Low Power Wide Area Networks for the Internet of Things

Framework, Performance Evaluation, and Challenges of LoRaWAN and NB-IoT

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Tutorial Outcomes

- How do LPWAN complement traditional cellular and short-range wireless technologies?
- What are the fundamental mechanisms that enable to meet the LPWAN requirements?
- What are the major design choices made in the LoRaWAN and NB-IoT specifications?
- How do we evaluate the performance of a LoRaWAN and NB-IoT deployment in terms of coverage and capacity?
- What are the recent research directions for radio resource management in LoRaWAN and NB-IoT?

Feedback and Material

- Feedback form
- Presentation slides are available

Outline

Link Budget

Enhanced Network Capacity

- LoRa employs orthogonal spreading factors which enables multiple spread signals to be transmitted at the same time and on the same channel
- Modulated signals at different spreading factors appear as noise to the target receiver
- The equivalent capacity of a single 125 kHz LoRa channel is:

$$SF12 + SF11 + SF10 + SF9 + SF8 + SF7 + SF6$$
$$= 293 + 537 + 976 + 1757 + 3125 + 5468 + 9375$$
$$= 21531 \text{ b/s} = 21.321 \text{ kb/s}$$

Link Budget

- The link budget is a measure of all the gains and losses from the transmitter, through the propagation channel, to the target receiver
- The link budget of a network wireless link can be expressed as:

$$P_{Rx} = P_{Tx} + G_{System} - L_{System} - L_{Channel} - M$$

where:

P_{Rx} = the expected received power

P_{Tx} = the transmitted power

G_{System} = system gains such as antenna gains

L_{System} = system losses such as feed-line losses

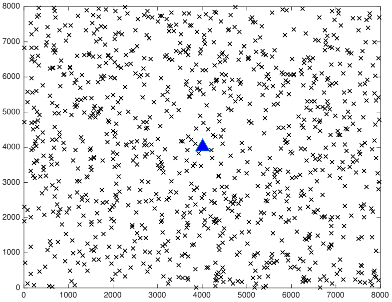
$L_{Channel}$ = losses due to the propagation channel

M = fading margin and protection margin

Coverage of LoRaWAN

Evaluation Scenario

- Area
  - Surface: square of 8 Km $\times$ 8 Km
  - Number of end-devices: 1000
  - Distribution of end-devices: uniform
  - Single gateway
  - Environment type: urban
- Radio link
  - Bandwidth: 125 kHz
  - Transmit power: 14 dBm
  - Gateway height: 30 m
  - End-device height: 1.5 m
  - Antenna gains: 3 dBi
  - Noise floor: -153 dBm
  - Pathloss: Okumura-Hata
  - Shadow fading: lognormal $\mathcal{N}(0, 8)$



Pathloss Model

- Using the Okumura-Hata urban model, the pathloss between device i and the gateway is proportional to the logarithm of the distance $d(i, g)$ in Km:

$$L_{Channel}(i) = A + B \log_{10}(d(i, g))$$

- The two parameters A and B depend on the antenna heights ($h_b = 30$ m for the gateway and $h_d = 1.5$ m for the end-device) and the central frequency $f_c = 868$ MHz

$$A = 69.55 + 26.16 \log_{10}(f_c) - 13.82 \log_{10}(h_b) - 3.2(\log 10(11.75 h_d))^2 + 4.97$$

$$B = 44.9 - 6.55 \log_{10}(h_b)$$

Link Budget

- We consider the following parameters:
  - Transmit power: $P_{Tx} = 14$ dBm
  - Sum of antenna gains: $G_{System} = 6$ dBi
  - Fading and protection margin: $M = 10$ dB
  - Noise floor: $N = -153$ dBm
- We can now compute the received power $P_{RX}(i)$ and $\mathrm{SNR}(i)$ for end-device i:

$$P_{Rx}(i) = P_{Tx} + G_{System} - L_{Channel}(i) - M$$

$$\mathrm{SNR}(i) = P_{Rx}(i) - N$$

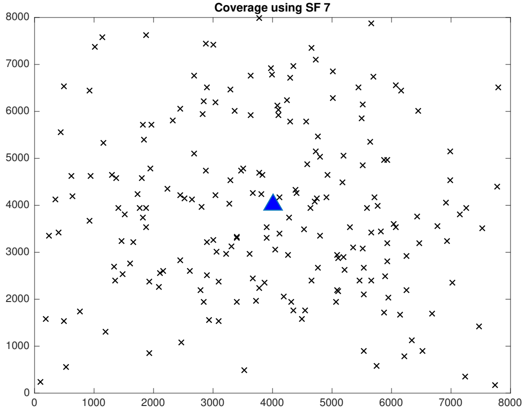
Spreading Factor Selection

- The spreading factor for each end-device is selected using the following matching table:

SNR Interval (dB)	Spreading Factor
[-7.5, $+\infty$[	7
[-10, -7.5[	8
[-12.5, -10[	9
[-15, -12.5[	10
[-17.5, -15[	11
[-20, -17.5[	12

- Note that for SNR values lower that -20 dB, the end-device is considered out of coverage of the gateway

Coverage Study



Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	40.50	51.60	61.60	70.40	77.70	86.10

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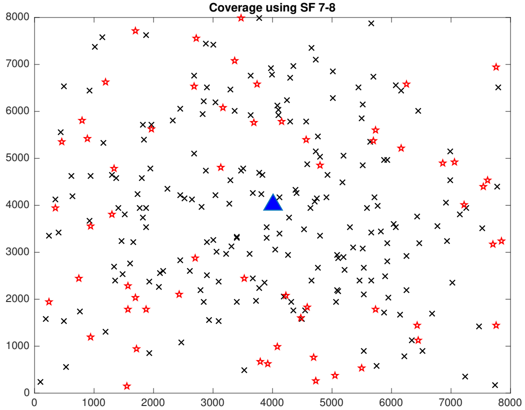

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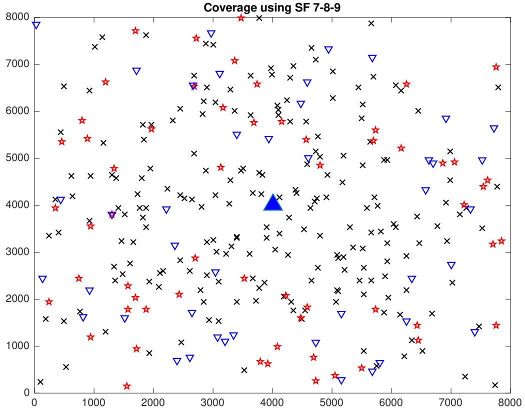

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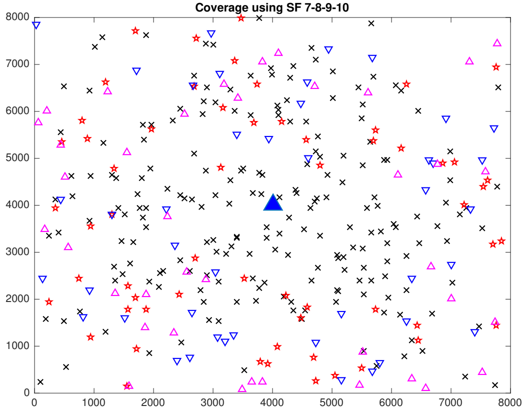

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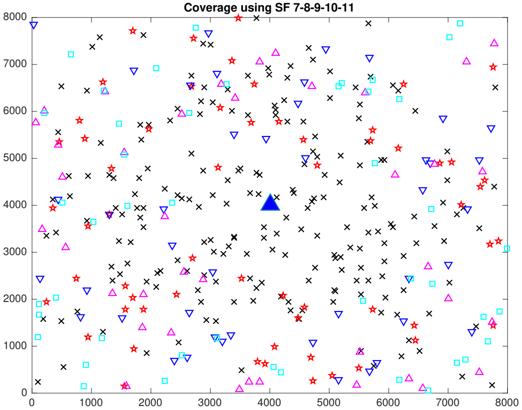

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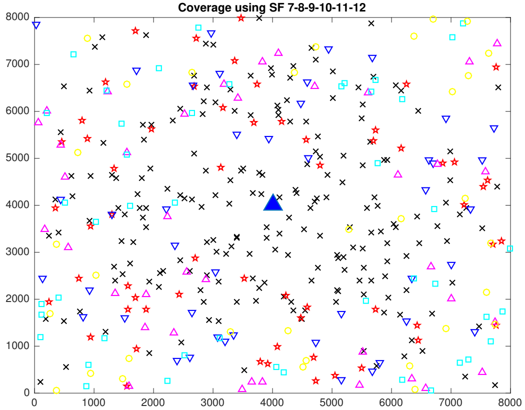

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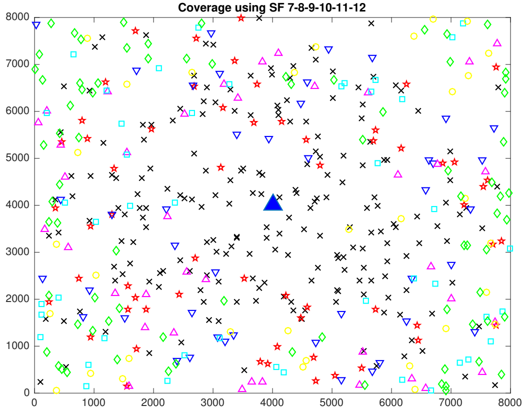

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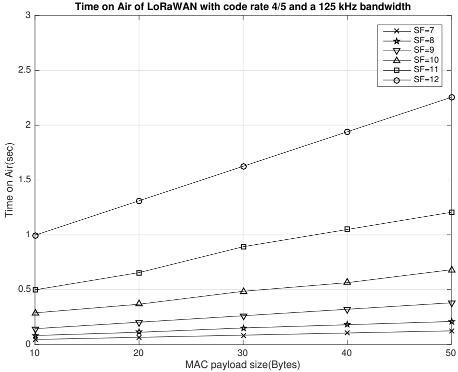
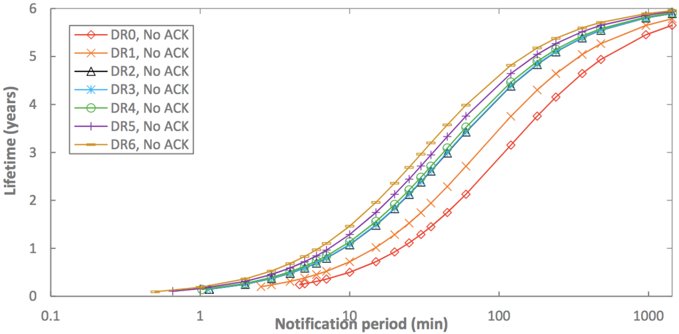
Spreading Factor and Time on Air

- The Time on Air is defined as the time required to transmit a packet in a sub-band
- The selection of the spreading factor impacts the Time on Air and consequently determines the duty cycle limitation



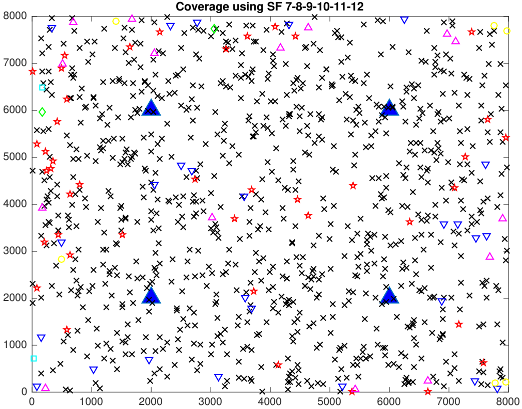
Spreading Factor and Energy Consumption



Source: Lluís Casals *et al.*, Modeling the Energy Performance of LoRaWAN, Sensors, 2017

- DR0 to DR5 correspond to spreading factors 12 to 7 with a bandwidth of 125 kHz. DR6 correspond to spreading factor 7 and bandwidth of 250 kHz
- For an end-device sending messages every 100 minutes, changing the spreading factor from 12 to 7 can increase its lifetime by almost 1.5 years

Enhancing the Coverage with Multiple Gateways



Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	88.70	94.50	97.60	99.20	99.60	100.00

Capacity of LoRaWAN

ALOHA Model

- ALOHA with duty cycle

$$\frac{\delta}{\tau}N\exp(-2N\frac{\delta}{\tau})$$

- ALOHA with multiple receivers and perfect packet capture

$$\frac{\delta}{\tau}N\exp(-2N\frac{\delta}{\tau})(1+\sum_{n=2}^{N}\frac{(2N\frac{\delta}{\tau})^n}{n!}(1-(1-\frac{1}{n})^r))$$

- ALOHA with multiple receivers and realistic packet capture

$$\frac{\delta}{\tau}N\exp(-2N\frac{\delta}{\tau})(1+\sum_{n=2}^{N}\frac{(2N\frac{\delta}{\tau})^n}{n!}(1-(1-\frac{K^{n-1}}{n})^r))$$

with

$$K=\frac{1}{2}10^{-\frac{\Delta}{10\alpha}}$$