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IoT Challenge #3, Exercises LoRaWAN

INTERNET OF THINGS

Authors: **Kevin Zioldi - 10764177**
Matteo Volpari - 10773593

Professors: Alessandro Redondi, Fabio Palmese, Antonio Boiano
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1 | EQ1 - LoRa SF calculation

1.1. Data

In this chapter we answer to question EQ1, asking to find the biggest LoRa SF for having a success rate of at least 70% in a LoRaWAN Network with the following parameters:

- Carrier frequency: $CF = 868MHz$
- Bandwidth: $BW = 125kHz$
- Number of gateways: $N_G = 1$
- Number of sensor nodes: $N_S = 50$
- Intensity of Poisson process: $\lambda = 1$ packet/minute
- Success rate: $SR \geq 0.7$

We compute the payload size based on the last two digits of the leader's person code (XY), according to the formula:

$$L = 3 + XY \text{ Bytes} \quad (1.1)$$

Our leader's person code is 10773593, so the payload size is:

$$L = 3 + 93 = 96 \text{ Bytes} \quad (1.2)$$

1.2. Maximum Spreading Factor calculation

Since LoRaWAN uses an ALOHA-like procedure to handle channel access and retransmissions, we compute the success rate, SR, as the ALOHA success rate:

$$SR = S/G = e^{-2G} = e^{-2N\lambda t} \quad (1.3)$$

Thanks to this formula, we can compute the maximum airtime to have a success rate greater than 70%.

$$SR \geq 0.7 \quad (1.4)$$

$$e^{-2N\lambda t} \geq 0.7 \quad (1.5)$$

By applying the natural logarithm, we get:

$$-2N\lambda t \geq \ln(0.7) \quad (1.6)$$

$$t \leq \frac{-\ln(0.7)}{2N\lambda} = \frac{-\ln(0.7)}{2 \cdot 50 \cdot \frac{1}{60 \cdot 10^3 \text{ ms}}} = 214.005 \text{ ms} \quad (1.7)$$

We now use the API <https://www.thethingsnetwork.org/airtime-calculator> to find the highest SF that guarantees an airtime smaller than the value we found. We use payload size of 96 Bytes, as computed before, region EU868 and bandwidth 125 kHz. The API says that the maximum payload size for EU868 with SF from 10 to 12 is 51 Bytes; this means that we can evaluate SF values starting from 9 and lowering the SF until we find an airtime smaller than 214.005 ms. The values of airtime corresponding to the SF are report in the following table.

Spreading Factor	Airtime
SF9	594.9 ms
SF8	328.2 ms
SF7	184.6 ms

Table 1.1: Airtime based on SF

The only value of SF that leads to an airtime smaller than 214.005 ms and a success rate greater than 70% is SF7.

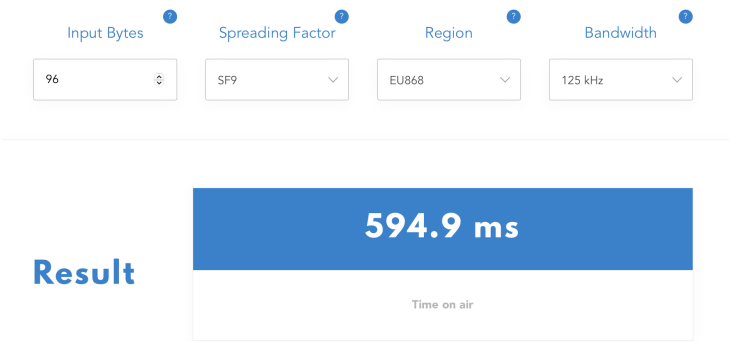


Figure 1.1: Airtime with SF9

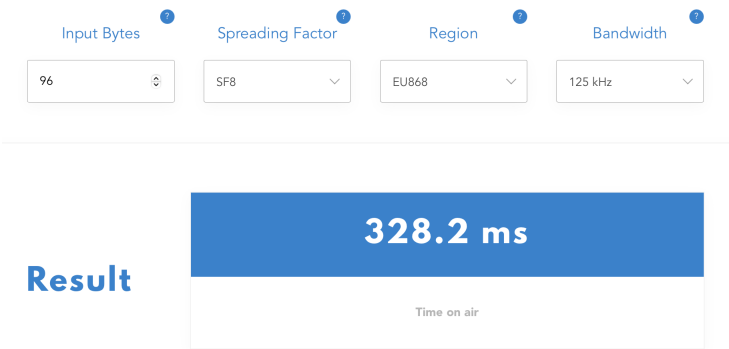


Figure 1.2: Airtime with SF8

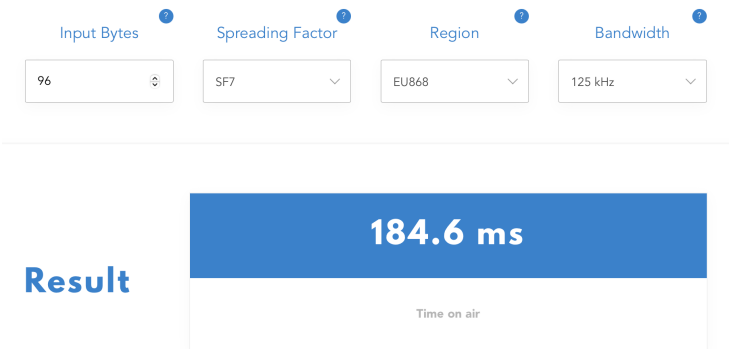


Figure 1.3: Airtime with SF7

2 | EQ2 - LoRaWAN system design

The aim of this chapter is to present a system that meets the requirements imposed by EQ2. The entire Node-Red flow is shown here with high-level blocks that will be described in the following sections.

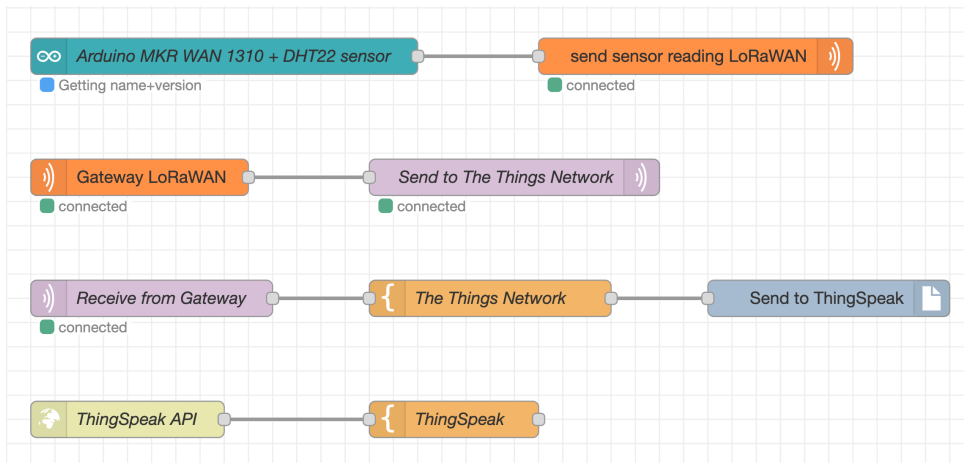


Figure 2.1: Node Red flow

2.1. Hardware

In this section we present the hardware components needed to build and operate the system.

- **Arduino MKR WAN 1310:** this board already includes a LPWAN module called Murata CMWX1ZZABZ.
- **External antenna:** the Arduino documentation suggests the following antenna: *Dipole Pentaband Waterproof Antenna* ([Arduino store](#)).
- **DHT22 sensor:** this is the humidity and temperature sensor that will be connected via a digital pin to the Arduino board.

- **LoRaWAN Gateway:** for the LoRaWAN gateway there are many equivalent options:
 - Use a public gateway: we can search if we have a nearby gateway from the The Things Network at <https://www.thethingsnetwork.org/map>.
 - Buy a gateway from those available online: you can search the best LoRa Gateway online for indoor or outdoor usage, based on your needs, e.g. indoor (*Mikrotik wAP LR8*) outdoor (*TEKTELIC KONA MACRO OUTDOOR GATEWAY*).
 - Build the gateway: you can build your own gateway, by using a computer, e.g. a *Raspberry Pi 4*, a LoRa concentrator board, such as a *RAK2245 Pi Hat*, and an antenna.
- **Network Sever The Things Network:** To use a The Things Network server, simply register at [The Things Network](#) and add an application that will run in the cloud on The Things Industries infrastructure.
- **ThingSpeak:** To create a ThingSpeak channel, you need to log in with your account at [ThingSpeak](#) and generate a new public channel.

2.1.1. Connections

Here is described how the different components are interconnected.

Arduino and DHT22 are physically connected via a digital pin present on the Arduino board.

Arduino then communicates with the Gateway through a LoRaWAN connection.

The Gateway can communicate with The Things Network with the gateway connector protocol, that uses as network protocol gRPC or MQTT.

TTN communicates the data to ThingSpeak through the built in integration, using the HTTP API exposed by ThingSpeak.

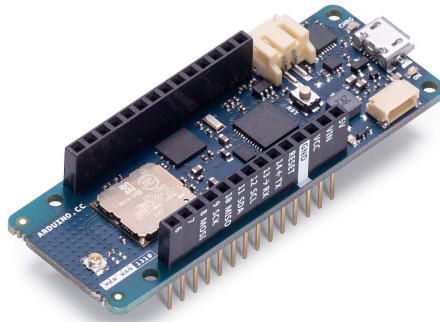


Figure 2.2: Arduino MKR WAN 1310

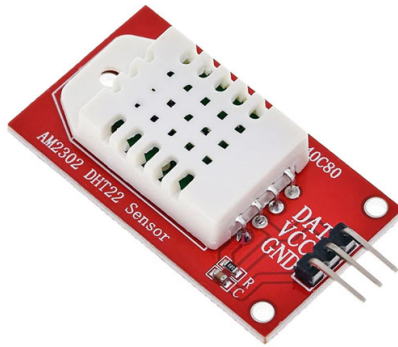


Figure 2.3: DHT22 sensor



Figure 2.4: Dipole Pentaband Waterproof Antenna

2.2. Software

In this section we present the software components used to allow the system to work. Since we don't own some hardware components, we were not able to test the whole system, but we tested individual components, as will be explained in the following sections.

2.2.1. Code Arduino MKR WAN 1310

The code that we will run on the Arduino MKR WAN 1310 is reported here.

```
#include <MKRWAN.h>
#include <DHT.h>

#define DHTPIN 7
#define DHTTYPE DHT22
DHT dht(DHTPIN, DHTTYPE);

LoRaModem modem(Serial1);

// TTN credentials
String appEui = "0000000000000000";
String appKey = "9D265EE3895BE505824143EBD5FDC46B";

void setup() {
    // initialization
    Serial.begin(115200);
    dht.begin();

    // LoRa module initialization
    if (!modem.begin(EU868)) {
        Serial.println("Errore_avvio_LoRa");
        while (1);
    }

    // join network server
    int connected = modem.joinOTAA(appEui, appKey);
    if (!connected) {
```

```

    Serial.println("_Something_went_wrong;_are_you_indoor?_
        Move_near_a_window_and_retry...");
    while (1);
}
}

void loop() {
    // read humidity and temperature
    float t = dht.readTemperature();
    float h = dht.readHumidity();

    // check readings
    if (isnan(h) || isnan(t)) return;

    // encode readings
    byte payload[4];
    int16_t tt = t * 100;
    int16_t hh = h * 100;
    payload[0] = highByte(tt);
    payload[1] = lowByte(tt);
    payload[2] = highByte(hh);
    payload[3] = lowByte(hh);

    // send message
    modem.beginPacket();
    modem.write(payload, sizeof(payload));
    modem.endPacket();

    // send a reading every minute
    delay(60000);
}

```

In the first line of the program, we include libraries needed to use LoRaWAN to communicate readings values and to use DHT22 sensor to measure temperature and humidity. Then, we define the digital PIN to which the DHT22 sensor is connected and the DHT-TYPE, representing the sensor model. The code is formed by two functions: setup and loop. In setup, we initialize both the DHT22 and the LoRa communication, setting the

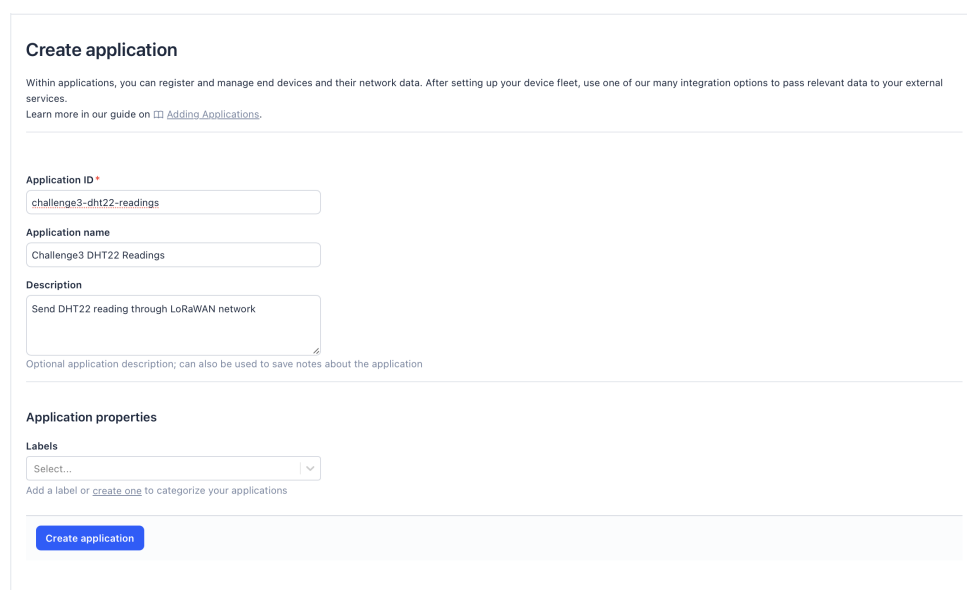
Carrier Frequency to 868 MHz. Moreover, we join the network server thanks to the joinOTAA function. In the loop function, instead, we perform sensor readings for temperature and humidity, encode these values and send them over LoRaWAN network. Finally, we insert a delay of 1 minute to wait for the next reading and message.

2.2.2. The Things Network Console and ThingSpeak

In this section, we provide a detailed explanation of all the work we have done to setup The Things Network (TTN) and ThingSpeak to make the system fully functional. We present all the steps in chronological order and add figures to document the result.

Create an Application on TTN

After creating an account on TTN, we created an Application and set the Application ID, a name and a description.

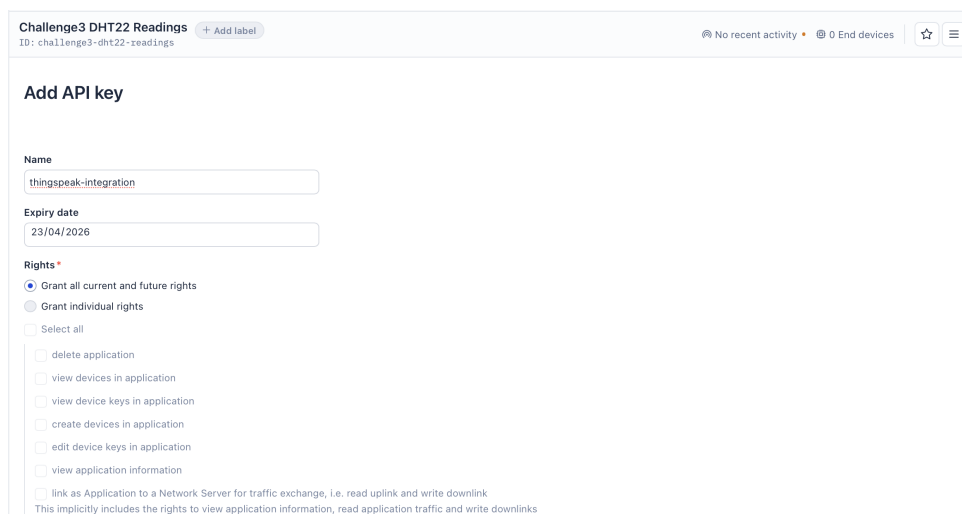


The screenshot shows the 'Create application' form in the TTN Console. The form has a title 'Create application' and a subtitle 'Within applications, you can register and manage end devices and their network data. After setting up your device fleet, use one of our many integration options to pass relevant data to your external services. Learn more in our guide on [Adding Applications](#).' Below this, there are three input fields: 'Application ID' with the value 'challenge3-dht22-readings', 'Application name' with the value 'Challenge3 DHT22 Readings', and 'Description' with the value 'Send DHT22 reading through LoRaWAN network'. Below the description field, there is a note: 'Optional application description; can also be used to save notes about the application'. Below this, there is a section 'Application properties' with a 'Labels' dropdown menu showing 'Select...'. Below the labels section, there is a note: 'Add a label or [create one](#) to categorize your applications'. At the bottom of the form, there is a blue button labeled 'Create application'.

Figure 2.5: Create an Application on TTN

Generate an API key

From the API keys section of TTN Console, we generated an API key for the newly created Application.



Challenge3 DHT22 Readings + Add label No recent activity 0 End devices ☆ ☰

Add API key

Name
thingspeak-integration

Expiry date
23/04/2026

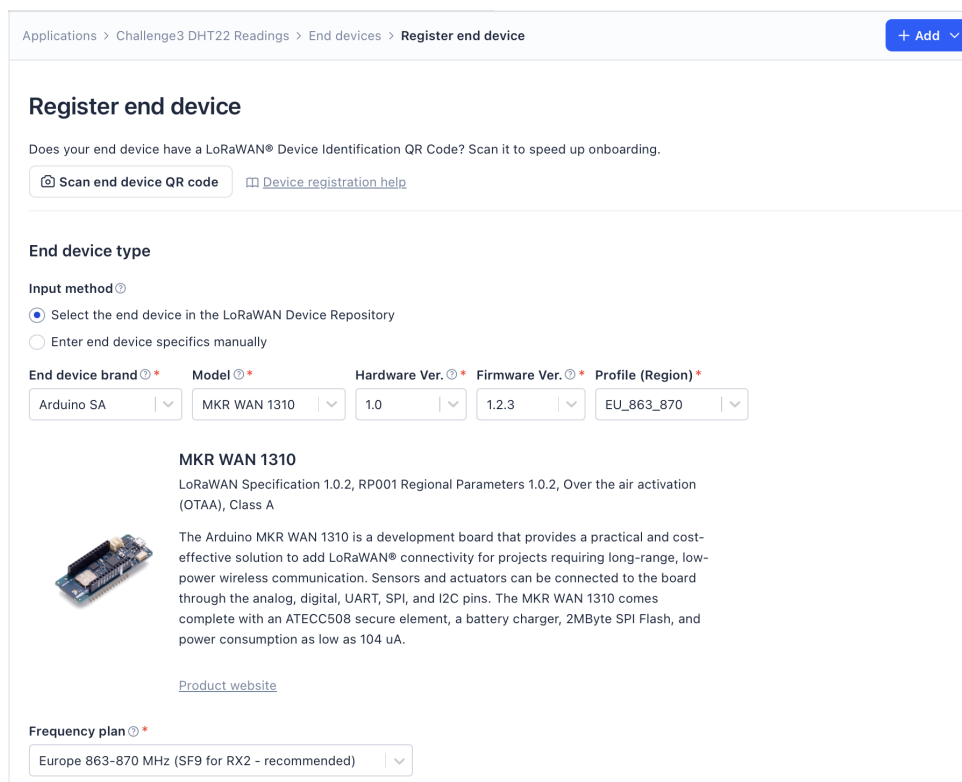
Rights *

- ☒ Grant all current and future rights
- ☐ Grant individual rights
- ☐ Select all
 - ☐ delete application
 - ☐ view devices in application
 - ☐ view device keys in application
 - ☐ create devices in application
 - ☐ edit device keys in application
 - ☐ view application information
 - ☐ link as Application to a Network Server for traffic exchange, i.e. read uplink and write downlink
This implicitly includes the rights to view application information, read application traffic and write downlinks

Figure 2.6: Generate an API key

Register Arduino MKR WAN 1310 End Device

In the End devices section of TTN Console, we added the Arduino MKR WAN 1310 End Device by setting the brand, the model and other details about the board, as well as the recommended frequency plan.



Applications > Challenge3 DHT22 Readings > End devices > **Register end device** + Add

Register end device

Does your end device have a LoRaWAN® Device Identification QR Code? Scan it to speed up onboarding.

[Scan end device QR code](#) [Device registration help](#)

End device type


Input method ⓘ

- ☒ Select the end device in the LoRaWAN Device Repository
- ☐ Enter end device specifics manually

End device brand ⓘ * **Model** ⓘ * **Hardware Ver.** ⓘ * **Firmware Ver.** ⓘ * **Profile (Region)** *

Arduino SA MKR WAN 1310 1.0 1.2.3 EU_863_870

MKR WAN 1310
LoRaWAN Specification 1.0.2, RP001 Regional Parameters 1.0.2, Over the air activation (OTAA), Class A

 The Arduino MKR WAN 1310 is a development board that provides a practical and cost-effective solution to add LoRaWAN® connectivity for projects requiring long-range, low-power wireless communication. Sensors and actuators can be connected to the board through the analog, digital, UART, SPI, and I2C pins. The MKR WAN 1310 comes complete with an ATECC508 secure element, a battery charger, 2MByte SPI Flash, and power consumption as low as 104 uA.

[Product website](#)

Frequency plan ⓘ *

Europe 863-870 MHz (SF9 for RX2 - recommended)

Figure 2.7: Register an end device part 1

We also generated the AppKey, AppEUI and DevEUI, some of these values are chosen arbitrarily, because we don't have the real Arduino board.

The screenshot displays a web interface for provisioning a LoRaWAN end device. It is divided into several sections:

- Provisioning information:**
 - JoinEUI:** A field containing eight hexadecimal digits (00 00 00 00 00 00 00 00) with a "Reset" button.
 - DevEUI:** A field containing eight hexadecimal digits (70 B3 D5 7E D0 07 02 35) with a "Generate" button and a "1/50 used" indicator.
 - AppKey:** A field containing sixteen hexadecimal digits (9D 26 5E E3 89 5B E5 05 82 41 43 EB D5 FD C4 6B) with a "Generate" button.
 - End device ID:** A text input field containing the string "arduino-sensor-readings".
- Device properties:**
 - Labels:** A dropdown menu with "Select..." and a downward arrow.
 - A link: "Add a label or [create one](#) to categorize your devices".
- After registration:**
 - Two radio buttons: "View registered end device" (selected) and "Register another end device of this type".
- Register end device:** A blue button at the bottom.

Figure 2.8: Register an end device part 2

Configure Uplink Payload Formatter

We configured the uplink payload formatter to decode the data coming from the Arduino board. We chose a custom JavaScript formatter and wrote the JS code that decodes the data in the same way we have encoded it in the Arduino code. We return a JS object that has the correct format for the integration with ThingSpeak, as shown in the following figure.

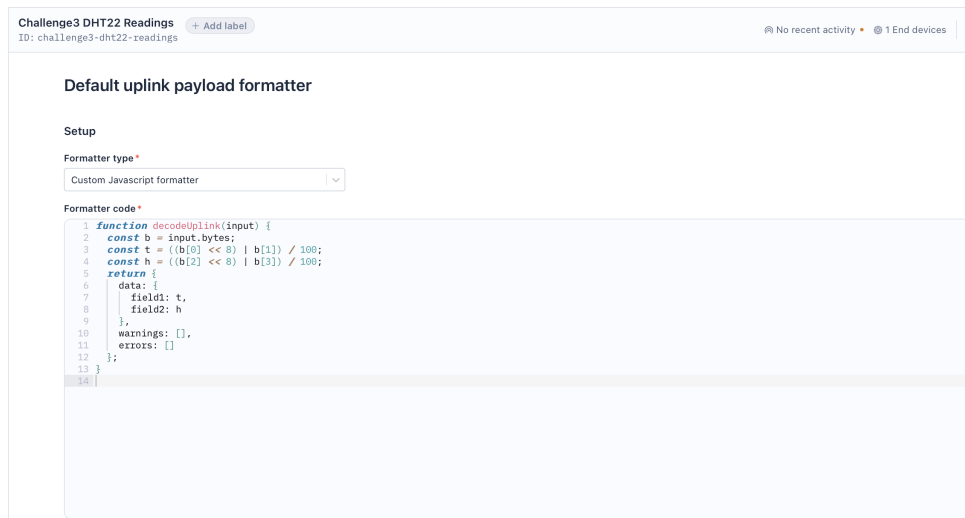


Figure 2.9: Configure Uplink Payload Formatter

Create ThingSpeak Channel

We created the ThingSpeak Channel that receives the temperature and humidity values from TTN. We assigned a name and a description to the channel and we create the two desired fields. Finally we made it publicly available at <https://thingspeak.mathworks.com/channels/2931560>.

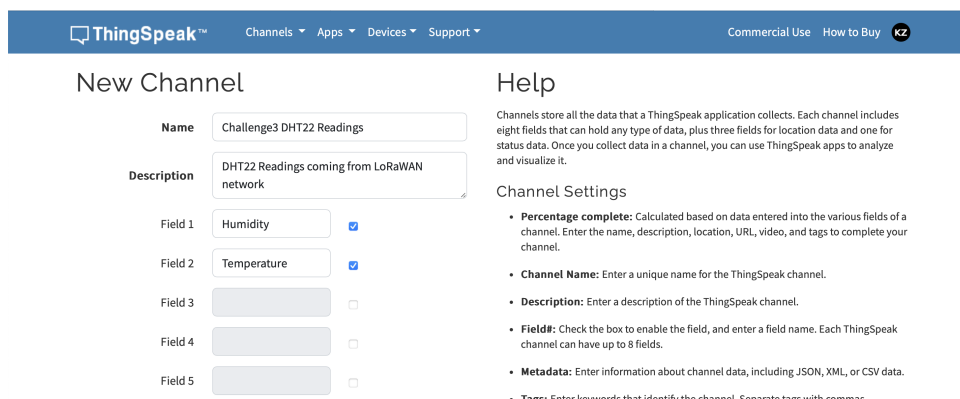


Figure 2.10: Create ThingSpeak Channel

Integrating The Things Network and ThingSpeak

In order to integrate TTN and ThingSpeak, we setup a webhook for ThingSpeak and insert the Channel ID and write API Key, which we take from ThingSpeak.

Challenge3 DHT22 Readings + Add label
ID: challenge3-dht22-readings

Setup webhook for ThingSpeak
Send data to ThingSpeak channel
[About ThingSpeak](#)

Webhook ID *
thing-speak-ttn-webhook

Channel ID *
2931560
ThingSpeak Channel ID

API Key *
MSOEJN78HT050Q28
ThingSpeak Write API Key

Create ThingSpeak webhook

Figure 2.11: Integrating TTN and ThingSpeak

2.2.3. Test TTN and ThingSpeak Integration

Finally, we used test payload function of TTN to send some test payloads to ThingSpeak and test the integration between the two.

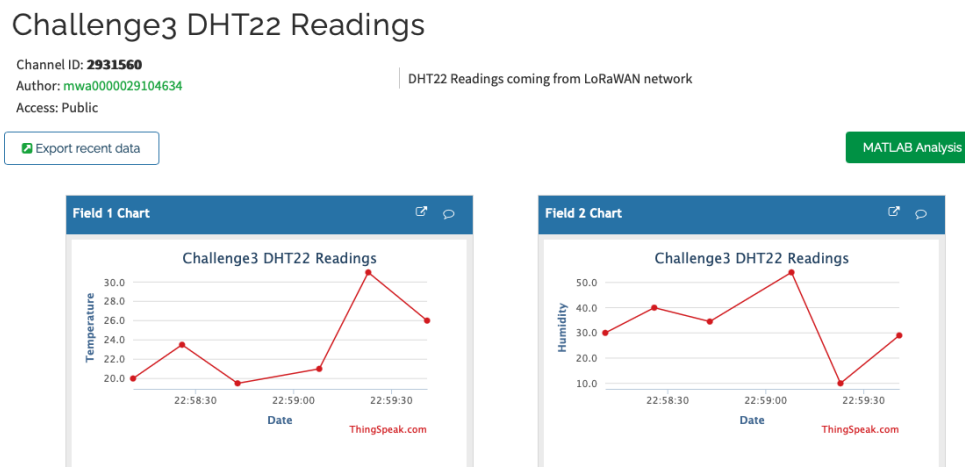


Figure 2.12: ThingSpeak fields charts

2.3. References

- <https://docs.arduino.cc/learn/communication/lorawan-101/>
- <https://docs.arduino.cc/libraries/mkrwan/>
- <https://docs.oyoclass.com/unoeditor/Libraries/dht/>

3 | EQ3 - Use LoRaSim to replicate simulations

In this chapter we use the paper "Do LoRa Low-Power Wide-Area Networks Scale?" by M. Bor et al. and the LoRa simulator LoRaSim to reproduce the figures reporting the results of two Experiments Sets from the paper. LoRaSim is a simulator based on SimPy for simulating collisions in LoRa networks and consists in four Python scripts simulating different types of network, that can be run setting some parameters. In order to replicate the two figures, we need to understand which transmitter configuration was user for every configuration SN^i and use the correct simulator with the correct parameters.

3.1. Figure 5: Experiment Set 2

The Experiment Set 2 evaluates the impact of dynamic communication parameter selection on the Data Extraction Rate (DER) and compares three transmitter configurations, called SN^3 , SN^4 and SN^5 in the paper.

First of all, we need to choose the correct Python script in the simulator; the paper says that nodes transmit to a single sink ($M=1$), so we choose the script `loraDir.py`. From the LoRaSim documentation, we check the parameters used from the selected script, that are reported here:

```
./loraDir.py <NODES> <AVGSEND> <EXPERIMENT> <SIMTIME>
[COLLISION]
```

For all experiments, we choose:

- The number of nodes, `<NODES>`, is chosen from a list built based on the data point of Figure 5 from the paper.
- The average sending interval in milliseconds, `<AVGSEND>`, is set to 1 million of milliseconds, i.e. 16.7 minutes.
- The simulation time, `<SIMTIME>`, is not specified from the paper; we choose a

simulation time of 58 days, the same as the one used in Experiment Set 1.

- We set `<COLLISION>` to 1 to enable the full collision check.

The key difference between the different configurations is represented by the `<EXPERIMENT>` parameter that determines with which radio settings the simulation is run. We are going to choose the experiment looking at how the Experiment Set is described and at the LoRaSim documentation. The paper says that SN³ uses the settings used by common LoRaWAN deployments, which refers to `<EXPERIMENT> = 4`. SN⁴, instead, is the configuration that minimizes the airtime for each node, by setting the BW, SF and CR, with constant TP; this description corresponds to `<EXPERIMENT> = 3`. Finally, SN⁵ minimizes first airtime and then Transmission Power, as done by the simulator with `<EXPERIMENT> = 5`.

The complete code used to simulate the network with LoRaSim and plot the DER is reported here.

```
import os
import subprocess
import math
import pandas as pd
import matplotlib
import matplotlib.pyplot as plt

def simulate(n_nodes, tx_rate, exp, duration):
    env = os.environ.copy()
    env["MPLBACKEND"] = "Agg"
    # Use subprocess.run to execute the command and capture output
    result = subprocess.run(
        [
            "python2",
            "lorasim/loradir.py",
            str(int(n_nodes)),
            str(int(tx_rate)),
            str(int(exp)),
            str(int(duration)),
            str(int(1))
        ],
        env=env,
        capture_output=True,
        text=True, # Capture output as text
    )

# Der in aloha defined as  $S/G = e^{(-2G)}$ 
```

```

def aloha_der(n_nodes,t):
    rate = 1e-6
    return math.exp(-2 * n_nodes * rate * t)

def main():
    duration = 58 * 86400000
    tx_rate = 1e6

    for n_nodes in list(range(1,10)) + list(range(10,100,10)) + list(range(
        100,1000,100)) + list(range(1000,
        1601,200)):

        print(f"Simulating {n_nodes} nodes")
        simulate(n_nodes, tx_rate, 4, duration)
        simulate(n_nodes, tx_rate, 3, duration)
        simulate(n_nodes, tx_rate, 5, duration)

    data_sn3 = pd.read_csv("exp4.dat", sep=" ")
    data_sn4 = pd.read_csv("exp3.dat", sep=" ")
    data_sn5 = pd.read_csv("exp5.dat", sep=" ")
    data_sn3["der"] = (data_sn3["nrTransmissions"] - data_sn3["nrCollisions"]
        ) / data_sn3["nrTransmissions"]
    data_sn4["der"] = (data_sn4["nrTransmissions"] - data_sn4["nrCollisions"]
        ) / data_sn4["nrTransmissions"]
    data_sn5["der"] = (data_sn5["nrTransmissions"] - data_sn5["nrCollisions"]
        ) / data_sn5["nrTransmissions"]

    plt.plot(data_sn3["#nrNodes"], data_sn3["der"], marker = 'o', label="
        SN3")
    plt.plot(data_sn4["#nrNodes"], data_sn4["der"], marker = 'o', label="
        SN4")
    plt.plot(data_sn5["#nrNodes"], data_sn5["der"], marker = 'o', label="
        SN5")

    plt.title("Success Rate (%)")
    plt.xlabel("Number of nodes")
    plt.ylabel("Rate")
    plt.legend()
    plt.grid()

    plt.savefig("figure5.pdf")
    plt.show()

if __name__ == '__main__':
    main()

```

The plot that corresponds to Figure 5 from the paper is reported here.

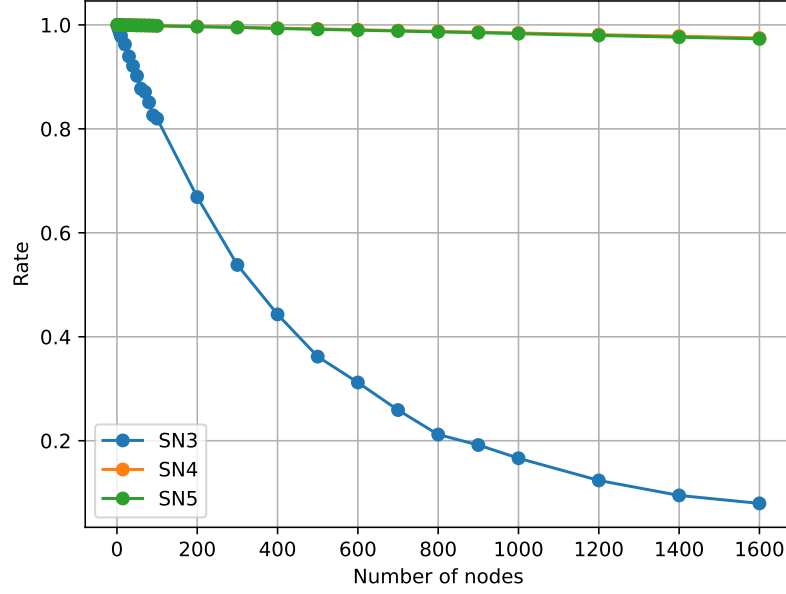


Figure 3.1: Plot corresponding to Figure 5: Experiment Set 2

3.2. Figure 7: Experiment Set 3

The Experiment Set 3 analyzes the impact of the number of sinks M on the network performance, while Figure 7 focuses on the impact on the DER. The experiment uses the configuration called SN¹, with $SF = 12$, $BW = 125$ kHz and $CR = 4/8$, and tests different numbers of sinks (1, 2, 3, 4, 8, 24).

The Python script of the LoRaSim simulator that allows to test multiple sinks is `loraDirMulBs.py` and takes the following parameters:

```
./loraDirMulBS.py <NODES> <AVGSEND> <EXPERIMENT> <SIMTIME>
<BASESTATIONS> [COLLISION]
```

The only new parameter with respect to the previous Experiment Set is `<BASESTATIONS>` which is the number of gateways we have in the network. The parameters that are common to Experiment Set 2 are:

- Parameter `<NODES>`, chosen from the same list of numbers.
- `<AVGSEND>` is set to 1 million of milliseconds.
- `<COLLISION>` is set to 1.

We modified the `<SIMTIME>` to 1 day, because it is not specified by the paper and Google Colab can't handle a very long simulation time for this Experiment Set, since it saturates

the available RAM. The paper says that the used setting is the one of SN¹, which uses the most robust LoRa transmitter settings leading to transmissions with the longest possible airtime and with fixed Carrier Frequency. This description refers to <EXPERIMENT> = 0, which uses a constant frequency. The number of gateways, contained in the parameter <BASESTATIONS> changes among the different simulations and is set to 1, 2, 3, 4, 8 and 24, as done in the paper. The complete code used to simulate the network with LoRaSim and plot the DER is reported here.

```
import os
import subprocess
import math
import pandas as pd
import matplotlib
import matplotlib.pyplot as plt

def simulate(n_nodes, tx_rate, exp, duration):
    env = os.environ.copy()
    env["MPLBACKEND"] = "Agg"

    # Use subprocess.run to execute the command and capture output
    result = subprocess.run(
        [
            "python2",
            "lorasim/loradir.py",
            str(int(n_nodes)),
            str(int(tx_rate)),
            str(int(exp)),
            str(int(duration)),
            str(int(1))
        ],
        env=env,
        capture_output=True,
        text=True, # Capture output as text
    )

    # Der in aloha defined as  $S/G = e^{(-2G)}$ 
    def aloha_der(n_nodes, t):
        rate = 1e-6
        return math.exp(-2 * n_nodes * rate * t)

    def main():
        duration = 30 * 86400000
        tx_rate = 1e6
```

```

for n_nodes in list(range(1,10)) + list(range(10,100,10)) + list(range(
    100,1000,100)) + list(range(1000,
    1601,200)):

    print(f"Simulating {n_nodes} nodes")
    simulate(n_nodes, tx_rate, 0, duration, 1)
    simulate(n_nodes, tx_rate, 0, duration, 2)
    simulate(n_nodes, tx_rate, 0, duration, 3)
    simulate(n_nodes, tx_rate, 0, duration, 4)
    simulate(n_nodes, tx_rate, 0, duration, 8)
    simulate(n_nodes, tx_rate, 0, duration, 24)

data_bs_1 = pd.read_csv("exp0BS1.dat", delim_whitespace=True, comment="#"
    , names=["nrNodes", "DER"])
data_bs_2 = pd.read_csv("exp0BS2.dat", delim_whitespace=True, comment="#"
    , names=["nrNodes", "DER"])
data_bs_3 = pd.read_csv("exp0BS3.dat",delim_whitespace=True, comment="#"
    , names=["nrNodes", "DER"])
data_bs_4 = pd.read_csv("exp0BS4.dat", delim_whitespace=True, comment="#"
    , names=["nrNodes", "DER"])
data_bs_8 = pd.read_csv("exp0BS8.dat", delim_whitespace=True, comment="#"
    , names=["nrNodes", "DER"])
data_bs_24 = pd.read_csv("exp0BS24.dat", delim_whitespace=True, comment=
    ="#", names=["nrNodes", "DER"])

plt.plot(data_bs_1["nrNodes"], data_bs_1["DER"], marker = 'o', label="1
    sink")
plt.plot(data_bs_2["nrNodes"], data_bs_2["DER"], marker = 'o', label="2
    sink")
plt.plot(data_bs_3["nrNodes"], data_bs_3["DER"], marker = 'o', label="3
    sink")
plt.plot(data_bs_4["nrNodes"], data_bs_4["DER"], marker = 'o', label="4
    sink")
plt.plot(data_bs_8["nrNodes"], data_bs_8["DER"], marker = 'o', label="8
    sink")
plt.plot(data_bs_24["nrNodes"], data_bs_24["DER"], marker = 'o', label=
    "24 sink")

plt.title("Success Rate (%)")
plt.xlabel("Number of nodes")
plt.ylabel("Rate")
plt.legend()
plt.grid()
plt.savefig("figure7.pdf")
plt.show()

```

```
if __name__ == '__main__':
    main()
```

The plot that corresponds to Figure 7 from the paper is reported here.

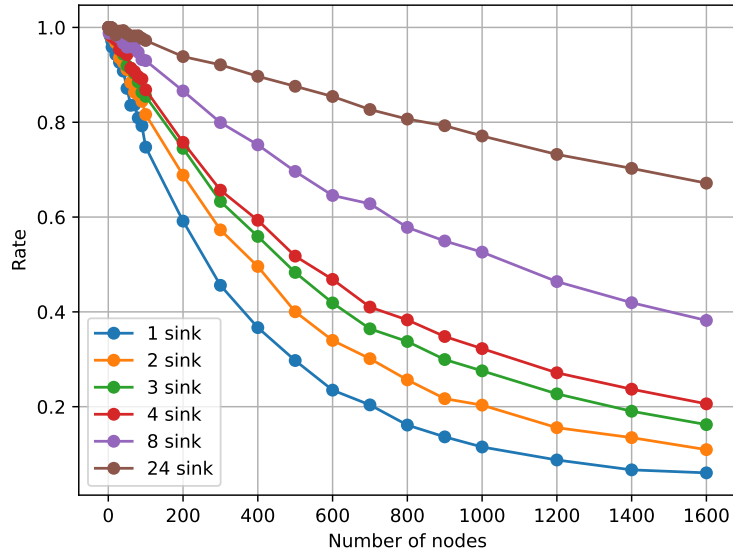


Figure 3.2: Plot corresponding to Figure 7: Experiment Set 3

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