LoRa: Long Range Communication System for IoT

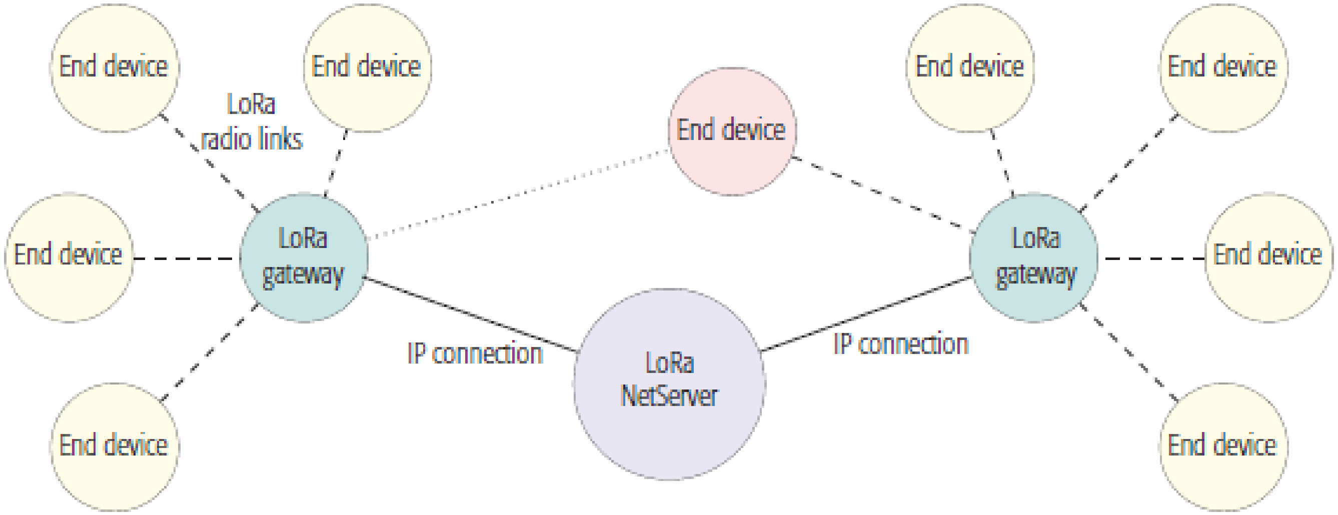
LoRa IoT Networks

❖ LoRa Component

- Composed of end devices, gateways, and a network server
  - End devices are connected with one or more gateways through one-hop LoRa link
  - Gateways forward all successfully decoded messages from end devices to their associated network server through standard IP link

❖ LoRa Topology

- Star-of-Stars



Classification of Long Range IoT Applications

❖ Traffic pattern

- Uplink
  - A control station collects the data produced by the end devices
  - Smart metering, monitoring applications
- Uplink & Downlink
  - A control station sends the command to the end devices according to the collected data
  - Environmental control

❖ Energy constraints

- With strict energy constraints
  - Most end devices have strict energy constraints
- Without strict energy constraints
  - Some end devices connected to the power have less strict energy constraints

Short Summary of LoRa Features

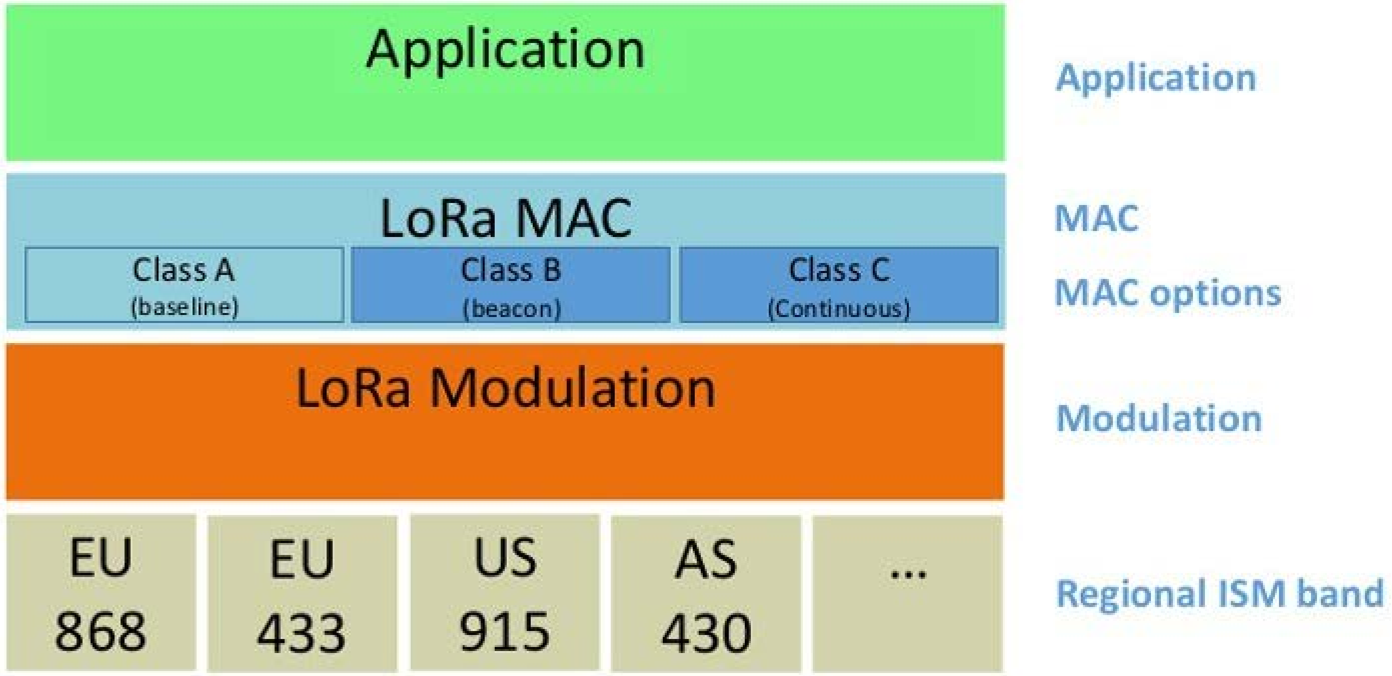
- **Low bandwidth on sub-GHz band**
  - Regional ISM bands
    - 863-870 MHz (EU), 902-928 MHz (US), 917-923.5 MHz (KR, SKT)
  - Bandwidth: 125 kHz (250 kHz, 500 kHz, 150 kHz)
- **Low data rate**
  - Range from 0.3 kbps to 50 kbps
- **Long range**
  - Rural : 10-15 km
  - Urban : 3-5 km
- **Long Life Time**
  - < 10 years
- **Low Cost**
  - < 1 USD

LoRa End Devices

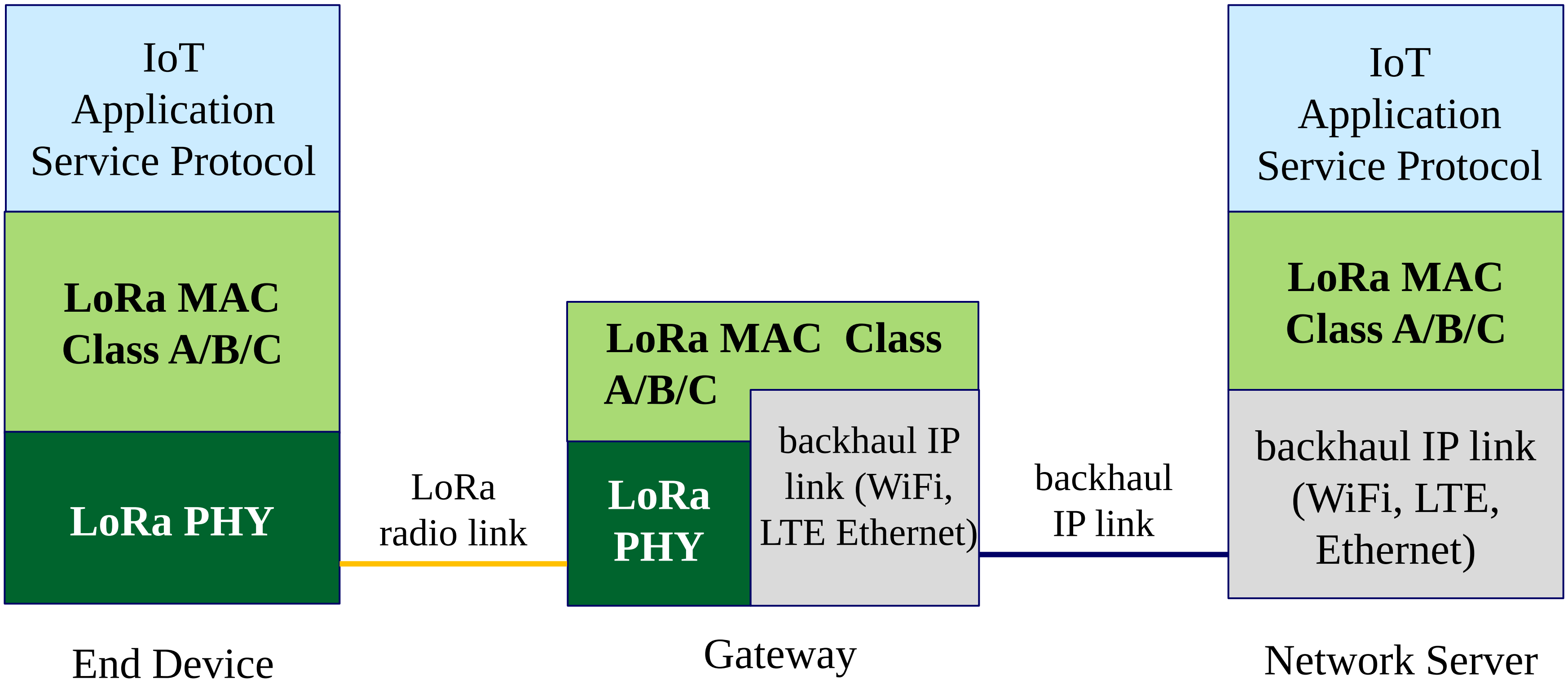
❖ Three Classes

- Class A (All)
  - Default functions which should be supported by all LoRa devices
  - Asynchronous uplink transmission (transmission at any time accoring to pure ALOHA), followed by two downlink receive windows
  - Intended for monitoring applications
- Class B (Beacon)
  - End devices synchronize with the server by using beacon packets
  - Open extra receive windows at scheduled times
  - Intended for control applications
- Class C (Continuously listening)
  - End devices continuously open receive windows except for time when transmitting
  - Intended for devices without strict energy constraints

Standard Protocol Stack



Protocol Stack

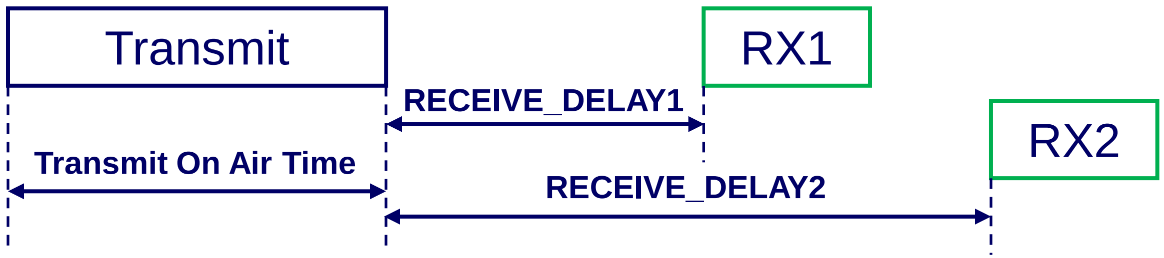


Any gateway that receives an uplink message relays it to network server.
=> multiple copies of an uplink message can be delivered to the server.
A downlink message is sent to an end device by only one gateway.

Receive Windows (1)

❖ Class A Receive Windows

- First receive window (RX1)
  - Opens RECEIVE_DELAY1 after the end of uplink modulation
  - Use same frequency channel as the uplink channel
  - With the same data rate as last uplink data rate
- Second receive window (RX2)
  - Opens RECEIVE_DELAY2 after the end of uplink modulation
  - Use fixed configurable frequency channel
  - Does not open when the frame for the end device is detected and demodulated during the first receive window



Receive Windows (2)

- If a preamble is detected during one of the receive windows, the radio receiver stays active until the downlink frame is demodulated.
- If a frame was demodulated during the first receive window and the frame was intended for this end-device after address and MIC checks, the end-device does not open the second receive window.

LoRa Channels

❖ Reginal ISM Band

- In Korea
  - 8 default channels with 125 kHz bandwidth
  - 1 channel for RX2 and 7 channels for RX1

Channel ID	Channel Freq	RX1/RX2
25	921.9 MHz	RX2 (DR0, SF12)
26	922.1 MHz	RX1
27	922.3 MHz	
28	922.5 MHz	
29	922.7 MHz	
30	922.9 MHz	
31	923.1 MHz	
32	923.3 MHz	

- In Europe
  - 3 default channels with 125 KHz : 868.1 MHz, 868.3 MHz, 868.5 MHz
  - At maximum, 5 channels can be added at association

LoRa Data Rates

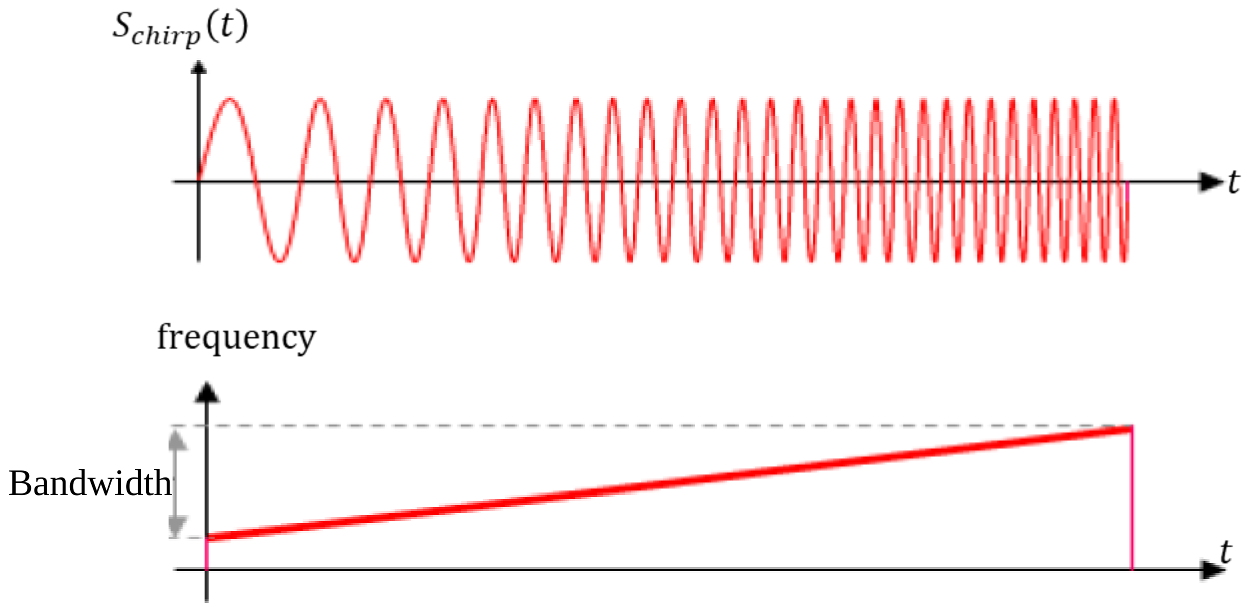
- Achievable bit rate for each data rate by using different spreading factors (SF) and LoRa modulation on 125 KHz bandwidth

Data rate	SF	Physical bit rate (bps)
0	12	250
1	11	440
2	10	980
3	9	1760
4	8	3125
5	7	5470

- Rate 6: 11 kbps by using SF 7 and Lora modulation on 250 KHz bandwidth
- Rate 7: 50 kbps using GFSK modulation on 150 KHz bandwidth

LoRa Modulation

- LoRa uses **chirp spread spectrum** (CSS) for modulation
  - Spread the spectrum by generating a chirp signal
  - Chirp signal : frequency increases or decreases over time
  - Length of the spreading code is 2^{SF} ($SF : Spreading\ Factor$)



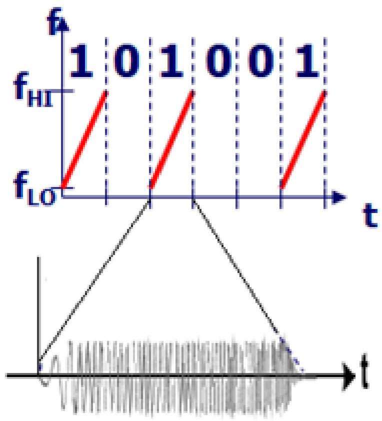
Up-Chirp

How to code using CSS: Examples

❖ Example Modulation techniques:

- ***On-Off-Keying (OOK)***
  - Up-Chirp = “1”
  - Null = “0”

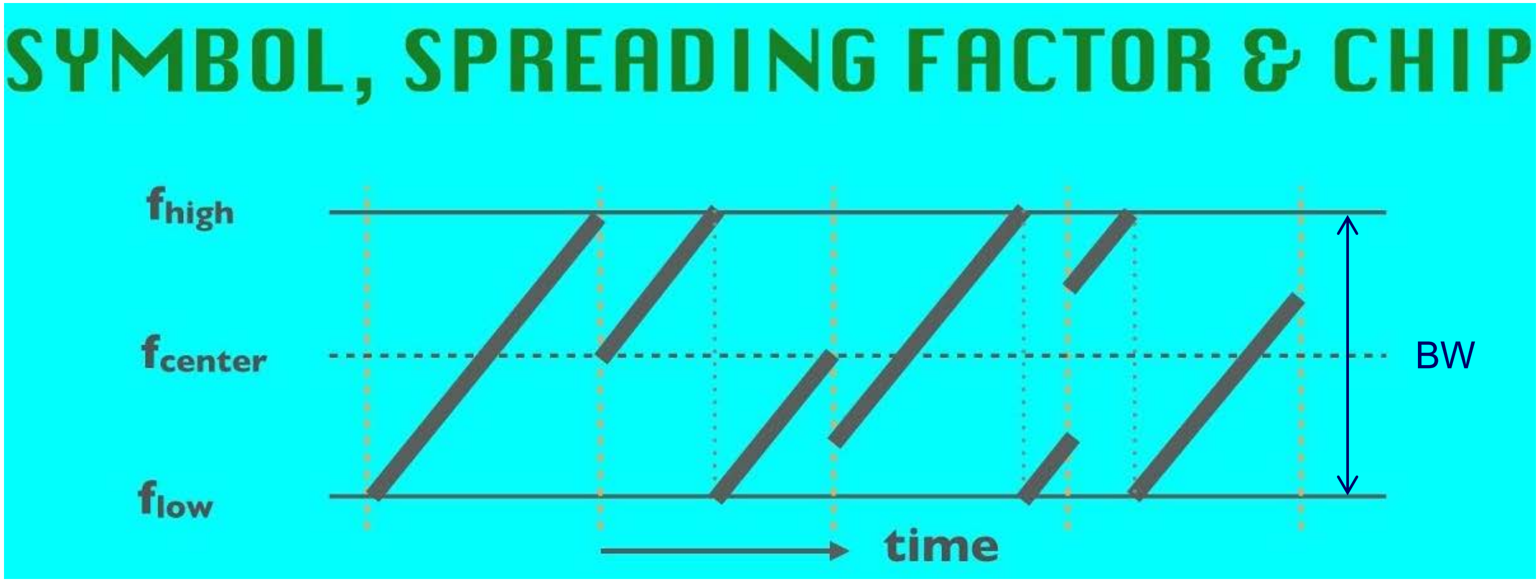
Up-chirp signal



- ***Superposed Chirps (4 possible states)***
  - Null/Up-Chirp/Down-Chirp/Superposition of Up-Chirp and Down-Chirp
  - allows one network double the data rate

- **LoRa uses different modulation technique**

LoRa modulation using CSS (1)



One symbol: 2^{SF} chips
A chip duration (fixed): 1/BW

Symbol time: 2^{SF} / BW

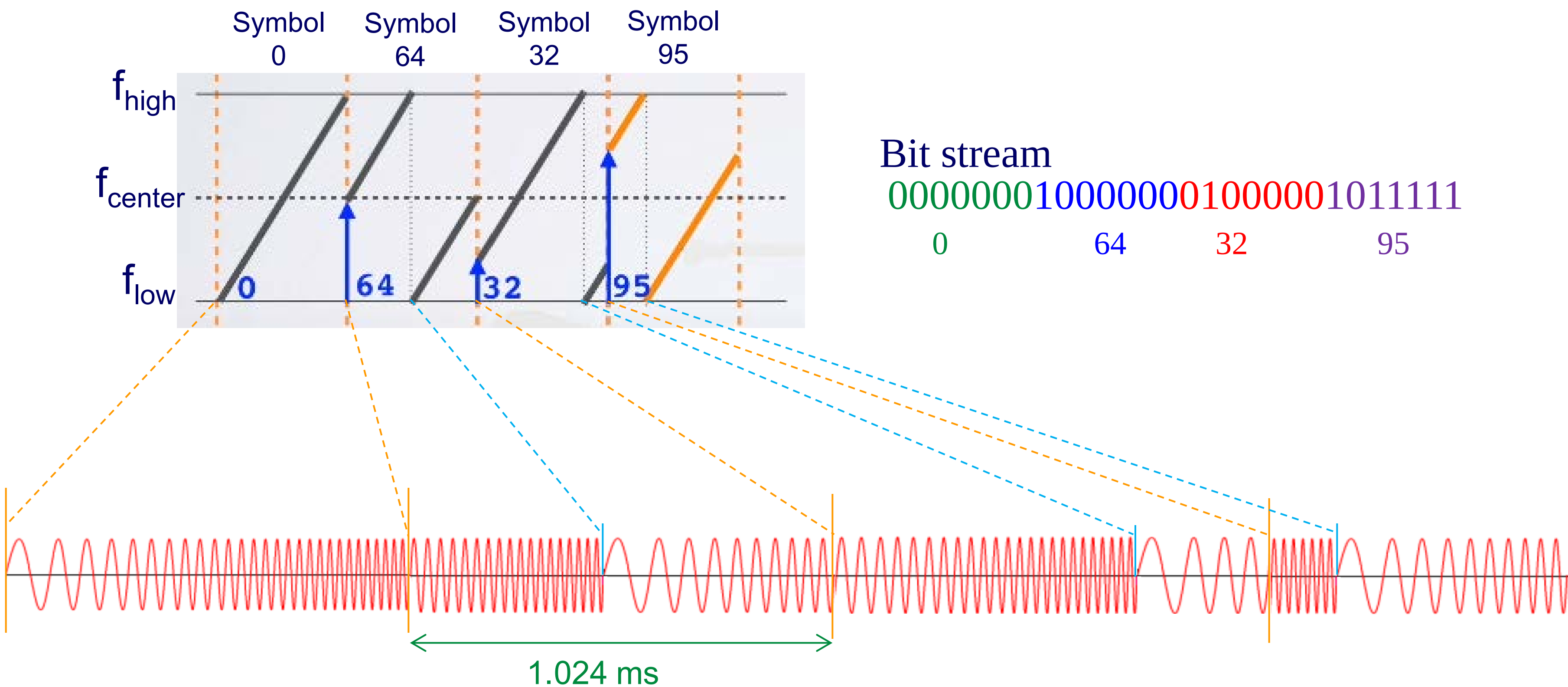
SF bits are encoded by a symbol
Data Rate: BW x SF / 2^{SF}
Baseband signal bandwidth: BW x SF / 2^{SF}
CSS signal bandwidth : BW

Spectrum spreading: 2^{SF} / SF

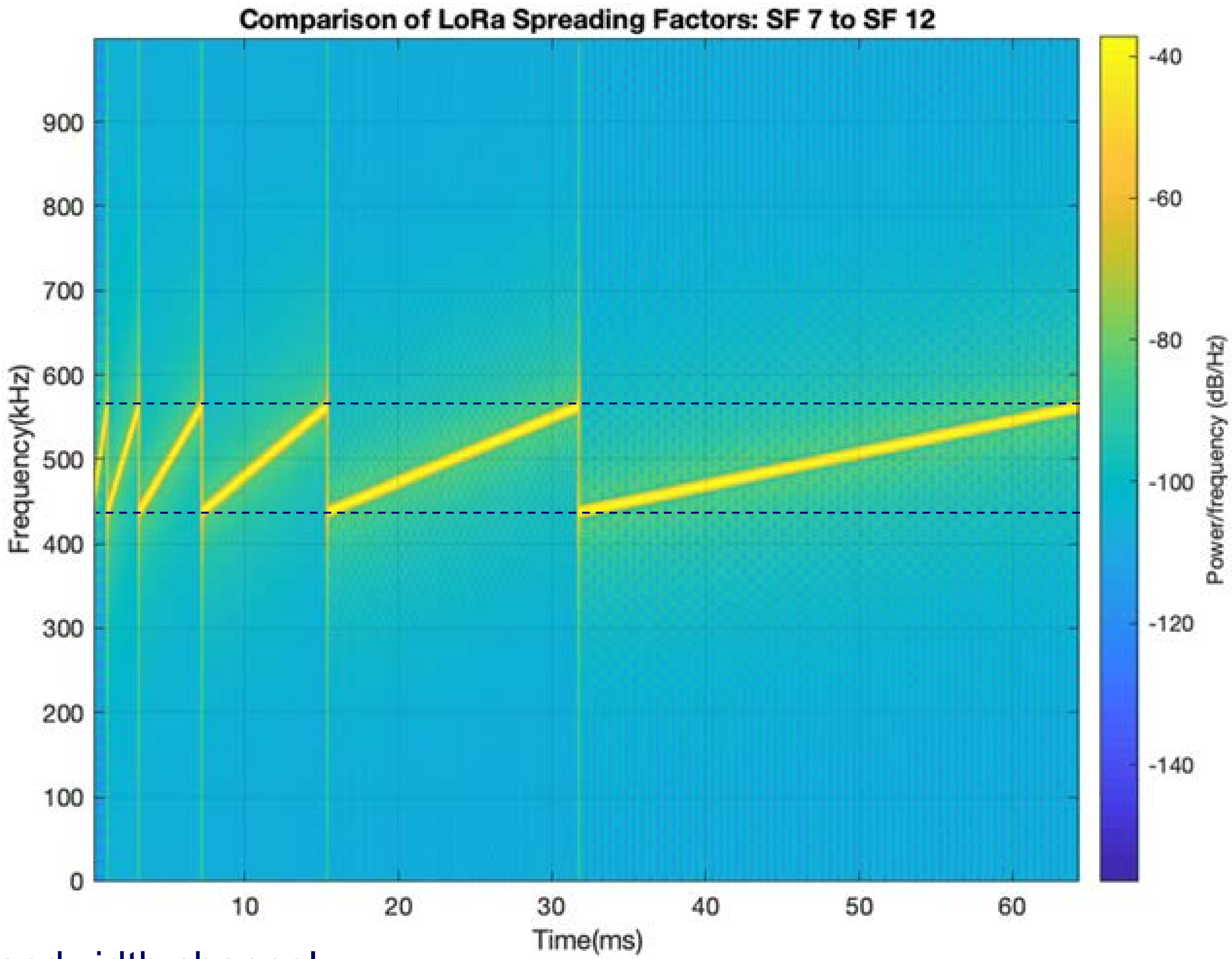
LoRa modulation using CSS (2)

Example: SF=7, BW=125 kHz

- one symbol : 128 chips = 128 x 8 μs = 1,024 μs, encoding seven bits



Variable Data Rate by adjusting SF



125kHz bandwidth channel:

- one chip: 8 μs
- a symbol: 8 x 2^{SF} => (SF 7) 1.024 ms, (SF 8) 2.048 ms, … , (SF 12) 32.768 ms

Message Types (1)

❖ PHY Message

- Format

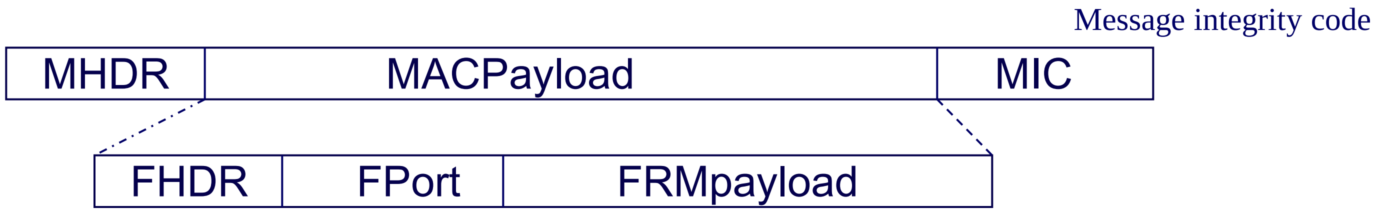
preamble	PHY header	Header CRC	Payload	Payload CRC

  - Preamble
    : used to synchronize the receiver with the incoming data flow
  - PHY header
    : payload length, FEC coding rate of payload
  - Payload CRC: exists only for the uplink
- Preamble, header CRC, payload CRC: inserted by radio transceiver

Message Types (2)

❖ MAC Message (PHY payload)

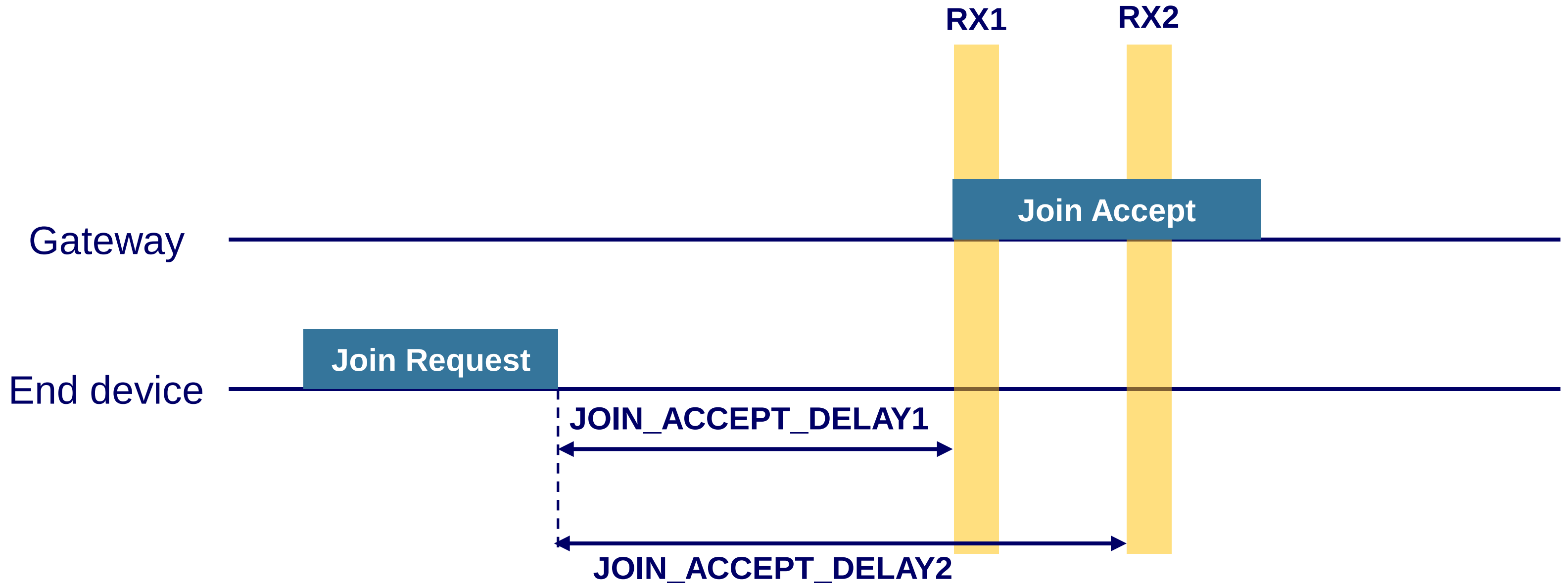
- Format



  - MHDR : header which specifies the message type
  - MACPayload : data frame with header and Fport
    - FHDR: device address, ADR control bits, ACK bit, Pending bit, …
    - Fport: 0 (MAC Command), application-specific (destination)
  - MIC : Encrypted version of message (for security), based on AES-128
- Type
  - Join request : Request from an end node, for joining to the network
  - Join accept : Acceptance that end node can join to the network
  - Rejoin request
  - Unconfirmed data up/down : Data transmission without acknowledgment
  - Confirmed data up/down : Data transmission with acknowledgment

LoRa End-Device Activation

- To participate in a LoRaWAN network, each end device has to obtain
  - A unique id of the device within a current network (a device address)
  - Some keys for security (eg., key for calculating and verifying MIC)
- End device sends *join-request* message to a server, and server replies a *join-accept* message if the join request is accepted

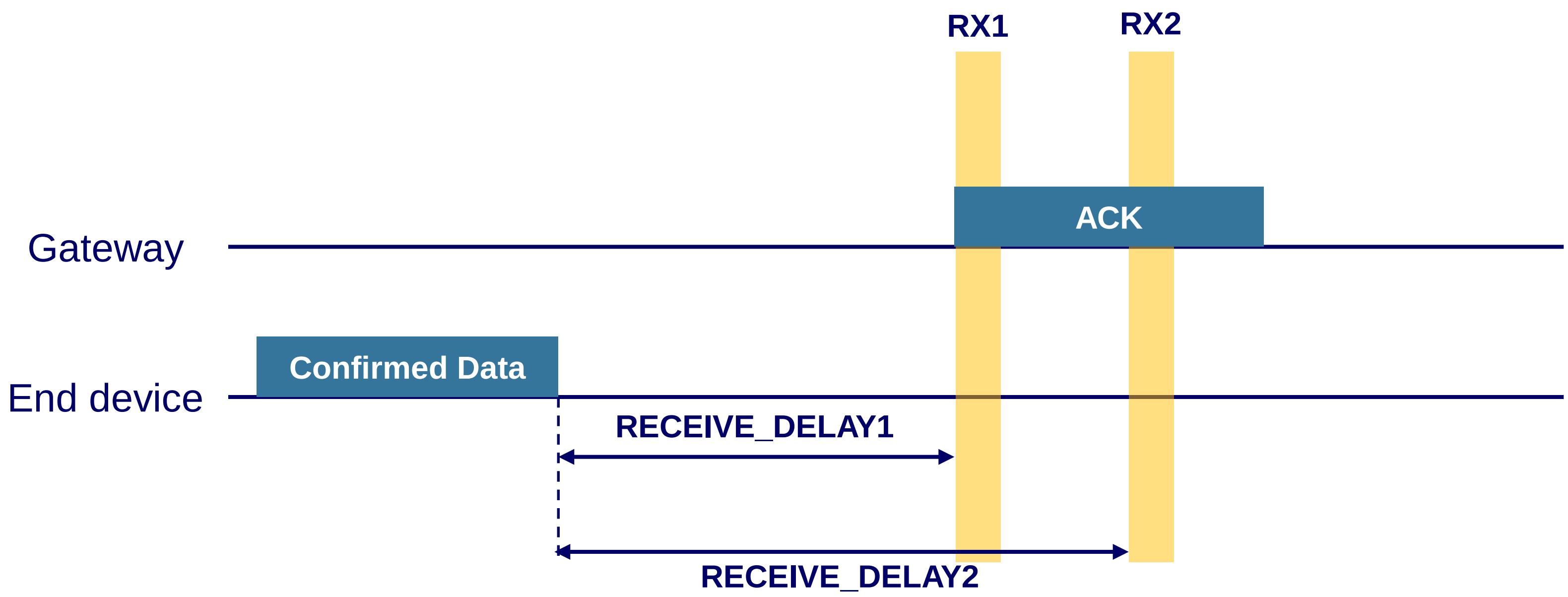


LoRa Class-A Procedure (1)

An end device transmits frames by using pure ALOHA protocol

❖ Confirmed Data Up

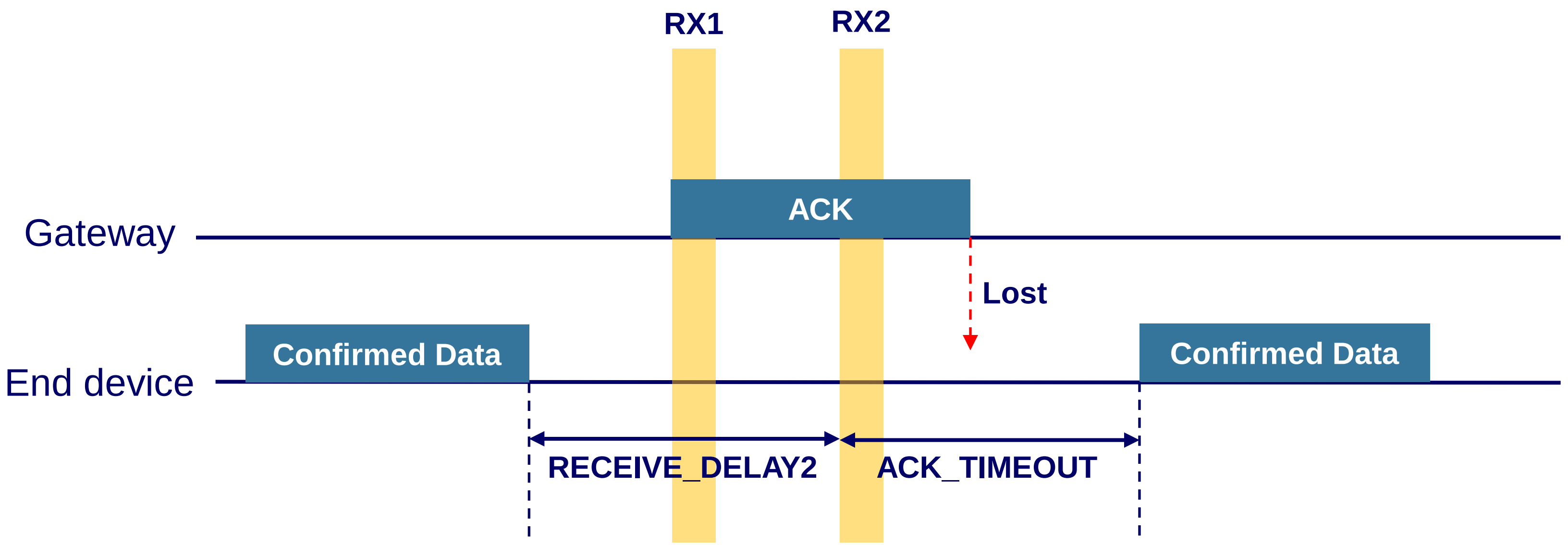
- When the network receives the frame, the network generates a downlink frame with the ACK bit set RECEIVE_DELAY1 seconds later
- ACK frame can also contain data or MAC commands



LoRa Class-A Procedure (2)

❖ Confirmed Data Up (cont.)

- If an end device does not receive an ACK frame in one of two receive windows, the end device may resend the same frame ACK_TIMEOUT seconds after the second receive window
- Retransmission must be done on another channel



LoRa Class-A Procedure (3)

Data Rate Adaptation

- Data rate can be adjusted to ensure reliable packet delivery and optimal network performance
- Rate adaptation is allowed (individually for each device) when ADR bit (within FHDR) is set
- ADR bit can be set by an end device or network server

- Server can adjust the data rate of each end device
  - Server sends a *LinkADRReq* message to the end device
    - Contains requested data rate, TX output power, and usable channels
  - End device answers to server with a *LinkADRAns* message
- Uplink rate control by an end device (next two slides)

LoRa Class-A Procedure (4)

❖ Rate Adaptation for Confirmed Up Transmission

- Every two confirmed up transmission fails, end device lowers the data rate and try again
- If frame has not been acknowledged after 8 transmissions, end device re-initiates the transmission a little later

Transmission nb	Data Rate
1 (first)	DR
2	DR
3	max(DR-1,0)
4	max(DR-1,0)
5	max(DR-2,0)
6	max(DR-2,0)
7	max(DR-3,0)
8	max(DR-3,0)

LoRa Class-A Procedure (5)

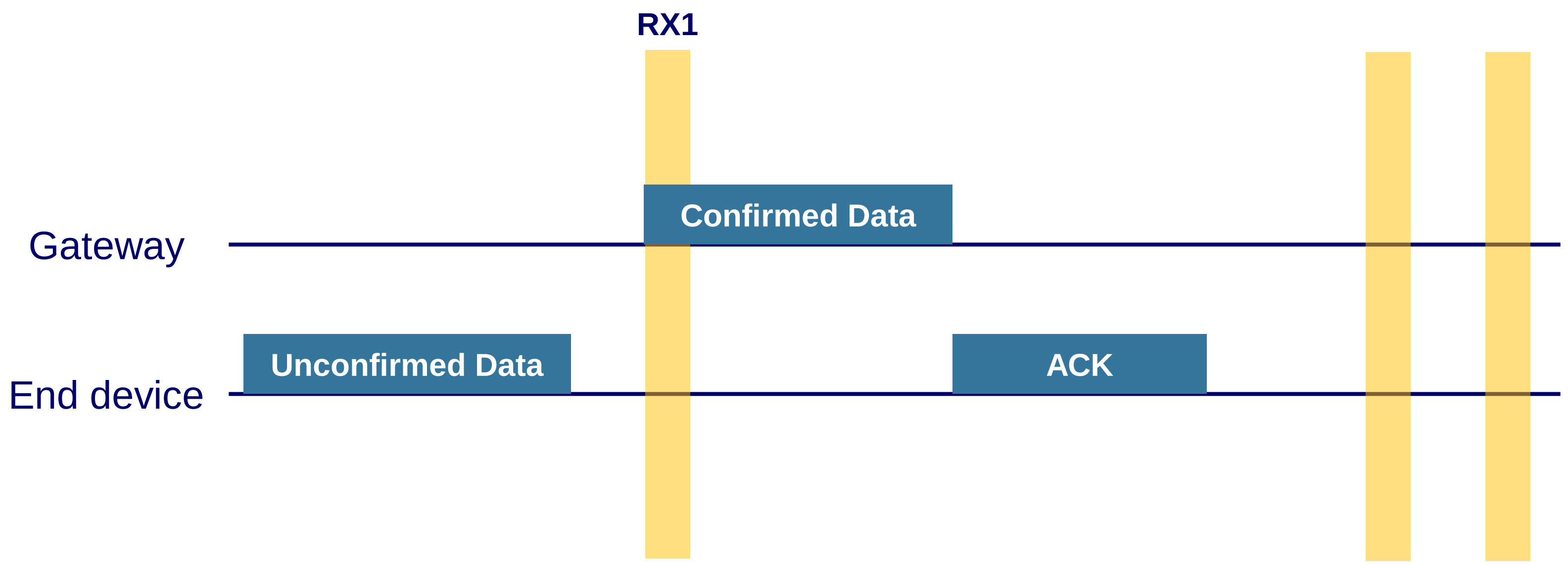
Rate Adaptation for Unconfirmed UP Transmission

- If the data rate of end device is higher than its default data rate, the end device needs to validate the network still receives the uplink frame
- Validation procedure
  - For each new uplink frame, the device increments ADR_ACK_CNT counter
  - If any downlink frame is received, end device resets ADR_ACK_CNT
  - After ADR_ACK_LIMIT uplink frames without any downlink response, the end device sets the ADRACKReq bit (within FHDR)
  - The network is required to respond with a downlink frame within the next ADR_ACK_DELAY uplink frames
  - If no reply is received within next ADR_ACK_DELAY uplink frames, the end device switches to next lower data rate

LoRa Class-A Procedure (6)

Confirmed Data Down

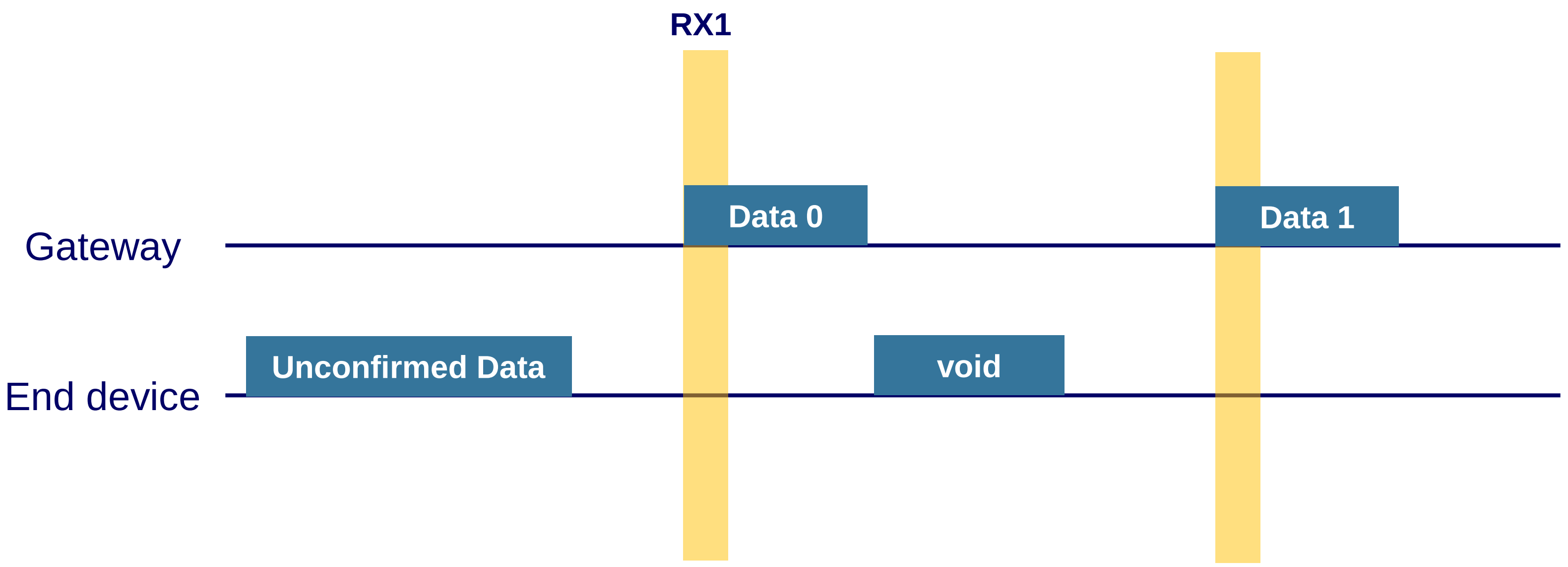
- Server sends downlink data frame after receiving frame from end device
- Uplink ACK is transmitted like any standard uplink frame
- Channel may be different



LoRa Class-A Procedure (7)

Frame Pending

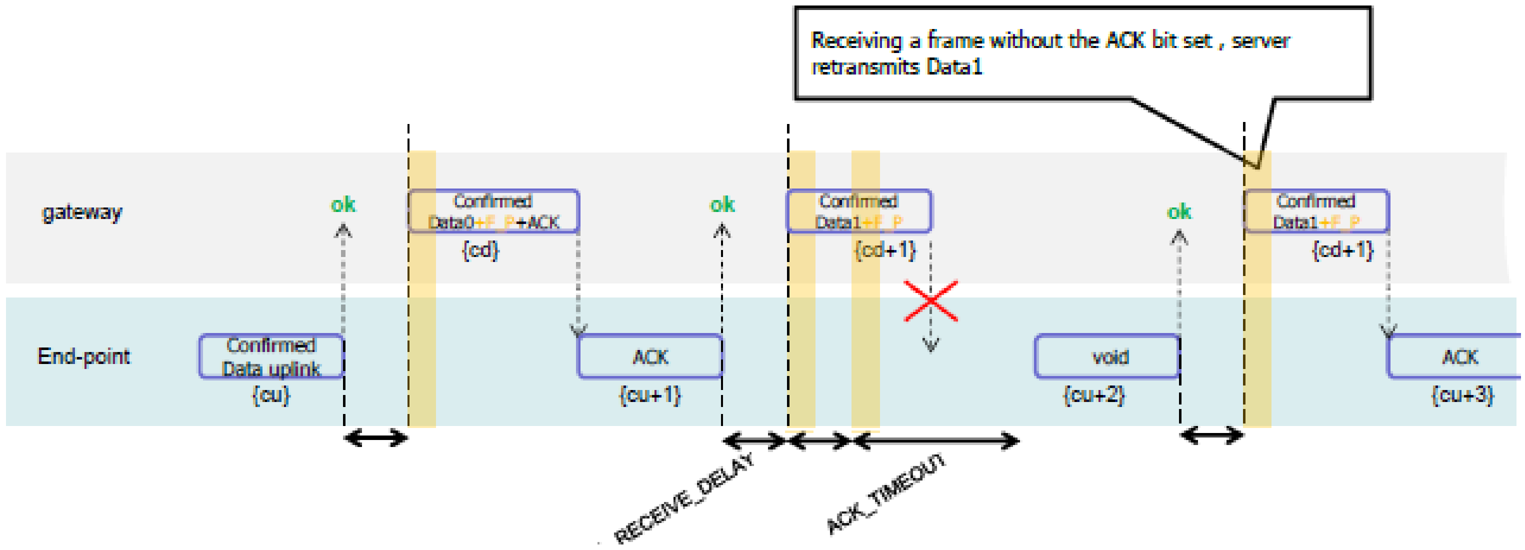
- Server sets FPending bit (within FHDR) to inform the end device that the network server has several frames pending for the ED
- Then, the end device opens another receive window as soon as possible by sending another empty uplink message



LoRa Class-A Procedure (8)

❖ Frame Pending (cont.)

- FPending bit, the ACK bit, and payload data can all be present in the same downlink message.
- If end device does not receive data from one of two receive windows, end device sends empty uplink message without ACK bit set after ACK_TIMEOUT



LoRa Class-A Procedure (9)

Duty Cycle Control

- The network limits the maximum transmit duty cycle over all channels of an end device

- Server sets the maximum aggregated transmit duty cycle by sending DutyCycleReq message
  - Contains MaxDCycle value which is between 0 and 15
  - Maximum end device transmit duty cycle:

$$aggregated\ duty\ cycle = 1/2^{MaxDCycle}$$

- End device answers to server with a *DutyCycleAns* message

LoRa Class-A Procedure (10)

Channel Control

- Server can create a new channel or modify the current existing channel
  - Device is able to handle at least 16 different channels
  - Default channels cannot be modified

- Server sends *NewChannelReq* message to the end device
  - Contains channel frequency and allowed data rate range information
  - Channel frequency can be set from 100 MHz to 1.67 GHz in 100 Hz steps

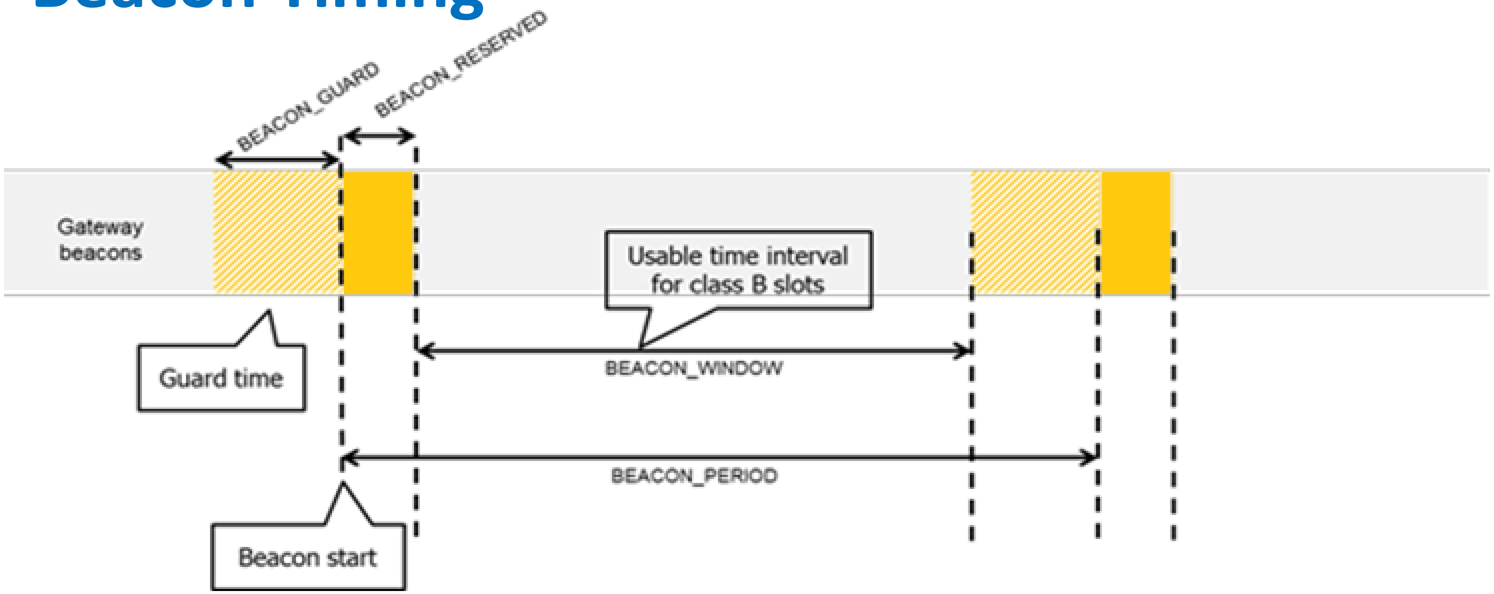
- End device answers to server with *NewChannelAns* message

LoRa Class-B Procedure (1)

- End devices open additional receive windows at fixed time intervals
  - for the purpose of enabling server initiated downlink message
- End device in class B
  - should start and join the network as an end device of class A
  - can switch to class B
- Gateway sends a beacon on a regular basis to synchronize the all end devices in the network
- End device application can decide to switch to class B
  - The end-device application requests the LoRaWAN layer to switch to Class B mode.
  - The LoRaWAN layer in the end-device searches for a beacon
  - Based on the beacon strength and the battery life constraints, the end-device application selects a ping slot data rate and periodicity
- If end device in class B does not receive a beacon for a given period, the end device switches back to class A

LoRa Class-B Procedure (2)

❖ Beacon Timing



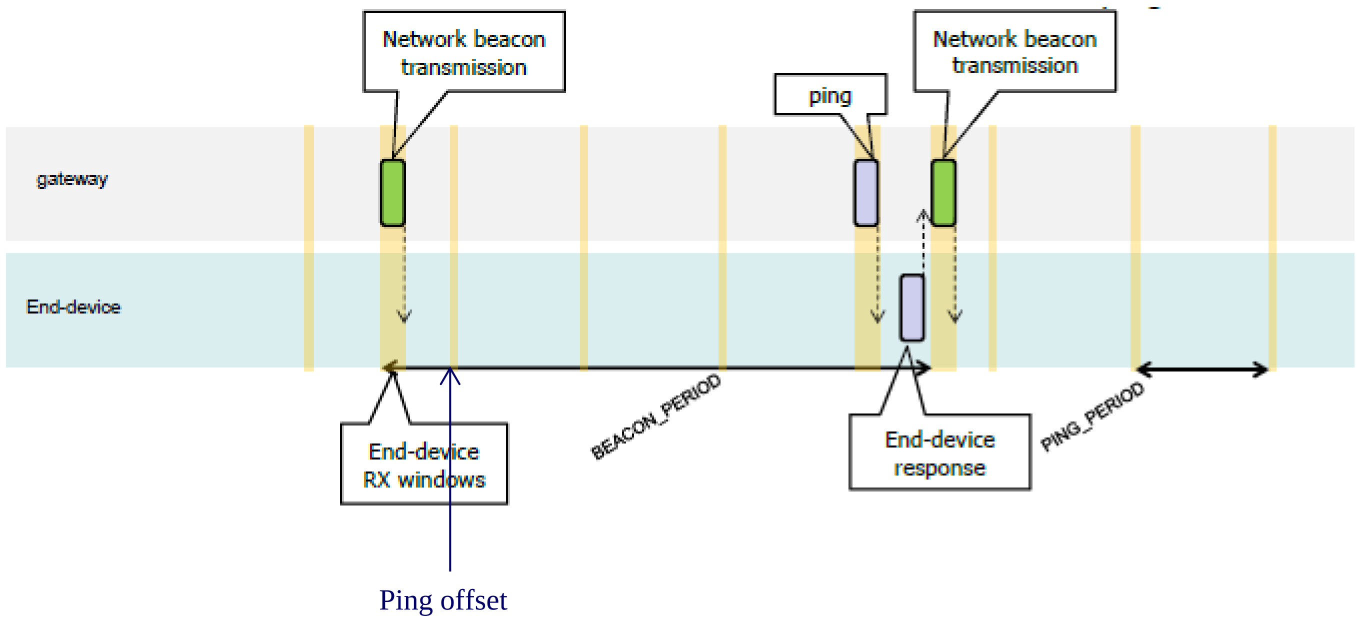
Beacon_period	128 s
Beacon_reserved	2.120 s
Beacon_guard	3.000 s
Beacon-window	122.880 s

- The beacon window interval is divided into 4096 ping slots of 30 ms each numbered from 0 to 4095.

LoRa Class-B Procedure (3)

❖ Beacon Reception Slots and Ping Slots

- In Class B, all gateways synchronously broadcast a beacon every BEACON_PERIOD seconds
- Each end device opens additional receive windows called “ping slots” every PING_PERIOD seconds



LoRa Class-B Procedure (4)

❖ Switch from Class A to Class B

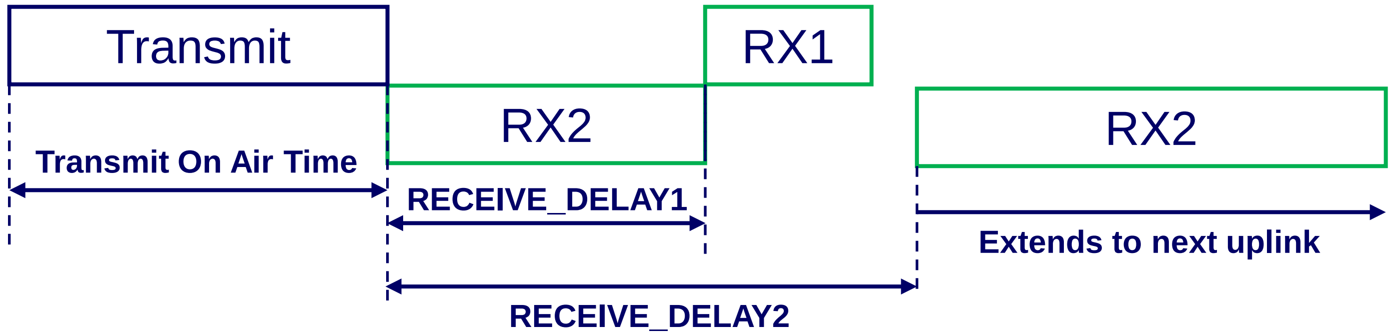
- End device sends *PingSlotInfoReq* message to the server when it wants to switch to Class B
  - Contains ping slot period and expected data rate of ping

$$pingSlotPeriod = 2^{Periodicity} \quad (Periodicity = [0 \ldots 7])$$

- Server sends *PingSlotInfoAns* to the end device.
- Server sets the unicast ping channel of an end-device by sensing *PingSlotChannelReq* message and the end device acknowledges with *PingSlotFreqAns* message.
- At each beacon period, the end-device and the server compute a new pseudo-random offset (ping offset) to align the ping slots
  - *Key* = 16 x 0x00
  - *Rand* = aes128_encrypt(Key, beaconTime | DevAddr | pad16)
  - *pingOffset* = (*Rand*[0] + *Rand*[1]x 256) modulo *pingSlotPeriod*

LoRa Class-C Procedure

- Class-C end device will continually listen with RX2 windows when it is not either sending or receiving on RX1
- End device can receive a downlink at nearly any time



LoRa Localization (1)

- Uplink signal from an end device can be received at multiple GWs which are time-synchronized with each other.
- Triangulation estimates the position of an target object (ED) by measuring a distance between the ED and several reference points (GWs)
  - Time of arrival (ToA)
  - Time difference of arrival (TDoA)
- ToA
  - calculates the distance between the ED and GW by measuring the one-way propagation time
  - Is applied, when the ED is also time-synchronized with GWs
- TDoA
  - determines the relative position of the ED by examining the difference of arrival times at multiple (three or more) GWs
  - Only the GWs are time-synchronized.

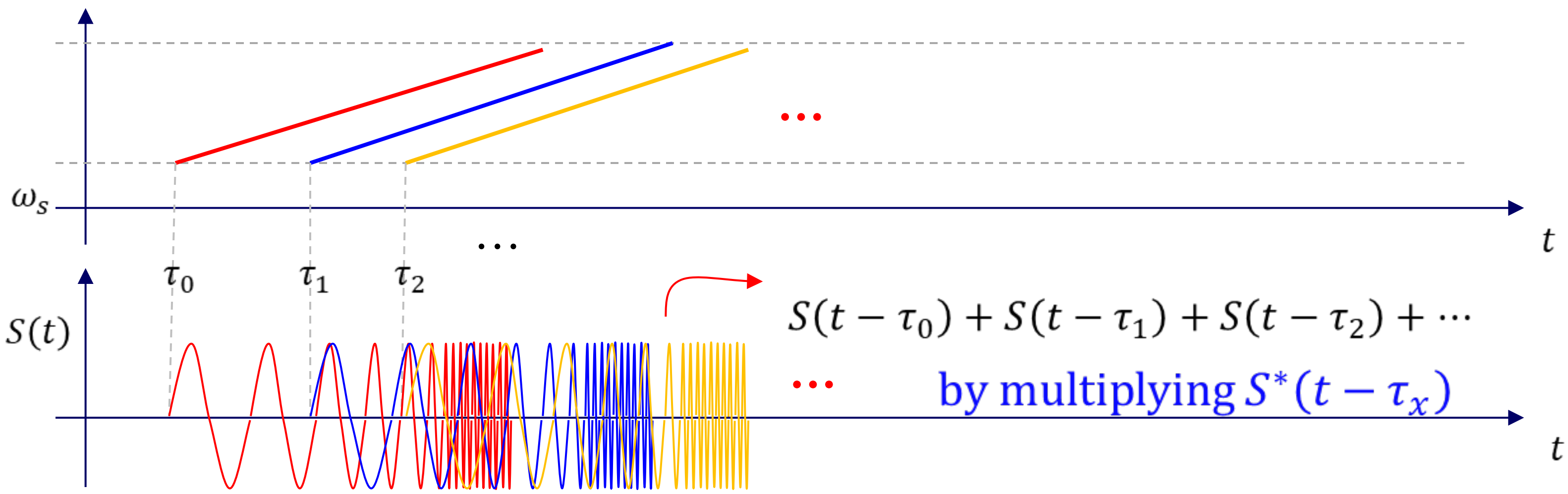
LoRa Localization (2)

❖ ToA and TDoA

- A LOS path should exist and be able to be easily searched (ToF)
- Three ToF values are needed => three GWs

❖ Chirp Spread Spectrum (CSS)

- In multipath environment, the LOS path can be more easily searched



LoRa Localization (3)

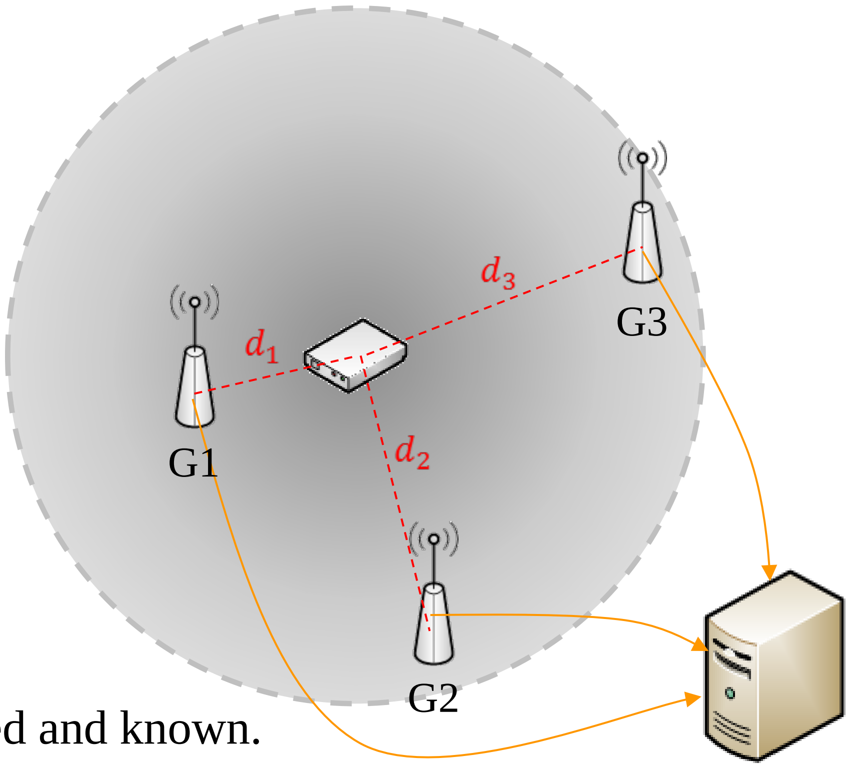
❖ ToA

- $d_i = c\,(t_i - t_0)$
  - c: propagation speed of light
  - t_i : signal reception time at GW1
  - t_0 : signal transmission time at a target ED

❖ TDoA

- $d_i - d_j = c\,(t_i - t_0) - c\,(t_j - t_0)$

  $= c\,(t_i - t_j)$



The position of each is fixed and known.

Application Example-1

❖ Low-cost, Long-range Open IoT for Smarter Rural African Villages

➢ Some typical IoT applications where real-time data collection could greatly increase quality and productivity in rural environments.

Livestock farming

Irrigation

Fish farming

Storage & Logistics

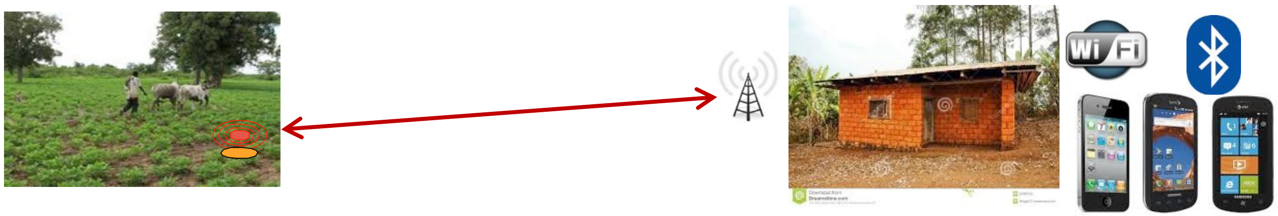
Agriculture

Fresh water

Application Example-1

❖ Low-cost, Long-range Open IoT for Smarter Rural African Villages

➢ Fully autonomous gateway scenario (No communication Infra)



- The gateway collects data from remote devices and stores data locally.
- After post processing, the data can be viewed by the gateway used as an end computer by just attaching a keyboard and a display.
- The gateway can also interact with the end-users' smartphone through WiFi or Bluetooth.

Application Example-2

❖ Low power wide area Bat communication networks

- Observing the behavior of large animal populations in their natural habitat
- Conventional Approach
  - employ radio telemetry utilizing directional antennas and manual triangulation.
  - To localize a single individual the receivers must be hand-operated by scientific staff resulting in considerable amount of human effort and costs.
  - Just few tracking samples are preserved

Application Example-2

- **Low power wide area Bat communication networks**
  - IoT-based Approach
    - Short range and long range communication networks
    - Sensors: bats
    - Observation of entire groups of bats in their natural habitat