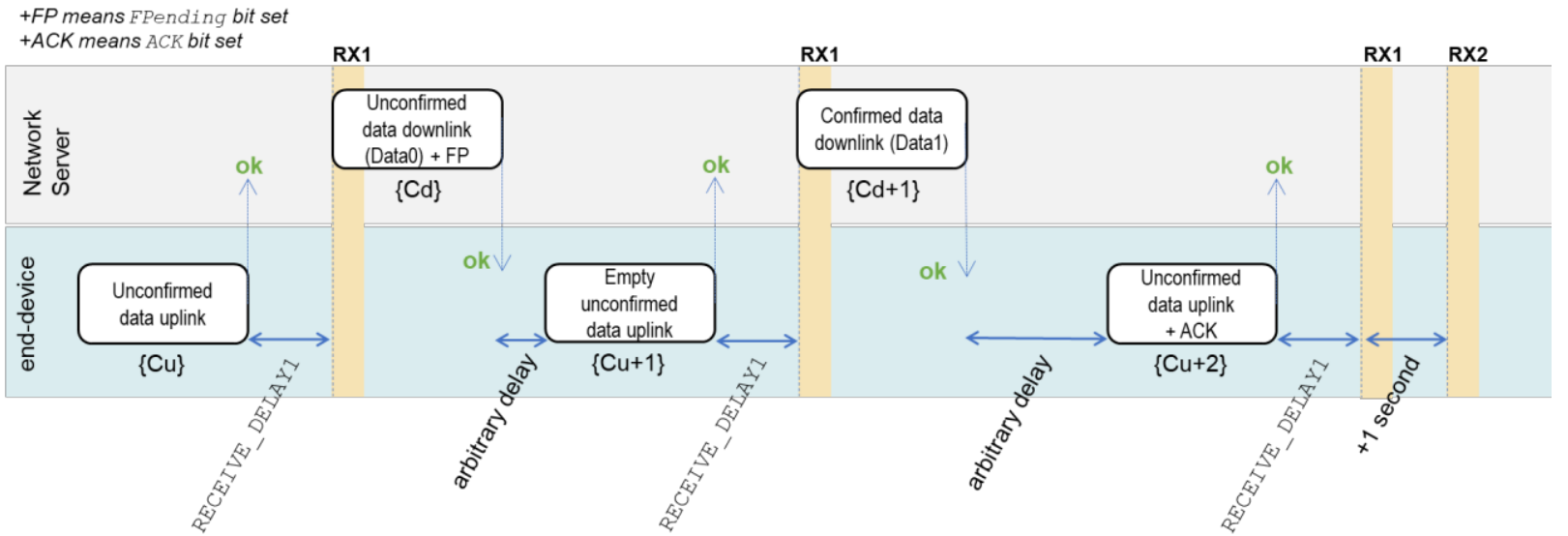
Uplink

Bits	7	6	5	4	[3..0]
FCtrl	ADR	ADRACKReq	ACK	ClassB	FOptsLen

- Frame pending bit (FPending): Only for downlink
  - NS indicates to end-device that it has pending data to be sent
  - End-device may send an uplink packet to receive the downlink data (Class A)
  - Class B continues to listen

Source: LoRa Alliance

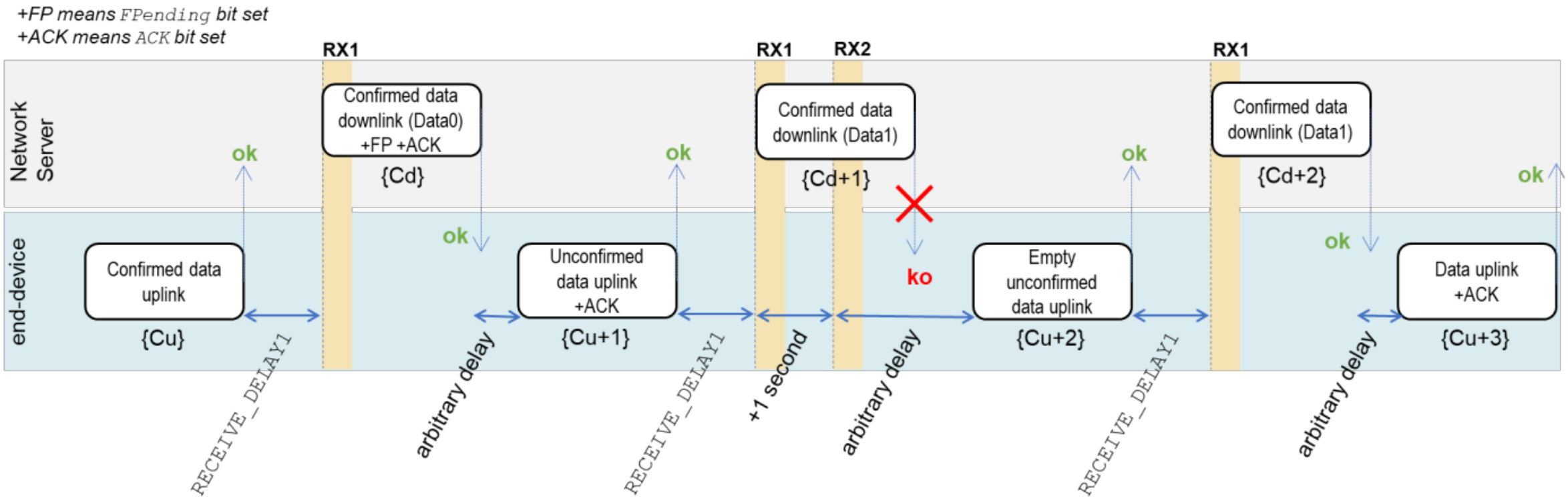
Multi-packet Communication



- Downlink
- NS has two packets to send
- FP bit is set in the first packet (unconfirmed, Data0)
- Upon receiving Data0, end-device transmits an empty packet
- Second packet is sent (confirmed, FP=0, Data1)
- End-device sends an ACK

Source: LoRa Alliance

FP, ACK, Piggyback in Action



Source: LoRa Alliance

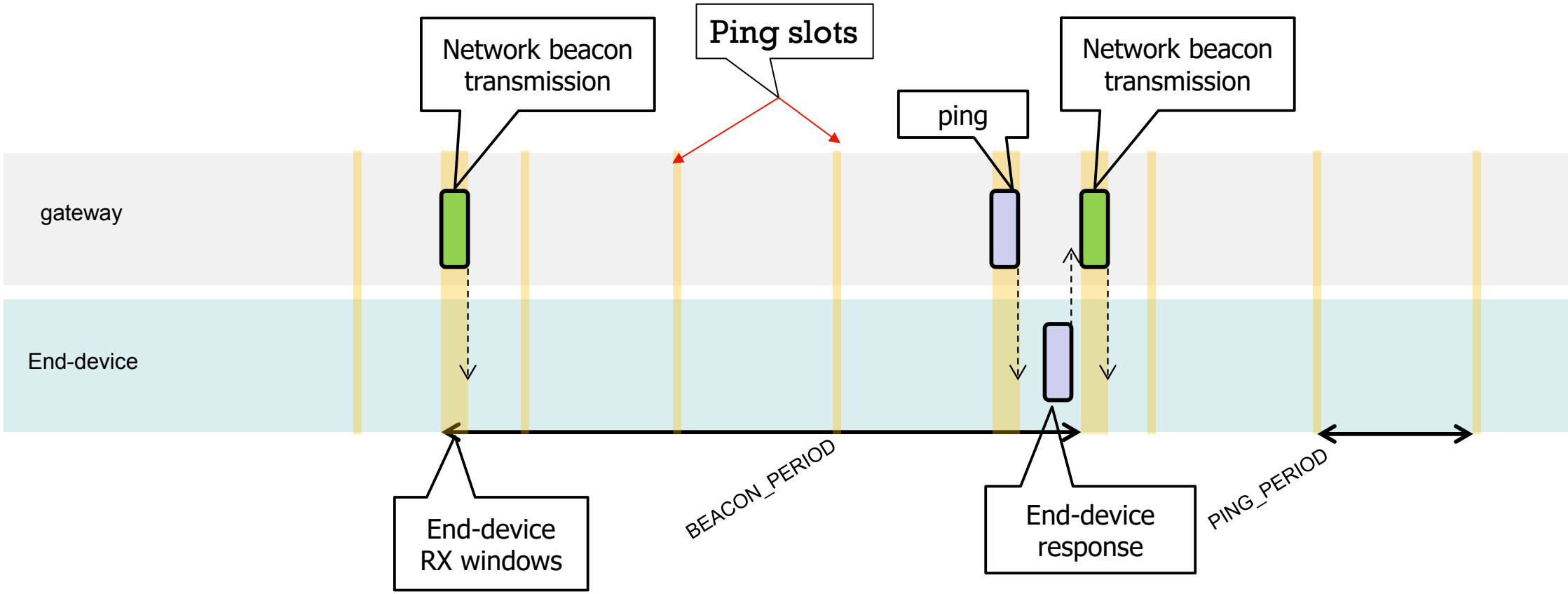
MAC

- Class A devices use ALOHA for arbitration during uplink transmission
- ALOHA – primitive CSMA
- Disadvantages
  - RX window is available only following random uplink transmissions
  - Does not provide delay guarantees for network-initiatied downlink transmission
- Class B: Adds synchronized reception window for end-devices
- Network broadcasts beacons to facilitate synchronization
- Class B devices periodically open receive windows (ping slots)
- Network can initiate downlink transmissions (pings) during ping slots

Class B Beacons

- Beacons serve as a timing reference for ping slots
- Gateways transmit beacons at a certain period (BEACON_PERIOD)
- End-devices open ping slots at a certain period (PING_PERIOD)
- Default values for
  - Ping-slot periodicity
  - Ping-slot data rate
  - Ping-slot channel
- Based on region and can be updated by the gateway

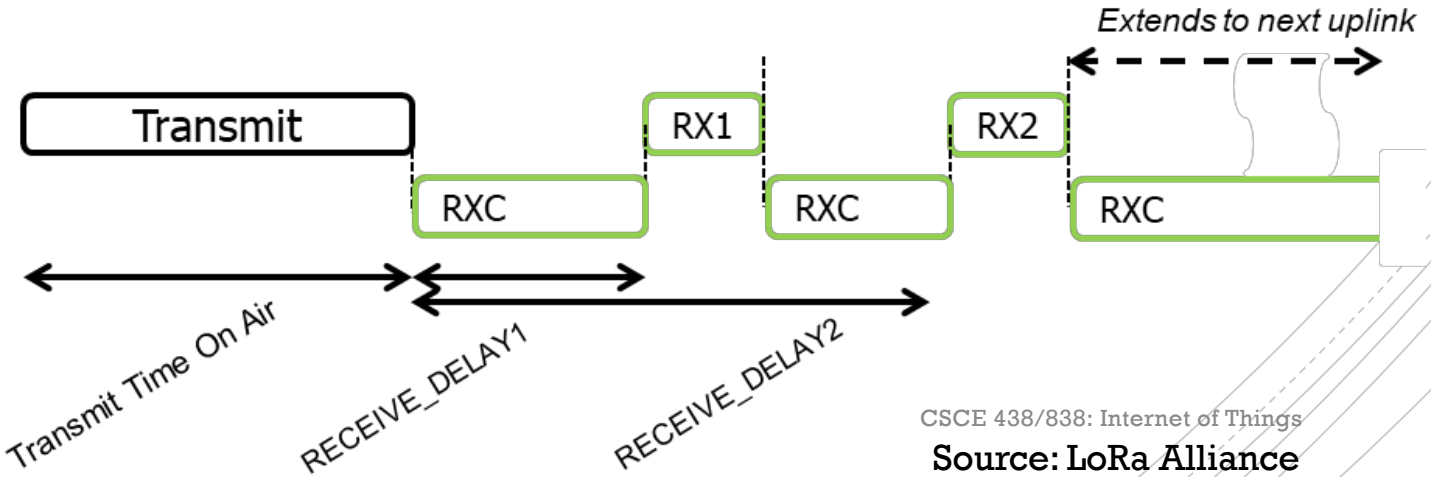
Class B Beacons



Source: LoRa Alliance

Class C

- Used for cases when continuous listening is required
- End-device listens as often as possible on RXC windows
  - Between end of TX and RX1
  - Between RX1 and RX2
  - After RX2 until TX



Source: LoRa Alliance

LoRaWAN

- Specification defines general operating conditions
- Specific parameters are set per operation region
- RP002-1.0.3 LoRaWAN® Regional Parameters

	Europe	North America
Frequency band	867-869MHz	902-928MHz
Channels	10	64 + 8 +8
Channel BW Up	125/250kHz	125/500kHz
Channel BW Dn	125kHz	500kHz
TX Power Up	+14dBm	+20dBm typ (+30dBm allowed)
TX Power Dn	+14dBm	+27dBm
SF Up	7-12	7-10
Data rate	250bps- 50kbps	980bps-21.9kpbs
Link Budget Up	155dB	154dB
Link Budget Dn	155dB	157dB

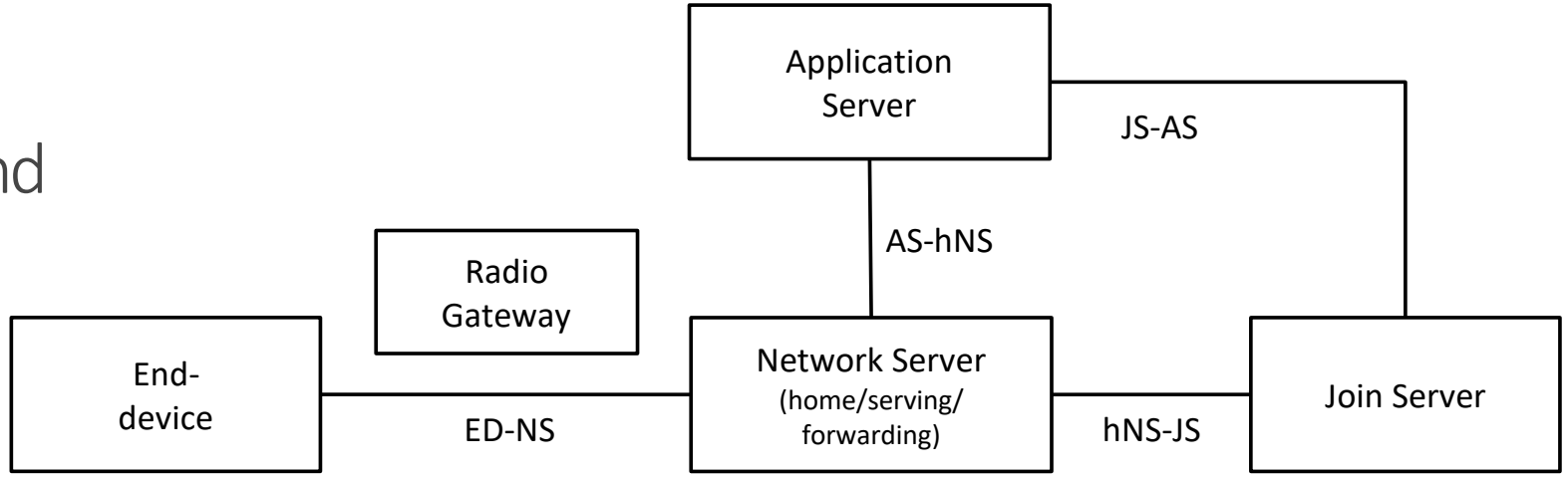
Source: LoRa Alliance

LoRaWAN US Data Rates

	Data Rate	Configuration	Indicative physical bit rate [bit/sec]
UL	0	LoRa: SF10 / 125 kHz	980
	1	LoRa: SF9 / 125 kHz	1760
	2	LoRa: SF8 / 125 kHz	3125
	3	LoRa: SF7 / 125 kHz	5470
	4	LoRa: SF8 / 500 kHz	12500
	5	LR-FHSS CR1/3: 1.523 MHz BW	162
	6	LR-FHSS CR2/3: 1.523 MHz BW	325
	7	RFU	
DL	8	LoRa: SF12 / 500 kHz	980
	9	LoRa: SF11 / 500 kHz	1760
	10	LoRa: SF10 / 500 kHz	3900
	11	LoRa: SF9 / 500 kHz	7000
	12	LoRa: SF8 / 500 kHz	12500
	13	LoRa: SF7 / 500 kHz	21900

Source: LoRa Alliance

LoRaWAN Backend

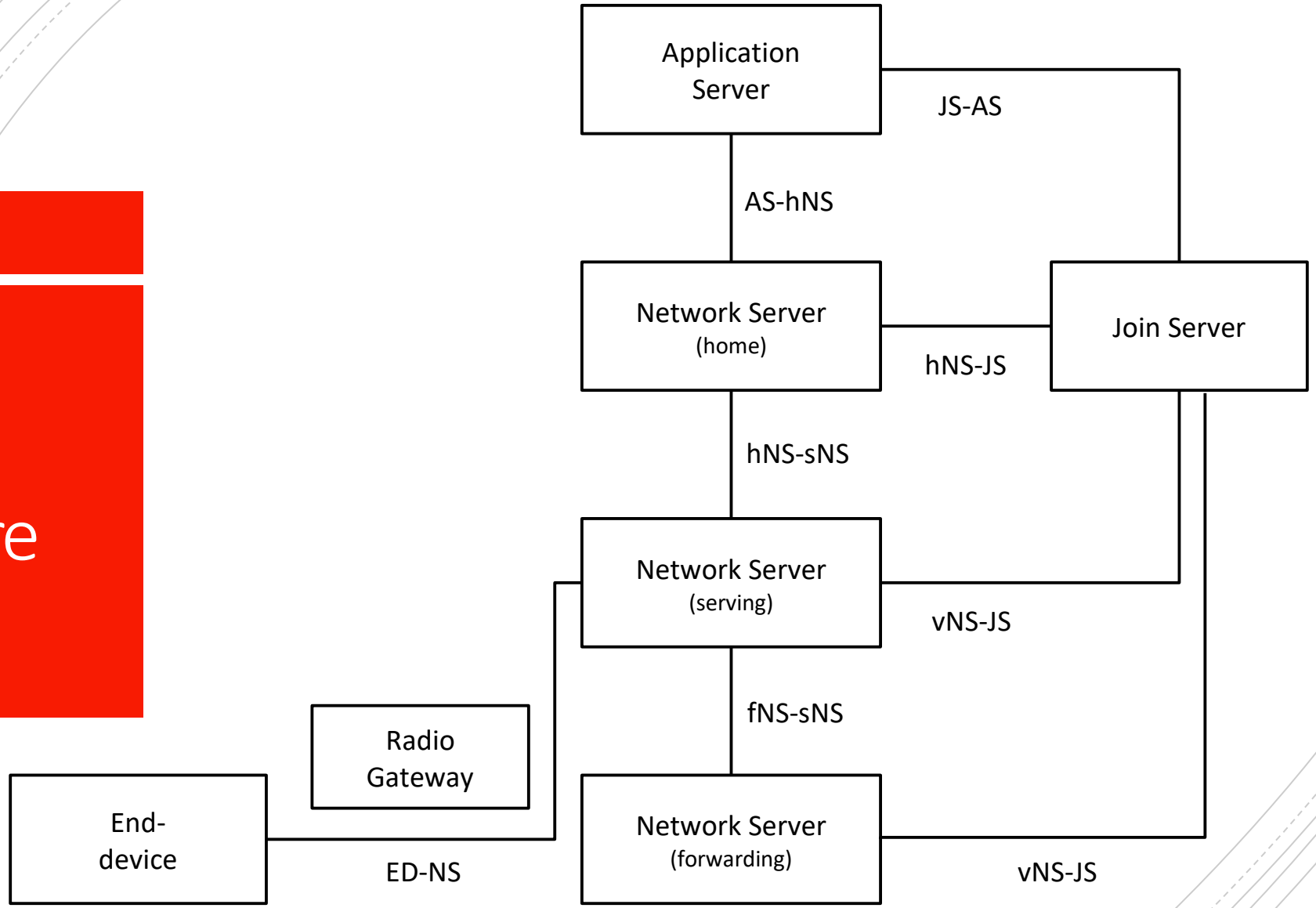


- TS2-1.1.0 LoRaWAN Backend Interfaces
- End-Device: Sensor or actuator
  - Wirelessly connected to Radio Gateways (GWs)
  - Application layer is connected to an application server in the cloud
  - All application layer payloads end up at the application server
- Radio Gateway: Forwards all packets to Network Server
  - Connected to NS via IP
  - Decode packets and forward them to NS or vice versa
- Network Server: Terminates the LoRaWAN MAC layer
  - Center of star-of-stars topology
  - Authentication, ACK, ADR, MAC, roaming
- Join Server: Manages end-device activation
- Application Server: Handles application layer payloads
  - Service to end-user
  - Multiple ASs to an NS, multiple NSs to an AS
- LoRaWAN defines interfaces b/w entities

Roaming

- LoRaWAN allows end-devices to roam between different LoRa networks (mobile) or be served by another LoRa network
- Network Server plays three roles
- Serving NS (sNS): Controls MAC layer of end-device
- Home NS (hNS): Stores Device Profile, Service Profile, Routing Profile, etc. of end-device
  - Connected to application server
  - Roaming agreement b/w sNS and hNS
  - UL/DL packets forwarded b/w/ sNS and hNS
- Forwarding NS (fNS): Manages radio gateways
  - Roaming agreement b/w fNS and sNS
  - Multiple fNSs may serve an end-device

Roaming Architecture



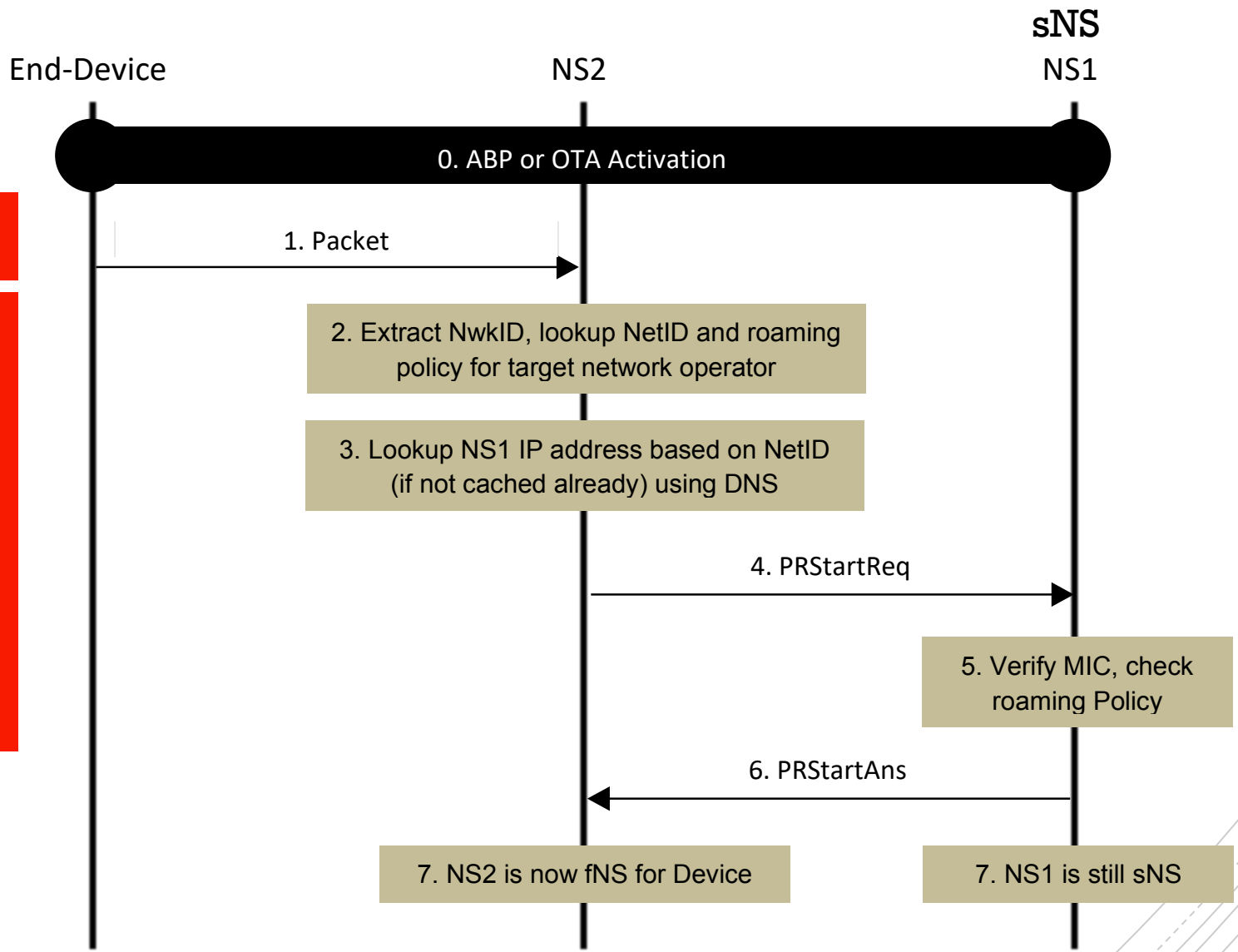
Roaming

- Two types
- Passive roaming: End-devices are logically connected to sNS even while physically connected to GWs of fNSs
- Handover roaming: Enables MAC-layer control transfer from one NS to another (i.e., transfer sNS)

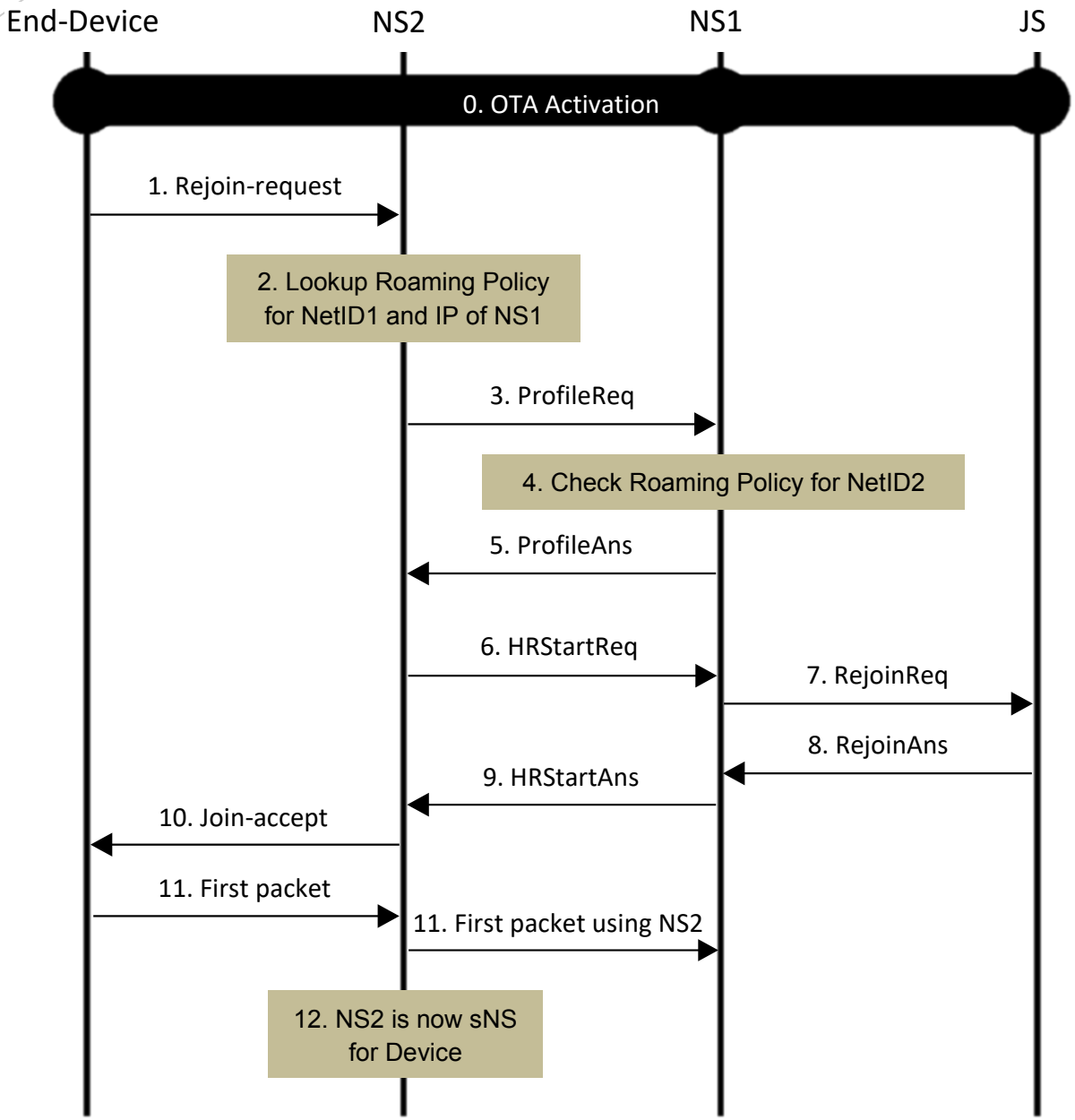
Passive Roaming

- End-device is connected to GWs of fNSs
- LoRa session and MAC-layer control are maintained by sNS
- 1 sNS + multiple fNSs

Passive Roaming



Handover Roaming



Other Functionalities

- Synchronization
- Geolocation
- Error control
- Encryption

LoRa + LoRaWAN Advantages

- License-free operation
  - Low cost
- LoRa - CSS
  - Extremely low noise floor
  - Greater coverage than cellular
  - Deeper indoor coverage
  - Robust to interference
- Range, data rate, air-time can be adapted by SF
- For a given BW, different symbols with different SF values are orthogonal
- Increased network density with parallel communications
- Low-power operation and long lifetime
- Open-source WAN
- Multi-tenant operation (roaming)

LoRa + LoRaWAN Disadvantages

- License-free operation
  - More sources of interference
- Proprietary PHY layer
  - Updates not easy
  - Future proof?
- Disjoint from 5G systems (Cellular + WiFi)
- Low data rates
  - Limited applications
- Low duty cycle requirements
  - EU – 1-10%
  - China - <1%
- Loose timeliness guarantees
  - Class B cannot guarantee strict delay and jitter requirements for real-time traffic (automation)