Developing Fully Autonomous Wireless Monitoring Systems for Smallholder Farmers Communities

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Abstract. Digital innovations still have low penetration in the smallholder farmer (SHF) communities which remain reluctant to adopt such technology-based systems. In this article, we present a robust, cost-effective, power-efficient, wireless and "fully autonomous" sensor system for "out-of-the-box" deployment using long-range LoRa technology. By "fully autonomous" we mean that, by default, the system operates without Internet access and still offers advanced data processing and prediction features. We describe our wireless sensor platform, how we achieved full autonomy for out-of-the-box deployment, how transmission coverage can be improved with transparent and optimized relaying functionalities, and how edge intelligence can be added to the framework. Piloting programs with agriculture service advisors and more than 60 SHFs validated the "fully autonomous" and "out-of-the-box" deployment approach in Algeria and Morocco.

Keywords: Cost-effective IoT · LoRa · Wireless sensor · Edge-AI

1 Introduction

Digital innovation in agriculture is not new, neither is the deployment of ground sensor systems for a smarter control of various agricultural processes, such as irrigation control. However, most of the available commercial solutions from companies in the smart agriculture sector are targeting big farms with high-end sensor systems that are highly specialized, very integrated, difficult to customize and can easily cost several thousand euros. In addition, these solutions heavily rely on cloud servers and proprietary software platforms, requiring customers to be bound to the infrastructure provider.

For all these reasons, digital innovations still have low penetration in the smallholder farmer (SHF) communities. Farmers and other actors are still very reluctant to adopt such technology-based systems. In that context, the PRIMA INTEL-IRRIS project (https://intel-irris.eu/) started in June 1st, 2021 with the ambition to make digital and smart farming technologies more attractive and accessible to SHFs. To address the needs of this community, the proposed solutions must be affordable, able to be integrated into existing farming practices and, most importantly, able to be deployed "out-of-the-box" by farmers themselves. INTEL-IRRIS promotes the concept of "intelligent irrigation in-the-box". Through a participatory piloting approach, INTEL-IRRIS strongly involved more than 60 SHFs and stakeholders into the innovation process itself. The innovative contribution of INTEL-IRRIS is to propose a robust, generic and edge-enabled wireless sensor framework that can be simply and quickly deployed by farmers themselves.

The rest of the paper is organized as follows. Section 2 provides a quick overview of the INTEL-IRRIS's project. Section 3 presents the proposed wireless sensing systems that can be deployed out-of-the-box by farmers. Section 4 then details how INTEL-IRRIS implements the "intelligent irrigation in-the-box" concept by embedding advanced configuration features and AI-based data processing in the edge-enabled IoT gateway. We highlight a proof-of-concept demonstrating the development and integration of custom applications using edge-AI features. Conclusions are given in Section 5.

2 Overview of INTEL-IRRIS project

Proposing cost-effective sensing systems is not new and INTEL-IRRIS have largely been inspired by makers and do-it-yourself (DIY) initiatives as well as by previous contributions [1–3]. There are also recent contributions in the same line than INTEL-IRRIS [4–8]. However, INTEL-IRRIS's unique feature is to propose a robust, power efficient and edge-enabled wireless sensor framework that can be simply and quickly deployed by farmers. Therefore, INTEL-IRRIS's objective is to develop a "fully autonomous" wireless sensor framework that enables "out-of-the-box" deployments by farmers themselves, even when transmission coverage is challenging. Robustness, accuracy and power efficiency that are strong requirements of INTEL-IRRIS make the proposed system an operational wireless monitoring system at TRL7-8.

In order to really provide the "fully autonomous" and "out-of-the-box" features INTEL-IRRIS proposes an architecture where all the control and recommendation system parts are embedded in a low-cost IoT gateway that is deployed locally in a farm, with no connection to Internet servers. Since INTEL-IRRIS focuses on optimizing water usage, we worked with soil specialists and agriculture experts to integrate the complex soil-water-plant-atmosphere interaction model into the gateway itself and provide increased accuracy on recommended actions. The ultimate objective of INTEL-IRRIS is to include agricultural models/knowledge with corrective and predictive analytics – from simple computer-based decision models to more advanced AI-based processing – in order to adapt the applied control to local conditions and practice (dry region, open field or greenhouse) and crop/plant varieties that usually have different water need profiles at their various stages of development.

Therefore, INTEL-IRRIS developed a starter kit where 1 pre-configured sensor device and 1 edge-enabled gateway are ready to be deployed by smallholders.

The sensor device can have a Gravity SEN0308 capacitive sensor from DFRobots or a Watermark tensiometer WM200 from Irrometer, see Fig. 2. Additional sensor devices can be added incrementally.

3 A cost-effective, autonomous wireless sensor system

3.1 The cost-effective hardware sensing platform

The cost-effective and open-source hardware platform is based on a DIY design that has been initially developed and validated in 2 EU H2020 projects (WAZIUP and WAZIHUB) with piloting sites deployed in several sub-Saharan countries. When INTEL-IRRIS started, the PCB v2 in Fig. 1 was deployed. INTEL-IRRIS's partner IRD (Institut de Recherche pour le Développement) improved the initial design to easily connect various types of sensor as well as to provide support for solar panel charging leading to the latest versions: v4.1 with raw LoRa and v5 with full LoRaWAN support. The PCBs manufacturing files are available and the fully assembled PCB can be ordered online from manufacturers for a cost of about 8€/unit for 80 units and above.

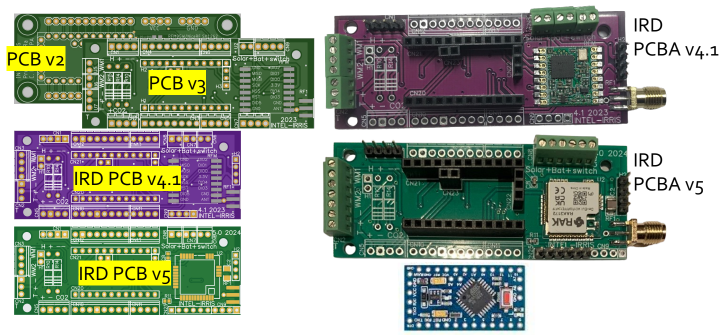

Fig. 1. The generic hardware platform evolution from v2 to v5. On the right side, the two assembled PCBs (PCBAs) allow easier deployment with terminal block connectors and header for the Arduino ProMini microcontroller.

The separate microcontroller that needs to be added (about 2€ to be added) and plugged on the PCB is the Arduino ProMini in its 3.3V and 8MHz version. Software building blocks include physical sensor management, long-range data transmission with LoRa radio technology and advanced power management that allows the device to be fully autonomous for more than 2 years when running on 2 AA batteries and transmitting data once every 60 mins [9]. Various power management mechanisms are included to prevent the board from draining the battery: mitigation of reboot loops due to low voltage, automatic increase of the data measurement period when battery levels go too low, etc. Fig. 2 and 3 show the off-the-shelf but robust integration where a solar panel option can be enabled if needed. The integration steps have been validated during numerous hackathons and capacity-building events, and we have devices that have been deployed and running for more than 3 years in harsh outdoor conditions.

Fig. 2. Off-the-shelf integration: the device's components, including sensors, can be chosen and obtained separately and independently, thus improving flexibility.

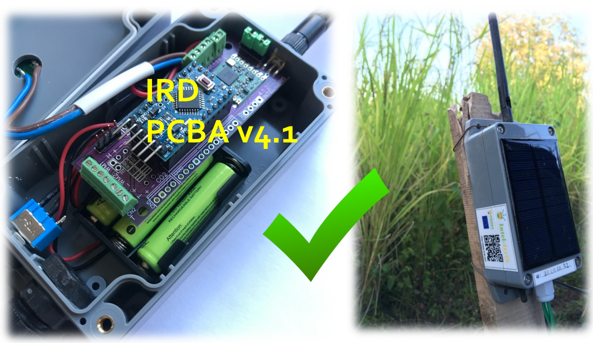

Fig. 3. Robust integration for outdoor deployment. The device is water-proof and designed for harsh climate conditions (sun exposure, temperature changes) in the field.

3.2 Raw LoRa or full LoRaWAN?

As shown in Fig. 1, there are 2 versions of the PCB that can be ordered from PCB manufacturers: v4.1 with raw LoRa radio module provided by an RFM95/96 and v5 with full LoRaWAN support provided by the RAK3172 radio module. The v4.1 can transmit LoRaWAN formatted uplink packets and can receive application-level downlink packets but does not have the full LoRaWAN protocol stack with link layer control such as Adaptive Data Rate nor Over-The-Air-Activation (OTAA) with Join procedure. Most of the starter kits distributed to smallholders for the piloting program are based on v4.1 where the sensor devices in the starter kit are already configured in ABP mode (Activation By Personalization) to work out-of-the-box with the IoT gateway. This will be presented in more detail in the next section on the IoT gateway. We use v5 with full LoRaWAN support in larger deployment scenarios where devices need to be registered on the local IoT gateway to enable a local OTAA procedure.

3.3 The edge-enabled IoT gateway

The INTEL-IRRIS edge-enabled IoT gateway is based on the WaziGate framework [10] that has been developed over the years by INTEL-IRRIS's partner WAZIUP e.V. Foundation in the context of several international Research & Development projects. WaziGate itself took its root from the early "Low-cost LoRa IoT gateway" framework [11] developed by the University of Pau since 2015, an open and versatile LoRa IoT gateway on a Raspberry Pi (RPi). WaziGate is now a separate development line with a maturity level of TRL8-9. The WaziGate framework is highly suitable for implementing the edge-enabled IoT gateway approach as customized applications can be hosted in the gateway and use its innovative features for fully edge operation mode such as embedded Network Server, Application Server (including databases), data visualization dashboard and management of application software containers. The default operating mode when deploying the infrastructure for remote rural communities is the full edge mode, without external connection. However, cloud synchronization as well as remote management can be enabled if an Internet connection is available, and if this is desirable.

WaziGate architecture The WaziGate software framework uses a microservice architecture to manage all local applications (referred to as WaziApps). This architecture allows each WaziApp to operate independently and in isolation using Docker containers. In addition, all WaziGate's components expose a well-defined API enabling efficient and secured calls to all WaziGate's services by user-defined WaziApps. WaziApps can be written in various programming languages and they communicate through a set of restful APIs. Actually, even the WaziGate's system components are considered as independent WaziApps interacting with each other through APIs. INTEL-IRRIS added backup and extraction scripts directly on the RPi [9].

The WaziGate dashboard For the smallholders, the WaziGate's main component is the dashboard that offers an intuitive interface with a simple data visualization module. Figure 4 illustrates the dashboard and also shows the responsive web interface allowing farmers to use a smartphone to interact with the dashboard that is locally accessible after connecting to the gateway's WiFi access point (by simply flashing a QR code). Besides, the gateway always displays simple irrigation notifications on a small embedded OLED screen to provide a more direct interface to smallholders.

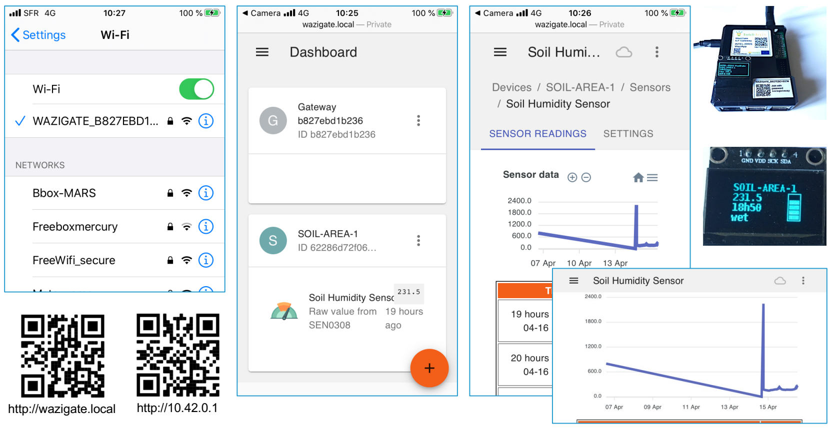

Fig. 4. The WaziGate's dashboard with generic sensor data visualization. The Gateway (top-right) hosts a WiFi cell and a dashboard the farmer can access scanning the QR (bottom-left) on a smartphone, displaying detailed data from devices and sensors.

The INTEL-IRRIS starter kit comes with a pre-configured dashboard. When the INTEL-IRRIS WaziGate boots up, the soil moisture sensor devices are already registered into the dashboard. When powering on the devices, new data will be received and displayed in the dashboard without needing any additional configuration as illustrated by Fig. 5. This feature definitely contributes to make the deployment of the kit simple thus increasing technology adoption by SHFs.

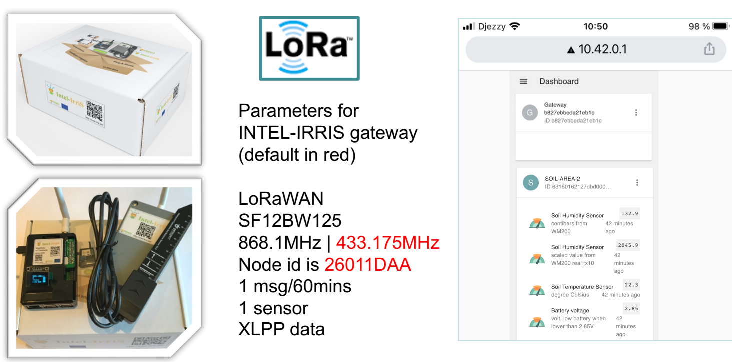

Fig. 5. The INTEL-IRRIS starter kit for out-of-the-box deployment: the pre-configuration enables a simple "power up and sense" for one Wazigate and one device.

The gateway radio hardware For a very cost-effective gateway targeting SHF communities, we use and deploy a single-channel gateway where a regular LoRa radio module provides the connectivity with deployed end-devices, most likely based on PCB v4.1. The simple RFM95/96 PCB breakout designed in the early "Low-cost LoRa IoT gateway" framework [11] can be integrated easily. An external RTC module can be plugged to provide accurate time information, required to store the collected data. A more integrated LoRa radio hat has also been designed by WAZIUP e.V. with an embedded RTC module. In case a full LoRaWAN connectivity (in particular its multi-channel feature) is required because some of the end-devices are based on the PCB v5 or come from the commercial market then a radio concentrator hat such as the RAK2245/5146 can be used with the WaziGate software without needing additional configuration.

3.4 Improving transmission coverage: antennas

One of the most frequent issues when deploying a wireless sensing system is the transmission range to the gateway. Even with LoRa, transmissions from devices deployed in plots can have difficulties to reach the locally deployed gateway. This is mainly because gateways that are deployed in local farms are deployed indoor and between 1-1.8m height (on a table or a shelf for instance) to simplify the installation process to an acceptable level by farmers. In addition to the simple antennas used by end-devices and advertised as "3dBi" (usually whip antennas) and "5dBi" (usually sleeve dipole antennas) that have very limited range (about 600m when the gateway is indoor), we tested 2 antennas with a higher gain in an indoor configuration as illustrated in Fig. 6: (1) a commercial fiber glass 5dBi N-connector plugged in a base and (2) a DIY ground plane antenna.

Fig. 6. Indoor higher-gain antennas at the gateway improving coverage.

Results from the tests showed that the performance of the DIY ground plane antenna is very close to those of the commercial fiber glass antenna with a cost of about 1/10th. Both can increase the reception range from about 600m to about 2km in a typical deployment environment. The detailed test results are available from [12]. Despite the much lower cost of the DIY ground plane antenna we favored the commercial fiber glass N-connector on a base solution as the DIY solution would have introduced too much complexity and overwhelming fragility for farmers.

3.5 Improving transmission coverage with relaying

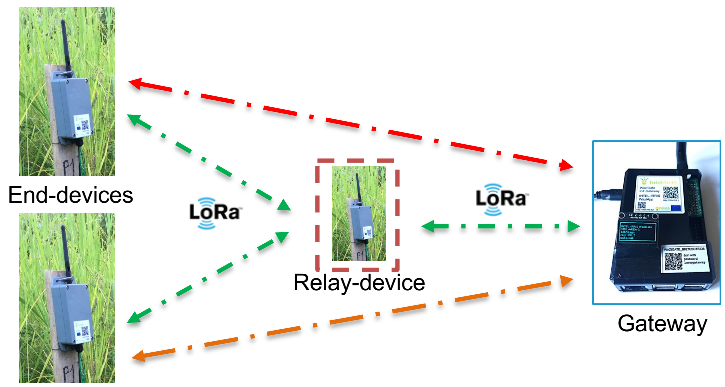

Fig. 7. Introducing intermediate and transparent relaying: shorter links (in green) are more reliable than longer ones (red).

During the piloting program, we observed that some farms still have plots that are too far for devices to reach the locally deployed gateway. As there is also very little alternative for the gateway location because it has to be powered, we tested the relaying feature that we developed some years ago in the H2020 WAZIUP project [13]. The PCB v4.1 can be used to build a relay node running on a 2xAA battery just like a regular end-device. In INTEL-IRRIS, it was a strong requirement to have the relay nodes only differing from end-devices by the uploaded software. The relaying principle is illustrated in Fig. 7.

The method we proposed in [13] is based on an observation phase where the relay node is added to the network after the deployment of both the end-devices and the gateway. It will then discover and learn the pattern of uplink transmissions from end-devices. By default for INTEL-IRRIS, all sensing devices are configured with a fixed transmission period of 60mins although this value can be changed before deployment. Each one may be powered up at a different moment. This approach of using an observation phase is illustrated in Fig. 8 where 8 devices are covered by a unique relay node.

In addition to the observation period that determines the various wake up moments for the relay node, there is a guard time window prior to each wake up where the relay node wakes up periodically for a very short time, e.g. every 100ms, to run a Channel Activity Detection (CAD) procedure with the LoRa radio. If activity is detected, typically because of a packet preamble, then the relay node switches to receive mode in order to catch the uplink transmission. The guard time window is necessary because the clocks of the devices and relay nodes are not synchronized and can drift away quite significantly due to the low cost electronic hardware. The CAD-based mechanism limits the energy consumption during this guard time window while the observation phase allows the relay node to go into deep sleep between each wake up. Our work on LoRa relaying was realized before this issue was taken into account by the LoRaWAN specification. Recently, a LoRaWAN relay specification has been released using only the periodic CAD procedure to scan for radio activity [14]. This approach consumes more energy and is better adapted to denser traffic as found in urban IoT deployment scenarios. We believe our solution is more suitable when deploying a smaller scale sensing infrastructure for individual farms.

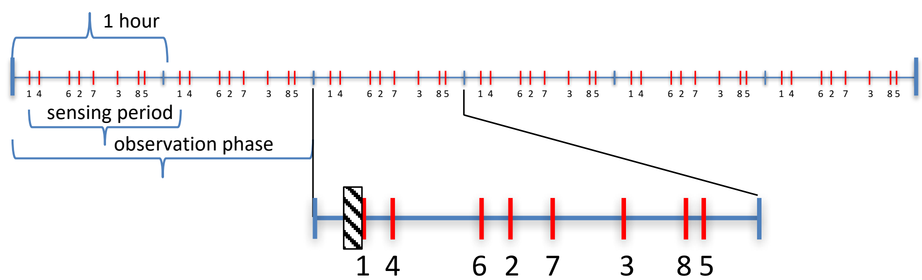

Fig. 8. Relaying with observation phase and short activity detection. The relay listens to its neighbors (observation phase) during more than a sensing period (1h), then uses Channel Activity Detection (CAD) to detect and forward frames.

3.6 Reducing further the relaying traffic

When introducing relay nodes in countries where there are regulations on the radio activity time per device, known as duty-cycle restrictions, there must be a mechanism to reduce the uplink traffic of the relay node which would otherwise be N times the traffic of a single node, N being the number of devices covered by the relay node.

There are 2 simple solutions to reduce uplink traffic: (i) increasing the time between 2 measures and transmissions at the device in an adaptive way and, (ii) the devices themselves avoiding transmitting similar values. One drawback on these solutions is the lack of global vision or knowledge that could be used to reach a given objective. For instance what "similar values" mean? Obviously an interval should be defined to consider 2 values as similar to avoid transmitting an update. If this decision is left to the device, then data coming from other devices can not be taken into account to optimize further the similarity detection towards a given objective. Therefore, we took the opportunity of the INTEL-IRRIS piloting program to integrate in the experimental deployments the uplink traffic reduction mechanism by similarity detection with data suppression proposed in [15]. The general approach of this method is described in Fig. 9 where data sent from 3 devices are considered.

At a first look, it enhances the previous relaying task of Fig. 8 with an additional data similarity detection procedure which objective is to determine the messages from devices deployed downstream that can be removed from the list of uplink transmissions to the gateway. However, by receiving data from all downstream devices, the relay node can implement a more sophisticated similarity detection and value suppression mechanism. In the approach proposed in [15], not only similarity detection can be realized for data coming from a given device, but data coming from different devices can also be considered similar under some conditions. Therefore, beyond value similarity, relay nodes can implement a device similarity leading to the concept of redundant device. Several criteria can be used to define whether data from devices can lead to device redundancy. In [15] we experimented and made a proof-of-concept using Euclidean distance but there are other metrics such as cosine distance, Jaccard similarity, Bray-Curtis distance, Canberra distance, etc. More detail on the proposed algorithm, implementation and energy consumption can be found in [15].

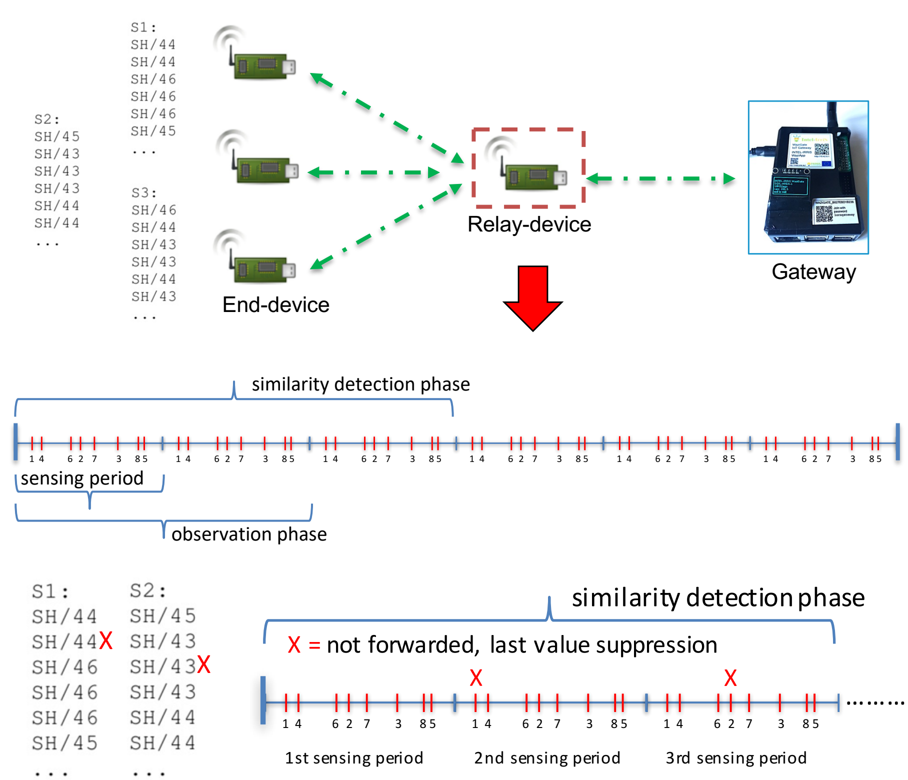

Fig. 9. Reducing uplink traffic with similarity detection. Relays avoid forwarding similar values in their covered zone, following a given criteria [15].

3.7 Results and lessons learned

Introducing digital technologies is always a trade-off, and this is particularly true when targeting the smallholder farmer communities that are running small scale farms. With the INTEL-IRRIS project which proposes Wireless monitoring systems to optimize the irrigation process there were a number of design choices that were dictated by this trade-off.

In addition to the obvious cost parameter, the proposed system must be simple and robust to be deployed by farmers themselves. Then, the system must be flexible enough to be incrementally scaled, again by farmers themselves. The system must run and provide information to the farmer without relying on Internet connectivity, and certainly not on cloud storage or external servers. To increase technology adoption and innovation capacities from local actors, the system should be open and interoperable, as well as being able to easily integrate systems provided by third-parties, provided that data format are available. For the particular case of irrigation addressed by INTEL-IRRIS, the system must be versatile enough to be integrated into existing irrigation infrastructures, different crop cultures and/or farming practices.

We believe the system we presented satisfies these requirements. The cost-effective design resulting in an open, robust, generic and versatile hardware platform to build efficient sensing systems can be adopted and improved by local actors. The robust, yet simple, integration has been validated and proved robust enough for outdoor harsh conditions. With long-range LoRa technology and pre-configuration of devices, the starter kit can be deployed out-of-the-box by farmers themselves. Connectivity issues can be solved by introducing a simple and transparent relay node that runs autonomously. Incremental addition of devices, including those from commercial market, is possible based on the evolution of the farmer's needs. Of course, in that case, technology support may be needed and can be provided from either governmental agriculture services, cooperatives or entrepreneurs. The "fully autonomous" approach with all data management and processing on the locally deployed IoT gateway is positively perceived by farmers who are reluctant to use Internet clouds, either because of trust or simply because a permanent Internet access is complex to be deployed by smallholders in remote rural areas as most of the farmers only connect to Internet from their smartphones.

4 Embedding intelligence

INTEL-IRRIS's objective is also to implement the "intelligent irrigation in-the-box" concept to validate the fully edge-mode approach for the SHF communities. The project develops 2 components as proof-of-concept: (1) a web-based platform running as a separate application on the IoT gateway (previously referred to as WaziApp) and (2) the integration of AI processing on the IoT gateway.

4.1 INTEL-IRRIS Irrigation WaziApp

On top of the generic dashboard, INTEL-IRRIS develops the INTEL-IRRIS Irrigation WaziApp (IIWA) which is a dedicated WaziApp for the project. Such dedicated WaziApp permits us to propose additional features specific to a particular application domain: better data visualization charts, additional data filtering and processing tasks, configuration of application-dependent parameters, etc. This approach appears more flexible and simpler to maintain than a separate mobile app. Running locally on the WaziGate itself, the WaziApp has access to all collected sensor data. The application is itself accessible once the user is connected to the gateway's WiFi access point, thus no Internet connection is needed. IIWA is built as a Python microservice with Docker. It primarily includes a Python program with HTML/CSS and JavaScript for the user-interface. It gets access to sensor's data using the well-defined WaziGate REST API.

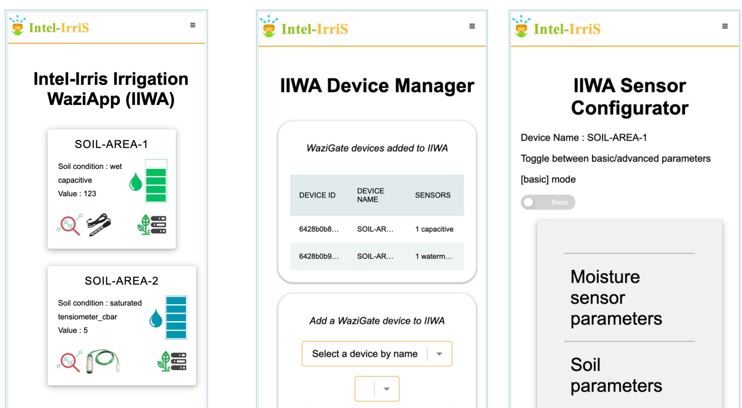

Fig. 10. The INTEL-IRRIS Irrigation WaziApp, IIWA. IIWA adds features to the interface specific to the context: e.g. crop and sensor types impact data processing.

For the purpose of irrigation optimization, IIWA offers advanced calibration and parameter configuration features: sensor type, soil type, soil salinity, soil bulk density, crop type, etc. These parameters can be defined at both the global level and individual sensor level. Of course, in the case of the starter kit, many of these parameters will be pre-configured for the farmers. It is expected that some parameters would still need to be manually selected by the end users among a list of propositions, e.g. soil type: clay, sandy, silty, peaty, chalky or loamy. To increase technology adoption, IIWA has multi-language support. Fig. 11 shows the Arabic version.

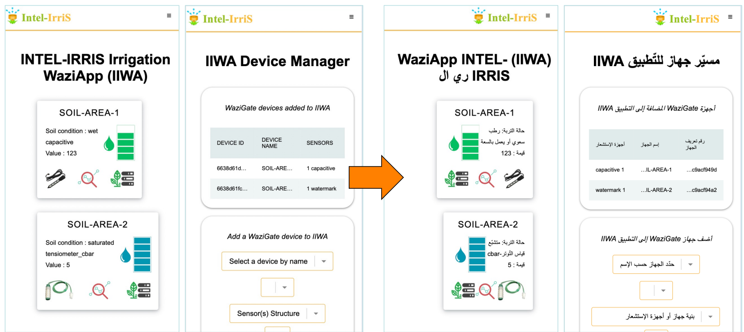

Fig. 11. Multi-language support in IIWA.

4.2 Edge-AI processing framework

The Edge-AI framework is a new component of the WaziGate ecosystem and provides both online and offline AI training capability. It consists of an environment for developers/users to conduct Artificial Intelligence and Machine Learning (ML) tasks.

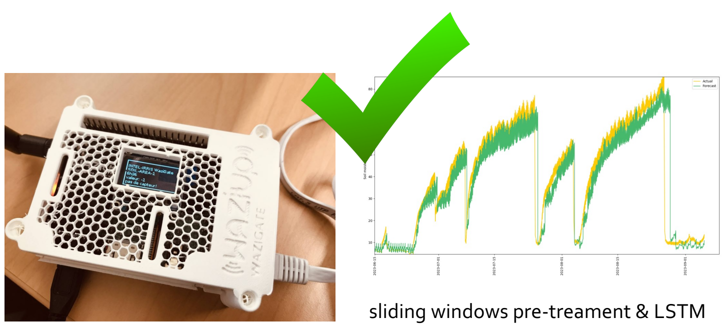

Fig. 12. Prediction of soil moisture with embedded AI. These preliminary results encourage further studies.

A dedicated system-oriented WaziApp with the full Jupyterlab functionality has been packaged as a Docker container where various ML packages with several regression models are available for developers. This framework is described in more detail in [16].

INTEL-IRRIS uses the WaziGate Edge-AI framework to implement a proof-of-concept of embedded soil moisture prediction based on AI/ML model: an LSTM network (Long Short-Term Memory) is applied on the time-series, e.g. from the collected soil moisture measures from devices (Fig. 12). Such predictions can then be fed back into the IIWA in order to include an AI-based prediction model in the application, and help the farmers in adjusting their irrigation plan. It is also possible to run several prediction models (in parallel on separate WaziApps) and let IIWA and/or the user select which model to use depending on local conditions and needs.

4.3 Going further with advanced AI methods

For the particular case of smallholder farmers and small-scale farms, 2 innovative AI/ML techniques show many promises: Federated Learning (FL) [17] and Transfer Learning [18]. The main interest of FL resides in the fact that farmers do not need to share their data with a central server in order to contribute in improving AI models for local agriculture needs. For TL, the main interest is to improve the efficiency of AI models when the size of the dataset is small. INTEL-IRRIS conducted preliminary work on FL and TL in Algerian and French farms using data collected by the various starter kits that have been deployed.

5 Conclusions

We presented INTEL-IRRIS's robust, cost-effective, power-efficient, wireless and fully autonomous sensor system for out-of-the-box deployment that was developed for the smallholder farmer communities. The proposed solution can be quickly deployed with a minimum of technological infrastructure, even in very remote and rural areas as it does not rely on Internet connectivity for remote clouds/servers. Piloting programs with agriculture service advisors and more than 60 SHFs validated the "fully autonomous" and "out-of-the-box" deployment approach in Algeria and Morocco.

The open and versatile hardware platform can be used with numerous other types of physical sensors to extend the range of applications. For instance, leveraging on INTEL-IRRIS's results, the developed framework has already been extended in the ANR PEPR AgriFutur project to develop a wider range of sensors to better qualify and quantify the impact of agroecological practices. With PCBA that can be ordered fully assembled from the PCB manufacturer, hardware availability for scaling-up should not be an issue. However, the production of starter kits would need a local technology actor that would take care of the integration.

At the moment, embedded AI is still a proof-of-concept and the starter kit can be used to build datasets that are more representative of the local conditions and farmer agricultural practices. Future work on Federated Learning and Transfer Learning, that are particularly adapted technologies for the smallholder farmer communities, will be conducted to seamlessly integrate these features into the autonomous sensor system framework.

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References

1. C. Pham, A. Rahim, P. Cousin. Low-cost, Long-range Open IoT for Smarter Rural African Villages. *Proceedings of IEEE ISC2*, Trento, Italy, Sep. 12-15, 2016.
2. C. Dupont, T. Bures, M. Sheikhalishahi, C. Pham, A. Rahim. Low-cost IoT, Big Data, and Cloud Platform for Developing Countries. *Proceedings of GECON'2017*, Biarritz, France, September 19-21, 2017.
3. C. Briciu-Burghina, J. Zhou, M.I. Ali, F. Regan. Demonstrating the Potential of a Low-Cost Soil Moisture Sensor Network. *Sensors 2022*.
4. P. Vandôme, S. Moinard, G. Brunel et al. A low cost sensor to improve surface irrigation management. *Precision Agric 25, 3072–3085, 2024*.
5. J. Dafonte, M.Á. González, E. Comesaña, M.T. Teijeiro, J.J. Cancela. Soil Water Status Monitoring System with Proximal Low-Cost Sensors and LoRa Technology for Smart Water Irrigation in Woody Crops. *Sensors 2024, 24, 8104*.
6. R. Nandi, D. Shrestha. Assessment of Low-Cost and Higher-End Soil Moisture Sensors across Various Moisture Ranges and Soil Textures. *Sensors 2024, 24, 5886*.
7. S. Steinbach et al. Low-Cost Sensors and Multitemporal Remote Sensing for Operational Turbidity Monitoring in an East African Wetland Environment. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 17, pp. 8490-8508, 2024*.
8. E. Ebstu, S. Hatiye, D. Goshime et al. Development and Testing of a Low-Cost Soil Moisture Sensor for Real-Time Irrigation Scheduling. *Irrigation and Drainage 1–15*.
9. C. Pham. `https://github.com/CongducPham/PRIMA-Intel-IrriS`
10. WAZIUP e.V. Wazigate. `https://github.com/Waziup/WaziGate` and `https://www.waziup.org/iot-edge-platform/#wazigate`
11. C. Pham. `https://github.com/CongducPham/LowCostLoRaGw`
12. C. Pham. `https://github.com/CongducPham/PRIMA-Intel-IrriS/blob/main/Tutorials/Intel-Irris-antenna-test.pdf`
13. M. Diop, C. Pham. Increased flexibility in long-range IoT deployments with transparent and light-weight 2-hop LoRa approach. *Proceedings of WD'2019*, Manchester, UK, April 23-25, 2019.
14. LoRaWAN Alliance, *LoRaWAN Relay Specification TS011-1.0.0*.
15. C. Pham, A. Makhoul, M. Diop. Similarity Detection for Smart and Transparent Long-Range IoT Relaying. *Proceedings of ISCC'19*, Barcelona, Spain, June 30-July 3rd, 2019.
16. C. Pham et al. Deploying low-cost and full edge-IoT/AI system for optimizing irrigation in smallholder farmers communities. *EAISA'2022 Workshop on Edge AI for Smart Agriculture, co-located with IE'2022*, Biarritz, France, June 20-23, 2022.
17. H. K. Kondaveeti, G. B. Sai, S. A. Athar, V. K. Vatsavayi, A. Mitra, P. Ananthachari. Federated Learning for Smart Agriculture: Challenges and Opportunities. *Proceedings of ICDCECE'2024*, Ballari, India, 2024.
18. A. S. Zahraa, A. Mariette. The power of transfer learning in agricultural applications: AgriNet. *Frontiers in Plant Science, Vol. 13, 2022*.