# Revised Gateway Selection for LoRa Radio Networks

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# LoRaWAN
## Model

- LoRa - physical layer technique
  - operates in the license-free ISM-bands
  - modulation is based on CSS (Chrip Spread Spectrum)
- LoRaWAN - open MAC layer developed around LoRa
  - LoRaWAN networks typically are built in a star-of-stars topology and consists of three important elements:
    - end-devices
    - gateways
    - Network Server
- LoRaWAN end-devices can be configurated into
  - Class A: Sensor nodes only send small number of data packets to the gateway and sleep for most of the time
  - Class B: Besides for the actions in Class A, end-nodes also can wake up at scheduled slots to receive downlink messages
  - Class C: Sensor nodes continuously listen to the channel

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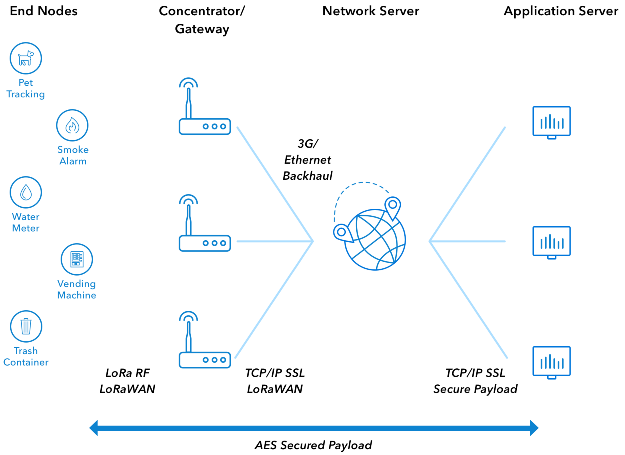



source: `https://www.thethingsnetwork.org/`

# LoRaWAN

## Problem

- one of the problems of a LoRa network is its **scalability**
- to achieve scalability we can for example
  - dynamically select transmission parameters
  - employ multiple gateways
- we consider the multiple gateways case
  - **pros:** the data extraction rate are high
  - **cons:** it suffers hugely from data duplication on the communication path between the gateways and Network Server
    - in remote areas the gateways are usually connected to a Network Server by cellular networks, which generate additional transmission costs
    - gateways aren't connected to each other and therefore cannot actively filter the traffic prior to sending it to Network Server

- **Our solution:** we propose a randomized algorithm that reduce duplication of packets sent to Network Server without communicating with other gateways

# Algorithm

## Gateway Selection

**Algorithm 1** GATEWAYSELECTION

**Setup:**

$R$ - number of rounds
$g^r(x)$ - special function defined for $r$-round

**Main algorithm:**

```
if received message from the end-node then
    x ← profit estimation                      ▷ based on RSSI
    for r = 0 ... R − 1 do                     ▷ loop for r-rounds
        if rand(0, 1) < g^r(x) then
            send message to the network server
            return
        end if
    end for
end if
```

# Probabilistic Analysis

## Definition

- $n$ - gateways
- $x_1, \ldots, x_n$ - the profit of received messages by the gateways (e.g. signal strength RSSI)
- $g^r(x_i)$ - the gateway $i$ transmission probability for $r$-th round of the algorithm
- $S^R(x_1, \ldots, x_n)$ - random variable denoting the selected gateway
- $P(S^R(x_1, \ldots, x_n) = i)$ - probability that the particular $i$-th gateway becomes the selected gateway

# Probabilistic Analysis

## Probability for a particular gateway of becoming selected one

Consequently, the probability $P(S^R(x_1, \ldots, x_n) = i)$ for $R \geq 1$ rounds is:

$$\sum_{r=0}^{R-1} \quad g^r(x_i) \prod_{j \neq i} (1 - g^r(x_j)) \cdot \left(1 - \sum_{k} g^r(x_k) \prod_{j \neq k} (1 - g^r(x_j))\right)^r .$$

If we choose the function $g^r(x)$ such that it does not depend on $r$ i.e. for all $r$ holds $g^r(x) = g(x)$ then can be transformed into a more succinct form:

$$P(S^\infty(x_1, \ldots, x_n) = i) = \frac{g(x_i) \prod_{j \neq i} (1 - g(x_j))}{\sum_{k=1}^{n} g(x_k) \prod_{j \neq k} (1 - g(x_j))}.$$

Moreover, we can calculate the expected profit of the selected gateway as

**Theorem**

*$E[X_{S^R(X_1,\ldots,X_n)}]$ is equal to*

$$\sum_{i=1}^{n} \int_0^L x_i P(S^R(X_1,\ldots,x_i,\ldots,X_n) = i) f_{X_i}(x_i) dx_i$$

*where $X_1,\ldots,X_n$ is a random variable reflecting a profit.*

Scenarios

i) let $g^r(x) = p$ and assuming that $X_i \sim U(0,1)$, we can calculate the expected profit as

$$E[X_{S^\infty(x_1,\ldots,x_n)}] = \frac{1}{2} .$$

ii) let

$$g^r(x) = \begin{cases} x^{n-1} & \text{for} \quad r = 0 \\ p & \text{for} \quad r \geq 1 \end{cases} .$$

Consequently, assuming that $X_i \sim \mathcal{U}(0,1)$, the expected profit is

$$E[X_{S^\infty(x_1,\ldots,x_n)}] = \frac{1}{2}(1 + \frac{n}{n+1}(1 - \frac{1}{n})^n)$$

Asymptotically it improves the normalized profit from $1/2 = 0.5$ to $1/2 + 1/2e \approx 0.68$. Those cases show that proper selection of function $g$ is very important.

# Probabilistic Analysis

## Precise expected number of rounds

- Another important characteristics is the expected number of rounds needed to select a gateway

| number of nodes | scenario (i) | | scenario (ii) | |
|---|---|---|---|---|
| | profit | expected no. rounds | profit | expected no. rounds |
| 10 | 0.50 | 2.58 | 0.65 | 2.57 |
| 100 | 0.50 | 2.71 | 0.67 | 2.70 |
| 1000 | 0.50 | 2.72 | 0.68 | 2.71 |
| 10000 | 0.50 | 2.72 | 0.68 | 2.71 |

# Simulations
## Overview

- After obtaining some theoretical results, we would like to assess our algorithm in more realistic scenario by performing simulation
- In practice there are significant differences
  - profit estimation couldn't be so uniformly distributed
  - messages can be transmitted at different times (collisions)

# Simulations
## Parameters

Selected parameters for simulations

- we employ LoRaSim's native settings
  - $SF = 12$
  - $BW = 125$
  - $CR = 4/8$
  - end-node chooses one of the three center frequencies (860 MHz, 864 MHz, and 868 MHz) uniformly at random for each frame
  - transmit power 14 dBm
- the simulated time frame was for about 24 hours
- each end-node sends packets towards gateways in the vicinity every 16.6 minutes (to comply with the LoRaWAN specification duty cycle)

We define two metrics that will help in evaluation of the algorithm

- Data Extraction Rate (DER)

$$\text{DER} = \frac{\#\text{unique packets received by network server}}{\#\text{packets sent by end-nodes}}.$$

- Packet Drop Rate (PDR)

$$\text{PDR} = \frac{\#\text{packets drop}}{\#\text{all packets received by gateways}}$$

# Simulations
## Scenarios

We consider three scenarios for simulations.

- for the scenario (i) and (ii) we chose the same function as in the theoretical analysis
- for the scenario (iii) we modify the function from scenario (ii) such that the function $x^{n-1}$ is selected for the first two rounds instead of only first round.

Namely, for $n$ gateways and for $r \in 1, 2, 3, 4$ ($R = 4$) we have

Scenario (i)

$$g^r(x) = 1/n$$

Scenario (ii)

$$g^r(x) = \begin{cases} x^{n-1} & \text{for} \quad r = 0 \\ 1/n & \text{for} \quad r \geq 1 \end{cases}$$

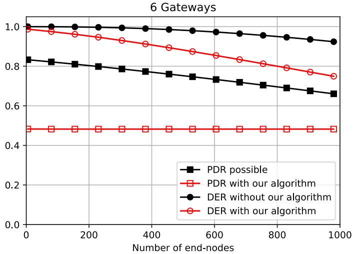
Scenario (iii)

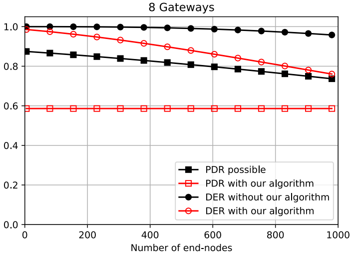
$$g^r(x) = \begin{cases} x^{n-1} & \text{for} \quad r = 0, 1 \\ 1/n & \text{for} \quad r \geq 2 \end{cases}$$

# Simulations

## DER and PDR for 6 and 8 gateways

### Scenario (i)

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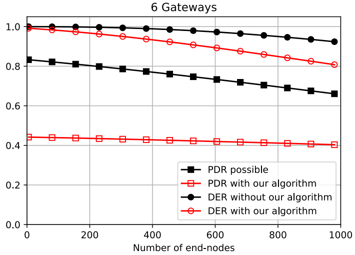
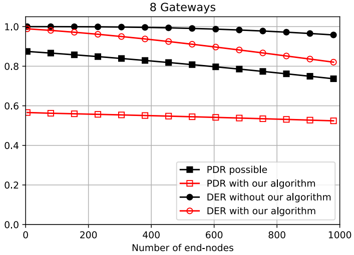
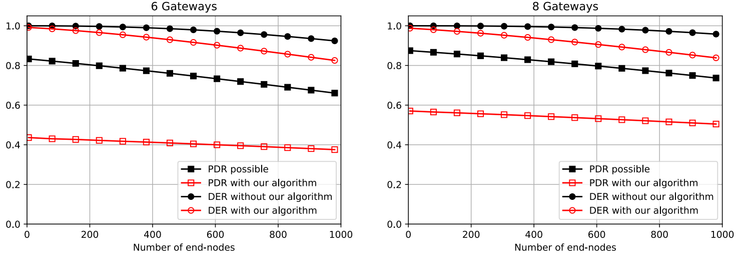


# Simulations
## DER and PDR for 6 and 8 gateways

### Scenario (iii)



# Simulations

## Numerical results

| Gateways | Scenario (i) | | Scenario (ii) | | Scenario (iii) | |
|---|---|---|---|---|---|---|
| | PDR% | Δ DER% | PDR% | Δ DER% | PDR% | ΔDER% |
| 3 | 19.7 | 8.1 | 12.6 | 4.5 | 10.1 | 3.4 |
| 4 | 31.6 | 12.3 | 23.0 | 7.7 | 19.8 | 6.3 |
| 6 | 48.2 | 17.4 | 40.3 | 11.5 | 37.5 | 9.8 |
| 8 | 58.6 | 19.7 | 52.4 | 13.7 | 50.4 | 11.9 |

# Conclusions

- we have presented a randomized algorithm that enables us to reduce the duplication of packets sent by gateways to network server
- the algorithm can be easily executed on low-end devices and poses no additional computational or memory overhead and utilises traffic metrics already in use by the LoRaWAN MAC layer
- we perform a theoretical probabilistic analysis
- we implemented algorithm in LoRaSim simulator and performed a number of simulations
- the simulations show that for 8 gateways and 1000 end-nodes we can drop more than 50% of packets thus cut the cost of transferring data between gateways and network server in half with small decrease of data extraction rate
- as a result, we can reduce overall energy consumption of the whole network

# THANK YOU