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

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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
- 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 communication 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
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

**On-board sensors:**
- Temperature + humidity
- Temperature + pressure
- Ambient light

**micrOBUS header**
for additional sensors/actuators

**Power supply:**
USB/battery + battery charging circuit

Crypto chip = Secure key storage + TRNG + cryptographic co-processor (ECC, AES, SHA)

- ARM Cortex M0+ MCU @16MHz
- 256KB of FLASH program memory
- 32KB of SRAM

**Quectel BC68**
NB-IoT module

**Multi-band GSM antenna**

**GNSS antenna**

**On-board sensors:**
- 6-axis IMU (accelerometer + magnetometer)
- Air temperature, pressure and humidity
- Ambient light

**Crypto chip:**
- SHA-256
- ECC NIST P256/P384 (sign, verify, key generation, and ECDH(E))
- RSA® 1024/2048 (sign, verify, key generation, encrypt and decrypt)
- Key derivation (TLS v1.2 PRF)

**MCU:**
- ARM Cortex M0+ MCU @18MHz
- 256KB of FLASH program memory
- 32KB of SRAM

**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

LIFE IS LIKE MACHINE LEARNING

YOU NEVER KNOW WHAT YOU'RE GONNA GET
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 (CiIoT)

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.**

<table>
<thead>
<tr>
<th></th>
<th>Precision</th>
<th>Recall</th>
<th>$F_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML-EDGE-Base</td>
<td>0.7047</td>
<td>0.6897</td>
<td>0.6971</td>
</tr>
<tr>
<td>ML-EDGE-Dropout</td>
<td>0.7349</td>
<td>0.6769</td>
<td>0.7047</td>
</tr>
<tr>
<td>ML-EDGE-L2</td>
<td>0.7926</td>
<td>0.6821</td>
<td>0.7332</td>
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<tr>
<td>ML-EDGE-Dropout-L2</td>
<td>0.7661</td>
<td>0.6821</td>
<td>0.7216</td>
</tr>
</tbody>
</table>
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!