Overview of research and development in the domain of IoT + ML@edge

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127.0.0.1

FTN (EE + CS department) and Technology Park

Novi Sad, Serbia

Dream team - ICONIC centre

About myself

- Teaching university courses in Electronics Fundamentals, Embedded Systems, Robotics and IoT since 2005
- Defended PhD thesis in WS(R)N (2015)
- Things I do for living, including but not limited to:
  - HW/SW co-design: PCB design + FW development
  - Sensors and actuators in mechatronics/robotics and IoT
  - IoT @edge: emphasis on LPWAN (LoRaWAN and NB-IoT)
  - IoT @server/cloud: Frontend + Backend+ DB design
  - **Lightweight ML @edge**
- Things I do for fun: features of low relevance for this presentation, therefore excluded in order to simplify the model

Challenges and motivation for TinyML

Principles of efficient and scalable IoT design:

- Ultra low-power HW
- Low-throughput communication
- Size matters!
- Security is mandatory

ML @edge motivation:

- Reduce comunication overhead
- Offload the work from the cloud by distributing the inference
- Fine-tune ML models to suit individual use cases

Implementation Flow:

- Create the dataset
- Properly label the dataset - **a huge challenge!**
- Training might be cumbersome, inference must be tiny => **NO PYTHON @EDGE!!!**
- Reduce the footprint of ML models without compromising the performance

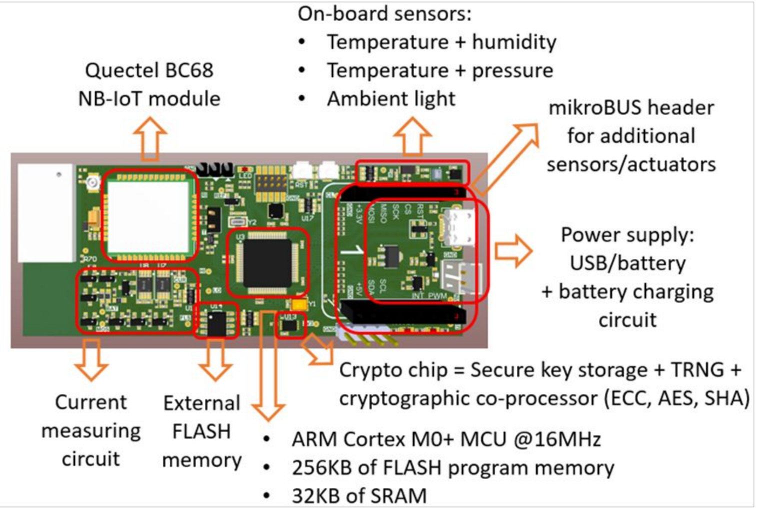
	Energy (J)
(c) C	1.00
(c) Rust	1.03
(c) C++	1.34
(c) Ada	1.70
(v) Java	1.98
(c) Pascal	2.14
(c) Chapel	2.18
(v) Lisp	2.27
(c) Ocaml	2.40
(c) Fortran	2.52
(c) Swift	2.79
(c) Haskell	3.10
(v) C#	3.14
(c) Go	3.23
(i) Dart	3.83
(v) F#	4.13
(i) JavaScript	4.45
(v) Racket	7.91
(i) TypeScript	21.50
(i) Hack	24.02
(i) PHP	29.30
(v) Erlang	42.23
(i) Lua	45.98
(i) Jruby	46.54
(i) Ruby	69.91
(i) Python	75.88
(i) Perl	79.58

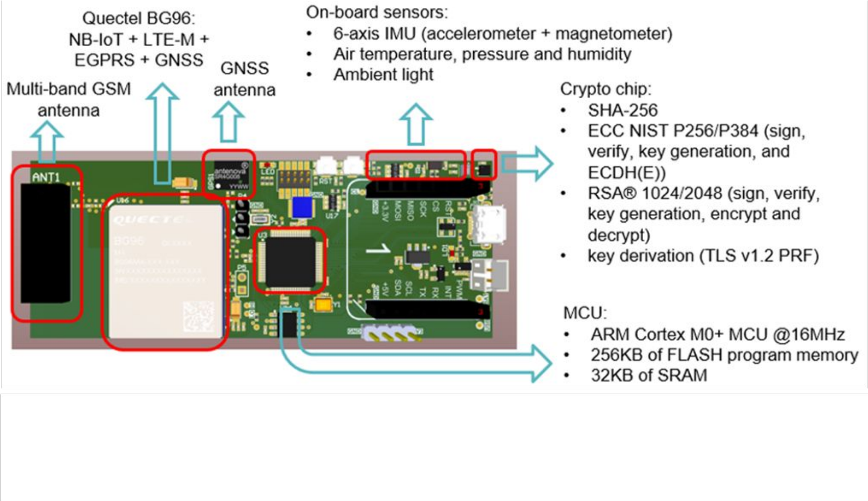
	Time (ms)
(c) C	1.00
(c) Rust	1.04
(c) C++	1.56
(c) Ada	1.85
(v) Java	1.89
(c) Chapel	2.14
(c) Go	2.83
(c) Pascal	3.02
(c) Ocaml	3.09
(v) C#	3.14
(v) Lisp	3.40
(c) Haskell	3.55
(c) Swift	4.20
(c) Fortran	4.20
(v) F#	6.30
(i) JavaScript	6.52
(i) Dart	6.67
(v) Racket	11.27
(i) Hack	26.99
(i) PHP	27.64
(v) Erlang	36.71
(i) Jruby	43.44
(i) TypeScript	46.20
(i) Ruby	59.34
(i) Perl	65.79
(i) Python	71.90
(i) Lua	82.91

	Mb
(c) Pascal	1.00
(c) Go	1.05
(c) C	1.17
(c) Fortran	1.24
(c) C++	1.34
(c) Ada	1.47
(c) Rust	1.54
(v) Lisp	1.92
(c) Haskell	2.45
(i) PHP	2.57
(c) Swift	2.71
(i) Python	2.80
(c) Ocaml	2.82
(v) C#	2.85
(i) Hack	3.34
(v) Racket	3.52
(i) Ruby	3.97
(c) Chapel	4.00
(v) F#	4.25
(i) JavaScript	4.59
(i) TypeScript	4.69
(v) Java	6.01
(i) Perl	6.62
(i) Lua	6.72
(v) Erlang	7.20
(i) Dart	8.64
(i) Jruby	19.84

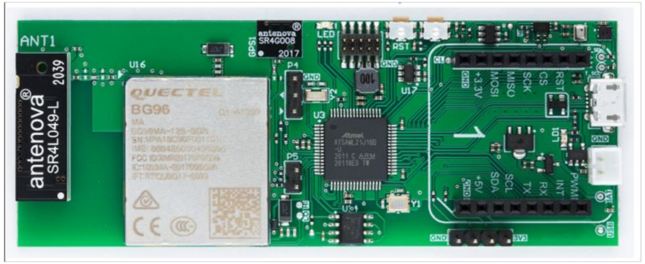
The global results (on average) for Energy, Time, and Mb normalized to the most efficient language in that category. **Source:** Pereira, et al. (2021)

Our babies <3





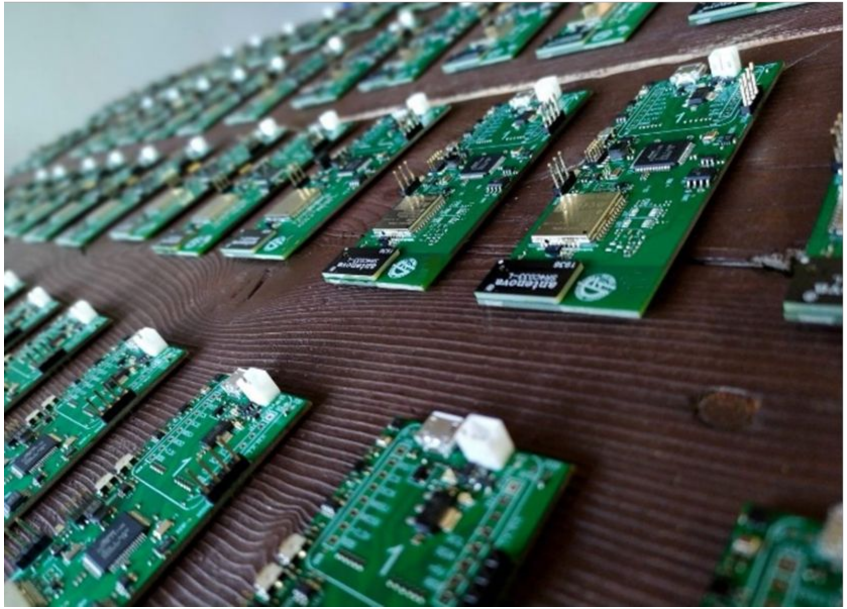
NB-IoT node v1

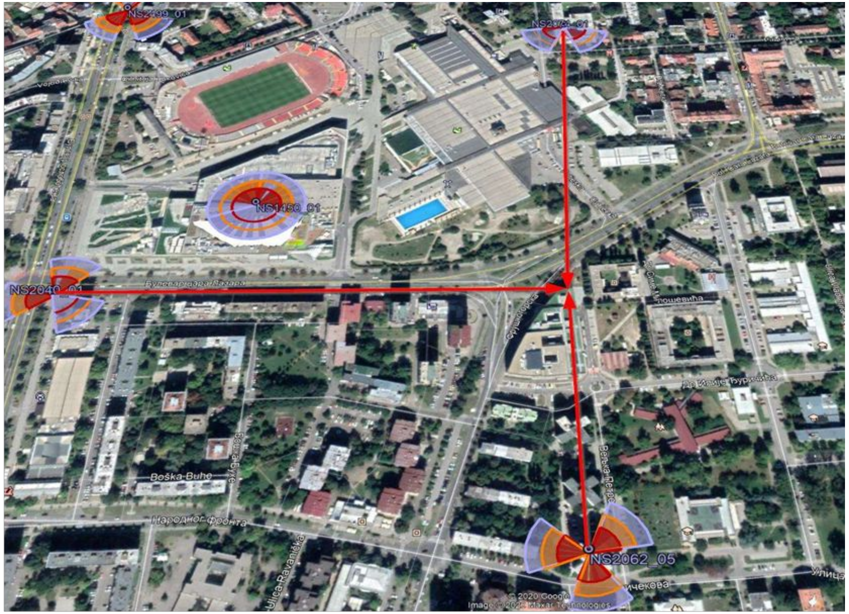


NB-IoT node v2

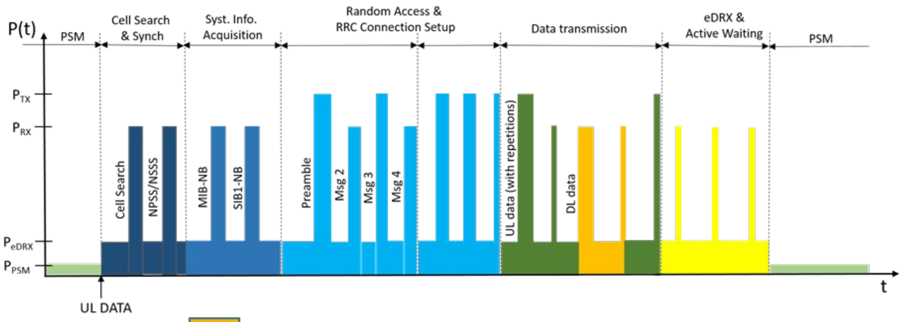
3GPP NB-IoT testbed

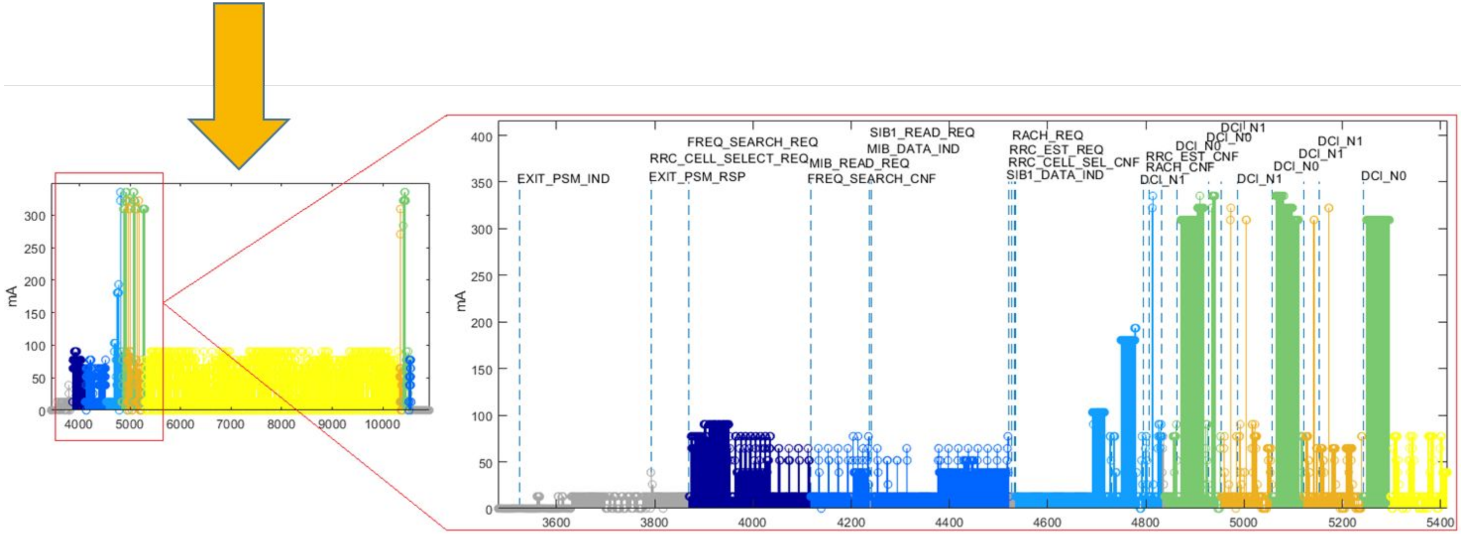
- Static Testbed: 80 NB-IoT devices with various sensors (T/H/P, illumination, etc.) for Smart Building applications (H2020 SENSIBLE)
- Mobile Testbed: 50 NB-IoT devices with GPS/accelerometers for Smart Logistics applications (H2020 C4IIoT)



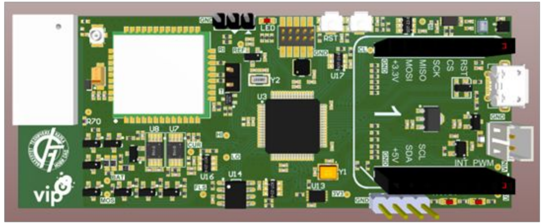


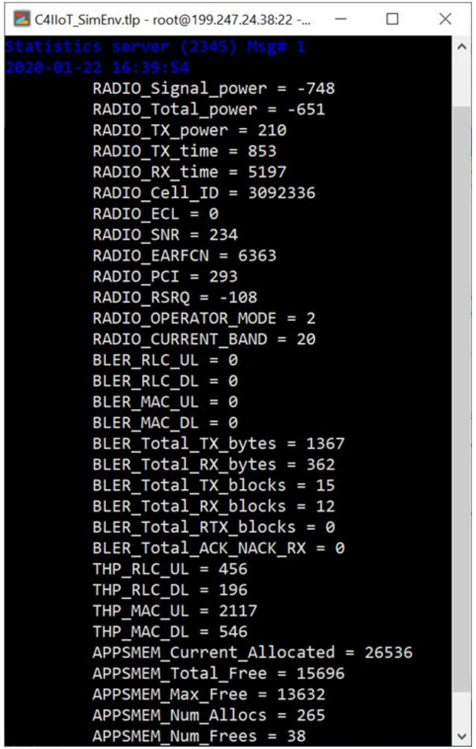
Challenge #1: Estimating Energy Consumption of NB-IoT Modules

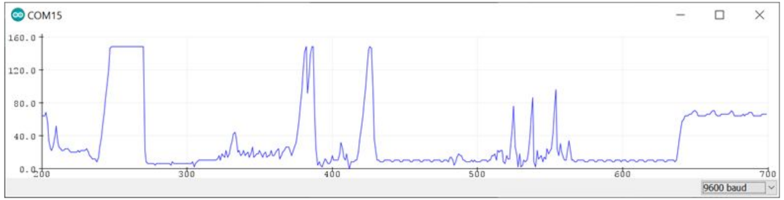




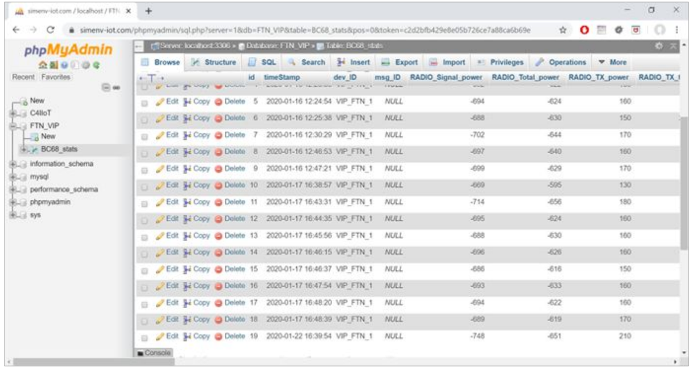
Testing and Data Gathering in NB-IoT network

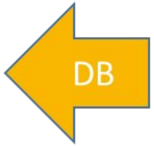






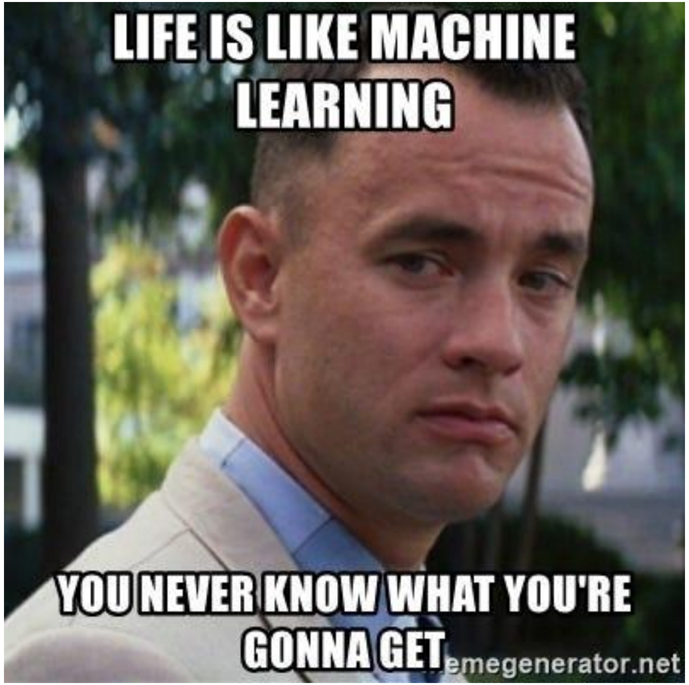
1) Precise NB-IoT Module Power Consumption



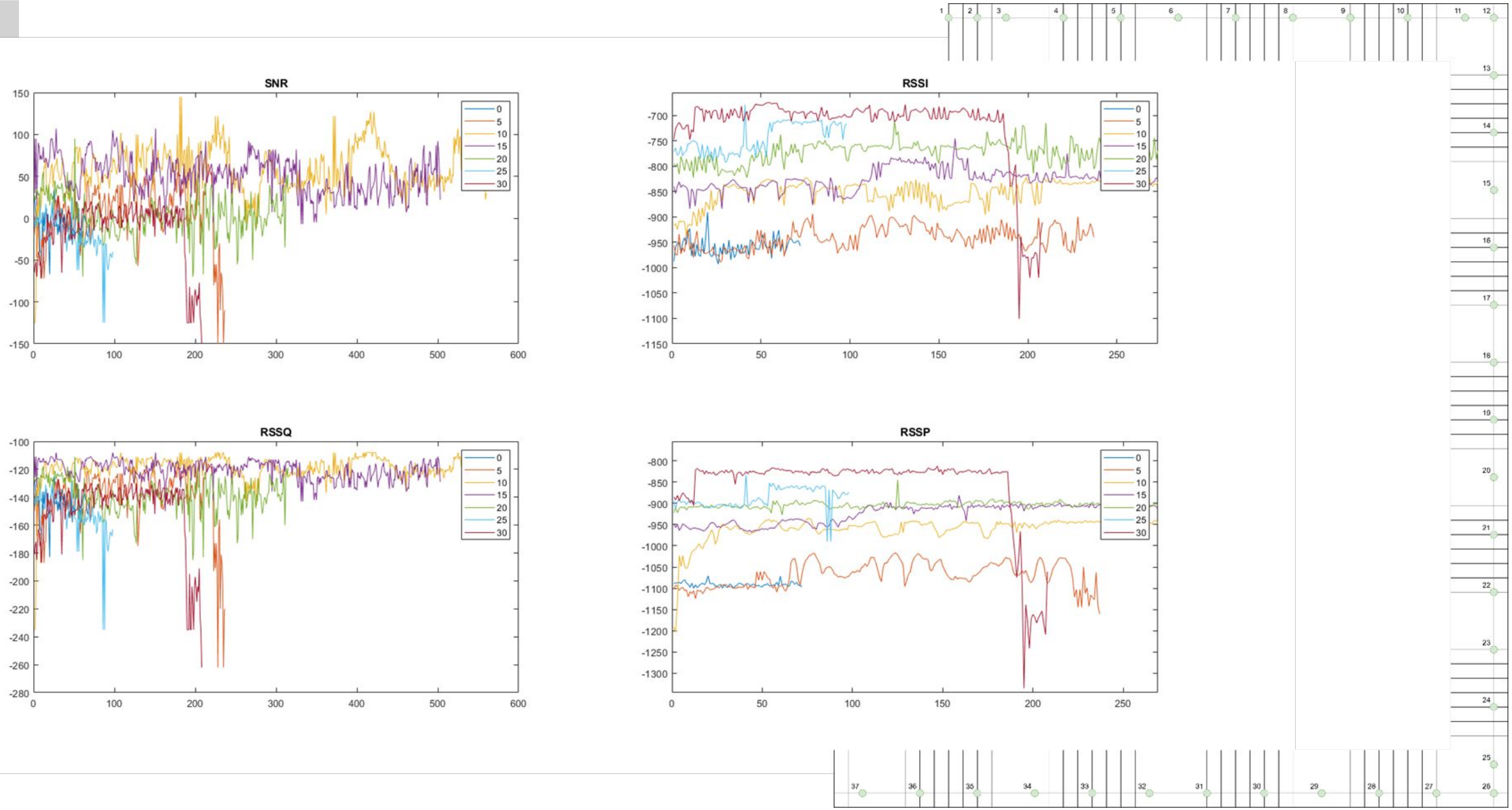


2) Complete UE-eNB Message Exchange Log

Unexpected plot twist



NB-IoT enabled indoor localization



Publications (1)

Already published:

In-depth Real-World Evaluation of NB-IoT Module Energy Consumption
M Lukic, S Sobot, I Mezei, D Danilovic, D Vukobratovic
2020 IEEE International Conference on Smart Internet of Things (SmartIoT)

3GPP NB-IoT for Smart Environments: Testbed Experimentation and Use Cases
M Lukic, S Sobot, I Mezei, D Vukobratovic
IEICE Proceedings Series 64 (ICTF2020_paper_27)

Secured by hardware client-server communication based on NB-IoT technology
D Bortnik, V Nikić, M Lukić, I Mezei
2021 Zooming Innovation in Consumer Technologies Conference (ZINC)

Firmware Updates Over The Air Using NB-IoT Wireless Technology
V Nikic, D Bortnik, M Lukic, I Mezei
2021 29th Telecommunications Forum (TELFOR)

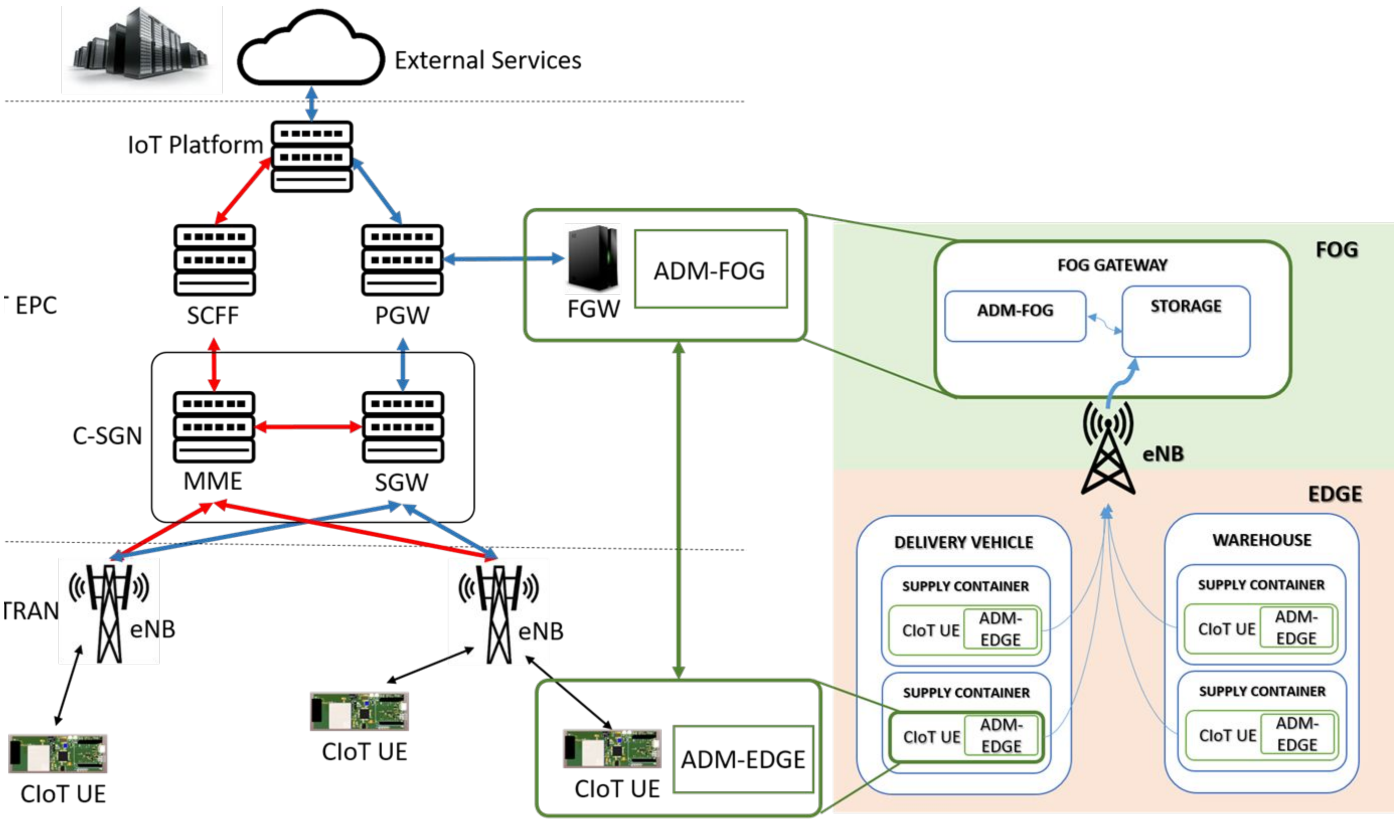
Comparisons of firmware delta updates over the air using WLAN and LPWAN technologies
V Nikic, D Bortnik, M Lukic, D Danilovic, I Mezei
2022 30th Telecommunications Forum (TELFOR)

Two-Tier UAV-based Low Power Wide Area Networks: A Testbed and Experimentation Study
S Sobot, M Lukic, D Bortnik, V Nikic, B Lima, M Beko, D Vukobratovic
2023 6th Conference on Cloud and Internet of Things (CIoT)

In preparation:

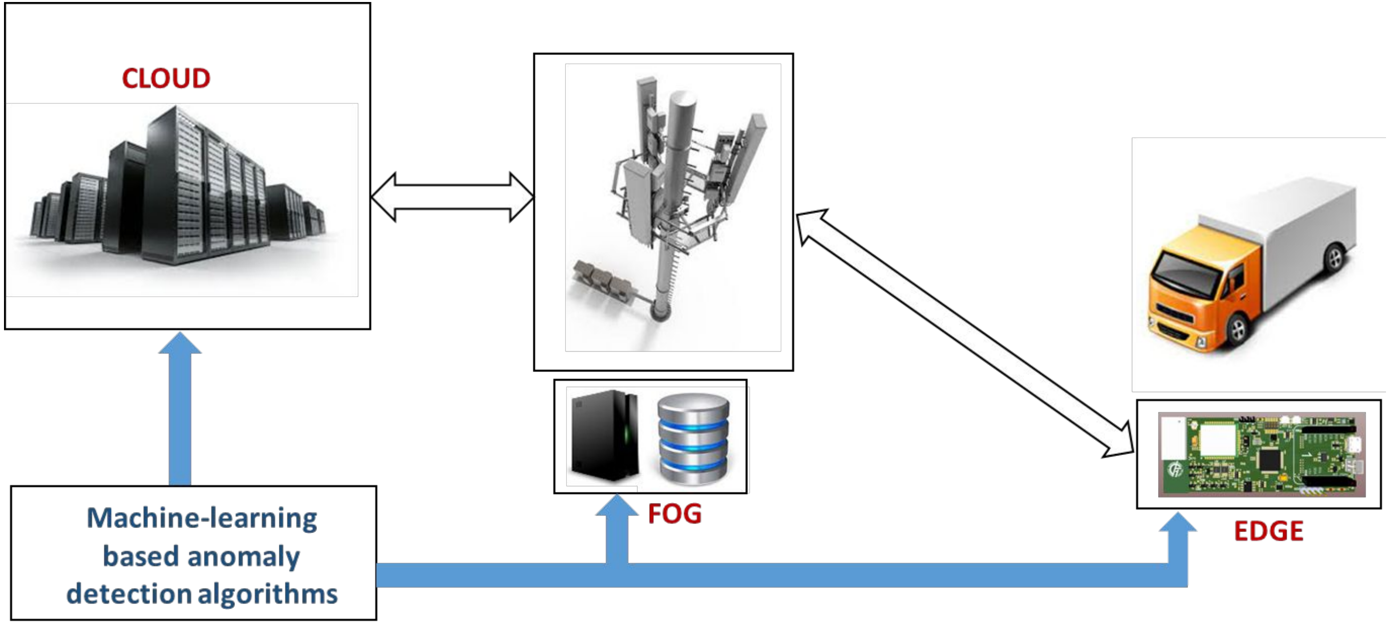
- **ML estimator of NB-IoT module power consumption based on radio parameters**
- **Indoor NB-IoT device localization based on radio fingerprinting**

Challenge #2: H2020 C4IIoT - Cyber security in Industrial IoT

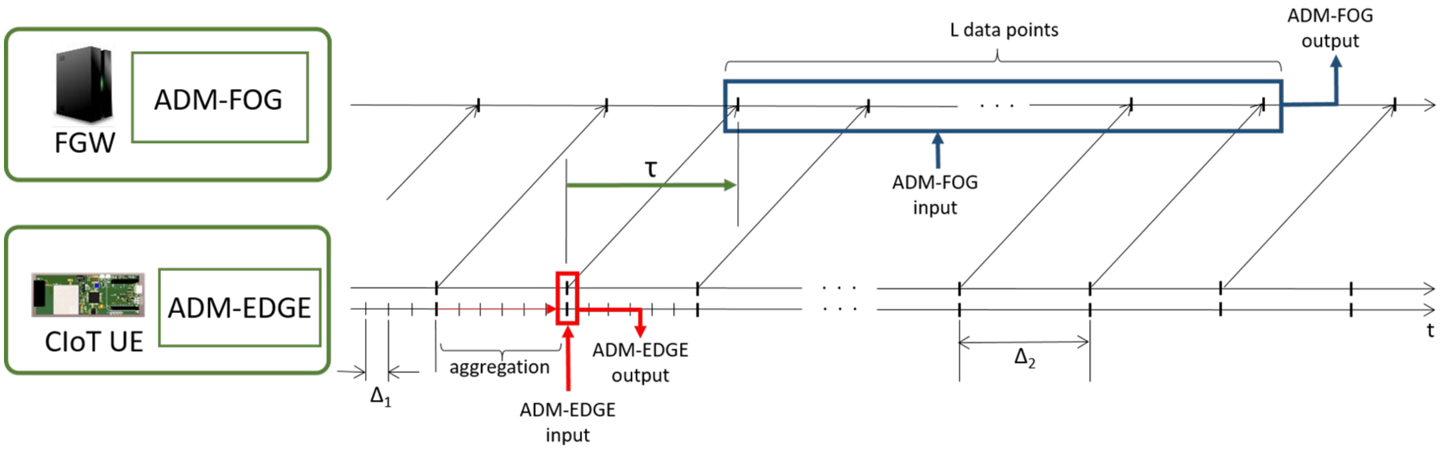


Deep Autoencoder Anomaly Detection in Smart Logistics

- NB-IoT device collects IMU data from logistics containers and uses anomaly detection to flag unusual behavior
- ML-based anomaly detection across three layers: Edge device, Fog Gateway and Cloud



Sampling vs Delay at ADM-EDGE and ADM-FOG



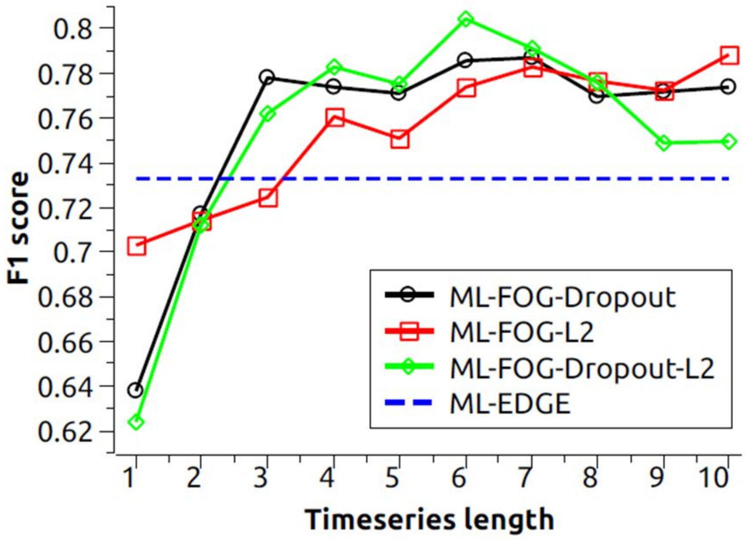
- ML-EDGE provides immediate decisions after each data - fast response time
- ML-FOG uses more powerful design (longer feature vector, complex architecture)
- NB-IoT uplink can be a bottleneck and cause unpredictable delays
- ML-EDGE module has access to raw data
- ML-FOG gets access to data aggregated by ML-EDGE in order to reduce communication load
- The final decision at the system level is achieved in coordination of ML orchestration engine

Example results: ADM-EDGE vs ADM-FOG

- ML-EDGE – single data point, single hidden layer
- ML-FOG – k data points, three hidden layers
- Dropout, L2 and combined regularization
- Compared by Precision, Recall and F1
- Time delay of ML-FOG depends on k

TABLE I: Evaluation of ML-EDGE autoencoders.

	Precision	Recall	F_1
ML-EDGE-Base	0.7047	0.6897	0.6971
ML-EDGE-Dropout	0.7349	0.6769	0.7047
ML-EDGE-L2	0.7926	0.6821	0.7332
ML-EDGE-Dropout-L2	0.7661	0.6821	0.7216



Publications (2)

Deep Learning Anomaly Detection for Cellular IoT with Applications in Smart Logistics

M Savic, M Lukic, D Danilovic, Z Bodroski, D Bajovic, I Mezei, D Vukobratovic, S Skrbic, D Jakovetic

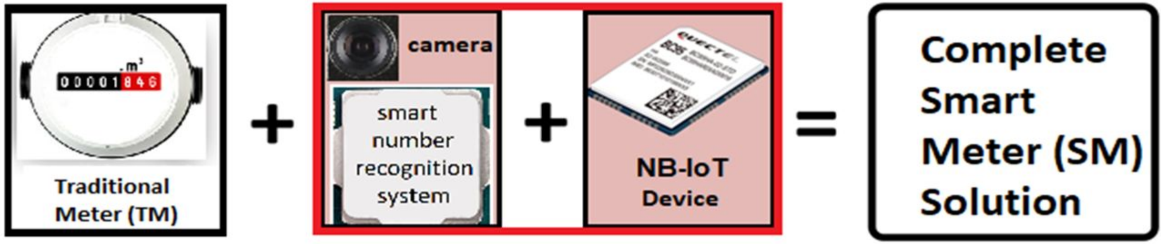
IEEE Access 9, 59406-59419

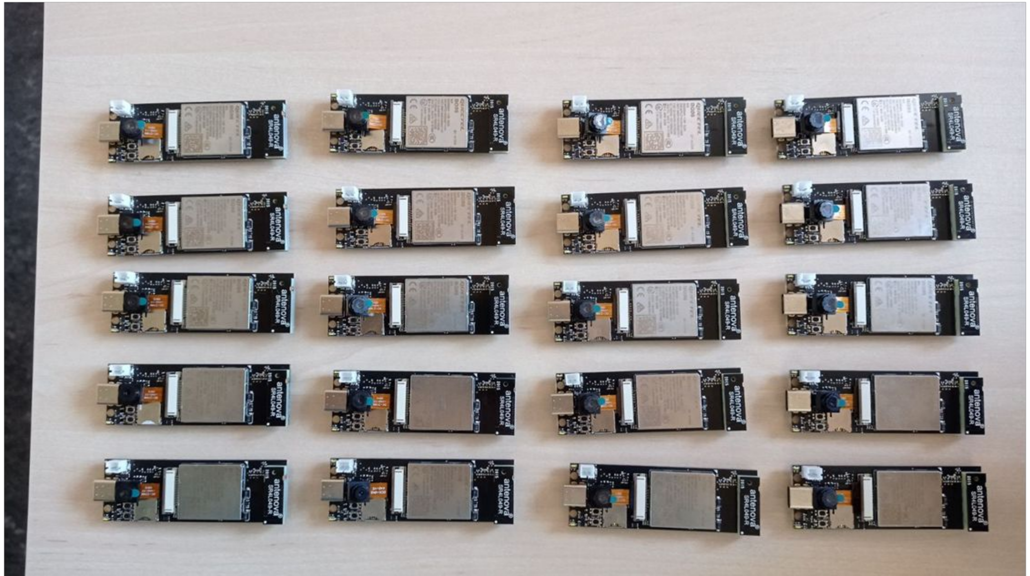
Cybersecurity 4.0 Industrial Internet of Things: Architecture, Models and Lessons Learned

G Bravos et al.

IEEE Access 10, 124747-124765

Challenge #3: NB-IoT Devices for Digit Recognition





NB-IoT + CAM node architecture

ESP32 MCU:

- 32-bit dual core
- 240MHz
- 520KB SRAM
- 8MB FLASH)

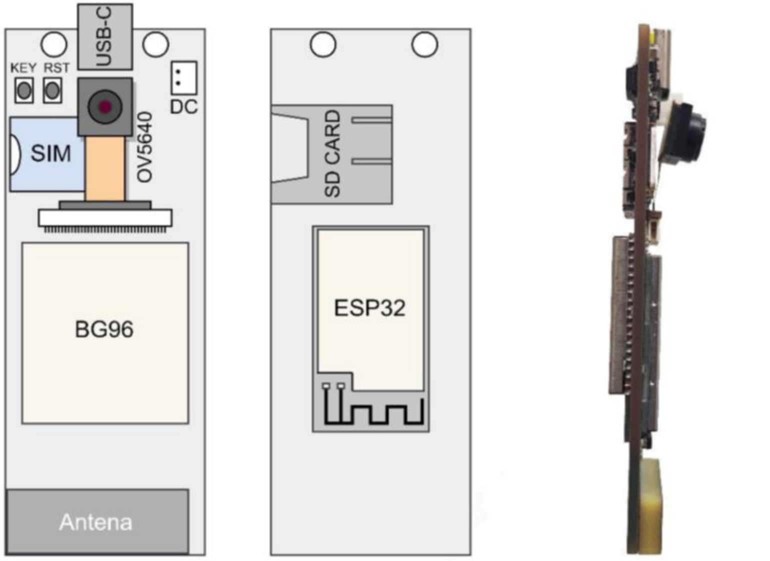
Communication:

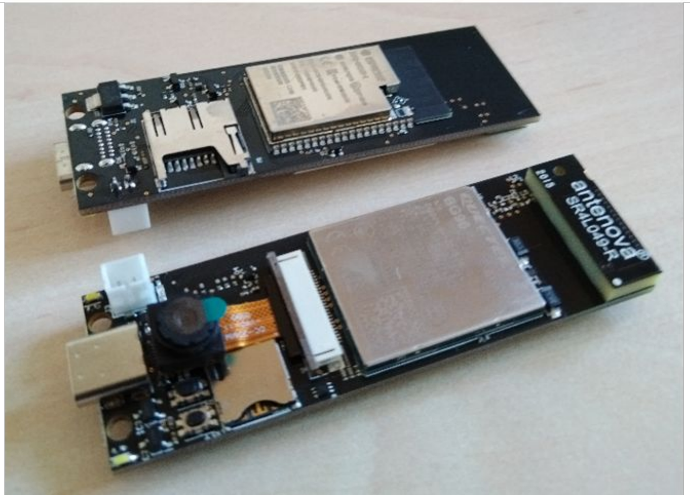
- Quectel BG96 (NB-IoT + LTE-M + GPRS)
- WiFi + Bluetooth Classic + BLE (integrated within ESP32)

Camera:

- OV5640 5 Megapixel

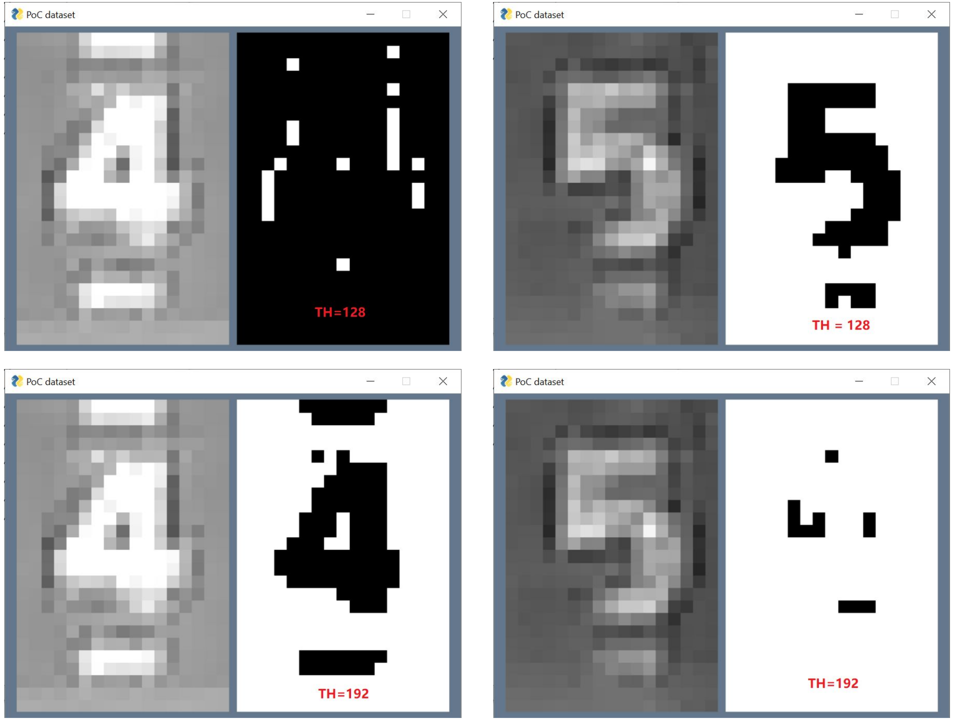
SD card for local data logging





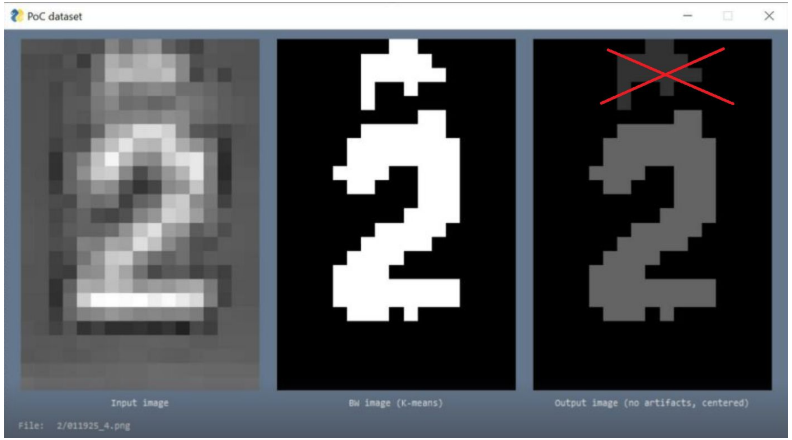
50++ shades of gray

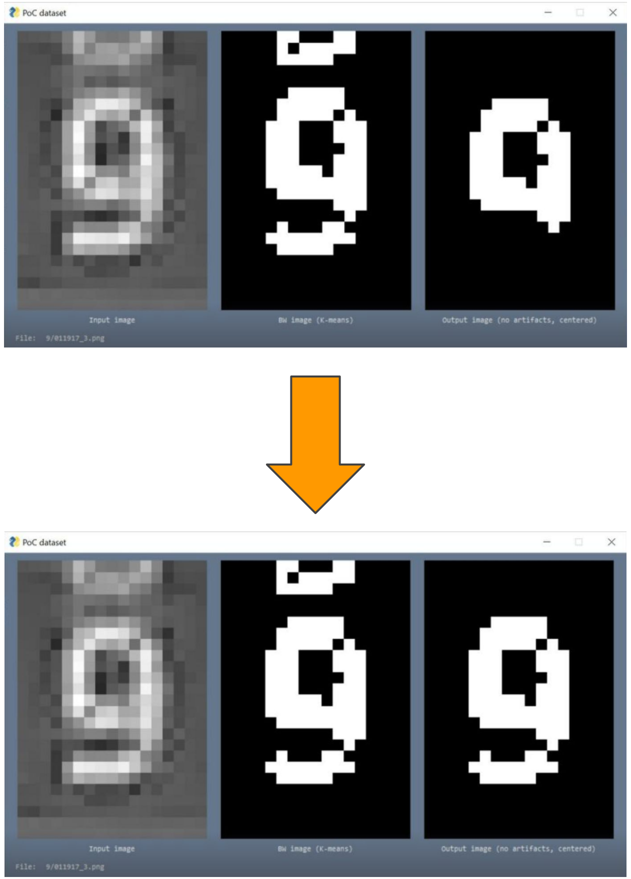
- Picture resolution 17x25
- Using grayscale pictures -> reduction from 24 to 8 bits/pixel
- Transforming to B/W -> reduction from 8 to 1 bit/pixel
- One threshold to rule them all? -> **BAD IDEA**



Cleaning up the mess

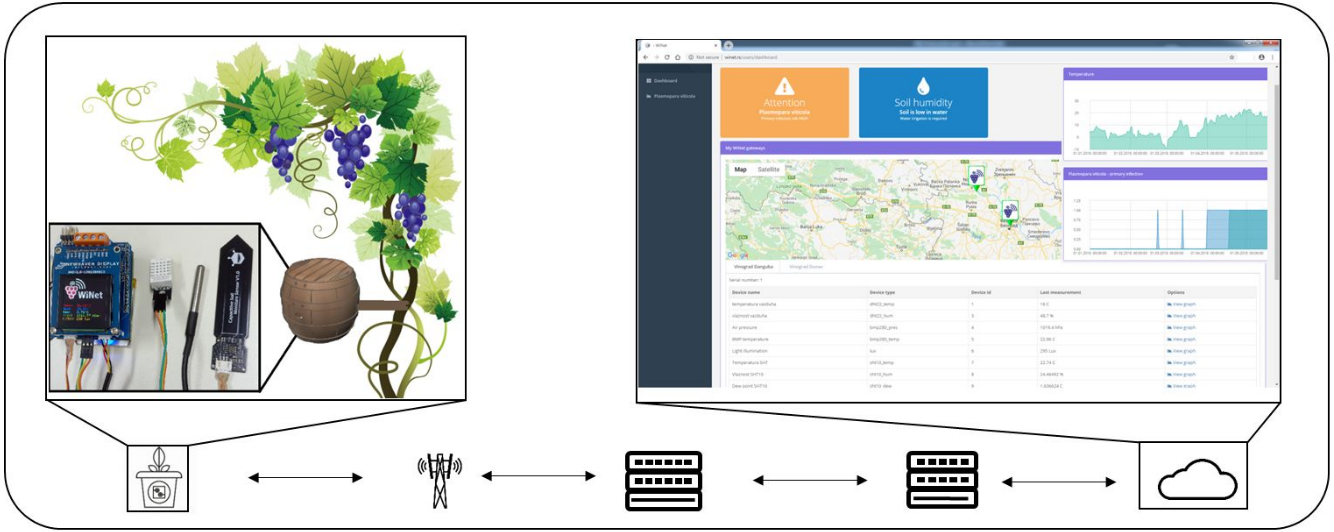
- Transformation to B/W -> **k-means clustering, k=2**
- Eliminating artifacts -> coloring algorithm
- Improvement: merge differently colored areas that have pixels touching in corners
- After preprocessing, the NN for digit recognition achieved >98% of accuracy





To transmit or not to transmit, that is the question…

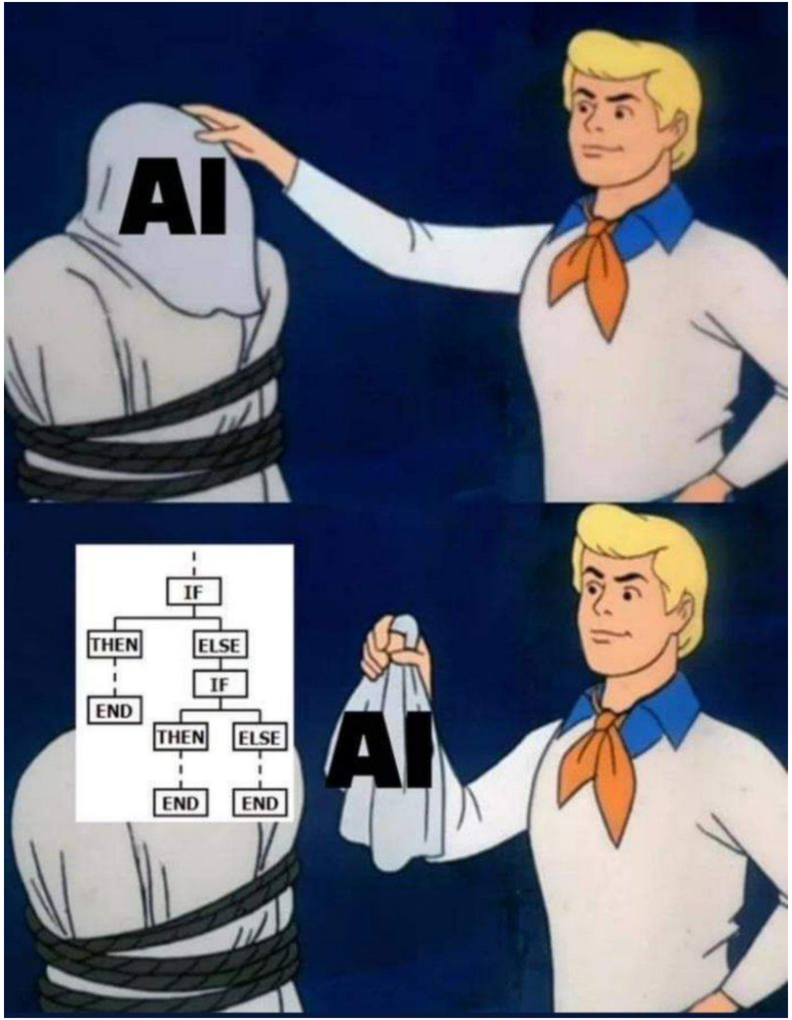
Challenge #4: Detection of fungal disease outbreak risk in agriculture

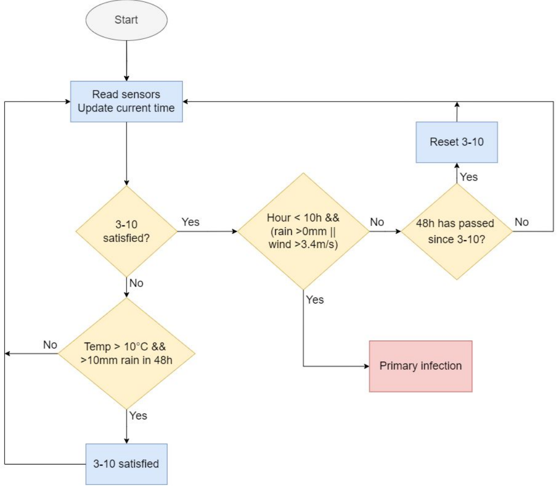


Grapevine Downy Mildew Warning System Based on NB-IoT and Energy Harvesting Technology

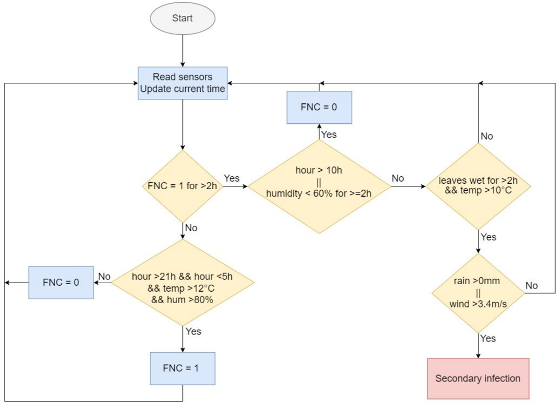
I Mezei, M Lukić, L Berbakov, B Pavković, B Radovanović

Electronics 11 (3), 356





Algorithm for primary infection alarms



Algorithm for secondary infection alarms

Thank You!

Grazie!

Хвала!

谢谢你!

Merci！

Danke！

¡Gracias!