TOWARDS THE NEXT GENERATION OF LPWA NETWORKS : A TURBO-FSK BASED APPROACH FROM PHY TO MAC LAYERS ANALYSIS

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OUTLINE

1 Introduction & context

2 Introduction to Turbo-FSK
- Turbo-FSK definition
- Physical layer performance

3 MAC strategies for Turbo-FSK

4 Massive access

5 Conclusion

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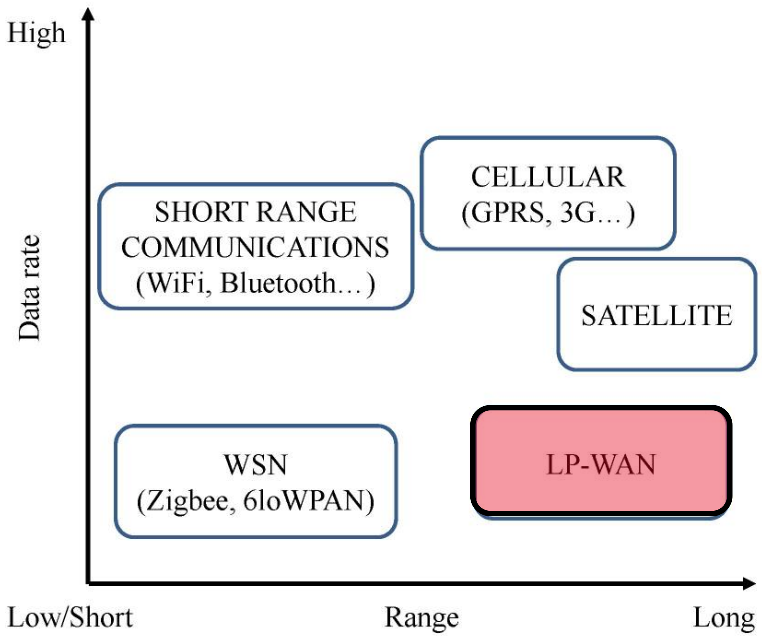
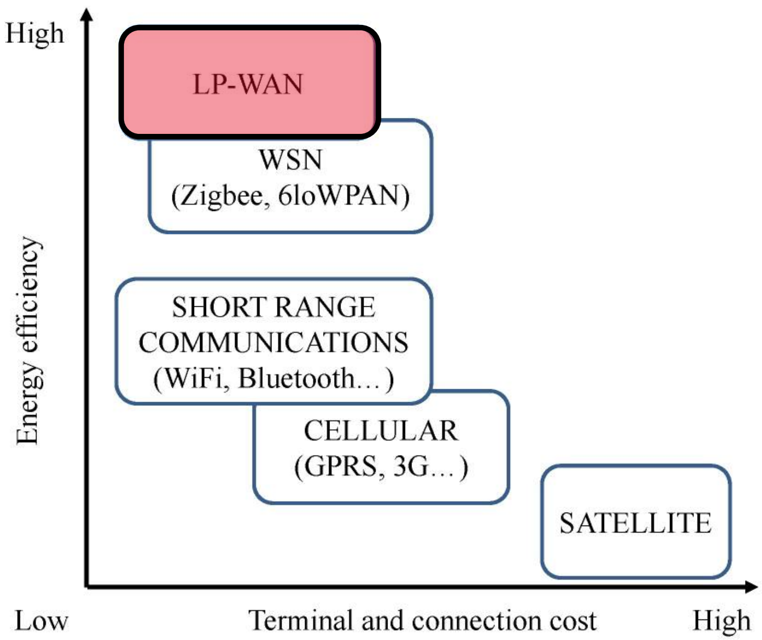
INTRODUCTION

- **Machine to machine communication:**
  - Communication without any human intervention (sensor, industrial machinery or software application running on wearables and smart devices).
    - Short-range radio connectivity (e.g., Bluetooth and ZigBee)
    - Wifi and IEEE 802.15.4 WAN
    - Cellular technology (2G, 3G and 4G)
    - **LPWA communication system**





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    - **LPWA communication system**
  - Main requirements
    - Long range communications
    - Low power consumption at the device level
    - Low data rate
    - Large capacity of users
    - Low cost

→ Low level of receiver sensitivity,
Low level of SNR at receiver

INTRODUCTION

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    - Long range communications
    - Low power consumption at the device level
    - Low data rate
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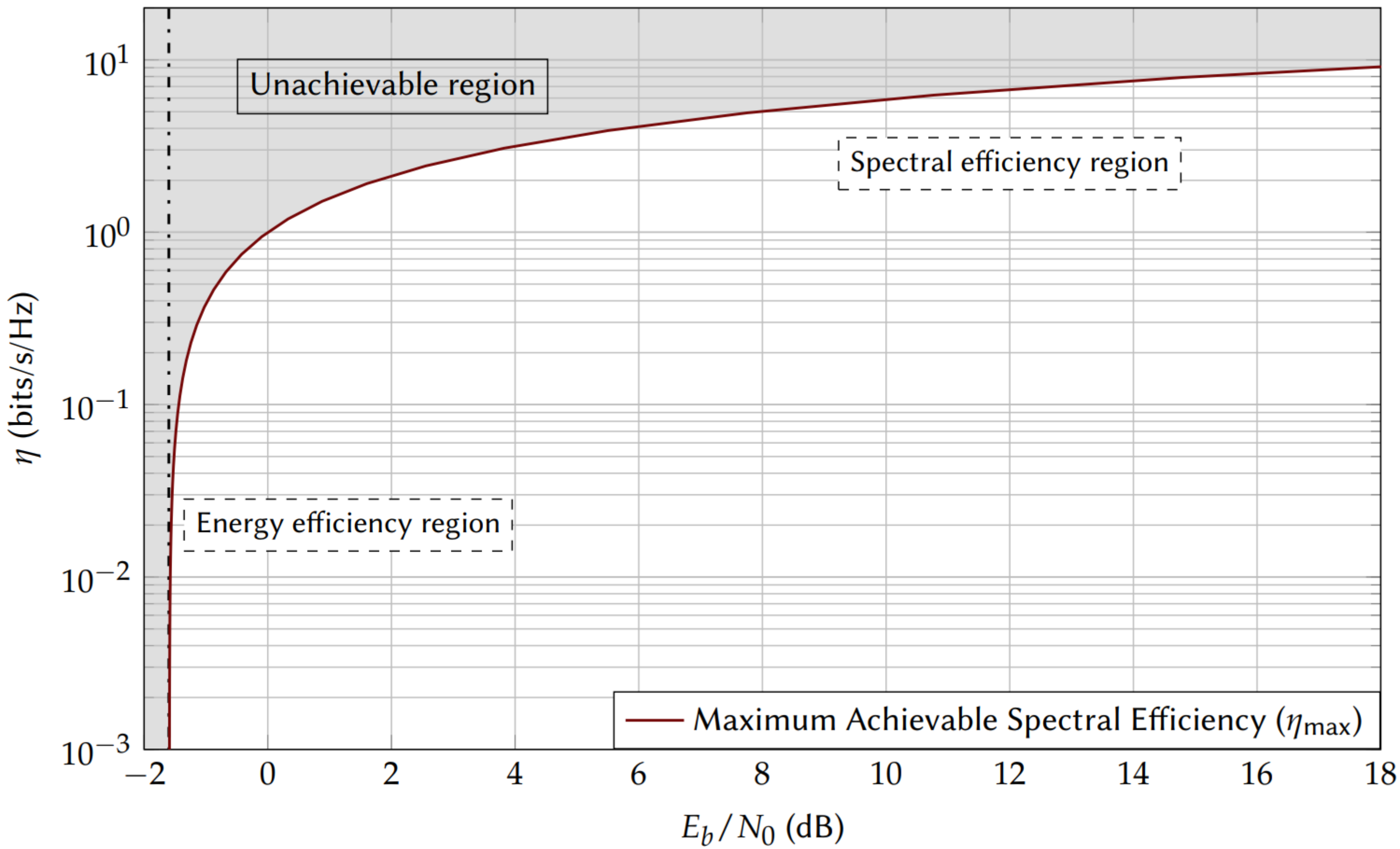
→ Low level of PAPR (low protocol overhead, device complexity, etc.)

INTRODUCTION

- **Motivation to propose a new LPWA waveform:**
  - Shannon limit and area of efficiency



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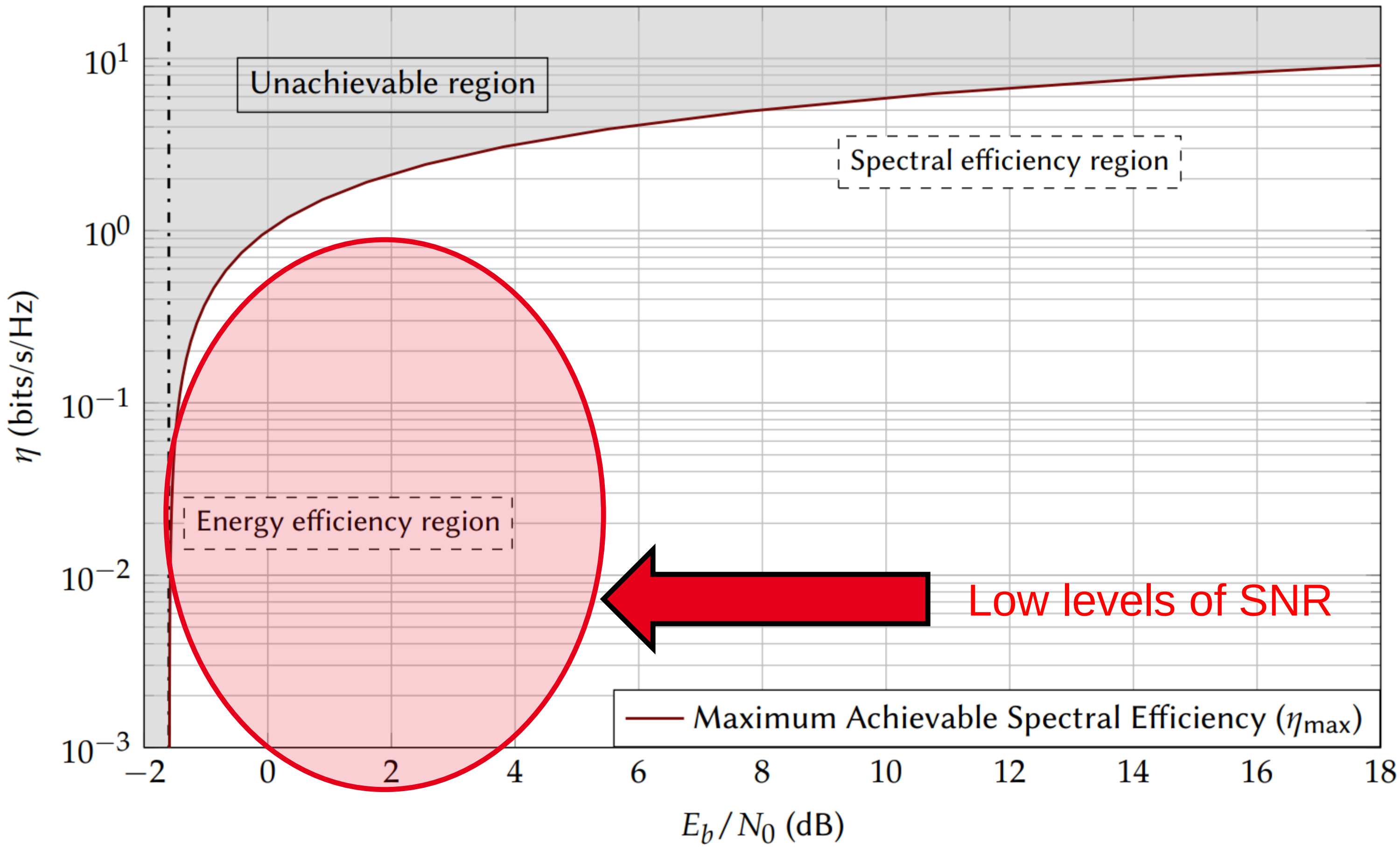
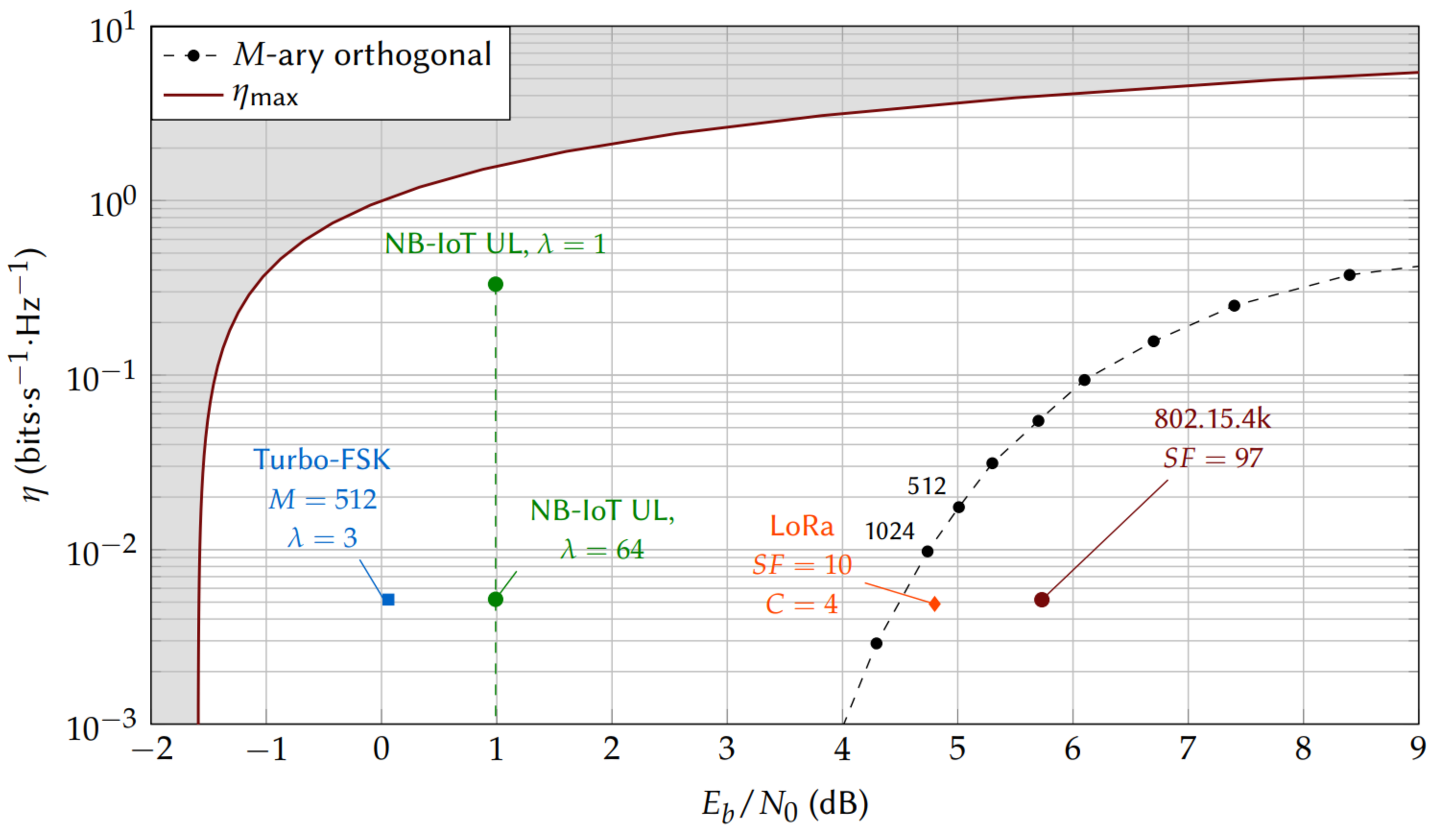


INTRODUCTION

- **Motivation to propose a new LPWA waveform:**
  - Turbo-FSK
    - 0dB PAPR
    - Performance similar to NB-IoT



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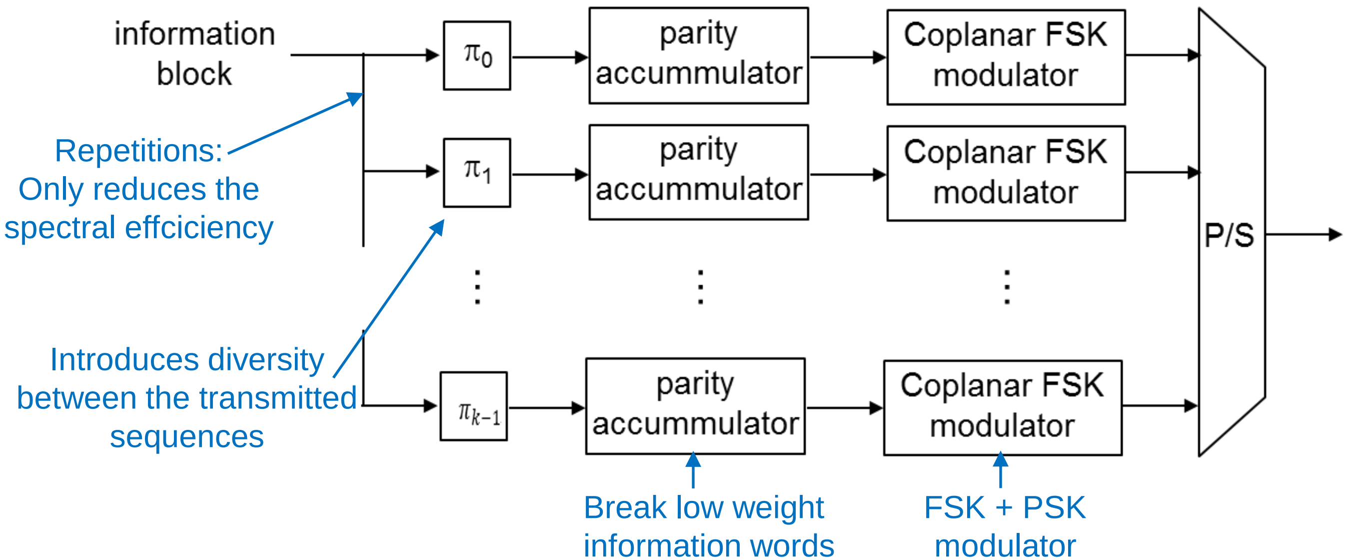
TURBO-FSK PRINCIPLES

- **Turbo-FSK waveform**
  - Constant envelope waveform based on an orthogonal alphabet (FSK codeword) combined with a set of parallel concatenated simple convolutional codes.



➔ 0dB PAPR adapted to low power consumption

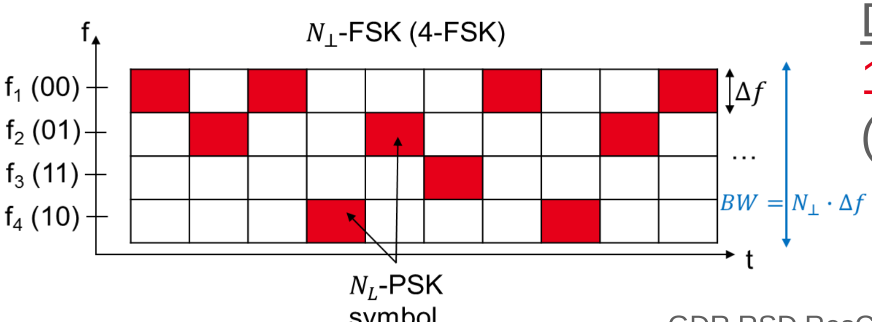
Parameters:

$N_\perp$: Number of carriers in the FSK (FSK modulation order)

N_L : Modulation order of the PSK

k : Number of branches

Δf : Carrier Spacing



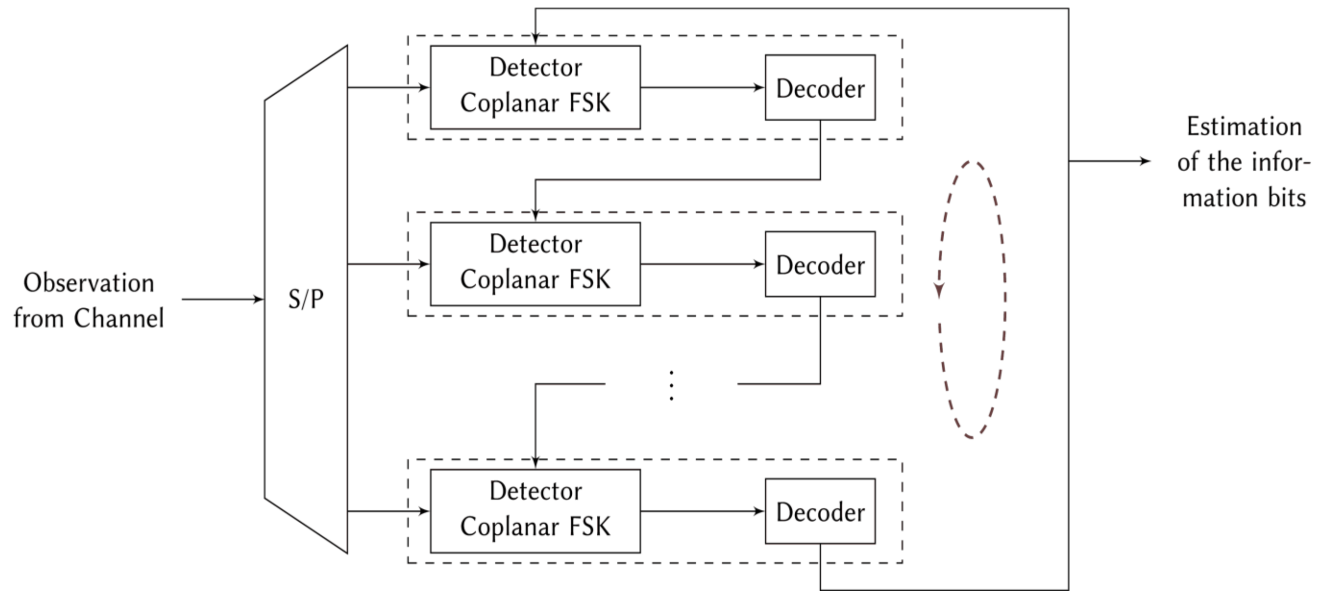
Data rate:

1.7 kb/s → 70 kb/s

(30 kHz to 960 kHz)

TURBO-FSK PRINCIPLES

- **Turbo-FSK waveform**
  - Rx architecture



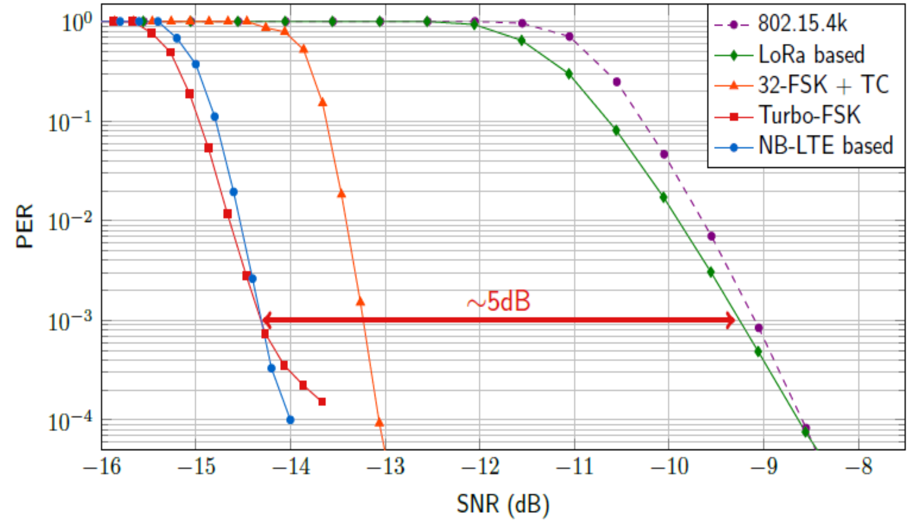
- Reconstruction of the k stages:
  - Soft decoder and message passing algorithm
  - **Modified BCJR** adapted to double coding scheme: CC + FSK

➔ Adapted to Turbo Reception

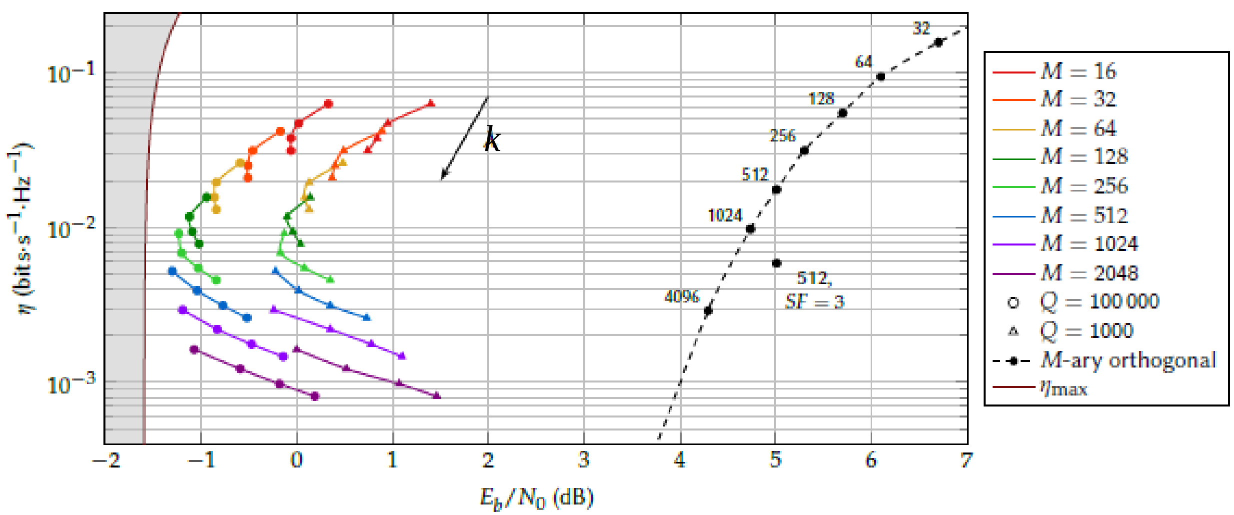
TURBO-FSK PERFORMANCE

- **Turbo-FSK – Performance**
  - AWGN channel

➔ **Similar or close to “OFDM + Turbo-code” for the same level of spectral efficiency but with a PAPR = 0dB**



- Asymptotic Optimization using EXIT charts is possible
  - Allows for selection of Turbo-FSK parameters for a given spectral efficiency

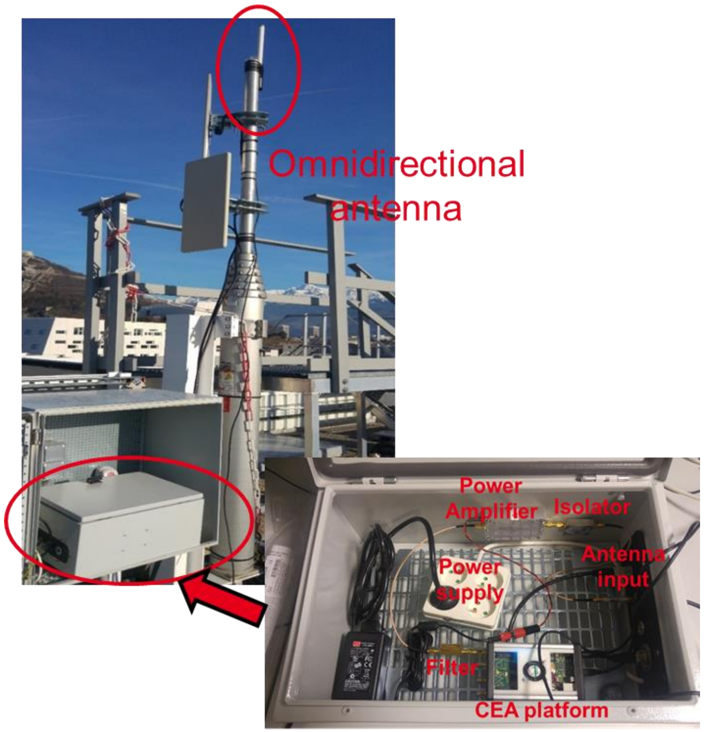


➔ **Very close to the Shannon limit (0.28 dB) for the low spectral efficiencies.**

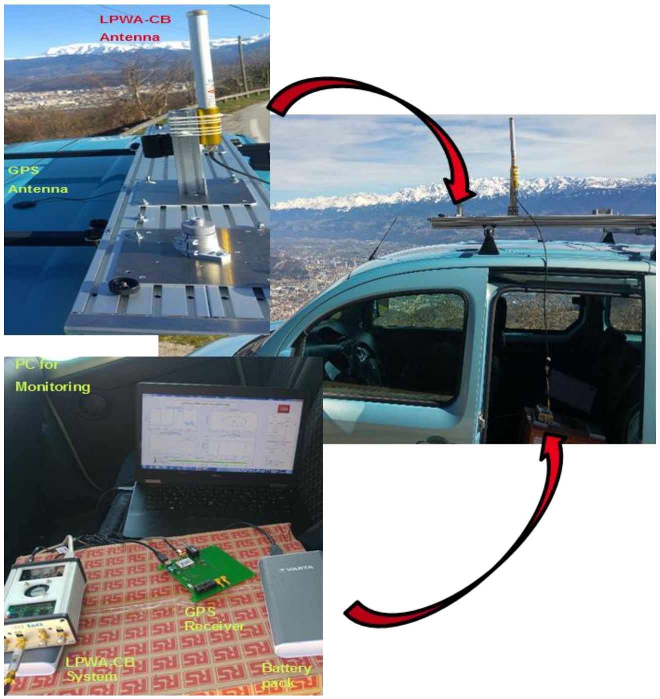
TURBO-FSK / FIELD TRIAL

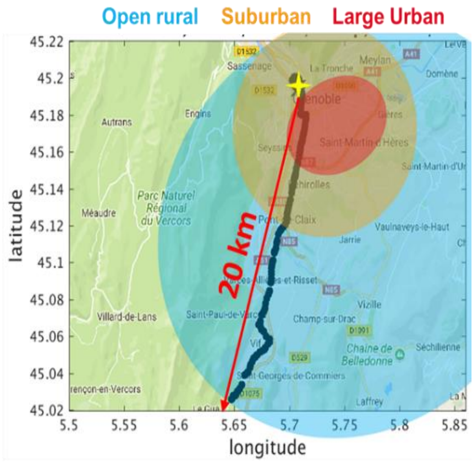
- **Field trial:**
  - <u>Objective</u>: Evaluate and measure the performance of the Turbo-FSK waveform over the air in one of the most characteristic propagation environment
  - Grenoble using ISM 868 MHz band (14 dBm)
  - Point-to-point demonstration

<u>Transmitter</u>



<u>Receiver</u>

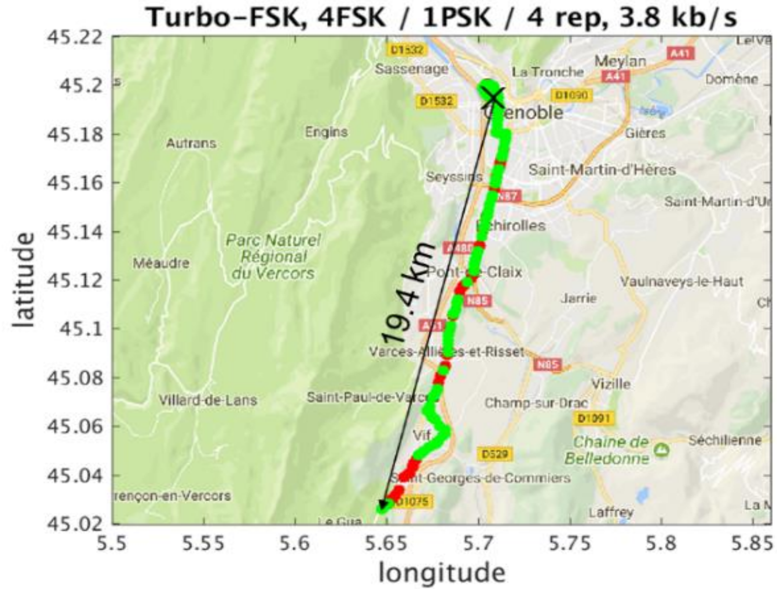




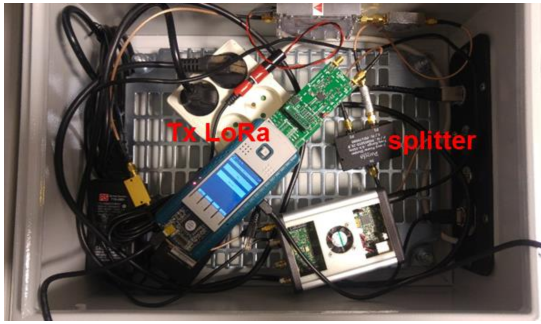
<u>Typical test path (Non-line of sight)</u>

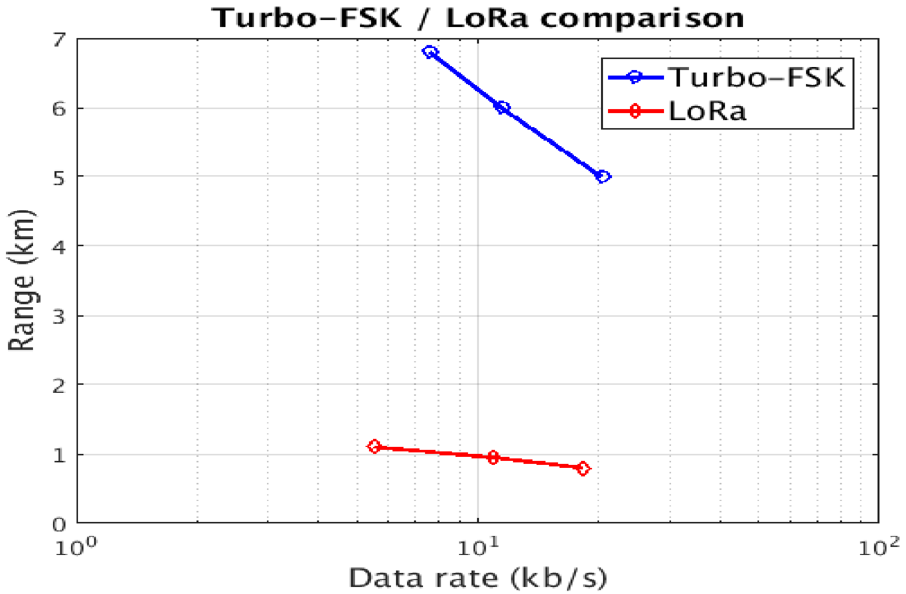
TURBO-FSK / FIELD TRIAL

- **Field trial: Results**
  - **Turbo-FSK (4 FSK, 1PSK, 4 rep): 3.8 kb/s**
    ➔ Range of 19.4 km



- Performance comparison between LoRa and Turbo-FSK
  - Performance of both systems has been simultaneously evaluated (P_{Tx} = 8 dBm)





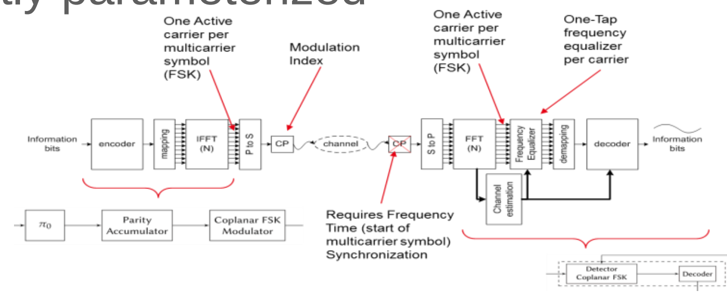
➔ Turbo-FSK significantly outperforms LoRa for every measured configuration by around 4/6 km

➔ Explained by the difference in terms of channel coding (5 dB minimum)

TURBO-FSK PHY SUMMARY

- **Turbo-FSK:**
  - Parallel combination of orthogonal modulation and convolutional code
  - Performance close to Shannon's limit
  - Constant envelope modulation

- **Suited for LPWA applications**
  - Adapted to low energy applications (future 5G NR NB-IoT)
  - Flexible: Spectral efficiency can be significantly parameterized
  - Transmission scheme is similar to OFDM



- **Turbo-FSK waveform proposes more than 60 available MCS trading sensitivity, throughput and energy consumption**

  ➔ Which are the optimal configurations for adaptive LPWA networks?

- Performance of massive LPWA networks including PHY/MAC protocols

OUTLINE

PHY ANALYSIS FOR TURBO-FSK

- The most **relevant configurations** are selected from the PHY and MAC layers point of view.
  - At the **PHY** layer, a trade-off between **data rate**, **spectral efficiency**, **energy** consumption and **range** is considered
  - The **MAC** layer deals with the **reliability**, the **latency**, the network **capacity**, the **multi-user access** (number of users, traffic intensity) to adapt the network.

- Methodology
  - **Comparison** for each configuration using the **same FSK** modulation order
  - **Comparison of optimal configurations** between each FSK modulation
  - **MCS selection** analysis and **trade-offs**

$$(N_{\perp} FSK, N_L PSK, k\ repetitions)$$

<u>Parameters:</u>

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PHY ANALYSIS FOR TURBO-FSK

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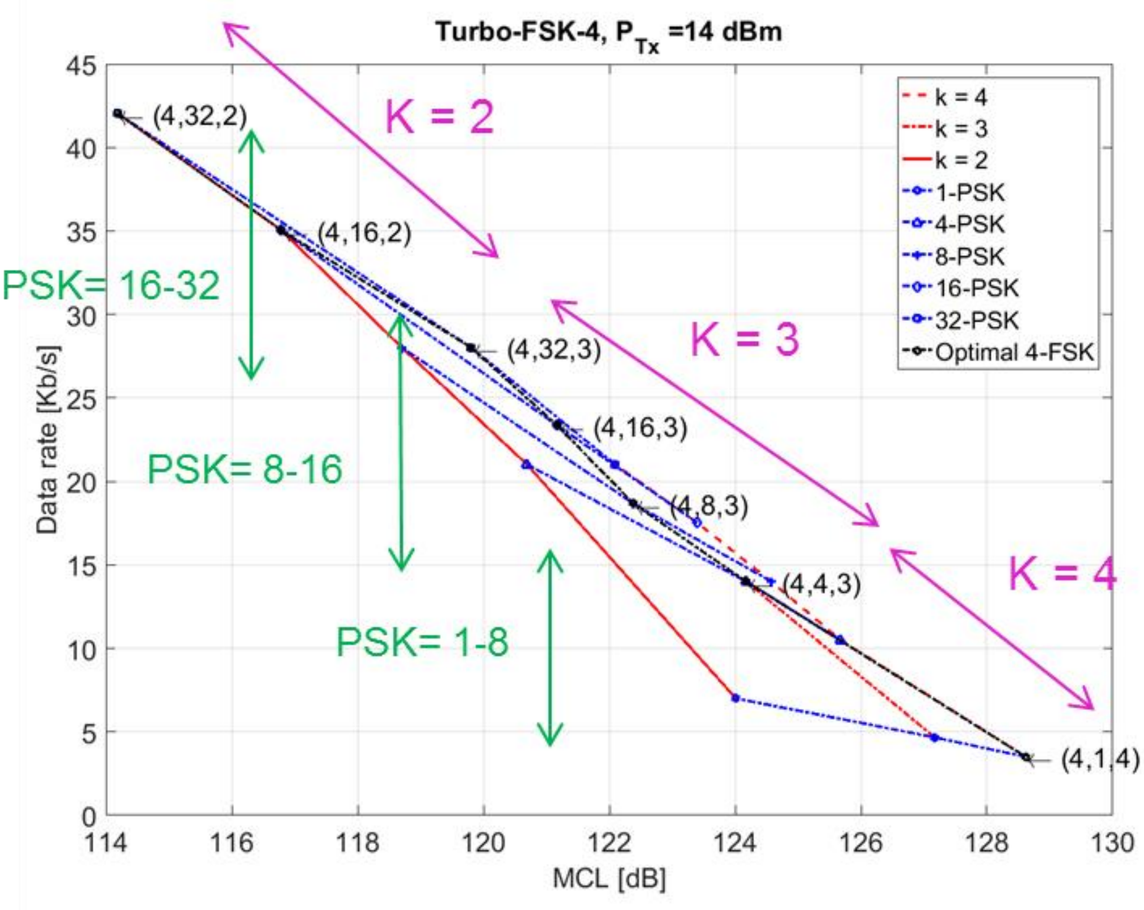

The black curve represents the **optimal configuration for 4-FSK modulation**

$(N_{\perp} FSK, N_L PSK, k\ repetitions)$

PHY ANALYSIS FOR TURBO-FSK

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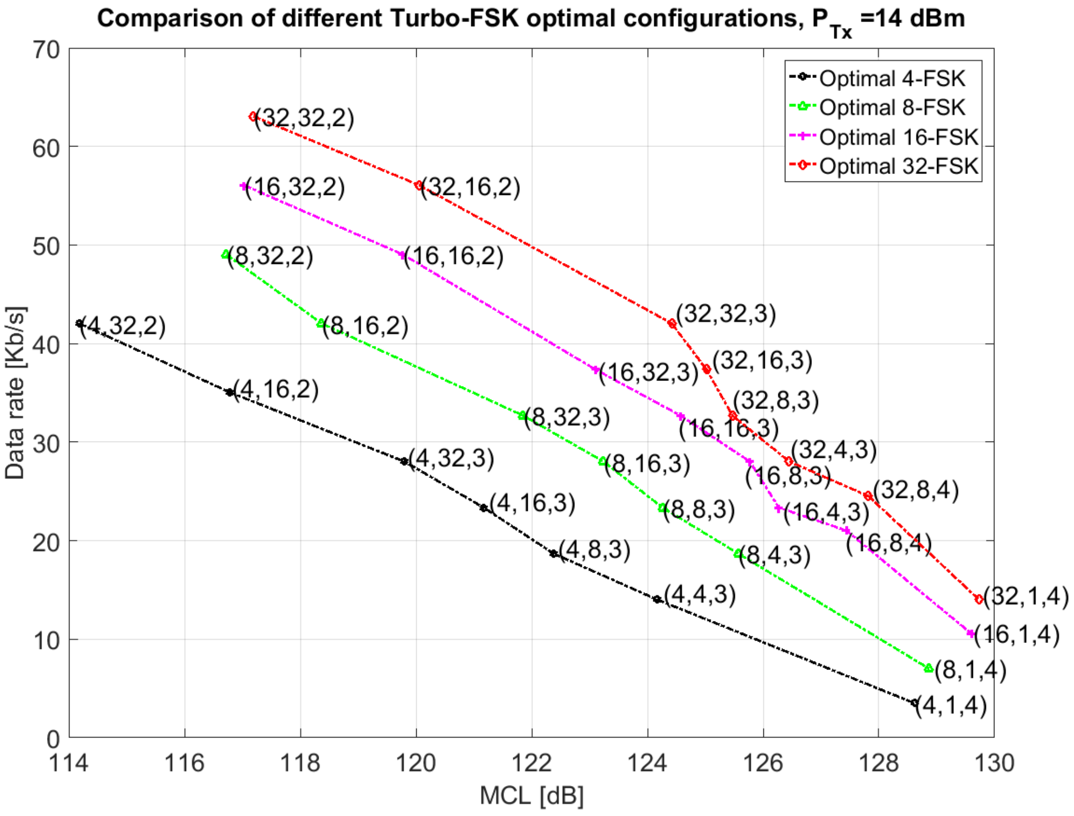

Select the **best schemes** to reduce the Degree of Freedom and to achieve the **optimal configurations** in terms of**:**

- **data rate**
- **spectral efficiency**
- **sensitivity**
- **energy consumption**

$(N_{\perp}FSK, N_{L}PSK, k\ repetitions)$

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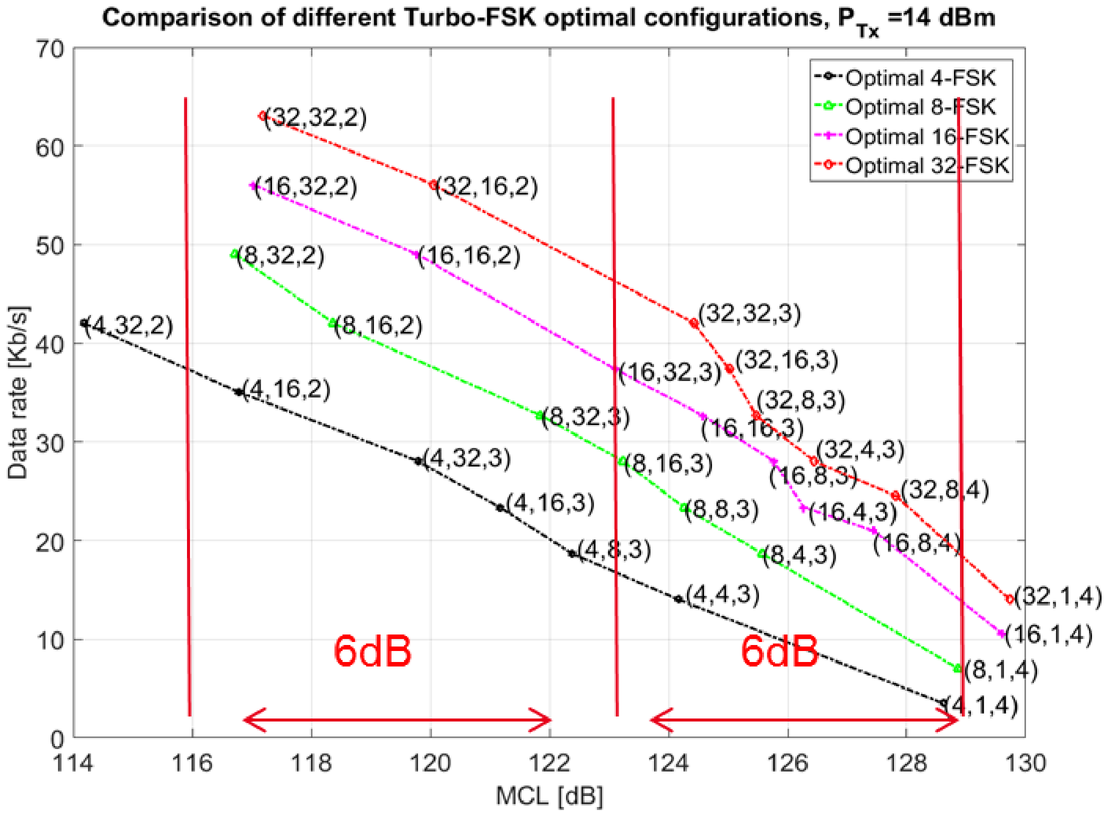

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Hard for MAC Layer or decision module to adapt with such granularity ➔ 6dB

$(N_{\perp}FSK, N_{L}PSK, k\ repetitions)$

PHY ANALYSIS FOR TURBO-FSK

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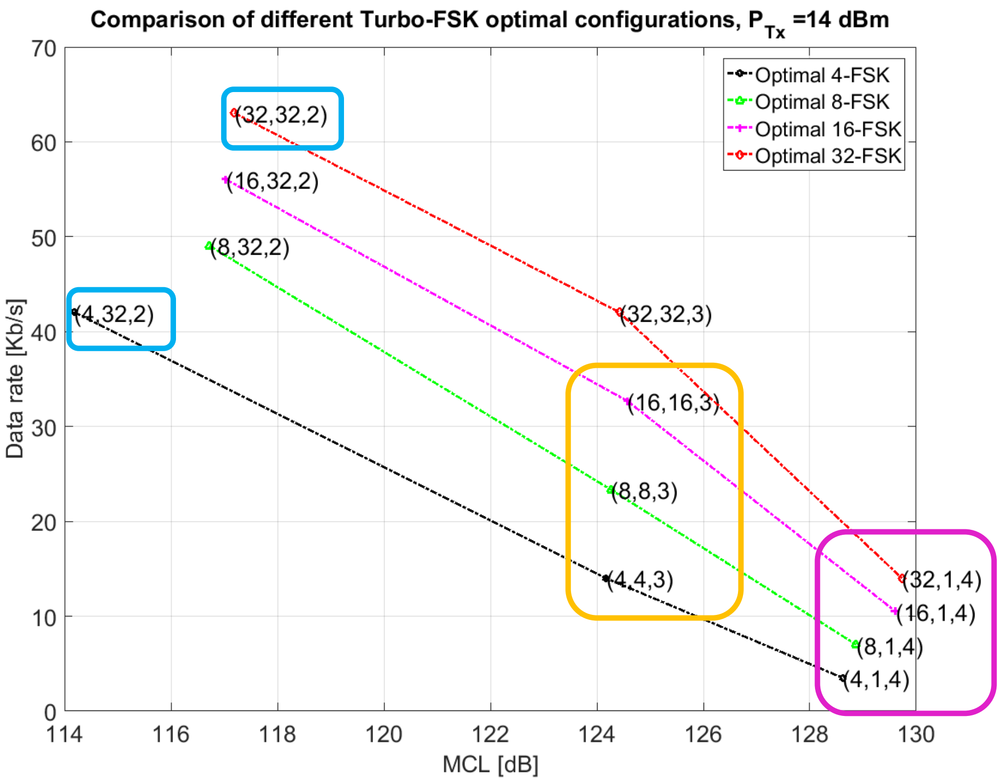
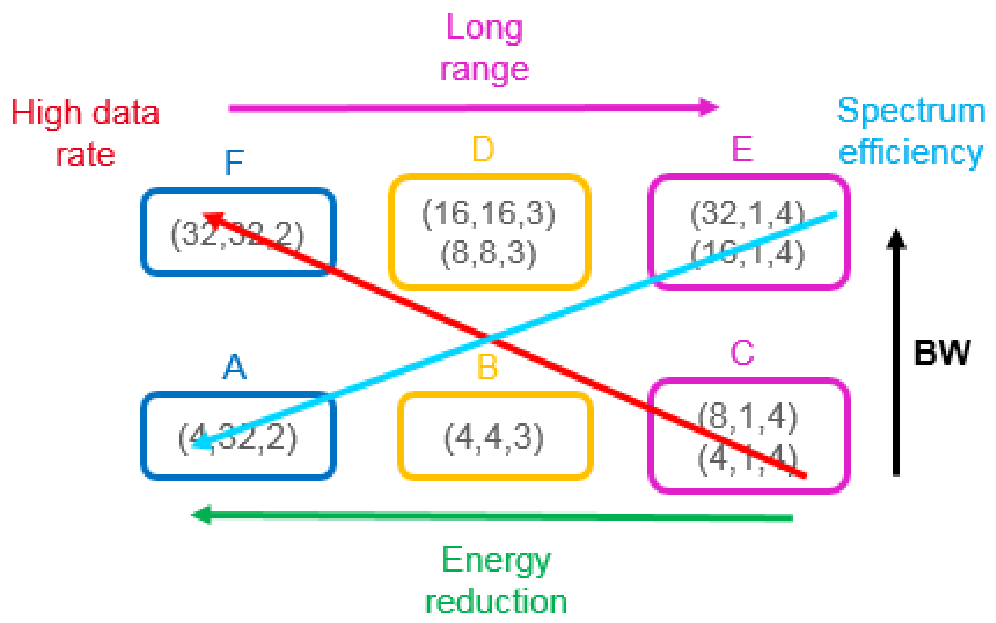


- Short range with higher data rate :
  - (4,32,2)
  - (32,32,2)
- Medium range with moderate data rate:
  - (4,4,3)
  - (16,16,3) (8,8,3)
- Long range with lower data rate:
  - (8,1,4) (4,1,4)
  - (32,1,4) (16,1,4)

$$(N_{\perp}FSK,\ N_{L}PSK,\ k\ repetitions)$$

MAC STRATEGIES FOR ADAPTIVE TURBO-FSK

- We made a selection of the **best MCS** configurations to be exploited by the **decision** module
  - We selected **6 main MCS** (from 60 possible configurations) that cover the main LPWA scenario requirements
  - **Decision** module **optimally selects** the MCS according to the scenario criteria (support mobility, save energy, increase data rate, release network congestion)



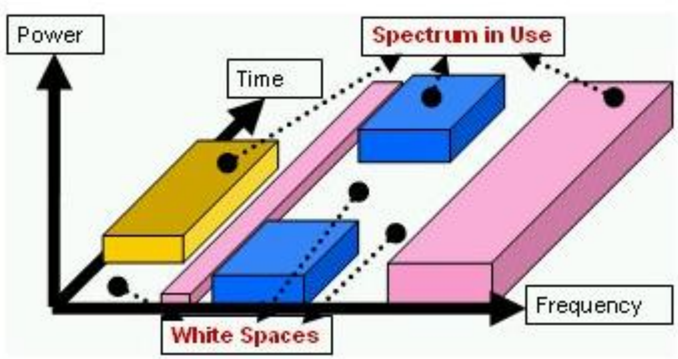
How do these configurations behave in a LPWA multi-user context?

$(N_{\perp} FSK, N_L PSK, k\ repetitions)$

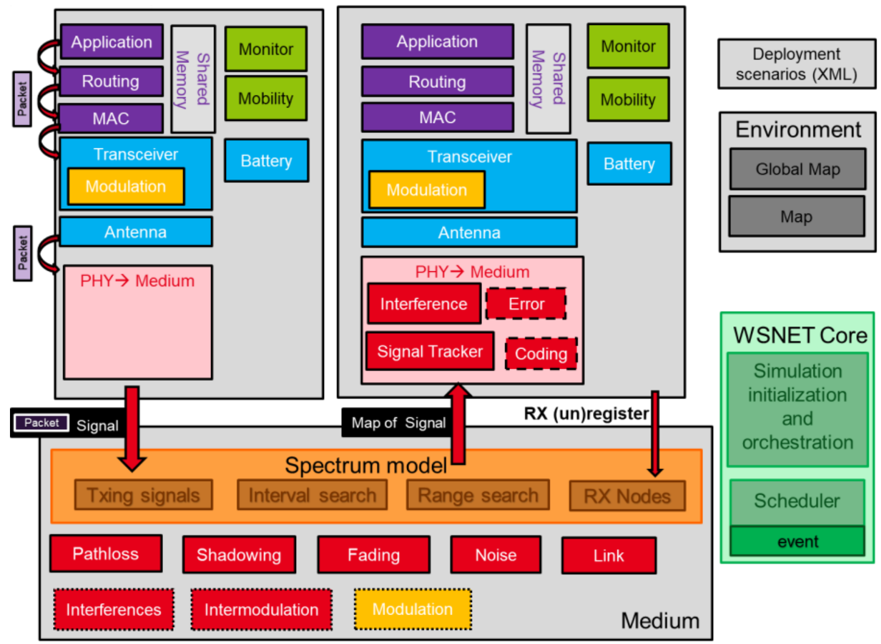
OUTLINE

SIMULATION SETUP AND SCENARIOS

- **WSNet**-based simulator (C/Modern C++) under CeCILL free license.
  - Modular event-driven wireless network simulator simulating the communication **protocol** layers and the **network** behavior with a high level of accuracy.
  - **Accurate PHY** model including spectrum use, modulation, interference, capture effect…
  - The **spectrum** models both time and frequency aspects of communications



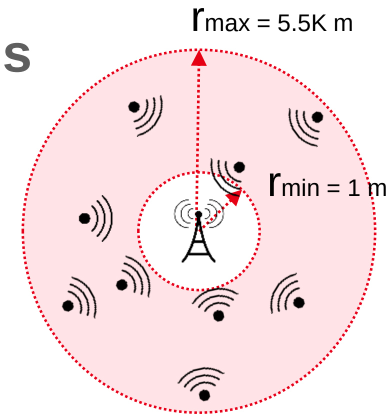
https://github.com/CEA-Leti/wsnet



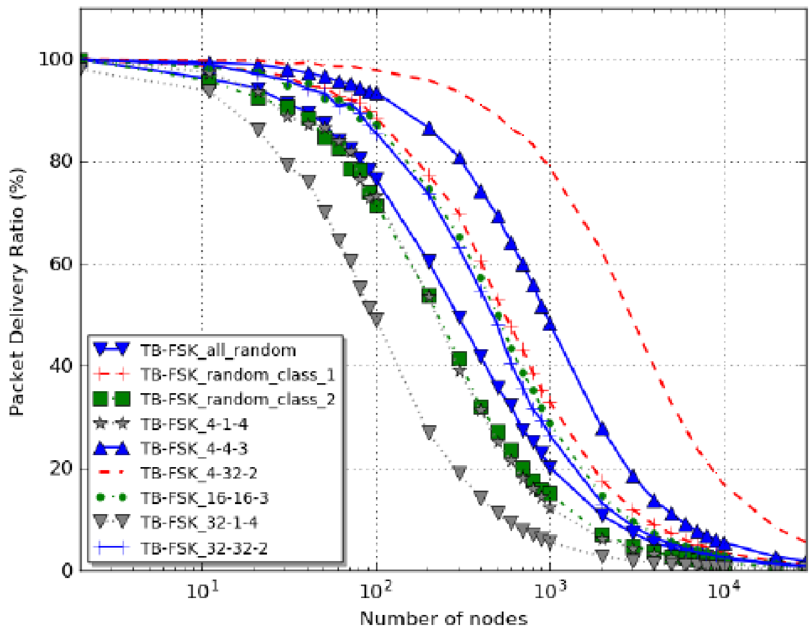
➔ Evaluation of the performance and **limits of Turbo-FSK** waveform for the selected applications (**Smart Metering, Agri, Factory of the Future** systems) through four metrics (i.e. **Resilience**, Network **Capacity**, **Lifetime** and End-to-end **latency**)

PERFORMANCE EVALUATION (MASSIVE ACCESS)

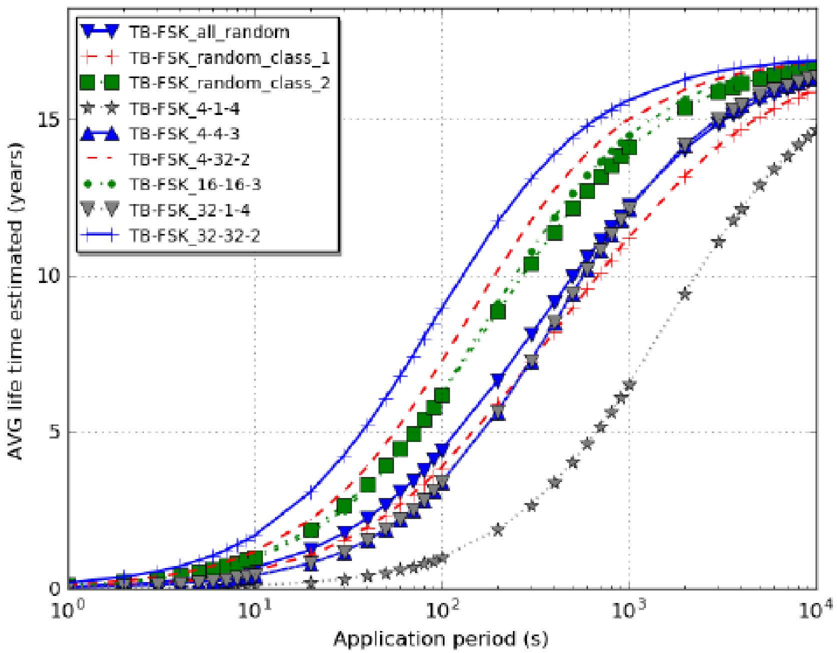
- **Simulation results of massive access for Agri-systems**
  - Nodes send one data packet (**100 Bytes**) randomly in an application period
  - **Random frequency** selection with **Δf = 15KHz** (sub-carrier)
  - Transmission power is fixed to 14dBm
  - Path loss set in **open rural**
  - 1 physical band (**1 MHz**) starting at 868MHz
  - Nodes remain **static** at random positions in a disk
  - The radius max is always set at **5.5 Km**



PDR with 1s application period



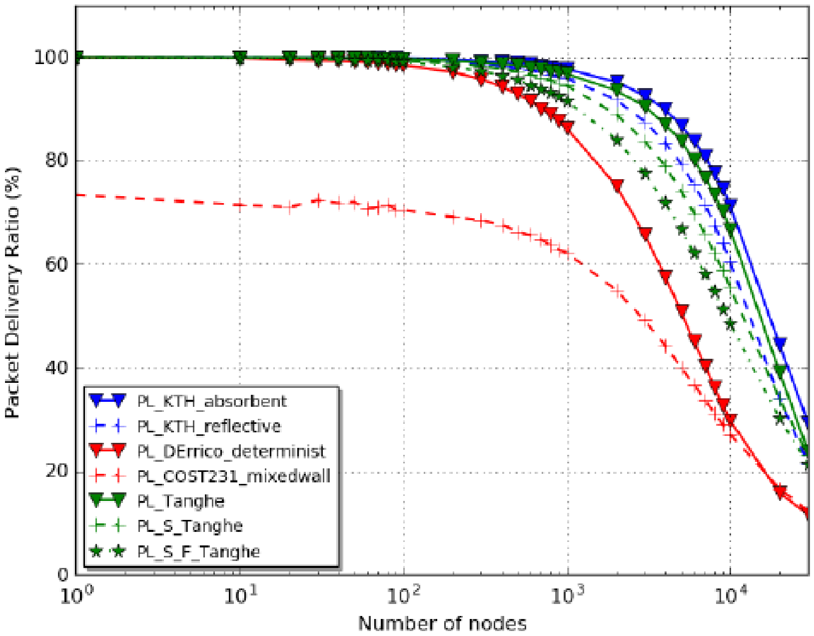
Average **Battery Lifetime** with 30000 nodes



PERFORMANCE EVALUATION (MASSIVE ACCESS)

- ## Simulation results for FoF
  - 1 gateway at the center of the **industrial** zone (50mx50m)
  - 1 physical band (**1 MHz**) starting at 868MHz
  - **Random frequency** selection with **Δf = 15KHz** and **Ideal capture effect**
  - Up to 30000 nodes, uniformly deployed
  - Nodes send one data packet (100 Bytes) randomly in an application period (1 minute)
  - Transmission power is fixed to 14dBm
  - Homogeneous deployments (using the same MCS during a simulation)
  - **Several FoF Path loss** [18][19][20][21]

PDR as a function of the FoF pathloss model with Turbo-FSK (8,1,4)



COMPARISON LORA AND TURBO-FSK IN FOF

- **Equivalent MCS of LoRa and Turbo-FSK**

Turbo-FSK			LoRa (CR 4/5)		
MCS	**Data rate (kb/s)**	**Spectral efficiency (b/s/Hz)**	**MCS**	**Data rate (kb/s)**	**Spectral efficiency (b/s/Hz)**
(8,1,4) 120 kHz	7.0	0,059	SF7 125 kHz	5.4	0,043
(16,1,4) 240 kHz	10.5	0,044	SF7 250 kHz	10.9	0,043
(32,1,4) 480 kHz	14.0	0,029	SF7 500 kHz	21.9	0,043
			SF8 500 kHz	12.5	0,025

➔ **Add LoRa Models in WSNET**

- LoRa modulation with 7 quasi-orthogonal Spreading Factor (SF6 to SF12)
- Interference module taking into account the effect of the quasi-orthogonality of SFs.
  - Co-Channel rejection matrix
- LoRa SX1276 and SX1301 Transceivers capabilities and capture effect
  - SX1276 architecture for nodes
  - SX1301 architecture for the Gateway
  - ➔ The Gateway can simultaneously receive several LoRa packets (with different SFs and up to 8 channels)

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- **Simulation results for FoF**
  - 1 gateway at the center of the **industrial** zone (50mx50m)
  - Channel bandwidth of **1MHz**, divided in **non overlapping** sub-channels (up to 8)
  - Up to 30000 nodes, uniformly deployed
  - Nodes send one data packet (100 Bytes) randomly in an application period (1 minute)
  - Transmission power is fixed to 14dBm
  - Homogeneous deployments (using the same MCS during a simulation)
  - FoF propagation model set to Tanghe (Pathloss, Shadowing and Fading)

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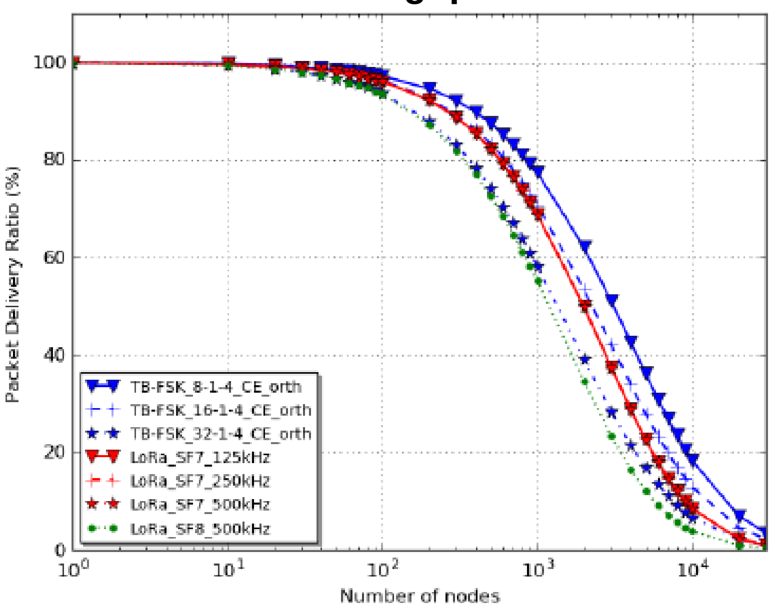
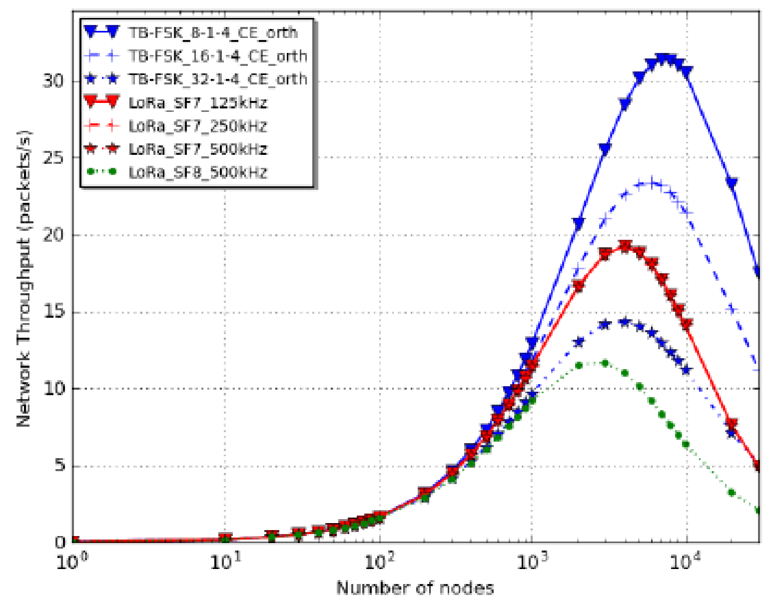
PDR and **Throughput** of LoRa and Turbo-FSK in FoF (Application period = 1 minute)





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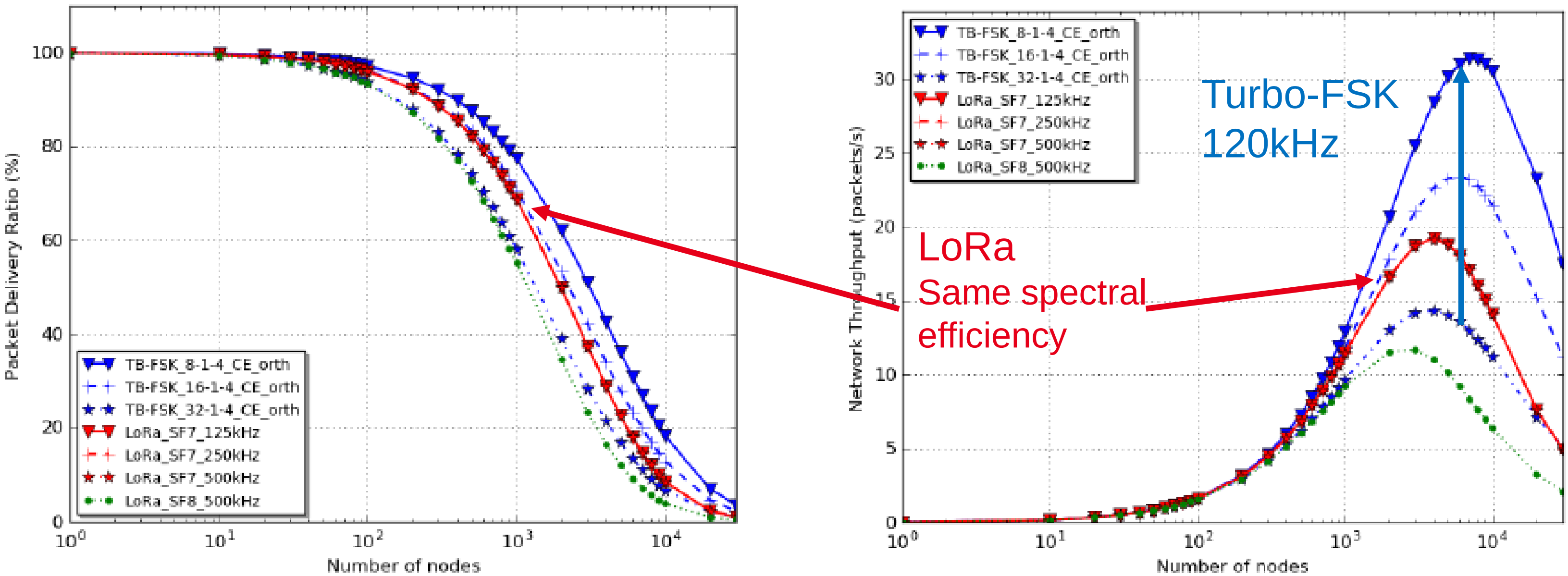

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CONCLUSION

- LPWA networks need to cover a large variety of applications with contradictory requirements: **Long range, Low power consumption and Adaptive throughput**
- We proposed a **flexible Turbo-FSK waveform** trading throughput, sensitivity, spectral efficiency and energy consumption
- We proposed an **adaptive** LPWA network exploiting the **flexibility** of Turbo-FSK thanks to a **decision** module selecting the most appropriate RF/PHY configuration
- Large-scale **LoRa** / **Turbo-FSK deployments** have been studied and compared in the **FoF** context with **WSNet** simulator
  - **PHY** flexibility and specificities of different **LoRa** / **Turbo-FSK** configurations
  - **Random** massive access
  - **FoF application** models considering **mMTC** traffic (non-URLLC scenario)
  - **FoF propagation** models considering pathloss, shadowing and multi-path fading
- **Others studies not presented today**
  - Evaluation of **multi-gateway** impact on LoRa performance in FoF environment.
  - Impact of DL communication on the LoRa network performance
  - Define and simulate **cross-layer decision** modules to enable adaptive operation with single or multi-gateway infrastructure.

ACKNOWLEDGEMENT

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