HELLENIC REPUBLIC
National and Kapodistrian
University of Athens

DEPARTMENT OF
INFORMATICS &
TELECOMMUNICATIONS

Νέες και Παλιές Προκλήσεις στα Δίκτυα Κινητών Επικοινωνιών (M301)

LoRa/LoRaWAN Low-Power Wide Area Networks: Analysis, Simulation, Implementation, Stochastic Modeling of Access

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Green, Adaptive and Intelligent Networking (GAIN) group

Today’s Agenda

Introduction to Low-Power Wide Area Networks

A top-down approach in LoRaWAN MAC/LoRa PHY

Research challenges and methodology

Our work: Simulation study & Implementation study

Fundamental topics on Stochastic Processes and Markov chains
- Markov chains use cases

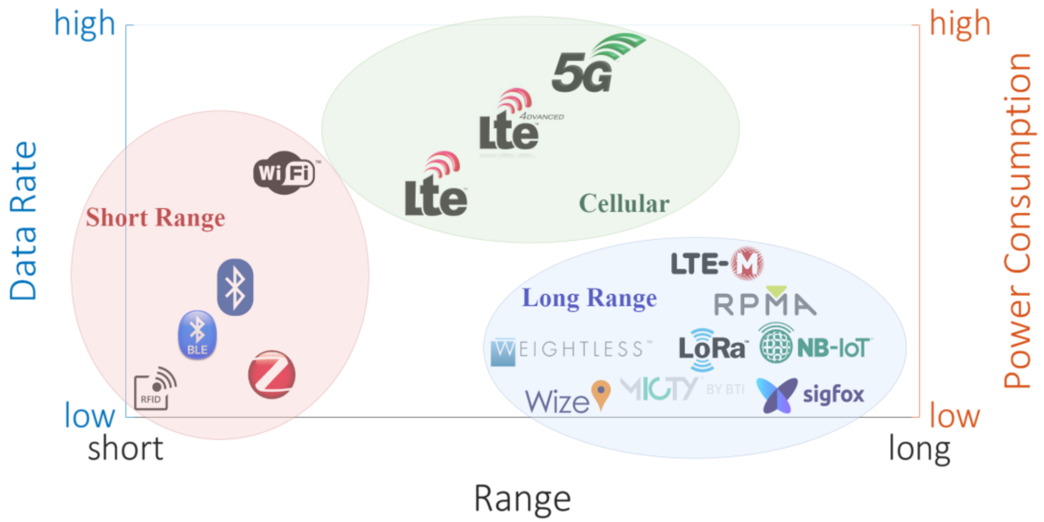
Apply stochastic modeling methodology to LoRaWAN channel access challenge
- “*Performance analysis of the on-the-air activation in LoRaWAN*”, J. Toussaint, N. El Rachkidy and A. Guitton, IEEE 7th Annual IEMCON, Vancouver, BC, 2016
  - Key points from LoRaWAN protocol
  - Analysis of access in LoRaWAN systems in terms of device activation procedure
    - Expected delay to activation
    - Expected energy consumed

IoT

A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies [1]

Proliferation

- Cisco predicts 500B devices by 2030 [2], Ericsson 25B by 2025 [3]

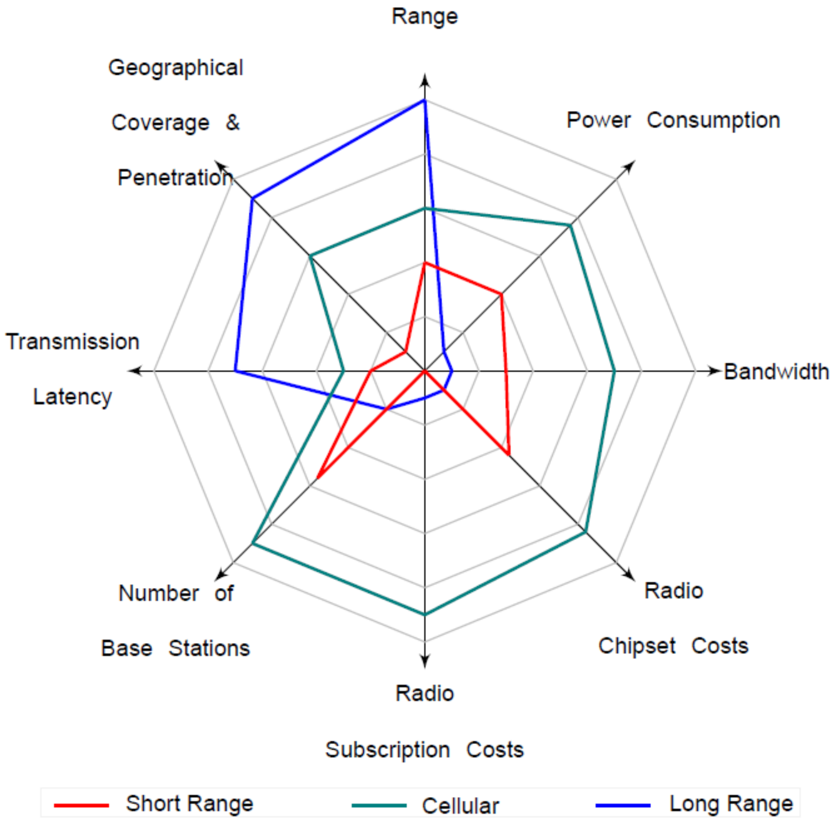


LPWAN

Networks that can cover very large areas by supporting large numbers of extremely low-cost, low-throughput devices with very low power consumption [4]

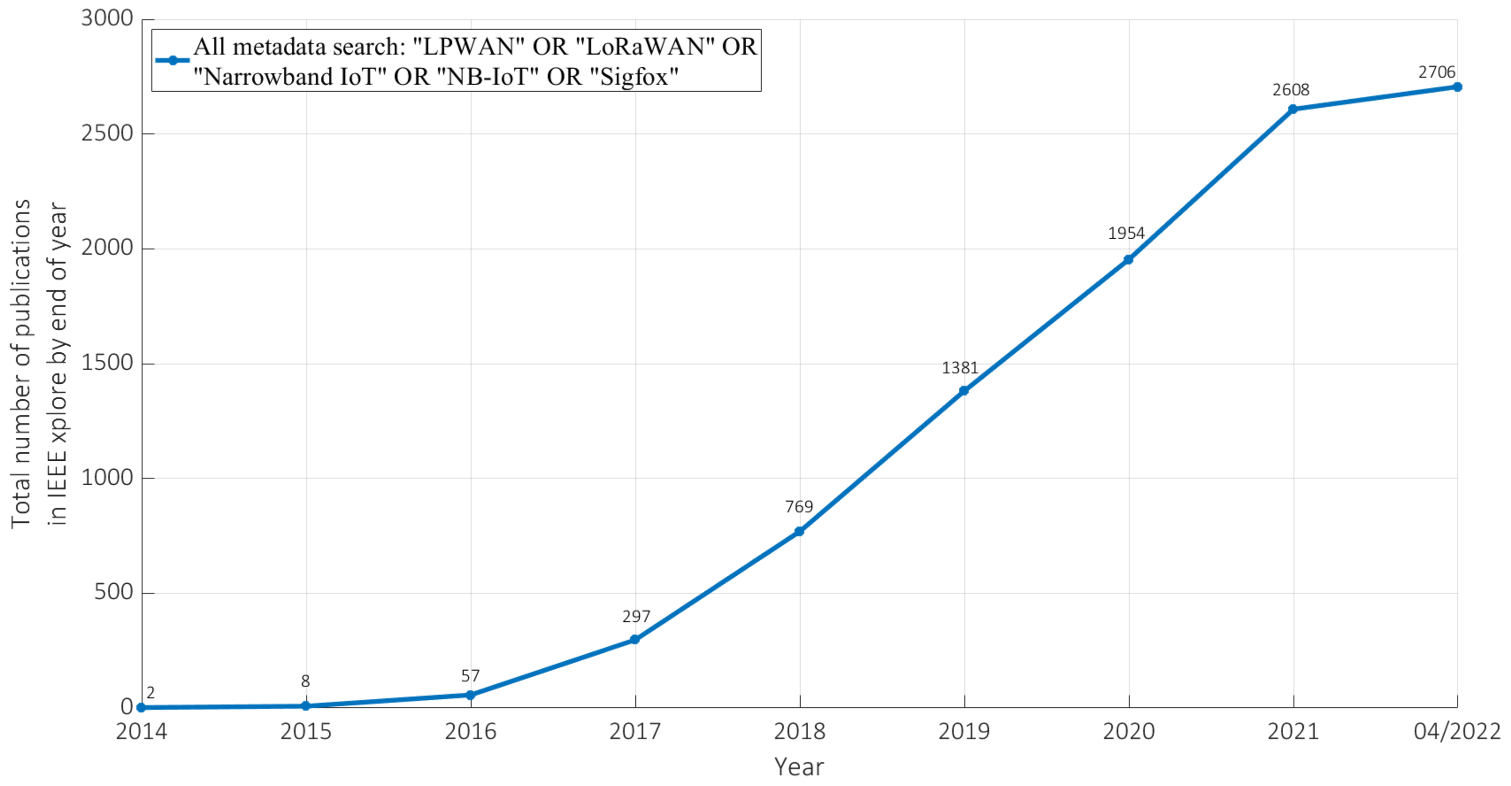
Main characteristics

- Low power
- Long range
- Low data rates
- CapEx, OpEx efficiency



[5] W. Guibene et al., "Survey on Clean Slate Cellular-IoT Standard Proposals," IEEE CIT, 2015

The growth of interest in LPWANs



Standardization

3GPP

NB-IoT

LTE-M

EC-GSM-IoT

non-3GPP

sigfox
Sigfox

WEIGHTLESS™
Weightless Alliance

RPMA
Ingenu Inc.

MIOTY BY BTI
ETSI (implementation)

LoRa™
Semtech Corporation

LoRaWAN®
LoRa Alliance

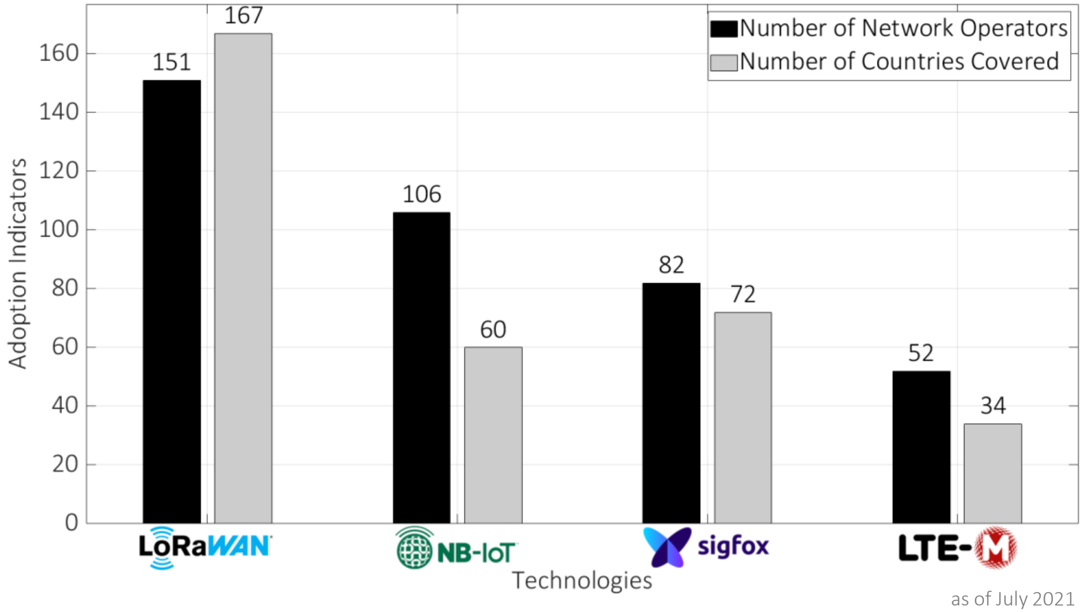
ITU (approval)

Wize
Wize Alliance

LPWANs: Which one?

A lot of technologies!

NB-IoT, LoRa, LTE-M, sigfox, WEIGHTLESS, Wize, EC-GSM-IoT, RPMA, MIOTY BY BTI

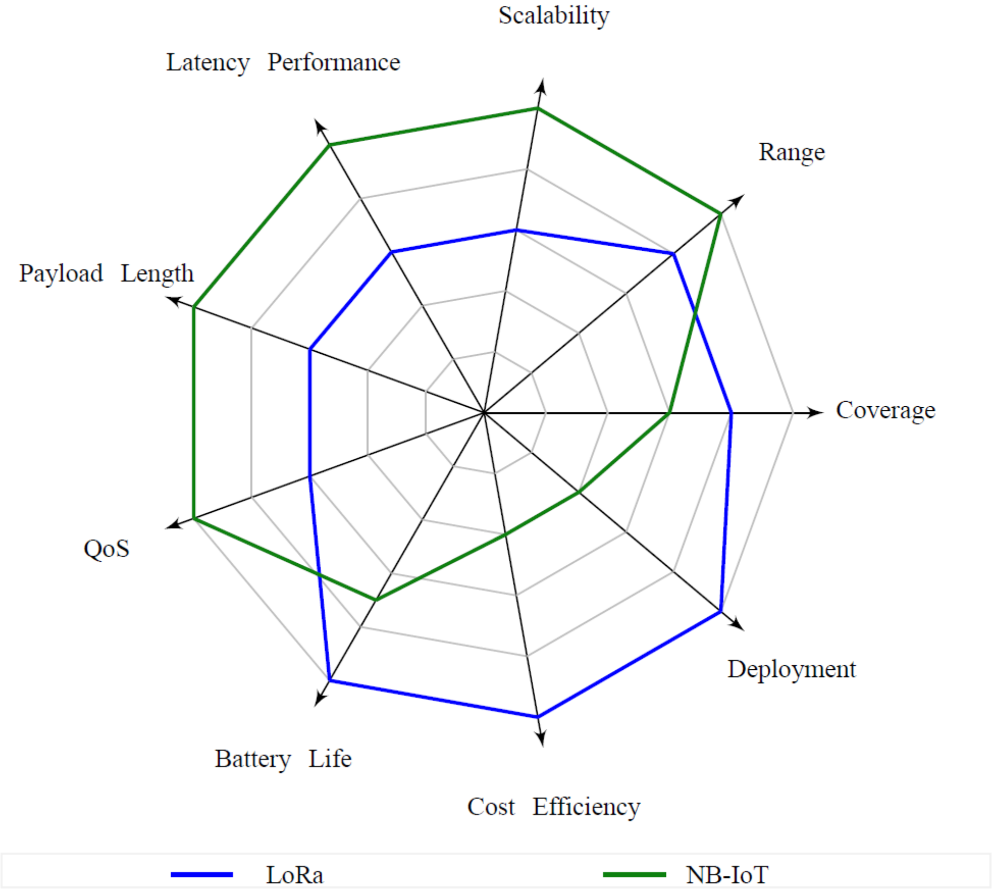


as of July 2021

There is no *one solution to rule them all*

However, there are promising technologies

LoRa and NB-IoT complementarity

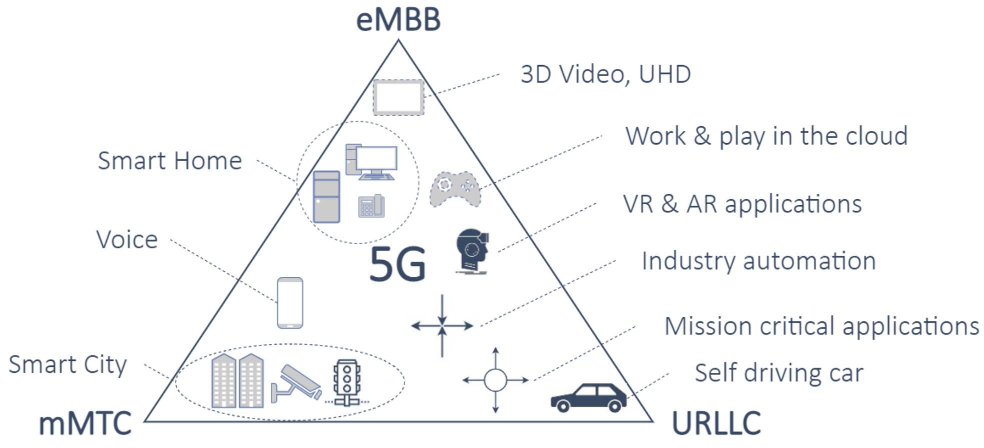


[6] R. S. Sinha et al., "A survey on LPWA technology: LoRa and NB-IoT," ICT Express, 2017
[7] K. Mekki et al., "A comparative study of LPWAN technologies for large-scale IoT deployment," ICT Express, 2019

LoRa in Networks beyond 2020 & 5G

The mMTC usage scenario [8]

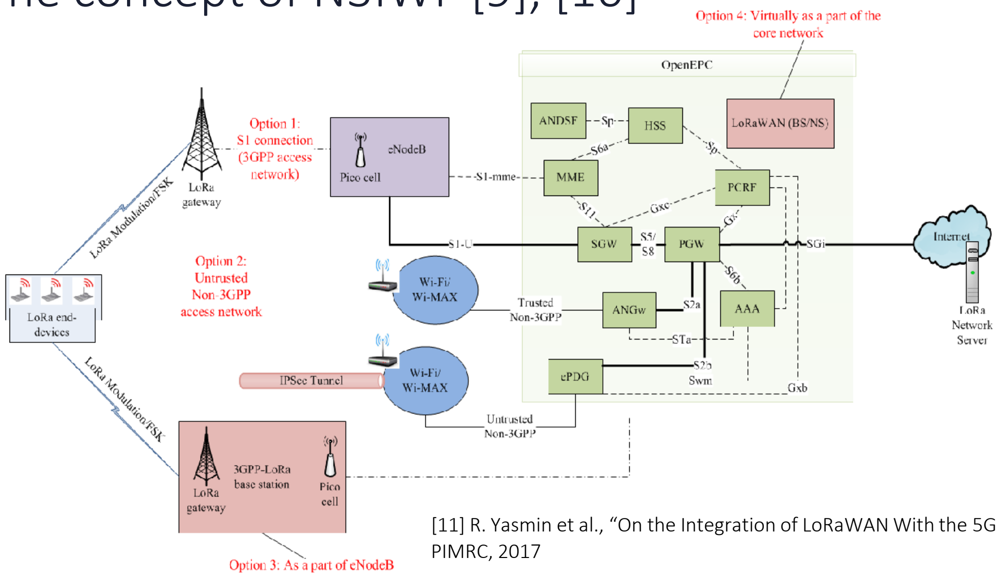
- Vertical markets as will be described
- Network slicing approach suits the concept



Deployment options considering the part of the network

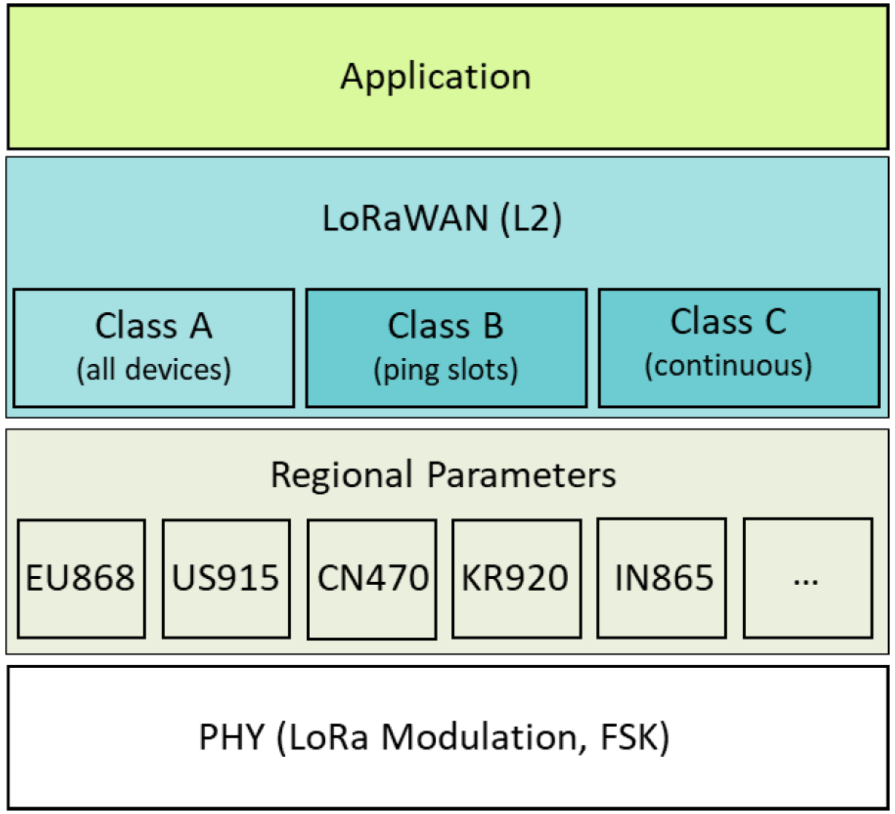
- multi-RAT paradigm
- LoRa in the RAN, 5G as backhaul link

The concept of N3IWF [9], [10]



[11] R. Yasmin et al., “On the Integration of LoRaWAN With the 5G Test Network,” IEEE PIMRC, 2017

LoRaWAN Protocol Stack



[12] LoRaWAN™ 1.0.4 Specification, LoRa Alliance, Technical Specification, 2020
[13] Low power protocol for wide area wireless networks, ITU-T, Recommendation Y.4480, 2021

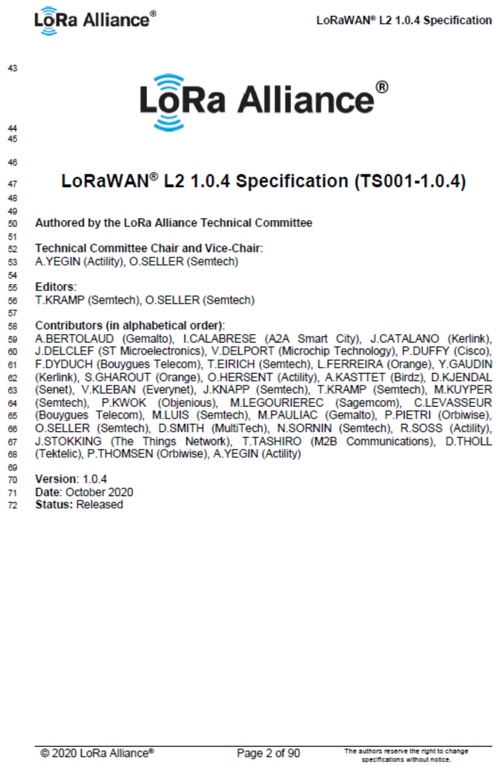
LoRa Alliance Open Specification

Fully open protocol
- https://resources.lora-alliance.org/technical-specifications/ts001-1-0-4-lorawan-l2-1-0-4-specification

A set of specifications that define device classes, activation procedures, over the air communication, backend interfaces, etc.

Two current versions
- 1.0.4 (latest, and last of 1.0.x family)
- 1.1
- eventually, they will converge

Thanks to openness, publicly available codebases
- e.g., https://github.com/search?q=lora



LoRa Alliance® LoRaWAN® L2 1.0.4 Specification

LoRa Alliance®

LoRaWAN® L2 1.0.4 Specification (TS001-1.0.4)

Authored by the LoRa Alliance Technical Committee

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Version: 1.0.4
Date: October 2020
Status: Released

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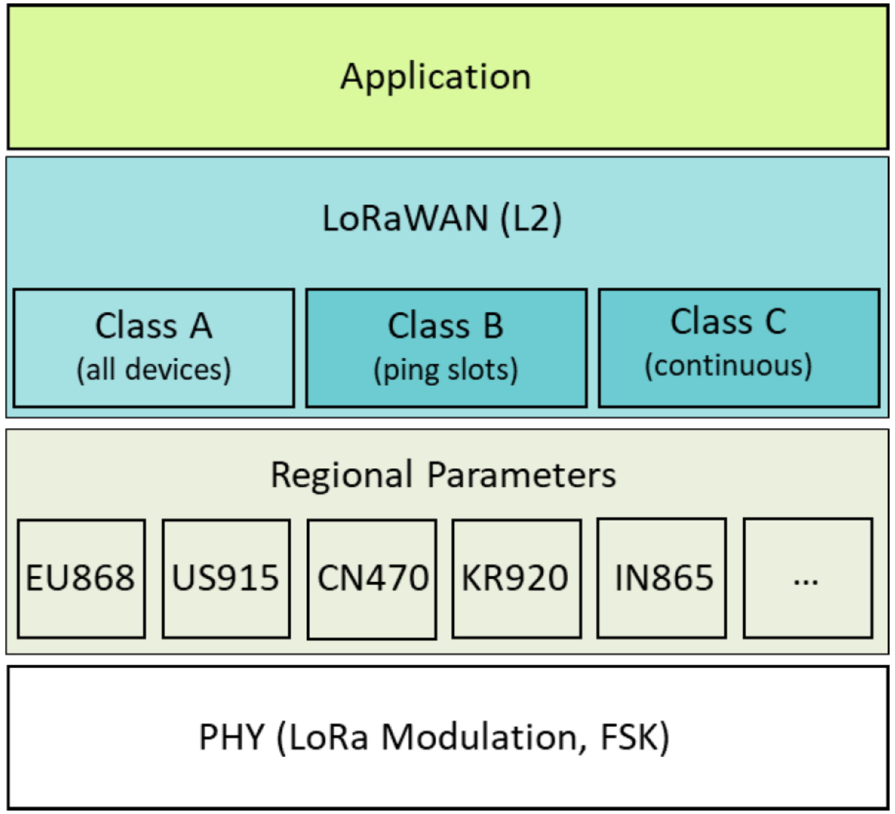
LoRaWAN Protocol Stack



[12] LoRaWAN™ 1.0.4 Specification, LoRa Alliance, Technical Specification, 2020
[13] Low power protocol for wide area wireless networks, ITU-T, Recommendation Y.4480, 2021

ITU-T Recommendation

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GLOBAL INFORMATION INFRASTRUCTURE, INTERNET PROTOCOL ASPECTS, NEXT-GENERATION NETWORKS, INTERNET OF THINGS AND SMART CITIES

GLOBAL INFORMATION INFRASTRUCTURE	
General	Y.100–Y.199
Services, applications and middleware	Y.200–Y.299
Network aspects	Y.300–Y.399
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Security	Y.700–Y.799
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Definitions and terminologies	Y.4050–Y.4099
Requirements and use cases	Y.4100–Y.4249
Infrastructure, connectivity and networks	Y.4250–Y.4399
Frameworks, architectures and protocols	Y.4400–Y.4549
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Identification and security	Y.4800–Y.4899
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International Telecommunication Union

ITU-T **Y.4480**

TELECOMMUNICATION STANDARDIZATION SECTOR OF ITU

(11/2021)

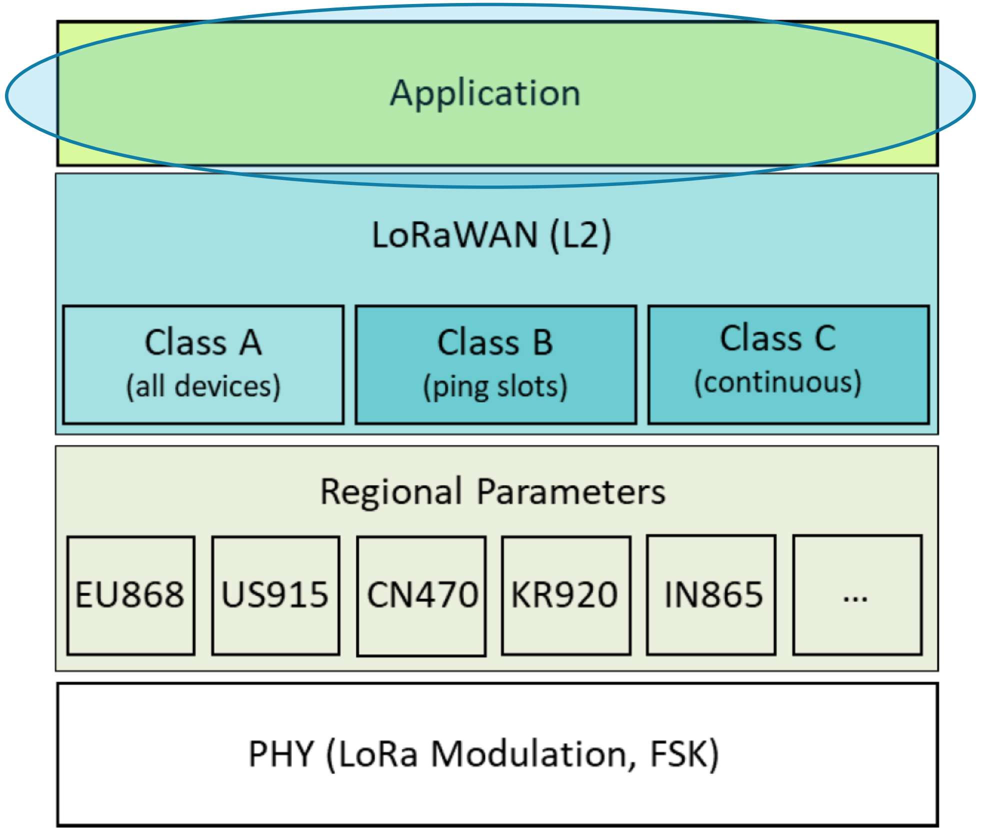
SERIES Y: GLOBAL INFORMATION INFRASTRUCTURE, INTERNET PROTOCOL ASPECTS, NEXT-GENERATION NETWORKS, INTERNET OF THINGS AND SMART CITIES

Internet of things and smart cities and communities – Frameworks, architectures and protocols

Low power protocol for wide area wireless networks

Recommendation ITU-T Y.4480

LoRaWAN Protocol Stack



Applications

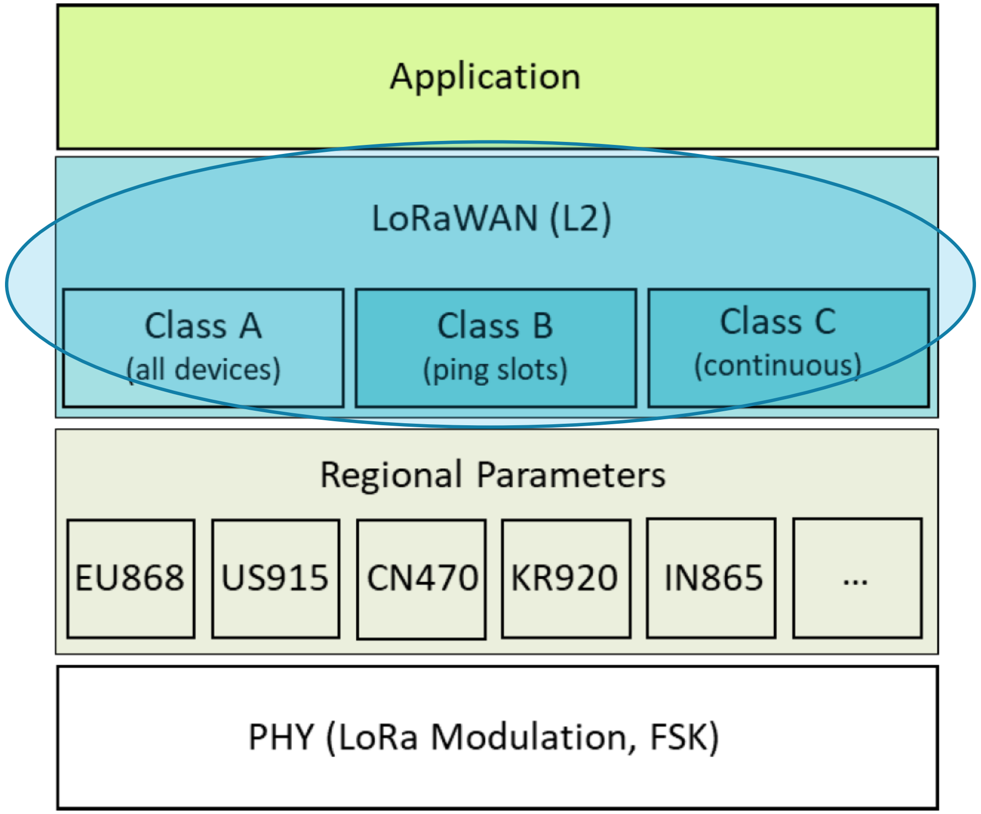
Semtech Corporation (LoRa)

- Critical V Mass-scale
- Industrial, Enterprise, Consumer applications

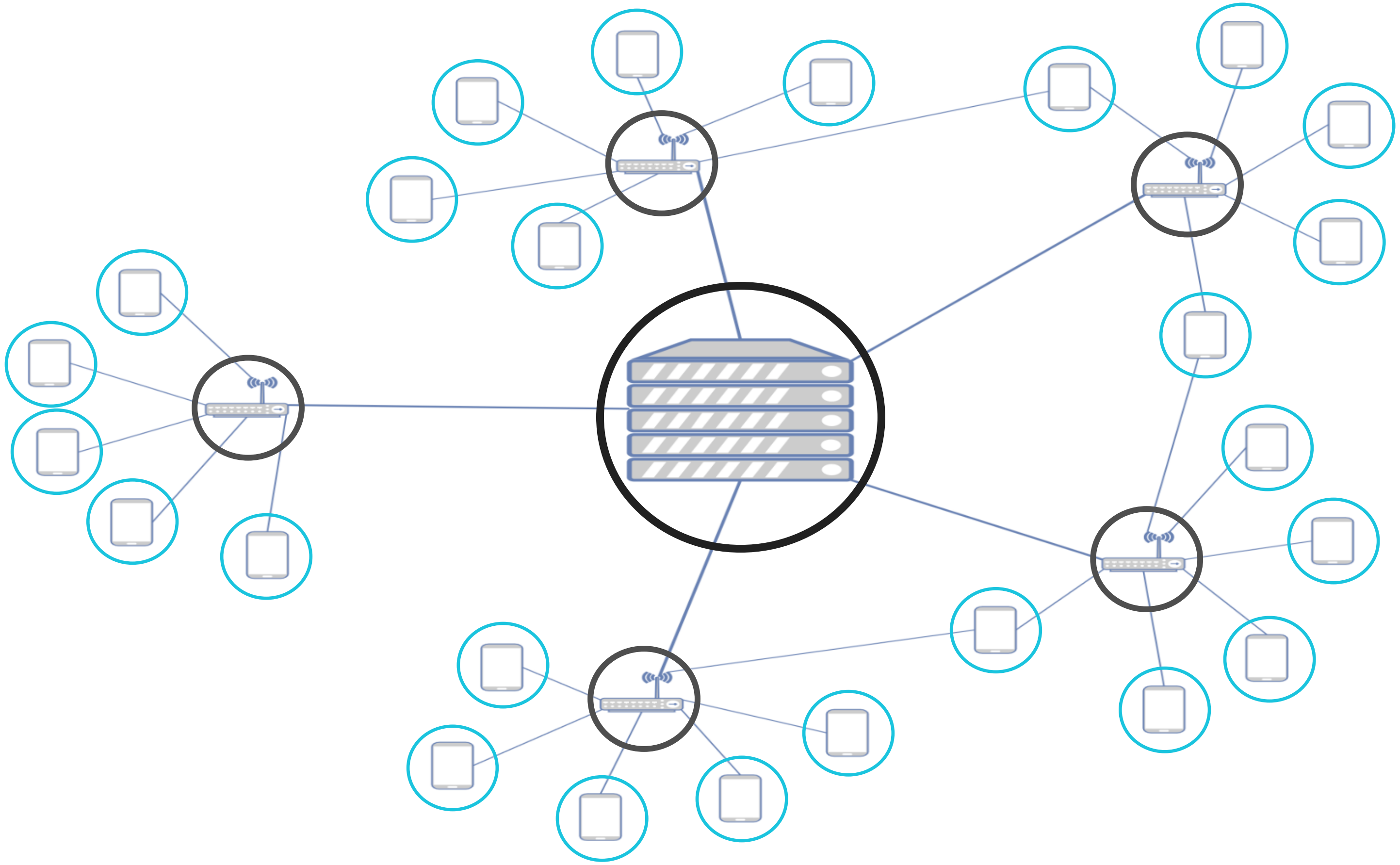
LoRa Alliance (LoRaWAN)

- The “smart” paradigm
  - Smart agriculture
  - Smart buildings
  - Smart cities
  - Smart industry
  - Smart logistics
  - Smart utilities

LoRaWAN Protocol Stack

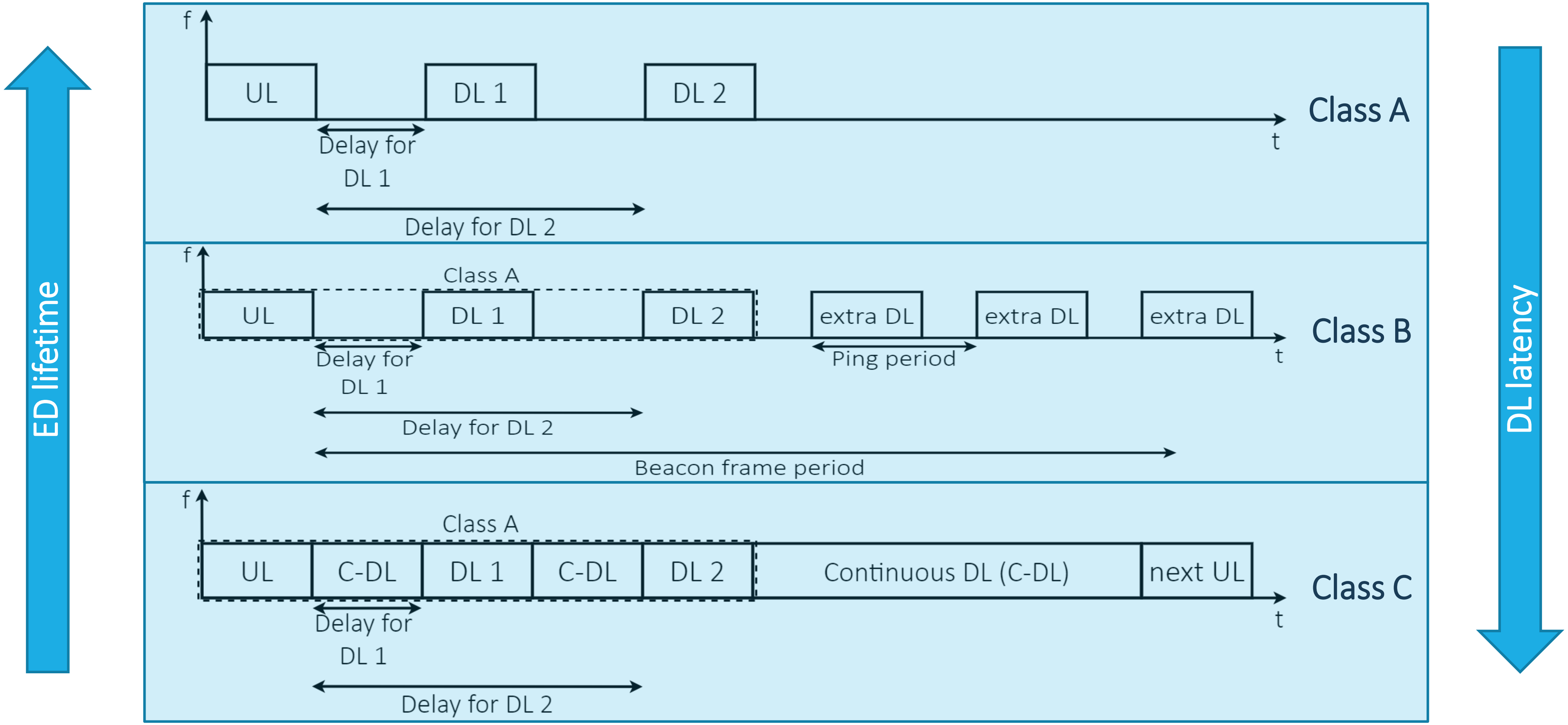


LoRaWAN: star-of-stars topology

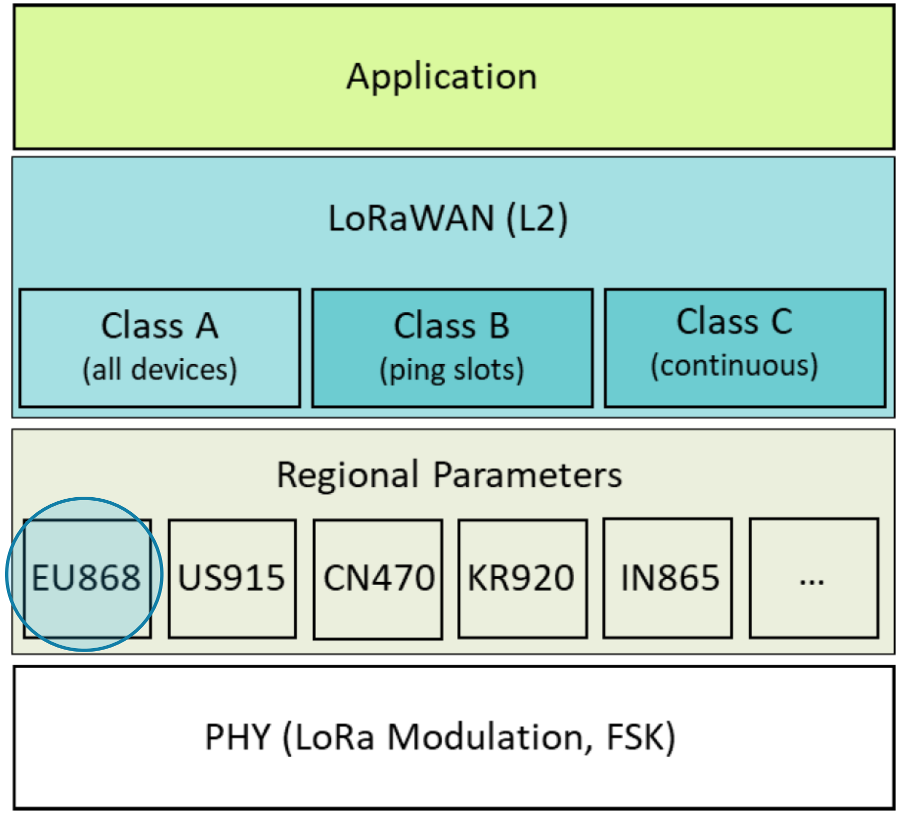


End Device (ED)
Gateway (GW)
Network Server (NS)

LoRaWAN device classes



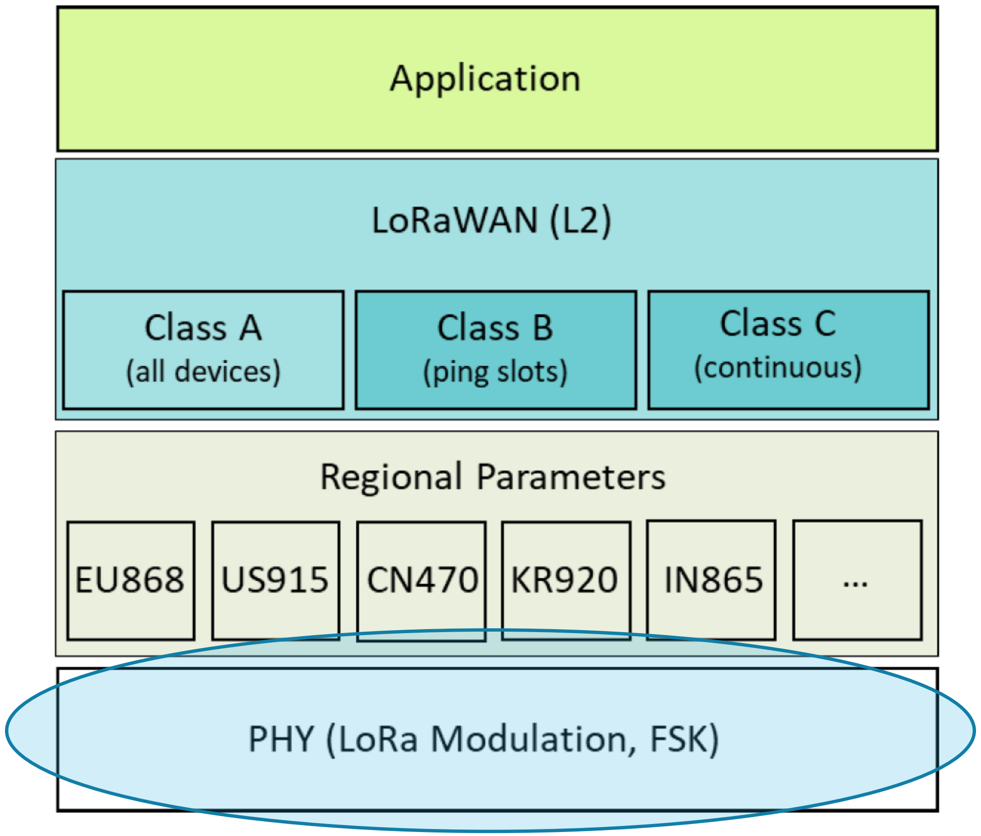
LoRaWAN Protocol Stack



Transmission Channels (MHz) – UL *	
1. *868.1*: SF7BW125 μέχρι SF12BW125	Mandatory
2. *868.3*: SF7BW125 μέχρι SF12BW125 και SF7BW250	Mandatory
3. *868.5*: SF7BW125 μέχρι SF12BW125	Mandatory
4. *867.1*: SF7BW125 μέχρι SF12BW125	TTN extra
5. *867.3*: SF7BW125 μέχρι SF12BW125	TTN extra
6. *867.5*: SF7BW125 μέχρι SF12BW125	TTN extra
7. *867.7*: SF7BW125 μέχρι SF12BW125	TTN extra
8. *867.9*: SF7BW125 μέχρι SF12BW125	TTN extra
9. *868.8*: FSK	TTN extra

* For DL, channels are the same, plus a high power channel of 0.5W at *869.525MHz* with SF9BW125

LoRaWAN Protocol Stack



LoRa Basics

LoRa: an implementation of Chirp Spread Spectrum (CSS)

CSS: an implementation of Spread Spectrum (SS)

Spreading Factor (SF): # of times the signal has been spread

chip: the way to encode information in spread spectrum systems

$SF \rightarrow$ chip sequence: # of bits used for a symbol
- in CSS context: symbol == chirp
- # of ways to encode information: 2^{SF}

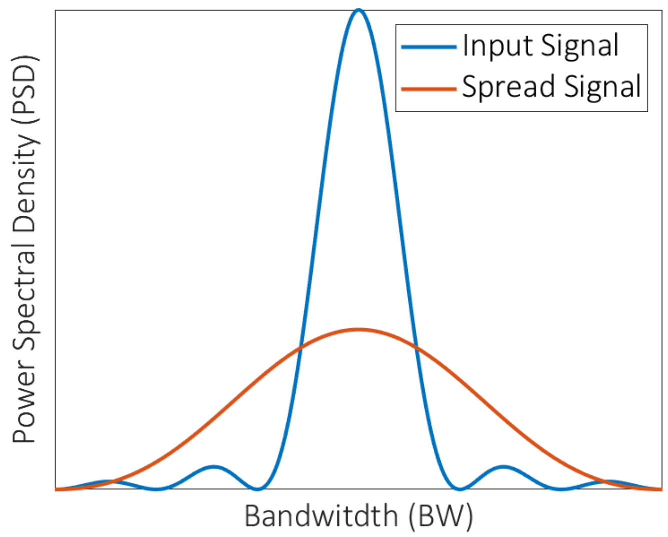
Symbol rate: $R_s = \frac{R_c}{2^{SF}}$, where R_c is the chip rate ($R_c = BW$)

Duration T_s: the reciprocal of rate, $T_s = \frac{2^{SF}}{R_c}$

Bit Rate: $R_b = \frac{SF}{T_s}$

FEC is implemented in LoRa: Rate Code = $\frac{4}{4+CR}$, CR = $\{1, 2, 3, 4\}$

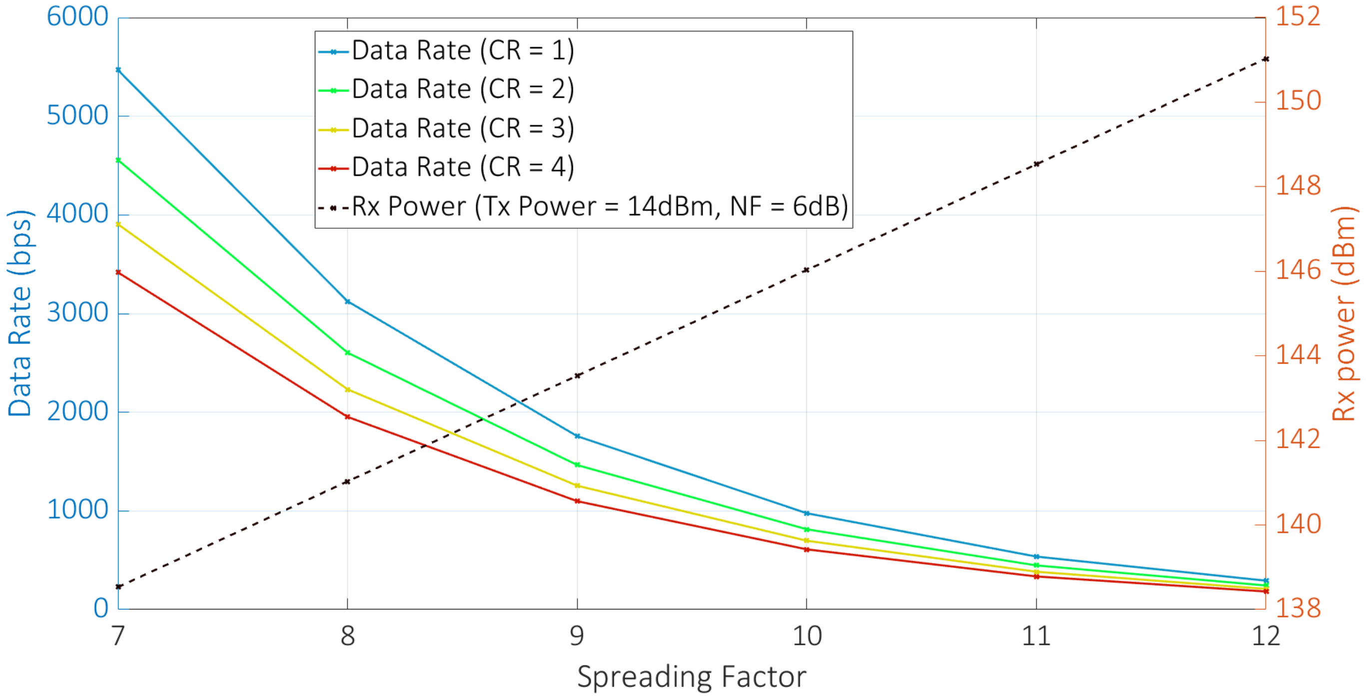
Bit Rate: $R_b = SF * \frac{4}{4+CR} * \frac{BW}{2^{SF}}$



The Data Rate V Range trade off

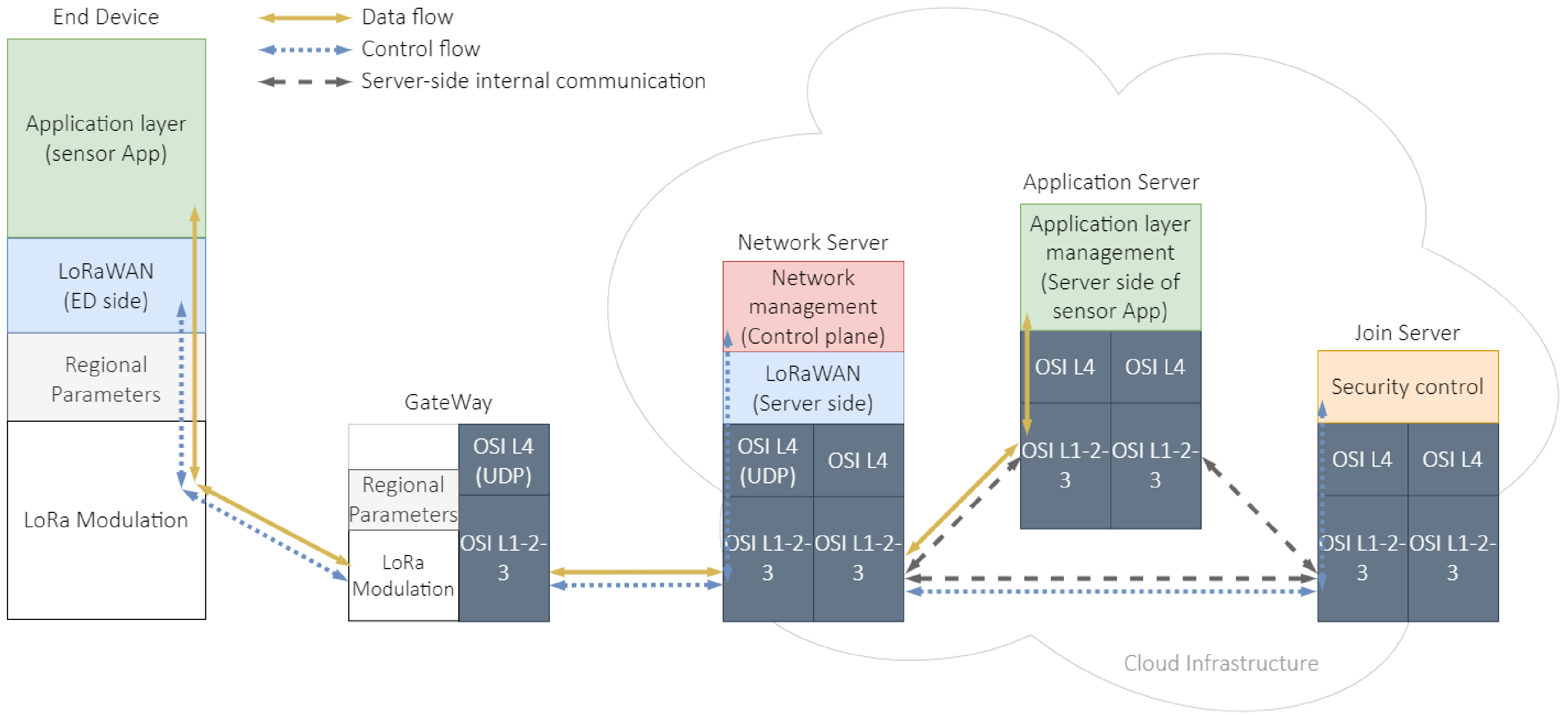
Data Rate: $R_b = SF * \frac{4}{4+CR} * \frac{BW}{2^{SF}}$

Receiver Sensitivity: $S_{(dBm)} = -174 + 10\log_{10}(BW_{(Hz)}) + NF_{(dB)} + SNR_{(dB)}$



SF	SNR (dB)
SF7	-7.5
SF8	-10
SF9	-12.5
SF10	-15
SF11	-17.5
SF12	-20

Protocol stack inside architecture's nodes



Research work: challenges

Robust PHY, e.g., [14]

ED activation, e.g., [15]

Transmission's parameters configuration (ADR algorithm): TP, CF, SF, BW, CR ("nuts and bolts"), e.g., [16], [34]

Node (ED, GW) placement, e.g., [17]

Multiple access and transmission scheme, e.g., [18], [19], [20], [21], [28]

Mobility and roaming support, e.g., [22]

ED's energy efficiency, e.g., [23], [32], [34], [35]

Information management, e.g., [24]

End-to-end cross-layer security, e.g., [25], [26], [39]

Combinations

- parameters configuration + node placement = **spatial coverage, range, path loss models**, e.g., [27], [36], [37]
- collective study of EDs' power consumption = **system lifetime**, e.g., [28]
- robust PHY + parameters configuration + multiple access = **successful reception, scalability**, e.g., [20], [21], [33], [34], [35], [36], [38]
- advanced information management = **utilization of ML algorithms**, e.g., [29]
- advanced parameters configuration = **resource allocation, network slicing, SDN**, e.g., [30]
- distributed security = **applicability of blockchain protocols**, e.g., [31]

Research work: methodology

Analytical studies

- **Fast Fourier Transform**, e.g., [14]
- **Markov Chain**, e.g., [15]
- **Type – A, – B uncertainty**, e.g., [20]
- **Kruskal-Wallis testing**, e.g., [22]
- **Security Analysis**, e.g., [25], [26], [39]
- **Federated Learning**, e.g., [29]
- **Game Theory**, e.g., [30]
- **Markov Decision Process**, e.g., [32]
- **Stochastic Geometry**, e.g., [33]

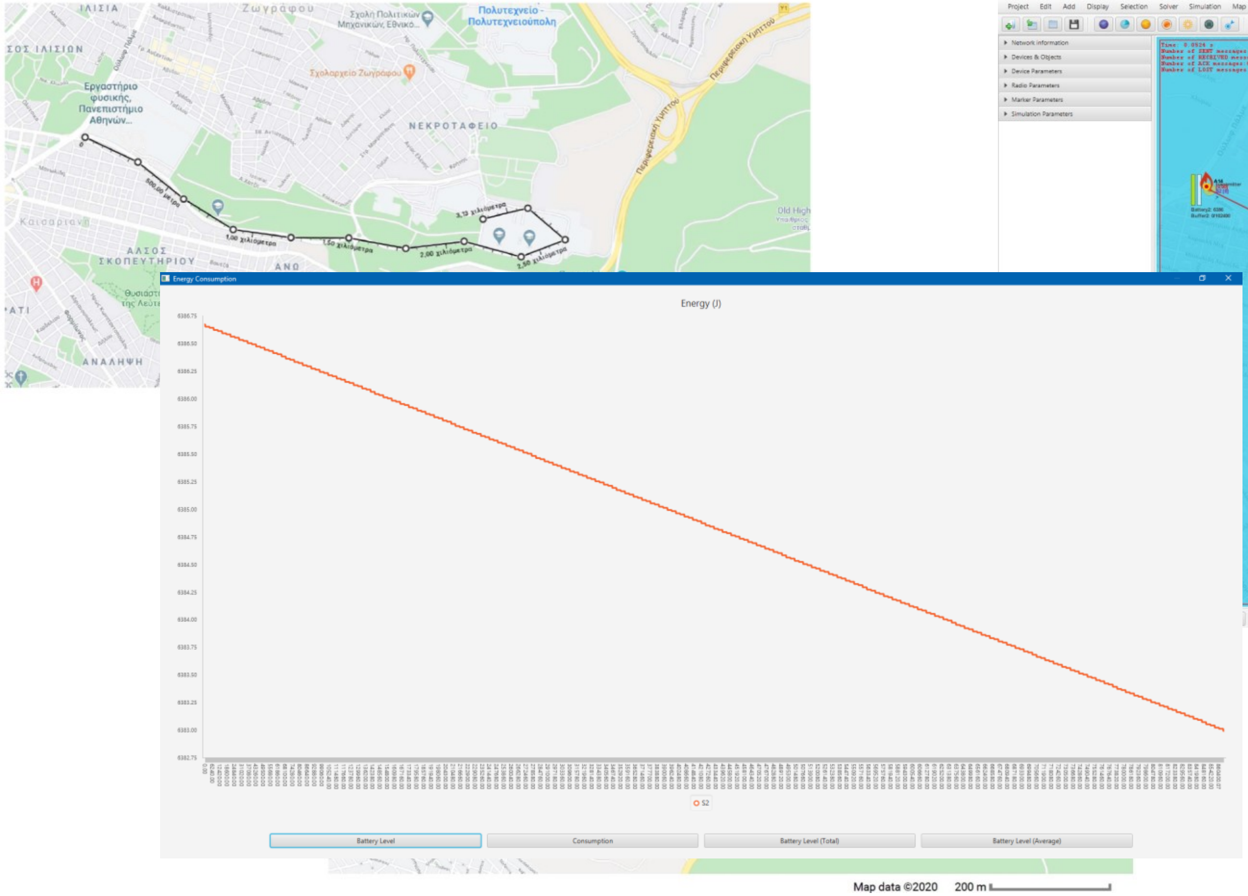
Simulation studies

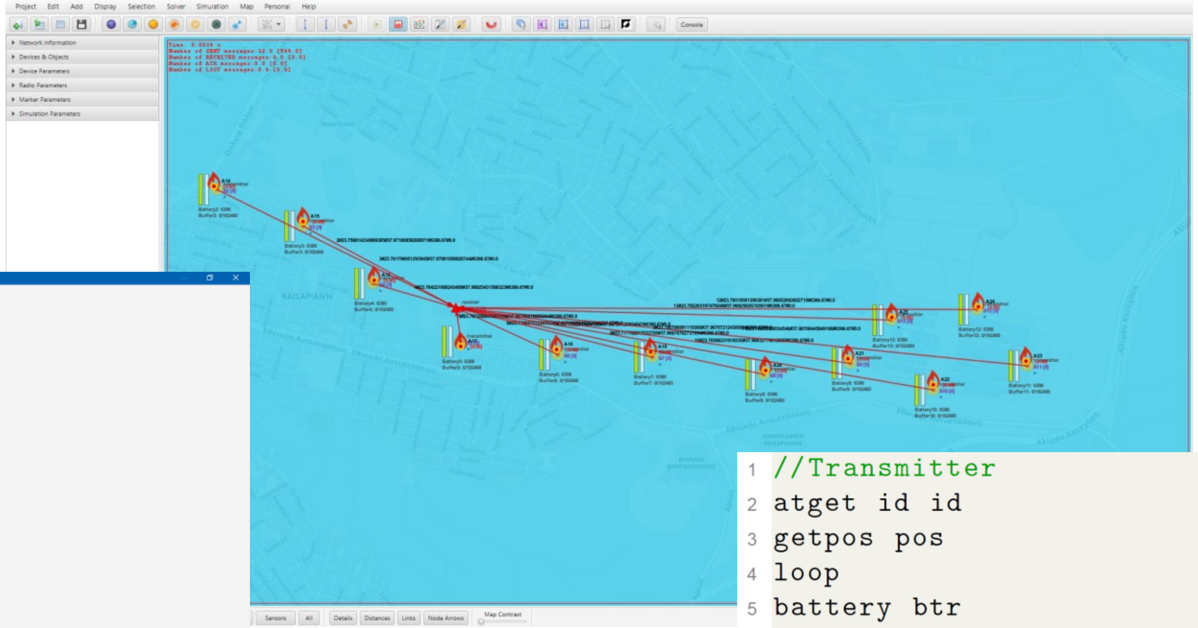
- Network-specific
  - **ns-3**, e.g., [17], [28], [30]
  - **OMNeT++**, e.g., [34]
- WSN-specific
  - **Cooja**
  - **TOSSIM**
  - **CupCarbon**
- LoRa/LoRaWAN-specific
  - **MATLAB**, e.g., [18], [19], [23]
  - **Scilab**, e.g., [15]
  - **Python (SimPy)**
    - **LoRaSim** and its successors, e.g., [16], [20]
    - **LoRa-FREE**, e.g., [21]
    - **LoRa-MAB**, e.g., [35]
  - **Java**
    - **LoRaSim**, e.g., [36]
- Domain-specific
  - ML, e.g., **Tensorflow** [29]
  - Blockchain, e.g., **Ethereum client** [31]

Real Deployments

- **Environment of ED and GW (Outdoor/Indoor) – Mobility (none/low/high/medium) – Number of EDs (low/high/medium)**
  - Indoor-to-Indoor (I2I) – fixed position – 1 GW covering 15 EDs, e.g., [28]
  - O2O Suburban – high mobility – low number of EDs, I2I – fixed position – medium number of EDs, etc., e.g., [18], [19], [20], [24], [27]
- **Advanced scenarios**
  - **water-to-land**, e.g., [27]
  - **underground-to-land**, e.g., [37]
  - **satellite-to-land**, e.g., [38]

CupCarbon simulations






```
//Transmitter
atget id id
getpos pos
loop
battery btr
areadsensor sensorValue
rdata $sensorValue a b temp
data p $id $pos $btr $temp
send $p 1
delay 3600000
```

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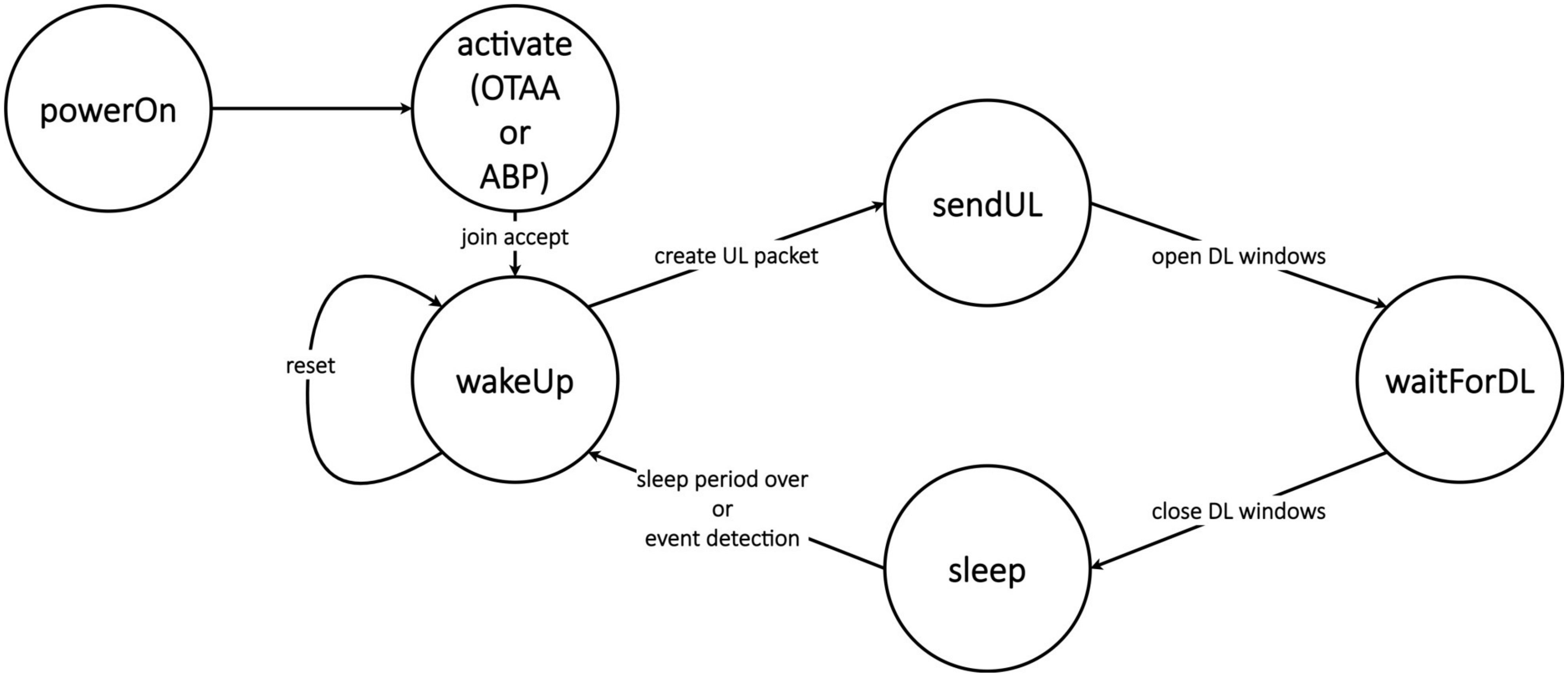
The implemented testbed

The Things Node:
- RN2483 LoRa module
- MEGA32u4 processor
- printed antenna
- MMA8652FC accelerometer
- MCP9804 temperature sensor
- NOA1212 light sensor
- button for event triggering
- LED
- 3 AAA batteries

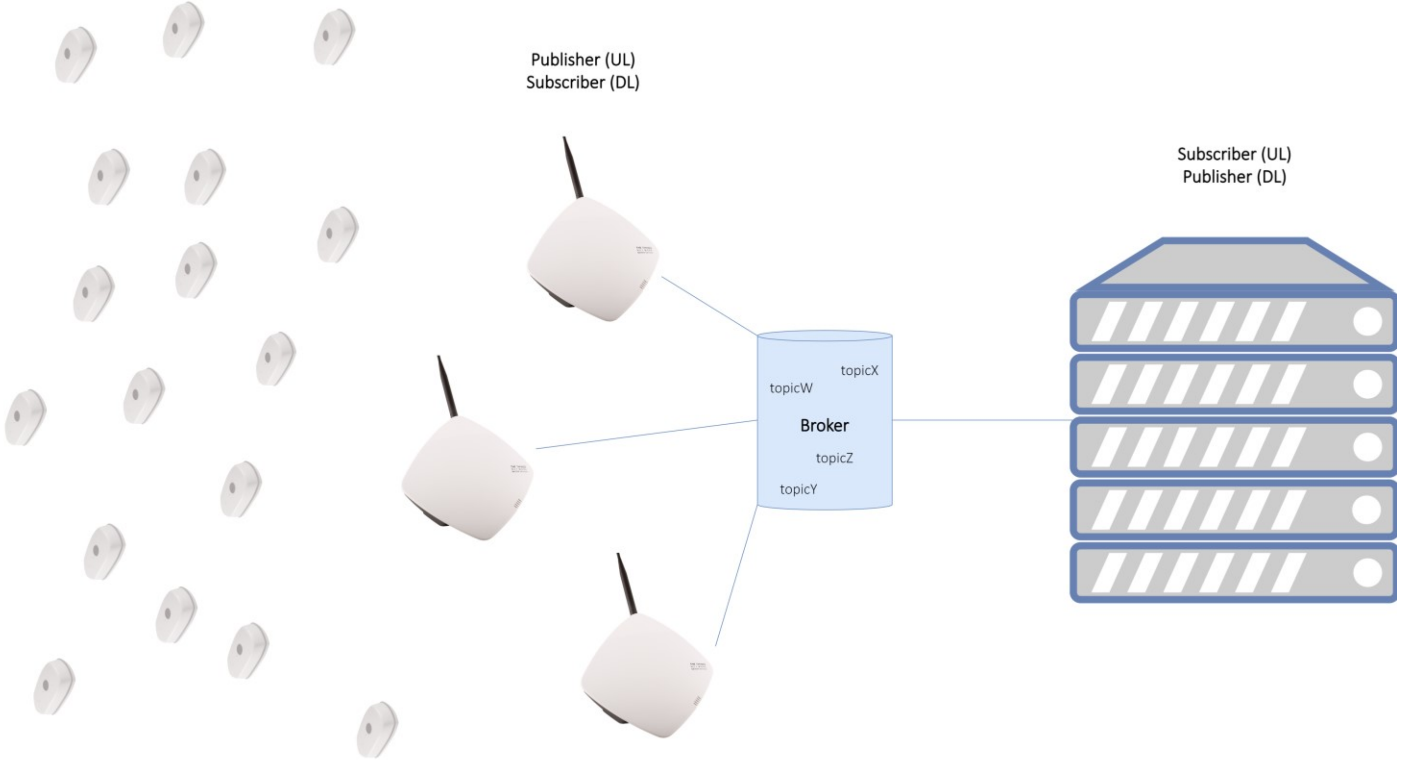
The Things Uno
- RN2483 LoRa module
- MEGA32u4 processor
- printed antenna
- LED

State Transition Diagram



Based on "TheThingsNetwork.h", "TheThingsNode.h" Arduino libraries stored in EDs

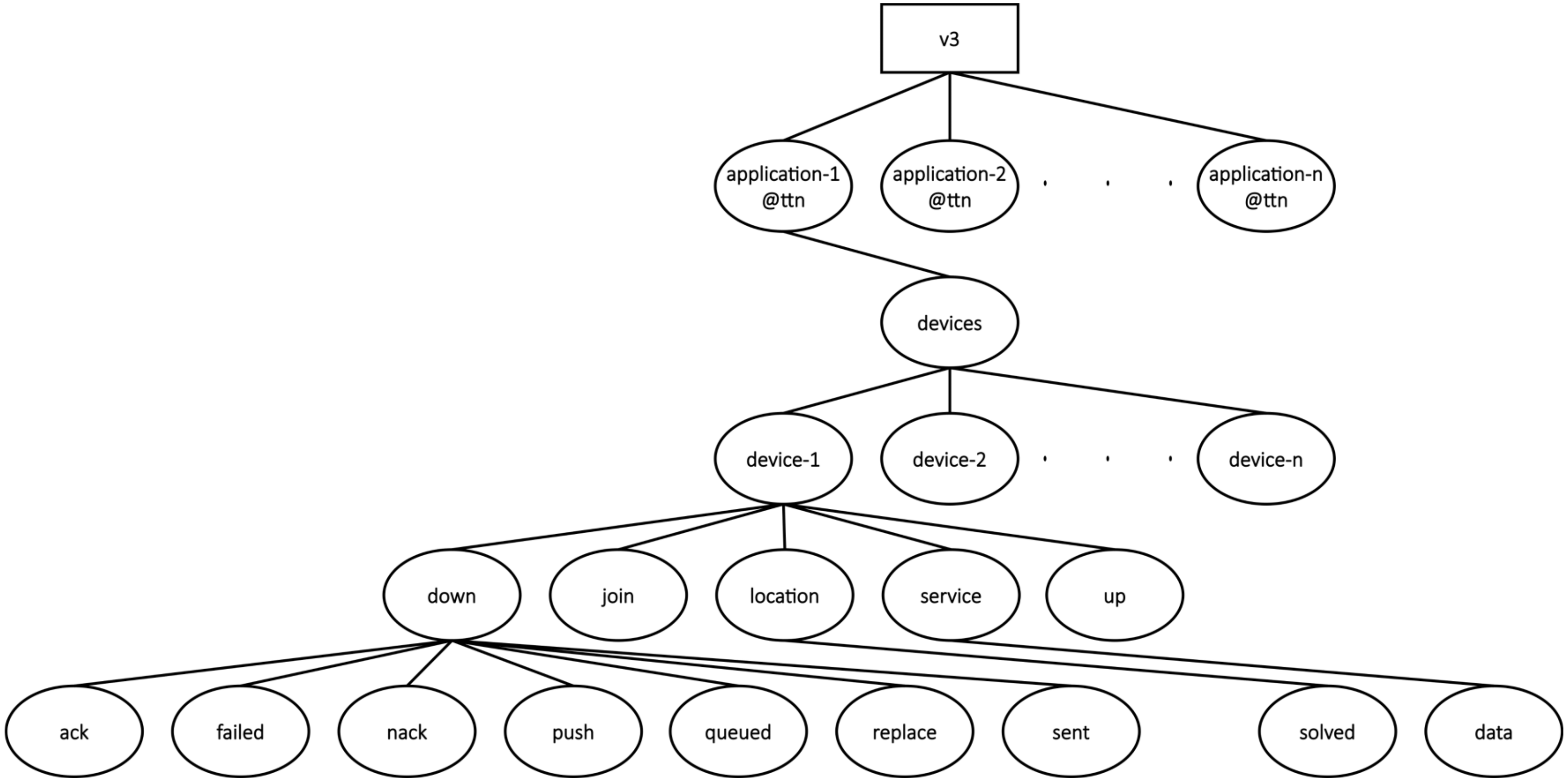
Sending UL/DL message



mosquitto_pub -h <HOST> -p <PORT> -u <USERNAME> -P <PASSWORD> -t <TOPIC>

mosquitto_sub -h <HOST> -p <PORT> -u <USERNAME> -P <PASSWORD> -t <TOPIC>

MQTT Tree


v3
application-1 @ttn
application-2 @ttn
application-n @ttn
devices
device-1
device-2
device-n
down
join
location
service
up
ack
failed
nack
push
queued
replace
sent
solved
data

Wireshark capture

TTN NS

MQTT topic

MQTT QoS class

message decoding

```
No. Time Source Destination Protocol Length Info
46 5.530079403 52.169.76.255 192.168.1.11 MQTT 633 Publish Message
[testing_application_2/devices/testing_node/up]
Frame 46: 633 bytes on wire (5064 bits), 633 bytes captured (5064 bits) on
    interface any, id 0
Linux cooked capture
Internet Protocol Version 4, Src: 52.169.76.255, Dst: 192.168.1.11
Transmission Control Protocol, Src Port: 1883, Dst Port: 35874, Seq: 5, Ack
    : 1, Len: 565
[3 Reassembled TCP Segments (568 bytes): #42(1), #44(2), #46(565)]
MQ Telemetry Transport Protocol, Publish Message
  Header Flags: 0x30, Message Type: Publish Message, QoS Level: At most
    once delivery (Fire and Forget)
  Msg Len: 565
  Topic Length: 45
  Topic: testing_application_2/devices/testing_node/up
  Message: 7b226170705f6964223a22746573746696e675f6170706c69...
```

{"app_id": "testing_appli...

Management Platforms

TagoIO

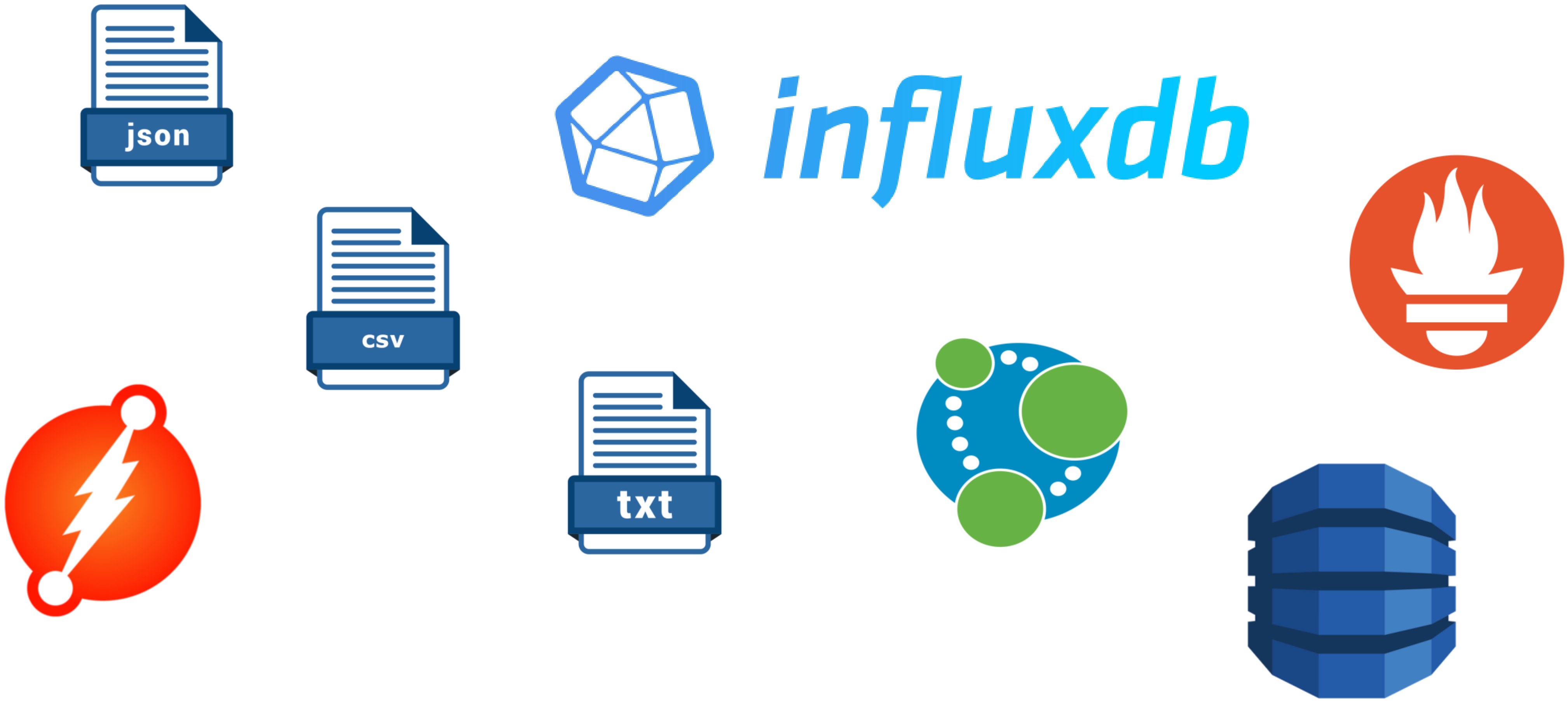
THE THINGS NETWORK

Microsoft Azure IOT

aws

ThingSpeak

Storing the data



Visualization

TagoIO

Grafana

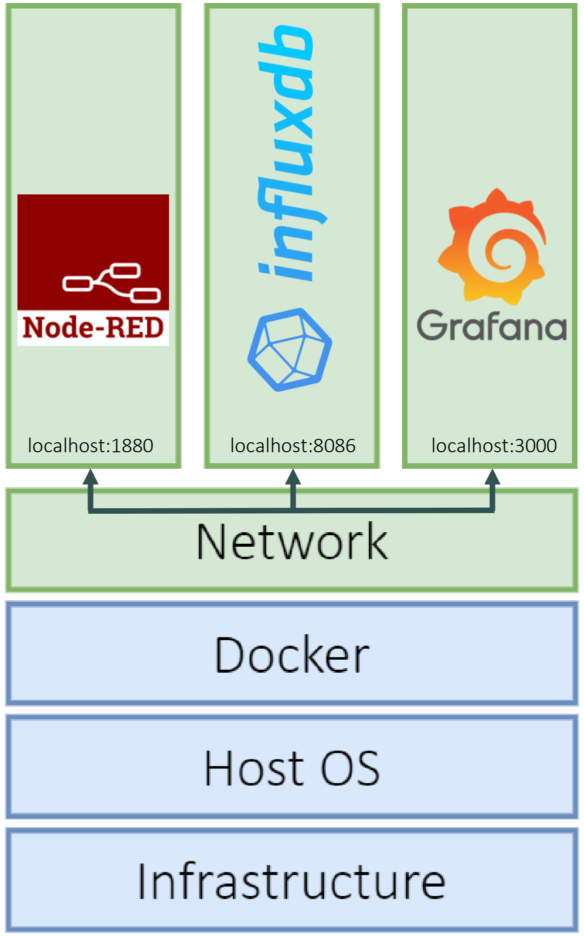
aws

matplotlib
(locally)

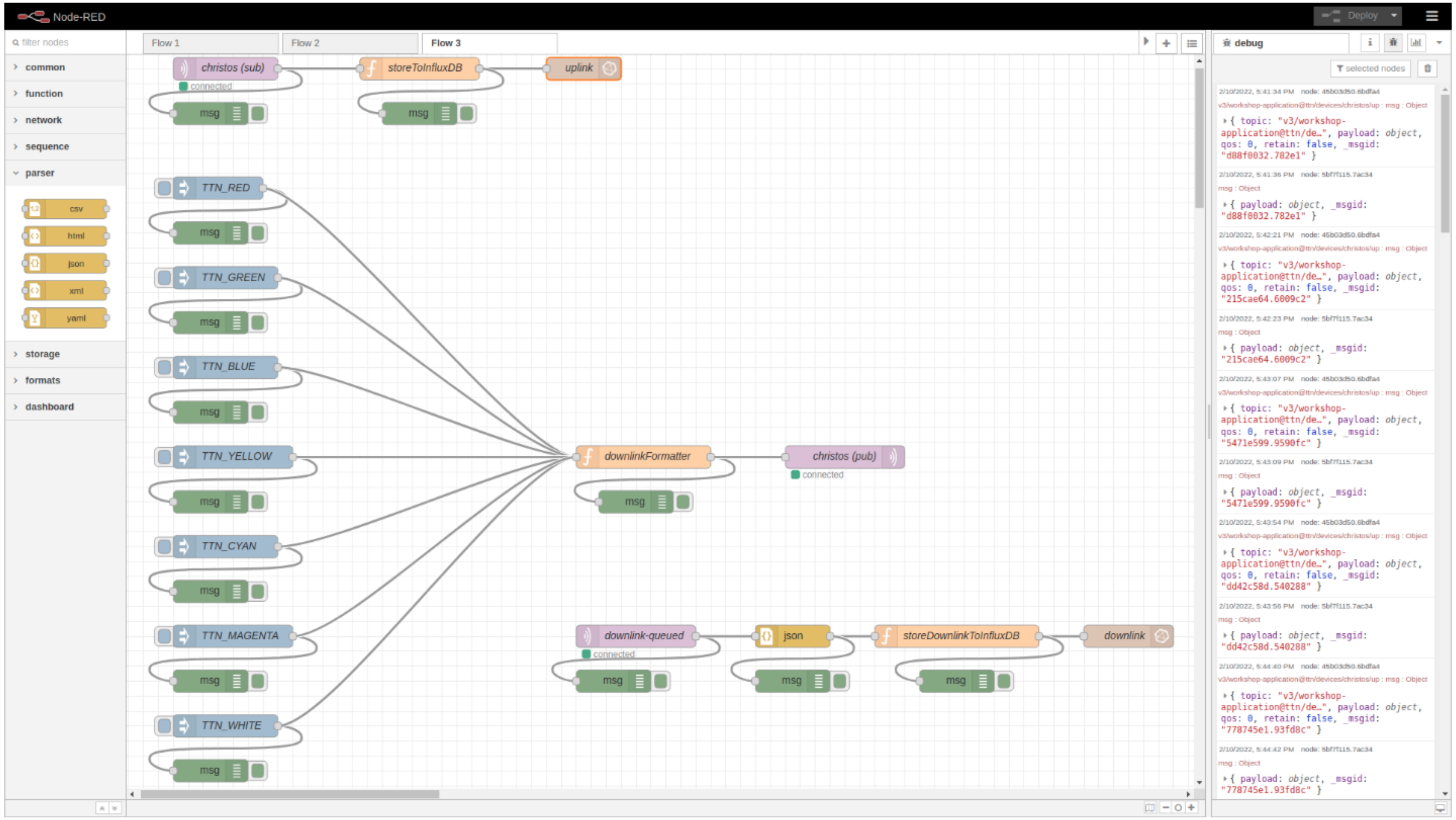
ThingSpeak

(locally)

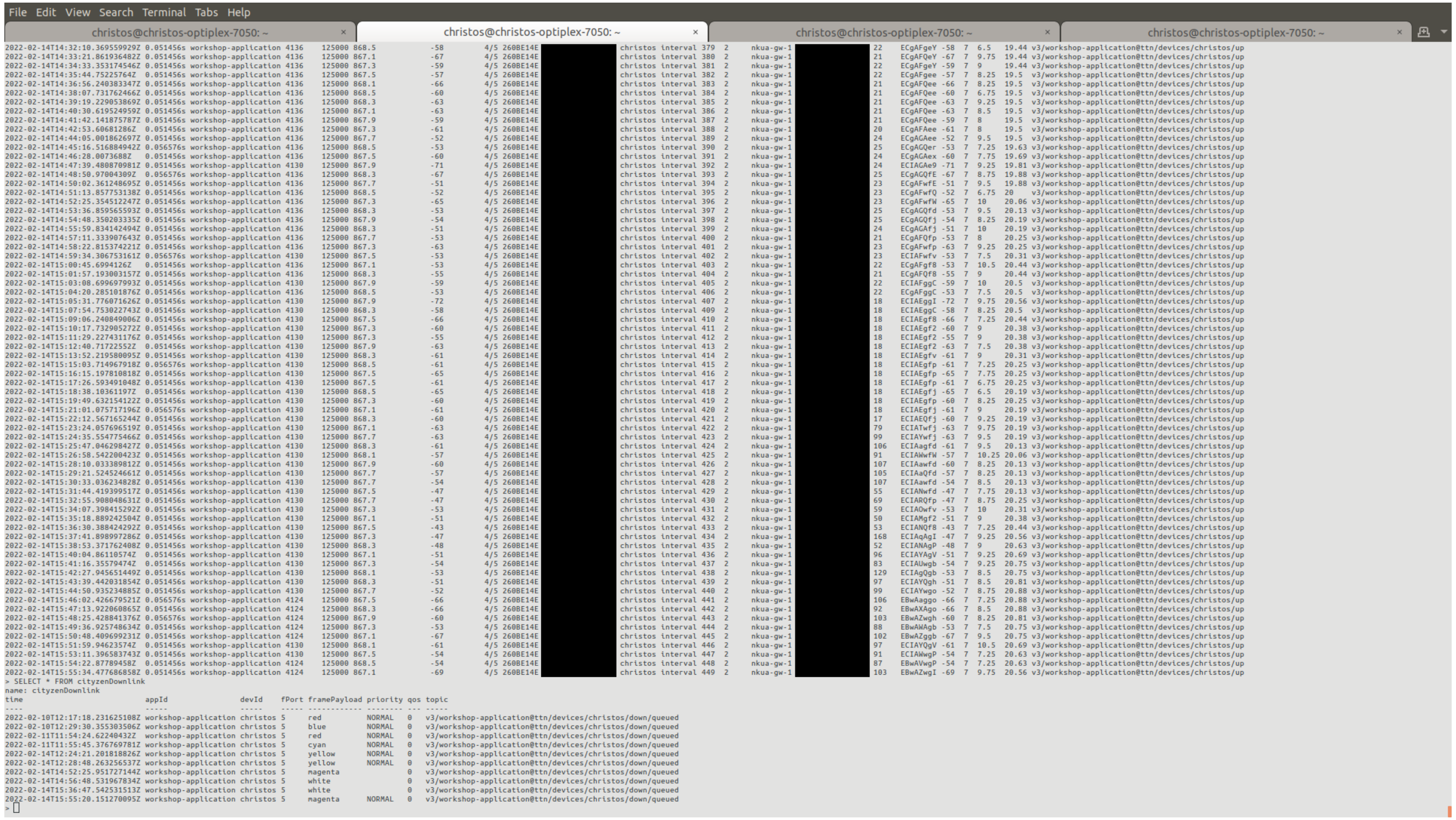
Docker setup as Proof-of-Concept



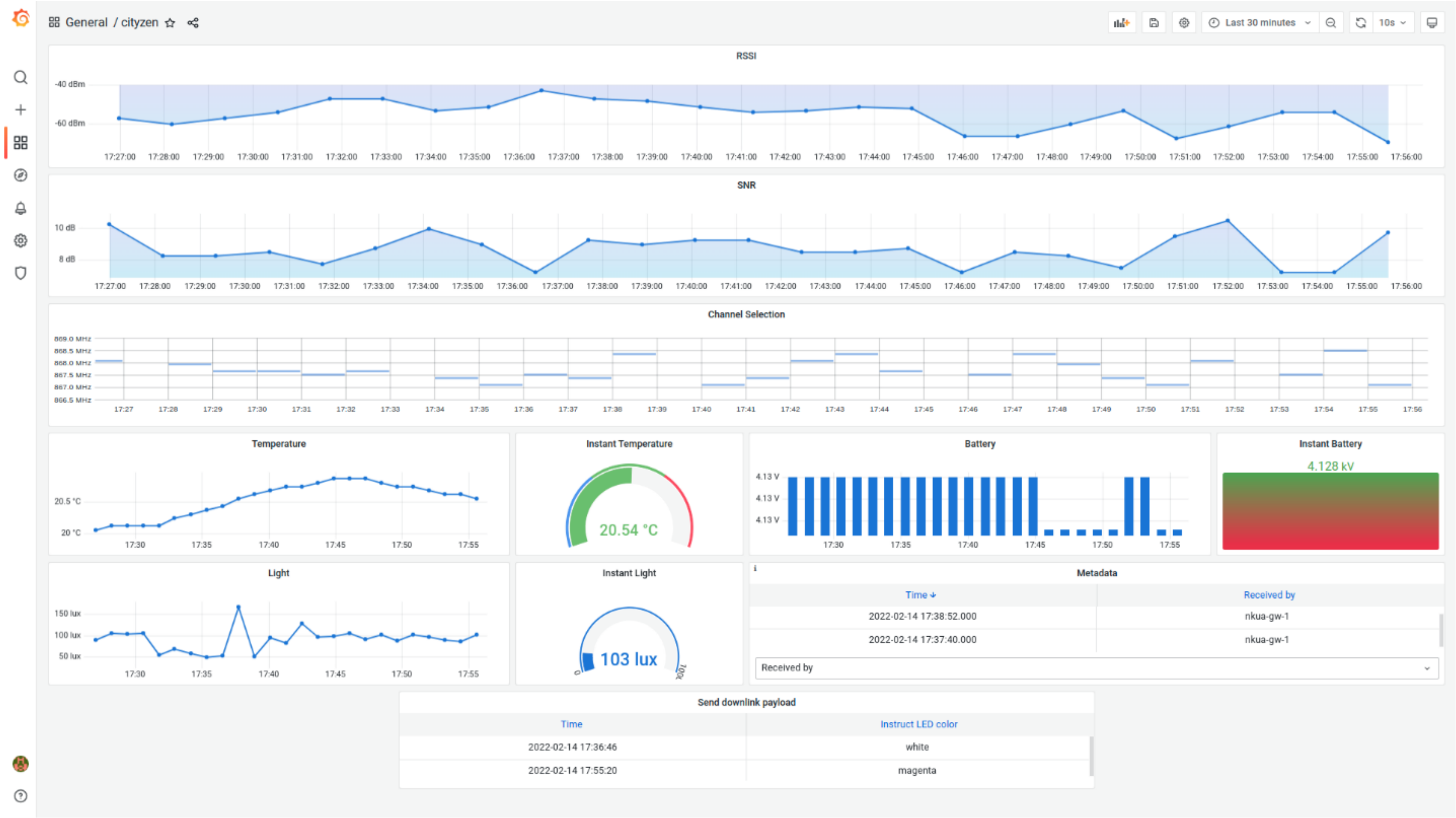
Node-RED flow



An instance from InfluxDB



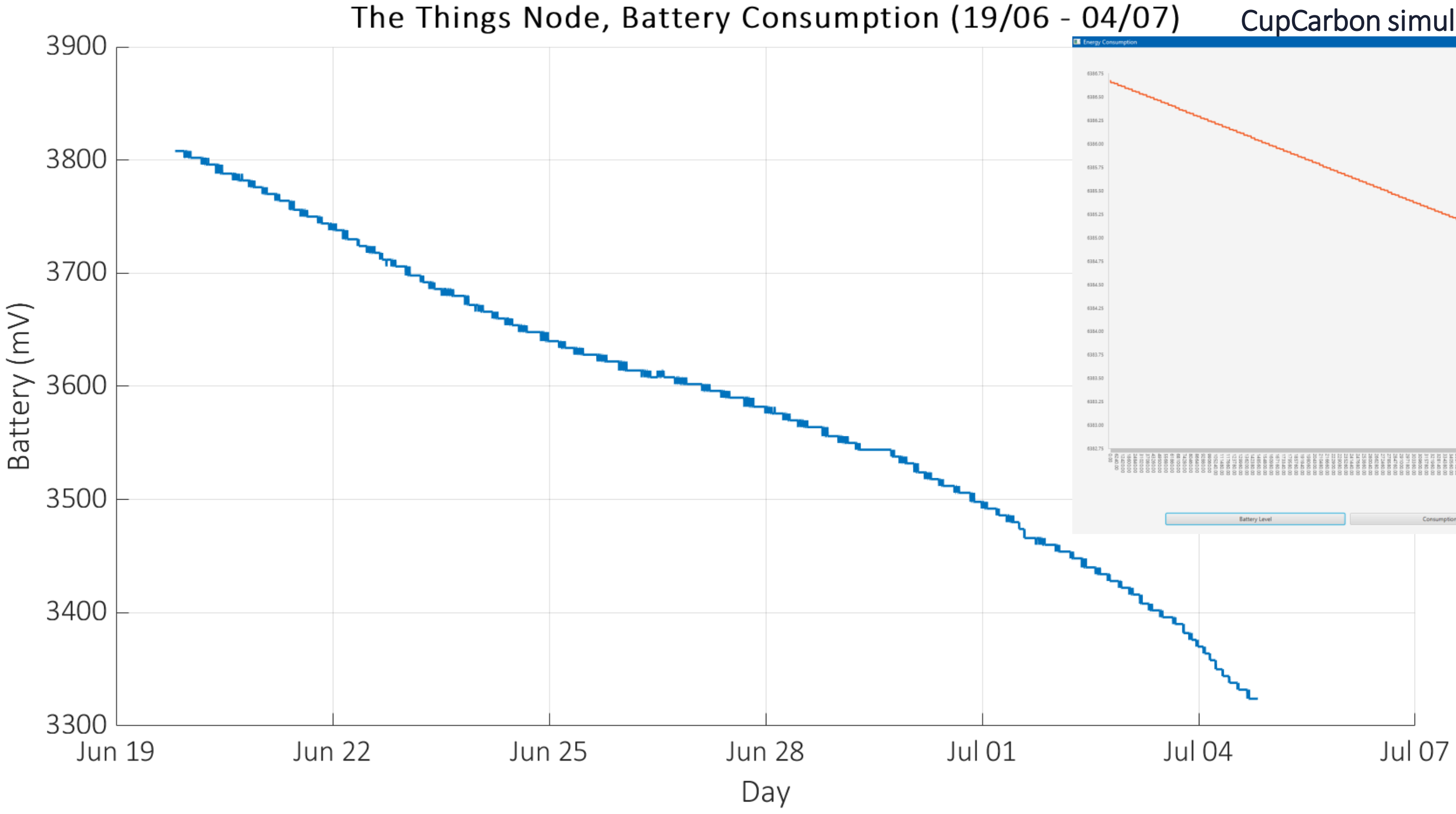
Grafana visualization



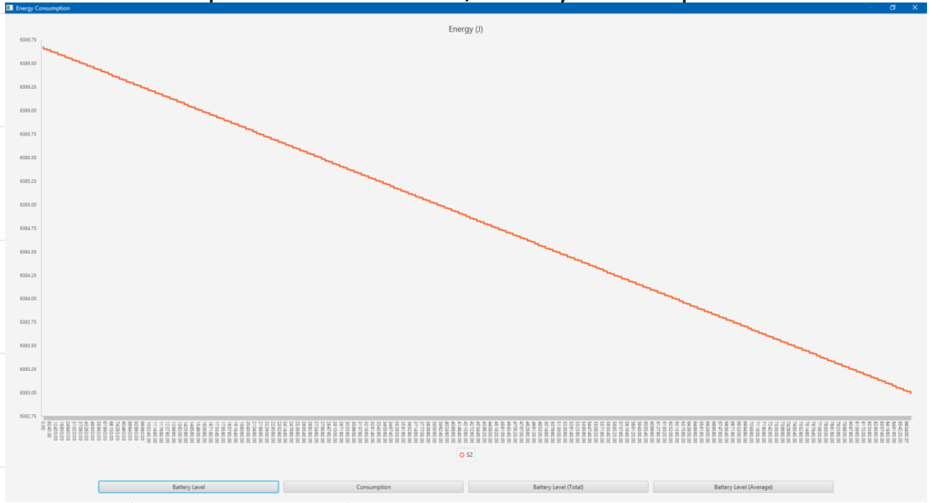
Experiments based on testbed

1. Examine power consumption and the longevity of EDs
   a. 1 stationary GW, 4 stationary EDs, suburban
   b. Focus on one ED, transmit a payload of 19 bytes every 2 mins with SF7, CR=4
2. Test GWs range capabilities
   a. GW again stationary, environment again suburban
   b. Mobile ED, transmitting to find out its location
3. Packet delivery ratio
   a. Same setup as in 1st experiment
   b. Try to find out percentage of successful transmissions with regards to parameter selection
4. Channel selection
   a. Examine the pseudorandom channel selection in UL transmissions

Power Consumption



CupCarbon simulations, Battery Consumption



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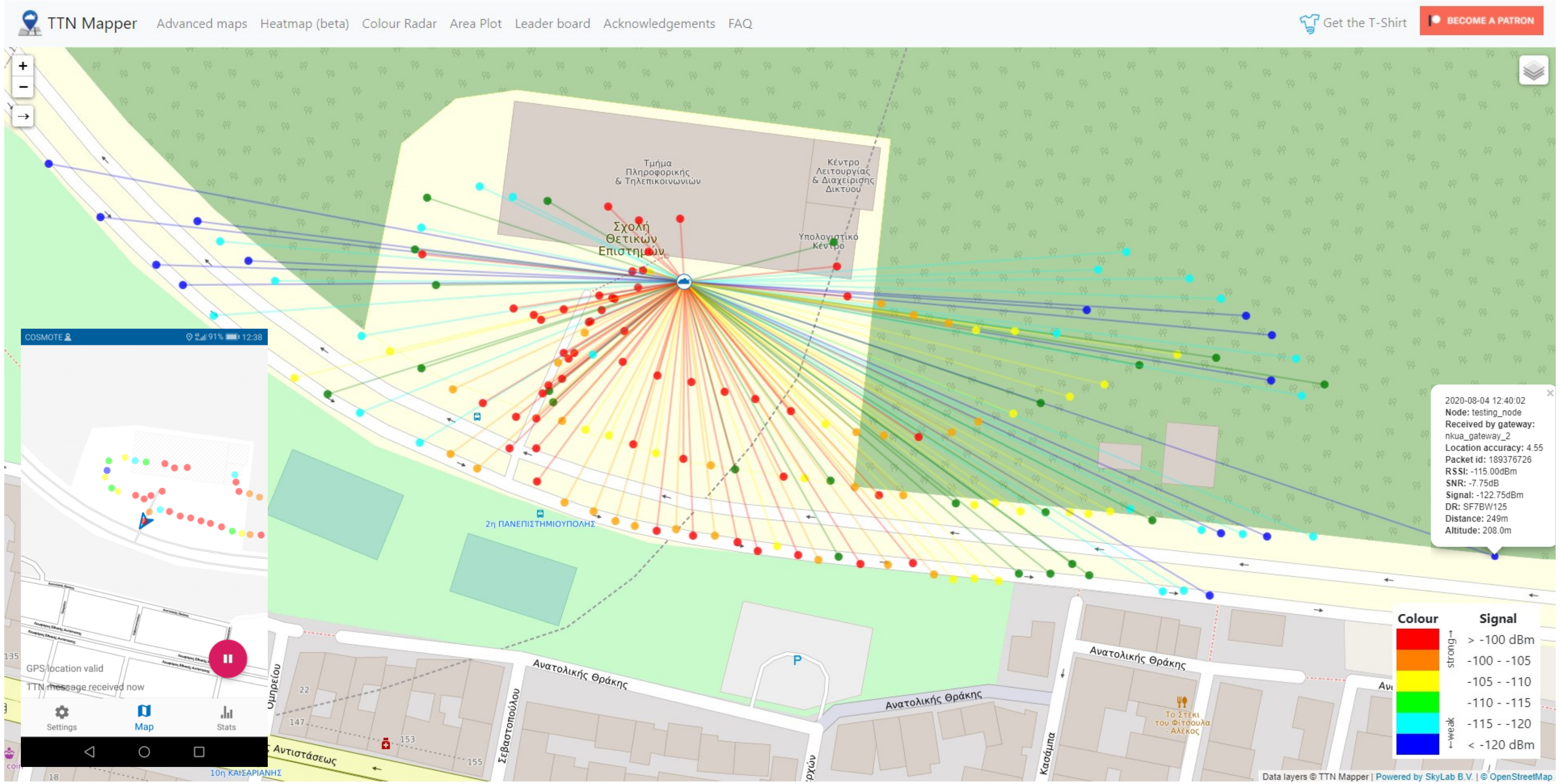
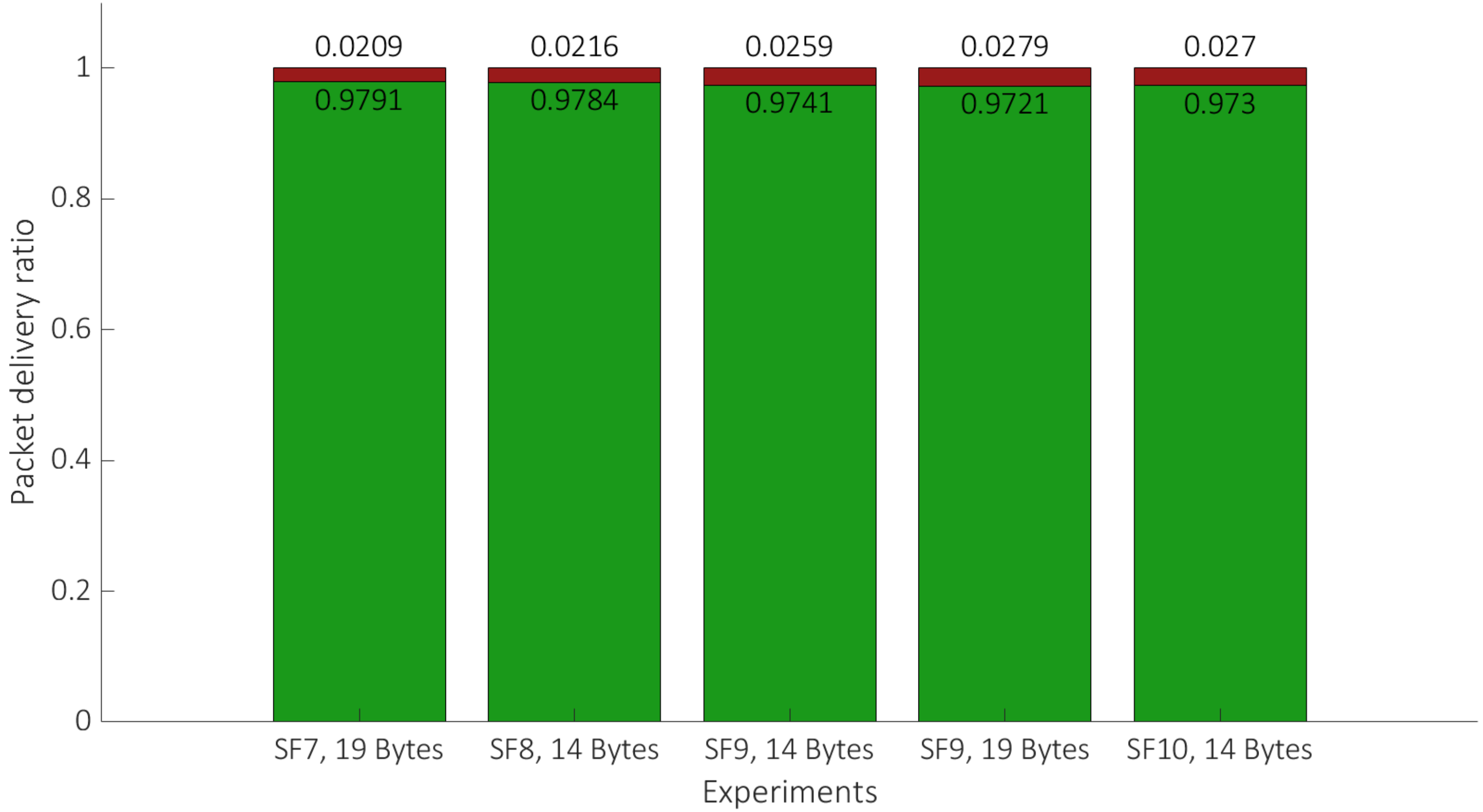
TTN Mapper



Packet Delivery Ratio



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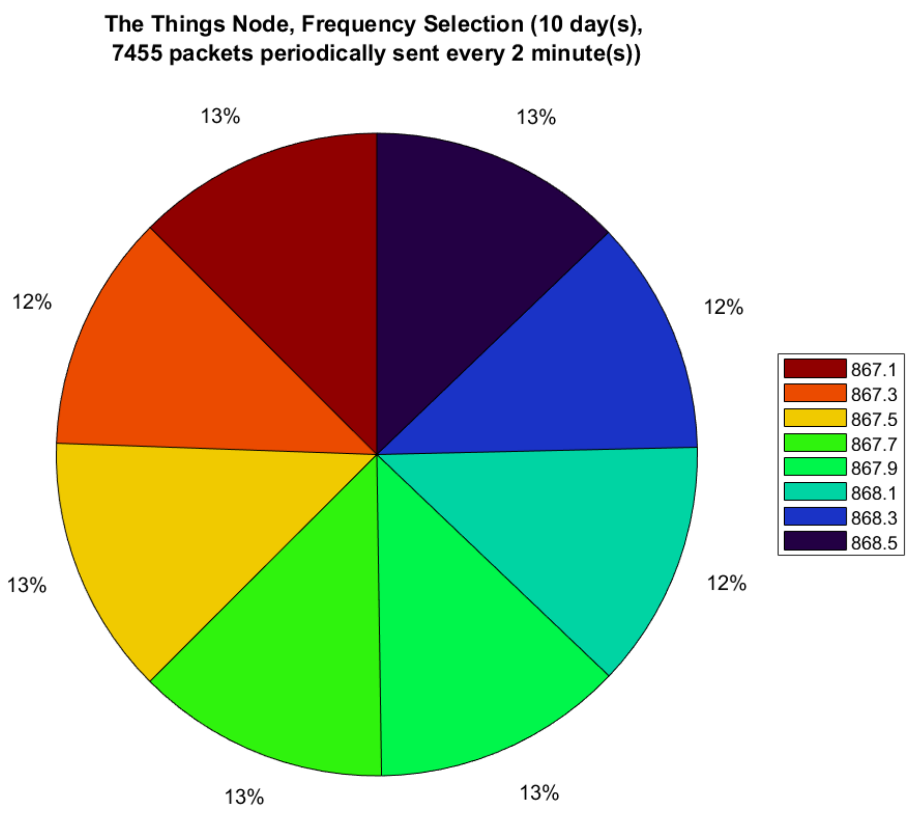
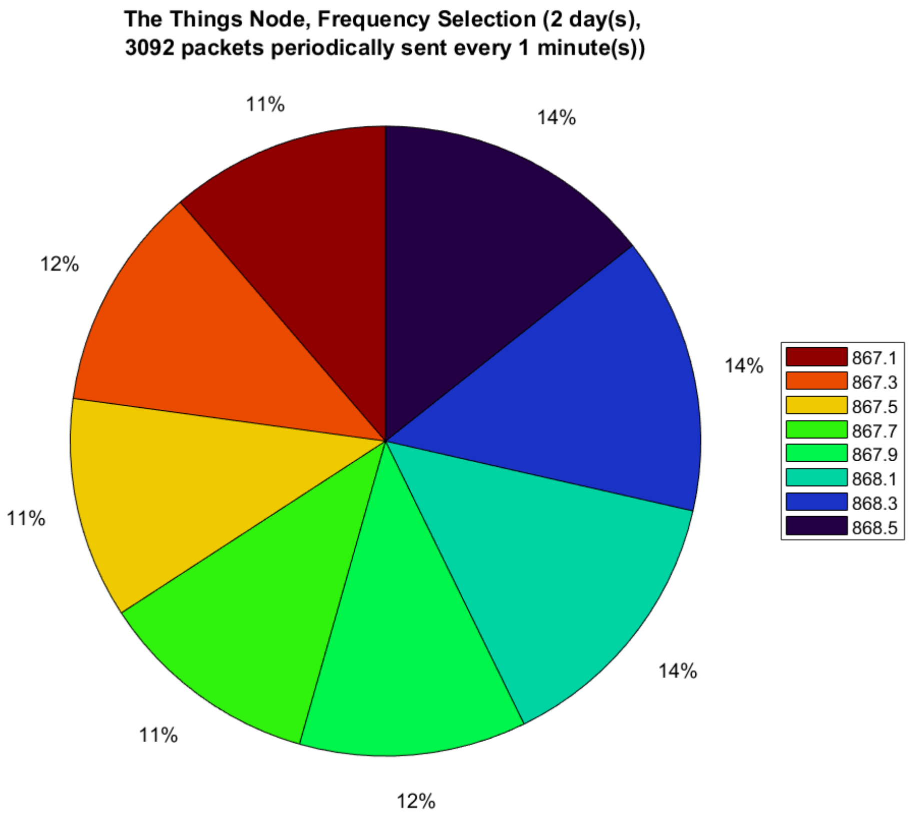
Pseudorandom Channel Selection





Part I - Conclusions

A theoretical and practical study of LoRa/LoRaWAN

Research directions based on published work

- research challenges
- research methodology

From methodology perspective, we have worked with simulators and real testbed

- both methodologies agree on power consumption behavior
- testbed reveals
  - promising results on range
  - high PDR
  - fair channel selection
- development of a modular and scalable framework via Docker

A first glance on Stochastic Processes

Stochastic Process

- *"A collection of random variables* $\{X(\tau), \tau \in T\}$*, indexed by the parameter* τ *taking values in the parameter set* T*. The random variables take values in the set* S*, called the state-space of the stochastic process."*

A plethora of them

- Bernoulli, Poisson, Discrete Time Markov Chains, Continuous Time Markov Chains, Renewal, Regenerative, Diffusion, …

How to study them

- Definition
- Characterization
- Transient Behavior
- First Passage Times
- Limiting Behavior
- Costs / Rewards
- Applications

[40] V. G. Kulkarni, *Modeling and Analysis of Stochastic Systems*, CRC Press, 3rd Edition, 2017

Initial intuition

Law of Large Numbers applies to independent and identically distributed (iid) RVs

Can it be applied to RVs that have some dependency among them?
- How much dependency?

Allow full dependency
- Impossible to compute

One step
- Dependency in pairs (time pairs, space pairs, …)

Andrey Andreyevich Markov (1856 – 1922)
[Image from Wikipedia]

iid — Markov property — complete dependency

[41] Joseph K. Blitzstein, Jessica Hwang, *Introduction to Probability*, CRC Pres, 2nd Edition, 2019

Markov chains primer

Markov property: a step further

- Future and Past are independent assuming knowledge of Present → conditional independence
- $P(X_{n+1} = i_{n+1} | X_n = i_n, X_{n-1} = i_{n-1}, \ldots, X_1 = i_1, X_0 = i_0) = P(X_{n+1} = i_{n+1} | X_n = i_n)$

Assuming a space of states S, a Markov chain is a stochastic process, modeled by a graph G with a set of vertices V (practically V is S) and connections among them called edges E, symbolized $G = (V, E)$, that:

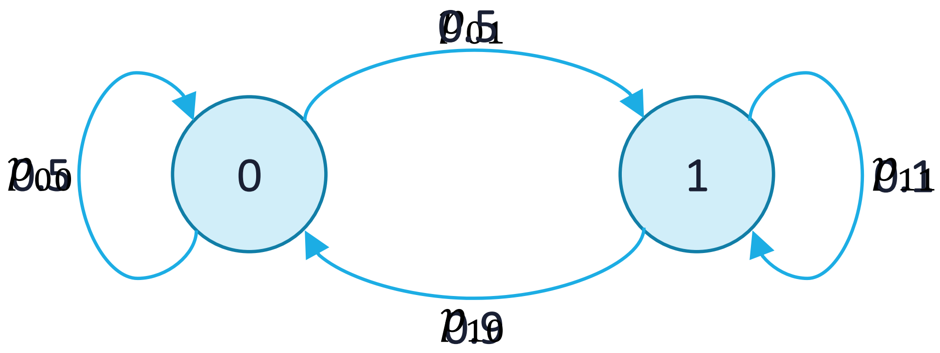
- holds the Markov property for every transition p, i.e., edge in E, from a state i to a state j, $\forall i, j \in S$
- every possible transition p_{ij}, i.e., edge in E, is non-negative
- for each of its states in S, i.e., vertices in V, the sum of transitions from (out-edges) is 1, $\sum_j p_{ij} = 1$

Assumptions

- discrete time
- discrete space
- finite number of states
- probabilities do not change over time (time-homogeneous)

$\boldsymbol{P} =$

n \ $n+1$	0	1
0	p_{00} 0.5	p_{01} 0.5
1	p_{10} 0.9	p_{11} 0.1



Terminology: States

Accessible: state j is accessible from state i if there is a valid sequence of transitions leading from i to j

Communicating: states i and j are said to be communicating, if i is accessible from j and j is accessible from i

Recurrent: starting from one state, there is a positive probability that we get back to this state
- positive recurrent (or recurrent non-null): come back in finite steps
- recurrent null: come back but after infinitely many steps

Transient: by complementarity, if not recurrent

Periodic: a state that occurs in a periodic manner, i.e., $\gcd(returns\_to\_state) \neq 1$

Aperiodic: by complementarity, if not periodic, i.e., $\gcd(returns\_to\_state) = 1$

Ergodic: Recurrent non-null + Aperiodic

Absorbing: a state that when reached there is no escape from it, i.e., $p_{ii} = 1$

[41] Joseph K. Blitzstein, Jessica Hwang, *Introduction to Probability*, CRC Pres, 2nd Edition, 2019

Terminology: Chains

Irreducible: All states communicating
- Strongly connected graph (useful property)

Reducible: by complementarity, if not irreducible

Periodic: if at least one state is periodic
- Cyclic graph

Aperiodic: if all states are aperiodic
- Finite recurrent non-null states: aperiodic = irreducible [1]

Ergodic: Irreducible + Aperiodic
- all states are ergodic

Absorbing: chain with at least one absorbing state, that is accessible from any other non-absorbing state

Markov chain on steady state: transition probabilities have reached stationary distribution

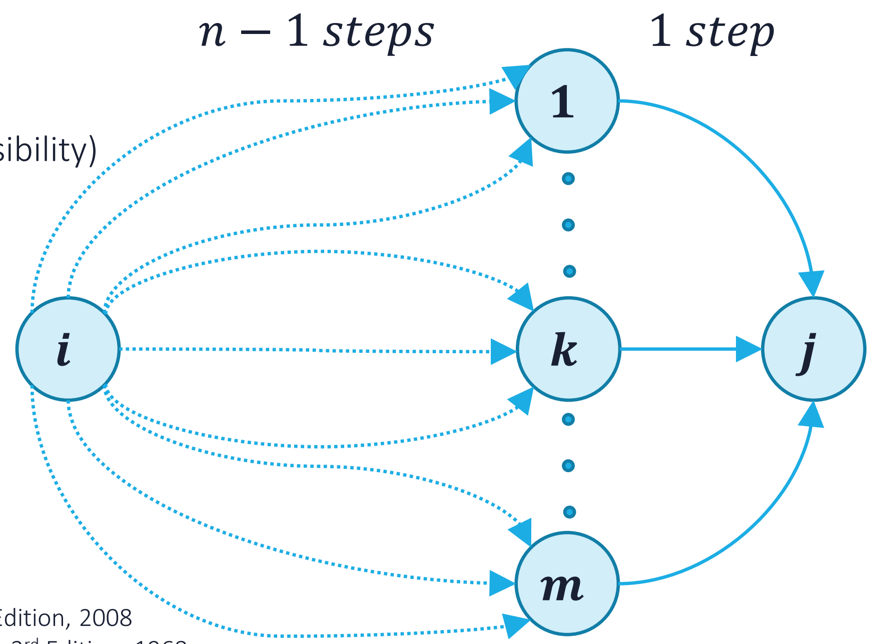
Reversible: long-run percentage of transitions from i to j are equal to the long-run percentage of transitions from j to i
- intuition: you can look MC backwards in time without noticing any difference

[1] [42] https://brilliant.org/wiki/markov-chains/#markov-chain, Accessed: 22/01/2020

Chapman – Kolmogorov equation

Probability of reaching state j starting from state i in n steps

- Intuition
  - Reach some state k in $n-1$ steps and from there transition to j in 1 step (assuming j is accessible from k)
  - Proceed recursively
- Formula: $p_{ij}(n) = \sum_{k=1}^{m} p_{ik}(n-1) * p_{kj}$
- The opposite approach can also work
  - Transition from i to k in 1 step and from k reach j in $n-1$ steps (again, assuming accessibility)
  - $p_{ij}(n) = \sum_{k=1}^{m} p_{ik} * p_{kj}(n-1)$



Generalization: in m steps transition to intermediate state and in n steps to destination

- $p_{ij}(m+n) = \sum_{k} p_{ik}(m) * p_{kj}(n)$

[43] D. P. Bertsekas, J. N. Tsitsiklis, *Introduction to Probability*, Athena Scientific, 2nd Edition, 2008
[44] W. Feller, *An Introduction to Probability Theory and its Applications – Volume I*, Wiley, 3rd Edition, 1968

Stationarity

Stationary distribution (steady-state distribution): a row vector ($\vec{\pi}$) describing the long-run probabilities of each state, $\vec{\pi} = \vec{\pi} * P$

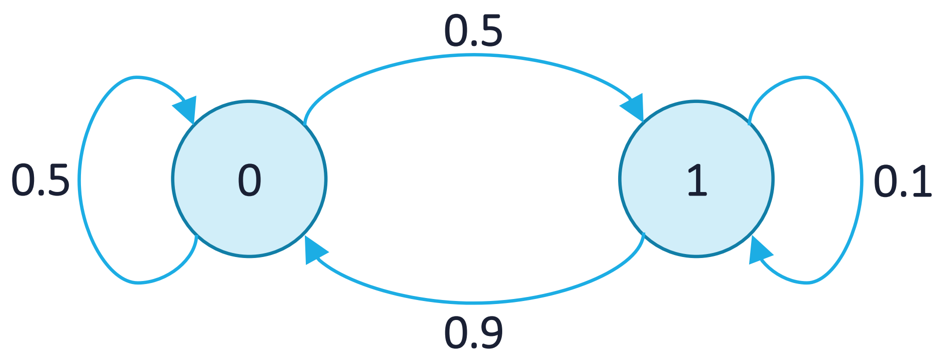
Key on explaining a Markov chain's behavior
- Average time spent on each state
- Average visits to each state

Questions:
- Does a steady state exist?
- Is it unique?
- Is it limiting?

$\boldsymbol{P}^n =$

	0	1
0	0.5 / 0.64	0.5 / 0.36
1	0.9 / 0.64	0.1 / 0.36

$\vec{\pi} = (0.64, 0.36)$



For **ergodic Markov chains** the answer is yes to everything

For other types of Markov chains, the answers may vary, but a steady state does exist for finitely many states

Stationarity calculation

Chapman – Kolmogorov equation for n steps

- Recursive formula: $p_{ij}(n) = \sum_{k=1}^{m} p_{ik}(n-1) * p_{kj}$

From the above expression as $n \to \infty$:

- $\pi_j = \sum_{k=1}^{m} \pi_k * p_{kj}, \forall j$ (balance equations)

Remember, $\vec{\pi}$ is a distribution row vector

- $\sum_{j=1}^{m} \pi_j = 1$ (normalization equation)

These set of equations (balance equations, normalization equation) form a linear system that gives stationary distribution vector

- Also called "Steady-state convergence Theorem" or "The Big Theorem of Markov chains" [2]

Essentially, to calculate the distribution vector in time n:

- $\vec{\pi}^{(n)} = \vec{\pi}^{(n-1)} * P^1$
- $\vec{\pi}^{(n)} = \vec{\pi}^{(0)} * P^n$

For "large" n, if there is a steady state: $\vec{\pi} = \vec{\pi} * P^n, \forall n$

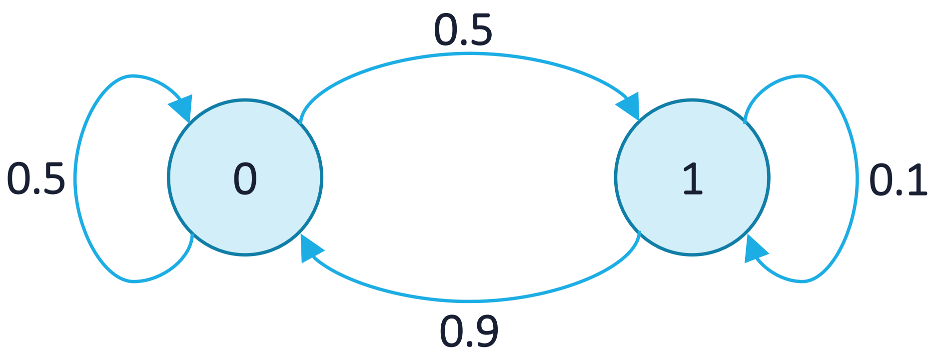
- Remember, each row of P^n equals to stationary distribution vector
  - Iterative self-multiplications of stochastic matrix P lead to stationary distribution

[2] [45] John Tsitsiklis' lectures on "Probabilistic System Analysis and Applied Probability", fall 2010, *via MIT OCW*

How to interpret “large” n?

$$\vec{\pi} = (0.64, 0.36)$$

$$P = \begin{array}{c|cc} & 0 & 1 \\ \hline 0 & 0.5 & 0.5 \\ 1 & 0.9 & 0.1 \end{array}$$

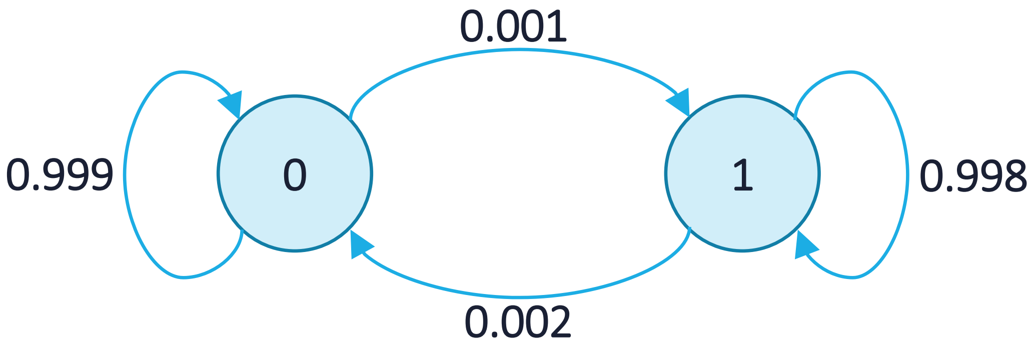



```
rowTable = | 1.000000 0.000000 |
| 0.500000 0.500000 |
| 0.700000 0.300000 |
| 0.620000 0.380000 |
| 0.652000 0.348000 |
| 0.639200 0.360800 |
| 0.644320 0.355680 |
| 0.642272 0.357728 |
| 0.643091 0.356909 |
| 0.642764 0.357236 |
| 0.642895 0.357105 |
| 0.642842 0.357158 |
| 0.642842 0.357158 |
Final probability for each state after 12 iterations: | 0.642842 0.357158 |

rowTable = | 0.000000 1.000000 |
| 0.900000 0.100000 |
| 0.540000 0.460000 |
| 0.684000 0.316000 |
| 0.626400 0.373600 |
| 0.649440 0.350560 |
| 0.640224 0.359776 |
| 0.643910 0.356090 |
| 0.642436 0.357564 |
| 0.643026 0.356974 |
| 0.642790 0.357210 |
| 0.642884 0.357116 |
| 0.642884 0.357116 |
Final probability for each state after 12 iterations | 0.642884 0.357116 |
```

$$\vec{\pi} = (0.65, 0.35)$$

$$P = \begin{array}{c|cc} & 0 & 1 \\ \hline 0 & 0.999 & 0.001 \\ 1 & 0.002 & 0.998 \end{array}$$




```
| 0.648604 0.351396 |
| 0.648658 0.351342 |
| 0.648712 0.351288 |
| 0.648766 0.351234 |
| 0.648819 0.351181 |
| 0.648873 0.351127 |
| 0.648926 0.351074 |
| 0.648979 0.351021 |
| 0.649032 0.350968 |
| 0.649085 0.350915 |
| 0.649138 0.350862 |
| 0.649191 0.350809 |
| 0.649243 0.350757 |
| 0.649295 0.350705 |
| 0.649348 0.350652 |
| 0.649399 0.350601 |
| 0.649451 0.350549 |
| 0.649503 0.350497 |
| 0.649554 0.350446 |
| 0.649606 0.350394 |
| 0.649657 0.350343 |
| 0.649708 0.350292 |
| 0.649759 0.350241 |
| 0.649810 0.350190 |
| 0.649860 0.350140 |
| 0.649911 0.350089 |
| 0.649961 0.350039 |
| 0.650011 0.349989 |
| 0.650011 0.349989 |
Final probability for each state after 1229 iterations | 0.650011 0.349989 |
```

Types of stationarity

Does a steady state exist?

- If MC has finite state space: YES
- Interpretation: if I assign initial probabilities equal to stationary distribution, then, after achieving stationarity, in every run of the chain I will get the same distribution

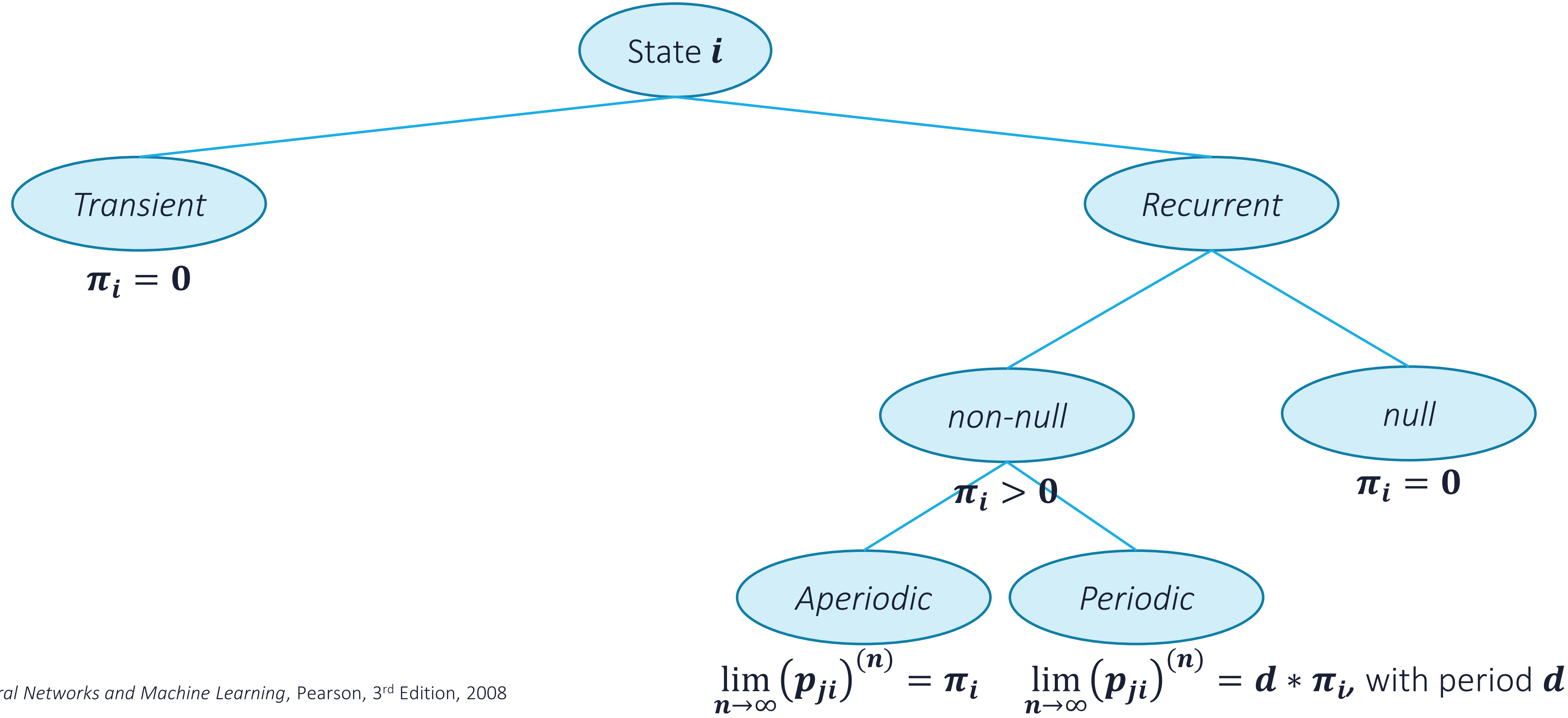
Is it unique?

- If MC is irreducible: YES
- If MC has only one absorbing state accessible from all other states: YES
- Interpretation: initial distribution vector does not play a role in the long-run

Is it limiting?

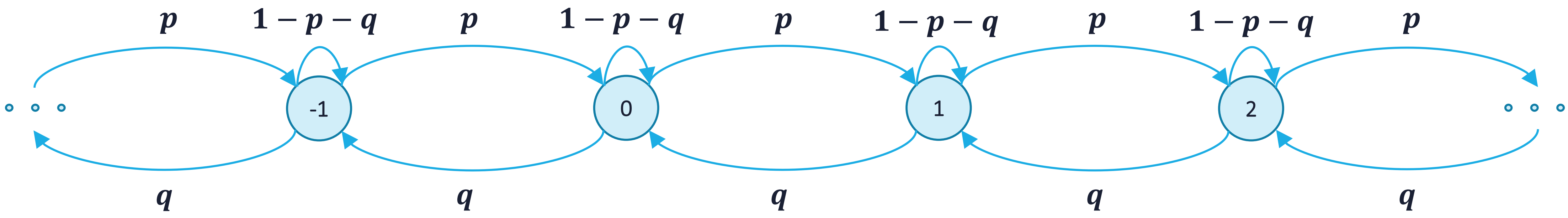
- If MC is irreducible + aperiodic (=ergodic): YES
- Interpretation: The chain converges to this stationarity, meaning that each row of stochastic matrix of $n-th$ order (n appropriately selected, as discussed before) will converge to stationary distribution

States categorization

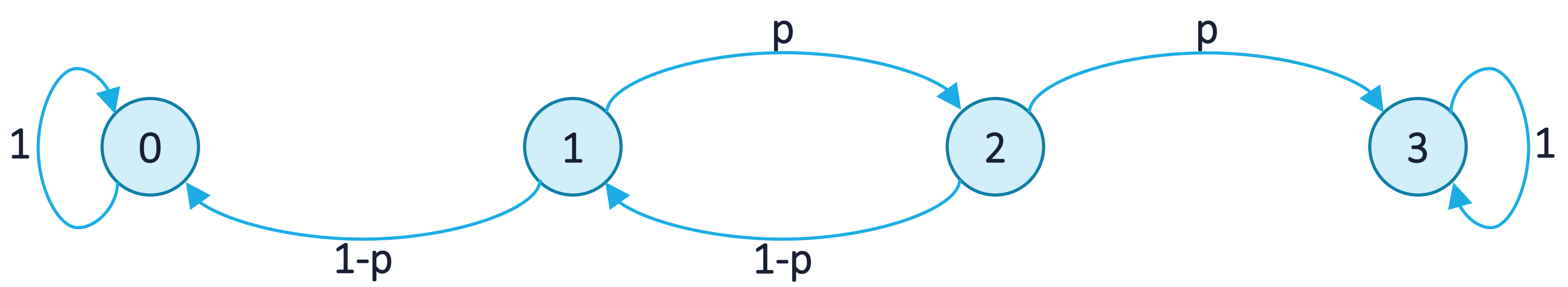


[46] Simon Haykin, *Neural Networks and Machine Learning*, Pearson, 3rd Edition, 2008

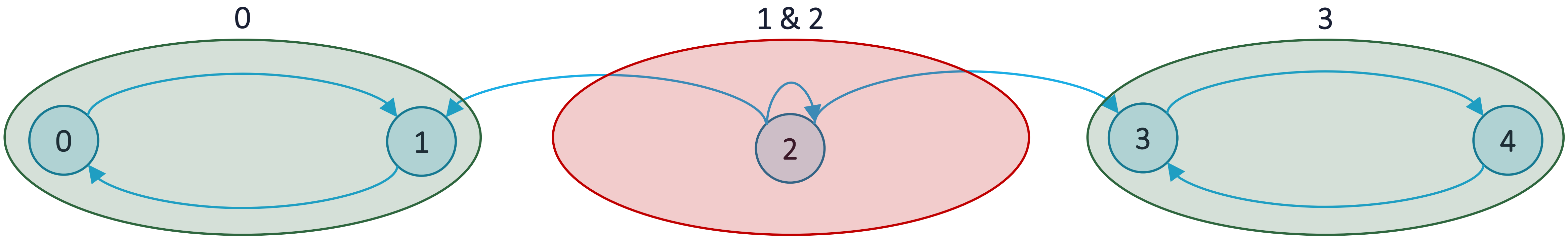
Common Examples – Random Walk

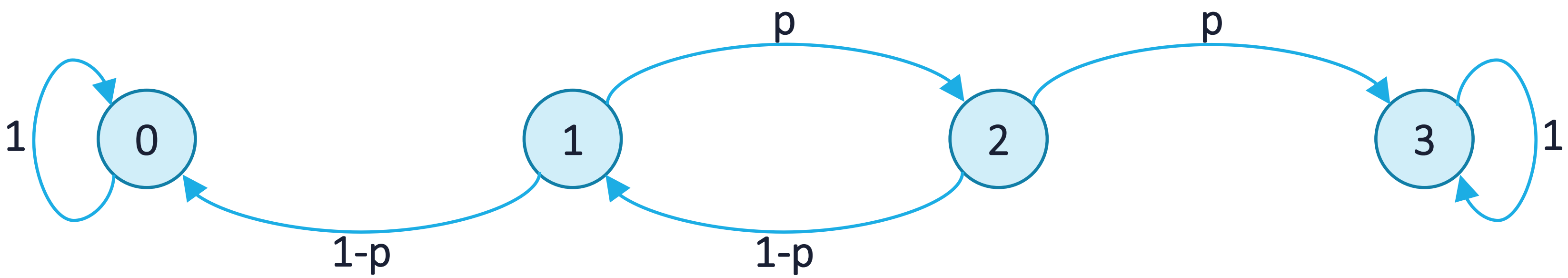


Common Examples – Gambler's Ruin

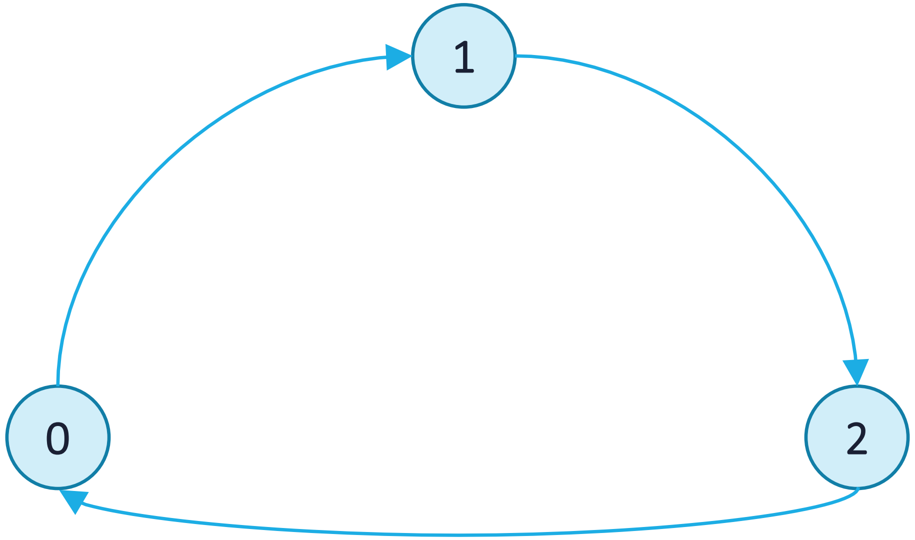


Common Examples – Gambler's Ruin



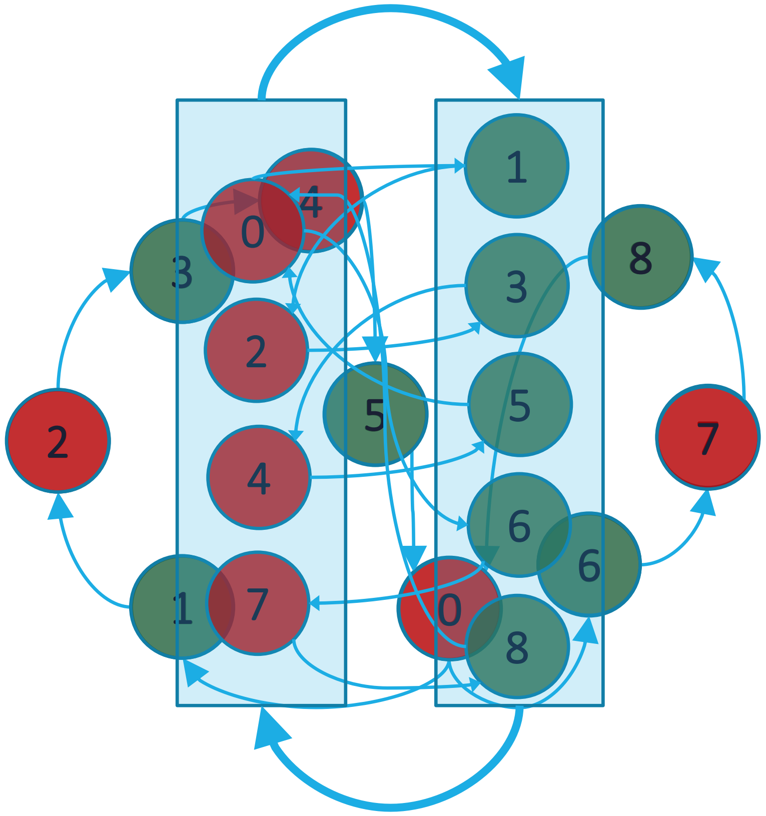


Common Examples – Periodicity



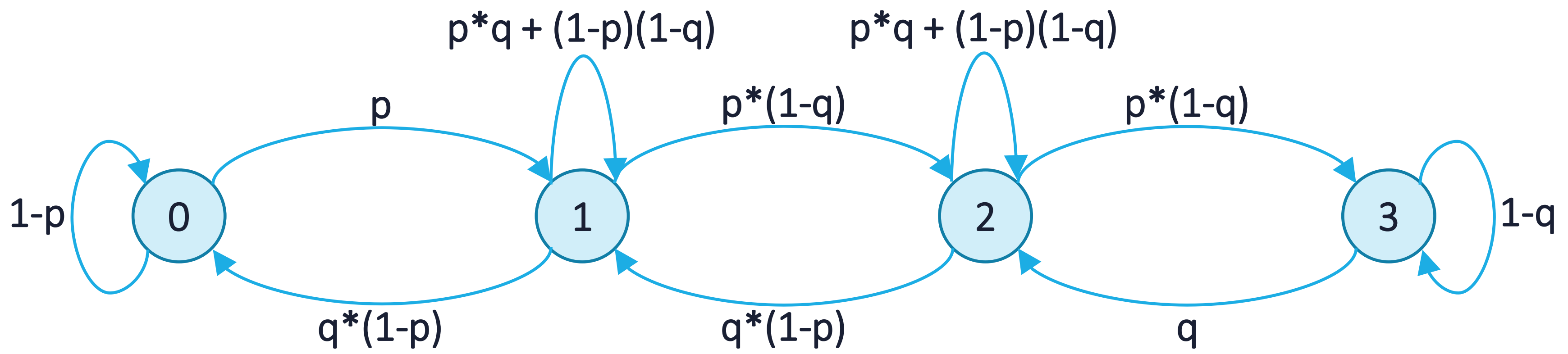
Common Examples – Periodicity

Common Examples

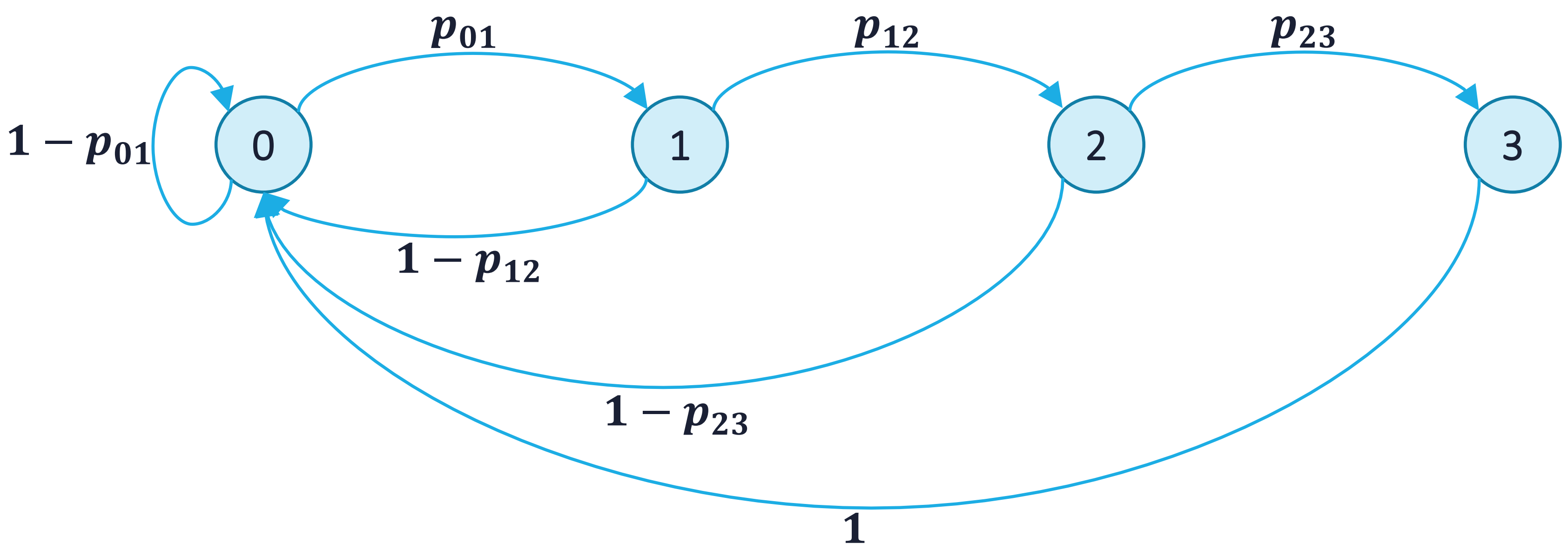


[45] John Tsitsiklis' lectures on "Probabilistic System Analysis and Applied Probability", fall 2010, *via MIT OCW*

Common Examples – Birth/Death Chain



Common Examples – Slowly Spreading Chain



[47] John G. Kemeny, "Slowly spreading chains of the first kind," Journal of Mathematical Analysis and Applications, Volume 15, Issue 2, pp. 295-310, 1966, ISSN 0022-247X, https://doi.org/10.1016/0022-247X(66)90121-1.
[48] Kanal Laveen, Sastry Ark , "Models for Channels with Memory and Their Applications to Error Control," Proceedings of the IEEE. 66, pp. 724 – 744, 1978, 10.1109/PROC.1978.11013

Usage Examples

Wide area of applications: networks, operating systems, ML, finance, genetics, epidemiology, earthquake study, particle physics, sports analytics, etc.

- Even in one domain the field of applications is vast
  - search engine indexing, network caching, wireless network access, network resource utilization, etc.

PageRank: probably the most famous implementation

- the way that Google ranks the indexed webpages
- $Webpage\ Rank = \sum_{i\,=\,all\ in-edges} rank_i$
  - a variation counts both in- and out-edges

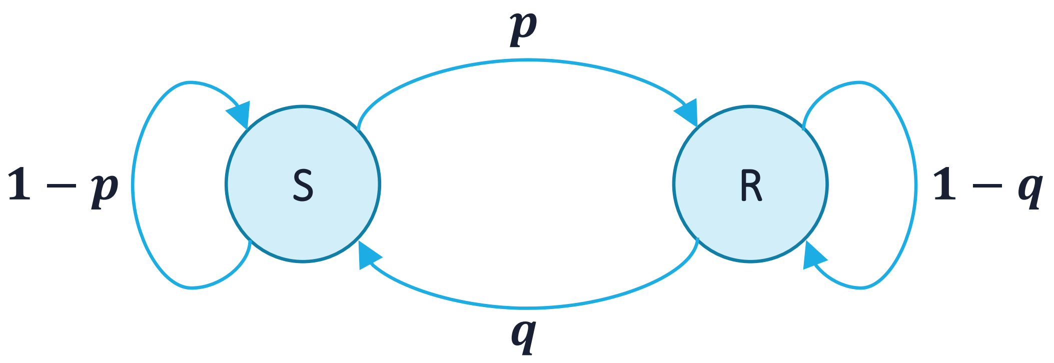
Wide use in networks to evaluate nodes' behavior: routers, switches, links

- Modelling of systems, like M/M/1, M/G/1, G/M/1, M/M/m, …
- Birth-death chains
  - "birth": packet arrival, "death": packet departure ("served")

Weather Modeling

Suppose a simple two-weather model: S: Sun, R: Rain

Probability of sun tomorrow according to today's weather



If p is close to 0 and q is close to 1, we observe an area with a nice weather!

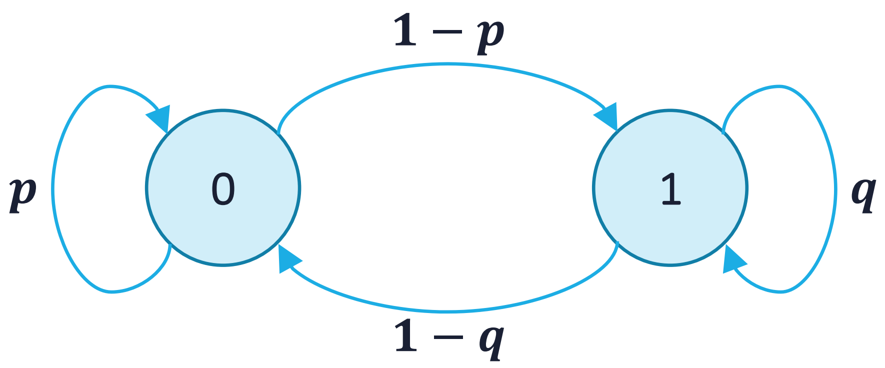
Clinical Trials

2 tested drugs for a disease

Clinical trials on patients

Ethical reasons dictate *play the winner* rule

	0	1
0	p	$1-p$
1	$1-q$	q



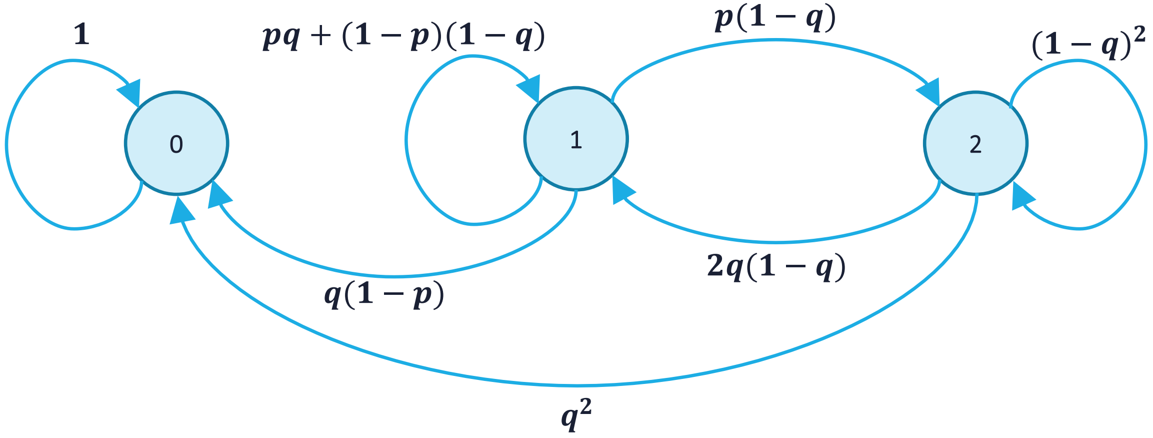
If $p > q$ after many trials, we select drug 0, otherwise drug 1

[40] V. G. Kulkarni, *Modeling and Analysis of Stochastic Systems*, CRC Press, 3rd Edition, 2017

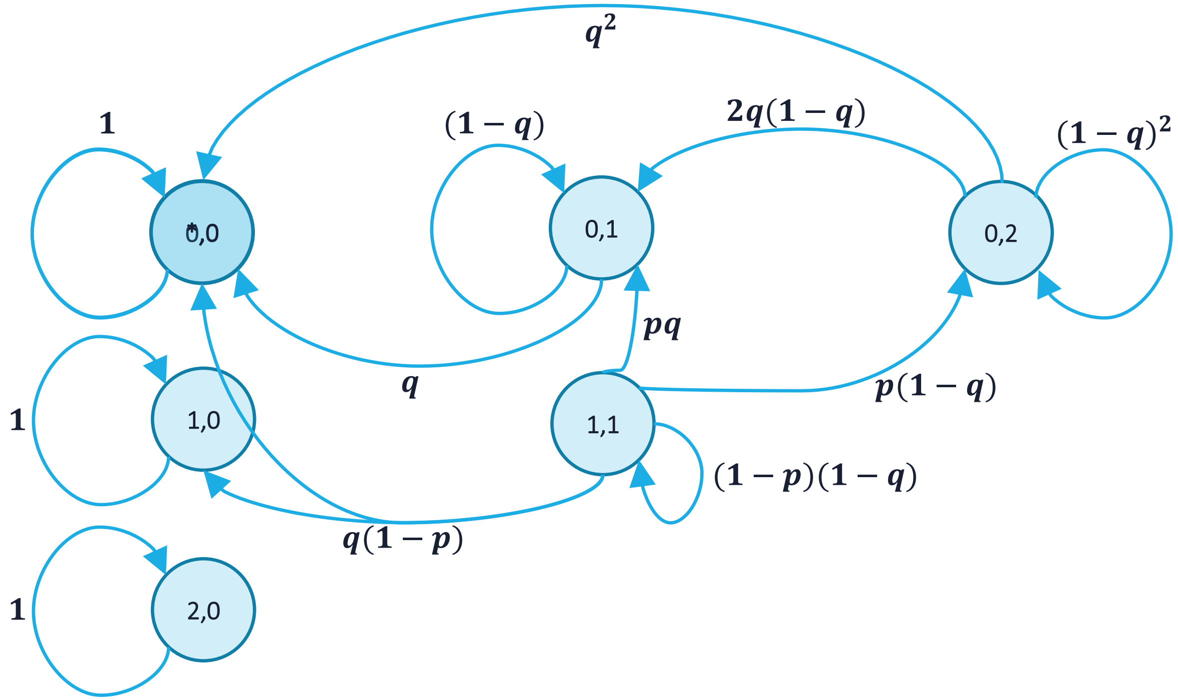
Susceptible - Infected - Recovered Model

Susceptible (S): people in danger of getting diseased
Infected (I): people carrying the virus
p: prob. get infected, q: prob. get well

Recovered (R): people recovered



SIS model



SIR model ((S,I) States)

[45] John Tsitsiklis' lectures on "Probabilistic System Analysis and Applied Probability", fall 2010, *via MIT OCW*

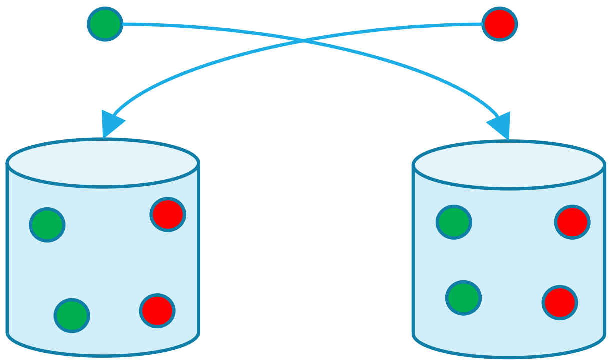
Urn Model

Let’s play a game!

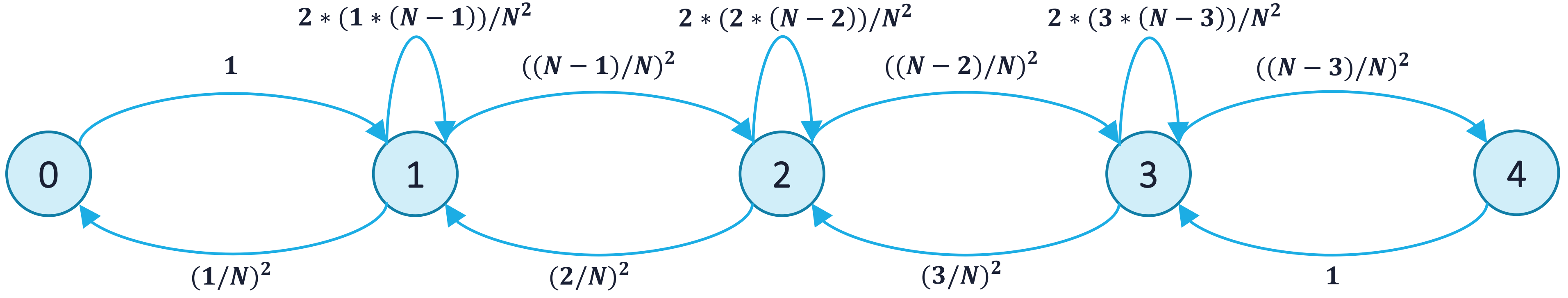
$2 * N$ balls in total, N green, N red

N balls in each urn

Urn 1: i greens, the rest are red



Probability of having $k, k \in \{0, \dots, 4\}$ greens in Urn 1?



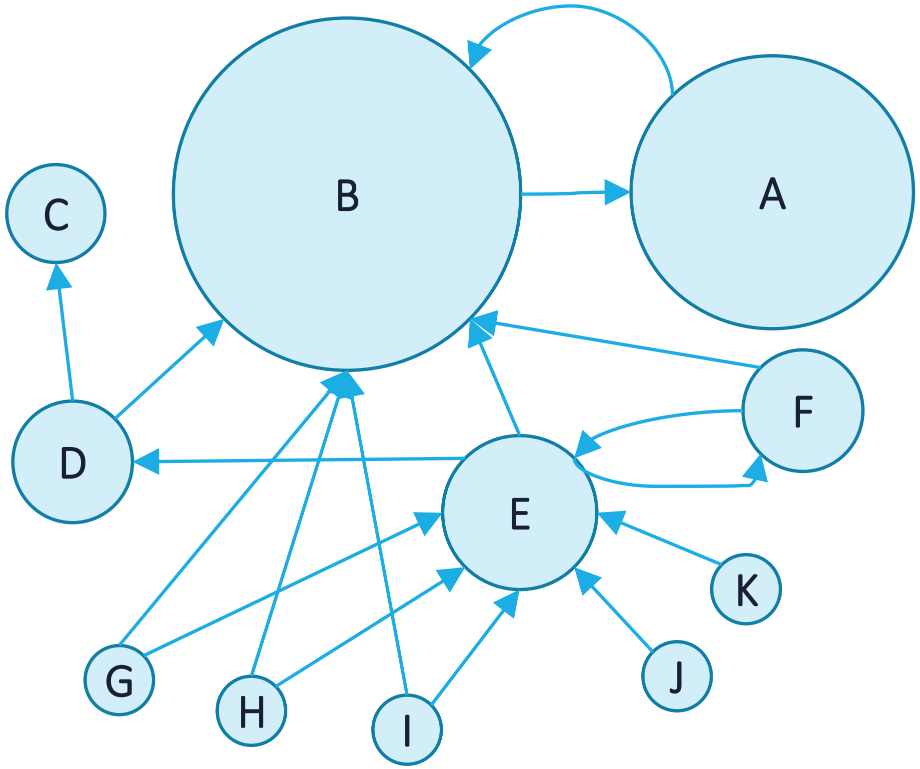
PageRank Algorithm

Intuition: A webpage is important when a lot of webpages cite it (academic citation)

- Extension: It does not matter what *someone* says, but also **who** is this *someone*
  - how much important this *someone* is

$$PR(A) = \frac{(1-d)}{N} + d\left(\frac{PR(T1)}{C(T1)} + \ \dots \ + \frac{PR(Tn)}{C(Tn)}\right)$$

- A: some webpage A
- $T1 \dots Tn$: pages 1…n with a link to page A
- $C(A)$: number of out-links from A
- d: damping factor ($1 - d$: probability of "teleporting" to a random page)
  - In Brin's and Page's publication, $d = 0.85$



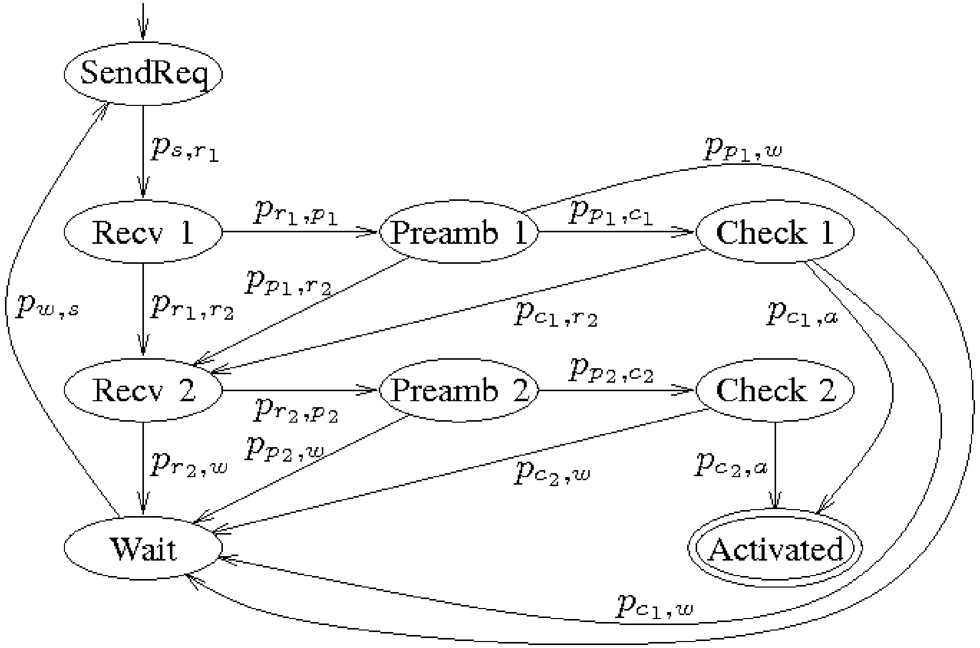
[PageRank in Wikipedia]

[49] S. Brin, L. Page, "*The anatomy of a large-scale hypertextual Web search engine*," Computer Networks and ISDN Systems, Volume 30, Issues 1–7, 1998

Markov chains in Network Access

Wireless networks with excessive number of end devices trying to access the medium

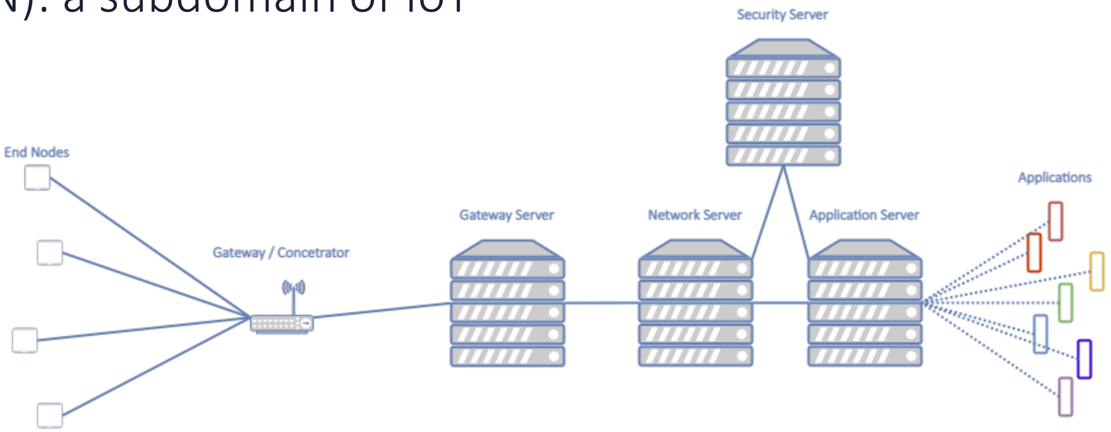
"*Performance analysis of the on-the-air activation in LoRaWAN*", J. Toussaint, N. El Rachkidy and A. Guitton, 2016 IEEE 7th Annual IEMCON, Vancouver, BC, 2016



[15] J. Toussaint, N. El Rachkidy and A. Guitton, "Performance analysis of the on-the-air activation in LoRaWAN," in IEMCON, 2016

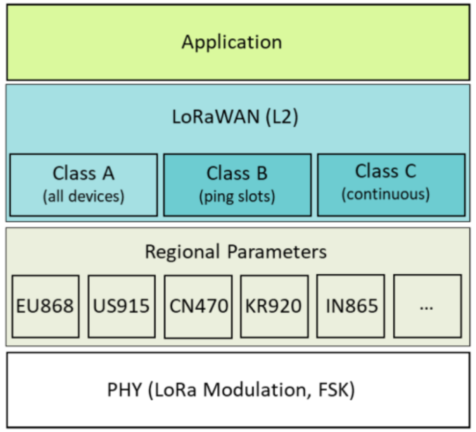
LoRaWAN primer

Low-Power Wide Area Network (LPWAN): a subdomain of IoT



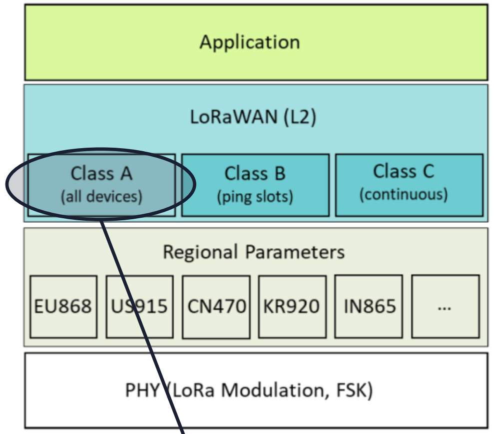
Interconnection of devices:
- power constraints
- communication in wide areas
- small data rates
- low cost

LoRaWAN: a MAC protocol in the space of LPWAN
- open protocol developed by LoRa Alliance
- based on LoRa PHY, proprietary modulation by Semtech



State of the problem

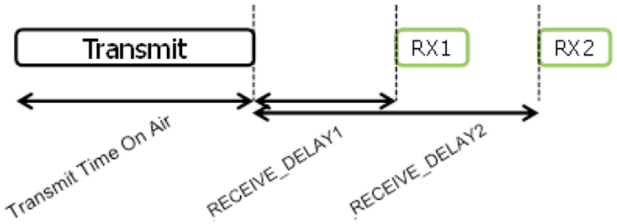
Three main entities:
- End Device (ED)
- Gateway (GW)
- Network Server (NS)



EDs are deployed in massive numbers: how to access the medium?

First time an ED tries to access the channel: during activation
- Activation By Personalization (ABP): hardcoded access keys
- Over The Air Activation (OTAA): based on join request/accept messages between ED and server-side

Successful activation is based on successful communication and proper key generation

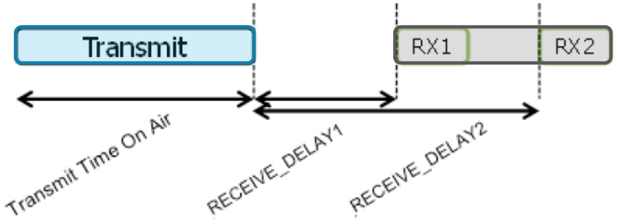


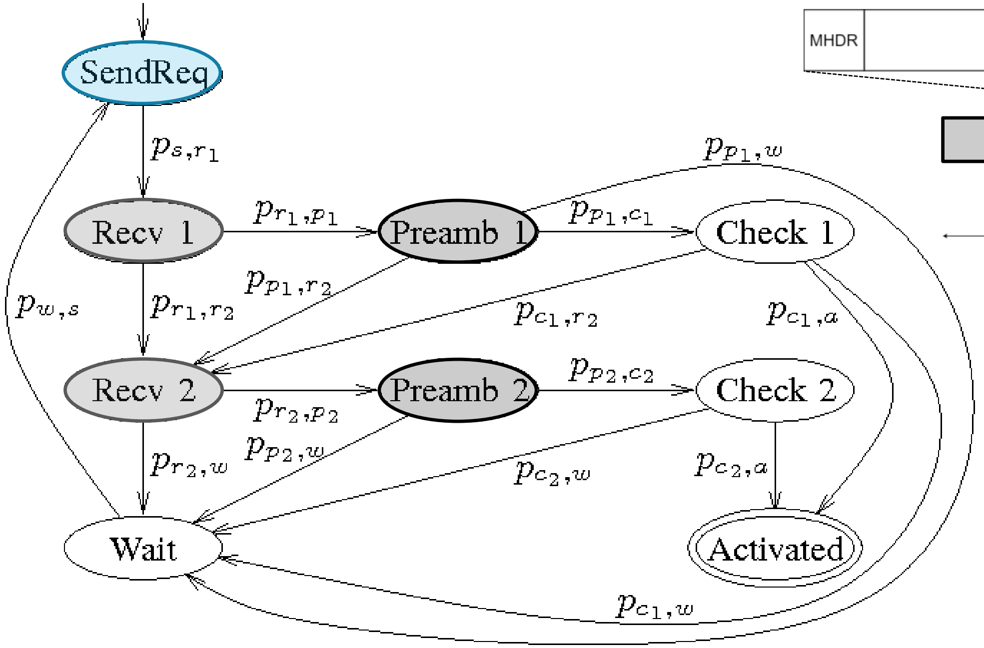
2 questions:
- How much time until successful activation?
- How much energy until successful activation?

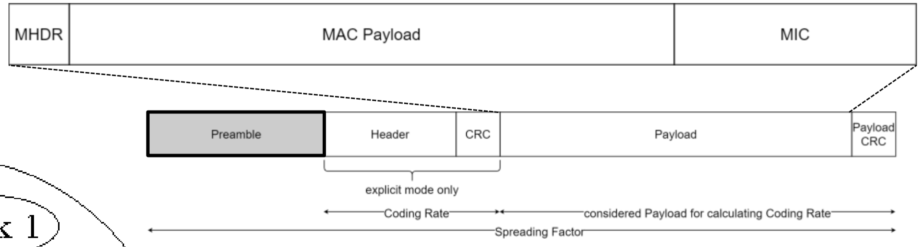
Markov chain of the problem

Wireless networks with excessive number of end nodes trying to access the medium

“*Performance analysis of the on-the-air activation in LoRaWAN*”, J. Toussaint, N. El Rachkidy and A. Guitton, 2016 IEEE 7th Annual IEMCON, Vancouver, BC, 2016

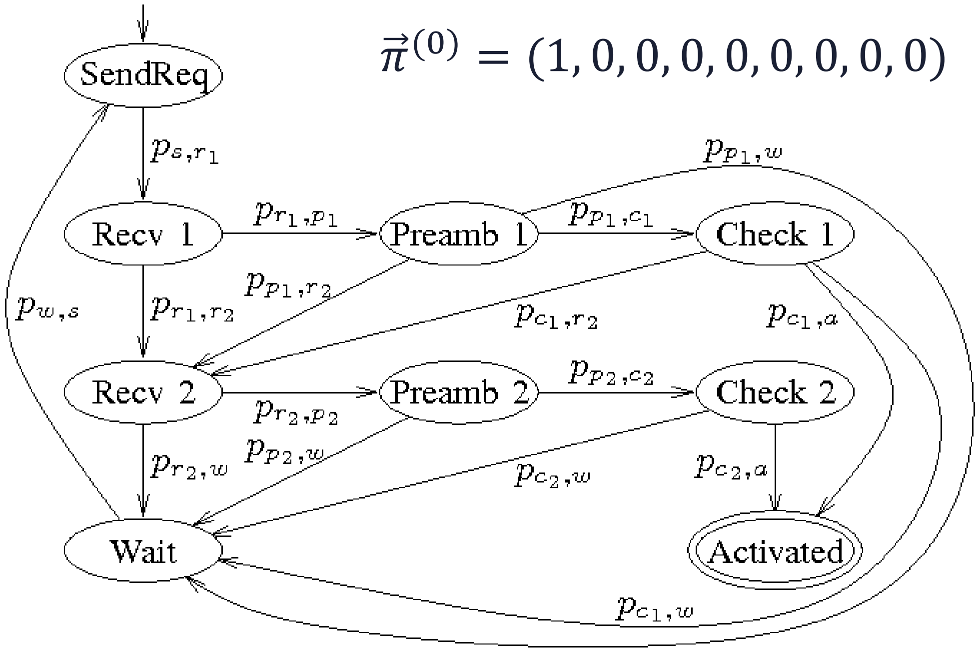






[15] J. Toussaint, N. El Rachkidy and A. Guitton, "Performance analysis of the on-the-air activation in LoRaWAN," in IEMCON, 2016

Transition Matrix



$\vec{\pi}^{(0)} = (1,0,0,0,0,0,0,0,0)$

[15] J. Toussaint, N. El Rachkidy and A. Guitton, "Performance analysis of the on-the-air activation in LoRaWAN," in IEMCON, 2016

States 0 – 7 are transient State 8 is recurrent (absorbing)

	s	r1	p1	c1	r2	p2	c2	w	a
s	0	~~p_{s,r_1}~~ 1	0	0	0	0	0	0	0
r1	0	0	p_{r_1,p_1}	0	p_{r_1,r_2}	0	0	0	0
p1	0	0	0	p_{p_1,c_1}	p_{p_1,r_2}	0	0	~~$p_{p_1,w}$~~ 0	0
c1	0	0	0	0	p_{c_1,r_2}	0	0	$p_{c_1,w}$	$p_{c_1,a}$
r2	0	0	0	0	0	p_{r_2,p_2}	0	$p_{r_2,w}$	0
p2	0	0	0	0	0	0	p_{p_2,c_2}	$p_{p_2,w}$	0
c2	0	0	0	0	0	0	0	$p_{c_2,w}$	$p_{c_2,a}$
w	~~$p_{w,s}$~~ 1	0	0	0	0	0	0	0	0
a	0	0	0	0	0	0	0	0	1

Q R 0 I

Transition Matrix (cont'd)

$N = (I - Q)^{-1}$: *fundamental matrix*

- Gauss – Jordan elimination

$N_{i,j}$: Expected number of visits to state j starting from state i

- $V = 1_s * N,\ where\ 1_s = \vec{\pi}^{(0)}$

Column vector D (expected duration of each state)

- $V * D$: expected delay of activation procedure

Column vector E (expected energy consumption of each state)

- $V * E$: expected energy consumption of activation procedure

0	~~p_{s,r_1}~~ 1	0	0	0	0	0	0	0
0	0	p_{r_1,p_1}	0	p_{r_1,r_2}	0	0	0	0
0	0	0	p_{p_1,c_1}	p_{p_1,r_2}	0	0	~~$p_{p_1,w}$~~ 0	0
0	0	0	0	p_{c_1,r_2}	0	0	$p_{c_1,w}$	$p_{c_1,a}$
0	0	0	0	0	p_{r_2,p_2}	0	$p_{r_2,w}$	0
0	0	0	0	0	0	p_{p_2,c_2}	$p_{p_2,w}$	0
0	0	0	0	0	0	0	$p_{c_2,w}$	$p_{c_2,a}$
~~$p_{w,s}$~~ 1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1

Q R
0 I

Performance Evaluation

Scilab environment

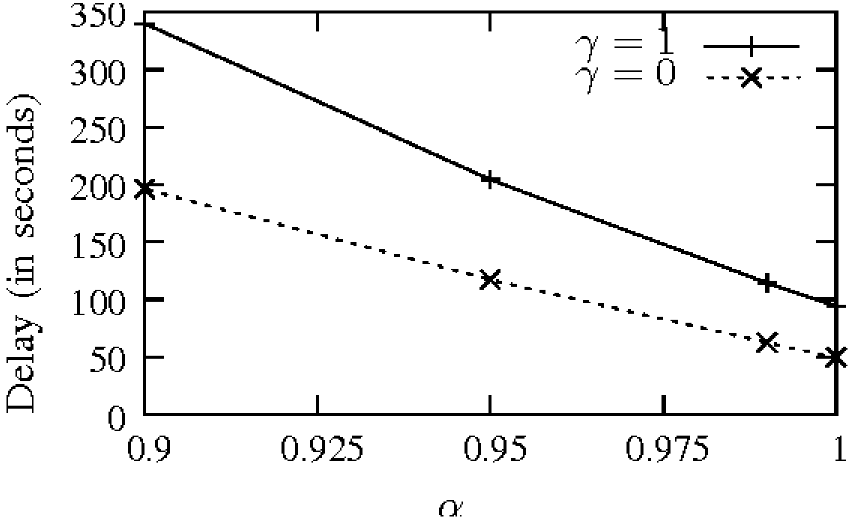
Key parameters: channel quality a, used receive window γ

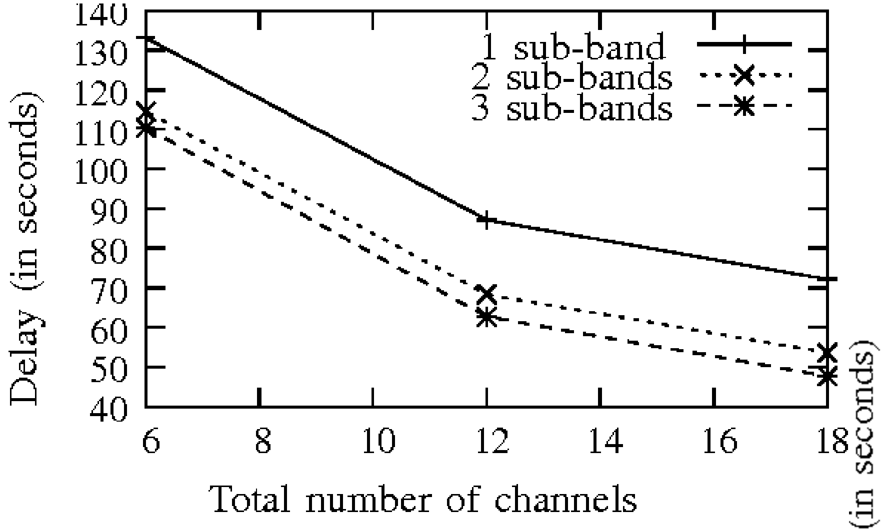
- $a \in [0, 1]$
  - 0: low quality
  - 1: high quality
- $\gamma = \{0, 1\}$
  - 0: 2^{nd} receive window
  - 1: 1^{st} receive window

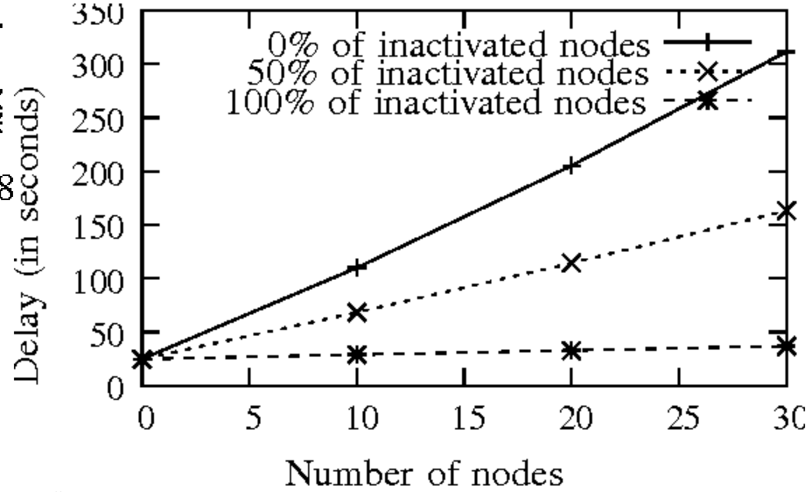
Assumptions for other parameters as well (network saturation, # of channels, # of sub-bands, # of inactivated / activated EDs, duty cycle)

Energy consumption setting from Semtech (SX1272)

Expected delay to activation







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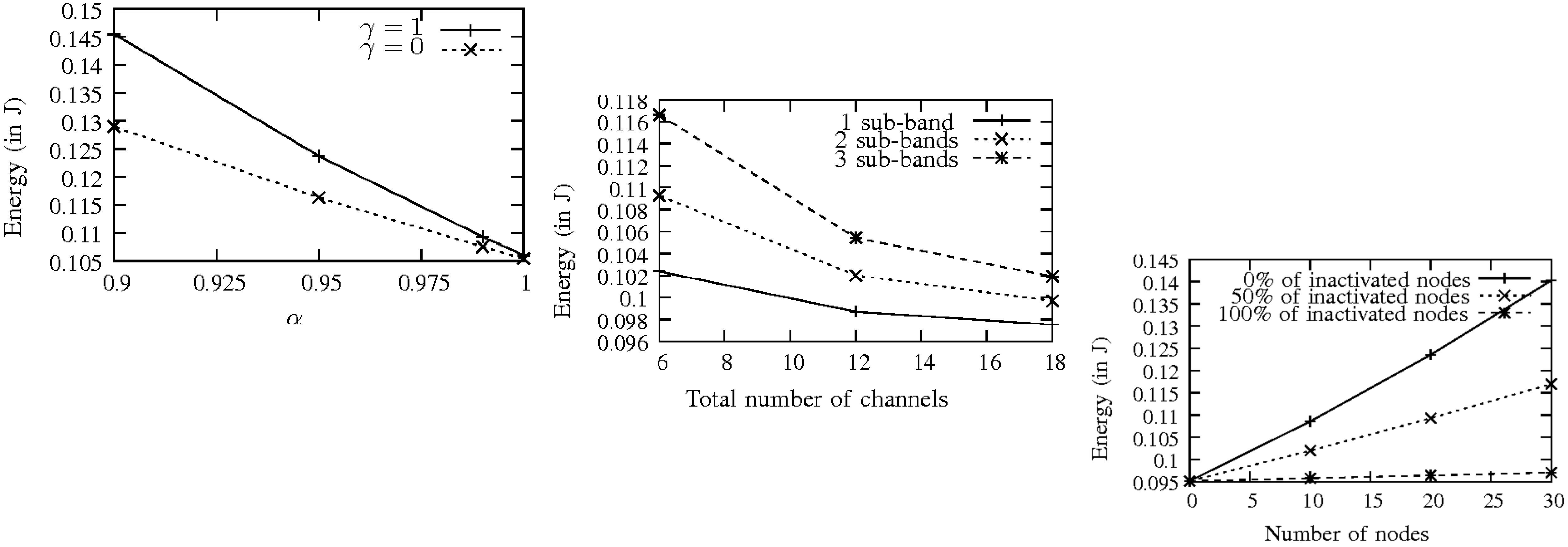
Expected energy consumed



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Outlines of the paper

Low channel quality leads to packet losses → EDs visit more often state *Wait* → delay issues due to duty cycle

More sub-bands → more traffic → more collisions → delay issues

- But *Wait* state lasts less due to more sub-bands (duty cycle applies to each sub-band)

***Wait* state duration has greater impact than traffic**

Energy follows delay's behavior

- But in figures that are respect to total number of channels the behavior of the two performance metrics is the opposite
- Little detail
  - Delay Vs total number of channels: absolute difference is steady among the sub-bands but proportion changes
  - Energy Vs total number of channels: absolute difference changes among the sub-bands but proportion is steady

Outlines of the paper (cont'd)

Assumptions: No capture effect, 1 GW, Data Rate 0 - DR0 (Spreading Factor 12 - SF12), EU868 bands

US915 bands

- dedicated DL channels → no DL / UL interference
- more UL channels → less interference
- DR0 equals SF10

China matches EU case but EDs have less max. transmission power

- Less energy consumption

DR0 = SF12

- higher SF, greater DR changes some of the probabilities in stochastic matrix
- Most important: smaller Time On Air (ToA)
  - smaller collision probability
  - less *Wait* state duration

Summing up

LPWAN paradigm: a new IoT networking family

LoRa/LoRaWAN: a top-down approach

Research challenges and methodology

Discussion on our simulations and experimental testbed

Stochastic Modeling – Discrete Time Markov Chains: Definitions, Terminology, Key Properties

Modeling of LoRaWAN Access

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