

# 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

## 1 Performance Evaluation



## 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:

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



# 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



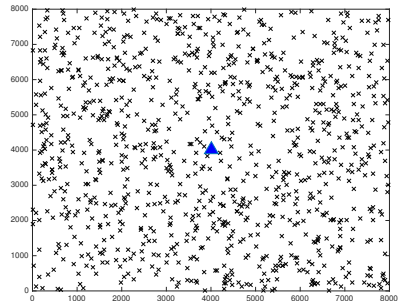
# Evaluation Scenario

## ■ 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

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

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



# 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 SNR( $i$ ) for end-device  $i$ :

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

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



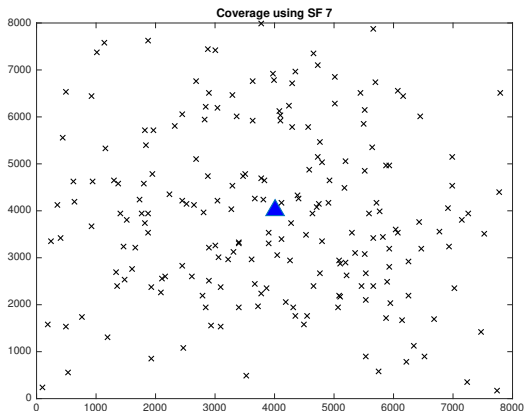
# Spreading Factor Selection

- 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

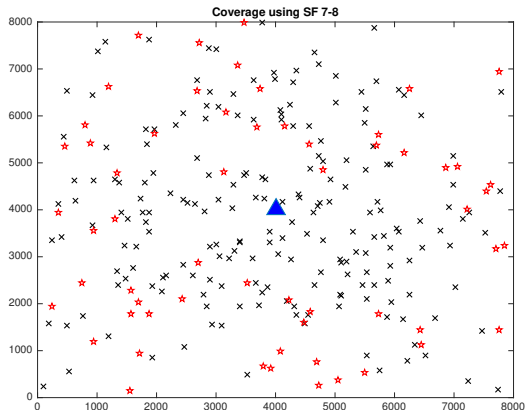
- Note that for SNR values lower than -20 dB, the end-device is considered out of coverage of the gateway

# Coverage Study



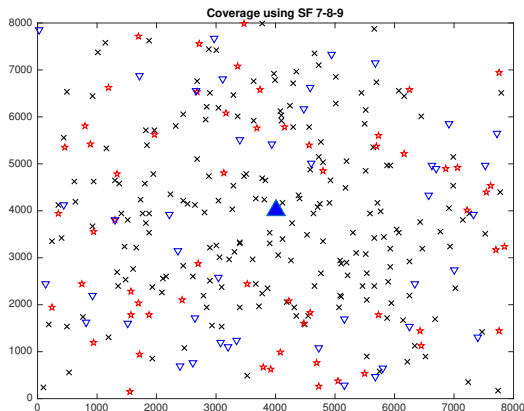
Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	40.50	51.60	61.60	70.40	77.70	86.10

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# Coverage Study




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9

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11

12

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Cumulative coverage (%)

40.50

51.60

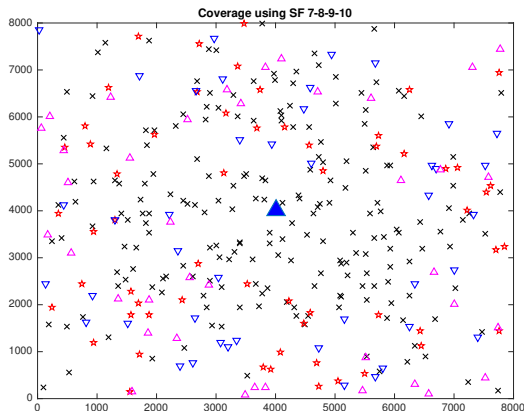
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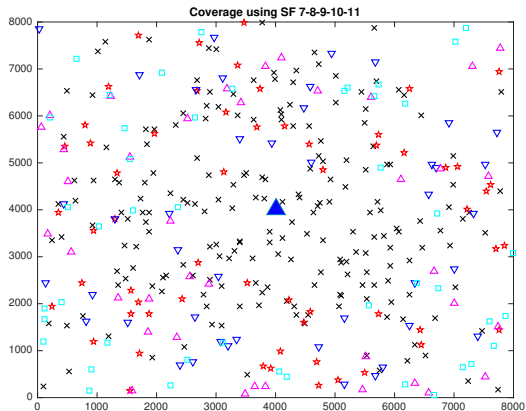
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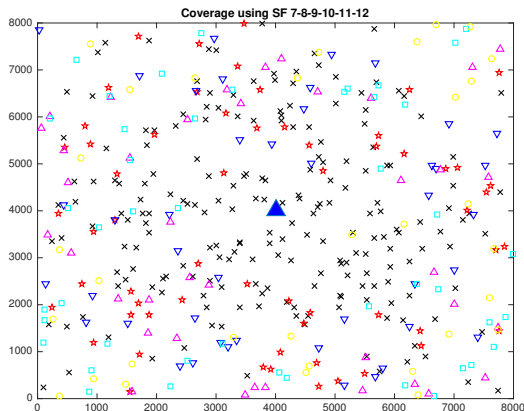


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51.60

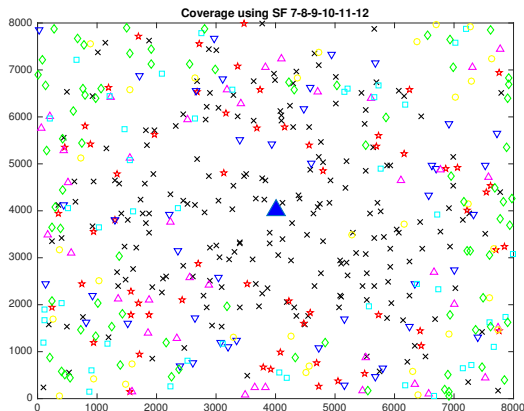
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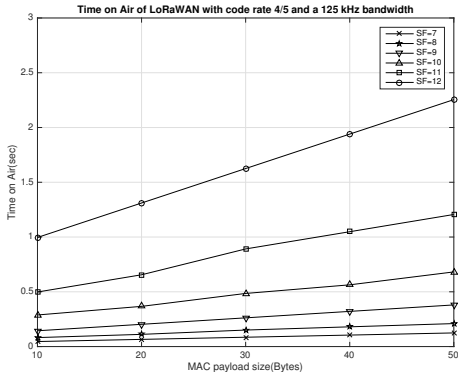
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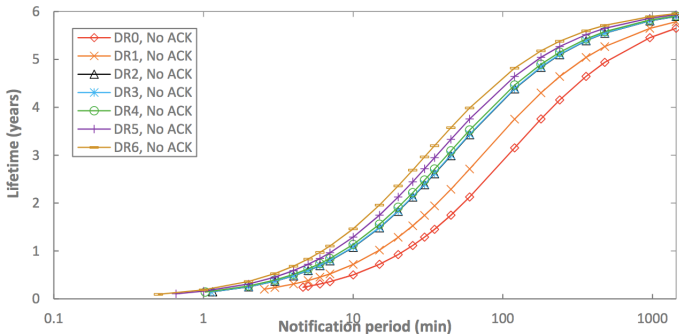
Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	40.50	51.60	61.60	70.40	77.70	86.10

# 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



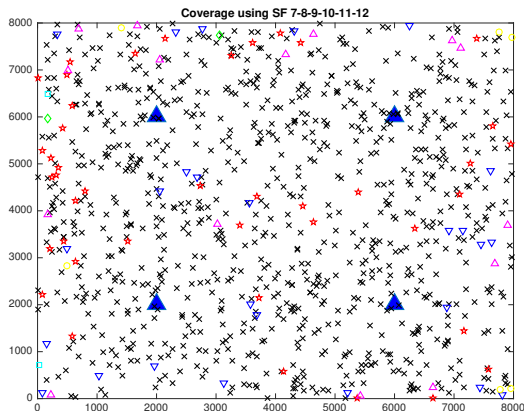
# Spreading Factor and Energy Consumption



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 a bandwidth of 250 kHz
- For an end-device sending packets every 100 minutes, changing the spreading factor from 12 to 7 increases 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

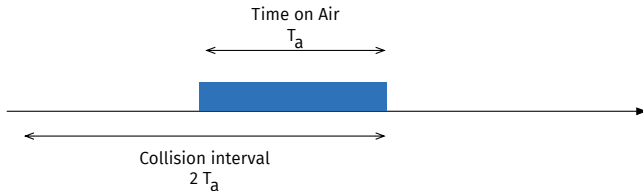


## Capacity of LoRaWAN



## Pure ALOHA Model

- The start times of the packets in an ALOHA channel is modeled as a Poisson point process with parameter  $\lambda$  packets/second



- If each packet in the channel lasts  $T_a$  seconds, the normalized channel traffic can be defined as

$$G = \lambda T_a$$

- The normalized throughput of the ALOHA random access channel is given by

$$S = G \exp(-2G)$$





# ALOHA Model for LoRaWAN

- We consider the case where only *one* spreading factor and *one* sub-channel are available
- The general case of multiple sub-channels and spreading factors can be easily inferred
  - Multiple spreading factors are orthogonal
  - Packets are uniformly transmitted on available sub-channels
- The time to transmit a packet of  $l$  bytes (size of MAC payload) on spreading factor  $s$  is denoted  $T_a(l, s)$
- Given a duty cycle limitation of  $d = 1\%$ , the packet generation rate for each end-device operating on spreading factor  $s$  must verify:

$$\lambda(s) \leq \frac{d}{T_a(l, s)}$$

- The normalized channel traffic for  $N$  end-devices is obtained as follows:

$$G = N \cdot \lambda(s) \cdot T_a(s)$$



# Capacity Formulas for LoRaWAN

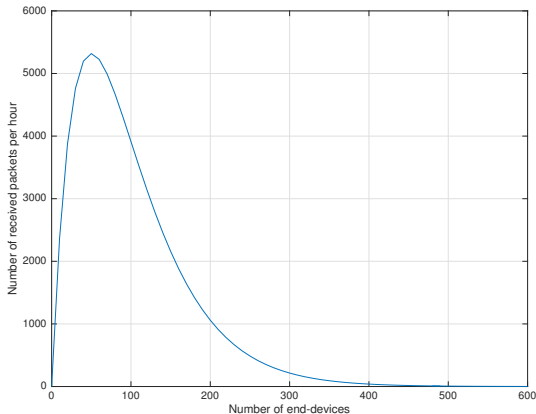
- We consider a LoRaWAN network with  $N$  end-devices and one gateway
  - One spreading factor  $s$  and one sub-channel are available
  - Transmit attempts are done according to a Poisson distribution
  - All end-devices have the same packet generation rate  $\lambda(s)$
  - All packets have the same length of  $l$  bytes
- The normalized throughput of the LoRaWAN network is given by:

$$S = G \exp(-2G) = N\lambda(s)T_a(l, s) \exp(-2N\lambda(s)T_a(l, s))$$

- The total number of successfully received packets during  $D$  is obtained by:

$$\frac{D}{T_a(l, s)} \times S$$

# Test



- Deduce the number of nodes
- Deduce the arrival rate
- Put all results for SF7
- Compare two SF



# Introduce Multiple Gateways



# ALOHA Model

- ALOHA with duty cycle

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

- ALOHA with multiple receivers and perfect packet capture

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

- ALOHA with multiple receivers and realistic packet capture

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

with

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