Impact of the DL traffic on the capacity of a LoRa network

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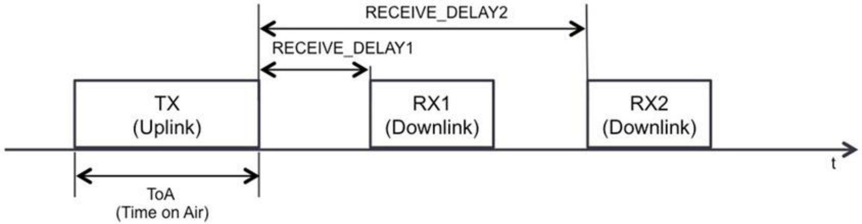
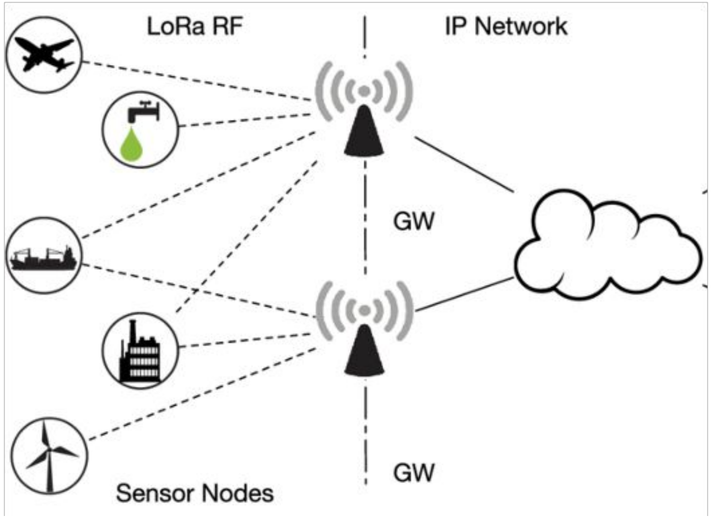
Agenda

1. Back to LoRaWAN
2. Problem: limited downlink communication!
3. Objective: quantify the impact of the DL on network capacity
4. Modeling and assumptions
5. Proposed Model
6. Performance evaluation results
7. Concluding remarks

1/ LoRaWAN

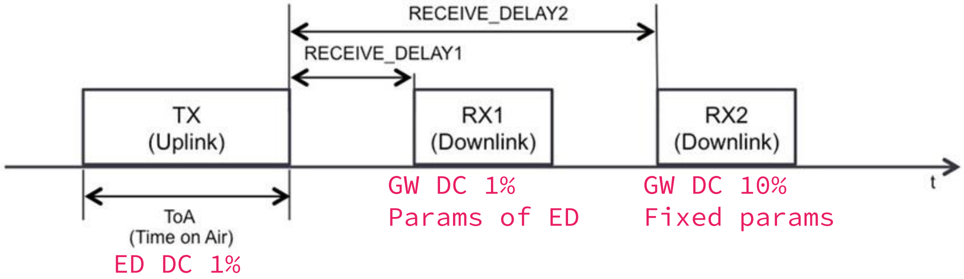
- Long range communication
- Low power consumption
- Support of uplink & downlink
- Medium access: Aloha
- Class A:





2/ Problem: limited downlink communication!

1. Gateway has limited duty cycle (DC): 1-10%
2. Different Tx parameters (SF, frequency) on RX1 and RX2



3. UL and DL are not completely orthogonal [1]
4. Gateway is half-duplex

[1] R. Saroui, A. Guitton, O. Iova, F. Valois, “La rumeur disait faux : ils ne sont pas orthogonaux !”, CoRes, Paris Saclay, June 2022.

3/ Objective: quantify the impact of DL on network capacity

- Propose a model to characterize the loss of capacity because of the DL traffic (mainly acknowledgement traffic)
  - when UL and DL are not fully orthogonal
  - DC 1% for RX1, DC 10% RX2
  - confirmed traffic and non-confirmed traffic
  - study different SF policies for RX2:
    - fixed SF9 (The Things Network)
    - fixed SF12 (LoRa Alliance)

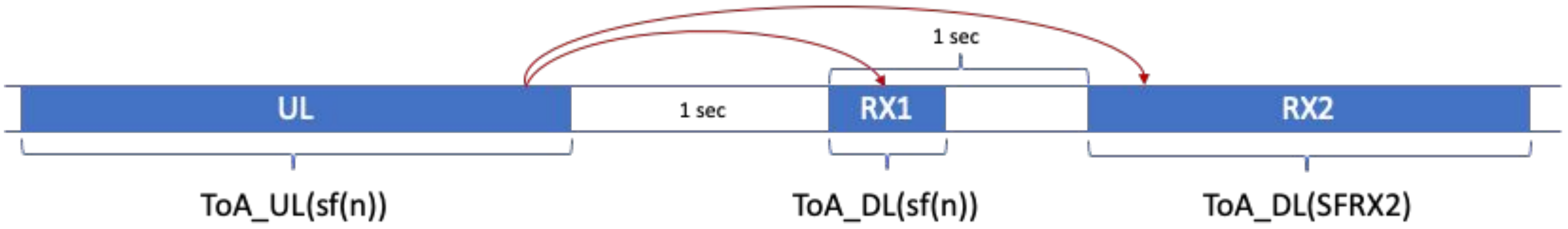
4/ Modeling and assumptions

- 1 gateway, N nodes
- Ideal physical layer (no interference, no fading & co.)
- Traffic model (application):
  - Periodic UL transmission that needs to be ACKed
  - Data payload size: 51 bytes
  - ACK payload size: 0 byte
  - Time-on-Air (ToA) computed using: https://loratools.nl/#/airtime

5/ Proposed model - Input

- The general parameters:
  - BW, CR, ToA for UL and DL
- The set of nodes per SF:
  - Nf = {N7, N8, N9, N10, N11, N12}
- The number of transmissions for each node:
  - time period of 1h
  - 1,...,k pkt/s
- The scheduling of the UL frames for each node:
  - periodic with time step 1h/(nb Tx)

5/ Proposed model - Pre-Computation



- t_j^i: j^{th} UL frame of node n_i
- $t1_j^i$: DL frame on RX1 window associated with t_j^i
- $t2_j^i$: DL frame on RX2 window associated with t_j^i

5/ Proposed model - Frame model

- Type:
  - UL, RX1, RX2
- Associated node n_i:
  - sender of UL or receiver of DL
- Associated SF:
  - $sf(n_i)$ for UL and DL on RX1,
  - SF_{RX2} for DL on RX2
- Occupation $[s_j^i, e_j^i]$ with length $ToA(sf(n_i))$
- Boolean ACK:
  - does the frame need to be confirmed?

5/ Proposed model - Optimization model

- Variables (divided among frame types):
    - $y1_{t1^i_j} = 1$ if t^i_j is acknowledged on RX1
    - $y2_{t2^i_j} = 1$ if t^i_j is acknowledged on RX2
    - $y_{t^i_j} = 1$ if the UL collides with either:
        - Another UL from at least another node on same SF
        - A DL of the gateway: since the gateway is half-duplex, it cannot listen to the UL while sending a DL

5/ Proposed model - Objective function

- Maximize the number of DL frames sent by the gateway:
  - For correctly received UL (without collisions and half-duplex property)
  - Priority is given on DL during RX1 over RX2 when the two are possible (with parameter α=0.0001)

$$\max \sum_{n_i \in N} \sum_{t_j^i \in \mathrm{ul}(n_i)} \left((1+\alpha) y1_{t1_j^i} + y2_{t2_j^i}\right) \tag{1}$$

5/ Proposed model - Overview of the constraints

- Duty-cycle of the gateway
  - The gateway should not exceed its duty-cycle while transmitting (1% duty-cycle on RX1, 10% on RX2)
- No DL simultaneously at a time
  - The gateway cannot send more than 1 frame at a time
- UL collision
  - When two ULs are sent simultaneously on same SF, both are lost
  - The gateway is half-duplex, so an UL is lost if a DL is scheduled
- DL only if the UL is received
  - The gateway can only acknowledge frames that have been correctly received (that is, without collision)

5/ Proposed model - Duty-cycle of the gateway

- The gateway should not exceed its duty-cycle while transmitting (1% duty-cycle on RX1, 10% on RX2)

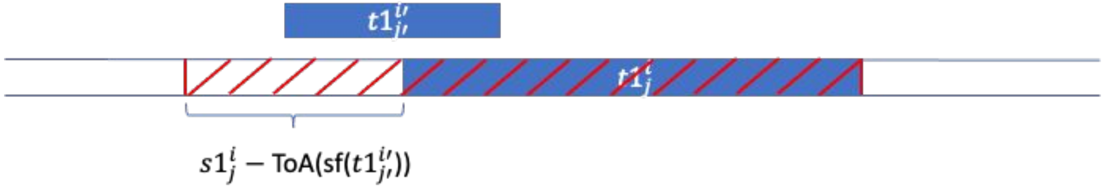
$$y1_{t1^i_j} + y1_{t1^{i'}_{j'}} \leq 1 \qquad (2)$$

$$\forall t1^i_j = \{s^i_j, e^i_j\}, t1^{i'}_{j'} = \{s^{i'}_{j'}, e^{i'}_{j'}\} \text{ such that } s^i_j < s^{i'}_{j'} < s^i_j + 100 * ToA_{DL}(\text{sf}(n_i)).$$

$$y2_{t2^i_j} + y2_{t2^{i'}_{j'}} \leq 1 \qquad (3)$$

$$\forall t2^i_j = \{s^i_j, e^i_j\}, t2^{i'}_{j'} = \{s^{i'}_{j'}, e^{i'}_{j'}\} \text{ such that } s^i_j < s^{i'}_{j'} < s^i_j + 10 * ToA_{DL}(SF_{RX2}).$$

5/ Proposed model - No DL simultaneously



- The gateway cannot send more than 1 frame at a time

$$y1_{t1_j^i} + \sum_{t1_{j'}^{i'} \cap t1_j^i \neq \emptyset} y1_{t1_{j'}^{i'}} + \sum_{t2_{j'}^{i'} \cap t1_j^i \neq \emptyset} y2_{t2_{j'}^{i'}} \leq 1, \ \forall t1_j^i \tag{4}$$

$$y2_{t2_j^i} + \sum_{t1_{j'}^{i'} \cap t2_j^i \neq \emptyset} y1_{t1_{j'}^{i'}} + \sum_{t2_{j'}^{i'} \cap t2_j^i \neq \emptyset} y2_{t2_{j'}^{i'}} \leq 1, \ \forall t2_j^i \tag{5}$$

5/ Proposed model - UL collision

$$y_{t_j^i} = 1 \tag{7}$$

$\forall t_j^i$ such that $\exists t_{j'}^{i'}$ on same SF (i.e. $\mathrm{sf}(n_i) = \mathrm{sf}(n_{i'})$) with $t_{j'}^{i'} \cap t_j^i \neq \emptyset$.

$$y_{t_j^i} \geq y1_{t1_{j'}^{i'}} \tag{8}$$

$\forall t_j^i$ such that $\exists t1_{j'}^{i'}$ (any DL on RX1 for any node $n_{i'}$ on any SF) with $t1_{j'}^{i'} \cap t_j^i \neq \emptyset$.

$$y_{t_j^i} \geq y2_{t2_{j'}^{i'}} \tag{9}$$

$\forall t_j^i$ such that $\exists t2_{j'}^{i'}$ (any DL on RX2 for any node $n_{i'}$) with $t2_{j'}^{i'} \cap t_j^i \neq \emptyset$.

5/ Proposed model - DL if UL correctly received

- The gateway can only acknowledge frames that have been correctly received

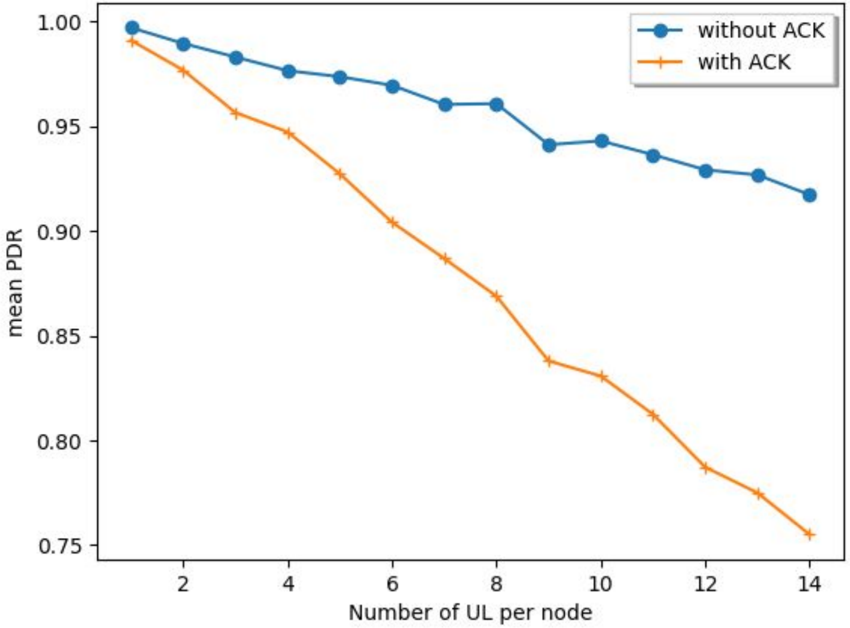
$$y1_{t1_j^i} + y2_{t2_j^i} \leq 1 - y_{t_j^i}, \ \forall t_j^i \tag{6}$$

6/ Performance evaluation results

- Model solved using IBM Cplex 20.1
- Fair SF limits [3.03,3.77,4.3,4.68,4.88,5] (km) from [2]
- Inverse square node density
- RX2 policy : SF9 like in TTN
- Traffic model : 1 to 14 pkts/s, all to be ACKed
- Periodic traffic :
    - time step = 1h/(nb UL frames)
    - first UL frame chosen randomly in first step
    - other frames regular at each step +- 2 sec.

[2] C. Caillouet, M. Heusse, F. Rousseau, “Bringing Fairness in LoRaWAN through SF Allocation Optimization”, ISCC 2020 - 25th IEEE Symposium on Computers and Communications, Jul 2020, Rennes, France.

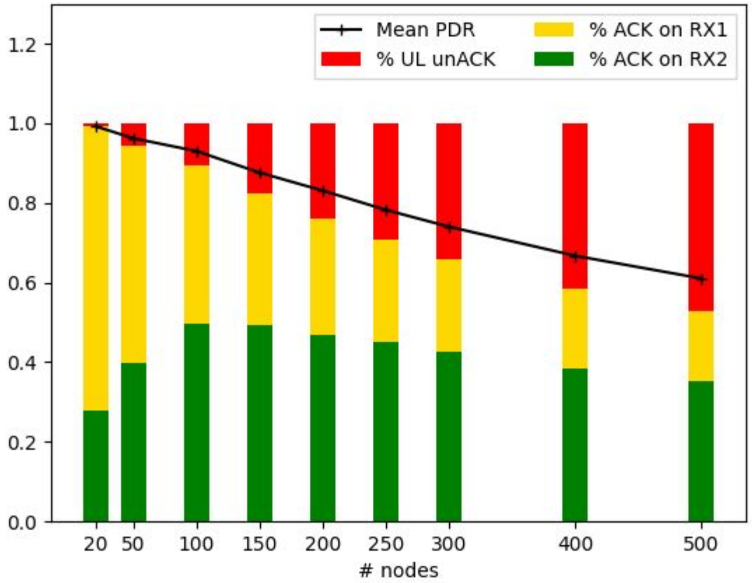
6/ Performance evaluation results - PDR



- 200 nodes with the spatial distribution: [74, 41, 35, 27, 15, 8]
- All UL frames have to be acknowledged
- Impact of DL traffic on the PDR of nodes:

PDR = #UL received / #UL sent

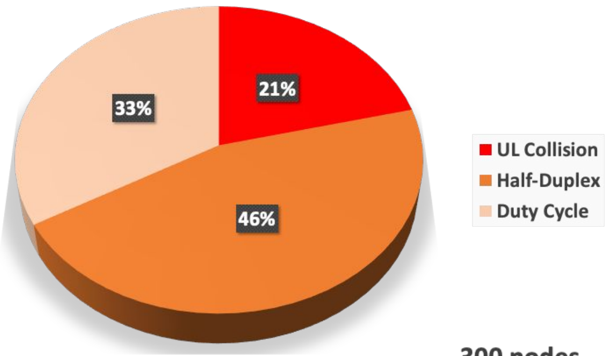
6/ Performance evaluation results - ACK policy



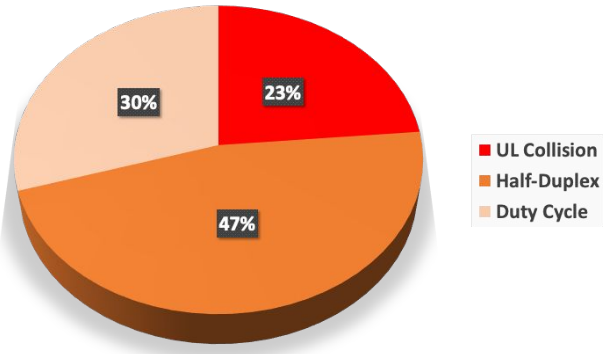
- 10 UL frames sent per node
- priority for RX1

6/ Performance evaluation results - ACK failures

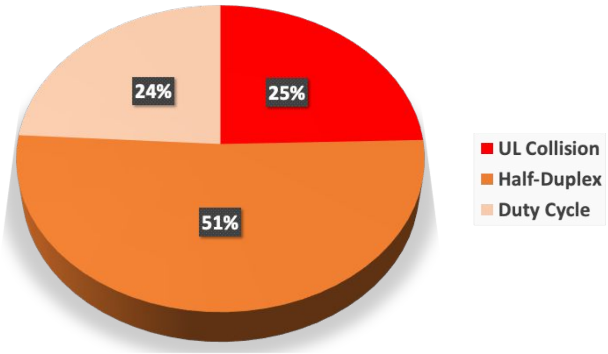
100 nodes



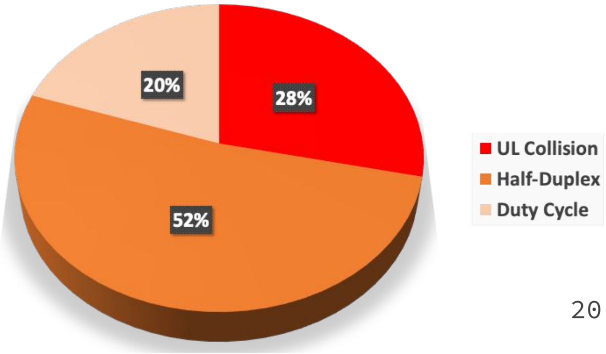
200 nodes



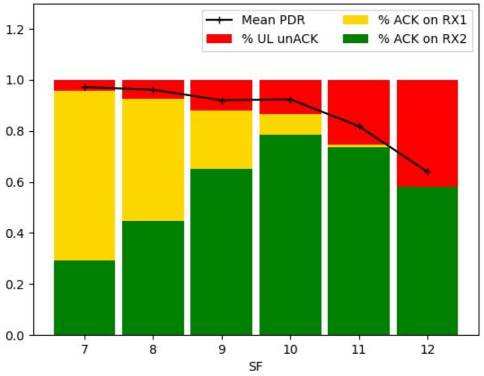
300 nodes

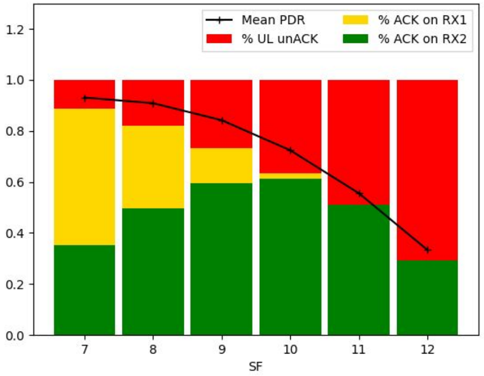


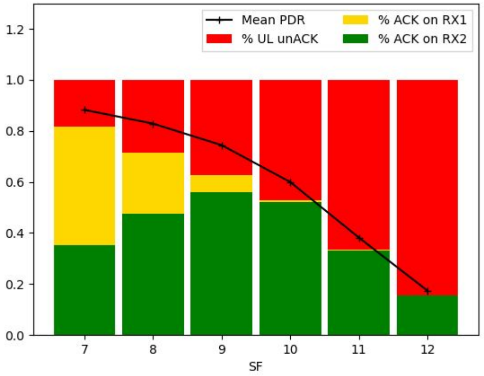
400 nodes



6/ Performance evaluation results - ACK policy per SF





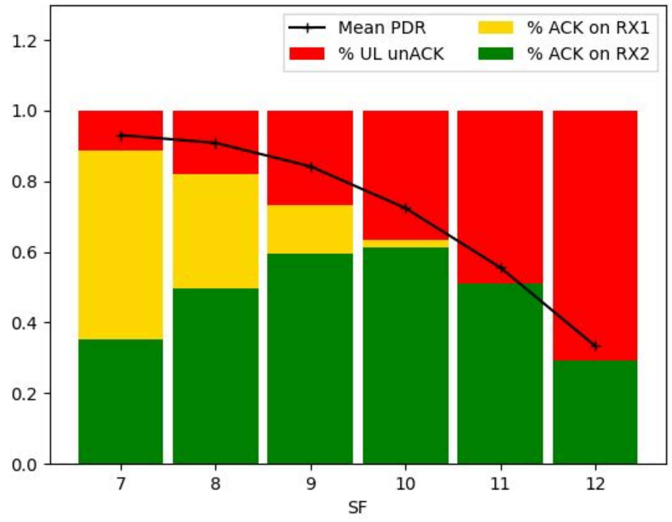


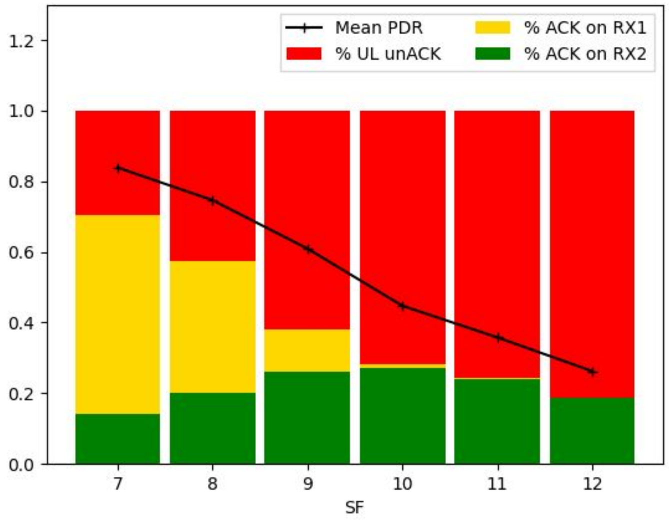
100 nodes
[37, 21, 18, 13, 7, 4]
mean PDR = 93%

200 nodes
[74, 41, 35, 27, 15, 8]
83.1%

300 nodes
[111, 61, 52, 40, 22, 14]
74%

6/ Performance evaluation results - SF RX2 policy





SF = 9 (TTN)
PDR = 83.1%

200 nodes
10 UL

SF = 12 (LoRa Alliance)
PDR = 66.8%

7/ Concluding remarks

- The DL has a significant impact on the performance
  - It is mainly due to the RX2 configuration
  - DL traffic mostly limited by the half-duplex property of the gateway
- On-going work:
  - Extension of the model for multi-gateways, with a realistic channel model, and with a non-orthogonality of ULs and DLs
  - Evaluate several strategies for RX2 configuration

Thank you for your attention

Questions?

We are hiring!
PhD and Postdoc

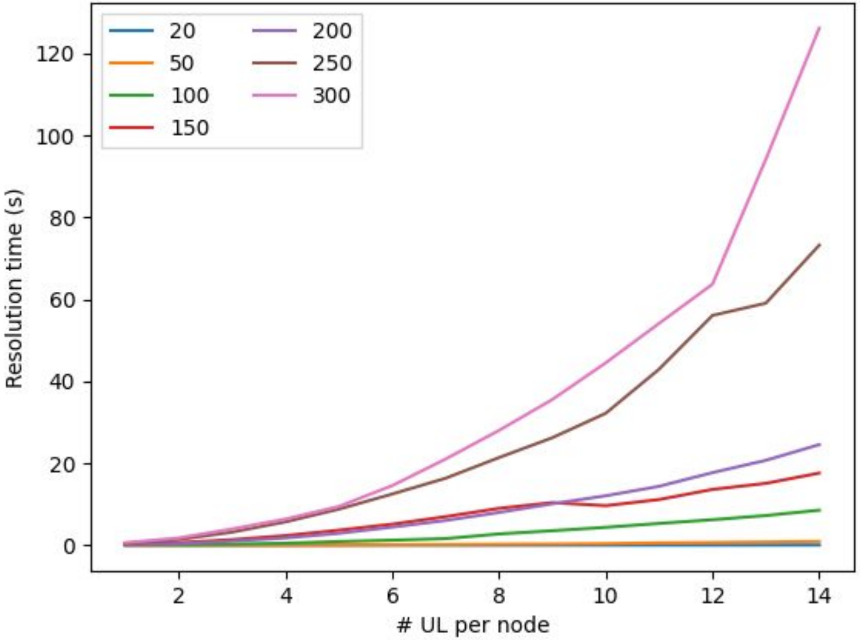
Backup slides

Time on Air

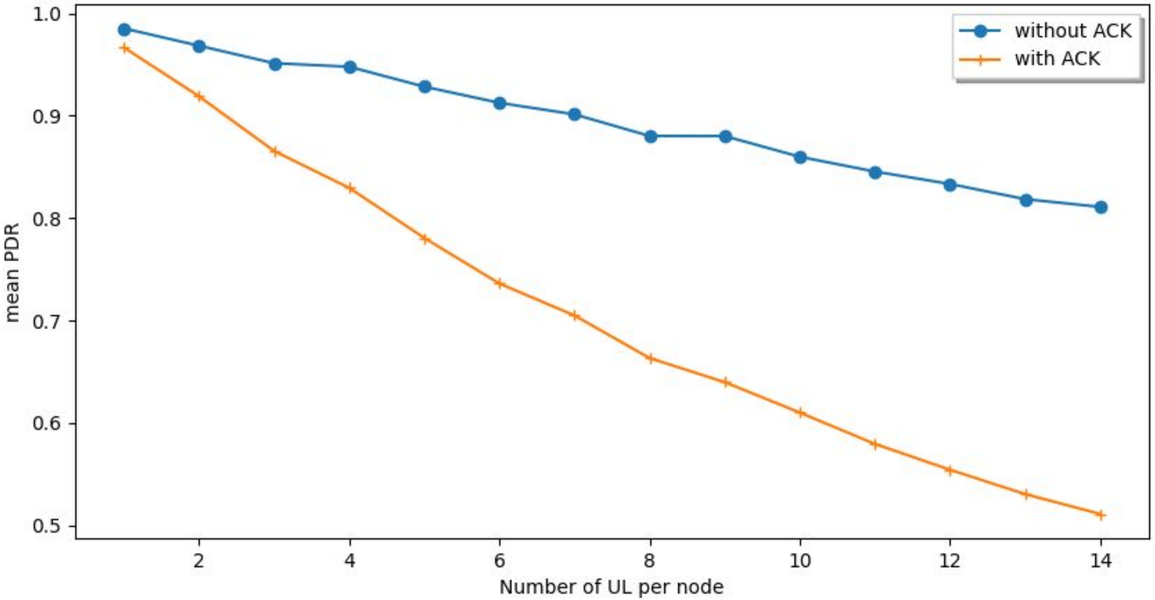
```
trame UL (payload-length=51 bytes, explicit=yes, CRC=yes)
SF=12 => 2465.79 ms
SF=11 => 1314.82 ms
SF=10 => 616.45 ms
SF=9=> 328.70 ms
SF=8=> 184.83 ms
SF=7=> 102.66 ms
```

```
trame DL (payload-length=0 bytes, explicit=yes, CRC=no)
SF=12 => 663.55 ms
SF=11 => 331.78 ms
SF=10 => 165.89 ms
SF=9 => 82.94 ms
SF=8 => 41.47 ms
SF=7 => 20.74 ms
```

6/ Performance evaluation results - Resolution time

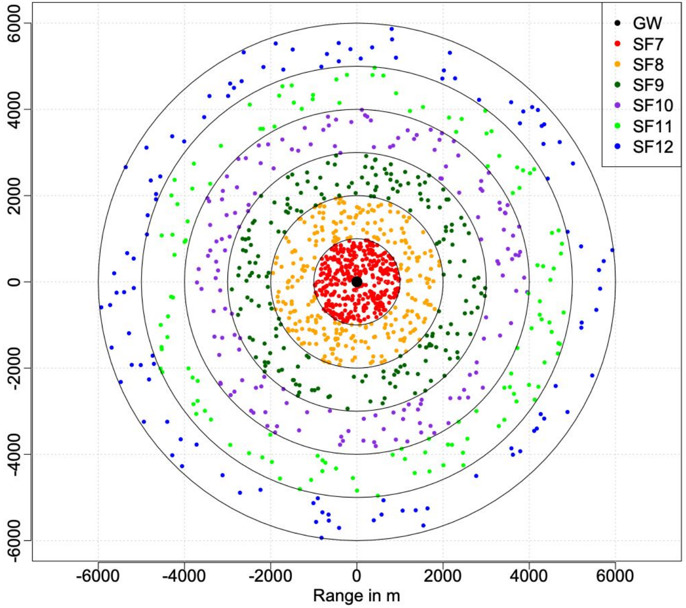


6/ Performance evaluation results - PDR



- 500 nodes: [184, 101, 86, 68, 38, 23]

6/ Node density



(b) Inverse squared density

[3] Andrzej Duda, Martin Heusse. Spatial Issues in Modeling LoRaWAN Capacity. Proceedings of the 22Nd International ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, Nov 2019, Miami Beach, United States, pp.191-198.