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 deployment in terms of coverage and capacity?

Outline

Link Budget Analysis

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

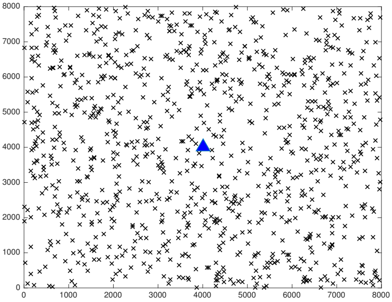
Additional Margins

- Fading margin
- Interference margin
- Penetration margin:
  - indoor penetration loss (first wall): $\sim$ 18 dB (in dense urban environment), $\sim$ 15 dB (in urban environment), and $\sim$ 10 — 12 dB (in rural environment)
  - deep indoor penetration loss (second wall): +3 dB
- 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 $\text{SNR}(i)$ for end-device i:

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

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

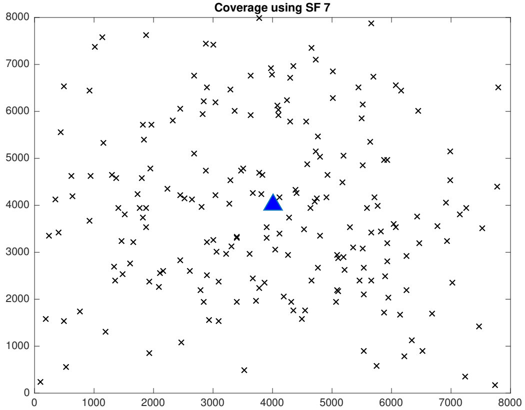
Spreading Factor Selection

- The spreading factor for each end-device is selected using the following matching table (Source: SX1276/77/78/79 Semtech datashet):

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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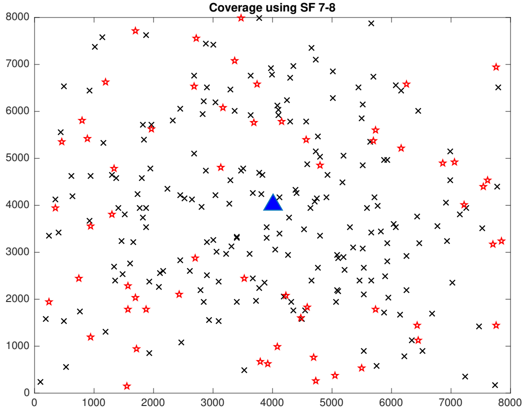

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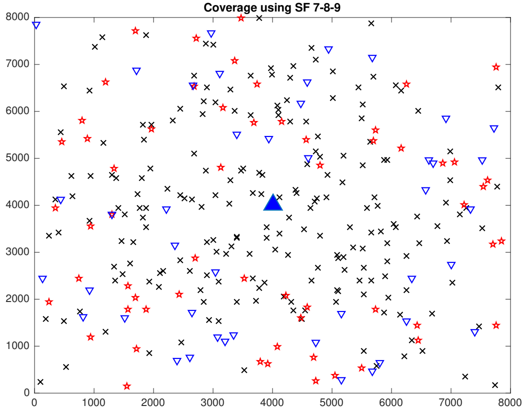

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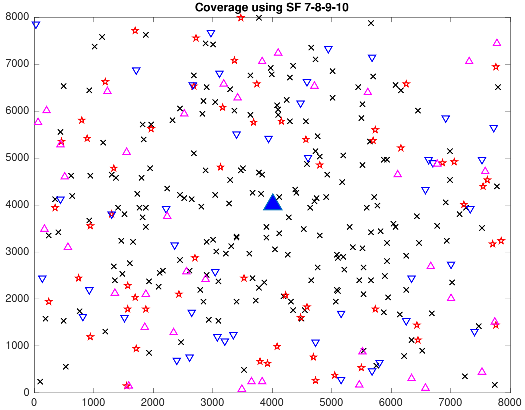

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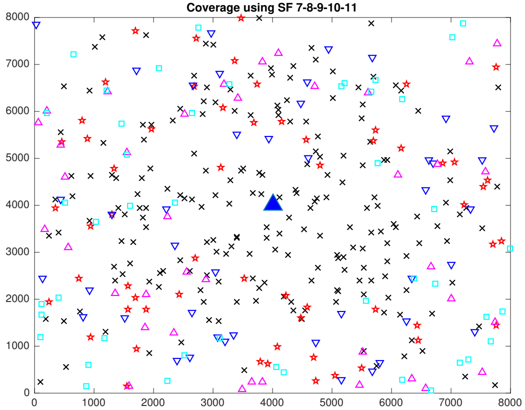

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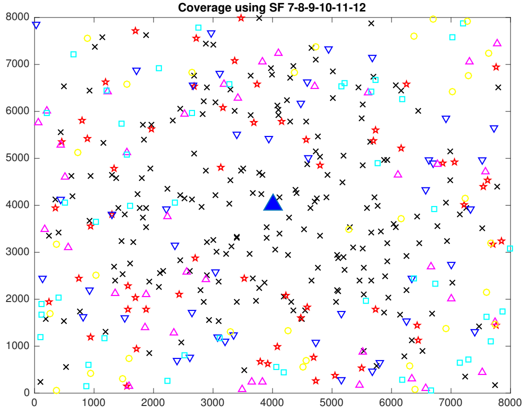

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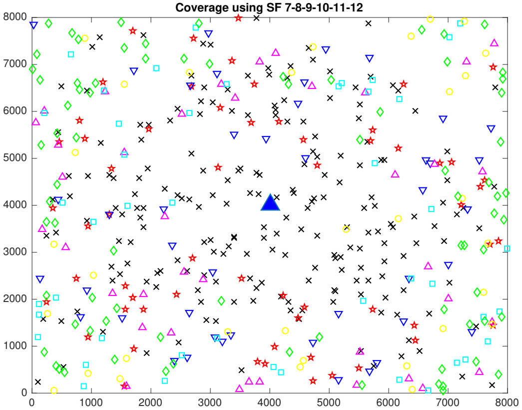

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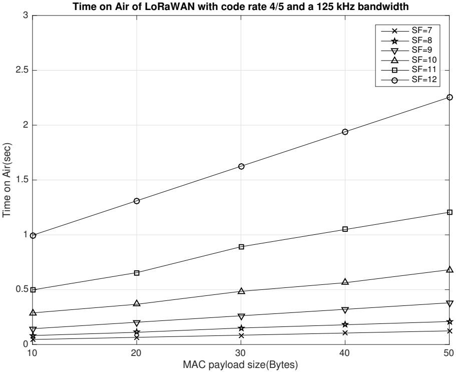
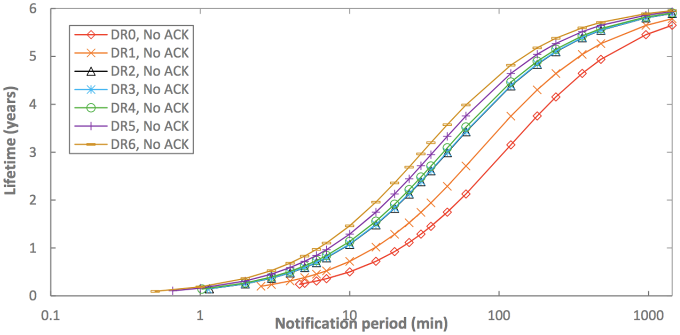
Spreading Factor and Time on Air

- 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



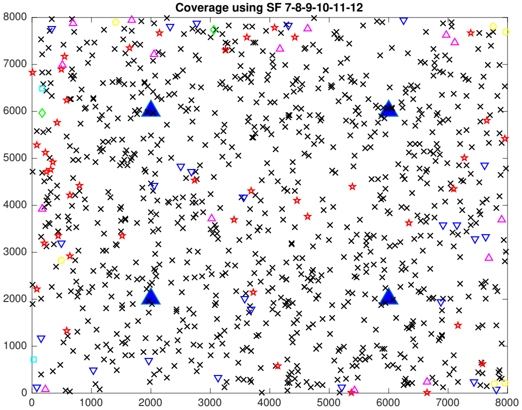
Spreading Factor and Energy Consumption



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 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

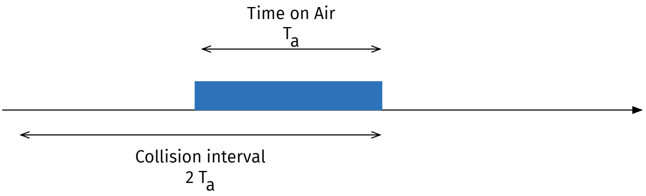


Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	88.70	94.50	97.60	99.20	99.60	100.00

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 λ 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:

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

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:

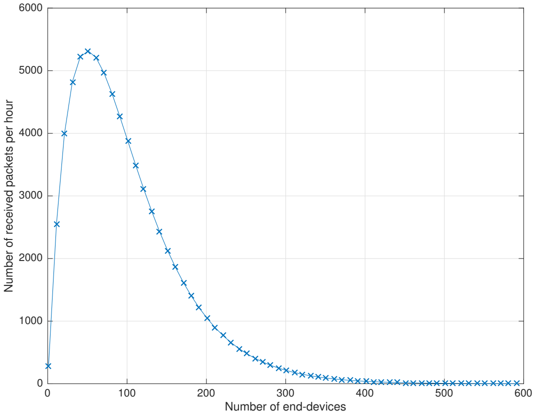
$$S = G \exp(-2G) = N\lambda(s)T_a(l,s) \exp(-2N\lambda(s)T_a(l,s))$$

- The total number of successfully received packets per second is obtained by:

$$\frac{1}{T_a(l,s)} \times S$$

Received Packets per Hour

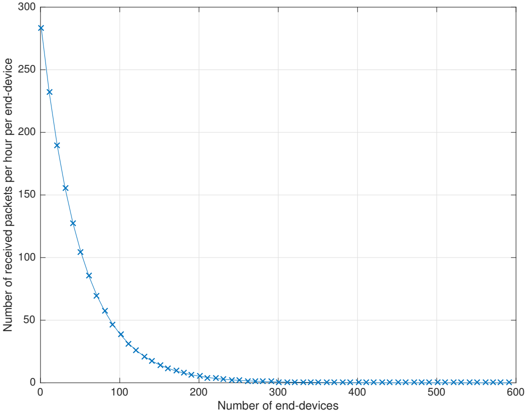
- The number of received packets per hour decreases for more than 50 end-devices



l=50 bytes, SF=7, $\lambda(s) = \frac{d}{T_a(l,s)}$

Received Packets per End-Device per Hour

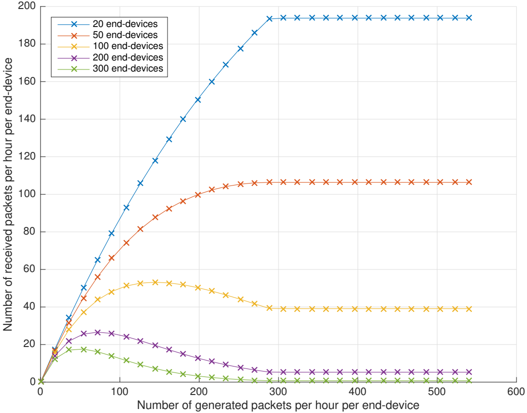
- For 100 end-devices generating 289 packets per hour, the average number of received packets per end-device equals 40 per hour



l=50 bytes, SF=7, $\lambda(s) = \frac{d}{T_a(l,s)}$

Packet Generation Rate

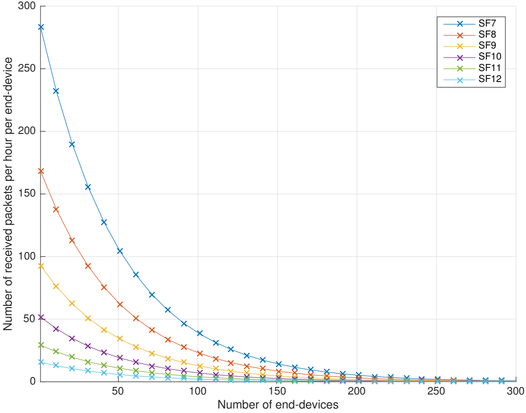
- For small number of end-devices, the throughput is limited by the duty cycle
- For large number of end-devices, the throughput is limited by collisions



l=50 bytes, SF=7

Spreading Factors and Packet Reception

- For 50 end-devices, the average number of received packets per end-device per hour increases from 6 to 106 when SF decreases from 12 to 7



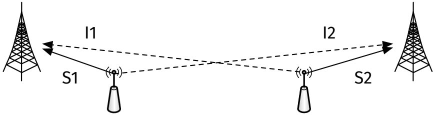
l=50 bytes, $\lambda(s) = \frac{d}{T_a(l,s)}$

Use Case Conclusion

- Conclude for use case

Collisions and Capture Effect

- It is assumed by default that all transmitted signals that collide will fail to be received
- In practice, the strongest received signal may be successfully received despite the presence of interfering signals $\Rightarrow$ capture effect
- The capture effect depends on:
  - The receiver sensitivity
  - The signal to noise plus interference ratio SINR
- The presence of multiple receivers favors the capture effect



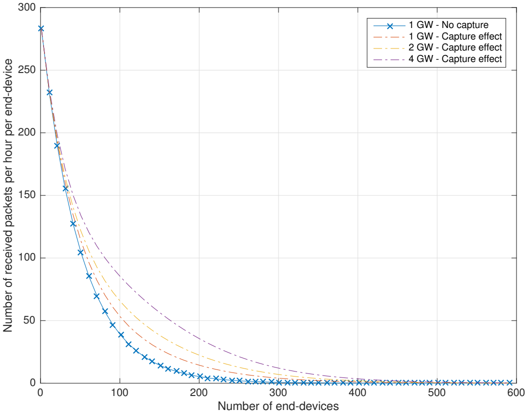
Applying the Capture Effect for LoRaWAN

- We consider a LoRaWAN network with N end-devices and r gateways
- We take $G = N\lambda(s)T_a(l,s)$, where $\lambda(s)$ is the packet generation rate of each end-device, and $T_a(l,s)$ the time to transmit a packet of l bytes
- We assume that a packet is successfully received by one gateway if the corresponding received signal power is higher than the maximum interferer
  - We consider an additional margin Δ (3 dB or 6 dB in practice)
- The probability of successful reception of one packet when n collisions occur is denoted by $P_{cap}(n)$
- The normalized throughput of the LoRaWAN network is given by:

$$S = G\exp(-2G)(1 + \sum_{n=2}^{N} \frac{(2G)^n}{n!}(1 - (1 - P_{cap}(n))^r))$$

Received Packets with Multiple Gateways and Capture Effect

- The number of received packets per hour per end-device increases from 38 to 52 when considering the capture effect with one gateway, and reaches 84 with 4 gateways



l=50 bytes, SF=7, $\lambda(s) = \frac{d}{T_a(l,s)}$, $\Delta = 6$ dB