LoRaWAN Literature Survey

1. Introduction:

The Long Range Wide Area Network, also known as LoRaWAN, is a noteworthy development in the wireless communication space. This Media Access Control (MAC) layer protocol governs how devices use LoRa hardware, particularly in the transmission of data and the formatting of messages. It operates on the foundation of LoRa modulation.

The development and continuous refinement of the LoRaWAN protocol are overseen by the LoRa Alliance, a consortium committed to advancing Low-Power Wide-Area Networking (LPWAN) technologies. The LoRaWAN specification was first released in January 2015, ushering in a revolutionary era for long-distance communication and the Internet of Things.

The International Telecommunication Union (ITU) has officially recognized LoRaWAN® as a standard for low-power wide-area wide area networks (LPWAN), according to information released by the LoRa Alliance® on December 7, 2021.

LoRaWAN is a technology that can transmit small-sized payloads, such as sensor data, over long distances. When compared to other wireless data transmission technologies, LoRa modulation offers a considerably greater communication range with lower bandwidths. A comparison of various access technologies for wireless data transmission and their expected transmission ranges versus bandwidth is shown in the figure below.

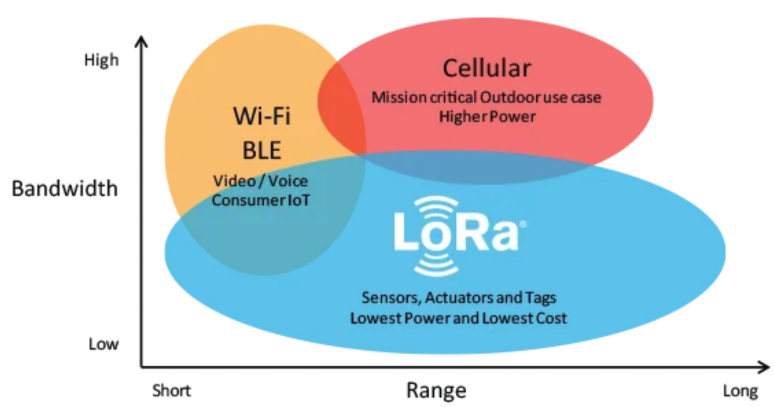

Fig. 1. Comparison of Wireless Networks

2. Background:

2.1 **Key milestones**

Several key milestones have marked LoRaWAN's journey to its current state. These include:

- Release of Initial Specification (January 2015): The LoRa Alliance released the first LoRaWAN specification, defining the fundamental aspects of the protocol, and setting the stage for widespread adoption.[1]
- **Global Expansion:** LoRaWAN's global reach expanded rapidly as networks were deployed worldwide, enabling the interconnectivity of IoT devices across borders. [3]
- Release of LoRaWAN 1.1 Specification (October 2017): This update introduced enhanced security features, further solidifying LoRaWAN's appeal for critical IoT applications.
- **ITU Standardization (December 2021)**: LoRaWAN's official recognition as a standard by the International Telecommunication Union (ITU) marked a significant milestone, reaffirming its status as a global LPWAN solution.

2.2 **Driving Factors Behind the Adoption:**

- **Ultra-low power** - LoRaWAN end devices are optimized to operate in low power mode and can last up to 10 years on a single coin cell battery.
- **Long range** - LoRaWAN gateways can transmit and receive signals over a distance of over 10 kilometers in rural areas and up to 3 kilometers in dense urban areas.
- **License-free spectrum** - You don't have to pay expensive frequency spectrum license fees to deploy a LoRaWAN network.
- **Geolocation**- A LoRaWAN network can determine the location of end devices using triangulation without the need for GPS. A LoRa end device can be located if at least three gateways pick up its signal.
- **Public and private deployments** - It is easy to deploy public and private LoRaWAN networks using the same hardware (gateways, end devices, antennas) and software (UDP packet forwarders, Basic Station software, LoRaWAN stacks for end devices).
- **End-to-end security**- LoRaWAN ensures secure communication between the end device and the application server using AES-128 encryption.

- **Firmware updates over the air** - You can remotely update firmware (applications and the LoRaWAN stack) for a single-end device or group of end devices.
- **Ecosystem**- LoRaWAN has a very large ecosystem of device makers, gateway makers, antenna makers, network service providers, and application developers.

3. LoRaWAN Architecture:

To enable long-range, low-power communication for Internet of Things (IoT) devices, the LoRaWAN architecture is made up of a number of connected parts. Gaining an understanding of these elements is necessary to comprehend how the LoRaWAN network operates.[2]

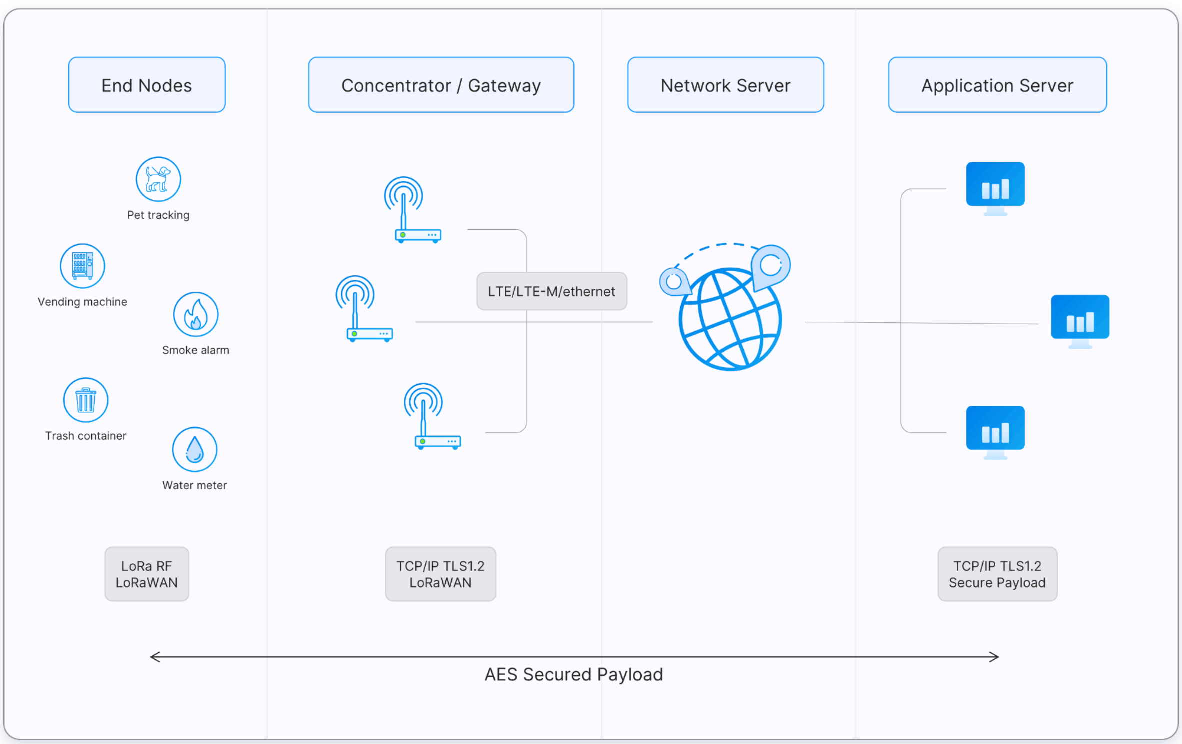

Fig.2 LoRaWAN Network Server

Endnode -> Gateway -> Network Server + Join Server -> Application Server

3.1 End Devices:.

End devices in the LoRaWAN architecture are a diverse group of IoT sensors and actuators. They are responsible for sending LoRa-modulated wireless messages to gateways or receiving messages wirelessly from gateways. These devices are typically located at the network's edge, often in remote or difficult environments, and are designed to consume as little power as possible. [5]

3.2 Gateways:

Gateways act as a go-between for end devices and the core network infrastructure. They play a critical role in the LoRaWAN ecosystem by receiving messages from end devices and forwarding them to the Network Server.[12] Gateways are strategically placed across the coverage area to ensure that messages are reliably transmitted to their intended destinations.

3.3 Network Server:

The Network Server is a fundamental component of the LoRaWAN architecture. It is a piece of software that runs on a server and is responsible for managing the entire network. Its key functions include message routing, network security, and efficient resource utilization. It ensures that messages from end devices are routed correctly to their respective Application Servers.

In simpler terms, the Network Server is like the brain of the LoRaWAN network. It is responsible for keeping the network running smoothly and securely.

3.4 Application Servers:

Application servers are specialized software that runs on servers and processes application-specific data received from the network server. They interpret and process the raw data, applying logic and algorithms relevant to the specific IoT application. Application servers are tailored to the unique requirements of individual use cases, making them highly adaptable and versatile.[10]

- Join Server - a piece of software running on a server that processes join-request messages sent by end devices (The Join Server is not shown in the above figure).

4. Technical Overview:

LoRaWAN is the MAC stack whereas the secret lies in the physical layer i.e. LoRa, LoRa is a modulation technique, LoRa is a wireless modulation technique derived from Chirp Spread Spectrum (CSS) technology. It encodes information on radio waves using chirp pulses - similar to the way dolphins and bats communicate! LoRa-modulated transmission is robust against disturbances and can be received across great distances.

LoRa can be operated on the license-free sub-gigahertz bands, for example, 915 MHz, 868 MHz, and 433 MHz. It can also be operated on 2.4 GHz to achieve higher data rates compared to sub-gigahertz bands, at the cost of range. These frequencies fall into ISM bands that are reserved internationally for industrial, scientific, and medical purposes.

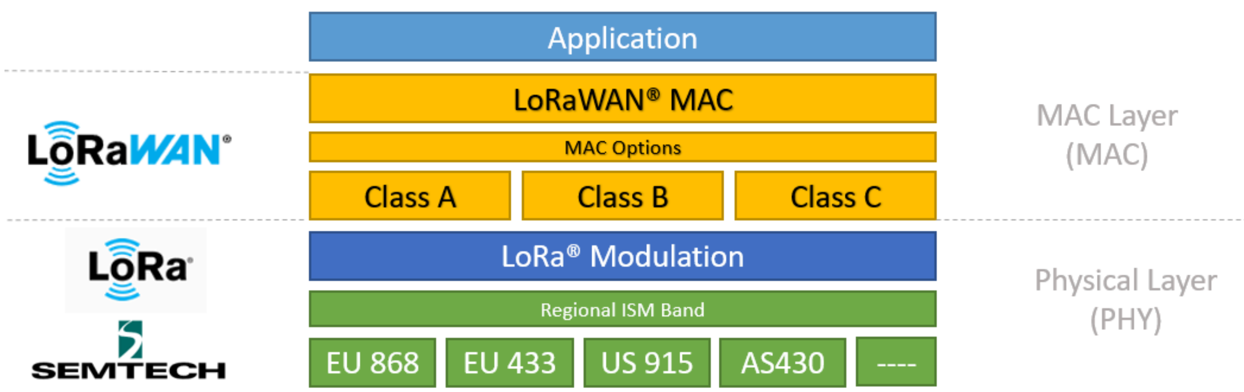

Fig.3 LoRa Stack and LoRaWAN Stack

4.1 Modulation Technique:

LoRa technology is based on Chirp Spread Spectrum (CSS) modulation. CSS is a departure from conventional modulation methods such as Frequency Shift Keying (FSK) or Amplitude Shift Keying (ASK). Instead of using abrupt changes in frequency or amplitude to transmit data, CSS uses chirp signals. A chirp signal is a signal whose frequency changes linearly over time. This allows CSS to transmit data at very low power levels while still being able to be received over long distances. [9]

5. Inherent Data Reduction Technique of LoRaWAN:

One of the remarkable features of LoRaWAN is its inherent ability to reduce data consumption, primarily facilitated by the mechanism known as "Adaptive Data Rate." This mechanism, supported by various spreading factors tailored to specific regions, plays a crucial role in optimizing data transmission.

5.1 Data Rate Control: The Three Knobs

LoRaWAN provides users with three adjustable parameters, often likened to knobs, which collectively determine the data rate: transmission power, bandwidth, and spreading factor. Understanding how these parameters interplay is essential for efficient communication in LoRaWAN networks.

- **Transmission Power:** The first knob controls the transmission power of the device. By lowering the transmission power, you conserve the device's battery life. However, this reduction in power also limits the range over which the signal can effectively propagate. It's a trade-off between energy efficiency and signal reach.
- **Bandwidth:** The second knob is bandwidth. It determines how wide the communication channel is. Wider bandwidth allows more data to be transmitted simultaneously. Doubling the bandwidth, for example, enables you to send twice as many bytes at the same time. This choice significantly impacts the data rate.
- **Spreading Factor:** The third knob, the spreading factor, influences data transmission in a unique way. Lowering the spreading factor effectively shortens the time it takes to send a given amount of data. For instance, reducing the spreading factor from SF10 to SF9 enables the transmission of twice as many bytes in the same time frame.

5.2 Spreading Factors:

LoRa is based on Chirp Spread Spectrum (CSS) technology, where chirps (also known as symbols) are the carrier of data. The spreading factor controls the chirp rate and thus of data transmission.[8] Lower spreading factors mean faster chirps and therefore, a higher data transmission rate. For every increase in the spreading factor, the chirp sweep rate is halved, and so the data transmission rate is halved.

Using lower spreading factors in LoRa transmissions reduces the processing gain and increases the bit rate, which in turn limits the range. However, by changing the spreading factor, networks can adjust the data rate for each end device, albeit at the cost of range. Additionally, spreading factors play a crucial role in controlling congestion. As these factors are orthogonal, signals modulated with different spreading factors and transmitted on the same frequency channel at the same time do not interfere with each other.

5.3 Influence of Spreading Factors

LoRa modulation has a total of six spreading factors, from SF7 to SF12. Spreading factors influence data rate, time-on-air, battery life, and receiver sensitivity, as described here.

5.3.1 Data rate

Compared to a higher spreading factor, a lower spreading factor provides a higher bit rate for a fixed bandwidth and coding rate. For example, SF7 provides a higher bit rate than SF12.

Doubling the bandwidth also doubles the bit rate for a fixed spreading factor and coding rate.

The following table presents bit rates calculated with the SF7 and Coding Rate (CR) = 1 for bandwidths, 125, 250, and 500 kHz.[14]

Spreading Factor	Bandwidth	Bit rate (kbits/s)
7	125	5.5
7	250	10.9
7	500	21.9

5.3.2. Distance

Signals with larger spreading factors have greater processing gain, which means they can be received with fewer errors and travel a longer distance than signals with lower spreading factors. For example, a signal modulated with SF12 can travel a longer distance than a signal modulated with SF7.

5.3.3 Time-On-Air

Sending a fixed amount of data with a higher spreading factor and a fixed bandwidth requires more time on air than sending the same data with a lower spreading factor. The Things Network's LoRaWAN airtime calculator can be used to calculate the time-on-air using the input bytes (payload size), bandwidth, and spreading factor. [14]

5.3.4 Receiver Sensitivity

Higher spreading factors provide higher receiver sensitivity. Usually, LoRa uses higher spreading factors when the signal is weak.

The following table shows how spreading factors impact receiver sensitivity.

Spreading factor	Receiver sensitivity for bandwidth fixed at 125 kHz
SF7	-123 dBm
SF8	-126 dBm
SF9	-129 dBm
SF10	-132 dBm

SF11	-134.5 dBm
SF12	-137 dBm

5.3.5 Battery Life

The battery life of an end device is highly dependent on the spreading factor used. Higher spreading factors result in longer active times for the radio transceivers and shorter battery life.

6. Adaptive Data Rate

Adaptive Data Rate (ADR) is a mechanism for optimizing data rates, airtime, and energy consumption in the network. **[14]**

The ADR mechanism controls the following transmission parameters of an end device.

- Spreading factor
- Bandwidth
- Transmission power

ADR can optimize device power consumption while ensuring that messages are still received at gateways. The network server will inform the end device to increase the data rate or decrease transmission power when ADR is active. End devices that are close to gateways should use a lower spreading factor and a higher data rate, whereas devices that are farther away should use a high spreading factor because they need a larger link budget.

6.1 Modulation and Data Rate

In most cases, LoRaWAN uses LoRa modulation. LoRa modulation is based on Chirp spread-spectrum technology, which makes it work well with channel noise, multipath fading, and the Doppler effect, even at low power.[12]

The data rate depends on the used and spreading factor. LoRaWAN can use channels with a bandwidth of either 125 kHz, 250 kHz, or 500 kHz, depending on the region or the frequency plan. The spreading factor is chosen by the end device and influences the time it takes to transmit a frame.

7. End node activation:

End node activation in LoRaWAN is a critical process that enables devices to join and securely communicate with the network. There are two primary activation methods: Over-The-Air Activation (OTAA) and Activation By Personalization (ABP). Here, we'll focus on the activation process for Class A devices.

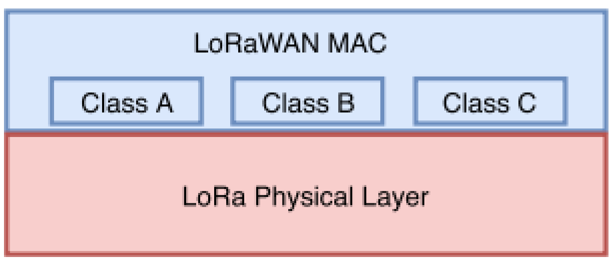

Fig.4. LoRa protocol Stack

7.1 Class A

LoRaWAN defines several device classes, with Class A being the most common and widely supported. All LoRaWAN end devices must support Class A implementation due to its fundamental capabilities:

Uplink Transmission: A Class A device can send an uplink message at any time. This flexibility allows devices to transmit data when needed, making it suitable for various IoT applications.

Receive Windows: Following an uplink transmission, Class A devices open two short receive windows to listen for downlink messages from the network. These receive windows are known as RX1 and RX2.

RX1 Delay: There is a predefined delay between the end of the uplink transmission and the start of the RX1 receive window. This delay ensures that the network has time to schedule a downlink message if needed.

RX2 Delay: Similarly, there is a delay between the end of the RX1 receive window and the start of the RX2 receive window. If the network server does not respond during these receive windows, the next downlink will be scheduled immediately after the next uplink transmission.

This Class A behavior allows for efficient two-way communication between the end device and the network server. It provides a balance between uplink and downlink communication, ensuring that devices can send data while also being receptive to network commands and instructions.

7.2 Class B:

Class B is one of the LoRaWAN device classes, providing enhanced capabilities compared to Class A. Class B devices support all the features of Class A but also introduce synchronized receive windows for downlink communication. Here's a breakdown of Class B functionality:

Uplink Transmission: Similar to Class A devices, Class B devices can send uplink messages at any time.

Receive Windows: In addition to the RX1 and RX2 receive windows found in Class A, Class B devices have scheduled receive slots known as ping slots. These ping slots occur at specific intervals and are synchronized with the network's beacon.

Beacon: The network periodically transmits a beacon signal to synchronize Class B devices. This beacon contains timing information for the Class B devices, allowing them to align their receive windows precisely.

Enhanced Downlink: With synchronized receive windows, Class B devices can receive downlink messages at scheduled intervals, even when they are not actively transmitting. This allows network servers to send commands or updates to Class B devices efficiently.

Class B is suitable for applications that require a more predictable and immediate downlink response, such as industrial control systems or asset tracking. However, it does come with increased power consumption compared to Class A due to the need to periodically wake up for scheduled downlink slots.

7.3 Class C

Class C is another LoRaWAN device class, offering continuous receive windows for downlink communication. Unlike Class A and Class B devices, Class C devices keep their receive windows open at all times, except during uplink transmission. Here's an overview of Class C functionality:

Continuous Receive: Class C devices have continuous receive windows for downlink messages, meaning they can receive downlink data at any time, even when not actively transmitting.

Low Latency: This constant listening capability results in low-latency communication. Class C devices can receive downlink commands or updates almost immediately after an uplink transmission.

Increased Power Consumption: Due to persistent listening, Class C devices consume more power than Class A or Class B devices. This makes them less suitable for battery-operated applications with strict power constraints.

Class C is ideal for applications where low latency and real-time responsiveness are critical, such as smart home devices or remote control systems. However, users must carefully consider the power requirements of Class C devices and ensure they have a continuous power source or are designed to handle higher power consumption.

7.4 OTAA

7.4.1 Join Request:

The joining procedure is always initiated by the end device. The end device sends the Join-request message to the network that is going to be joined. The Join-request message consists of the following fields.

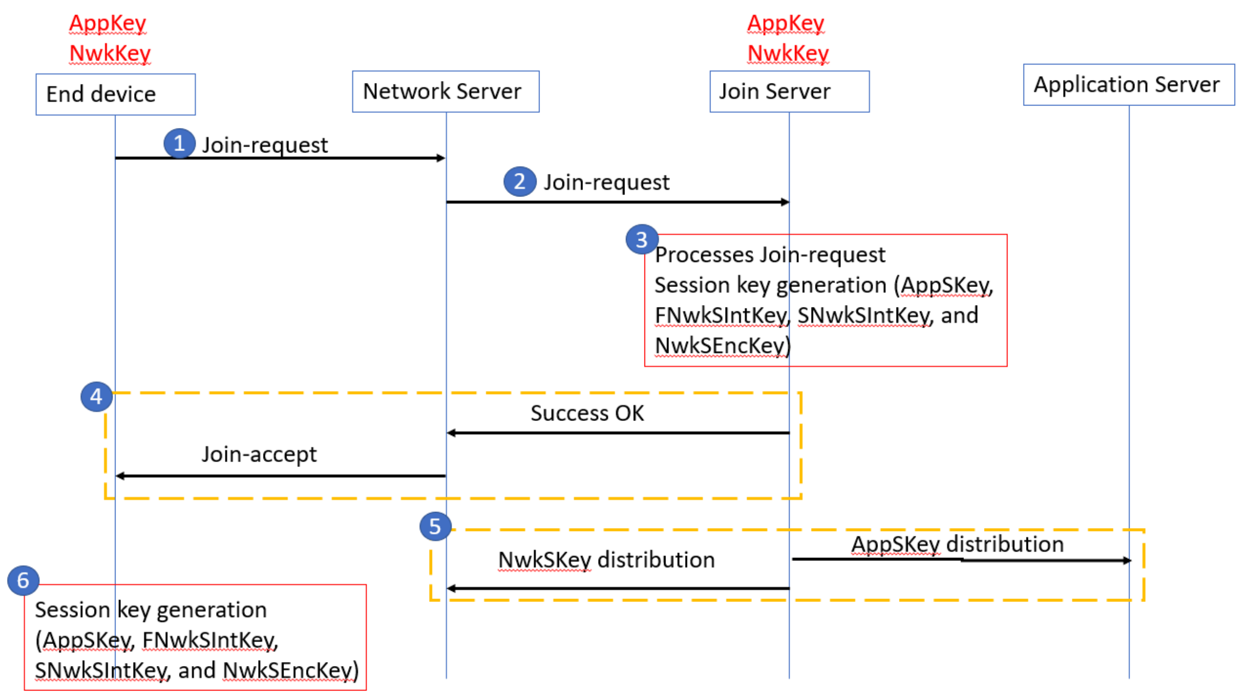

Fig. 5. OTAA Payload Format

8 bytes	8 bytes	2 bytes
JoinEUI	DevEUI	DevNonce

- JoinEUI is a 64-bit global application identifier in IEEE EUI64 address space that uniquely identifies the Join Server and can assist in the processing of the Join request and derivation of the session keys.
- DevEUI is a 64-bit global device identifier in IEEE EUI64 address space that

uniquely identifies the end device.

- DevNonce is a 2-byte counter, starting at 0 when the device is initially powered up and incrementing with every join request. The DevNonce value is used to prevent replay attacks.

7.4.2 Join accept:

If the above step is successful, the Network Server generates the Join-accept message. The Join-accept message consists of the following fields.

1 byte	3 bytes	4 bytes	1 byte	1 byte	16 bytes
JoinNonce	NetID	DevAddr	DLSettings	RXDelay	CFList

- The session keys FNwkSIntKey, SNwkSIntKey, NwkSEncKey, and AppSKey are derived by the end device from the JoinNonce counter value, which is supplied by the Join Server.
- a 24-bit distinctive network identifier called NetID.
- DevAddr is a 32-bit device address that the network server assigns to a device to identify it in the current network.
- A 1-byte field called DLSettings contains the downlink settings the end device should employ.
- RxDelay - contains the time difference between TX and RX
- A list of available channel frequencies for the network the end device is joining is called CFList. These frequencies are region-specific.

8. LoRa Physical Layer Packet Format

LoRa uses two types of packet formats for data transmission: explicit and implicit.

In explicit mode, a LoRa packet includes the following elements:

- The preamble synchronizes the receiver with the transmitter. It MUST consist of 8 symbols for all regions, as mentioned in the LoRaWAN Regional Parameters document. However, the radio transmitter will add another 4.25 symbols, resulting in a final preamble length of 8 + 4.25 = 12.25 symbols.
- PHDR (Physical Header) is an optional element only present in the explicit mode that contains information about payload size and CRC (Cyclic Redundancy Check).
- PHDR_CRC (Header CRC) is an optional field that contains an error-detecting code for correcting errors in the header.

The PHDR and PHDR_CRC are encoded with a Coding Rate of 4/8.

- PHYPayload contains the complete frame generated by the MAC layer. The maximum payload size varies by DR (Data Rate) and is region-specific.
- CRC is an optional field that contains an error-detecting code for correcting errors in the payload of uplink messages.

The PHYPayload and CRC are encoded with one of the Coding Rates (4/5, 4/6, 4/7, or 4/8). The complete frame is then sent using one of the Spreading Factors (SF = 7 to 12).

The following figure shows the physical layer structure of uplink and downlink packets that use explicit mode.

Preamble	PHDR	PHDR_CRC	PHYPayload	CRC

The physical structure of an uplink packet

Preamble	PHDR	PHDR_CRC	PHYPayload

The physical structure of a downlink packet

In implicit mode, the header is removed from the packet, and the payload size and Coding Rate are fixed or known in advance.

Beacons use LoRa radio packet implicit mode for sending time-synchronizing information from gateways to end devices.

The following figure shows the structure of a LoRa packet that uses the implicit mode.

Preamble	BCNPayload

9. Message format

The MAC payload of the data messages consists of a frame header (FHDR), followed by an optional port field (FPort), and an optional frame payload (FRMPayload).

7 to 22 bytes	0 to 1 byte	0 to N bytes
FHDR	FPort	FRMPayload

The frame header (FHDR) of the MAC payload consists of the following fields.

4 bytes	1 byte	2 bytes	0 to 15 bytes
DevAddr	FCtrl	FCnt	FOpts

The maximum length of the MAC Payload field is region and data rate-specific.

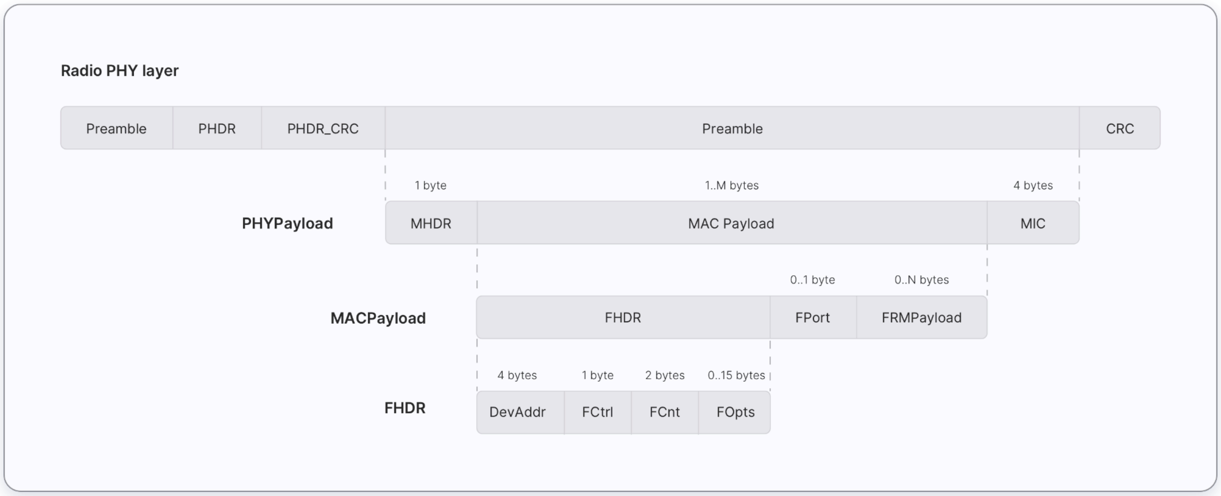

Fig. 6. Message Format

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