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Department of Information Engineering

Bachelor thesis in
Computer Engineering

An LPWAN MAC protocol for agricutural applications

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Year 2022/2023

Abstract

Low Power Wide Area Networks (LPWAN) are getting very popular these days in Internet of Things (IoT) applications thanks to their capability of both consuming low amounts of power and of covering long distances. This technology is widely used in the 4^{th} industrial era for manufacturing, health care, and automation in general.

This thesis has the objective to propose a Media Access Control (MAC) protocol called Bacco. It is based on LoRa modulation and has a narrow focus on agricultural applications, where achieving high power efficiency is crucial due to the lack of reliable power sources. Another aspect taken into consideration is the cost effectiveness of the devices required to develop a functional network.

First, the thesis establishes an introduction of LoRa and LoRaWAN; then the requirements for a MAC protocol used in LPWANs will be discussed. After that, there will be a description of the Bacco protocol itself, alongside with some example applications of it.

Sommario

Le reti Low Power Area Network (LPWAN) stanno prendendo piede oggigiorno nel mondo dell'Internet of Things (IoT) grazie al loro basso consumo energetico e alle ampie distanze che possono coprire. Questa tecnologia è un caposaldo dell'industria di quarta generazione, soprattutto negli ambiti di manifattura, assistenza sanitaria e in generale dell'automazione.
Questa tesi ha l'obiettivo di proporre un protocollo Media Access Control (MAC), chiamato Bacco. Questo sfrutta la modulazione LoRa e si rivolge a applicazioni in ambito agricolo, dove è cruciale raggiungere un'alta efficienza energetica data la mancanza di fonti energetiche affidabili. Un altro aspetto che viene considerato è il costo dei dispositivi rischiesti per sviluppare una rete funzionale.
Inizialmente la tesi si occuperà di dare una breve introduzione a LoRa e LoRaWAN, per poi discutere i requisiti di un protocollo MAC per LPWAN. Successivamente, verrà data una descrizione del funzionamento di Bacco, accompagnata da alcuni esempi applicativi.

Glossary

GSM Acronym for "Global System for Mobile Communications", it's a 2nd generation mobile communication standard, see [1] for more information.

LTE Acronym for "Long Term Evolution", it's a 4th generation mobile communication standard, see [2] for more information.

FTP Acronym for "File Transfer Protocol", built on top of TCP, see [3] for more information.

VHF Acronym for "Very High Frequency", it refers to the radio frequency band between 30 and 300 MHz.

PHY Stands for physical layer protcol specification.

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Chapter 1

Introduction

Place introduction here

Chapter 2

Bacco protocol

The goal of this chapter is to give a description of the *Bacco* protocol and to discuss the implementation choices that were made in order to deploy it. This is achieved using a top-down ordering for the level of detail, meaning that an overview of the network is presented before the specifics of the MAC protocol.

2.1 Network overview

I will start by describing a simple network that makes use of the protocol to better understand the integration of the Bacco protocol into an LPWAN. The network is built upon 4 categories of devices:

- Sender node - collects data and sends it to the gateway using LoRa
- Repeater node - listens to the incoming LoRa messages form Senders and sends them to a Gateway [1]
- Gateway node - collects data coming from the sender nodes and sends it to the web server. In the example shown, this will be achieved with the FTP protocol over a mobile network such as GSM or LTE. This node has also the role of coorinating and syncronizing Sender nodes. It can also be optionally configured to perform pre-processing operations (e.g. filtering, smoothing, interpolation ...) on the incoming data
- Web server - receives data coming from the Gateways, elaborates it and makes it available through a web application

[1] The use of Repeaters where physical obstacles compromise the integrity of the signals is of very high relevance in agricultural contexts, since natural barriers such as hills can easily block VHF radio signals.

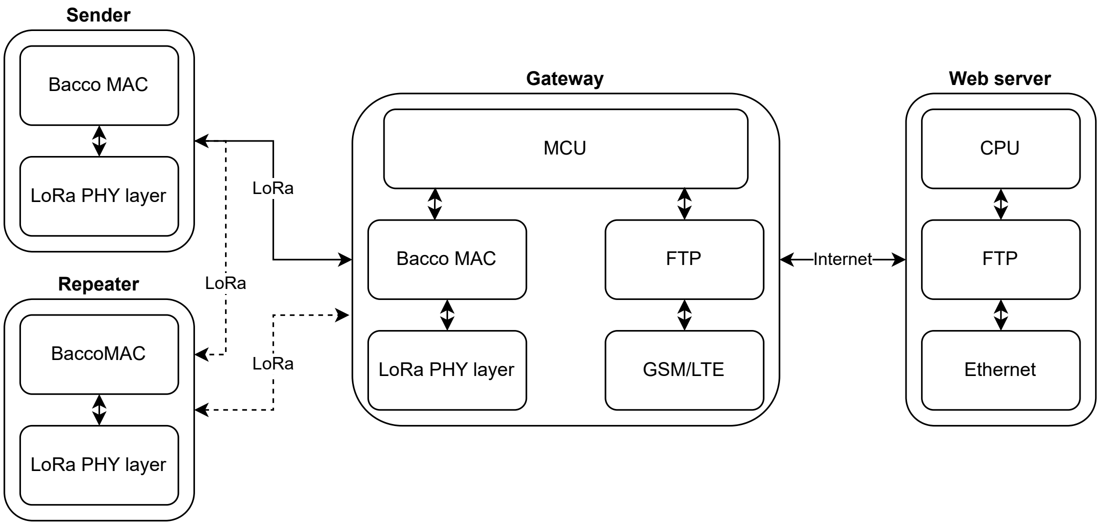


Figure 2.1: Schematic representation of the example network

2.2 Topology

The network has a star-of-stars topology, in which the zeroth level is occupied by the Web server, the first level by the Gateways and Repeaters, and the second level contains the Senders. Figure 2.2 shows the type of devices that are involved and their communication schema.
The structure is equivalent to a tree, hence we can define a hierarchy of nodes. The root node is the central web server and its children nodes are the Gateways. All sender nodes are children of either a Gateway or a Repeater and have to chlidren, so they correspond to the leaves of the tree.

2.3 Addressing

It is crucial to identify each Sender node in order to contextualize the messages coming to the Gateway node. This is achieved by assigning them a unique identifier, represented by a natural number in the range $[1, 254]$. Address 0 is reserved for the Receiver and address 255 is used as a globally invalid address. This fact limits the number of Sender nodes connected to a single Gateway to 254 [2]. If nec-

[2]This choice is influenced by the current Italian regulations
TODO: Scrivi e inserisci citazione a paragrafo su regolamentazione e calcolo numero massumo di devices
CITAZIONE PARAGRAFO REGOLAMENTAZIONE E CALCOLO MASSIMO NUMERO DI DEVICI
[4] on duty cycle for the 868MHz band and the fact that most agricultural contexts do not require a huge amount of sensors

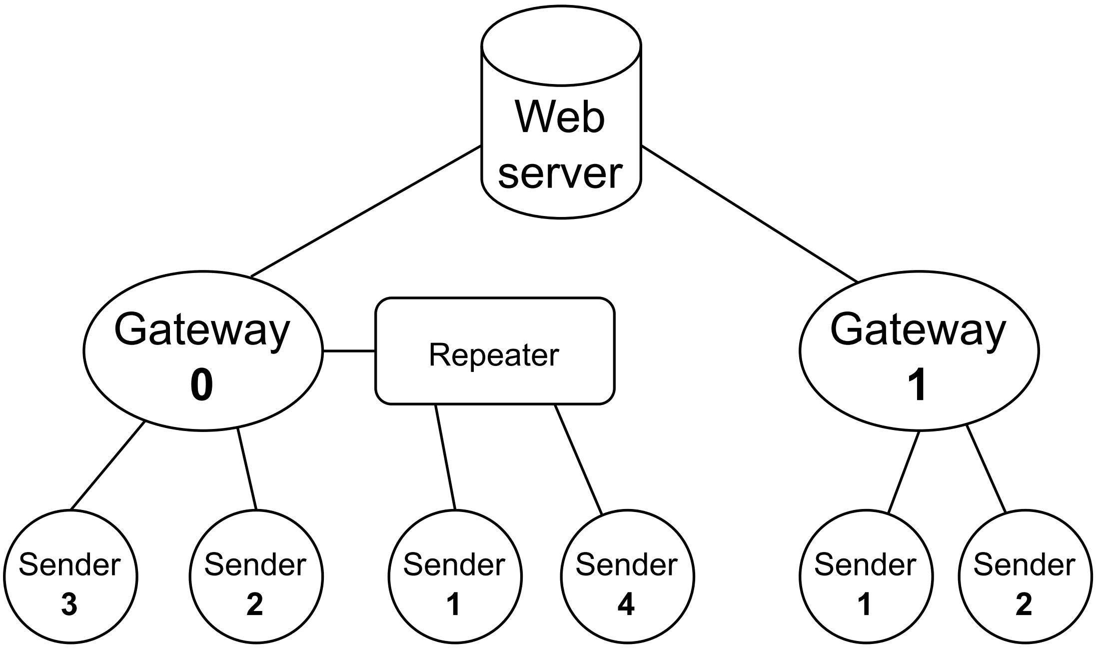


Figure 2.2: Example network topology

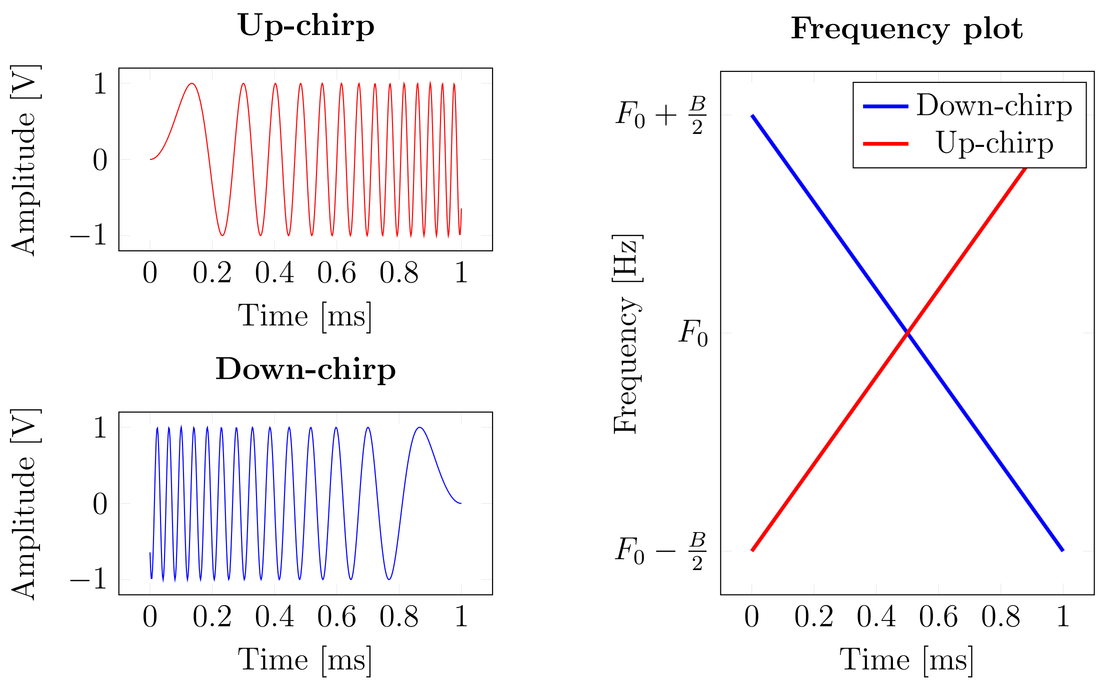
essary, the network can scale up by using additional Gateways. Note that since Repeaters do not modify the forwarded messages and do not produce messages themselves, they do not play an active role in the network and thus they will not be given an identifier.

2.4 Interference mitigation

The LoRa PHY protocol specification does not fully cover the matter of sharing the communication link between multiple devices, thus it is necessary to define mothods for doing so, in order to minimize interference and achieve a realiable exchange of information. Different techniques are applied in the domain of both time and frequency

2.4.1 Channel activity detection

Channel Activity Detection, or CAD, is a feature available for most LoRa transcievers[5]. In this mode, the LoRa node listens for any transmission on a specific frequency; if it detects a signal, it retuns an interrupt to the MCU. This presents a possible Carrier Sense Multiple Access mechanism, also called CSMA.
Bacco does not make use of CAD for data packets, but it enables it in specific situations such as network discovery (discussed in section 2.5).



2.4.2 IQ inversion

IQ inversion is a LoRa primitive that makes it possible to have 2 modes of transmissions that are easily distinguishable for a receiver. The name stands for *In-phase / Quadrature*, and it usually refers to signals that are out of phase from each other by $\frac{\pi}{4}$ rad. Despite of that, LoRa uses that term to describe 2 signal with inverted chirp direction, namely up-chirp and down-chirp. Bacco uses this technique to discriminate between uplink messages (i.e. from Sender to Gateway/Repeater) and downlink messages (i.e. from Gateway to Sender/Repeater). This implies that devices belonging to the same category are not able to communicate with each other (e.g. a Sender would not detect other Senders' transmissions).

2.4.3 Subnetting

The LoRa procol supports a wide range of carrier frequencies in the VHF spectrum [3]. This feature makes it possible to apply various techniques to mitigate interference.
Bacco exploits it to build sub-networks that operate at different frequencies, and thus achieve a communication with very low interference between different sub-

[3]For reference, the SX1262[6] transciever features a continuous frequency coverage from 150 MHz to 960 MHz

nets. Specifically, all the Sender nodes connected to a Repeater and the Repeater itself operate at a frequency that's different from the frequency used by the Gateway and other Repeaters. Figure 2.4 shows a schematic representation. This technique is particularly useful to solve the problem of bouncing, that occours when a message is sent back to the original Repeater.
It is necessary to define a set of frequencies at which Repeaters and Gateways operate. This choice is done based on current regulations in the specific country of operation; this thesis will focus on Italian and/or European standards. 868 MHz is the base frequency at which the Gateway node operates, and the set of 6 frequencies of operation is so composed:

$$\{f_k : f_k = 868\text{MHz} + k \times 125\text{KHz}, k \in \{0..10\}\} \tag{2.1}$$

This implies that a Bacco network can have up to 10 Repeaters operating on different frequencies, however if more coverage is needed, it is possible to have multiple Repeater nodes working at the same frequency, given that they are not in reach with each other.

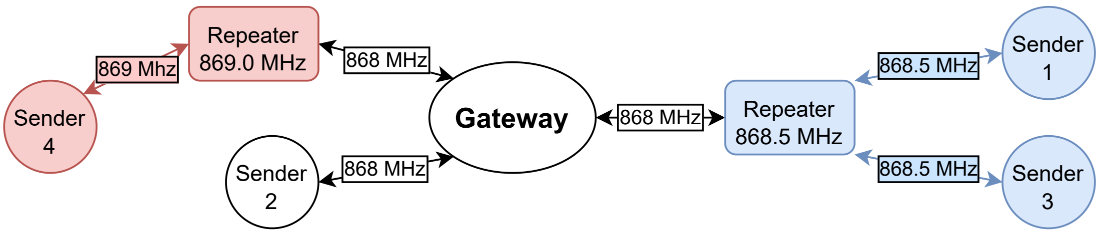


Figure 2.4: Example network with repeaters in subnets

2.4.4 Distribution of transmission activity

The Bacco protocol distributes the activity on the channel over time using defined frames reserved for each Sender, using an approach that was first introduced by the AlohaNet[7] protocol. The frames are equally distributed between all the Senders and the start of each transmission frame is function of the identifier. The time delay between 2 consecutive transmissions from a same Sender is a constant value and it is called cycle. At the end of a cycle, some time is reserved for the Gateway to upload the collected data. Figure 2.5 shows a schematic representation of the time slot management used by Bacco. The cycle time is a user-defined parameter, and all the other values are calculated based on it as shown in table 2.1.

Parameter	Value
Gateway frame time	$0.2 \cdot C$
Sender frame time	$\frac{0.6 \cdot C}{N}$
Silence frame time	$\frac{0.2 \cdot C}{N}$

Table 2.1: Time parameters calculation, where C is the cycle time and N is the number of Senders

Compensating clock drift

All the devices in the network need to transmit during their assigned frame for the protocol to be effective; this means that all the clocks are required to have a certain degree of syncronization. This is hard to achieve in practice, because all commercial clock oscillators do not provide a costant frequency source due to manifacturing imprecisions, temperature gradient etc... .
In order to deal with with this problem, Bacco assigns the Gateway node the role of coordinating the network timings through the dispatch of downlink messages containing the network timestamp when a Sender node transmits out of its assigned frame. The downlink message is sent as soon as the Gateway receives the uplink message. Figure 2.5 shows this behavior during the transmission involving Sender2.

2.5 Network discovery

When a Sender node is first started, it needs to decide at what frequency it has to operate for minimizing the power needed to reach a Repeater or Gateway. In order to do this, Bacco introduces method 1 for scanning nearby devices and selecting the most suitable. It tries to establish a communication with Repeaters and Gateways spanning all the available frequencies by sending a particular type of message that triggers a response containing a SYN/ACK message. Note that the CAD technique will be used by the Sender to not interfere with ongoing communications because the board does not yet have an allocated time frame.

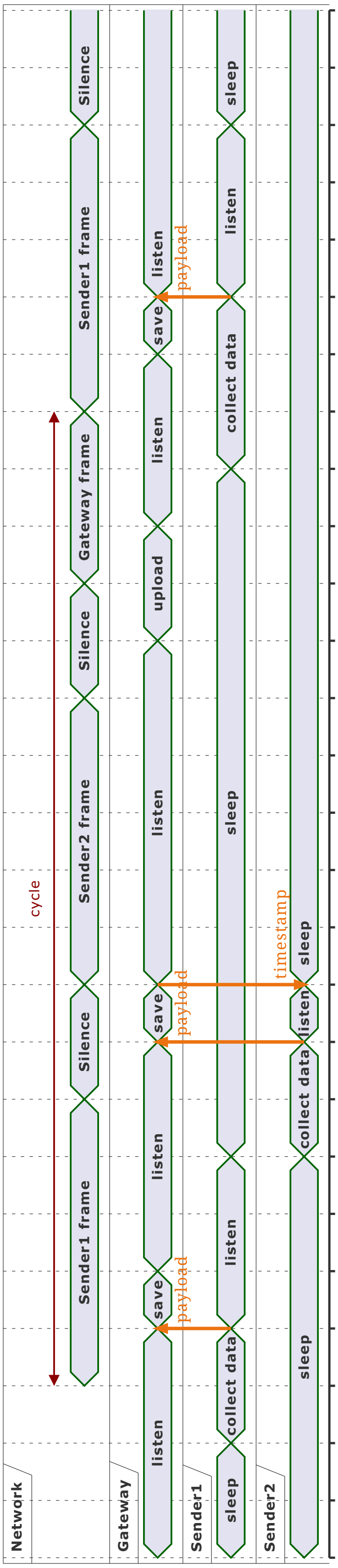


Figure 2.5: Timing diagram

Algorithm 1 Network discovery algorithm

```
rssi_values ← [0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
while all rssi_values are equal to 0 do
    for k from 0 to 10 do
        f_k ← 868 × 10^6 + k × 125 * 10^3
        for i from 0 to 10 do
            do
                sleep for 1 second
                enter CAD mode at frequency f_k for 1.5 seconds
            while activity detected by CAD
            send sensing message
            enter receive mode for 3 seconds
            if received SYN/ACK then
                rssi_values[k] ← current rssi
                break
            end if
        end for
    end for
end while
```

2.6 Network joining

When a Sender node needs to connect to a Gateway node for the first time, it does not yet have an identifier nor is in sync with the network. The procedure to achieve that will be called the joining process. Note that we assume that the Sender node has already selected its frequency of operation, as descibed in section 2.5.

We will ignore the act of forwarding made by an optional Repeater node, as it is transparent for both ends of the communication. All the messages sent from Sender and Receiver make use of CAD to make sure the channel is free before the actual transmission; this step will be omitted in the description for brevity. First, the Sender transmits a SYN message to the Gateway and waits for a SYN/ACK response for 3 seconds. If no message is received, another SYN message is sent for a maximum of 10 times. After that, the Gateway waits for 3 seconds for an ACK message from the Receiver, and if no message is received it will try again for a maximum of 10 times. The SYN/ACK message contains the timestamp of the network as well as the assigned identifier. If the maximum number of iterations are reached in any of the steps, the whloe process starts again after 30 minutes. Figure 2.6 show a schematic representation of the process.

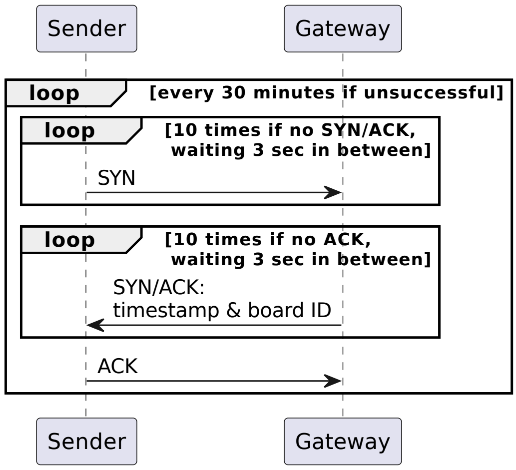


Figure 2.6: Network joining process

2.7 Downlink commands

2.8 Transmission power adaption

2.9 Packet format

Uplink packet format

Downlink packet format

Chapter 3

Performance

The goal of this chapter is ...

3.1 Time on air

3.1.1 Regulations

3.1.2 Lab tests

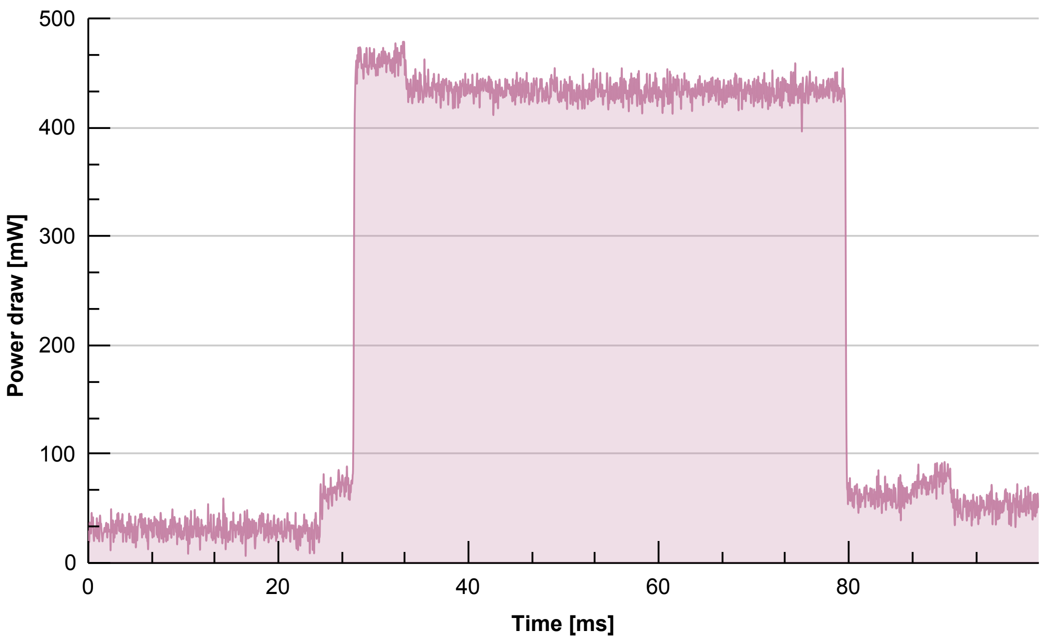


Figure 3.1: Power draw during transmission of a Bacco packet with payload size of 15 bytes, using SF7, 14dBm, 125kHz bandwidth

delta time is 51.6ms and total energy is 21.3mJ

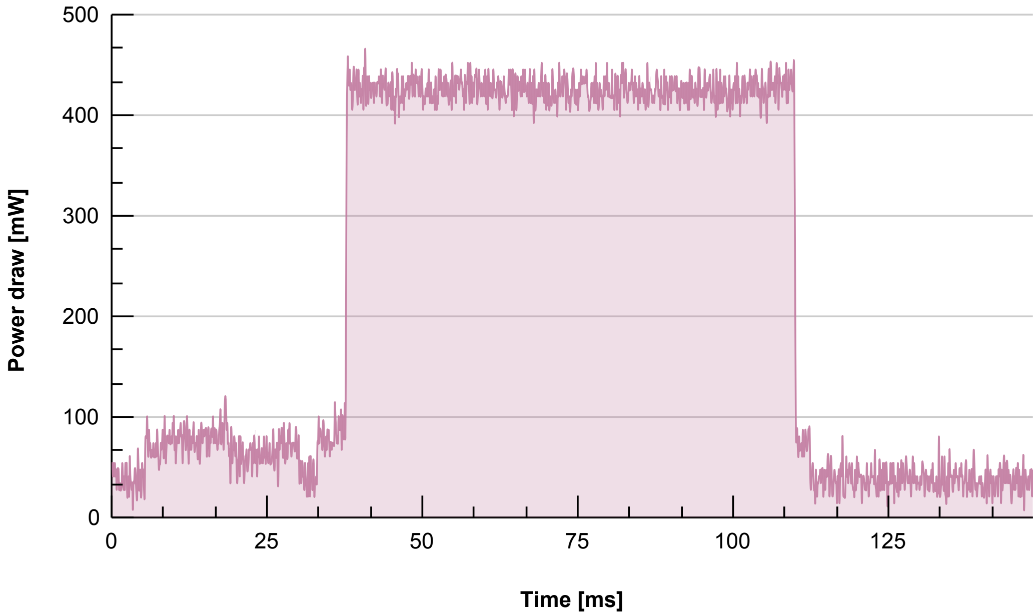


Figure 3.2: Power draw during transmission of a LoRaWAN packet with payload size of 15 bytes, using SF7, 14dBm, 125kHz bandwidth

delta time is 71.8ms and total energy is 30.8mJ

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